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Channel Patterns of the Grand River in Southern Ontario, Canada—An Example in a Post-Glaciated Landscape

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CHANNEL PATTERNS OF THE GRAND RIVER IN SOUTHERN ONTARIO, CANADA - AN EXAMPLE IN POST - GLACIATED LANDSCAPE

By

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ABSTRACT

River channel patterns are recognised as important features associated with the dynamic system of stream flow. This study examines different channel patterns and the associated geometric variables of a section of the Grand River. It also suggests different interrelationships of the geometric variables for different channel patterns. Comparisons are made between the channel characteristics and other experimental, theoretical and field examples discussed in the literature review.

The study was carried out in a section of the Grand River between Kitchener and Paris. This section was further divided into an upper reach, between Kitchener and Cambridge, and a lower reach, between Cambridge and Paris.

Descriptive statistics, map and aerial photograph interpretation, and statistical correlation method are employed in the analysis. In particular, varied bed topography, variation of the width-depth ratio and floodplain confinement serve to indicate the differences between this section of the stream and the results found in alluvial streams with low gradients.

This study has found it useful to differentiate channel patterns as straight, meandering or braiding in a general way. The upper reach is pseudomeandering and has high topographic sinuosity index. The thalweg slope is flatter than in meandering patterns. The floodplain is wide and vegetated, thus reducing the erosional capability of the reach. However, some portions of the reach are incising and irregular bends are common.

The lower reach is straight, and braided in some portions, and has rapids. The thalweg slope is steeper than the upper reach showing nickpoints in some sections. The high rate of increase in depth compared to width increases the erodability of the stream. Most of the reach is incising.

Interrelationships between the geometric parameters between the study reaches are indicators of differences in channel patterns. The lower reach has higher correlation coefficients than the upper reach, although the adjustment of width is more significant in the upper reach than the lower reach. On the other hand, depth is more significant in the lower reach than the upper reach.

Thalweg slope is applied as an independent variable. The use of channel symmetry as a technique in channel pattern investigation compares well with the application of the sinuosity ratio. Topographic sinuosity index and valley symmetry have served to explain some of the impacts of the inherited slope on channel pattern development.

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CHAPTER 1

INTRODUCTION

This thesis investigates the channel patterns of two reaches of the Grand River.

Channel patterns are dependent on the hydraulic factors which are in turn controlled by climate and the geohistory of a region.

Geomorphologists believe that the study of river patterns can provide a good indication of past and present processes. To a large extent, this is the procedure used to predict future channel erosion and sedimentation by hydraulic engineers and hydrologists (Gregory, 1977, pp. 2 - 12).

Flood studies and landuse and management seem to have generated research on the Grand River in response to the disastrous effects of unusual weather conditions. Among the major reports are those by the Ministry of Mines and Forestry in 1962 and 1964, published by the Government of Ontario and Mitchell, et al, (1977) investigation of the management problems of the flood prone municipalities. Attention has also been given to the fluvial processes and sedimentology of some neighbouring streams and tributaries of the Grand River. Martini (1977) did a sedimentological study of Irvine creek, near the Elora gorge. Gardner (1977) has also researched into the geomorphological aspects of the Conestoga River and the Grand River. But little has been done to analyse channel patterns and the contribution of the geometric parameters.

STATEMENT OF THE PROBLEM

The geometric variables of a stream both describe and themselves contribute to the development of channel patterns. These are the main concern of the present study. In addition, the incremental effect of flow on a cross sectional shape and other geological and river training structures are used to explain the observed channel patterns.

The objectives of the study are fourfold:

(a) to make comparisons between alluvial streams and streams occupying post-glaciated landscapes whose valleys are not particularly products of their present regimes,

(b) to relate the effects of topography on channel pattern development,

(c) to show how distinctive the upper reach and the lower are according to morphological differences and similarities,

(d) to suggest some levels of change of geometric variables using slope as an independent variable.

The geometric variables used to achieve these objectives include slope (of the floodplain and the thalweg), width, depth, width-depth ratio, shear velocity, slope-width ratio, channel and valley symmetry. Cross sectional shapes and estimates of discharge variations are also included to explain the impacts of floods on channel pattern development.

METHODOLOGY

Several geometric factors have been associated with different channel patterns (meandering, braiding and straight). These patterns can be shown qualitatively from topographical maps and aerial photo mosaics, and quantitatively by measuring the form plan of the patterns. However, an insight on the formation and development of channel patterns can be gained considering the major geometric factors (valley and thalweg slopes, width and depth). For ease of comparison, the study area is divided into two reaches from which data were acquired and analysed.

A reach is defined as any length of a channel, or any appropriate length, of which hydrological and geological conditions remain sufficiently uniform. The site locations are given in Table 1.2 below. The following conditions were also considered important for data collection and analysis:

(a) the availability of data on stream depth;

(b) the availability of 1:25,000 topographical maps and aerial photo mosaics for location and pattern identification within each reach. The topographical map references are given in Table 1.1 below.

(c) both are reaches where it is reasonable to assume relatively minor human interference, i.e. the urbanised sections were omitted.

TABLE 1.1

TOPOGRAPHICAL MAPS USED IN THE STUDY

Title	Scale	Copyright
Kitchener-Breslau	1:25,000	series 40P/8e, edition 2, 1976
Cambridge-Preston	1:25,000	series 40P/8f, edition 2, 1976
Galt	1:25,000	series 40P/8c, edition 2, 1968
Brantford-St. George	1:25,000	series 40P/1f, edition 2, 1976

The section of Grand River between Kitchener and Paris seemed close by, had the required information and distinct channel patterns. From the preliminary survey of topographical maps and aerial photo mosaics, it seemed possible to divide the area of study into two reaches based on geometric characteristics. The upper reach is between Kitchener and Cambridge, a stretch of approximately 14 miles. The lower reach is between Cambridge and Paris, a stretch of approximately 10 miles.

TABLE 1.2

LOCATION OF THE STUDY REACHES IN LATITUDES AND LONGITUDES

Reach	Latitude	Longitude
Upper reach	43°23'24"N 43°29'22"N	80°22'30"W 80°28'15"W
Lower reach	43°12'30"N 43°20'54"N	80°21'54"W 80°21'54"W

Source: Topographical Maps.

The data collection was done from two sources. First, from topographical maps and aerial photo mosaics, and secondly from cross sectional data from the Grand River Conservation Authority.

The general physiography and channel patterns were interpreted using topographical maps and photo mosaics. The basic equipment used was a planimeter and a stereoscope. This information was then spot-checked for ground truth in the field. Comparisons were also made between the 1955 and 1972 aerial photo mosaics, but no difference was observed. These morphological features are relatively permanent under contemporary conditions in most years.

The valley and channel lengths were measured, in yards, from topographical maps to scale 1:25,000 with a 10 foot contour interval. These measurements (valley and channel lengths) were used to calculate valley slope and sinuosity indices.

The cross section of the Grand River had been surveyed for the Grand River Conservation Authority by an engineering consultancy. The cross sections were surveyed and recorded as elevation and distance in H-4 format. An example of this format is given for station 113 in Table 1.3. The survey was downstream from the left bank to the right bank. The interval of the cross sections along the channel vary from 100 feet to about 2,000 feet apart. The reasons why these intervals were selected are not known to me or to the Grand River Conservation official in charge of data collection.

The floodplain was taken to be delineated by the elevation where a maximum flood of 56,000 cfs at Galt, and of 26,000 cfs at Doon gauge could be conveyed within the floodplain. The lower reach conveys higher discharges than the upper reach.

OPERATIONAL DEFINITIONS

(a) Channel patterns refer to the two dimensional shape of a stream channel as determined from the air or a map (Mueller, 1967, p. 372).

(b) A constrained channel pattern, adopted from Lewin and Brindle (1977, P. 222), means a channel which impinges against, or is partly developed in a media which alter the form or alter the rate of develop-

TABLE 1.3

CROSS SECTION DATA FORMAT

1	2	3	4	5	6	7				
X113	32.0	270.0	524.0	3400	3350.0	3600.0				
	A	B	C	D	E	F	G	H	I	J
GR	996.2	0.0	980.6	60.0	980.5	130.0	977.5	137.0	975.2	153.0
GR	973.1	230.0	970.9	270.0	969.0	350.0	970.4	455.0	970.0	500.0
GR	970.5	524.0	976.2	543.0	978.9	549.0	970.5	580.0	972.0	590.0
GR	982.6	620.0	977.2	636.0	978.6	770.0	974.3	837.0	975.4	900.0
GR	980.0	930.0	980.6	1057.0	989.0	1160.0	990.0	1173.0	990.8	1208.0
GR	1021.3	2160.0	1027.1	2298.0				2046.0	1022.5	2137.0

Key

1. Cross section number
2. Number of data points
3. Distance at left bank, facing downstream
4. Distance at right bank, facing downstream
5. Distance to next station on left bank
6. Distance to next station on right bank
7. Distance to next station in the channel

A Elevation
B Distance
C Elevation
D Distance, E, F, G, H, I follow the same pattern.

ment in comparison to locations where such confinement is absent.

(c) Slope, also referred to as gradient, is the average fall in a vertical section between two points compared to the horizontal distance between the same points.

(d) A negative slope, also referred to as a "non-sustaining slope", applies where the rate of change is not constant or reverse in the downstream direction.

(e) Sinuosity ratio is the ratio of the channel length, taken approximately at the middle of the stream, to the straight-line distance of the same profile. The following sinuosity indices have been used in this paper:

Hydraulic sinuosity is the percent total sinuosity contributed by channel wandering within the floodplain, while topographic sinuosity is the percent total sinuosity contributed by non-hydraulic factors.

Hydraulic Sinuosity Index (HSI)

$$= \text{\% equivalent of } \frac{CI - VI}{CI - 1}$$

Topographic Sinuosity Index (TSI)

$$= \text{\% equivalent of } \frac{VI - 1}{CI - 1}$$

Where CI is ratio of channel length to air length of the same reach

VI is the ratio of valley length to air length of the same reach

1 is a unit which signifies that HSI + TSI = 100

(Source: Mueller, 1967, p. 375)

(f) Width is the cross sectional distance of the channel from one bank to the other at the water surface, perpendicular to the direction of flow.

(g) Depth is the height of water from the deepest point of the stream to the water surface.

(h) Width-depth ratio is the ratio of (f) and (g).

(i) Longitudinal profile measures the vertical changes of any stretch of the channel in a direction from stream source to mouth or vice versa.

(j) Cross section symmetry is the ratio of stream or floodplain width from the left bank to the deepest point in the stream to total width of cross section. The symmetry of the stream is referred to as channel symmetry, and the symmetry of the floodplain is referred to as the valley symmetry.

(k) Slope-width ratio is the ratio of (c) to (f).

(l) Shear velocity is the speed of stream near the channel boundary.

(m) Stream incision index is a measure of how far the channel has incised its floodplain. It is the ratio of slope of the thalweg to valley slope.

(n) Stream aggradation index is applied to a condition where the valley slope is steeper than the thalweg slope.

CALCULATIONS

Using bridges as starting points, the cross sections were drawn on a tracing paper superimposed on a topographical map. The tracings are reproduced in Appendix 7. The cross section data format is given in Table 1.3 with a key.

From distances at left bank (column 3) and right bank (Column4) the width of the channel was calculated. In case the cross section was not perpendicular to the channel, width was measured from the aerial photo mosaics.

Depth was calculated from the lowest elevation, giving the position of the thalweg. The differences between the left and the right bank elevations were corrected by estimating the angle and the elevation on the topographical maps.

Thalweg slope was calculated as the difference between the upstream and downstrem thalweg elevations. The length of the sections are from column 7 in Table 1.3. There were some sections with non-sustaining slopes. These sections' elevations were omitted, although the distance between them was included in the calculation (see Appendices 2 and 3). The method is an approximation of the hydraulic slope along the thalweg. However, all thalweg points are included in the discussion of the channel bed morphology (incision, aggradation, rapids and braids).

The ratio of the channel width from the left bank to the thalweg to top channel width (channel symmetry) was also calculated from the sections. Valley symmetry was also calculated as the ratio of the floodplain width to the width from the left bank of the floodplain to the channel thalweg.

From thalweg slope, width and depth, other ratios and shear velocity were generated.

SUMMARY

The thesis is composed of four major chapters, and an introduction. In chapter two, the literature related to the study is discussed. This includes the approaches, the variables and results from previous research. Chapter three deals with the study area and includes the general setting of the Grand River basin and the study reaches in particular. The variables used in this study are also discussed. Chapter four deals with the statistical correlation and regression analysis and some geomorphological implications. The results of the study are discussed and conclusions drawn in chapter five.

CHAPTER 2

LITERATURE REVIEW

Theories and relationships of river channel patterns have recently been summarised by Chitale (1977) adding to the classical work of Leopold, Wolman and Miller (1964). Despite extensive work, there is still a need to test and refine existing theories and discover new approaches. Lewin (1977), p. 1979) concluded that:

> ... no general model - perhaps linking patterns and rate of change to channel shape, discharge and water sediment and bank materials - is yet possible ... The purposes, methods and measures are so diverse and diffuse to a confusing extent.

For this reason alone, fluvial geomorphologists are compelled, for river training and landuse planning purposes, to continue the studies to help in selecting some of the important variables which can be used in channel pattern classification.

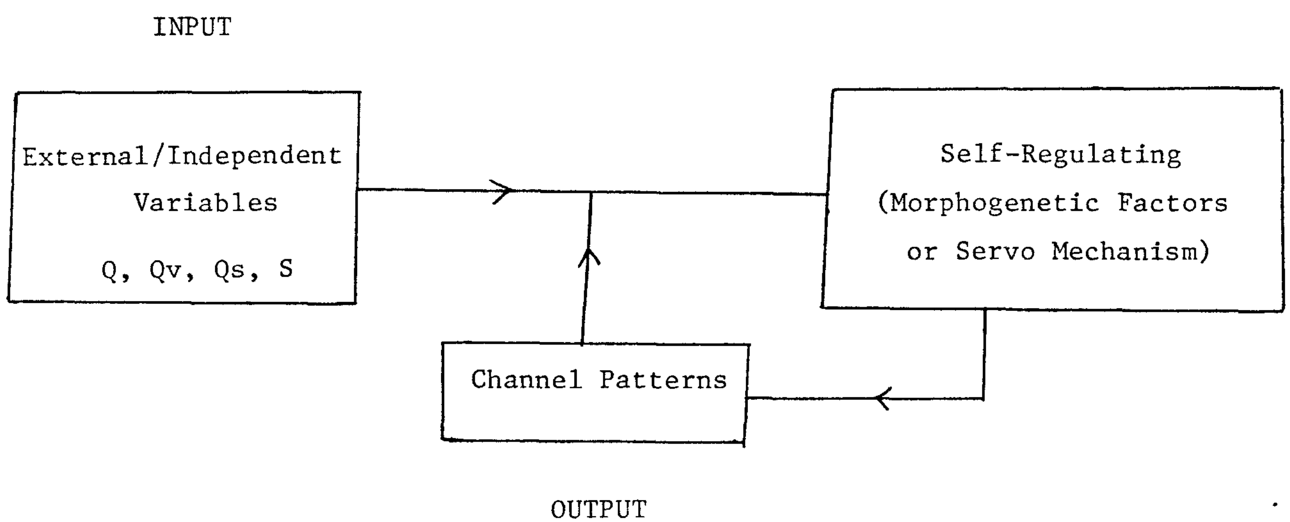
Chorley and Kennedy (1971) had given a start for analysis by reducing the complex physical reality into system components. Two independent or external variables affecting fluvial patterns are climate and geology, the former affecting discharge and discharge variability, and geology affecting sediment discharge and slope. The system components can be summarised as in Figure 2.1.

Apparently the inputs to this system are in a metastable equilibrium, the latter defined as:

FIGURE 2.1

REPRESENTATION OF COMPLEX CHANNEL RESPONSE IN CHANNEL PATTERNS

(adopted from Chorley and Kennedy, 1971, p. 203, with modifications)



> ... where stable equilibrium obtains only in the absence of a suitable trigger, catalyst, or minimum force, which carries the system state over into a new equilibrium regime. (Chorley and Kennedy, 1971, p. 201)

Pluvial cycles and human interference in drainage basins seem the kinds of factors of a metastable equilibrium, a feature not necessarily peculiar to mid-latitude climates.

Discharge has been used most often as an independent variable because of its relative statistical stability and ease of measurement. Its relationship with other variables can be shown in the form of single exponential equations, as has been summarised by Leopold and Miller (1956). Both cross sectional and downstream changes in channel pattern are related to these variables, the latter discussed by Gregory and Walling (1973).

The main prerequisite in the downstream variation of the hydraulic factors is the reliability of the discharge frequency distribution. However, in basins without such refined discharge measurements, the relationship of slope with depth, width and sinuosity and other hydraulic variables can be applied to discuss channel pattern characteristics.

Slope is an important variable in channel pattern development. It is an input in all energy equations, and other factors remaining constant, velocity will increase with an increase in slope. Lee and Henson (1978) found a strong relationship between slope and braiding and meandering channel patterns. Most of the categorizations of channel patterns have been based on differences of slope, as summarized by Chitale (1973).

Much of the research into channel patterns has concentrated on slope differentiation and two approaches to this can be identified. The first group explains slopes as an adjustment due to the decrease in the size of bed load material in the downstream direction. Shulits (1942), Leopold and Maddock (1953), Yatsu (1955), Broscoe (1959), Morisawa (1968), and Tanner (1971) agree in principle with Sternberg (1875) and Gilbert (1914) that slope adjustment is dependent on the downstream increase in discharge and a decrease in bed load size. The basis of this comminution theory is the reduction of the weight of sediment particles as they travel downstream. Comminution refers to the abrasion and/or attrition that wears the material down.

The second approach explains slopes in terms of inherited landscape, and base level changes. Miller (1958), Woodford (1951), Rubey (1952), Brice (1964), Lee (1977), and Lee and Hansen (1978) are some of the examples, although the approach has been criticised for being semi-qualitiative by the latter authors. On the other hand, the comminution theory has a simple solution which is unlikely to portray the physical process and the profiles.

Slope has been correlated to discharge and sediment discharge, Q/Qs. Lane (1955) found relationships between slope and discharge for both meandering and braided streams. Leopold and Wolman (1955) also found relationships between slope, discharge and median size of bed material. Chitale (1973) compared the findings of Lane, and Leopold and Wolman, although without success. Noting the difficulty of measuring sediment discharge in natural streams, it is expected that wide variations are likely to occur.

Schumm and Khan (1971) and Schumm (1977, pp. 138-139) have derived relationships of slope and sinuosity at constant discharge (Figure 3.26 below). Schumm (1977) argues that the channel slope is relatively stable and hence for a river to maintain stability, it will lengthen its course by meandering. Ackers and Charlton (1970) using the concept of limiting slope to channel patterns arrived at a differentiation between straight and meandering streams. Dolling (1968, pp.47-48) found that more sinuous reaches were associated with flat slopes, which in turn were related to bed load size. This is in tune with the ideas of Leopold, et al., (1964, pp. 304-305) about the differentiation between straight and meandering reaches.

Leopold, et. al. suggest that

> although the bed elevations of the meander reach are less regular than those of the straight reach, the reverse is true of bankful energy profile; the profile of the meander reach is more regular than the profile of the straight reach. (p. 305)

Also Yang (1971) using the concept of entropy stated that the stream "chooses" its course in such a way that the time rate of potential energy expenditure, per unit mass of water, P/T, along the channel is minimum. T is time required. Using the equation of conservation of mass and Manning's equation he showed that if P/T is to be minimised for a constant discharge then the stream will meander.

The meandering phenomenon is measured by a sinuosity index, defined as the ratio of longitudinal channel length to a corresponding air length. Schumm (1963) has given the following levels for differentiating channel patterns; 2.3 for tortuous pattern, 1.8 for irregular pattern and 1.7 for regular pattern, 1.3 for a transitional pattern and finally 1.1 for straight patterns. Chitale (1973, p. 286) commenting on these levels of differentiation says that

> these definitions are obviously logical as they follow the concept of a continuum of channel patterns which is normally the law in nature's processes.

Recent work by Savat (1975, pp. 161-180) has confirmed that channel patterns are not mutually exclusive.

Although the sinuosity index is a powerful technique, it masks the causes of meandering itself. For a clear differentiation of causes of meandering, and channel patterns in general, Mueller (1976) has suggested a technique which shows what percentage of tortuosity is contributed by topography and hydraulics. The indices are called topographic and hydraulic indices, which when added gives a 100% sinuosity. This technique is appropriate for isolating the contribution of topography in any type of channel pattern.

While authors (inter alia Leopold, et al. 1964, p. 281; Gregory and Walling, 1973, p. 247) agree that channel patterns overlap, other techniques have been applied to differentiate channel patterns. Direct discrimination between braided and non-braided channels has been done by Leopold, et al. (1964) and Henderson (1965), using discharge, slope and bed materials. Schumm, et al. (1972) have examined sediment discharge and bank material, and Dury (1969 , pp. 418-430) has brought forward a classification based on direct observations.

Channel patterns depend, also on the aggradability and/or degradability of the stream, either on the bed or bank. Differential bed erosion is a typical occurrence in open channels. These are in the form of plunge pools and rapids. Their contribution to erosion and sediment discharge contribute to channel pattern formation. Leopold and Miller (1956) observed that the deposition around a plunge pool proceeds upstream as fast as the plunge pool does. When a plunge pool exists, then deposition is from downstream to upstream, thus increasing the steepness of the adverse slope. When it forms grade of deposition as observed by the authors, the plunge pool also migrates upstream. Secondly, the plunge pool tends to increase depth faster than width causing the stream to be narrow and deep.

This plunge pool process is comparable to the retreat of knick points from the downstream to the upstream section. The contradiction which appears in this approach is that in pools there tends to be adverse bed slope and therefore sediments will tend to settle there, according to calibre. Keller (1971) has noted that sorting in varied bed topography is due to velocity reversal. Apart from the fact that there is lower energy dissipation in pools than riffles, fine sediments associated with pool areas tend to reduce turbulence as Yalin (1972, p. 186) argues it. By this process of flow reversal and neutralisation of turbulence by fine suspended sediment, large calibre sediment (bed-load) are deposited at the boundary of downstream flow profile and suspended sediment is moved back to the plunge pool by reversing flow. Ultimately by this repeated process, the plunge pool is swept clean of bed load.

In any case, slope can be applied to channel patterns study as an independent variable. The evidence shows that it has close relationships with depth, width and channel patterns. Similarly, there is a close relationship between slope and other hydraulic factors, for example, velocity, sediment discharge and bed topography. These relationships also demonstrate that degradability and aggradability of the channel, which in turn can be associated with different channel pattern development, depend on the angle of slope. However, other geometric factors also come into the equations of channel pattern differentiation.

The other variable which has received attention is the width-depth ratio of the channel. Leopold, et al. (1964) found that with decreasing width-depth ratio the sinuosity increases. Reasons for this have not been fully investigated in the literature. Hickin (1974, p. 437) arrived at a relationship between width and the radius of curvature. He noted that the critical curvature, $R_m/w = 2.2$, was always constant. This research was done on the Beatton River in British Columbia.

The above author and Nanson (1975) later used the same data to derive meander migration rate by correlating radius of curvature/ channel width to migration rate of meander bends. They concluded that at channel curvature to channel width of 2.5 to 3.2 there was usually a meander cutoff (Hickin and Nanson, p. 493). By the same analogy, Leopold and Wolman (1957 and 1960) arrived at $\frac{\lambda}{R} = 4$, and $R/w = 2$, where λ is the meander wavelength, R is the radius of channel curvature, and w is the width.

In a theoretical situation, Langbein and Leopold (1966, p. H5) arrived at sinuosities, k, between bend radius, R, of approximately 0.213λ, equivalent to sinuosity ratio of 4.7. Chitale (1973, p. 288) has suggested that sinuosity ratio above 5.0 is rare in nature. In the Langbein and Leopold equation, a "unique" function of sinuosity, w, is approximately 2.2, equivalent to 125°, a feature they refer to as "goose-neck" meander.

A deductive analogy shows that width-depth ratio is therefore related to sinuosity through the process of bend migration, a consequence of erosion. Narrow and deep sections in bends frequently cause maximum depth and bank erosion to lie near the apex of the bend. Probably, the continued bend erosion assists the meander to become "goose-neck" like, ultimately cutting off to reduce sinuosity. By the same argument, Leopold et al. arrived at the conclusion that decreasing width-depth ratio will cause an increase in sinuosity. Chitale (1973, p. 293) concluded that in wide, shallow channels, maximum depth and active bank erosion occur some distance from the apex of the bend thus accelerating the sinuosity of the stream.

Schumm and Khan (1971) have arrived at certain relationships between width-depth ratio and channel patterns. These are summarised in the Table below.

TABLE 2.1

SUMMARY OF THE RELATION BETWEEN WIDTH-DEPTH RATIO AND CHANNEL PATTERNS

Width-Depth Ratio	Channel Pattern
0 - 28.0	Straight Channel
28.0 - 83.0	Meandering Channel
83.0 and above	Straight and Braiding

Source: Schumm and Khan (1971)

Crickmay (1974, p. 21) also found that "all rivers are considerably wider than they are deep". He suggests that in large streams if width-depth ratio is less than 14.0, this probably suggests that an erosive condition prevails. He also noted that mountain streams with width-depth ratio below 12.0 are erosive, conditions involving a prevalence of bed rock in channel and banks, steep gradients and coarse, scanty alluvium. On the other hand, in large streams with width-depth ratios between 14.0 and 26.0, if the channel lies in alluvium, then that alluvium must be fine. Large ratios greater than 30.0 indicate a slowly progressive failture in the channel competence. Table 2.2 below summarises Crickmay's findings.

TABLE 2.2

RELATIONSHIP BETWEEN WIDTH-DEPTH RATIO AND CHANNEL CHARACTERISTICS

	Width-Depth Ratio	Channel Pattern Expected
1.	Depth greater than width	Sediment discharge is mainly silt.
2.	Less than 12.0	Narrow canyon-bound and bed rock exposures. Steep gradient, coarse and/or sandy alluvium.
3.	Less than 14.0	Erosive conditoins prevail.
4.	14.0 - 26.0 Mean of 20.0	Normal in large streams and has correlations with grain size and cross-sectional shape.
5.	Greater than 30.0	Progressive failure of stream competence.

Source: Crickmay, 1974, pp. 21-26.

Width-depth ratio has also been related to silt-clay index in the form; $F = 255.M^{-1.08}$, where F is width-depth ratio, and M is % silt-clay in the perimeter of the channel (Schumm, 1977, p. 108). With increasing width-depth ratio, the percent silt-clay decreases and the bed load increases. This compares well with Crickmay's results in Table 2.2. Leopold and Miller (1956, p. 31) too observed that:

> ... at a given discharge, the same suspended sediment load will be carried by a narrow, deep channel at a particualr velocity as in a wider shallower channel at a rather higher velocity.

Meandering channels are associated with sediment discharges with a high percent of clay and silt. On the other hand, braided channels are associated with bed load. These thresholds are discussed in detail because they form the basis of channel pattern classification.

Width-depth ratio, therefore, is significant in channel pattern development and classification. The connecting factor between development and classification is the fact that deeper channels have relatively higher velocity than wider channels, other hydraulic factors being similar. This consequently leads to higher erosive ability of deeper streams than wider ones, causing an increase in sediment discharge. Different sediment calibres can also be associated with different width-depth ratios. However, critical conditions occur where the erosive capability diminishes and deposition begins to occur. These critical conditions can therefore be related to straight, meandering and braiding channels.

Cross sectional symmetry has some implications on the velocity and energy distribution in a channel. Much hydraulic research has concentrated on planimetric symmetry or asymmetry (Leopold and Wolman, 1955, Einstein and Shen, 1964, Leopold et al., 1964, Allen, 1977, many others).

Dollings (1968) applied channel symmetry in a study on Bronte Creek in southern Ontario. He measured how the thalweg moves from one side of the channel bed to the other. This measurement is independent of the alignment of the valley section, unlike the present method of determining general sinuosity index. Channel symmetry will, therefore, create a connection between meandering streams and other channel pattern types, and is related to spiral motion and/or super elevation.

Einstein and Shen (1964, p. 5240) applied the theory of vortices to explain the spiral motion in a meandering stream. The authors concluded that the spiral motion was associated with the formation of alternating bars. While many authors agree that this is a prerequisite in meander development, the formation of point bars does not explain meander initiation. Further on the scale, point bar formation is suggested to be induced by spiral motion itself. On the other hand, Allen (1977, p. 22) argues that the super-elevation in meanders is a natural process of fluid flows. Goryki (1973) attributes the super-elevation to channel drag caused by channel roughness, which compares well with Bagnold's (1960) and Rozovskii's (1961) arguments on the theoretical concentration of transverse pressure and centrifugal forces in the downstream direction. The imbalance of forces lead to point bar formation (Leopold, et al. 1964, p. 299) which is a prerequisite in meander bend formation. Similarly Jackson II (1975) applied the bed cross sectional profile by calculating velocity-bedform-texture of meanders to estimate spiral motion, making it possible to predict bed symmetry (p. 1520). When different channel patterns are being compared, it seems possible that symmetry study is likely to be more appropriate than the valley wandering, which although explains the symmetrical/asymmetrical velocity distribution in a cross section, does not show the origin of alternating bars.

Channel symmetry, being related to spiral motion, super elevation and velocity-bedform-texture of the channel, moves the search for describing meandering phenomenon closer to its initiation. However more research is needed in this area to arrive at thresholds for different channel patterns. In the meantime the complexity of changes in a stream has also received attention.

The latest trend is to study the dynamic changes of geometric properties associated with different channel patterns. However, channel patterns evolve over time and they are open systems in a state of flux. Climatic and geological changes and human interference affect the proper analysis of the natural channel which is necessary for pattern change prediction (Gregory, 1977, p. 1-2). Much work is therefore concentrated upon channel pattern changes, but complex responses (Schumm, 1973) indicate that similar streams can react differently to what is seemingly the same change. This appears to depend on the level of thresholds of change. Schumm and Khan (1972) and Hickin and Nanson (1975) have, however, studied some thresholds of change in meandering and braiding streams.

The other difficulty of studying changes in channel pattern is that the plan form is stage dependent (Kellerhall et al., 1976, p. 82). Thus braid bars are usually only inundated during high discharges. Richards (1976, p. 75) found that as discharge increases, the difference in the energy grade line becomes uniform, thus eliminating the marked differences in bed topography. This has also caused criticism of the categorisation of streams as stable or unstable, a rather relative term which takes no account of horizontal aggradation or degradation (Chitale, 1973, p. 286; Schumm, 1977, p. 137). The term unstable would seem best reserved for cases of an appreciable change in bed levels of a channel, caused by flow (discharge) variability.

Apart from empirical approaches to the problems of channel pattern classification, the experiment done by Hickin (1969) explaining the process of pseudomeandering is important for explaining some stream patterns in glaciated landscapes. Firstly, these are confined by a floodplain which is not a product of the stream itself. Secondly, because the streams have, as in the case of the Grand River, steep slopes which is a characteristic of critical condition of flow.

Hickin carried out a flume experiment to corroborate the findings of Wolman and Brush (1961) on pseudomeandering theory. The latter had found that the phenomenon occurred when flow was critical, i.e. Froude number was equal to unity, nF = 1.

Hickin points out that the formation of the outer channel and the development of the braid implied that the stream was unstable and therefore not in equilibrium with the channel and bed topography. The argument compares well with Schumm and Khan (1977). Hickin further points out that "depth became stable after a longer run than width", an indication that flow was laterally deflected with minimum vertical erosion.

From the sequence of changes in the five stages of channel and bedform, it can be seen that, first, bed material movement started at supercritical flow (bed profile out of phase with energy profile and nF ≃ 1), leading to the formation of dunes at the upstream end of the flume. The occurence of dunes in the middle of the channel cross section created divergent flows which eroded the banks of the stream, and increased the rate of sediment discharge.

This is the beginning of the multiple-thread channel according to this experiment. Erosion of the banks of the channel caused rapid increases in width, associated with greater velocity in the outer channel than the inner channel. Since the outer channel was more eroded than the inner channel, with its higher discharge, it conveyed more of the sediment discharge than the inner channel.

During this process of erosion, transport is concentrated in the outer channel and the inner channel forms a semi-depositional environment. It seems possible that dune formation causes the deflection of high magnitide isovel to the outer channel and increases the general sinuosity of the reach.

Several important factors become apparent from these observations. The bar island remained comparatively stable because the outer channel, which has high velocity and most of the discharge, detoured the bar. The inner channel carried little discharge, with low velocity, causing little erosion to the channel geometry. The channel remained comparatively small, although silt and sand were likely to deposit along it. Meanwhile, with an increase in discharge, the velocity distribution over the section split according to depth variation, thus creating a similar island of low velocity over the bar.

These dynamic changes of width and depth with changes in slope are tested in the pseudomeandering tendency of the upper reach.

The above work appears to establish that slope can be an independent variable for discriminating changes in channel patterns. Different variables mostly tested for this relationship are width, depth, width-depth ratios, sinuosity, velocity and sediment discharge. One of the most systematic studies of different channel patterns has also been by Schumm and Khan (1972).

In a flume experiment, Schumm and Khan (1972) showed the dynamic changes of slope to changes in width, depth, width-depth ratio, velocity and bed load. The findings are given in Table 2.3. The columns are changes in slope and equivalent changes in the other variables. Table 2.4 shows the ratios of change from one series of experiment to the next. Since slope is an independent variable, the ratios of change are calculated as column 2 over column 1; column 3 over column 2; and so on. This is done for ease of comparison with data from the Grand River.

In Table 2.3, in a meandering pattern, mean width increases slowly as compared to increase in slope. On the other hand, in braided patterns, width increases slowly and remains constant. In a straight pattern, initially width increases faster than slope, then remains relatively constant.

TABLE 2.3

COMPARISON OF CHANNEL PATTERNS
AND HYDRAULIC GEOMETRY

Source: Schumm and Khan (1972, pp. 1758-1758)
Discharge constant while slope is varying as shown by columns

Meandering Pattern	1	2	3	4	5	6	7	8
Slope	.0026	.0043	.0059	.0064	.0075	.0085	.010	.013
Mean Width	3.10	3.80	4.0	4.1	4.5	4.7	4.7	4.9
Maximum Depth	0.108	0.112	0.10	0.094	0.090	0.084	0.074	0.07
Width-Depth Ratio	28.8	34.0	40.0	43.6	50.0	56.0	63.6	70.0
Velocity (at pool in fps)	0.82	0.94	1.08	1.13	1.13	1.2	1.22	1.35
Bed load (gm/min)	190.0	240.0	353.0	388.0	425.0	430.0	512.0	563.0

Braided Pattern	1	2	3	4
Slope	0.015	0.016	0.018	0.02
Mean Width	5.1	5.3	5.47	5.63
Maximum Depth	0.06	0.057	0.057	0.054
Width-Depth Ratio	85.0	93.0	96.0	104.0
Velocity (at pool in fps)	1.7	1.93	2.14	2.4
Bed load (gm/min)	738.0	825.0	926.0	1,003.0

Straight Pattern	1	2	3
Slope	0.00010	0.001	0.002
Mean Width	1.16	2.15	2.20
Maximum Depth	0.17	0.12	0.112
Width-Depth Ratio	6.8	17.9	19.7
Velocity (at pool in fps)	0.78	0.80	0.80
Bed load (gm/min)	119.0	134.0	147.0

TABLE 2.4

RATIO OF CHANGE OF HYDRAULIC GEOMETRY AND CHANNEL PATTERNS

Discharge is constant, and columns are according to variation in slope

Meandering Streams

	1	2	3	4	5	6	7
Slope	1.65	1.37	1.08	1.17	1.13	1.76	1.30
Mean Width	1.23	1.05	1.03	1.10	1.04	1.00	1.00
Max. Depth	1.04	0.89	0.94	0.96	0.93	0.88	0.95
W/D Ratio	1.18	1.18	1.09	1.15	1.12	1.14	1.10
Velocity	1.15	1.47	1.05	1.06	1.02	1.11	1.13
Bedload	1.26	1.47	1.10	1.01	1.04	1.19	1.10

Braided Streams

	1	2	3
Slope	1.07	1.13	1.11
Mean Width	1.04	1.03	1.03
Max. Depth	1.05	1.00	0.95
W/D Ratio	1.14	1.10	1.12
Bedload	1.12	1.12	1.08
Velocity	1.14	1.11	1.12

Straight Streams

	1	2
Slope	1.70	1.18
Mean Width	1.85	1.02
Max. Depth	1.06	0.93
W/D Ratio	2.63	1.10
Velocity	1.03	1.00
Bedload	1.13	1.10

Data Source: Table 2.3

The table also shows that depth decreases slowly in a meandering pattern up to a width-depth ratio of 70.0, becoming almost constant for incipient braiding pattern.

In a straight pattern, width also increases with increase in slope, although width increases faster than slope. Again, depth decreases. The rapid increase in width causes an increase in width-depth ratio while velocity and bed load remain comparatively constant for the three runs of the experiment. This means that at slope of 0.015 the stream begins to braid if velocity and width-depth ratio is greater than 0.8 ft/sec. and 85.0 respectively, first, due to increased velocity and two, due to limiting slope.

In all types of patterns, bed load progressively increased with slope and velocity which cause an increase in width-depth ratio, although in straight pattern, velocity and bed load increased more slowly than in meandering and braiding patterns. This also appears in the slow increase in width-depth ratio in a straight pattern.

The threshold of depth changes in various channel patterns is difficult to identify from the experimental results. However, the systematic changes in depth are compensatory to changes in slope, velocity and width-depth ratio. From the tables above, width-depth ratio changes seeem to explain the threshold changes more than width or depth when viewed singularly.

From Table 2.3, Froude number, $v/\sqrt{gD}$, where

v = velocity
g = gravity constant
D = depth,

was calculated. Froude number has been associated with different channel pattern formations and erosional capability of flow. Scheidegger (1969, p. 209) shows that free meandering will not occur when Froude number is greater than unity (nF > 1).

Simons, et al. (1965, pp. 35-37) have associated the following Froude number ranges to methods of sediment transport; in Table 2.5.

TABLE 2.5

RELATIONSHIP BETWEEN FROUDE NUMBER AND SEDIMENT MOTION

nF	Method of Sediment Motion
0.15 - 0.60	Sediment moved in discrete steps
0.60 - 1.00	Continuous sediment motion

While these Froude number ranges were associated with uniform sand size, they clearly show that the rate of bed load transport and Froude numbers can be compared to the data on Table 2.6. There is a possibility of delineating the different ranges of Froude number in relation to different channel patterns.

Table 2.6 below shows that there is a progressive increase in Froude numbers and bed load discharge with changes in channel patterns, although, the increases in straight channel pattern are less than in meandering and braiding patterns.

Simons, et al. (1965, p. 42) observed that with an increase in width-depth ratio; "the main flow current meandered from side to side, as in natural streams and bars of small amplitude, and large area, on which the bed forms" of ripples to dunes (Figure 3 in their paper)

TABLE 2.6

RELATIONSHIP BETWEEN FROUDE NUMBERS,
SEDIMENT DISCHARGE AND CHANNEL PATTERNS

Pattern Type	Qs	Froude Number Range
Straight	119.0 - 147.0	0.33 - 0.42
Meandering	190.0 - 563.0	0.44 - 1.02
Braided	738.0 - 1003.0	1.22 - 1.82

Source: Calculated from Schumm and Khan (1977, pp. 1758-1759)

"are super-imposed, develop in an alternating pattern adjacent to the walls." This is the beginning of the meandering pattern. It is possible to suggest that in geometric discrimination, width-depth ratio is a good indicator of threshold changes in pattern. Froude number is also important as a hydraulic discriminant because it controls erosional and depositional levels of the stream.

In the braiding pattern, depth decreases rapidly with increasing slope. As slope increases, width also increases but at a decreasing rate up to a slope of 0.014. Stream power also increases, which causes erosion. Because of braiding, multiple channels are eroded, thus dissipating power from incision and width enlargement. At this stage depth rapidly decreases.

In both field and flume experiments, it is apparent that differentiation of channel patterns is possible by associating slope, depth, width, width-depth ratio at different levels. In spite of the difficulty of non-exlusivity of patterns and dynamic changes in hydraulic variables, these thresholds have been confirmed by theoretical concepts. Among these theoretical concepts, the minimum variance theory has gained a lot of attention.

The theory of minimum variance (Langbein and Leopold, 1966) argues that streams tend to minimise variability of energy distribution over the longitudinal section. The authors, then conclude that in a channel with alternating pools and riffles, meandering is the most probable of the channel pattern because streams work towards achieving a uniform energy loss, and that is most compatible with a meandering channel pattern. This is related to stability in the sense that equilibrium conditions are associated with "continuous or uniform rate of energy loss" (Langbein and Leopold, 1966, p. H13). Two observations can be made here. One, that the stability can most probably be achieved when the stream meanders. Two, that there is a natural tendency of streams to meander to achieve equal distribution of energy on the longitudinal profile by riffles and pools developing into meanders. These possibilities are each examined with reference to the study area.

The theory has been extended to channel pattern by giving attention to riffles and pools. The theory further postulates that straight reaches tend to transform into meandering ones. This is based on the fact that straight reaches usually have shallows and deeps equivalent to riffle-pool sequence. The construct seems plausible when one examines the energy distribution over riffles and pools. The divergent flows over the riffles cause channel width enlargement while the convergent flows over pools cause the deepening of the bed. Tinkler (1970) elaborated this and concluded that riffles in straight reaches turn into point bars on bends while pools remain straight sections of the meander train. This thesis is elaborated by Ackers and Charlton (1970).

For these field, laboratory and theoretical examples it is possible to isolate certain hydraulic and geometric characteristics associated with channel pattern differentiation.

Three types of channel patterns frequently debated are meandering, straight and braiding. The following hydraulic factors have been associated with each of these patterns:

Meandering Streams:

(a) Discharge, Q, is an important variable as it helps to determine aggradation and degradation. It has been shown to interact with other variables in a form that can be expressed by a set of exponential equations (Gregory and Walling, 1973). However, it is believed that response is more complex than a two-variable relationship (see for example Ackers and Charlton, 1970).

(b) Channel slopes of meandering streams are related to lower slope angles than straight/braided streams (Leopold and Wolman, 1957). At channel slopes less than 0.002 the channel pattern is straight, between 0.0026 to 0.013 the channel pattern is meandering while at slopes greater than 0.015 the channel pattern is braiding.

(c) Meandering channel widths are smaller compared to other channel patterns. This, Richards (1978, p. 23) attributes to excess energy expenditure on bank roughness and sediment transfer (see also Leopold, et al., 1964, p. 304; Langbein and Leopold, 1966, p. 69; Tinkler, 1971, p. 1788). This is best shown by lower width-depth ratios.

Width-depth ratio controls the development of secondary flow in stream channels. Meandering decreases with increasing width-depth ratio. The threshold levels of changes are given in Table 2.3

(d) Relative changes in sediment discharge, (Q/QS), (Shahjahan, 1970; Schumm and Khan, 1972) are associated with changes in meandering pattern, but do not cause meandering itself. Leopold and Wolman (1960) have reported meandering in the waters of the Gulf stream, without sediment discharge.

Since the variables discussed above are not mutually exclusive, many regression equations combine two or more variables.

Braided/Straight Streams:

(a) Bed load or relative sediment discharge with a high portion of nonfines (Rust, 1969).

(b) Channel widths are wider than in meandering streams. Leopold, et al. (1964) give ratios of 1.6 - 2.0 in field examples, and 1.05 - 1.70 in flumes of braided streams as compared to meandering streams. This is associated with higher width-depth ratios in braiding sections than in meandering sections.

(c) Variability of stream flow, (Qv), is important because during rising flow, bank sapping and bed scouring occur. During low flows these lag deposits remain behind due to reduced stream competence. This helps the development of a braided channel pattern. On the other hand, flow variability destroys the meandering pattern by cutting off meander bends in general, and changing the isovels from the meandering thalweg.

(d) Higher regional slopes are associated with braiding stream patterns than in meandering patterns. The ratio between single and multi-thread channels slopes is approximately 1.4 to 2.3 in field examples, and 1.3 to 1.9 in flumes (Leopold, et al., 1964).

Straight channel patterns are rarely reported from field examples. However, Schumm and Khan (1972) have given geometrical properties of straight channel patterns from a flume experiment (Table 2.3 above). The straight channel patterns are characterised by lower slope angles, lower width-depth ratios, lower velocities and lower sediment discharge than the meandering and braiding stream patterns.

Besides the three major channel patterns discussed, Gregory (1977, p. 3), Chitale (1973) and Gregory and Walling (1973) have reported other categories of channel patterns. Gregory and Walling (1973, p. 247) have also reported other categories within meandering channel types according to their confinement and geometric properties. In spite of these increasing number of channel pattern types, different approaches have been attempted by analysing the variables which are associated with different channel patterns.

CHAPTER 3

PHYSICAL SETTING AND GEOMETRIC VARIABLES

The relative contribution of the geometric variables to channel pattern development in the mid-section of Grand River is affected by the location, geohistory, precipitation and vegetation of the area. These physical factors influence the river regime, erosion of the channel cross section, deposition and transportation of sediments. When these mechanisms (erosion, deposition and transportation) occur, they cause channel sinuosity, braiding and stream incision. The type of channel feature discussed are related to the type of the geomorphic mechanism.

PHYSICAL SETTING

The Grand River basin in Southern Ontario drains into Lake Erie (Figure 3.1). Its major tributaries are the Nith, Conestoga, Speed, and Eramosa (shown in Figure 3.2). Basic statistics of the Grand River basin and its tributaries are calculated from 1:25,000 topographical maps and are given in Table 3.1.

TABLE 3.1

BASIC STATISTICS OF THE GRAND RIVER BASIN

	River	Basin Area (miles)	Channel Length (miles)	Basin Length (miles)	Basin Width (miles)	Gradient	Sinuosity
1.	The Grand River	2614	180	118	9-15	6.4	1.53
2.	Conestoga	317.4	51	38	4-13	10.9	1.35
3.	Nith	432.1	98	45	10	7.1	2.18
4.	Speed	187.3	37	30	4-11	15.1	1.23

FIG. 3.1 AN OUTLINE MAP OF SOUTHWESTERN ONTARIO

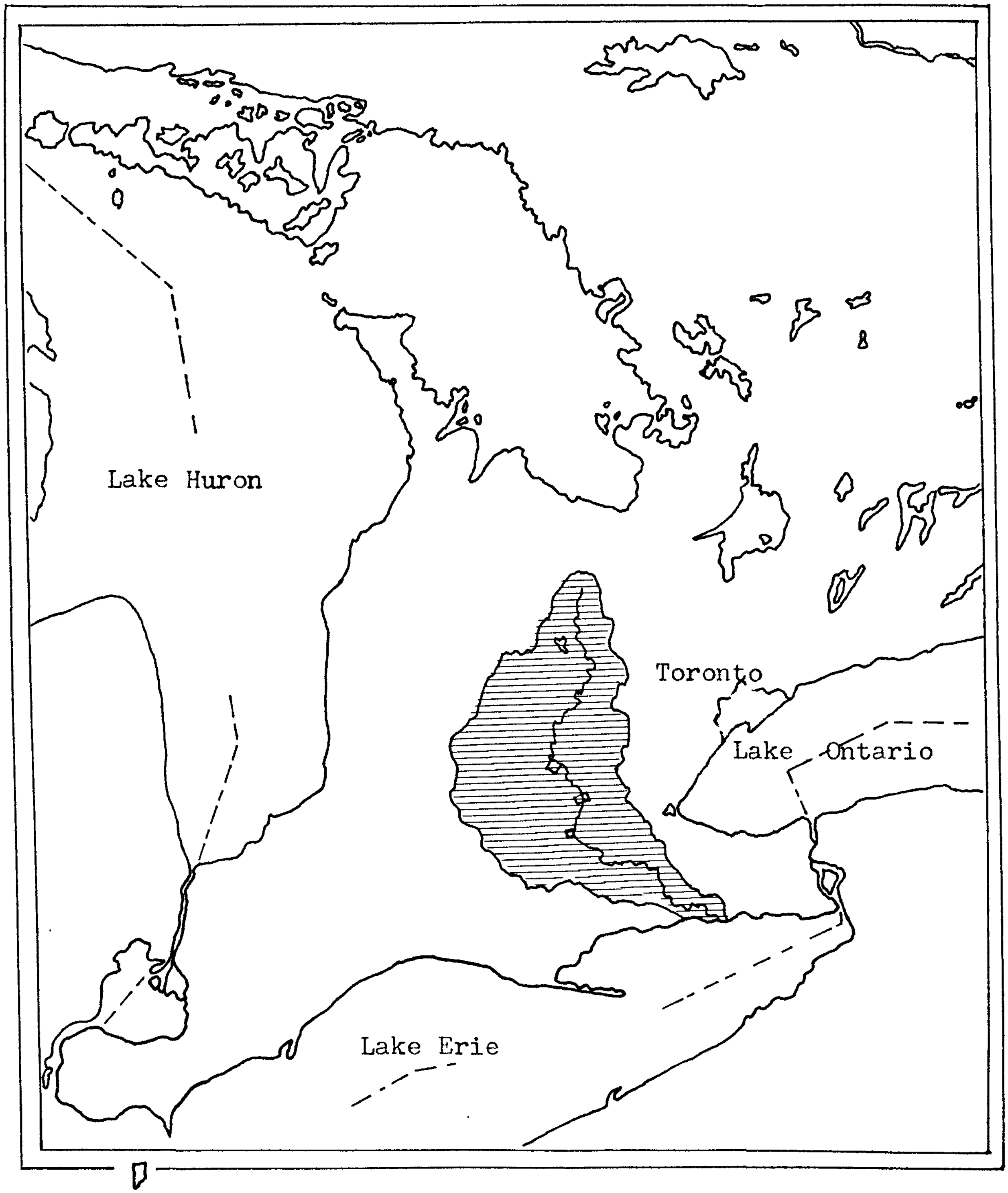
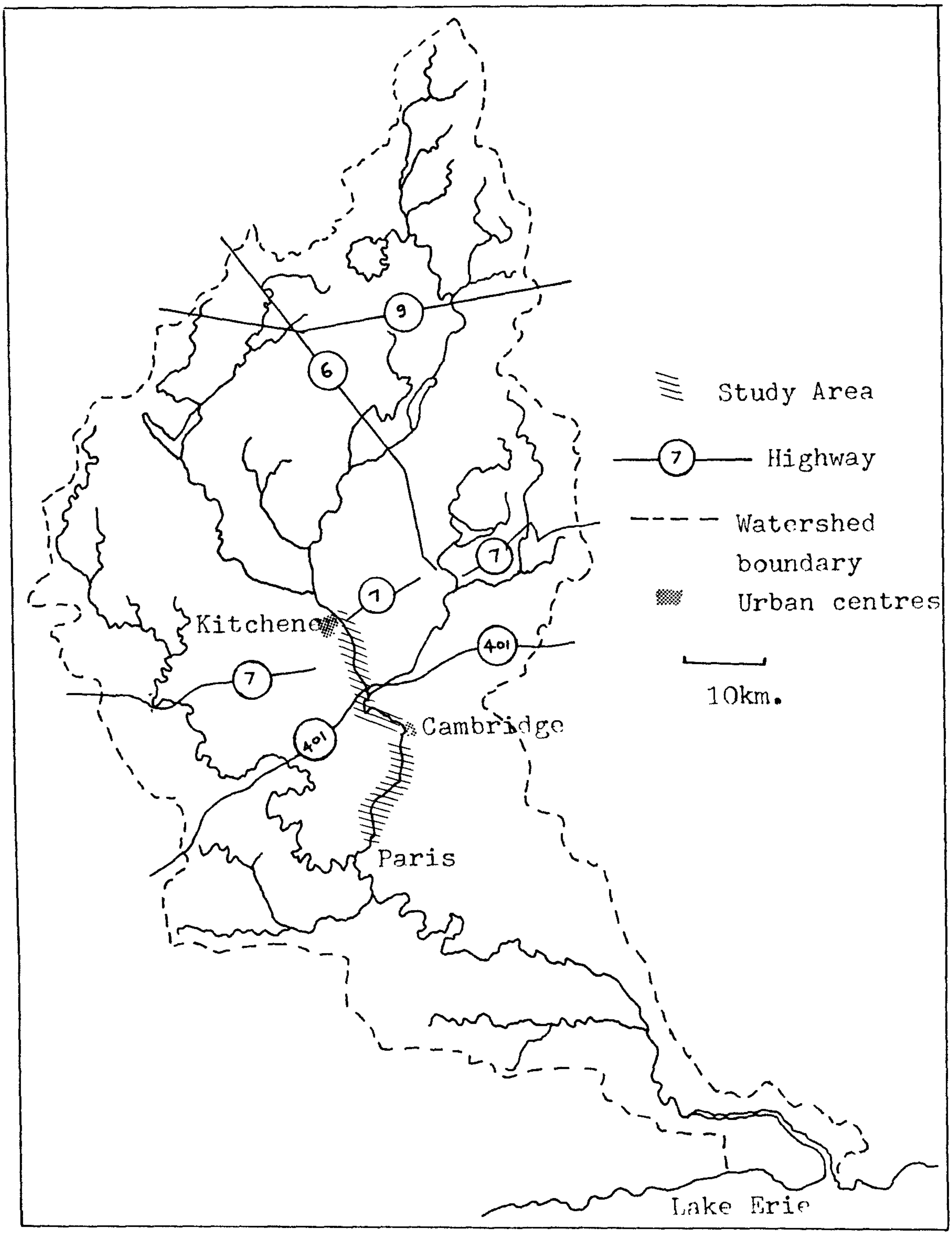


FIG.3.2 AN OUTLINE MAP OF THE GRAND RIVER WATERSHED



River	Basin Area (miles)	Channel Length (miles)	Basin Length (miles)	Basin Width (miles)	Gradient	Sinuosity
5. Eramosa	115.3	25	17	5	16.1	1.40
6. Irvine	104	16	11	5-7	20	1.50

GEOLOGICAL SETTING

The basin lies on south-western Ontario upland which was significantly modified by glaciation. Preglacial differential erosion of Palaeozoic beds composed of dolomites, shales, limestone and gypsum of different formations (Karrow, 1968; Cowan, 1972), has been subdued by the scouring and deposition of the Wisconsin Ice.

The splitting of the Wisconsin glacier into Georgian Bay - Lake Huron and Lake Ontario - Erie lobes has created symmetrical physiography composed of tills of interlobate and recessional moraines (Spelt, 1972, p. 336).

PRECIPITATION

Surface runoff over the basin is contributed by snowfall and rainfall. The southern third of the basin receives about 40 inches of snow per annum, while the northern third receives about 110 inches of snow per annum (Mitchell, et al. 1977, p. 25). The study reach is in the middle third, therefore it is possible to generalise that flow conditions experienced are both contributed by the upper and the immediate basin around the area.

The basin also experiences storms and even occasional tornadoes in spring, summer and early fall seasons. The station at Kitchener receives an average precipitation of 2.54 inches per month between February and June, with a maximum of 3.41 inches in June. The intensity of the storms has been a major factor in contributing to the annual flood hazard. A maximum of 2.8 inches to 3.97 inches in 24 hours has been recorded (Mitchell, et al. 1977). The basin receives, however, an annual mean precipitation of 30.26 inches. (Environment, Canada, 1966 - 1976).

VEGETATION

The original vegetation was composed of mixed forests of broad-leaved trees, and white and red pines of which much has been cleared for cultivation and lumbering. Extensive swamps and poorly drained areas sustain marshes and bog. The resulting human settlement has influenced the basin runoff, especially around the urbanised areas.

Along the wide floodplains, the vegetation is composed of tall grass and trees, and on some portions forest cover occur, although agriculture and recreational landuse tend to encroach some parts. Generally intensive landuse is restricted to the sections where flooding is less frequent. Along restricted floodplains, little vegetation cover occurs because of, possibly, flooding.

BASIN HYDROGRAPHS

The Grand River has an annual hydrograph common to many basins in southern Ontario. The basin has a high percentage of run-off concentrated within four months in a year. The peak of surface runoff is during the months of March to May, contributed by peak snowbelt and atmospheric disturbances. At this time, the detention storage capacity of the soil has been reduced thus increasing the possibility of floods.

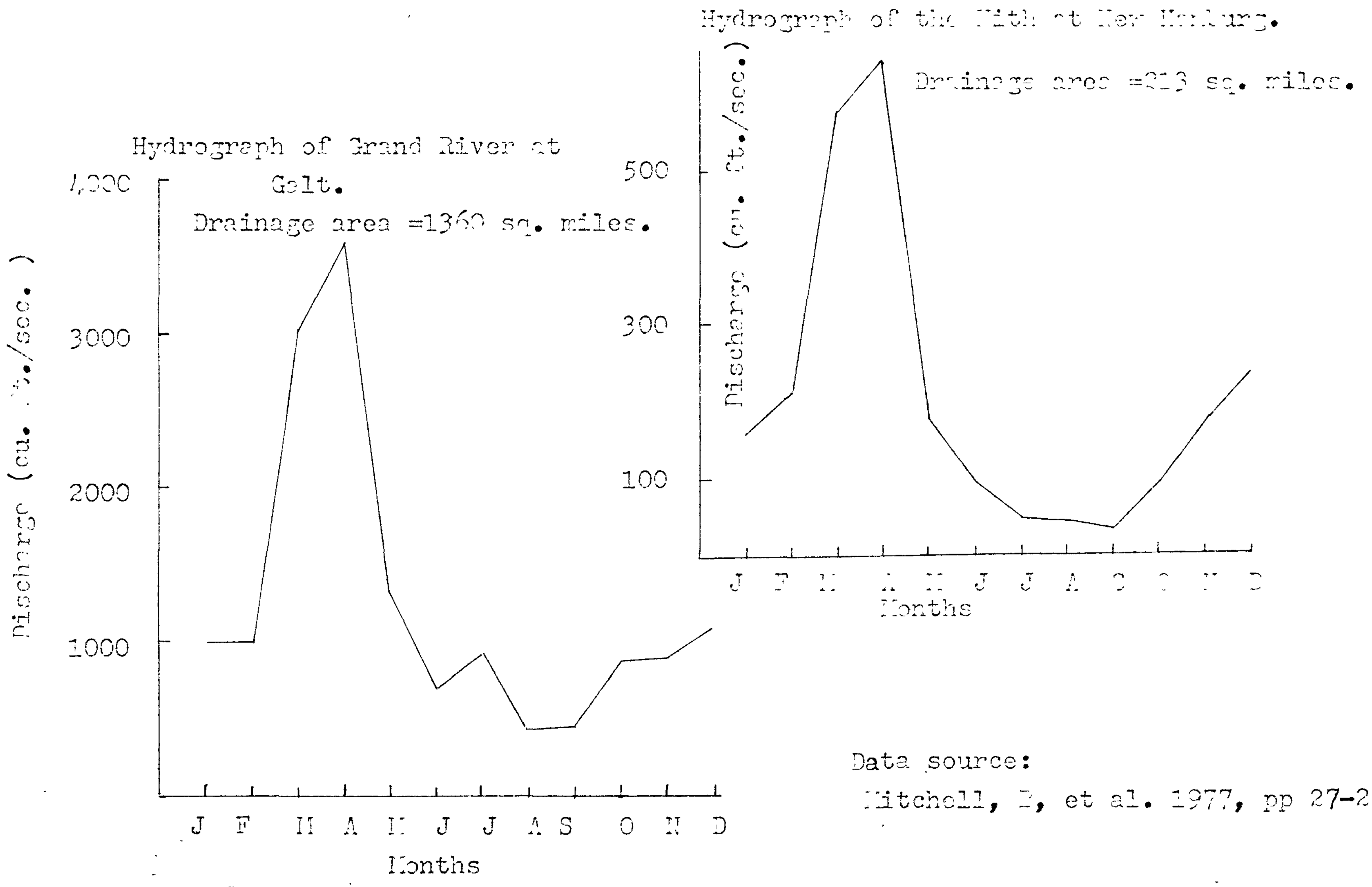
Figure 3.3 shows the annual hydrographs of the Grand River at river gauging station at Cambridge - Galt, and the Nith at New Hamburg. At peak maximum monthly runoff of April, the runoff per square mile is 2.6 cfs for the Grand River above Galt and for the Nith above New Hamburg.

Flow variability is also an important factor in the development of channel patterns. In the Grand River, it introduces another dimension in the interpretation of channel patterns because of its annual occurence. The level of channel conveyence to contain a varying flow depth would indicate whether the incremental depth is erosional, depositional or transportational. For example, the impact of flow increase over different cross sectional shapes will have different results on channel pattern development. In this thesis, this incremental flow is discussed in terms of increase in depth and width over a cross sectional area.

SUMMARY

The relative location of the basin and precipitation contributes to the nature of runoff for channel pattern development. The runoff is shown by the hydrographs indicating amount and variability of flow. Dense vegetation influence the nature of the processes by increasing channel roughness, while consolidating the floodplain top soil from erosion. These physical factors (geology, precipitation and vegetation) are independent of the stream, and therefore the stream tries to change or adapt to them by modifying its channel shape.

FIG.3.3 EXAMPLES OF ANNUAL HYDROGRAPHS OF GRAND RIVER AND THE NITH.



Data source:
Mitchell, B, et al. 1977, pp 27-28.

GENERAL PHYSIOGRAPHY AND CHANNEL PATTERNS

The reaches studied occupy a former glacial spillway confined on both sides of the section by Wisconsin and modern alluvium, and in some portions by the Paris-Galt moraine (G.R.C.A., Tech. Report, 1977). In many sections, outcrops of bed rock occur, controlling free incision. The palaeovalley is U-shaped, with steep banks averaging 50 to 75 feet.

The Grand River Hydraulics Report (1962) dates most of the outcrops that form rapids south of Cambridge, as Silurian dolostones. Associated with these out-crops are large boulders, freshly plucked by floods. These remain as lag deposits (Dolling, 1968 and Martini, 1977) to form bars and ribs.

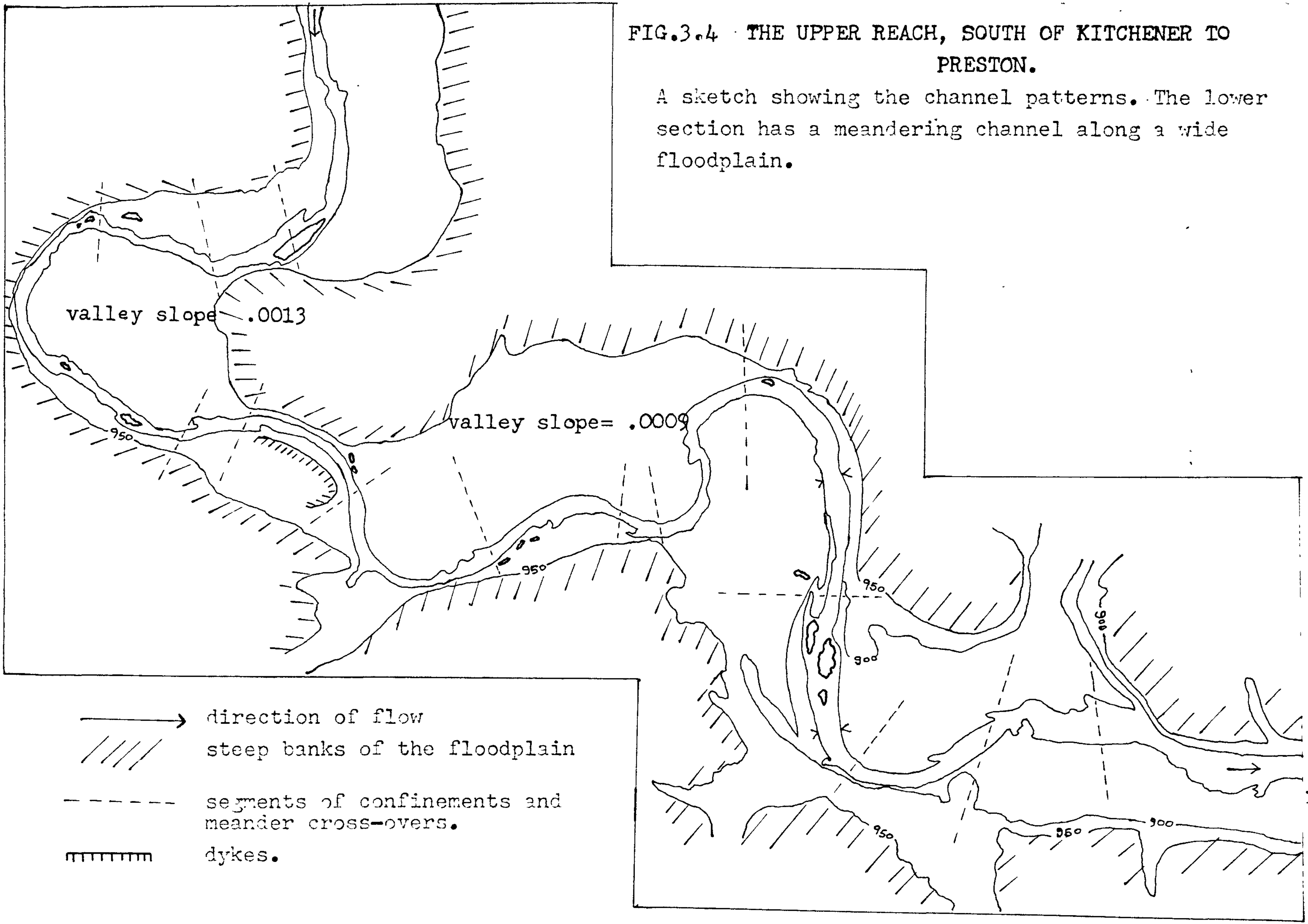
THE UPPER REACH

The upper reach has a general tendency of meandering on wide portions of the floodplain with varying sinuosity. The average floodplain width is 2,335.0 feet. In many portions, islands, bars, riffles, pools and channel modifications occur. From Cambridge to 6.2 miles upstream the channel is sinuous in a wide plain, narrowing futher upstream.

Figure 3.4 shows the meandering tendency in a wide floodplain. A sinuosity ratio of 2.53 was calculated for this stretch. The valley slope decreases downstream. Two segments of valley slopes are 1.3×10^{-3} and 0.9×10^{-3} toward downstream respectively. The dashed lines show the sections where the channel is confined. The islands seem to lie below the confined sections although their sizes vary.

FIG.3.4 THE UPPER REACH, SOUTH OF KITCHENER TO PRESTON.

A sketch showing the channel patterns. The lower section has a meandering channel along a wide floodplain.



Upstream of the islands tongue-shaped overflows on braids are common.

Figure 3.5 shows the upstream section of Figure 3.4. The floodplain width narrows, and also sinuosity decreases. Secondary streams contributed by springs oozing from the floodplain banks are common. The lower section of the figure is not as steep as the upper section. Similar bars and islands as in Figure 3.4 are also common. Plate 3.1 shows a portion of Figure 3.5 (location of Figures and Plates are given in Table 3.2).

At bridge number 18 crossing, the channel braids both downstream and upstream of the bridge structure. The bridge confines the channel and these might create morphological features similar to floodplain confinement. The position of braids is the approximate position of the meander cross-over.

Section A-A shows a divided section by an island formed at the meander bend which is confined on the outer side by the floodplain. The inner channel is wider and deeper than the outer channel (see cross section number 89 in Appendix). The outer channel is, probably, a depositional environment. The short-cut reduces frictional force over the meander bend while increasing hydraulic slope, thus moving the erosional apex downstream of A (this interpretation was made clear to me by Professor A.D. Abrahams). The consequence of this migration is discussed in the next section.

Width variation over short channel lengths can be noted from cross sections B-B and C-C. Also at cross section C-C, residual bar sediments occur. These narrow sections upstream of bar or island formation is common around meander bends, showing as submerged riffle, bar or island.

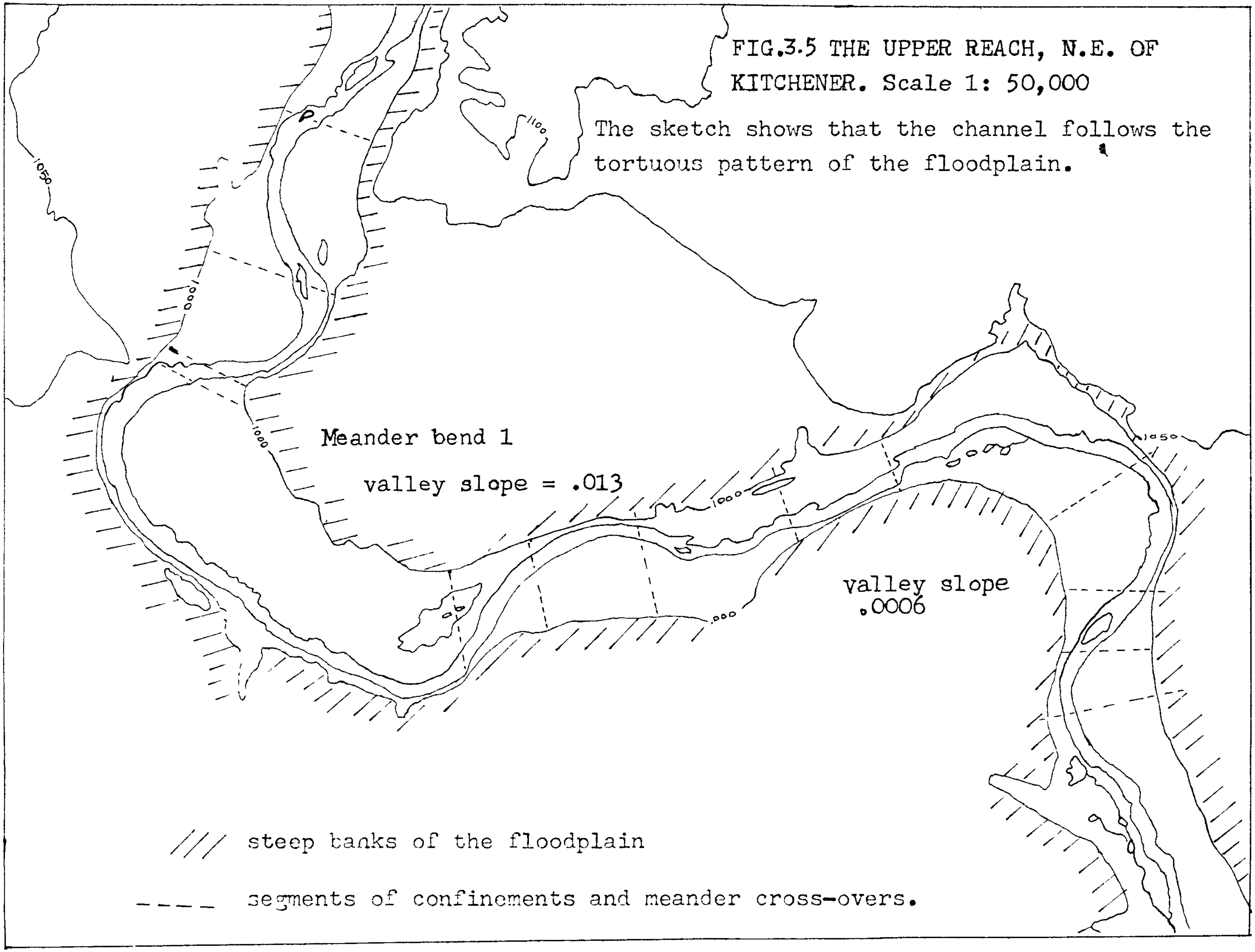


FIG.3.5 THE UPPER REACH, N.E. OF KITCHENER. Scale 1: 50,000

The sketch shows that the channel follows the tortuous pattern of the floodplain.

PLATE 31 RIVER CHANNEL FEATURES OF THE CROSS SECTION AT HIGHWAY 8 AT FREEPORT, IN THE UPPER REACH.

Section A - A shows an island which by its formation has reduced the sinuosity of the section. Sections B - B and C - C show how width variations within short channel lengths occur in the upper reach. The bridge crossing marked 18 shows the depositional environment associated with obstructions. Flow is from left to right.

TABLE 3.2

LOCATIONAL SITES OF FIGURES AND PLATES

Figure/Plate	Latitudes	Longitudes
Plate 3.1	43^{o} 24' 12" N	80^{o} 24' 52" W
	43^{o} 26' 26" N	80^{o} 25' 48" W
Plate 3.2	43^{o} 17' 19" N	80^{o} 20' 06" W
	43^{o} 18' 41" N	80^{o} 19' 18" W
Plate 3.3	43^{o} 18' 54" N	80^{o} 19' 00" W
	43^{o} 20' 54" N	80^{o} 19' 19" W
Figure 3.4	43^{o} 23' 25" N	80^{o} 25' 00" W
	43^{o} 25' 00" N	80^{o} 22' 08" W
Figure 3.5	43^{o} 30' 00" N	80^{o} 25' 00" W
	43^{o} 27' 32" N	80^{o} 28' 18" W
Figure 3.7	43^{o} 17' 20" N	80^{o} 19' 09" W
	43^{o} 20' 12" N	80^{o} 19' 30" W

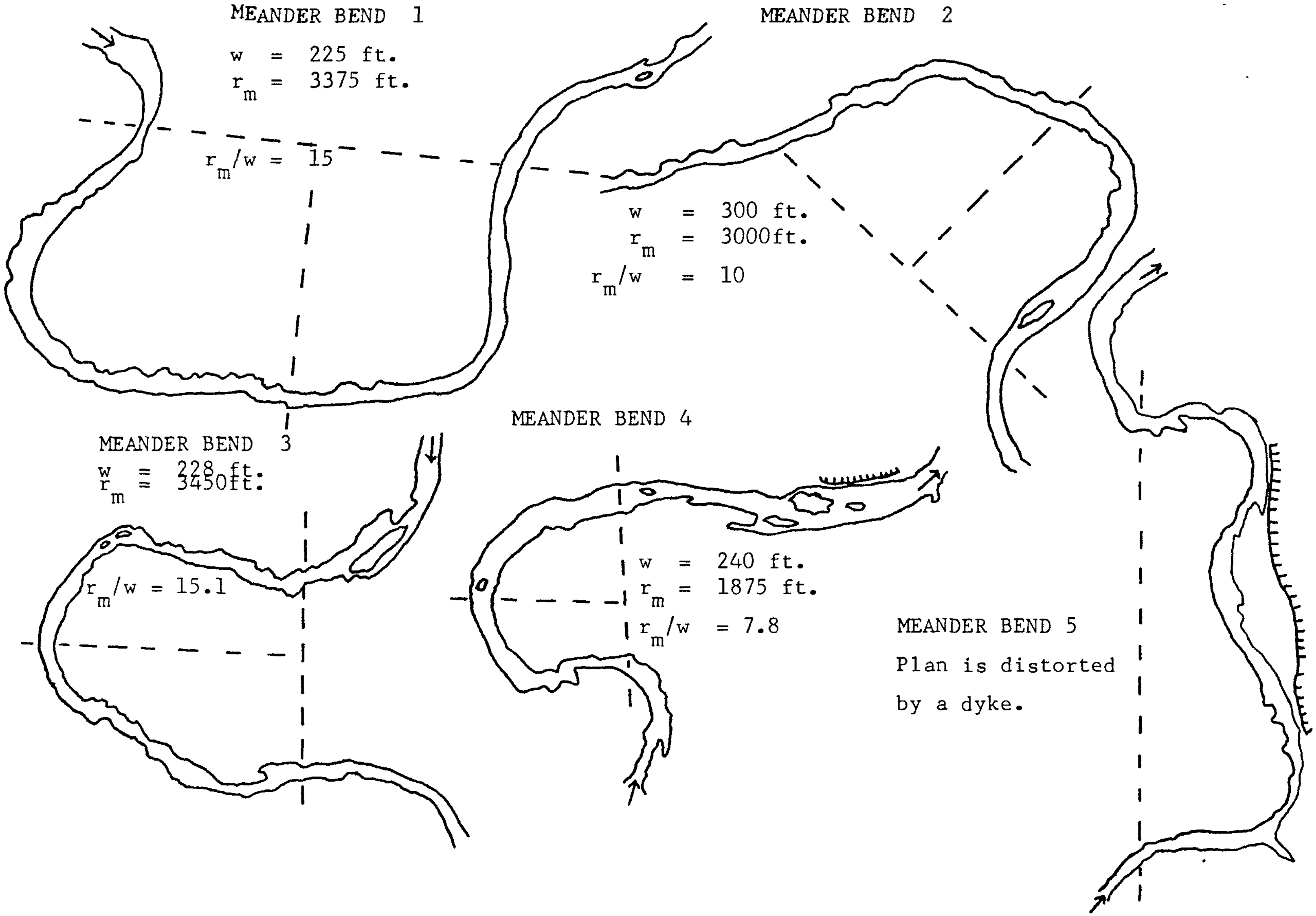
THE MEANDERING TENDENCY

Different meander bend shapes are identifiable from the topographical map and aerial photo mosaics. The types of meander bends are given in Figure 3.6. Width, W, is measured at the apex of the bend along the radius of curvature, r_m. The line bisecting the the stream was established by the approximate position of the meander cross over, $\simeq 90^{o}$. All the types are irregular meanders although with varying degress of asymmetry.

Meander bend I, is approaching a T - shaped bend. Perhaps it formed by horizontal migration of erosional apex. Its early formation was asymmetric like the other bends, but it developed to a similar plan to 5. It is suggested that meander bend 5 will consequently develop as plan form for bend 1. Lewin and Brindle (1977, p. 221) refer to such meander bends (nos. 1 and 5) as "boxed or deformed" meanders. The channels follow the steep sections of the floodplain. Meander bend 1 has a steeper valley slope (0.013) than the other irregular bends. Meander bend 5 occurs where the valley slope is 0.002. This implies that complete boxed meander bend 5 associated with steep valley slopes, which is exptected to have higher velocity, have higher erosional capability than flat valley slopes.

The other meander bends are confined by the steep floodplain banks on the outer sides. But several plan form features seem to be common to all of them. The islands or bars, observed in figures 3.4 and 3.5 are located at positions of the floodplain bank confinement. Around these bars or islands, the channel widens into a pool, usually associated with the confinement. For example, in meander bend 4, the dyke causes an added confinement to the floodplain bank and over-

FIG.3.6 DIAGRAMATICAL PRESENTATION OF MEANDER BENDS IN THE UPPER REACH.



flows on the bar separates the bar or island. Similar mechanism has been noted at bridge 18 crossing in Plate 3.1

Lobes of flooded banks upstream of these pools (III) are remnants of former thalweg which was abandoned when the erosional apex moved downstream (Lewin, 1978, p. 29). In bends where no island or bar exists, there are submerged riffles. These lobes cause variations in width observed in Plate 3.1 above. For example at section IV in bend 4, the upstream depth before the deltaic pool is 1.7 feet (at cross section 79) and 4.5 feet (at cross section 78, Appendix 7) in the pool.

The ratios of radius of curvature to width (7.8-15.1) are shown by Hickin to be at the initial stage of meander growth (Hickin, 1977, p. 61). The description of these trends of confined meander do not conflict with Lewin and Brindle (1977). The development of bars or islands at the meander bend 5 is a consequence of downstream migration of horizontal erosional axis.

THE LOWER REACH

The lower reach has, generally, a narrower floodplain than the upper reach. The average floodplain width is 1332 feet. The reach is straight, has rapids, braids and islands.

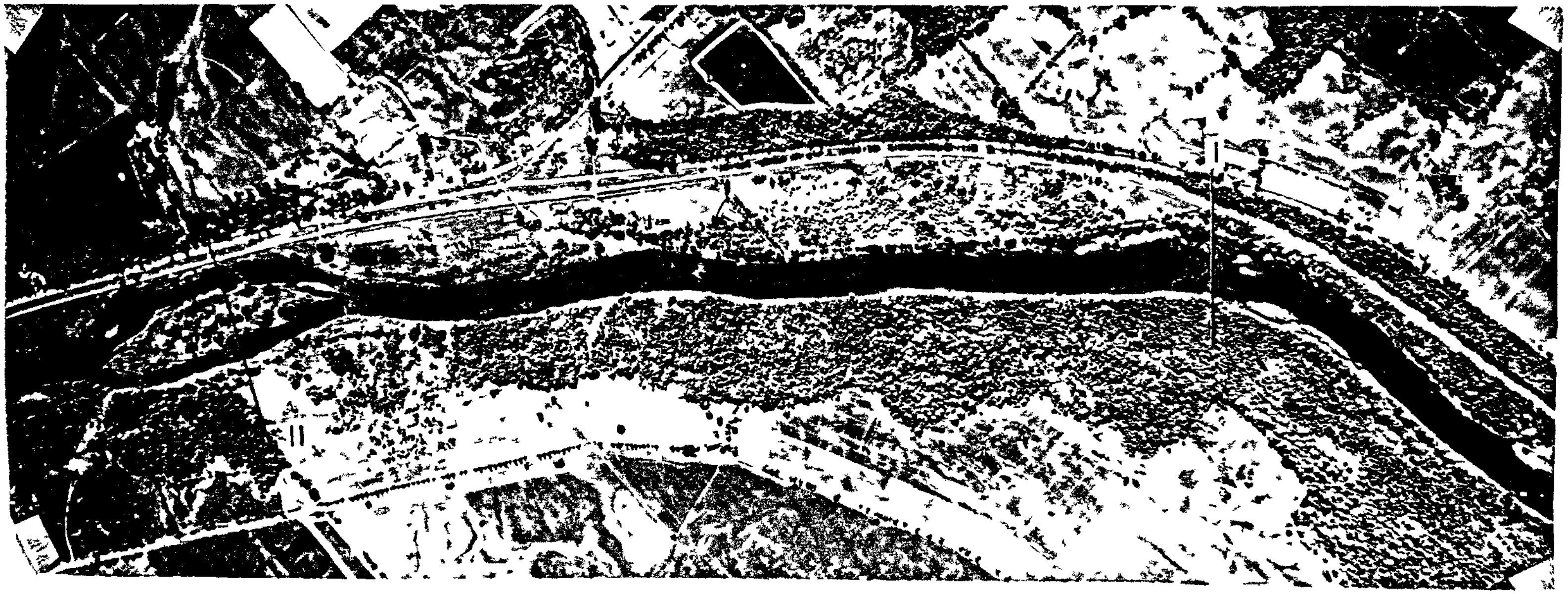
The islands and braids occur after every 1.25 miles. At some sections, islands occur downstream of the rapid. The mean channel width is 344 feet. Taking this to compare with the frequency of braids, islands and bars give 15 channel widths. Along the reach, sections of bars and islands form negative residuals, and the pools form positive residuals when the deviations of mean depth are calculated. Richards (1976, p. 80) found that riffle and pool sequence occur after every 15.7 channel widths. This is in agreement to meander a length (L_m = 17.2w) reported by Leopold and Wolman (1960 in straight-line regression and L_m = 6.5w 1.1 (1957) in nonlinear regression).

In plate 3.2, it can be seen that total width at cross section II where the island divides the channel is twice wider than sections without the island, while at cross section I, where rapids occur, the cross section is wider than other sections without rapids. For example single-channel width without rapids is 422 feet wide, the rapid cross section I is 844 feet wide and the cross section II with the island is 1478 feet.

Towards Cambridge, the channel divides into multi-thread patterns, shown in plate 3.3. This is associated with the narrow floodplain as shown in Figure 3.8. Some islands appear to be well forested indicating that they have been there for a long time. Cross section D-D also shows the rapids occurring along a relatively narrow channel. In single channel cross sections, channel width is about 274 feet, while at cross sections 34 and 36, the channel width is 900 feet and 1278 feet repsectively, including the islands. Since the size of the islands vary considerably, the total width of these sections vary accordingly.

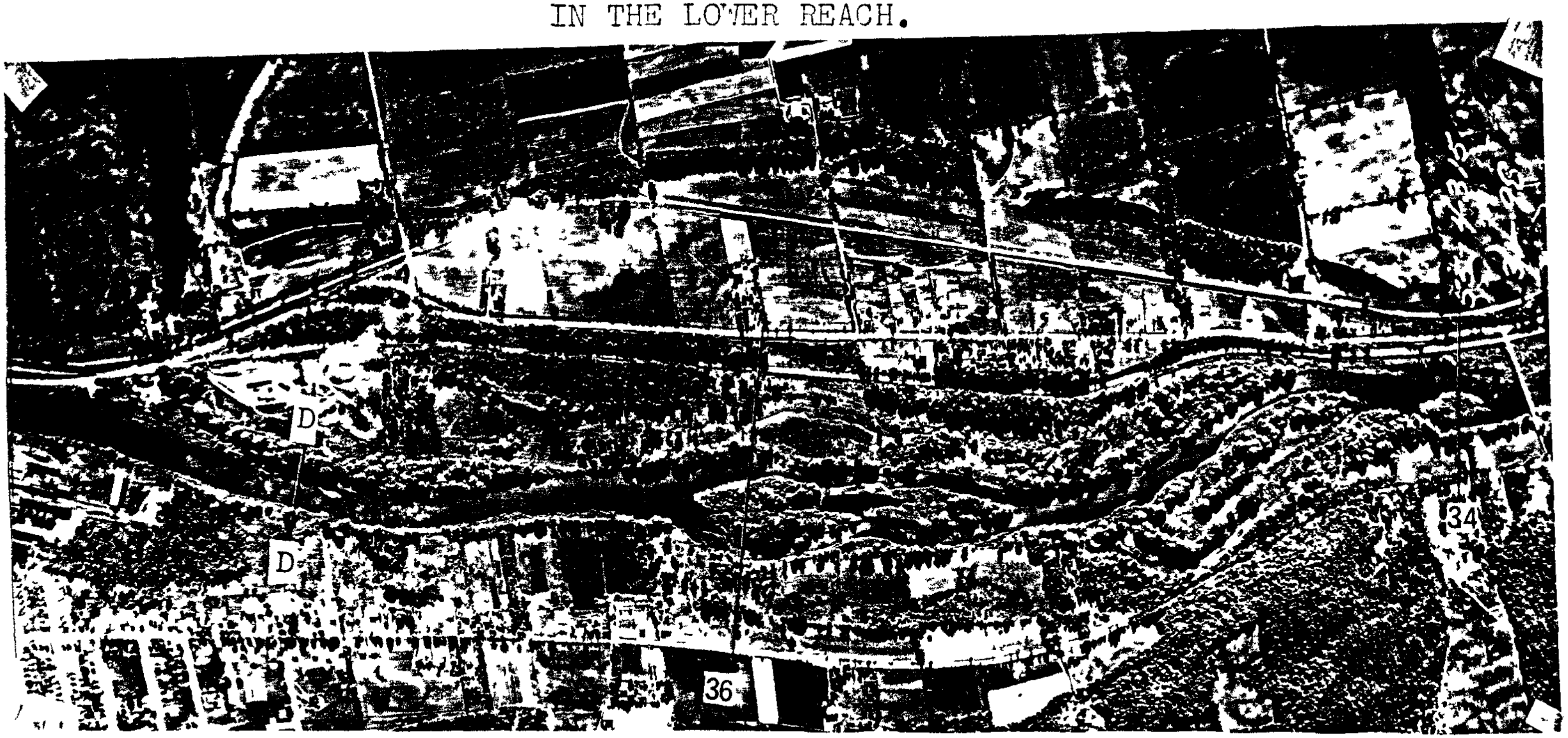
From Figure 3.8, the floodplain width at cross section 34 and 36 indicate a difference (900 feet and 1278 feet respectively). Similarly, single floodplain cross section with no rapids show little variation from multi-channel sections, although sections with rapids are relatively narrow (Figure 3.8). The relative positions of these sections in the lower reach are shown in Table 1.2 above.

PLATE 3.2 THE STRAIGHT CHANNEL SECTION AROUND GLENN MORISS SOUTH OF CAMBRIDGE IN THE LOWER REACH.



Cross section marked I shows rapids, while the section marked II shows a developed island. Flow is from left to right.

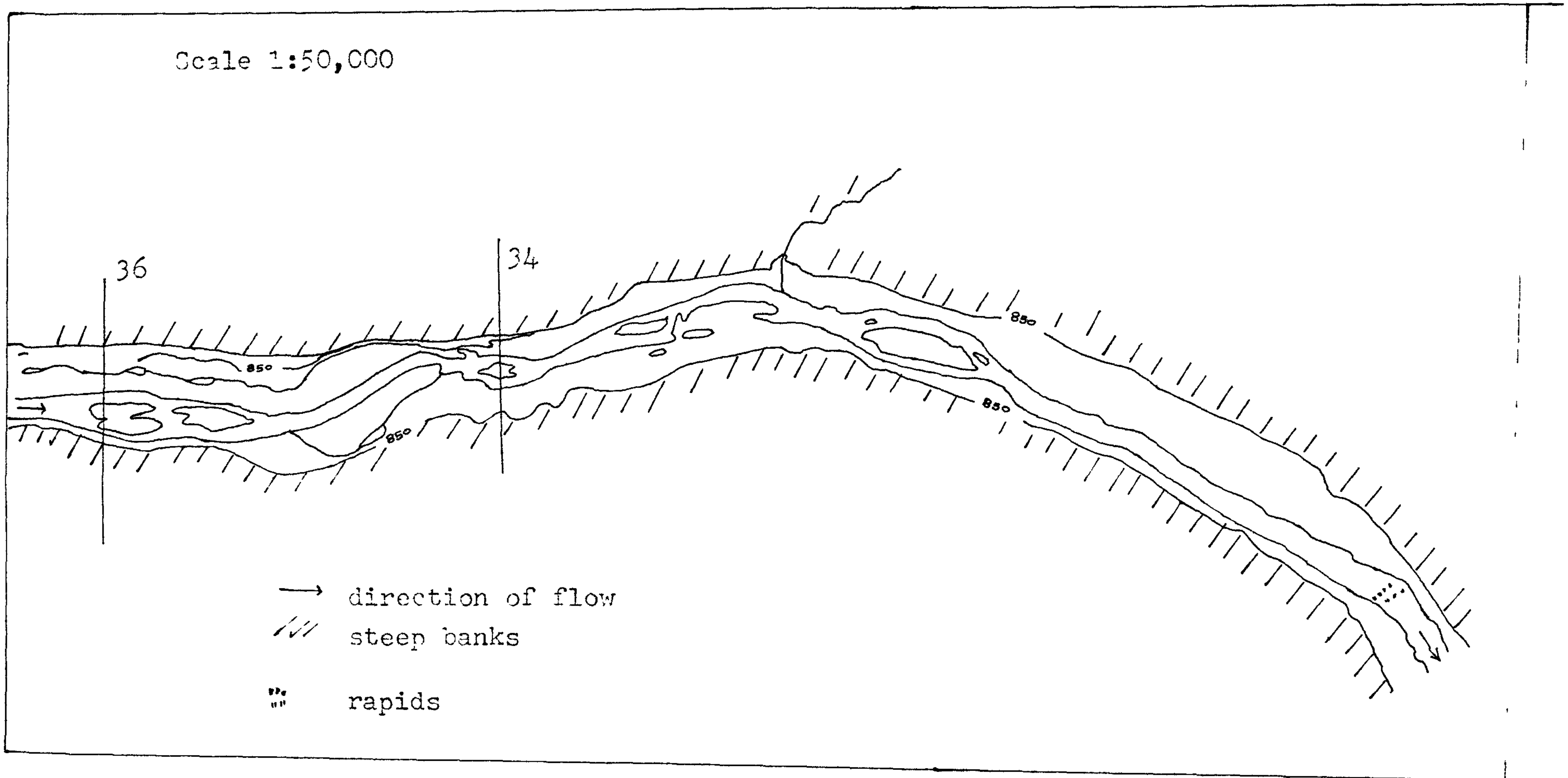
PLATE 3.3 MULTICHANNEL SECTION IMMEDIATELY SOUTH OF CAMBRIDGE IN THE LOWER REACH.



Cross section 36 shows bars undergoing modification by seepage between them. Cross section 34 shows stream thalweg diverted by an island. This section of the reach is confined by steep banks.

Flow is from left to right.

FIG.3.7 THE LOWER REACH, IMMEDIATELY SOUTH OF CAMBRIDGE.



A sketch showing multi-channel section with permanent islands. The channel follows the pattern of the floodplain. Section #34 and #36 are drawn for comparison of widths in the text.

CROSS SECTION SHAPES

The cross sections from both reaches were drawn from the data from the Grand River Conservation Authority compiled in the form of distance v.s. elevation points. There are three gauging stations along the study reaches, one in the upper reach and two in the lower reach. The one in the upper reach and one in the lower reach are explained.

From these cross sections, it will be possible to show that the types of cross sections have some influence on channel patterns. Hydraulic variables, i.e. velocity and Froude number have also been calculated for the upper reach and the lower reach at the gauging stations.

Figure 3.8 (code number 88) and 3.9 (code number 73) are typical examples from the upper reach. The cross sections are relatively wider than they are deep, with a ridge at the centre of the cross section. Figure 3.10 is a particular example of free meandering pattern with levees on both sides of the channel. The section is in the lower part of the upper reach.

The average ratio of floodplain width to channel width range from 8.7 to 12.8 for most sections in the upper reach.

At the time of survey the gauge height at Doon gauge in the upper reach was 2.9 feet. The area of the cross section was calculated and found to be 304 square feet. From the rating curve at Doon, a gauge height of 2.9 feet is equivalent to 1360 cfs, thus giving average velocity of 4.47 feet/second. A similar measurement in the lower reach at Galt has a cross section of 84.6 square feet and at the time of survey, the gauge height was 4.7 feet, giving a discharge of 2630 cfs and an average velocity of 3.1 feet/second.

CROSS SECTION IN THE UPPER REACH, DOWNSTREAM OF A BRAID BAR.

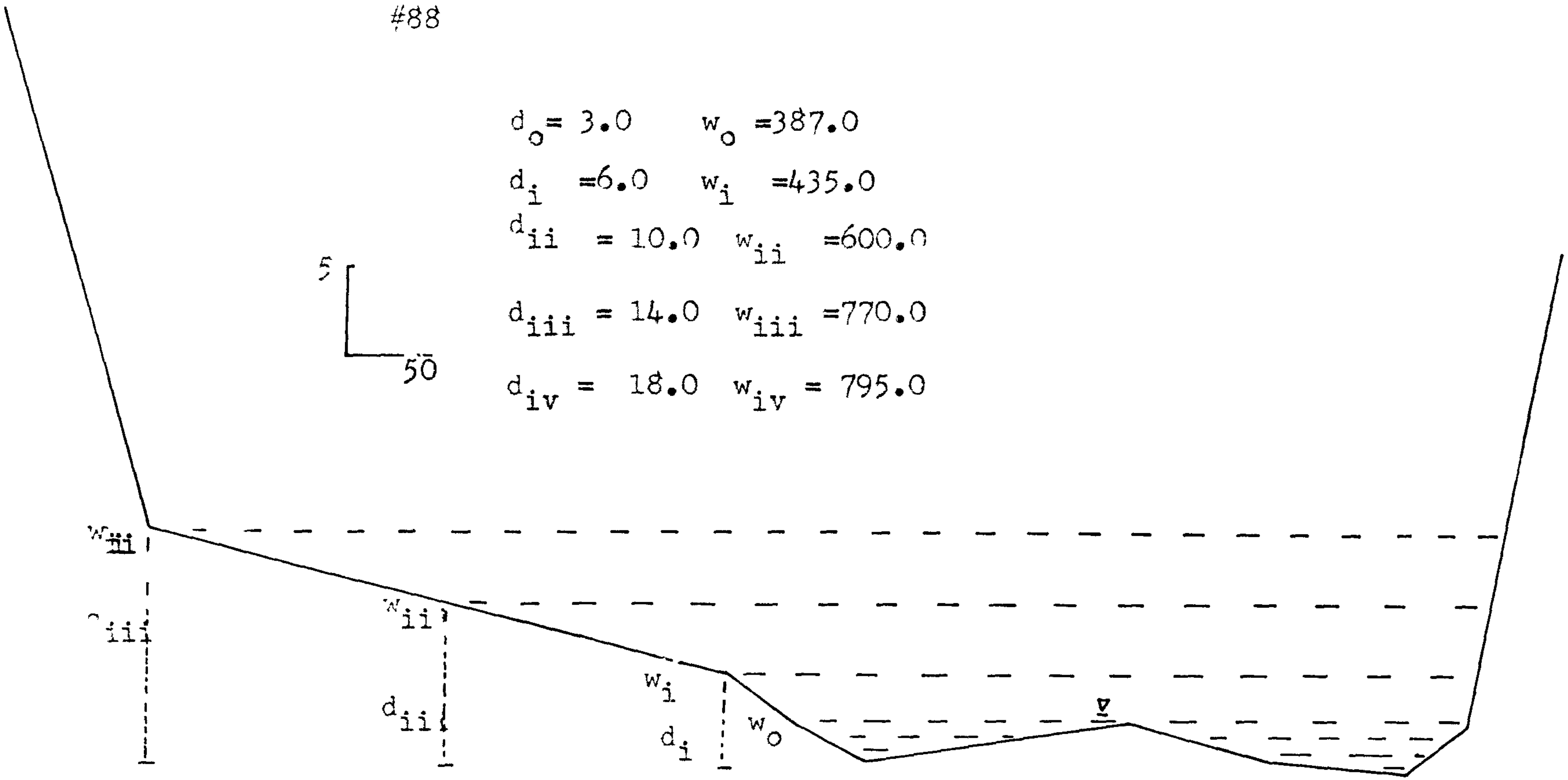
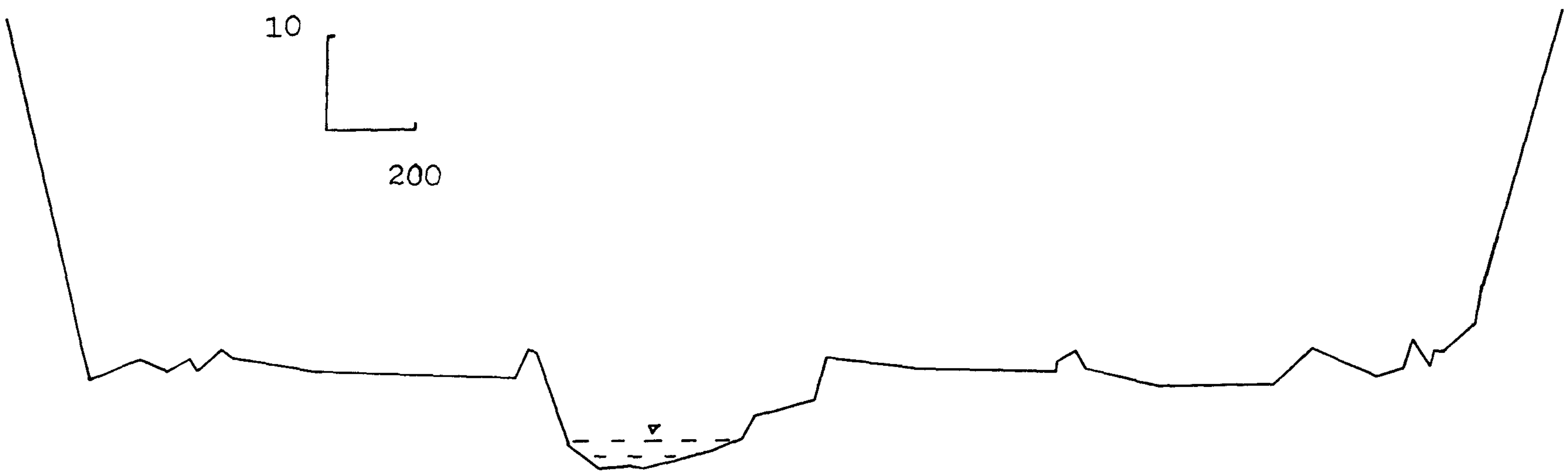


FIGURE 3.8

FIG. 3.9 CROSS SECTION # 73 IN THE UPPER REACH



The floodplain width is 3500 ft. at an elevation of 933.3 ft. The channel width is 380 ft. at an elevation of 885.3 ft. This is a typical example of free meandering, with levees and a wide floodplain.

Working back from these calculations, the Froude number ($v/\sqrt{gD}$, where v is velocity, g is gravity constant (≃ 32.174) and D is depth) at Doon is 0.27 and at Galt is 0.38.

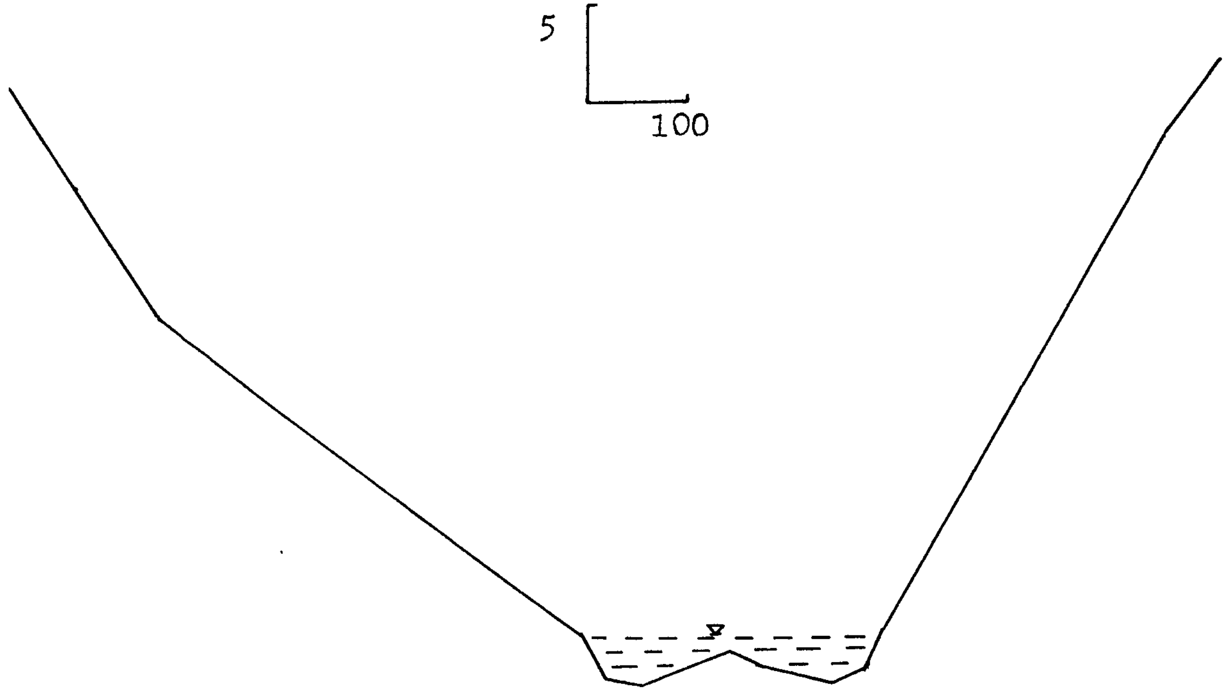
Figures 3.10 and 3.11 show the typical cross sections in the lower reach. The channel sections are more V-shaped rather than the typical U-shaped cross sections in the upper reach. The channel is wider than it is deep.

The average ratio of flood plain widths, to channel widths for Figures 3.11 and 3.12 is 1.44 and 4.98 respectively. This ratio range is common to most of the sections in the lower reach. The ratio is later compared with other data to determine the level of floodplain confinement.

In summary, the cross sections of the floodplain in both reaches are asymmetric in plan form. But sections from the upper reach have concave-bank benches which are usually associated with meandering patterns (Hickin, 1978, p. 200). The cross sections (sections 96, 97, 110 and 113, included in Appendix 5) from meander bends show prominent concave-bank benches.

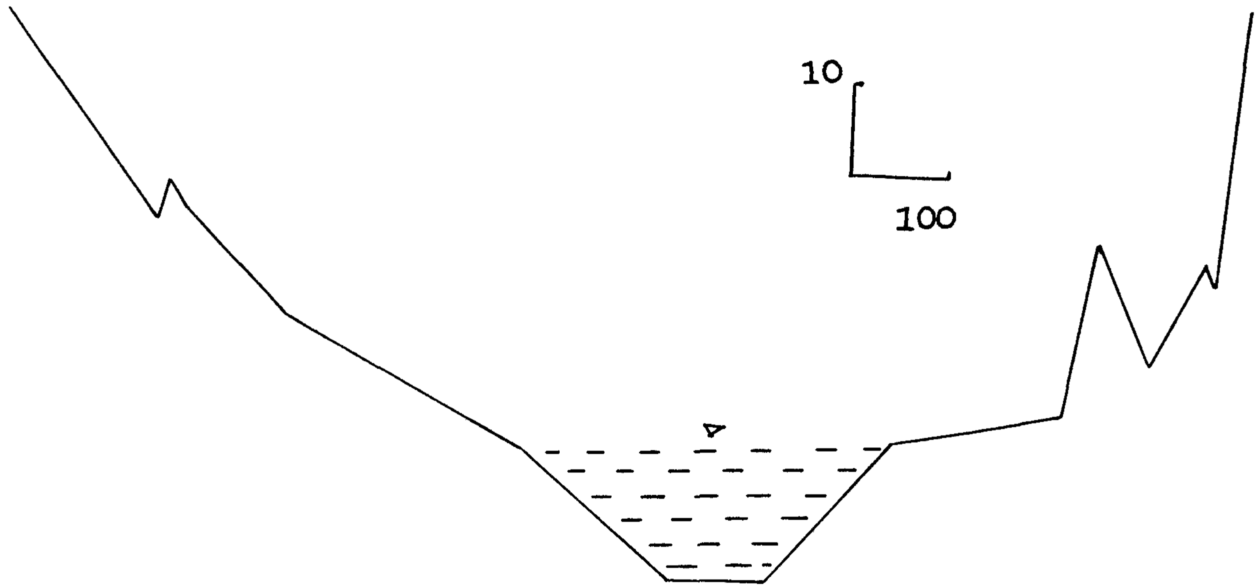
The cross sections from the upper reach also have levees or remnants of meander scrolls (for example, see #73, 90, 95-97, 89, 96, and 113 in Appendix 5). In the lower reach specific examples occur in the braided section but they are less frequent and less marked than in the upper reach. Table 3.3 below summarises some differences between the two reaches.

Fig.3.10 Cross section #25.1 in the Lower Reach .



The floodplian width is 1290.0 feet at an elevation of 832.0 feet. The channel width is 303.7 feet at an elevation of 802.7feet.

Cross section # 34 in the Lower Reach.



The floodplain width is 1319 ft. at an elevation of 858.7ft. The channel width is 401 ft. at an elevation of 831.8 ft.

FIGURE 3.11

TABLE 3.3

DIFFERENCES IN CROSS SECTIONS OF THE UPPER AND LOWER REACHES

Reach	Floodplain Width (f)	Channel Width (c)	f/c	Levees
Upper reach	2335.0	246.3	9.5	F
Lower reach	1332.0	344.8	3.9	R

F = Frequent, R = rare

THE IMPACT OF INCREMENTAL FLOW OVER THE CROSS SECTIONS

The increase of depth and width at a cross section in relation to increase in discharge, Q, takes the form of exponential equations, i.e. $w = aQ^b$, and $d = cQ^f$; where w is width, d is depth, and a and c are constants while b and f are exponents (inter alia, Leopold and Maddock, 1955, Knighton, 1972, p. 3815). Richards (1976, p.83) also found that width tended to change less with discharge in deep sections than in shallow sections.

The application of depth-width relationship gives an indication about erosion and deposition regimes over the cross sections, by evaluating the reciprocal impact of an increase of discharge on width.

For example Church (1977, p.8) uses the "regime" relationship of $W = aQ^{0.5}$, and suggests that the equation is usually repeatable. But the constant, a, varies for different channel types. The constant, a, for braided streams is 0.55 and meandering streams is 0.40. Calculating for Q gives an average of 1300 cfs which is the average spring discharge at Galt gauging station. Considering that there are few tributary entrants within each reach, then changes in width will be compensated by velocity and channel roughness. Since these figures are averages, Manning 'n' will be constant, so only velocity will vary along the reaches. The velocity variations are reflected in depth. A greater rate of increase in width relative to depth means a decrease in channel competence.

Samples of seven cross sections in the upper reach and six cross sections in the lower reach (see Appendix) were drawn. The relationships between increasing depth on width giving a family of curves (figures 3.12 and 3.13) for the upper and lower reaches respectively indicate that there are some similarities and differences between the study reaches. The depth-width curves of the upper reach have three breaks while the curves of the lower reach have one or none. Also, unlike the upper reach, the lower reach has curves which show that an increase in depth has a reciprocal increase in width. The curves of the upper reach which do not conform to the trend (cross sections 88, 97 and 113) are drawn from sections which have relatively narrow floodplains.

In the depth-width curves of the lower reach, the sections with more than one break in slope have braided bars and islands within the channel. These sections have wide floodplains. The typical upper reach curves are from the sinuous sections along the wide floodplain.

From the family of depth-width curves, the typical curves for the upper and lower reaches are given in figure 3.14. Width will increase faster than the increase in depth in the upper reach. At higher flood levels the rate of increase of width will decrease as the valley section becomes U-shaped. The curve for the lower reach shows uniform increase in depth and width.

FIG. 3.12 THE RELATIONSHIP BETWEEN AN INCREASE OF DEPTH AND WIDTH IN THE UPPER REACH

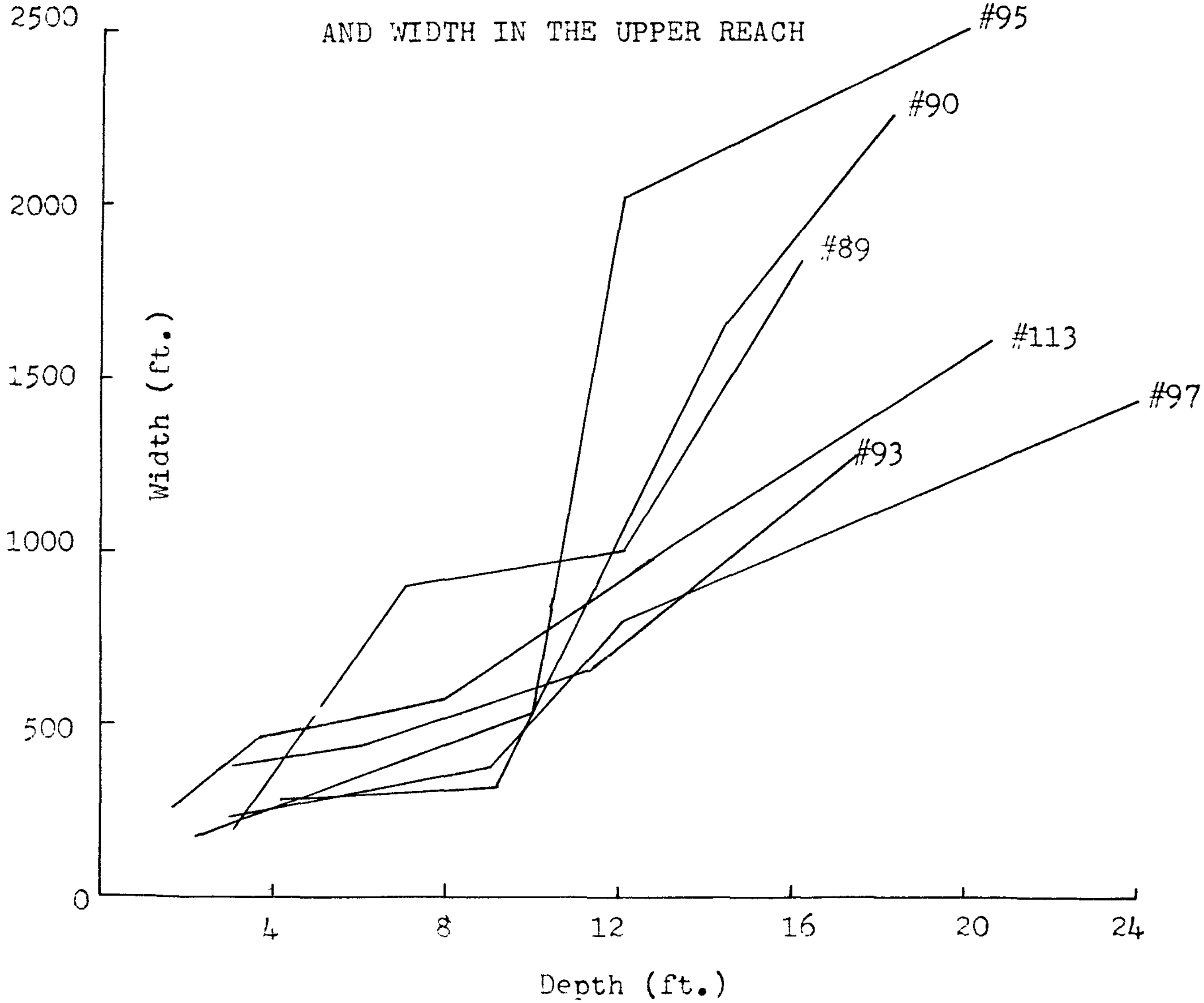


FIG. 3.13 THE RELATIONSHIP BETWEEN AN INCREASE IN DEPTH AND WIDTH IN THE LOWER REACH

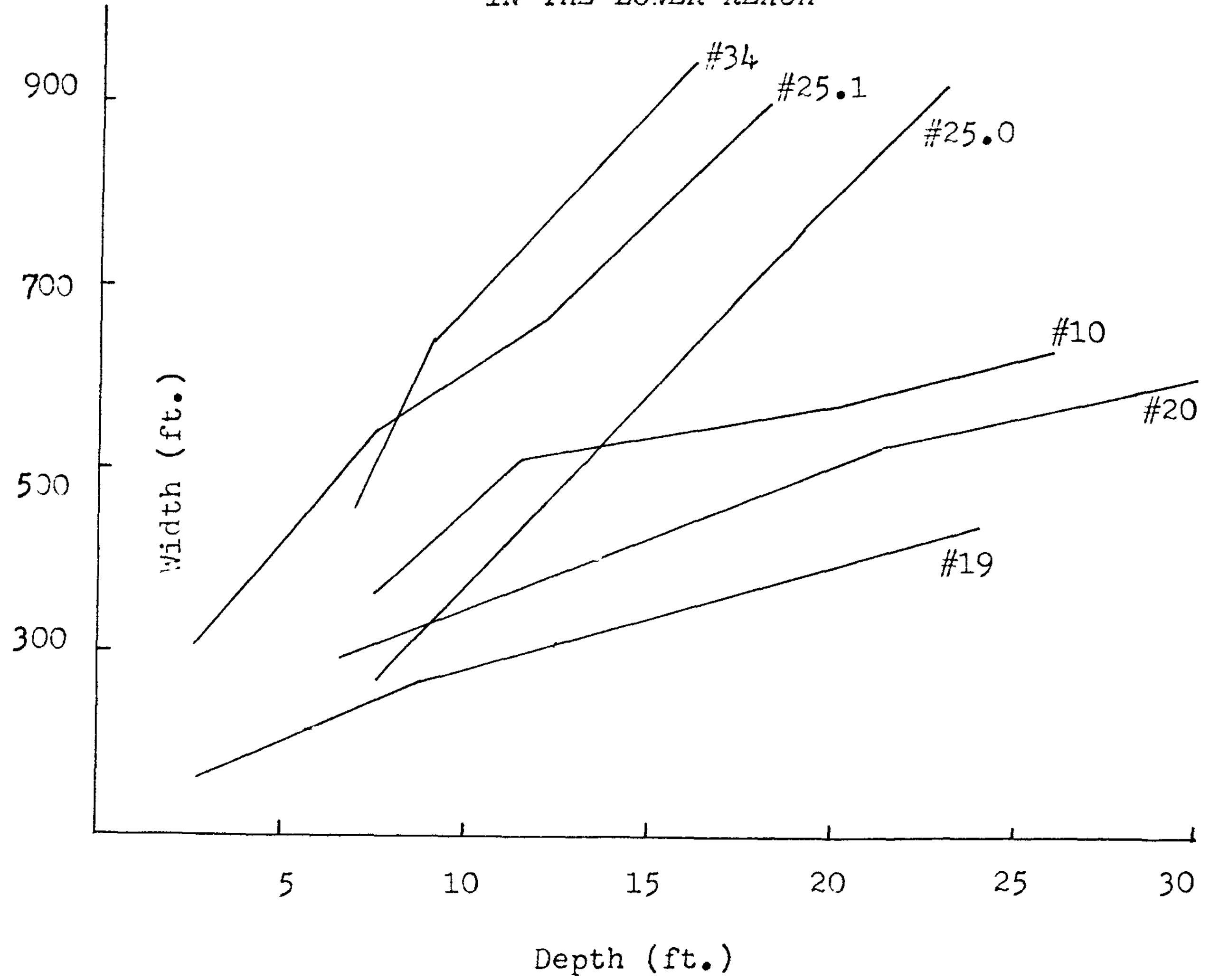
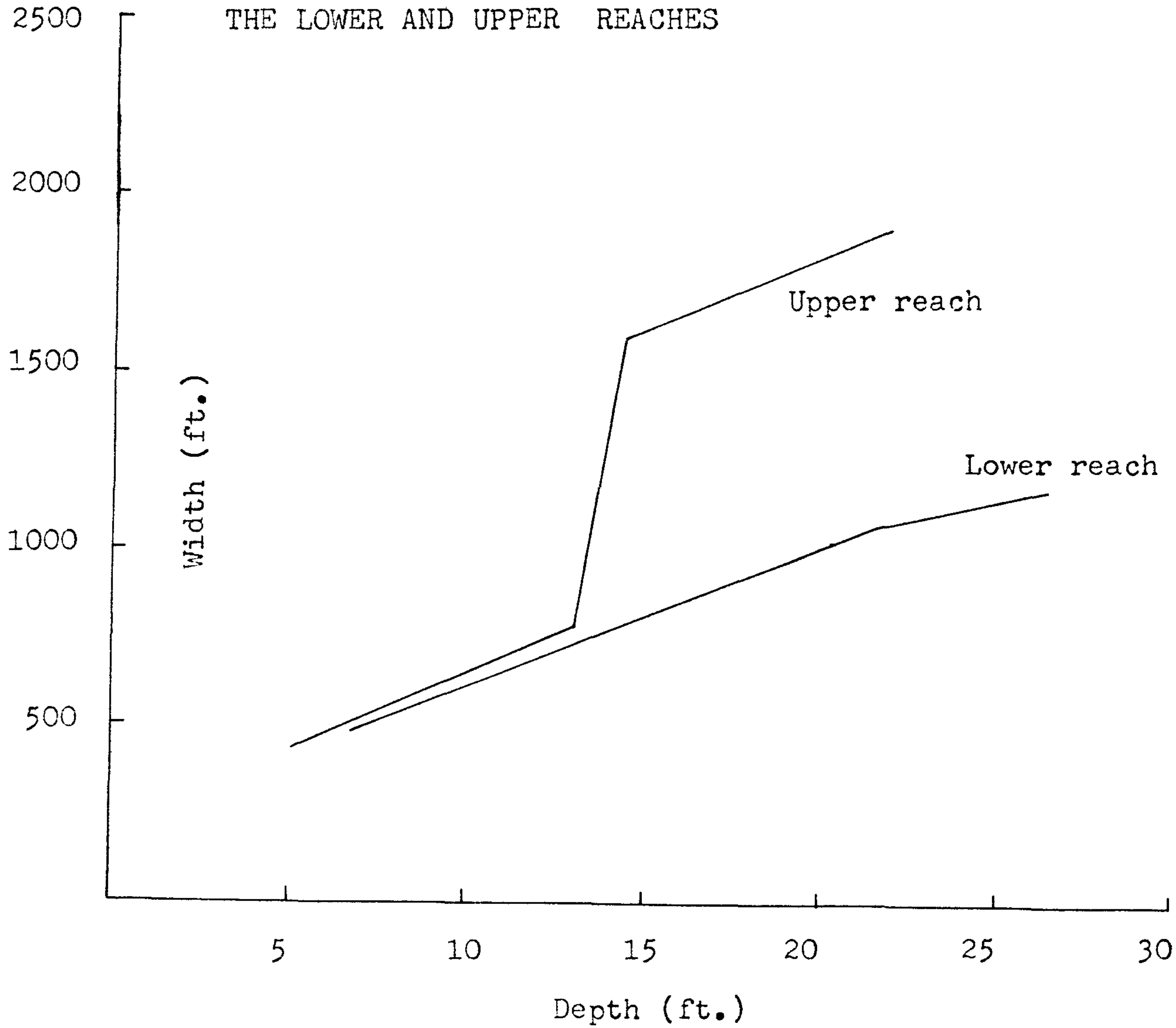


FIG. 3.14 THE COMPARISON BETWEEN AN INCREASE IN DEPTH AND IN WIDTH FOR THE LOWER AND UPPER REACHES



SUMMARY

The general physiography and channel patterns show different characteristics between the upper reach and the lower reach. However, the two reaches (the upper and the lower reaches) have typical examples of braid bars, islands and rapids. The differences observed are that the floodplain in the upper reach is relatively wider than the floodplain in the lower reach. The upper reach also shows a meandering tendency while the lower reach is straight/braided in many sections. The meandering tendency in the upper reach is also associated with higher relative floodplain widths to channel widths. Three types of channel sections were observed, namely, cross sections without braids, islands or rapids; cross sections with rapids or islands; and multi-channel sections. The cross sections have also secondary channels of which the ones in the upper reach are situated at relatively lower elevations than the lower reach. The rate of increase in width and depth in the upper reach is also different from the lower reach.

THE VARIABLES STUDIED

The variables studied are slope, width, depth, width-depth ratio, shear velocity, slope-width ratio and channel and valley symmetry. Slope is considered here as an independent variable through which changes in other variables depend. Valley slope and thalweg slope are considered for measuring the magnitude of stream incision and the impact of the inherited floodplain to the present channel patterns.

The other variables (apart from slope) are dependent variables. This categorisation depends on the methods of analysis reviewed in the literature. The changes of the variables are reflected in channel pattern characteristics which have been described and differentiated.

VALLEY SLOPE

Valley slopes were measured from topographical maps of 1:25,000 with contour intervals of 10 feet along the profile of the river. At every contour crossing along the stream, channel length was measured at mid-section of the river. The channel patterns were then interpreted from the topographical maps and photo mosaics.

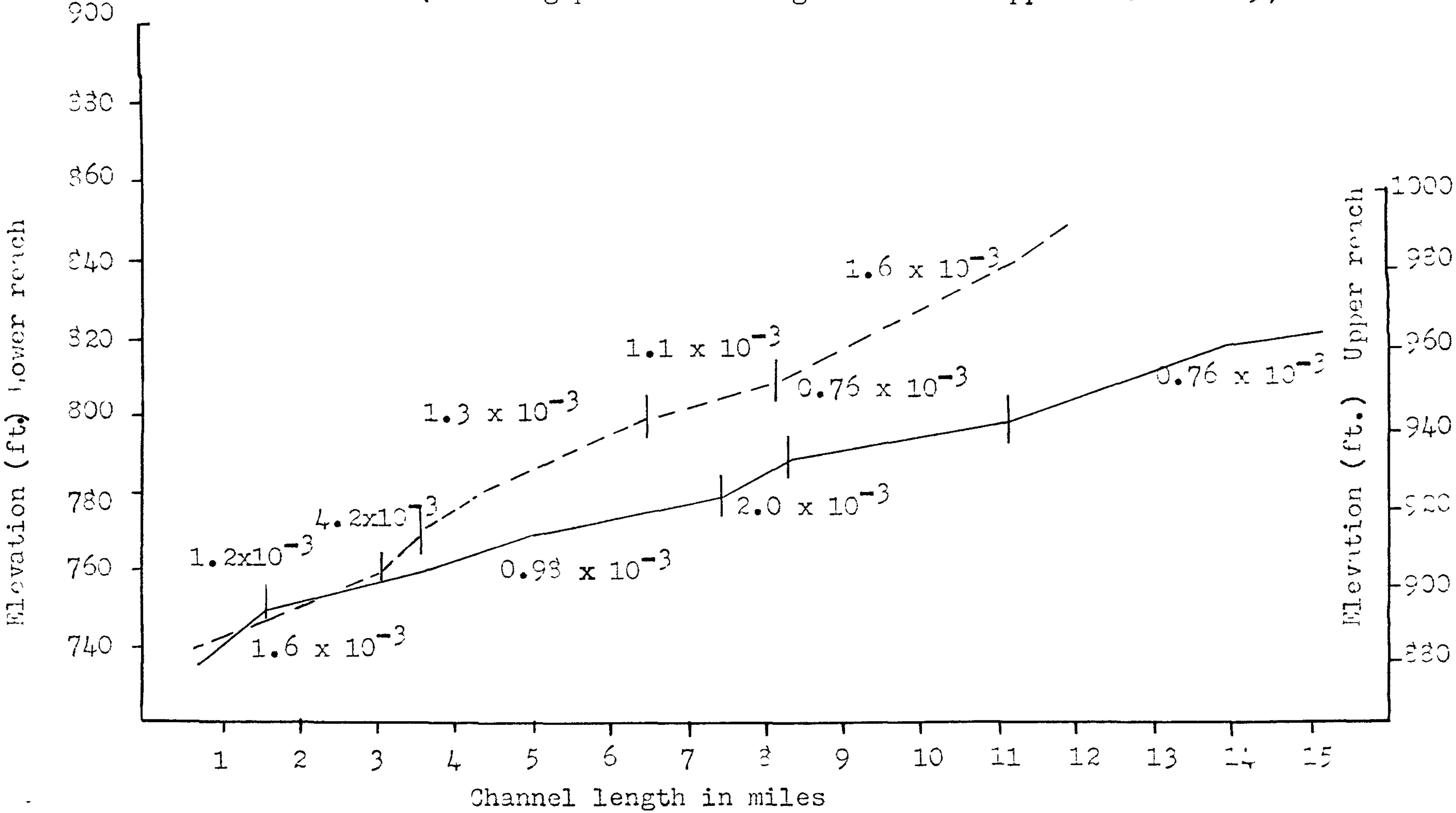
The aim of this calcualtion is to show association of the valley slope with different channel patterns observed in each reach. In post-glaciated landscapes, the floodplain might not be a product of the stream, in part or in whole. While in alluvial floodplains, the valley tends to be in phase with the stream itself, in post-glaciated landscapes, the stream is likely to be out of phase with the floodplain either due to underfitness phenomenon or other glacio-geological features. The floodplain in alluvial streams therefore represents differing changes in channel migration.

It will be shown how the stream has changed or maintained the inherited slope, and how the inherited slope has influenced the present channel characteristics. This will be done by calculating topographic and hydraulic sinuosity indices. Topographic sinuosity index will present percent sinuosity contributed by stream flow. A 50-50 percent sinuosity will indicate equal contribution of topography and stream flow. The valley slopes are drawn from the data in Appendix 1, and drawn in Figure 3.15 .

The average valley slope for the upper reach is 1.1×10^{-3} while in the lower reach, the average valley slope is 1.6×10^{-3}.

FIGURE 3.15 VALLEY SLOPES OF THE UPPER REACH AND THE LOWER REACH

(Plotting positions are given in the Appendices 2 and 3)



Upper Reach

Lower-Reach

TABLE 3.4

PRELIMINARY ANALYSIS OF VALLEY SLOPE

Reach	Channel length (miles)	Valley length (miles)	General Sinuosity Ratio	AIR	Channel index	Valley index	HSI (%)	TSI (%)	Valley slope ($x10^{-3}$)
Upper reach	18.6	15.9	1.17	8.45	2.2	1.9	27.3	73.7	1.1
Lower reach	11.5	11.3	1.01	9.45	1.2	1.2	5.3	94.7	1.6

NB. The calculation of the valley and channel lengths were extended to the nearest contour interval instead of extrapolating the mid-evaluation.

TABLE 3.4

PRELIMINARY ANALYSIS OF VALLEY SLOPE

(Continued)

CL	=	Channel length (in miles)
VL	=	Valley length (in miles)
AIR	=	Shortest of air distance (in miles)
CI	=	Channel Index, $= \frac{CL}{AIR}$, or an index of total sinuosity
VI	=	Valley Index, $= \frac{VL}{AIR}$, or an index of total topographic sinuosity
HSI	=	Hydraulic Sinuosity Index = % equivalent of $\frac{CI - VI}{CI - 1}$
TSI	=	Topographic Sinuosity Index = % equivalent of $\frac{VI - 1}{CI - 1}$

General Sinuosity ratio, $P = \frac{\text{Channel length}}{\text{Valley length}}$

Different sinuosity indices have been calculated. The lower reach has a lower sinuosity ratio than the upper reach. The upper reach has a general sinuosity ratio of 1.17 and a topographic sinuosity index of 73.7 percent. The general sinuosity ratio for the lower reach is 1.01 and it has a topographic sinuosity index of 94.7 percent. This implies that the study reaches are topographically controlled. The meandering tendency in the upper reach, as shown by a high channel index (2.2) may not be a product of the stream itself.

The description of channel patterns according to the division of the upper reach as meandering and the lower reach as straight and/or braiding can therefore apply to this study in a general way. Using Chitale's (1973, p. 286) "concept of a continuum", it is possible to show different patterns within short channel lengths separated by breaks of valley slope.

Breaks in valley slope along the channel length have been calculated from Figure 3.17. A systematic summary of the channel patterns of the two (upper and lower) reaches are also given. The channel lengths are given in miles from downstream, i.e. from Paris in the lower reach, and from Cambridge in the upper reach, in Table 3.5 below.

THALWEG SLOPE

The thalweg slope has some implications on energy distribution in a channel. Velocity increases with thalweg slope, assuming other factors are held constant. This increase in velocity will

TABLE 3.5

SUMMARY OF THE CHANNEL PATTERNS IN THE UPPER AND LOWER REACHES

The Upper Reach

Distance from Cambridge (Miles)	Average Valley Slope ($x10^{-3}$)	Channel Pattern
Up to 1.7	1.6	Highly sinuous in a wide floodplain
1.7 - 7.5	0.98	Braided in a narrow floodplain
7.5 - 8.4	2.0	Low sinuosity in a narrow floodplain, occasional braids
8.4 - 11.0	0.78	Straight, with occasional braids
11.0 - 15.0	0.76	Mostly straight, few braids

The Lower Reach

Distance from Paris (Miles)	Average Valley Slope ($x10^{-3}$)	Channel Pattern
Up to 3.1	1.2	Rapids
3.1 - 3.6	4.2	Narrow floodplain
3.6 - 6.4	1.3	Braided, wide floodplain and rapids
6.4 - 8.2	1.1	Channel anabranches with rapids, narrow floodplain
8.2 - 12.0	1.6	Channel anabranches with rapids, narrow floodplain

increase erosional capability and stream competence. In varied bed topography, this would suggest that some sections of non-sustaining slopes are depositional while the sustaining slopes are erosive. This differential channel erosion in some portions and deposition in some sections cause different channel patterns, suggesting that channel patterns are not exclusive.

Thalweg slopes were calculated from the Grand River Conservations Authority's data. The lowest elevation across the section is the position of the thalweg. This lowest elevation is subtracted from the lowest elevation in the upstream section. The procedure was continued until each reach was completed.

The aim of this calculation is to relate thalweg slope to different channel patterns. Thalweg slopes influence channel bank and channel bed erosion. Steep thalweg slope section will be associated with flow convergence, while flat thalweg slopes will be associated with flow divergence. Flow divergence causes erosion of the channel banks while flow divergence causes erosion of the channel bed.

The thalweg slopes of the upper and the lower reaches are shown in Figure 3.18. The upper reach has a mean thalweg slope of 1.5×10^{-3}, while the lower reach has a mean thalweg slope of 1.9×10^{-3}. The upper reach was reduced from the original length shown on valley slope because some depth measurements were not available.

The upper reach is more sinuous than the lower reach i.e. channel index of 2.2 and 1.2 respectively. Alluvial systems have higher probability of maintaining a steady equilibrium state between valley slope, thalweg slope and sinuosity ratio because the floodplain

FIG.3.16 THALWEG SLOPES OF THE UPPER AND THE LOWER REACHES

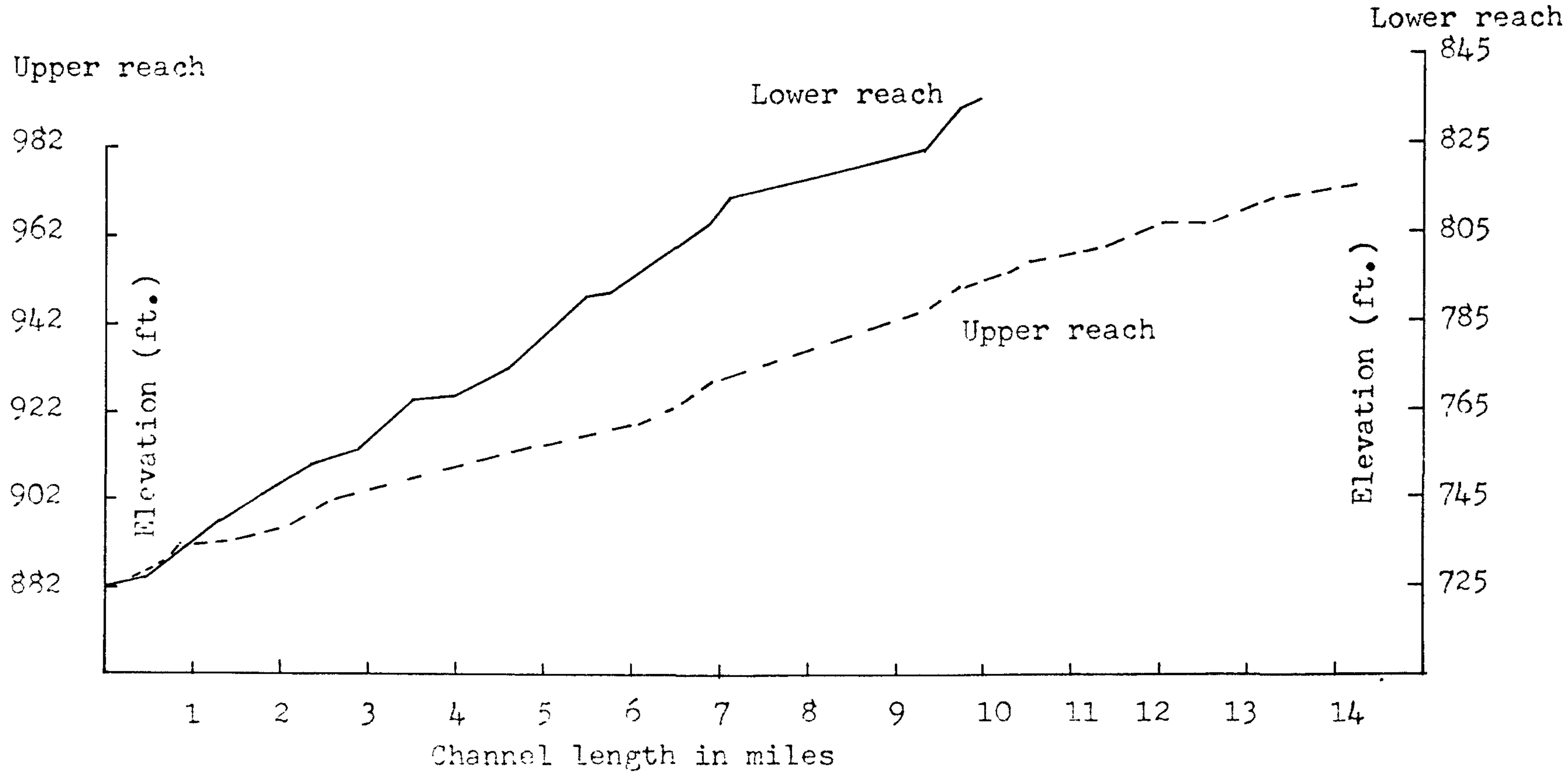


TABLE 3.6

SUMMARY OF THALWEG SLOPE CALCULATION

Reach	Elevation (ft.)	Elevation (ft.)	Thalweg Slope (x 10^{-3})
Upper reach	969.4	879.3	1.5
Lower reach	841.6	727.2	1.9

Source: calculated from data of cross sections from the Grand River Conservation Authority.

TABLE 3.7

COMPARISONS OF VALLEY SLOPES AND THALWEG SLOPES FOR THE UPPER AND LOWER REACHES

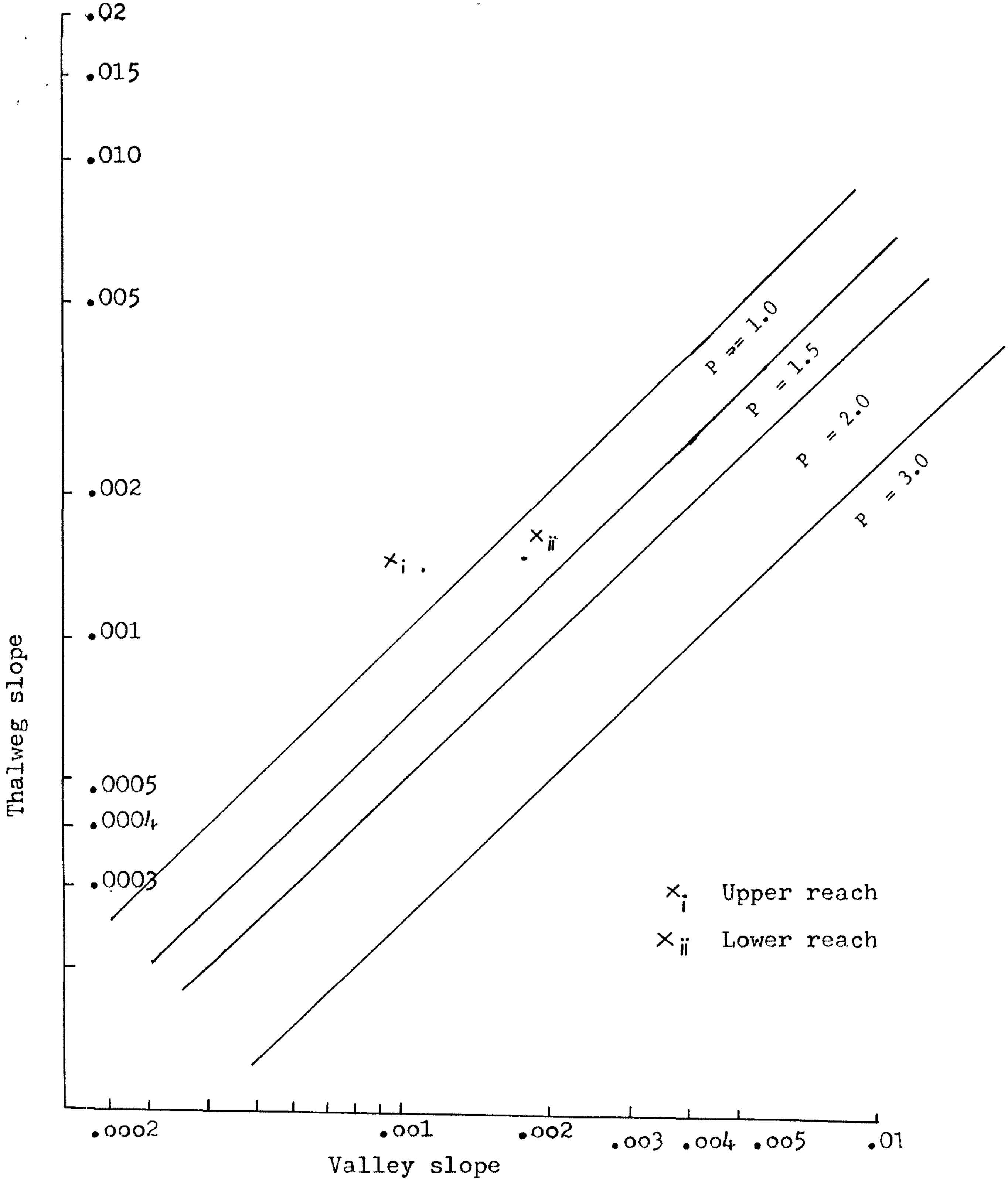
Reach	Valley Slope	Thalweg Slope	General Sinuosity
Upper reach	0.0011	0.0015	1.17
Lower reach	0.0016	0.0019	1.01

Source: Table 3.4 and Basic Statistics (Appendix 2) is a product of the differing erosional modifications caused by the stream occupying the floodplain. In regions where the channel occupies a post-glacial spillway, the equilibrium between valley slope and the thalweg slope, and sinuosity ratio would imply that the stream has adapted itself to the characteristics of the floodplain. This argument is used to compare the study reaches with the model developed for alluvial streams.

Schumm (1977, p.113) arrived at a relationship between the sinuosity ratios and the thalweg and valley slopes, reproduced in the Figure 3.17. When the study reaches are drawn on the model, the lower reach fits fairly well, but the upper reach has a higher thalweg slope than the one postulated by the model. This implies that the upper reach is unstable and the slopes (valley and thalweg) are not in equilibruim.

Since the lower reach is similar to the model, the comparison can be extended to channel patterns. Different thalweg slopes have been associated with different channel patterns shown in Table 2.3. This comparison shows that the upper and lower reaches are straight. The lower reach is straight as shown by general sinuosity ratio and channel index while channel index of 2.2 had been calculated for the upper reach. Perhaps the result based on Schumm's model (Tabel 2.3) for the upper reach is due to the fact that different portions of the channel have different patterns, and also non-uniform thalweg slopes. By applying different thalweg slopes along the study reaches, the difficulty created by summing thalweg slopes will be avoided.

FIG. 3.17 RELATION BETWEEN ALLUVIAL VALLEY SLOPE AND CHANNEL SLOPE (Source : Schumm, 1977, p, 113)



Breaks in thalweg slope

Thalweg slopes were drawn for all surveyed cross sections to identify the breaks of slopes. Figure 3.18 shows the thalweg slopes of the upper and lower reaches.

From these breaks of thalweg slopes, it will be possible to show the associations between the breaks of slopes and width and depth along the same sections. Also, levels of channel incision and/or aggradation will be shown for each of the sections. When the thalweg slope is steeper than the valley slope, then the stream is incising. When the valley slope is steeper than the thalweg slope, then the stream is aggrading.

The segments of the lower reach have lower variations between each segment than the segments of the upper reach. The section of the upper reach north of Cambridge (thalweg slope of 2.0×10^{-3}) seems to be continued in the lower reach. Most of the break points in the lower reach are associated with rapids.

Table 3.8 summarises the channel lengths of different segments of the upper and lower reaches.

TABLE 3.8

SUMMARY OF DIFFERENT SEGMENTS OF THE THALWEG SLOPES

The Upper Reach

Cumulative distance from Cambridge (miles)	Thalweg slope ($\times 10^{-3}$)
- 1.4	2.0
1.4 - 7.3	0.95
7.3 - 8.7	3.5
8.7 -12.0	1.5
12.0 -15.0	0.57

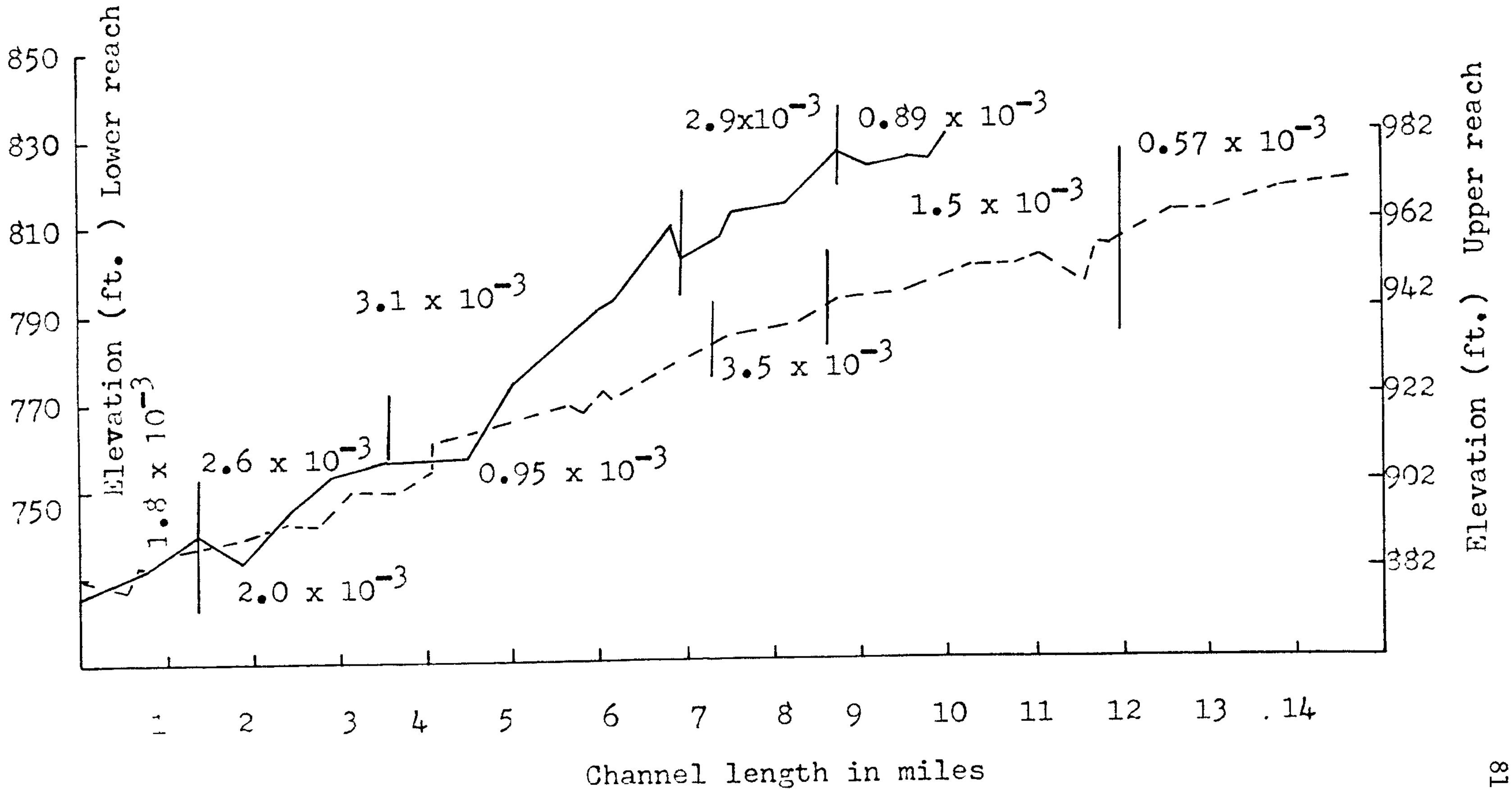
TABLE 3.8 (con't ...)

The Lower Reach

Cumulative distance from Paris (miles)	Thalweg slope (x 10^{-3})
1.4	1.8
1.4 - 3.5	2.6
3.5 - 7.0	3.1
7.0 - 8.8	2.9
8.8 - 10.0	0.89

The lower reach has steeper thalweg slopes than the upper reach. In the upper reach, steeper thalweg segment is compensated downstream by a flatter segment.

FIG. 3.18 THALWEG VARIATION ALONG THE UPPER AND LOWER REACHES



Comparison between thalweg and valley slopes

This comparison derives incision and aggradation indices along the two reaches. Incision and aggradation indices are calculated as the ratio of the thalweg slope over the valley slope in short channel sections separated by breaks of both (thalweg and valley) slopes. If the measured index (incision or aggradation) is greater than 1.0 then the channel is incising, while an index less than 1.0 means that the channel is aggrading.

The methodology is made possible because the break points of thalweg and valley slopes are similar. The terminology of incision and/or aggradation assumes that the channel is actively changing its morphology. Bed rock exposures commonly indicate resistance to erosion. These cause rapids which migrate upstream causing slight differences between the nickpoints on the thalweg and the valley slopes. The differences are close to facilitate the comparison.

The incision and aggradation indices are summarised in Table 3.8 for both reaches.

WIDTH

Width of a channel section was calculated by subtracting the point distances of the water level on the right bank from the left bank to get the top width of the channel.

Wide widths have been associated with shallow streams and flat slopes, while narrow widths have been associated with deep streams and steep slopes. The aim of width calculation is to find any associations with depth and slope. Trends and changes of width

TABLE 3.9

STREAM INCISION AND STREAM AGGRADATION, MEASURED AS A RATIO OF THE THALWEG SLOPE TO VALLEY SLOPE IN THE UPPER AND LOWER REACHES

UPPER REACH

From Cambridge (miles)	Valley Slope (x 10^{-3})	Thalweg Slope (x 10^{-3})	Index of Stream Incision	Index of Stream Aggradation
0 - 1.7	1.6	2.0	1.25	-
1 - 7.5	0.98	0.95	-	0.97
7.5 - 8.4	2.0	3.5	1.75	-
8.4 - 11.0	0.78	1.5	1.92	-
11.0 - 15.0	0.76	0.57	-	0.75

LOWER REACH

From Paris (miles)	Valley Slope (x 10^{-3})	Thalweg Slope (x 10^{-3})	Index of Stream Incision	Index of Stream Aggradation
0 - 3.5	1.2	2.2	1.83	-
3.5 - 6.4	1.3	3.1	2.38	-
6.4 - 8.2	1.1	2.9	2.69	-
8.2 - 12.0	1.6	0.89	-	0.56

will be shown by calculating cumulative deviations of width, and will show decreasing, increasing or fluctuating trend around the mean. The sections of change of the trend in the cumulative deviations will be isloated to be compared with breaks in thalweg slopes so that tentative levels of change can be isolated.

Figure 3.19 shows width variation along the longitudinal profile of the upper reach and the lower reach. The upper reach has uniform spatial distribution with oscillations of wide sections and narrow sections about 2 to 3 miles. The lower reach has a decreasing trend downstream.

The mean width is 250 feet for the upper reach and 345 feet in the lower reach.

Figure 3.20 and 3.21 show cumulative deviations of width from the mean width. The points are calculated by progressively summing mean deviations for each measurement, i.e. the first point is the deviation at the first section; the second point is the sum of deviations at a downstream and the first deviations; and so on. The mean width is given by an arbitrary number, zero.

In the upper reach, the trend seems to decrease in the first 5.0 miles associated with a narrow floodplain and low sinuosity. The trend then increases moderately up to 12.0 miles downstream where the channel pattern changes from a section of low sinuosity, a narrow floodplain with occasional braids to a more sinuous pattern near Cambridge. Figure 3.21 shows the cumulative deviations from the mean width in the lower reach. The trend seems to increase downstream with some fluctuations associated with the braided section south of Cambridge. The trend falls steeply 8.1 miles downstream, and then levels off.

FIG. 3.19 WIDTH VARIATION ALONG THE LONGITUDINAL PROFILES OF THE UPPER AND LOWER REACHES FROM UPSTREAM

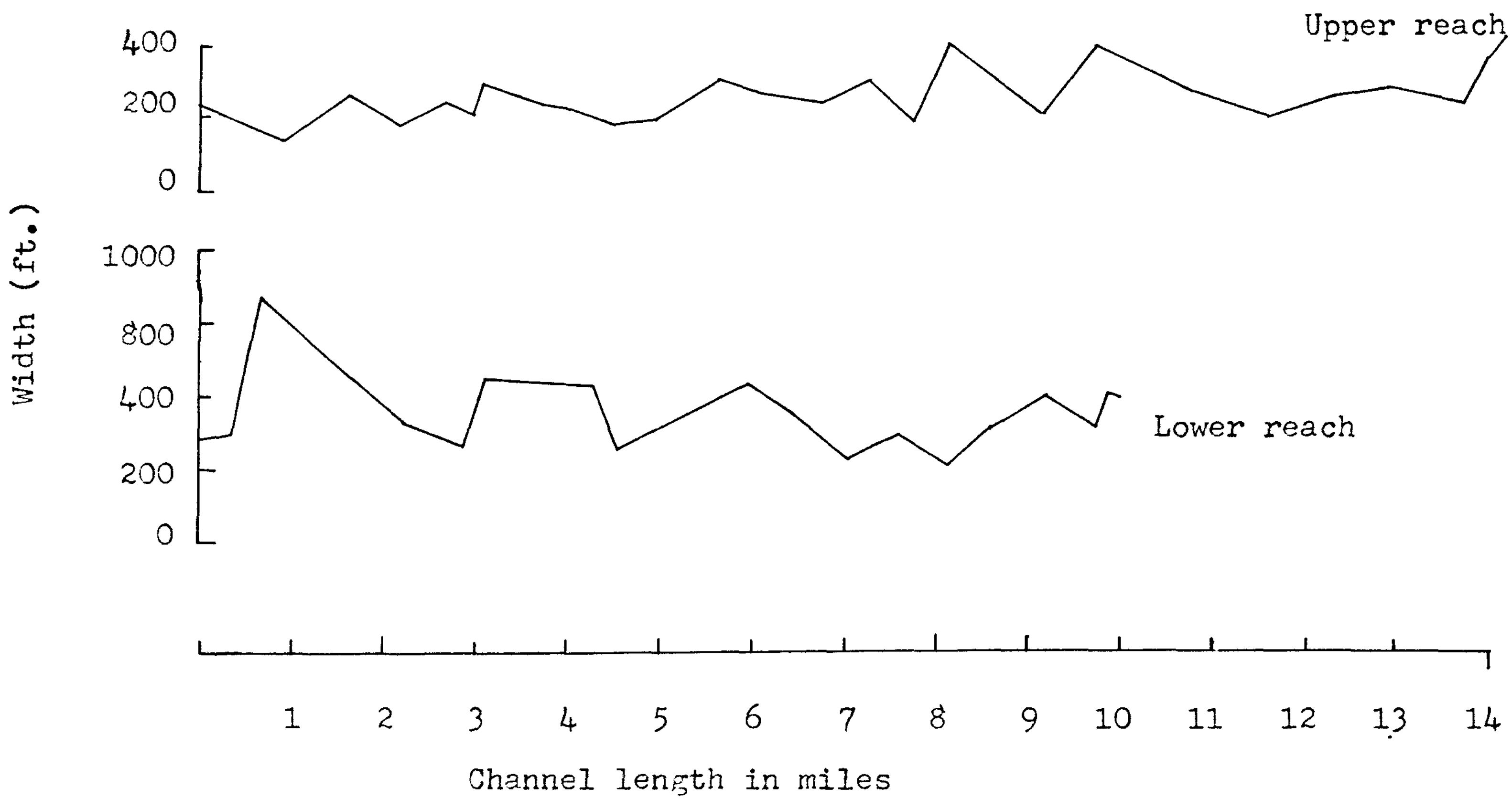


FIG. 3.20 CUMULATIVE DEVIATIONS OF WIDTH IN THE DOWNSTREAM DIRECTION FOR THE UPPER REACH

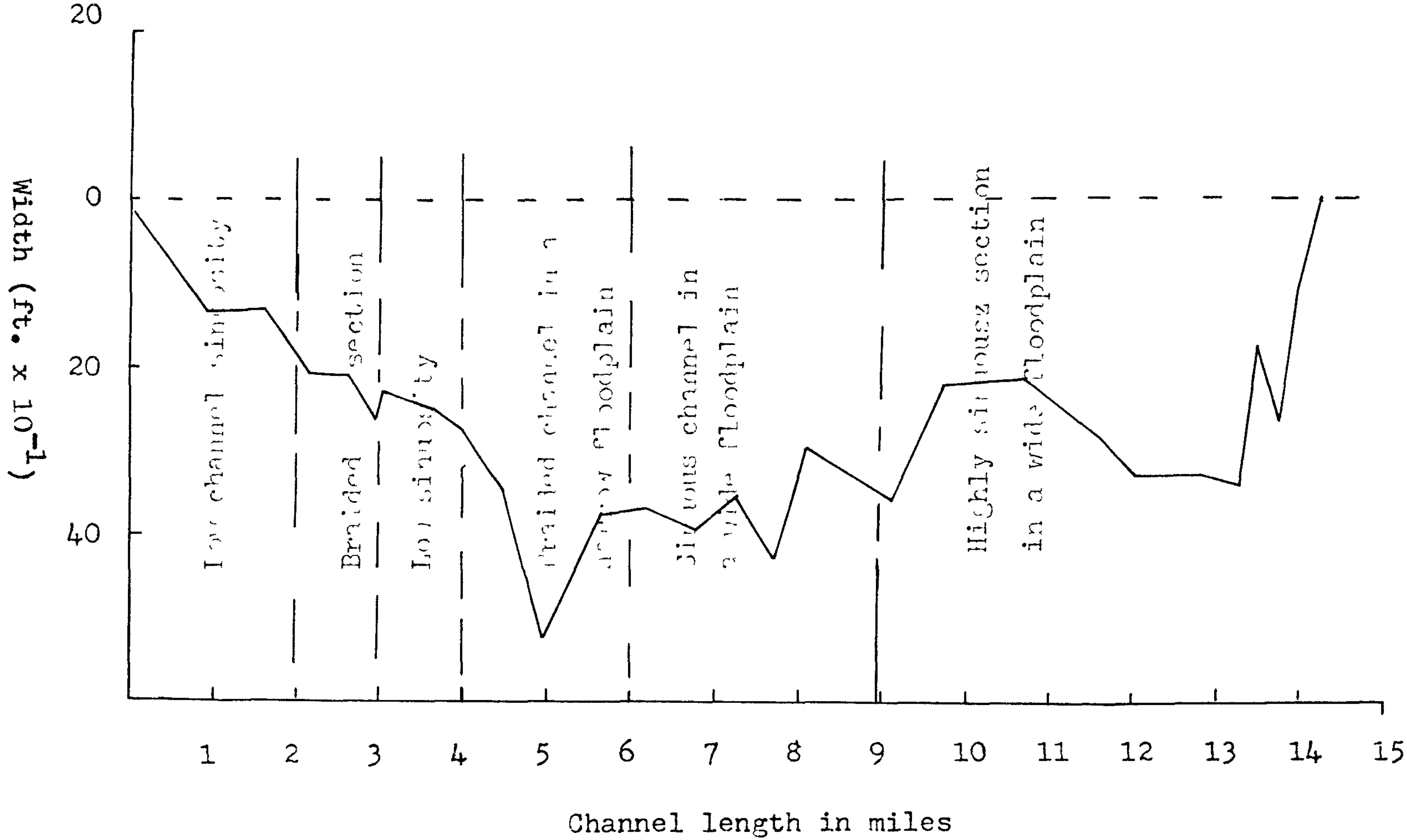
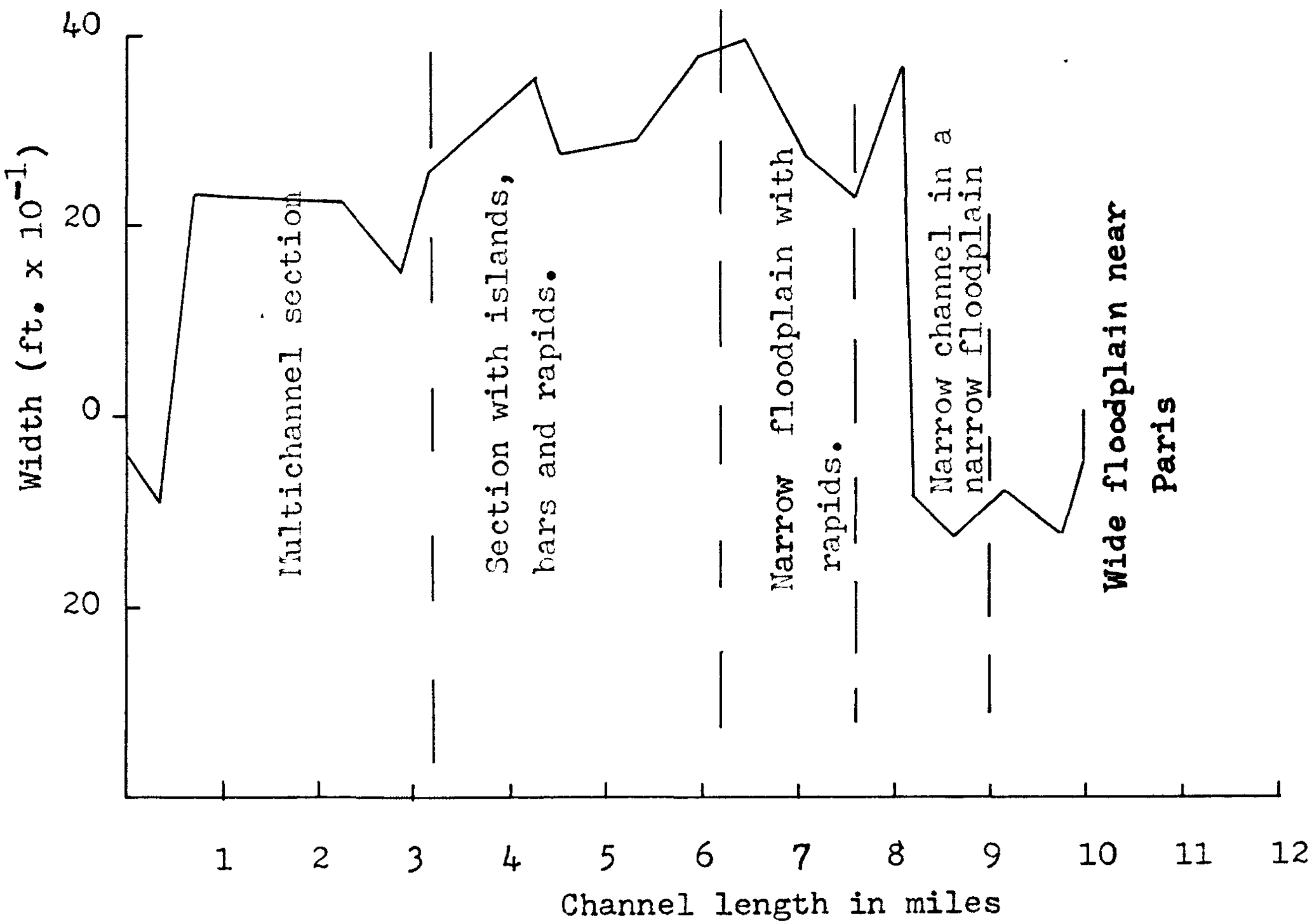


FIG. 3.21 CUMULATIVE DEVIATIONS OF WIDTH IN THE DOWNSTREAM DIRECTION FOR THE LOWER REACH



The section where the curve falls steeply is a section in the lower reach around Glen Morris where the stream makes a detour from a southeast direction to a sourthwest direction. The floodplain is wide around the detour section, but still it confines the bend. The section has many rapids, bars and islands.

DEPTH

Depth was calculated by subtracting the lowest elevation in the channel from the bank elevation. This gives the thalweg depth.

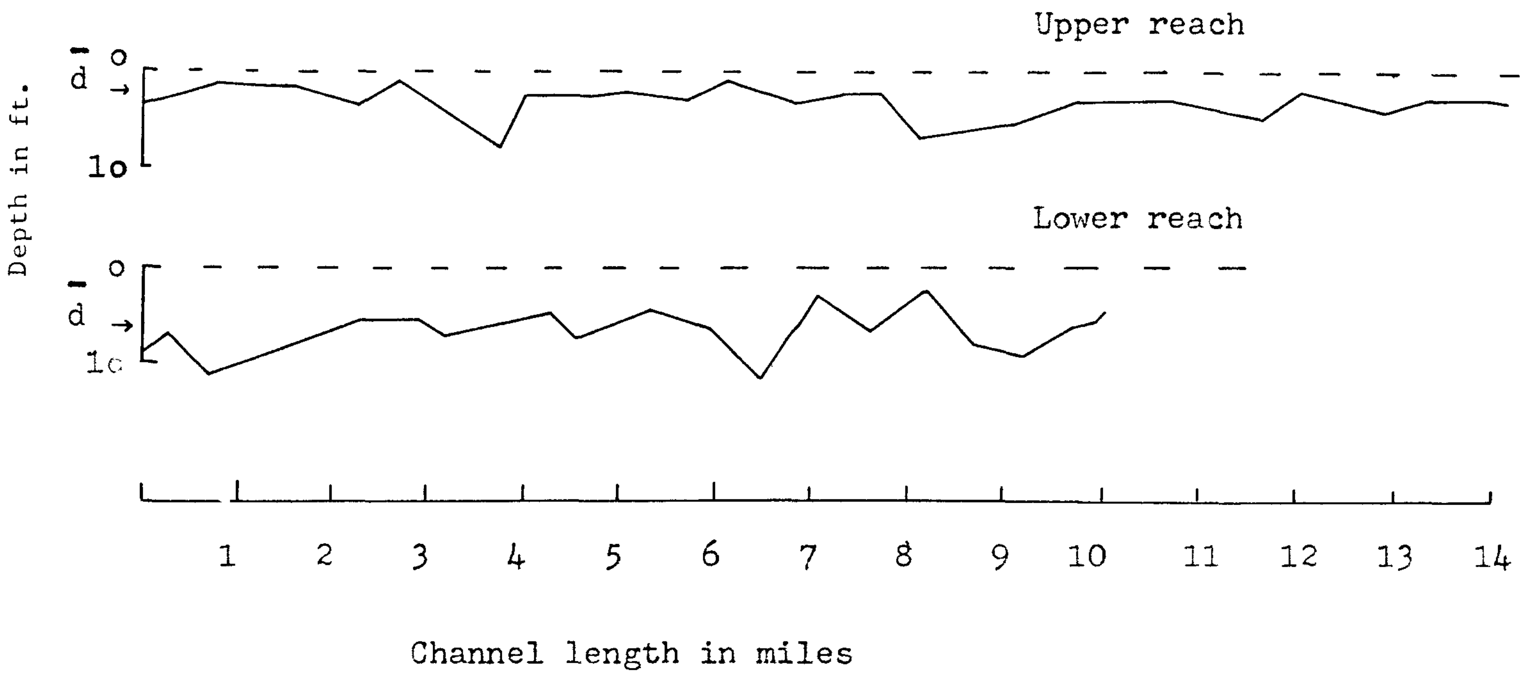
Width and slope are related by the association of steeper slopes with deeper sections and narrower widths than flat slopes. This can be explained by convergence - divergence flow phenomenon which cause erosion and/or deposition, thus patterning channel characteristics. The aim of this calculation is to relate associations of width to depth and slope.

The method of calculating cumulative deviations from mean width has also been adopted to show the trends of depth.
This will be used for comparison with width changes along the profile.

Figure 3.22 shows the variations of widths along the longitudinal profiles of the upper and lower reaches. The upper reach has a uniformly fluctuating trend downstream up to the middle of the reach, followed by deep sections towards Cambridge. Two sections of the upper middle reach are generally deeper than the upper and lower sections. The mean depth of the upper reach is 3.3 feet.

In the lower reach deep and shallow sections spread along the reach, depth then decreases toward Paris township. These deep sections are also reflected in the thalweg variations as plunge pools. The mean depth of the lower reach is 6.5 feet.

FIG. 3.22 DEPTH VARIATION ALONG THE LONGITUDINAL PROFILES OF THE UPPER AND LOWER REACHES



Figures 3.23 and 3.24 show cumulative deviations from the mean depth for the upper and lower reaches respectively. In Figure 3.23 the trend is a decreasing in the first 2.7 miles from Kitchener, and then a sharp increase which falls at 7.8 miles toward Cambridge. The trend then increases, reaching a peak 9.0 miles before generally fluctuating above the mean line.

In the upper reach, the deepest points are reflected as the peak points in the cumulative deviations of depth. In Figure 3.24, the shallow points occur 2.7 miles, 4.0 to 7.7 miles in the upper reach. The breaks of cumulative deviations curve in the upper reach have significant relationships with the trends of valley slope. At 2.7 miles and 7.8 miles downstream, the valley slope changes from 0.0013 to 0.006, at an elevation of 970 feet and 0.0014 to 0.0007 at an elevation of 950 feet. Small breaks can also be associated with minor changes in valley slope.

In Figure 3.24, the trend is generally decreasing, although with breaks before sharply falling south of Glen Morris. This follows a similar decrease in width in the same section. The trend is generally decreasing in the downstream direction. Generally the deepest points synchronise with the points with relatively wide channel widths. This can be easily seen by superimposing Figures 3.22 on 3.24 for the lower reach.

WIDTH-DEPTH RATIO

Width depth ratio measures the freedom the stream has to meander in its channel and also the energy available for it to erode the channel perimeter, transport or deposit sediments.

FIG. 3.23 CUMULATIVE DEVIATIONS OF DEPTH IN THE DOWNSTREAM DIRECTION OF THE UPPER REACH

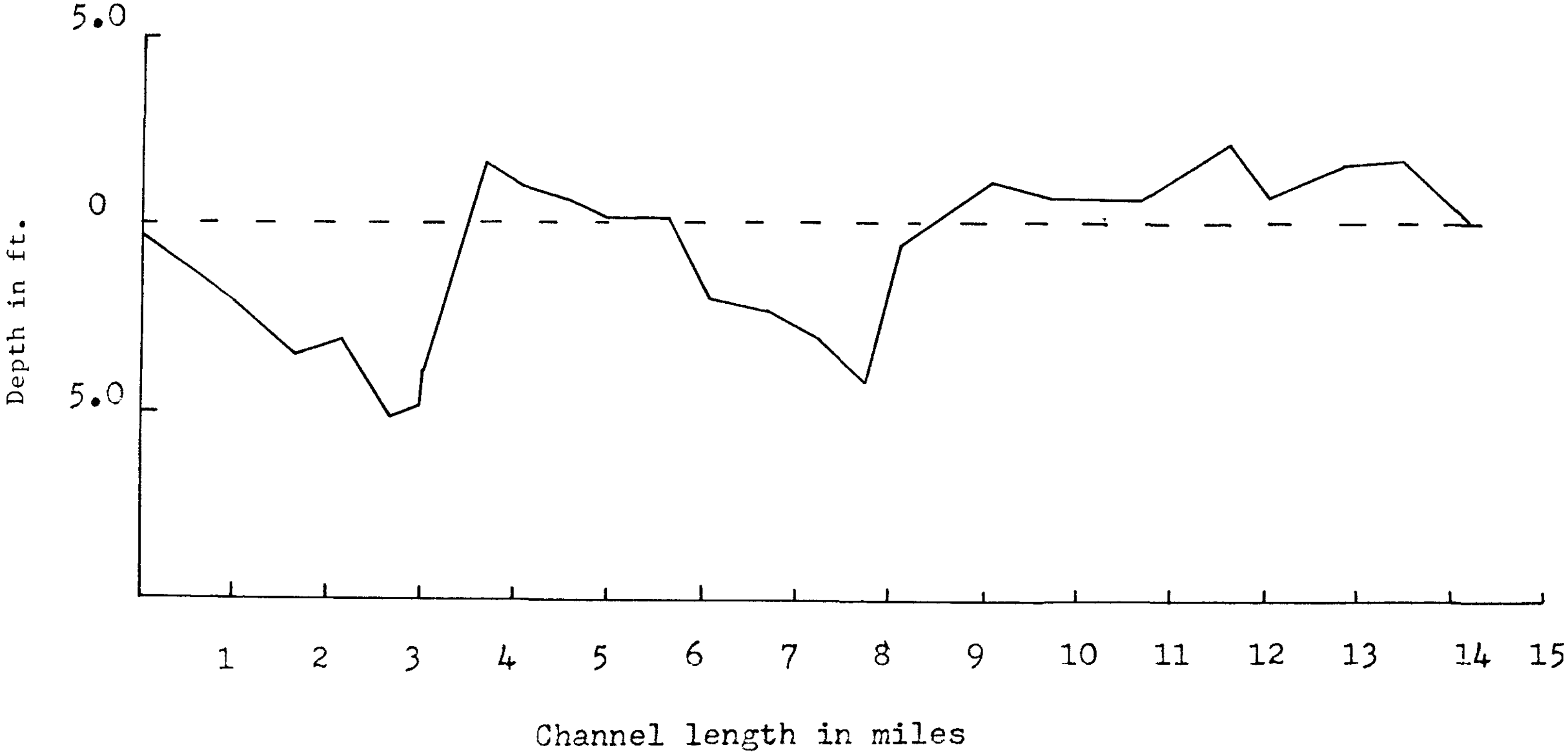
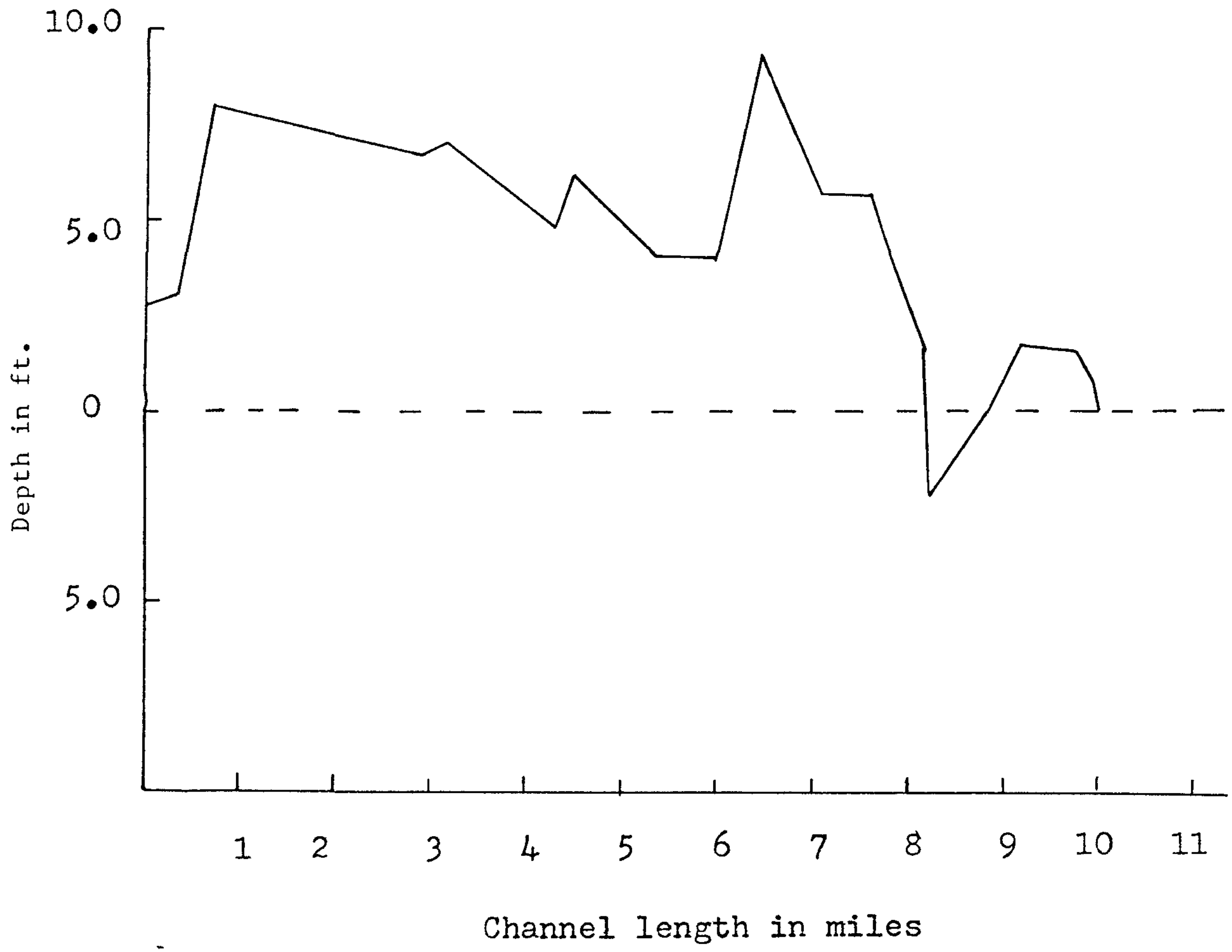


FIG. 3.24 CUMULATIVE DEVIATIONS OF DEPTH IN THE DOWNSTREAM DIRECTION OF THE LOWER REACH



Different channel patterns have been associated with specific width-depth ratios. It is related to sinuosity, sediment discharge and erosional ability of the stream. It is used to categorise the study reaches as eroding or silting. From these categories, it is possible to infer whether the channel is meandering, braiding or straight.

Table 3.10 below, shows the width-depth ratios of the study reaches and the expected channel characteristics (after Schumm, 1977, and Crickmay, 1974).

TABLE 3.10

WIDTH-DEPTH RATIO AND EXPECTED CHANNEL CHARACTERISTICS

Width-Depth Ratio	Upper Reach (Number of Cases)	Lower Reach (Number of Cases)	Channel Patterns Expected
29.00 - 83.00	17	17	Meandering, showing progressive failure in competence
83.00	10	3	Straight and braiding

The sections of the upper reach have almost equal number of sections of meandering or braiding patterns. In the lower reach, most of the sections are meandering. The mean width-depth ratios of the upper and lower reaches are 95.6 and 59.8 respectively. The upper reach has a higher variation than the lower reach (see Appendix 4).

SLOPE-WIDTH RATIO

This is the ratio of the thalweg slope to channel width. Leopold and Langbein (1964, p. 785) show that the rate at which water falls in a unit distance along its course is only slope. The rate of the channel to do work per unit length is in the form of uwDvs, where; u is the specific weight of water; w is channel width; D is depth of the channel; v is velocity. Discharge is wDv, therefore the power of doing work per unit width is uQs, where Q is discharge.

If there is equal distribution of work, then $\frac{uQs}{w}$ must be constant. When discharge and u are assumed to be constant, then the power per unit width over short reaches would be s/w. By using s/w in the study it will be possible to show the reach with higher ratios and more variations than the other. The s/w ratios also increases with decreasing width and depth, however the thresholds of change are not known.

Two cases in the upper reach and four cases in the lower reach have slope-width ratios greater than 10×10.0^{-5}. The mean s/w ratio for the upper and lower reaches are 11.2×10^{-5} and 8.5×10^{-5} respectively. Both reaches have normal distributions. The upper reach has a standard deviation of 4.3 while the lower reach has a standard deviation of 13.5. From the descriptive statistics, the upper reach has higher s/w ratios and lower variation than the lower reach (Appendix 4).

SHEAR VELOCITY

Shear velocity was calculated from the equation, $V_f = (gds)^{\frac{1}{2}}$, where : V_f is shear or friction velocity; g is acceleration due to gravity; d is depth; s is slope of the thalweg. This equation is adopted from $V_f = (gRs)^{\frac{1}{2}}$ where R is the hydraulic radius, others as defined above

(Chow, 1959, p. 201). Hydraulic radius is the ratio of the cross sectional area of a stream divided by channel perimeter. In open channels, R D, where D is the hydraulic depth. Hydraulic depth can be estimated by normal depth in wide rectangular channels.

Shear velocity is the driving force responsible for particle motion, which depends on the balance of forces of the submerged sediment, friction and gravity. It is used in this paper to predict the bed morphology of the study reaches. The thresholds of moving different sizes, however, is not known. It is applied here to find the correlation with the other variables so that any association or differences can be discerned between the upper and the lower reaches.

The mean shear velocity in the upper reach is 5.3×10^{-3}, and the lower reach has a mean of 21.6×10^{-3} feet per second. The variation of shear velocity in the lower reach is greater than the variation in the upper reach (Appendix 4).

CROSS SECTION SYMMETRY

Cross section symmetry is the ratio of the top width of a channel or floodplain from the left bank to the deepest point of the stream (thalweg) to the total top width of the channel or floodplain. The ratio of the channel is referred to as channel symmetry, which measures thalweg wandering. The ratio of the floodplain is the valley symmetry which measures total channel wandering.

Both valley and channel symmetries are discussed. Complete symmetry and asymmetry are given by the following thresholds, shown in Table 3.11 below.

TABLE 3.11

THE THRESHOLD LIMITS OF CHANNEL SYMMETRY

Type	Thresholds
Positive asymmetry	0.10 - 0.39
Complete symmetry	0.40 - 0.59
Negative asymmetry	0.60 - 0.99

This method of analysis has the advantage over sinuosity ratio because it is independent of channel valley alignments, and therefore can be applied to all types of channel patterns, i.e. meandering, braiding and straight. Although this technique is less discussed in the literature, it is, probably, possible to suggest how channel symmetry ties with channel patterns and energy distribution along profile.

The channel symmetry will show the probability of the stream to erode either left or right bank if the position of the thalweg is near either side of the channel bed. When the channel symmetry is less than 0.29, then the thalweg is near the left side of the channel bed. When the channel symmetry is greater than 0.79, then the thalweg is near the right side of the channel bed. For example, the thalwegs of cross section 90 is on the left side of the bed, cross section 20 is at the center of the channel and cross section 99 is on the right side of the bed. Since the thalweg is associated with higher velocity, hence higher erosive ability, the channel symmetry limits above can help in delineating cross sections which have higher possibility of being eroded than others which are not within those channel symmetry limits. The channel symmetry is also used in the correlation matrix because tortuosity of the thalweg is related to slope, width and depth.

The valley symmetry is used to compare the similarity and differences of the channel with respect to the floodplain in the upper reach and the lower reach.

The distribution of cases of channel and valley symmetry in the upper and lower reaches are given in Table 3.12 below.

TABLE 3.12

DISTRIBUTION OF CHANNEL AND VALLEY SYMMETRY ACCORDING TO THRESHOLD LIMITS IN TABLE 3.11 ABOVE

	Upper Reach		Lower Reach	
Symmetry	Channel	Valley	Channel	Valley
	Number of Cases			
0.01 - 0.39	14	12	7	7
0.40 - 0.59	4	6	8	7
0.60 - 0.99	9	9	5	6

The upper reach had mean channel and valley symmetry of 0.47 and 0.48 respectively. In the lower reach, there was no difference between mean channel and valley symmetry. In the upper reach, 12 cases fall between less than 0.29 and greater than 0.79, while in the lower reach, 6 cases fall between less than 0.29 and greater than 0.79. Considering the number of cases and length of each reach, both reaches have equal chance to erode the channel banks. This suggests that the impact of the wide floodplain affects the meandering channel in the upper reach in a more or less similar way as the relatively narrow floodplain.

SUMMARY

The valley and thalweg slopes of the upper reach are flatter, and the stream is more sinuous than the lower reach. The topographic sinuosity index is higher in the lower reach indicating that the channel is more constrained than the upper reach. The breaks of slopes are applied to derive incision and aggradation indices. Both reaches are incising more than they are aggrading.

From slope analysis, the two reaches are different. This difference is reflected also for width, depth and width-depth ratio. The lower reach is wider than the upper reach. The wide sections have aggradation indices while the narrow sections have incision indices in each reach. Width variation follows similar trends as thalweg and valley slopes. The lower reach is also deeper and wider than the upper reach.

The cumulative deviation curves follow some regularity. This regularity conforms to the trends of the thalweg and valley slopes. The trends have been related to different channel patterns and the confinement of the channel by the floodplain. To evaluate the differences between the lower reach and upper reach, width-depth ratios, shear velocity and channel and valley symmetry have also been considered

It is possible to differentiate the study reaches because the average width-depth ratio is higher for the upper reach than the lower reach. However, both reaches show progressive failure to competence. Similarly, the upper reach has higher slope-width ratio and a lower variation than the lower reach. The low slope-width ratio is related to high shear velocity in the lower reach. The high energy spent in friction is reflected in high variation of equal energy expenditure in the lower reach.

Channel and valley symmetry do not show distinctive differences from the upper and lower reaches. The impact of the floodplain seem to be uniform when thalweg wandering is considered. Statistical analysis will show the relationships of the variables.

CHAPTER 4

STATISTICAL ANALYSIS

CORRELATION ANALYSIS

The aim of this thesis is to explain the relationships of geometric parameters and relate these to different channel patterns. It has been shown that there are breaks in thalweg and valley slopes, and differences in width and depth. In addition width-depth ratio, aggradation/incision indices, slope-width ratio and shear velocity have also been used to differentiate the upper reach from the lower reach.

The correlation analysis of these variables (thalweg slope, width, depth, width-depth ratio, shear velocity, channel and valley symmetry) is done to achieve two aims. First, to isolate significant cells to describe the relationships between the parameters. Lee (1976, pp. 128-129) suggests that "cell significance can be applied for reaches as for different streams to descriminate different hydraulic compensations associated with grade". It can also be applied to descriminate channel patterns. Low significance is indicative of lack of modification of the parameter in stream pattern changes. Secondly, differences (positive and negative) in relationship of the parameters define the hydraulic compensation of each parameter with an increase or decrease in another parameter. The sign distinction is summarised for each reach.

Pearson correlation is used, and the results are given in Tables 4.1 and 4.2. The correlation coefficient, the number of cases in each variable and significance are also given. Statistical significance for 26 cases at 5 percent with 2 degrees of freedom means that

TABLE 4.1

PEARSON CORRELATION COEFFICIENTS FOR THE UPPER REACH

	VAR 001	VAR 002	VAR 003	VAR 004	VAR 005	VAR 006	VAR 007	VAR 008
VAR 001	1.00							
VAR 002	.27 s=.091	1.00						
VAR 003	-.092 s=.328	.20 s=.162	1.00					
VAR 004	.05 s=.392	.39* s=.024	-.58 * s=.001	1.00				
VAR 005	.73* s=.001	.39 * s=.024	.53 * s=.003	-.36 s=.035	1.00			
VAR 006	.82 * s=.001	-.28 s=.084	-.23 s=.134	-.76 s=.220	.48 * s=.006	1.00		
VAR 007	.20 s= .159	.27 s=.087	-.08 s=.342	.26 s=.104	.09 s=.336	.06 s=.383	1.00	
VAR 008	.24 s=.123	.30 s=.069	.05 s=.411	.18 s=.195	.20 s=.157	.06 s=.391	.35 s=.040	1.00

Key
VAR 001 - Thalweg Slope
002 - Width
003 - Depth
004 - Width-Depth Ratio
005 - Shear Velocity
VAR 006 - Slope-Width Ratio
007 - Channel Symmetry
008 - Valley Symmetry

* Significant at 5%

TABLE 4.2

PEARSON CORRELATION COEFFICIENTS FOR THE LOWER REACH

	VAR 001	VAR 002	VAR 003	VAR 004	VAR 005	VAR 006	VAR 007	VAR 008
VAR 001	1.00							
VAR 002	-.04 s=.438	1.00						
VAR 003	-.35 s=.067	.56 * s=.005	1.00					
VAR 004	.49 * s=.014	.10 s=.34	-.71 * s=.001	1.00				
VAR 005	.95 * s=.001	-.32 s=.085	-.48 * s=.015	.45 s=.023	1.00			
VAR 006	.62 * s=.002	.42 * s=.032	.17 s=.24	.12 s=.30	.41 * s=.37	1.00		
VAR 007	-.01 s=.489	.10 s=.335	.34 s=.073	-.19 s=.21	.04 s=.44	-.27 s=.12	1.00	
VAR 008	.28	.35	.24	.12	.21	.16	.66 *	1.00

Key VAR 001 - Thalweg Slope
002 - Width
003 - Depth
004 - Width-Depth Ratio
005 - Slope-Width Ratio
VAR 006 - Shear Velocity
007 - Channel Symmetry
008 - Valley Symmetry

* Significant at 5% level

the correlation must be greater than 0.39 for the upper reach . In the lower reach with 20 cases, the correlation coefficient must be above 0.4 to be significant at 5% with 2 degrees of freedom.

Interpretation of the Data

The correlation coefficient expresses an interrelationship and does not suggest any direct dependence between the two variables. Out of 31 variables, 5 in the upper reach and 9 in the lower reach are statistically significant at 5 percent level. Among these, shear velocity, slope-width ratio, depth and width are important in the upper reach. All the above parameters in the upper reach including width-depth ratio and channel symmetry are important in the lower reach.

However, among the insignificant correlation coefficents, the coefficients in the lower reach are generally higher than in the upper reach. For example slope has higher coefficients with slope-width ratio and width in the upper reach than the lower reach. This suggests that slope-width relationship in the upper reach is stronger than in the lower reach. Similary, width-depth relationship is stronger in the lower reach than in the upper reach. Channel symmetry, valley symmetry, shear velocity are also stronger in the lower reach. These differences are indicative of different adjustment patterns between the study reaches.

When slope increases, width and channel symmetry also increase in the upper reach, but decrease in the lower reach. Also when depth increases, channel symmetry decreases in the upper reach, but increases in the lower reach. An increase in width-depth ratio is related to a decrease in shear velocity and slope-width ratio in the upper reach but an increase in the lower reach. Lastly, an increase in shear velocity is related to an increase in channel symmetry in the upper reach and a decrease in the lower reach. These are summarised in Table 4.3 below.

TABLE 4.3

DIFFERENCES BETWEEN THE UPPER AND LOWER REACHES DERIVED FROM CORRELATION ANALYSIS

Variable	Variable	Upper Reach	Lower Reach
Slope	Width	+	-
	Channel symmetry	+	-
Depth	Channel Symmetry	-	+
	Shear Velocity	-	+
	Slope-Width Ratio	-	+
Shear Velocity	Channel Symmetry	+	-

Implications of the Correlation Analysis

With an increase of slope, width increases in the upper reach, but decreases in the lower reach. In the upper reach the floodplain is wide and therefore with an increase of slope, width will increase due to floodplain inundation . In the lower reach, the channel is confined in most sections. The steeper sections are the most incised, with rapids and islands interspaced along the channel. Due to thalweg steepness, an increase of slope will cause more incision than bank erosion.

This is also reflected in slope-width and depth relationship. As slope and depth increase, but slope increasing faster than width, depth will decrease. But an increase in depth causes an increase in width. It means that depth does not necessarily compensate changes in width in the two reaches. An increase in slope is related to a decrease in both width and depth for the lower reach. In the upper reach an increase in slope is associated with an increase in width and also a decrease in depth. An increase in S/W ratio is associated with a decrease in depth and width-depth ratio increases when thalweg slope increases. It appears slope compensates depth, but not width in the upper reach. While in the lower reach slope compensates both width and depth. Thalweg slope, therefore, seems to be an important adjustment mechanism in both reaches.

The importance of slope has been reflected on the type of meander bends, the occurrence of braids and islands and changes in width and depth. Incision means that the channel is increasing its relative depth. Most of the sections are incising. These relationships show the importance of slope as an independent variable in the study.

An increase in width in the upper reach and a decrease in width in the lower reach with increasing slope have another implication. An increase in width in the upper reach will direct steam power from the stream by flooding the plain. This will also direct active erosion from the channel bed and banks. In the lower reach, erosion will concentrate on channel bed excavation and channel widening, although dependent on floodplain banks. Channel bed excavation is therefore more probable than width enlargement in the lower reach.

These phenomena can be seen by the development of rapids and braids in the lower reach. Associated with a rapid rate of increase in depth than width, and migration of nickpoints in the lower reach, the energy expenditure is greater in the lower reach. This argument also agrees with greater depth, lower width-depth ratio, lower slope - width ratio and lower shear velocity in the lower reach than the upper reach.

Depth has a negative correlation coefficient with channel symmetry in the upper reach and a positive coefficient in the lower reach. But a decrease in width relative to depth is related to a decrease in sinuosity. In the upper reach width increases with an increase in slope, while depth decreases with an increase in slope, although width-depth ratio also increases with slope. In the lower reach, width decreases with an increase in slope. Depth and width-depth ratio also increase with an increase in slope. In both reaches an increase in width and a decrease in depth or vice versa are counter-influcenced by slope in a similar way. This is due to differences in width and depth relationships in both reaches as shown by width-depth curves.

As sinuosity increases, width-depth ratio decreases in straight and incipient meandering patterns. And as meandering changes to braiding pattern, width-depth ratio increases and sinuosity ratio decreases. A decrease in channel symmetry and increase in depth will imply that width increases at a faster rate than depth. This will cause the meandering pattern to change to braiding pattern (Schumm and Khan, 1972, p. 1761). The upper reach shows the relationship where the stream is progressively changing its pattern from meandering to braiding as shown by the negative coefficient.

Channel symmetry decreases with an increase in shear velocity in the lower reach, but increaes in the upper reach. Tight bends, hence increasing channel asymmetry, is associated with high boundary shear (Hickin, 1977, p. 62). This explains the difference in the relationships between channel symmetry in the upper and lower reaches. But the upper reach is more sinuous and has a lower shear velocity than the lower reach. The lower reach has a higher shear velocity which cannot be explained by tight bends. Channel symmetry appears to be useful in channel patterm analysis when its relationship with W/D ratio is considered but not with shear velocity in this study.

COMPARISON OF RATE OF CHANGES OF WIDTH, DEPTH AND WIDTH-DEPTH RATIO FOR CHANGES IN THALWEG SLOPE

From Tables 2.3 and 2.4 and also from Hickin's (1969) findings, different changes in width, depth and width-depth ratio with changes in thalweg slope are associated with different channel patterns. For example, in a meandering channel, width increases slower than depth and width-depth ratio than in a straight/braiding pattern. The same results have been found for pseudomeandering (Hickin, 1969). It is possible that the rates of changes in width, depth and width-depth ratio with thalweg slope for both reaches should be different.

Regression equations for width, depth and width-depth ratio for the study reaches are given in Table 4.4. Thalweg slope is used as an independent variable. Width increases at a lower rate in the upper reach (0.0025) than in the lower reach (-0.014) with thalweg slope. The rates of change in depth is also greater in the lower reach than in the upper reach. Rates of change in width-depth ratios are similar. The rates of change of width and depth can also be used to differentiate the two reaches.

From the correlation analysis there are both statistical and geomorphological differences between the upper reach and the lower reach. The results are useful in showing how the variables of the meandering

TABLE 4.4

INCREASE OF WIDTH, DEPTH AND WIDTH-DEPTH RATIO WITH INCREASING SLOPE

The Upper Reach

$$w = 0.0022 + 0.0025\ S$$
$$S_e = 0.007$$

$$D = 3.59 - 0.215\ S$$
$$S_e = 0.017$$

$$W/D = 0.088 + 0.035\ S$$
$$S_e = 0.004$$

The Lower Reach

$$w = 0.0035 - 0.014\ S$$
$$S_e = 0.001$$

$$D = 0.07 - 0.315\ S$$
$$S_e = 0.025$$

$$W/D = 0.005 + 0.033\ S$$
$$S_e = 0.014$$

Where S is thalweg slope
w is width
D is depth
W/D is width-depth ratio
S_e is standard error of estimate

upper reach, and the straight/braided lower reach interact with each other. The summary of these findings are discussed in the next chapter and some conclusions are drawn.

CHAPTER 5

DISCUSSION AND CONCLUSION

It was discussed in the literature review that different channel patterns can be observed within short reaches of the same river. The differentiation of the upper reach and the lower reach is possible when a general planimetric view of the reaches and statistical analysis are considered. However, when a systematic interpretation is made over short channel lengths, different patterns can be identified. Braid bars, for example, occur along meander bends, and in some portions these same bars develop to create a multi-channel section.

These channel pattern changes can be associated with changes in width of the floodplain and also its characteristics. From Plate 3.1 and Figures 3.5 and 3.6, it has been shown that the present trend of river tortuosity is influenced by the inherited valley slope, which is also reflected as high topographic sinuosity index.

The cross-section shapes, both of the floodplain and the channel, show differences between the upper reach and the lower reach.From the calculations of the ratio of floodplain width to channel width, it is shown that the upper reach has a ratio of 9.5, while the lower reach has a ratio of 3.9. This, in a general way, indicates that the upper reach is less constrained by the floodplain than is the lower reach. Planimetrically, the meandering bends are constrained by a sinuous floodplain in many parts. The boxed meanders shown in Figure 3.7 are typical of any constrained meander pattern.

The comparison of depth-width curves also indicates, by the inproportionate increase of width with increasing depth, that the upper reach has little of width constraint. The incremental flow is readily compensated by width rather than by depth. The comparison also shows that the upper reach has a wider floodplain than the lower reach. The wide floodplain of the upper reach has denser vegetation than the lower reach because floods inundate the narrow floodplain of the lower reach frequently. The vegetation causes an increase in roughness which, associated with energy loss around meander bends, reduces the erosive ability of the upper reach.

In the lower reach, lack of wide floodplain would cause the velocity to concentrate in the channel rather than on the floodplain. This causes more erosion, although the resistant dolomites on the channel banks and bed rocks do reduce the erosive capability of the stream. Most sections of the lower reach, therefore, have rapids created by corrasion in some sections and deposition of sediment after heavy floods in other sections.

Assuming an equivalent discharge increase over the sections in the upper reach and the lower reach, the increased energy of this incremental flow will have less impact on the wide cross sections than on the narrow sections. This, associated with steeper slopes in the lower reach, determines that the lower reach will experience greater stream power than the upper reach.

It is possible that in the upper reach, the floodplain and its characteristics cause the apparent reduction in effective erosion rather than a real reduction of erosional capability contributed by limiting slope. The average thalweg slope in the upper reach (0.0015) is comparable to thalweg slope of straight river patterns, however, steeper slopes occur in many sections. Table 3.7 shows different thalweg slopes greater than 0.002 for two segments of the upper reach. These sections have thalweg slopes greater than thalweg slope expected for straight channel patterns.

The study of the reaches shows that the stream is degrading and aggrading in some portions. The lower reach has more sections of incision than the upper reach. Although steeper slopes are compensated by flatter slopes immediately downstream, the tendency of the Grand River is to incise the inherited floodplain.

The inherited floodplain creates constraints on width enlargement. In some cases, bed rock causes another dimension of constraint to channel bed deepening. Basically the stream will erode the bed in narrow sections where the bed rock is not a constraint, but on the other hand, the stream will erode the channel banks where inherited floodplain banks is a constraint. In this case, the upper reach has less of width constraint than the lower reach because the floodplain confinement is less than the average floodplain confinement for the lower reach. It was observed that even within each reach, the breaks in valley slope are related to floodplain width.

In the upper reach, the less steep upper section is bounded by a narrow floodplain, while the steeper lower section is much wider and the channel has a higher sinuosity ratio. In the lower reach, the flat upper section has multi-channels and the lower section has rapids and occasional bars in the single channel.

The nature of the bed rock confinement was not fully investigated, but the occurrence of rapids and pools in both reaches points to the fact that the bed rock has some impact on the channel bed excava tion. This bed rock control is supported by variation of the thalweg slope from one section to the next, a feature associated with differential erosion.

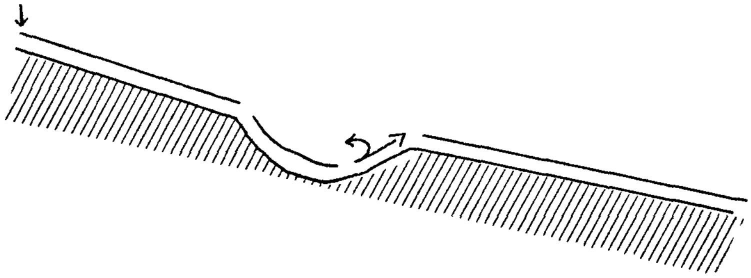
The thalweg slopes have a varied topography, with riffles, plunge pools and rapids in many sections. On the upstream of the plunge pools, flow forms a drawdown, while downstream a backwater effect is created. The rapids can be observed from the aerial photo mosaics and even from topographical maps. In any case, net flow condition still remains in the downstream direction because of the velocity head. The higher the velocity, the further downstream the profile of the plunge pool will begin.

During high discharges, the impact of adverse slope and plunge pools cause flow circulations, as schematically shown in Figure 5.1 below. In case I, the flow profile forms a drawdown upstream of the plunge pool and a hydraulic jump downstream of the plunge pool. In case II, the pool is drowned by the increasing discharge, Q_2. The drowning process is completed in case III.

The occurrence of a drawdown upstream of the plunge pool implies high velocities which are likely to clear the sediments out of the pool. The clearing of sediments is associated also with bed excavation which increases depth more than width. The reduction of velocity at the backwater section causes a reversal of fine sediments back to the pool, causing deposition to occur in the pool. This also causes width variation along the study reaches. Meandering patterns have relatively

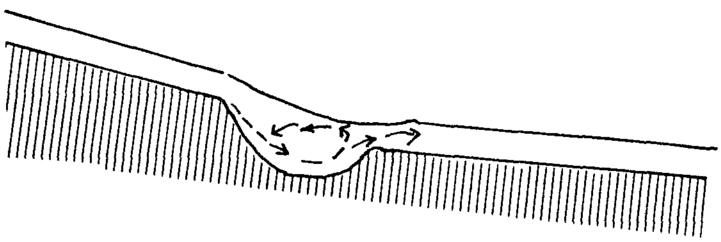
FIG.5.1 PLUNGE POOL DEVELOPMENT AND CHANGES IN FLOW PATTERN WITH AN INCREASE IN DISCHARGE

Q_1



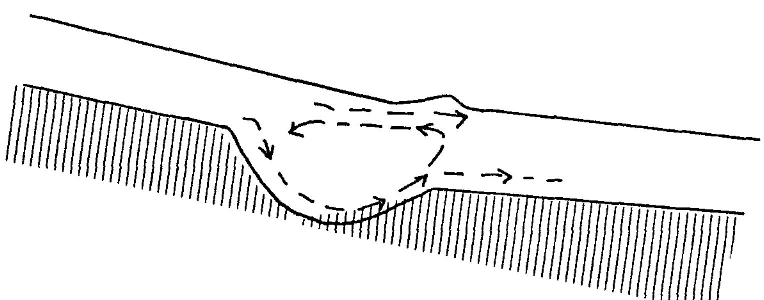
Eddy formation associated with a plunge pool and an adverse bed slope. Discharge, Q_1, is low, causing an undeveloped boil.

Q_2



With an increase in discharge, Q_2, a secondary circulation forms at the plunge pool. The reverse flow sinks without forming a boil.

Q_3



At discharge, Q_3, the secondary circulation develops with another downstream profile on top of the circulation.

narrower channels than braiding patterns. The criterion can be used to differentiate the patterns of the lower and upper reaches.

If the width trend is compatible with the meandering phenomenon, then the ratio of the valley slope and width of the upper reach should compare with the valley slope and average width of the lower reach. Leopold et al. (1964, p. 292) arrived at a ratio of valley slope and width of a meandering pattern to a straight or braiding pattern. The comparison is given in Table 5.1 below.

TABLE 5.1

COMPARISON OF THE VALLEY SLOPES AND WIDTHS OF THE UPPER AND LOWER REACHES

	Field	Flume	Study Reaches
Slope	1.43 - 2.3	1.3 - 1.9	1.25
Width	1.6 - 2.0	1.05 - 1.7	1.40

Source: Leopold, et al., 1964, p. 292

There is agreement with the field and flume examples.

Table 5.2 below is drawn from field experiences in Schumm's (1963) report. Some specific examples have also been given to be compared with the study reaches. The upper reach fits between tortuous and irregular patterns when valley slope, thalweg slope and general sinuosity index is applied. However, the upper reach has a higher width-depth ratio. The lower reach fits as straight channels with islands, although the width-depth ratio is higher than Schumm's examples.

The breaks in the trends of the cumulative deviation curves are also associated with breaks in slope. The analysis delineated breaks

TABLE 5.2

CHANNEL TORTUOSITY CLASSIFICATION

ACCORDING TO SCHUMM (1963, Table 1, P. 1092)

Pattern	Sinuosity	Channel Slope (x 10^{-3})	Valley Slope (x 10^{-3})	Width-Depth Ratio
Tortuous	2.3	0.95	2.23	5.2
*Upper Reach	2.2	1.5	1.11	95.2
Irregular	1.8	0.62	1.16	19.0
Red Willow Cr., Nebraska	2.1	0.77	1.7	6.3
Regular	1.7	0.77	1.32	25.5
Sappra Cr., Standord, Neb.	1.9	0.70	1.3	5.3
Transitional	1.3	1.54	1.93	56.0
Straight	1.1	1.45	1.75	43.0
Straight With Islands	1.1	1.48	1.70	52.0
*Lower Reach	1.2	1.9	1.6	59.8
Arikare, Heigler Nebraska	1.1	2.0	1.8	23.0

Source: Schumm, 1963, Table 1, P. 1092.

* Study reaches.

in slopes, as shown in Figure 3.20, and related to the observable channel patterns. Slope, being an independent variable, can then be associated with breaks on the cumulative deviation curves of width and depth.

In the upper reach, increasing depths in the upper section are associated with a narrow floodplain and low sinuosity, while decreasing depths are associated with wide floodplains and sinuous channel sections (Figure 3.21). In the lower reach, braided sections are associated with increasing depths, while sections bounded by narrow floodplains are associated with rapids which are reflected in high variation of depth. These changes in geometric variables with different channel patterns support the results of flume experiment (Table 2.3).

The turning points in cumulative deviation curves indicate, therefore, a change in channel and floodplain characteristics. By this analogy, the turning points are assumed to be indicative of thresholds where different channel patterns change from one type to the other.

Width showed greater trend of positive relationship with thalweg slope than depth in the upper reach. The correlation coefficients of thalweg slope with width is 0.27 and with depth is -0.09. In the lower reach, depth shows stronger negative relationship with thalweg slope than width.

These relative contributions of width and depth are not peculiar to this case. Hickin (1969) noted that stability of depth could only be attained by a longer run than width in the pseudomeandering phenomenon during the flume experiment. This compares well with the lower correlation coefficients of thalweg slope and depth than width.

In meandering patterns width increases and then remains constant with increase in slope. The upper reach has a lower rate of increase of width with thalweg slope than in the lower reach. This compares well with Tables 2.3 and 2.4 for meandering patterns compared with braiding patterns. Depth shows little difference in rate of change with thalweg slope, but depth decreases in the upper reach and increases in the lower reach. Changes of width-depth ratio also tend to be similar.

High width-depth ratios are associated with aggradation, low percent of silt and clay in the sediment discharge and high bed load. With varying width-depth ratios within short channel lengths sediment discharge, erosion and deposition will also vary within short channel lengths. Generally width-depth ratio can be used as indicator of the competence of a stream.

It is noticeable that some sections of the Grand River have steeper valley slopes than thalweg slopes. Steep sections of valley slopes tend to aggrade and flat sections tend to degrade. This is one method by which streams approach the Davisian concept of grade. Aggrading sections have higher width-depth ratios than degraiding sections.

There is fair agreement between the sinuosity index and the width-depth ratio for the lower reach. At Cambridge, when the highest average monthly discharge of April (3600 cfs) is compared to the average monthly dishcarge of August (420 cfs) and September, the highest discharge is 9 times greater between the two months. This variability possibly reduces sinuosity by cutting secondary channels and eroding channel banks. Schumm (1963, p. 1094) observed that the more sinuous streams are not among the rivers with the highest annual discharge. It is therefore possible that sinuosities and width-depth ratios of the study reaches are affected by discharge variability.

It seems that the general trend of the sections is to incise, but not in all sections. This is expected because of geological and topographical constraints. In sections where there is no constraint, the tendency is to hydraulically change the inherited slope, as shown by a general reduction of channel slope as compared to valley slope.

Uniform bank and thalweg slope, uniform slope-width ratio, higher shear velocity and width-depth compensation indicate that the upper reach is more adjusted towards a steady equilibruim condition, common in meandering streams.

The upper reach is an example of the "false" meandering phenomenon. Steep thalweg slopes in many sections, the development of secondary channels, statistical instability of depth in terms of compensating width and slope variations, and stable islands near the bends are all consistent with Hickin's pseudomeandering theory.

Hickin (1969) found that an irregular meandering pattern developed when the channel started being confined by the flume banks and has a critical flow, i.e. a Froude number greater than 1.0. Since most sections of the channel in the upper reach have rapids and pools and width variation over short channel lengths which are conducive to critical flow conditions, Froude number in many sections is expected to be greater than 1.0.

Lewin and Brindle (1977, p. 225) referred to a similar type of confinement which creates distortion to regular meandering pattern as "first degree of confinement". Steep thalweg slopes and lack of "free" meandering makes the upper reach different from the results observed in alluvial streams. This is expected since the Grand River is a glaciated rather than an alluvial stream.

The differences in the correlation matrix between the upper and the lower reaches are due to the differences by which the two reaches (upper and lower reaches) have adapted to the present hydrological regimes. These adaptation techniques are important in determining stream pattern behaviour, and therefore the development of channel patterns.

The lower reach is straight, has a narrow floodplain, has relatively higher coefficients of correlation between slope and depth and width-depth ratio than the upper reach, and has distinct features of nickpoint migration. Richards (1976, p. 84) found that significant differences in correlation occur between the geometric variables in different channel patterns.

The upper reach has a wider floodplain and lower thalweg slope than the lower reach. These resolve into lower stream power in the upper reach than the lower reach. However, the degree of bed incision varies with valley slope. In some sections, the channel has developed a less steep thalweg, than other sections. Degradation and aggradation vary from one section to the other for a channel to reach a graded profile.

The impact of incremental flow and geometric variations on channel pattern development has three implications. One, in the upper reach, exceptional floods serve mainly as a transportational agent away from the active channel and in the construction of natural levees, while, in the lower reach the same flood is effective in channel corrasion. The deeper the flow depth, the greater impact it creates in the lower reach. The higher correlation coefficient between thalweg slope and depth in the lower reach shows this difference.

Although the channel pattern in the lower reach is a product of all types of flows, the high flows should be sufficient to erode banks and bed rock, to carry the resulting boulders and be adequately frequent to have the additive effect of morphological mobilisation. The occurrence of ribs (Martini, 1977), bars and rapids shows that this high flow magnitude is not freuqent enough. The bed rock and banks are also resistant to erosion in some portions, thus causing rapids. From studies on Irvine and Bronte creeks, dolomitic shales and sandstone breaking into pebbly pieces which are more resistant to transport than the glacio-alluvial sediments have been reported. The latter seems to have been cleared from the lower reach.

Second, secondary erosional modifications occurring over braids, including profuse overflows over braids such as at the bridge of King Street and north of Preston are contributed by greater increments in flow depth in the upper reach than in the lower reach. The nature of the floodplain, size of the channel width and geological conditions of the banks and channel bed cause significant differences in stream power. The failure of the upper reach to modify the flood valley is partly due to essentially non-erosive magnitude of the floods.

Third, the underfit phenomenon on the Grand River might not be explainable by invoking hydrological and regime changes over the geological time, as suggested by proponents of the underfit theory. The explanation might be found in the erosive and/or depositional capability of the stream, i.e. channel patterns and its confinement. For example, the persistence of islands observed and described above, points to the fact that they have not been affected by recurrent annual floods. These bars are more frequent in the upper reach than in the lower reach. Instead, the lower reach is more braided and has more rapids than the upper reach.

Thus, it has been shown that the protion of the Grand River between Kitchener and Paris is represented by two reaches that differ from each other in width, depth, valley slope, and thalweg slope. These parameters, including width-depth ratio, shear velocity and slope-width interact with each other in a different way between the two reaches. These differences in the interrelationships can also be established by observations of plan form of the channel and the floodplain.

REFERENCES

Abrahams, A.D., Personal discussion, State University of New York at Bufflao, April 18, 1980.

Ackers, P. and F.G. Charlton, 1970, The geometry of small meandering streams. Proc. Inst. Civil Engineers, Paper 73285, pp. 289 - 317.

Allen, J.R.L., 1970, Physical Processes of Sedimentation. London. 248 pp.

Bagnold, R.A., 1960, Sediment discharge and stream power: A preliminary announcement. U.S.G.S., Circular 421, p. 23.

Brice, J.C., 1964, Channel patterns and terraces of the Loop River in Nebraska. U.S.G.S., Professional Paper 422-D. 41 pp.

Broscoe, A., 1959, Quantit ative analysis of longitudinal stream profiles of small watersheds. Off. Nav. Res., Tech. Report No. 18. 71 pp.

Cherkauer, D.S., 1972, Longitudinal profile of ephemeral streams in south eastem Indiana. Geol. Soc. Amer. Bull., 83, pp. 353 - 366.

Chitale, S.V., 1970, River channel patterns. J. Hydraul. Div. Amer. Soc. Civ. Engrs., 96, pp. 201 - 221.

____________, 1973, Theories and relationships of river channel patterns, J. Hydrol., 19, pp. 285 - 308.

Carlston, C.W., 1965, The relation of free meander geometry to stream discharge and its geomorphic implications. Amer. J. Scie.,

Chorley, F.J. and B.A. Kennedy, 1977, Physical Geography: A System Approach. London. 370 pp.

Chow, V.T., 1959, Open Channel Hydraulics. New York.

Cowan, W.R., 1972, Pleistocene Geology of the Brantford Area, Southern Ontario, Report No. 37. Ontario Dept. of Mines and Northern Affaris, Toronto.

Crickmay, C.H., 1974, The Work of the Rivers, C.H. Crickmay, London.

Dolling, R.K., 1968, Structural Variation in Channel Characteristics, Bronte Creek, Ontario. Unpublished M.Sc. thesis, Department of Geography, University of Western Ontario.

Dury, G.H., 1964, Principles of underfit streams. U.S.G.S., Professional Paper 452A. 67 pp.

__________, 1973, Theories and relationships of river channel patterns. J. Hydrol., 19, pp. 285 - 308.

Eistein H.A. and H.W. Shen, 1964, A Study on Meandering in Straight Alluvial Channels, J. Geophysical Res., Vol. 69, No. 24, pp. 5239 - 5247.

Emmet, W.W., 1974, Channel changes, Geol., 2, pp. 271 - 272.

Ferguson, R.I., 1973, Regular meander path model. J. Hydrol., 26, pp. 315 - 333.

Gardner, J.S., 1977, Some geomorphic effects of a catastrophic flood on the Grand River, Ontario, Canad J. of Earth Sci., Vol. 14, p. 2294 - 2300.

Gilbert, G.K., 1914, The transportation of debris by running water. U.S.G.S., Professional Paper 422G.

Goryki, M.A., 1973, Hydraulic drag: A meander initiating mechanism. Geol. Soc. Amer. Bull., 84, pp. 175 - 186.

Gregory, K.J., 1977, The context of river channel changes. In Gregory, K.J., (ed.), River Channel Changes. John Wiley and Sons, New York.

______________ and C.C. Park, 1976, Stream channel morphology in north western Yorkshire. Revue de Geomorph. dyn., 25, pp. 63 - 73.

______________ and D.E. Walling, 1973, Drainage Basic Form and Processes: A Geomorphological Approach. John Wiley and Sons, New York. 356 pp.

Hammer, T.R., 1972, Stream channel enlargement due to urbanization. Water Resource Res., 8, pp. 1530 - 1540.

Henderson, F.M., 1965, Open Channel Flow. London.

Hickin, W.D., 1974, The development of meanders in natural river channels. Amer. J.Sci., pp. 414 - 442.

Hickin, E.D., 1969, A new identified process of point bar formation in natural streams. Geol. Soc. Amer. Bull., 82, pp. 999 - 1010.

____________ and G.C. Nansen, 1975, The character of channel migration on the Beatton River, N.E.B.C., Canada. Geol. Soc. Amer. Bull., 86, pp. 487 - 494.

Howard, A.D., M.E. Keetch and C.L. Vincent, 1976, Topographical and geometrical properties of braided streams, Water Res. Research, Vol. 6, No. 6, pp. 1674 - 1688.

Jackson II, R.G., 1975, Velocity-bedform-texture patterns of the meander bends on the Lower Wabash River of Illinois and Indiana, Geol. Soc. Amer. Bull., Vol. 86, pp. 1511 - 1522.

Karrow, P.F., 1968, Pleistocene Geology of the Guelph Area. Ontario Department of Mines, Tronto, Canada.

Keller, E.A., 1971, Areal sorting of bed loads: The hypothesis of velocity reversal. Geol. Soc. Amer. Bull., 82, pp. 752 - 756.

Kellerhal, R., M. Church and D. I. Bray, 1976, Classification and analysis of river processes. J. Hydraul. Div.; Amer. Soc. Civil Engrs., 102, pp. 813 - 829.

Knighton, A.D., 1976, Stream adjustment in a small rocky mountain basin. Arctic and Alpine Res., 8(2), pp. 197 - 212.

__________, 1974 Variation in width-depth relation. Geol. Soc. Amer. Bull., 85, p. 1069.

__________, 1972, Changes in a braided reach. Geol. Soc. Amer. Bull., 83, p. 3813.

Lane, E., 1955, Design of stable channels. Amer. Soc. Civ. Engrs., Trans. 120, pp. 1234 - 1275.

Langbein, W.B. and B.L. Leopold, 1966, River meanders - Theory of minimum variance. U.S.G.S., Professional Paper 422H.

Larrone, J.B. and Carson, 1976, Interrelationships between bed morphology and bed material transport for a small gravelly bed channel. Sedimentology, 23, pp. 67 - 85.

Lee, L.J., 1977, Mississippi River regression equations, Z. Geomorph., 29(1), pp. 37 - 43.

__________ and Henson, 1977, The interrelationship of the longitudinal profiles and channel pattern for the Red River. J. of Hdrol., 35, pp. 37 - 43.

Leopold, L.B. and T. Maddock, 1953, The hydraulic geometry of stream channels and some physiographic implications. U.S.G.S., Professional Paper 252, p. 56.

__________ and W.B. Langbein, 1963, Association and determinancy in geomorphology. In C.C. Albritton (ed.), The Fabric of Geology, New York, pp. 184 - 192.

__________ and J.P Miller, 1956, Ephemeral Streams - hydraulic factors and their relation to the drainage net. U.S.G.S., Prof. Paper 282 A.

Leopold, L.B. and M.G. Wolman, 1957, River channel patterns - braided, meandering, and straight. U.S.G.S. Professional Paper, 282 B.

__________, M.G. Wolman and J.P. Miller, 1964, Fluvial processes in Geomorphology. San Francisco. 522 pp.

__________, 1973, River channel change with time: An example. Geol. Amer. Bull., 84, pp. 1845 - 1860.

Lewin, J., 1977. Channel pattern changes. In J.K. Gregory (ed.), River Channel Changes, John Wiley and Sons, pp. 167 - 179.

__________ and B.J. Brindle, 1977, Confined meanders. In J.K. Gregory (ed.). River Channel Changes, John Wiley and sons, pp. 221 - 232.

Martini, I.P., 1977, Gravelly flood deposits of Irvine Creek, Ontario, Canada, Sedimentology, 24, pp. 603 - 622.

__________ and J. Ostler, 1973, Ostler lenses: Possible environmental indicators in fluvial gravels and conglomerates. J. of Sedimentary Petro., 43, No. 2, pp. 418 - 422.

McDonald, B.C. and I. Barnajee, 1971, Sediments and bedform on a braided outwash plain. Canadian J. Earth Sci., 9, pp. 1282 - 1301.

Middleton, G.V., 1976, Hydraulic interpretation of sand size distribution. J. Geology, 84, pp. 71 - 88.

Mitchell, B., et al., 1977, Physical Adjustment and Institutional Arrangements for the Urban Flood Hazard in the Grand River Watershed, Ontario, Canada. University of Waterloo.

Morisawa, M.E., 1962, Quantitative geomorphology of some watersheds in the Appalachian Plateau. Geol. Soc. Amer. Bull., 73, pp. 1025 - 1046.

Mueller, J.E., 1967, An introduction to the hydraulic and topographic sinuosity indices. Annal. AAG, 58, pp. 371 - 385.

Nemec, J., 1964, Engineering Hydrology, McGraw - Hill Inc.

Nie, N.H. et al. 1975, Statistical Package for Social Sciences, McGraw - Hill Inc.

Ontario Department of Lands and Mines, 1962, Grand River Hydraulics Report, 2nd edition, Toronto, Ontario.

Richards, K.S., 1972. Meanders and valley slope. Area, 4(4), p. 10.

______________________, 1976, The morphology of riffle-pool sequence. Earth Sur. Processes, 1, pp. 71 - 88.

______________________, 1978, Simulation of flow geometry in a riffle-pool stream. Earth Surface Processes, 3, pp. 345 - 354.

______________________, 1977, Channel and flow geometry: A geomorphological perspective. Progress in Physical Geography, 1 (1), pp. 65 - 102.

Rozovskii, I.L., 1961, Flow of Water in Bends of Open Channels. Israel Programme for Scientific Translations, Jerusalem.

Rubey, W.W., 1952, Geology and mineral resources of the Hardin and Brussels Quanrungles, Illinois. U.S.G.S., Prof. Paper, 218, 179 pp.

Rust, B.R., 1972, Pebble orientation in fluvial sediments, Journal of Sedimentary Petrology, 42, 385 - 388.

Rust, B., 1969, The Sedimentology of a Braided River, Jr. of Sedimentary Petrology, Vol. 39, No. 2, pp. 649 - 679.

Savat, J., 1975, Some morphological and hydraulic characteristics of river-patterns in the Zaire Basin. Catena, 2, pp. 161 - 180.

Schumm, S.A., 1963, Sinuosity of alluvial rivers on the Great Plains. Geol. Soc. Amer. Bull., 74, pp. 1089 - 1100.

_____________, 1973, Geomophic thresholds and complex responses of drainage systems. In M.E. Morisawa (ed.) Fluvial Geomorphology, Gingham, 1973, pp. 299 - 310.

_____________, and H.R. Khan, 1972, Experimental study of channel patterns. Geol. Soc. Amer. Bull., 83, pp. 1755 - 1770.

_____________, 1971, Channel adjustment and river metamorphosis. In H.W. Shen (ed.), River Mechanisms, Fort Collins, pp. 5 - 1 to 5 - 22.

_____________, 1977, The Fluvial Systems, John Wiley and Sons.

Scheideggar, A.E., 1970, Theoretical Geomorphology, New York.

Schulits, S., 1941, Rational equation of river bed profiles. Trans. Amer. Geophy. Union, 41, pp. 622 - 629.

Spelt, 1971, in J. Warkentin, Canada: A Geographical Interpretation.

Simons, et al., 1965, Sedimentary structures generated by flow in alluvial channels. Soc. Econ. Paleo. Mineralogists, Spec. Publ. 121, pp. 34 - 52.

Tanner, W.F., 1971, The river profile. J. Geol., 79, pp. 482 - 492.

Tinkler, K.J., 1970, Pools, Riffles and Meanders, Geol. Soc. Amer. Bull., Vol. 81, pp. 547 - 552.

_____________, 1971, Active valley meanders in South Central Texas and their wider implications. Geol. Soc. Amer. Bull., 81, pp. 1873 - 1899.

Wolman, M.G. and L.M. Brush, 1961, Factors controlling size and shape of stream channels in coarse non-cohesive sands. U.S.G.S., Professional Paper 282G, 210 pp.

Woodford, A., 1951, Stream gradients and the Monterey sea valley. Geol. Soc. Amer. Bull., 62, pp. 799 - 852.

World Meteorological Organization, 1965, Guide to Hydrometereological Practices, WMO 168, TP82.

Yalin, M.S., 1972, Mechanics of Sediment Transport, Pergamon Press.

Yang, T., 1971, On river meanders, J. Hydr., 13, pp. 231 - 253.

Yatsu, E., 1954, On the formation of slope discontinuity at fan margins. J. Misc. Rep., 36, pp. 57 - 64.

APPENDIX 1

PRELIMINARY ANALYSIS OF VALLEY SLOPE

The Upper Reach

Elevation (ft.)	Valley Lenth (miles)	Cum. Valley Length (Miles)	Valley Slope ($x\ 10^{-3}$)
875	0.7	0.7	.0014
890	0.96	1.66	.002
900	1.95	3.61	.0009
910	1.4	5.01	.0013
920	2.45	7.46	.0008
930	0.9	8.36	.002
940	2.75	11.11	.0007
950	1.36	12.47	.0014
960	1.43	13.9	.0013
970	3.2	17.1	.0006
980	1.5	18.6	.0013

Source: Topographical Maps of Kitchener - Breslau, 40P/8e, (1976), Publisher: Min. of Energy Mines and Resources, Canada.

Appendix 1 (continued)

The Lower Reach

Elevation (ft.)	Valley Length (miles)	Cum. Valley Length (miles)	Valley Slope (x 10^{-3})
740	0.65	0.65	.0028
750	1.15	1.8	.0016
760	1.3	3.1	.0014
770	0.45	3.55	.004
780	0.6	4.35	.0016
790	0.95	5.3	.002
800	1.15	6.45	.0016
810	1.7	8.15	.0011
820	1.0	9.15	.0019
830	1.0	10.8	.0029
840	0.7	11.5	.0028

Source: Topographical Maps of Galt, Ontario, 40P/8c (1968), and Brantford - St. George, 40P/1f (1976). Publisher: Min. of Mines, Energy and Resources, Canada.

APPENDIX 2

BASIC STATISTICS OF THE UPPER REACH

Appendix 2 (i)	Calculation and plotting positions of thalweg slope, width and depth.
2 (ii)	Calculation of valley symmetry and plotting positons of thalweg variations.
2 (iii)	Complete data used in the correlation and regression analyses.

APPENDIX 2 (i)

UPPER REACH

St.#	(Yards) Dist.	(Miles) Dist.	(Cu.Mls) Dist.	Thalweg Slope x 10^{-3}	Width	Depth	W/D Ratio	Channel Symmetry
115	1000	.19	.19	-	233.0	2.8	83.2	.25
114	3900	.74	.93	1.0	133.0	1.6	83.1	.62
113	3600	.68	1.61	0.56	254.0	1.9	133.7	.31
112	2800	.53	2.14	1.31	174.0	3.7	47.0	.37
111	2560	.48	2.62	0.036	246.0	1.3	189.2	.31
110	1720	.33	2.95	1.56	200.0	3.4	200.0	.58
109-107	449	.08	3.04	1.33	284.0	4.4	64.5	.27
106-105	3383.5	.64	3.68	0.68	235.0	8.8	26.7	.36
104-103	1450	.27	3.95	1.59	222.3	3.2	69.5	.38
102	2650	.50	4.45	0.54	177.0	2.5	70.8	.64
101	2550	.48	4.93	1.13	186.0	2.3	80.9	.65
99	3650	.69	5.62	0.45	288.0	3.3	180.0	.82
98	2200	.42	6.04	1.37	256.0	1.0	256.0	.57
97	3800	.72	6.76	1.36	224.0	3.0	74.7	.25
96	2560	.48	7.24	1.13	292.0	2.5	116.8	.46
95	2400	.45	7.69	2.5	179.0	2.2	81.4	.71
93-92	1985	.38	8.07	1.46	382.5	6.7	61.4	.62
91-89	5450	1.03	9.1	0.57	185.5	5.1	4.4	.22
88	3300	.63	9.73	1.14	387.0	3.0	129.0	.83
87	4900	.93	10.66	1.18	258.0	3.3	78.2	.80
86-85	4970	.94	11.6	1.03	184.0	4.6	47.3	.40
84	2400	.40	12.0	2.46	205.0	2.0	102.5	.19
83-82	4360	.83	12.83	0.67	252.3	4.0	69.6	.37
81	2300	.44	13.27	0.52	234.0	3.4	68.8	.38
80-78	1137	.22	13.49	3.78	418.0	3.3	160.4	.86
77	1300	.25	13.74	1.85	244.0	2.8	80.0	.05
76-74	1167.5	.22	13.96	1.07	323.7	2.8	115.6	.07
73	1050	.20	14.16	-	380.0	3.0	126.7	.16

APPENDIX 2 (ii)

The Upper Reach

St.#	Total Width of Floodplain	Width From LB Floodplain-Thalweg	Thalweg Elevation	Valley Symmetry
115	-	-	972.2	-
114	2380.0	420.0	971.2	.18
113	2298.0	350.0	969.0	.15
112	2159.0	1186.0	964.3	.55
111	1150.0	270.0	964.2	.23
110	2178.0	1261.0	960.2	.50
109	2949.0	2163.0	957.9	.73
108	2681.0	1554.0	958.9	.58
107	1573.0	1366.0	957.3	.87
106	2342.0	1730.0	947.9	.74
105	1625.0	286.0	955.0	.18
104	1443.0	163.0	955.2	.11
103	1982.0	1395.0	953.3	.70
102	1674.0	1206.0	952.0	.72
101	953.0	250.0	949.0	.26
100	824.0	360.0	946.0	.44
99	2847.0	2549	944.5	.89
98	1599.0	1059.0	939.5	.66
97	2184.0	416.0	936.5	.19
96	1558.0	505.0	932.2	.32
95	2292.0	1960.0	928.3	.86
93 /	1863.0	750.0	922.3	.40
92	2557.5	950.0	924.8	.37
91	2885.0	196.0	919.4	.07
90	3081.0	201.0	920.8	.07
89	2523	903.0	919.2	.36
88	899.0	811.0	916.3	.90
87	3857.0	427.0	912.4	.11
86	1353.5	170.0	906.6	.13
85	1838.0	1588.0*	901.5	.86

Continued ...

Appendix 2 (ii) (continued)

St.#	Total Width of Floodplain	Width From LB Floodplain-Thalweg	Thalweg Elevation	Valley Symmetry
84	2587.5	217.0	901.5	.08
83	3305.5	721.5	895.6	.22
82	3220.5	248.5	896.5	.08
81	3296.0	2504.0	892.7	.76
80	3581.0	3093.0*	891.5	.86
79	3229.0	2937	891.5	.91
78	2503.0	2091.0	886.7	.84
77	3157.5	1604.0	887.2	.51
76	2586.5	1212.0	884.9	.47
75	1989.0	704.0	884.9	.35
74	3144.0	375.0	879.3	.12
73	3598.5	14180.0*	882.0	.39

* When the channel is divided by a ridge and two points coincide with the thalweg points, the nearest one ot the left bank of the floodplain has been slected.

APPENDIX 2 (iii)

The Upper Reach

St.#	(Miles) Cum. Channel Length	Thalweg Slope x 10^{-3}	(ft.) Width	(ft.) Depth	W/D Ratio	x 10^{-3} Shear Velocity	S/W Ratio	Channel Symmetry	Valley Symmetry
115	0.19	-	233.0	2.8	83.2	-	-	0.25	-
114	0.93	1.0	133.0	1.6	83.1	7.71	7.5	0.62	0.18
113	1.61	0.56	254.0	1.9	133.7	6.29	2.2	0.31	0.15
112	2.14	1.31	174.0	3.7	47.0	13.42	7.5	0.37	0.55
111	2.62	0.036	246.0	1.3	189.2*	1.32	0.15	0.31	0.23
110	2.95	1.56	700.0	3.4	58.9	7.61	7.8	0.58	0.58
109-107	3.04	1.33	284.0	4.4	64.5	14.74	4.7	0.27	0.73
106-105	3.68	0.68	235.0	8.8	26.7*	14.91	2.9	0.36	0.43
104-103	3.95	1.59	222.3	3.2	69.5	13.75	7.2	0.38	0.41
102	4.45	0.54	177.0	2.5	70.8*	7.08	3.1	0.64	0.72
101	4.93	1.13	186.0	2.3	80.9	9.83	6.1	0.65	0.26
99	5.62	0.45	288.0	3.3	180.0	7.43	7.6	0.82	0.89
98	6.04	1.37	256.0	1.0	256.0	7.13	5.4	0.52	0.66
97	6.76	1.36	224.0	3.0	74.7	12.31	6.1	0.25	0.89
96	7.24	1.13	292.0	2.5	116.8	10.24	3.9	0.46	0.32
95	7.69	2.5	179.0	2.2	81.4	14.29	13.9	0.71	0.86
93-92	8.07	1.46	382.5	6.7	61.4	19.06	3.8	0.62	0.39
91-89	9.1	0.57	185.5	5.1	41.4*	10.39	3.1	0.22	0.18
88	9.73	1.14	387.0	3.0	129.0*	11.27	2.9	0.83	0.90
87	10.66	1.18	258.0	3.3	78.2	12.03	4.6	0.80	0.11
86-85	11.6	1.03	184.0	4.6	47.3	13.27	15.6	0.40	0.50
84	12.0	2.46	205.0	2.0	102.5	13.52	12.0	0.19	0.08
83-82	12.83	0.67	252.3	4.0	69.6	9.98	2.7	0.37	0.15
81	13.27	0.52	234.0	3.4	68.8	8.10	2.2	0.38	0.76
80-78	13.49	3.78	418.0	3.3	160.4	21.52	9.0	0.86	0.87
77	13.74	1.85	224.0	2.8	80.0	13.87	8.3	0.05	0.51
76-74	13.96	1.07	323.7	2.8	115.6	10.55	3.3	0.07	0.31
73	14.16	-	380.0	3.0	126.7	-		0.16	0.39

APPENDIX 3

BASIC STATISTICS OF THE LOWER REACH

Appendix	3 (i)	Calculation and plotting positions of thalweg slope, width and depth.
	3 (ii)	Calculation of valley symmetry and plotting positions of thalweg variations.
	3 (iii)	Complete data used in the correlation and regression analyses.

APPENDIX 3 (i)

Lower Reach

St.#	(Yards) Dist.	(Miles) Dist.	(Cu.Mis.) Dist.	Thalweg Slope x 10^{-3}	Width	Depth	W/D Ratio	Channel Symmetry
36	860	.16	.16	1.05	298.0	9.1	32.7	.37
35.1	880	.17	.33	2.84	300.0	7.0	42.9	.06
35.0-24.0	1791	.34	.67	5.19	672.8	11.3	58.7	.58
33-31	8495	1.57	2.24	0.94	332.6	5.7	64.2	.61
30	3300	.63	2.87	0.70	270.0	5.8	46.6	.44
29	1500	.28	3.15	3.47	450.0	6.9	65.2	.19
28-25.1	5734	1.09	4.24	2.37	438.7	4.3	102.0	.55
25.0	1300	.28	4.53	0.33	269.0	7.6	35.4	.50
24	4450	.84	5.37	3.82	355.0	4.5	78.9	.29
23	3150	.60	5.97	1.78	430.5	6.3	68.3	.20
22	2400	.45	6.42	0.25	360.5	11.8	30.6	.90
21	3150	.60	7.02	3.68	228.0	2.7	84.4	.08
20	3000	.57	7.59	1.07	298.5	6.5	45.9	.64
19	2800	.53	8.12	1.71	160.5	2.6	61.7	.33
18	200	.04	8.16	13.5	212.5	2.4	88.5	.66
17-16	2250	.43	8.59	1.63	312.3	7.9	54.8	.53
15	3000	.57	9.16	2.67	391.0	9.0	43.4	.43
14	2980	.56	9.72	1.81	316.0	6.3	50.2	.72
13	800	.15	9.87	0.13	401.0	5.7	70.4	.54
12	100	.02	9.89	-	469.0	7.0	67.0	.42
11-10	390.0	.974	9.964	2.03	399.5	4.3	92.9	

APPENDIX 3(ii)

The Lower Reach

St.#	Total Width of Floodplain	Width From LB Floodplain to River Thalweg	Thalweg Elevation	Valley Symmetry
3.6	2014.7	967.0	835.9	.48
35.1	1507.0	150.0	835.0	.10
35.0	1412.0	1002.0	832.5	.71
34.2	1195.0	905.0	830.6	.76
34.1	1682	925.0	831.8	.55
34.0	1319.0	791.0	831.8	.60
33	1359.0	674.0	823.2	.50
32.1	2015.0	1015.0	825.4	.50
32.0	1317.0	540.0	823.8	.41
31	1510.0	634.0	826.0	.42
30	1571.0	401.0	815.2	.26
29	1408.0	708.0	812.9	.50
28	1975.0	1522.0	806.1	.77
27	1419.0	1039.0	802.8	.73
26	1344.0	810.0	810.5	.60
251	1249.0	856.0	856.0	.69
25.0	1374.0	272.0	792.5	.20
24	2716.5	769.0	791.0	.28
23	1089.0	409.0	774.0	.38
22	955.0	515.5	768.4	.54
21	1360.5	144.5	767.8	.11
20	950.0	442.0	756.2	.47
19	522.5	204.5	752.6	.39
18	669.5	483.5	747.8	.72
17	1125.0	709.5	745.1	.63
16	1095.5	799.5	733.9	.73
15	999.0	670.0	740.0	.67
14	809.0	592.0	736.7	.73
13	1158.0	581.5	727.3	.50
12	844.5	288.5	727.2	.34

APPENDIX 3 (iii)

The Lower Reach

St.#	(Miles) Cumulative Channel Length	Thalweg Slope x 10^{-3}	(ft.) Width	(ft.) Depth	W/D Ratio	S/W Ratio	x 10^{-3} Shear Velocity	Channel Symmetry	Valley Symmetry
36	0.16	1.05	298.0	9.1	32.7	3.5	18.84	0.37	0.48
35.1	0.33	2.84	300.0	7.0	42.9	9.47	42.35	0.06	0.10
35.0-34.0	0.67	5.19	672.8	11.3	58.7	7.71	46.67	0.58	0.66
33-31	2.24	0.94	332.6	5.7	64.2	2.83	15.29	0.61	0.46
30	2.87	0.70	270.0	5.8	46.6	2.59	12.28	0.44	0.26
29	3.15	3.47	450.0	6.9	65.2	5.53	29.82	0.19	0.50
28-25.1	4.24	2.37	438.7	4.3	102.0*	5.4	19.46	0.55	0.70
25.0	4.53	0.33	269.0	7.6	35.4	1.23	9.65	0.50	0.20
24	5.37	3.82	355.0	4.5	78.9	10.8	25.27	0.29	0.28
23	5.92	1.78	430.5	6.3	68.3	4.13	20.41	0.20	0.38
22	6.42	*0.25	360.5	11.8	30.6	.006	0.47	0.90	0.54
21	7.02	3.68	228.0	2.7	84.4	16.1	19.21	0.08	0.11
20	7.59	1.07	298.5	6.5	45.9	3.58	16.02	0.64	0.47
19	8.12	1.71	160.5	2.6	61.7*	10.7	12.85	0.35	0.39
18	8.16	13.5	212.5	2.4	88.5	63.5	34.69	0.66	0.72
17-16	8.59	1.63	312.3	7.9	54.8	5.22	21.87	0.53	0.68
15	9.16	2.67	391.0	9.0	43.4	6.83	29.88	0.43	0.67
14	9.72	1.81	316.0	6.3	50.2	5.73	20.58	0.72	0.73
13	9.87	0.13	401.0	5.7	70.4	0.32	5.25	0.54	0.50
12-10	9.96	2.03	399.5	5.6	71.3	5.08	20.59	0.42	0.34

APPENDIX 4

Descriptive Statistics of the Upper Reach

VARIABLE VAR001

MEAN =	1.241538	STD ERR =	.1519511	STD DEV =	.7748016
VARIANCE =	.6003175	KURTOSIS =	3.664067	SKEWNESS	1.537878
RANGE =	3.740000	MINIMUM =	.40000001-01	MAXIMUM =	3.780000
SUM =	32.28000				

VALID CASES 26 MISSING CASES 0

VARIABLE VAR002

MEAN	246.3192	STD ERR	13.79535	STD DEV =	70.34274
VARIANCE =	4948.102	KURTOSIS	.6254379	SKEWNESS	.9574276
RANGE =	285.0000	MINIMUM =	133.0000	MAXIMUM =	418.0000
SUM =	6404.301				

VALID CASES = 26 MISSING CASES 0

VARIABLE VAR003

MEAN	3.288462	STD ERR	.3305626	STD DEV	1.685545
VARIANCE =	2.841062	KURTOSIS =	3.875959	SKEWNESS	1.601418
RANGE =	7.800000	MINIMUM =	1.000000	MAXIMUM =	8.800000
SUM =	85.50000				

VALID CASES = 26 MISSING CASES 0

VARIABLE VAR004

MEAN	95.66924	STD ERR	10.33191	STD DEV	52.68263
VARIANCE =	2775.458	KURTOSIS	2.269074	SKEWNESS	1.477894
RANGE =	229.3000	MINIMUM =	26.70000	MAXIMUM =	256.0000
SUM =	2487.400				

VALID CASES 26 MISSING CASES = 0

VARIABLE VAR005

MEAN	11.21846	STD ERR	.8264934	STD DEV	4.214306
VARIANCE	17.76038	KURTOSIS	.9595858	SKEWNESS	.2068349
RANGE	20.17999	MINIMUM	1.320000	MAXIMUM	21.50000
SUM	291.6799				

VALID CASES = 26 MISSING CASES 0

```
VARIABLE   VAR006

MEAN          5.292308     STD ERR  -   .6305047      STD DEV  -   3.214955
VARIANCE -    10.33594     KURTOSIS     .[illegible]406143      SKEWNESS     .9665463
RANGE    =    13.70000     MINIMUM  =   .2000000      MAXIMUM  =   13.90000
SUM      =    137.6000

  VALID CASES - 26                 MISSING CASES    0

 VARIABLE   VAR007

MEAN     =    .4650000     STD ERR      .4588699E 01 STD DEV  -    .2339786
VARIANCE =    .5474600E-01 KURTOSIS- -.9152544       SKEWNESS      .1059941
RANGE    =    .8100000     MINIMUM  -   .5000000E 01 MAXIMUM  -    .8600000
SUM      =    12.09000

  VALID CASES   26                 MISSING CASES  - 0

 VARIABLE   VAR008

MEAN          .4786923     STD ERR  -   .5305718E-01 STD DEV       .2705396
VARIANCE =    .7319164E-01 KURTOSIS-    1.311931     SKEWNESS      .1505066
RANGE         .8200000     MINIMUM  -   .7999998E 01 MAXIMUM  -    .9000000
SUM      =    12.44600

  VALID CASES - 26                 MISSING CASES  = 0
```

KEY.

VAR001 - Thalweg slope
VAR002 - Width
VAR003 - Depth
VAR004 - Width-depth Ratio
VAR005 - Shear velocity
VAR006 - Slope - width Ratio
VAR007 - Channel symmetry
VAR008 - Valley symmetry

Descriptive Statistics for the Lower Reach.

VARIABLE VAR001

MEAN =	2.548500	STD ERR =	.6493557	STD DEV	2.904007
VARIANCE=	8.433255	KURTOSIS	11.24453	SKEWNESS	3.055443
RANGE =	13.37000	MINIMUM	.1300000	MAXIMUM	13.50000
SUM =	50.97000				

VALID CASES 20 MISSING CASES 0

VARIABLE VAR002

MEAN	344.8201	STD ERR	24.50924	STD DEV	109.6109
VARIANCE =	12014.55	KURTOSIS	3.254694	SKEWNESS	1.102426
RANGE =	512.3000	MINIMUM	160.5000	MAXIMUM =	672.8000
SUM =	6896.328				

VALID CASES 20 MISSING CASES 0

VARIABLE VAR003

MEAN	6.450000	STD ERR	.5749829	STD DEV	2.571402
VARIANCE	6.612105	KURTOSIS	.8612541 01	SKEWNESS	.939101
RANGE	9.400001	MINIMUM	2.400000	MAXIMUM	11.80000
SUM =	129.0000				

VALID CASES 20 MISSING CASES 0

VARIABLE VAR004

MEAN	59.80499	STD ERR	4.342655	STD DEV	19.42094
VARIANCE	377.1731	KURTOSIS	.3724367	SKEWNESS	[illegible]
RANGE =	71.39999	MINIMUM	30.60001	MAXIMUM	102.0000
SUM =	1196.100				

VALID CASES 20 MISSING CASES 0

VARIABLE VAR005

MEAN	8.513000	STD ERR	3.025162	STD DEV	13.52901
VARIANCE =	[illegible]	KURTOSIS	16.92066	SKEWNESS	[illegible]
RANGE	63.49999	MINIMUM =	.1000001 01	MAXIMUM	63.50000
SUM	170.2600				

VALID CASES 20 MISSING CASES 0

VARIABLE VAR006

MEAN	21.57249	STD ERR	2.389580	STD DEV	10.68653
VARIANCE -	114.2018	KURTOSIS	.5838348	SKEWNESS	.2045197
RANGE	41.42000	MINIMUM	5.250000	MAXIMUM	46.67000
SUM =	431.4500				

VALID CASES - 20 MISSING CASES 0

VARIABLE VAR007

MEAN	.4520000	STD ERR	.4844248 01	STD DEV	.2166432
VARIANCE -	.4693414 01	KURTOSIS	.1218173	SKEWNESS	.1110256
RANGE	.8400000	MINIMUM	.6000001 01	MAXIMUM -	.9000000
SUM	9.040002				

VALID CASES - 20 MISSING CASES 0

VARIABLE VAR008

MEAN	.4590000	STD ERR	.3957342 01	STD DEV	.1823383
VARIANCE	.3325251 01	KURTOSIS	.0833035	SKEWNESS	.3006619
RANGE -	.6300000	MINIMUM	.1000000	MAXIMUM	.7300000
SUM -	9.180000				

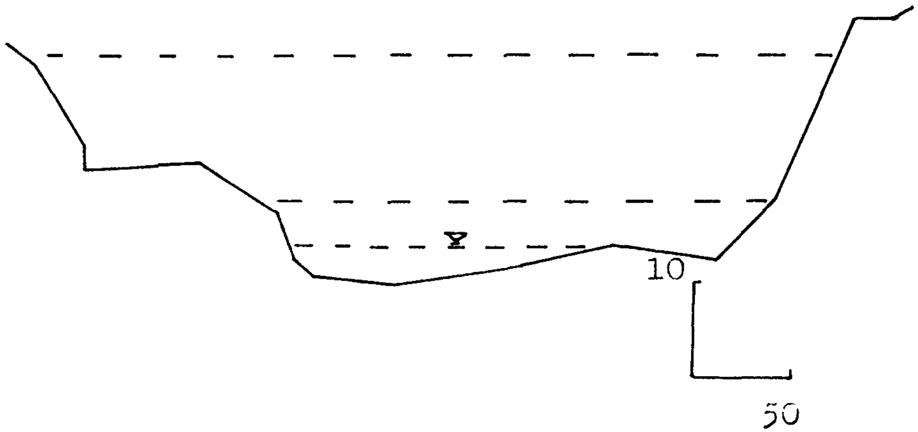
VALID CASES - 20 MISSING CASES 0

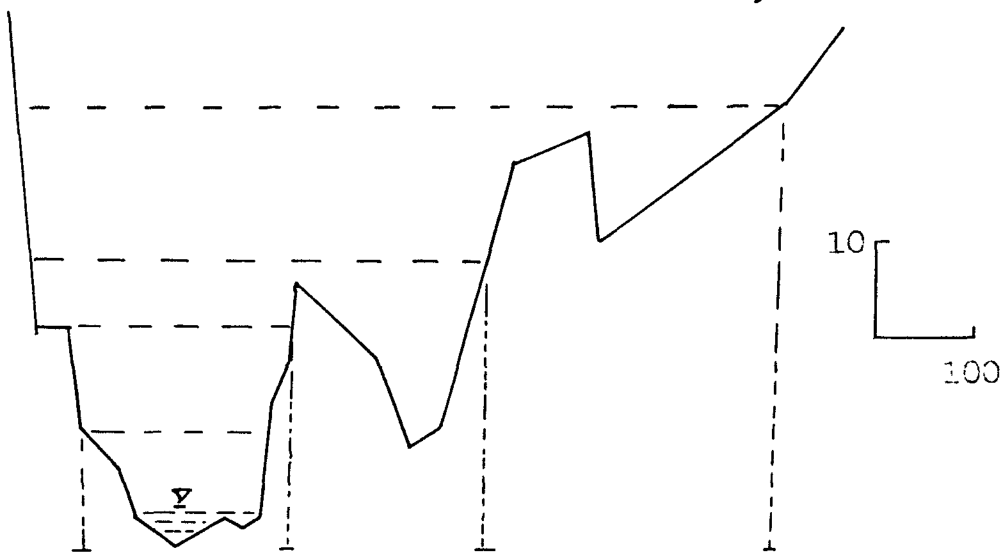
KEY

VAR001 - Thalweg slope
VAR002 - Width
VAR003 - Depth
VAR004 - Width - depth Ratio
VAR005 - Slope - width Ratio
VAR006 - Shear velocity
VAR007 - Channel symmetry
VAR008 - Valley symmetry

APPENDIX 6

Cross section #19 in the lower reach.





Cross section #113 in the lower reach.

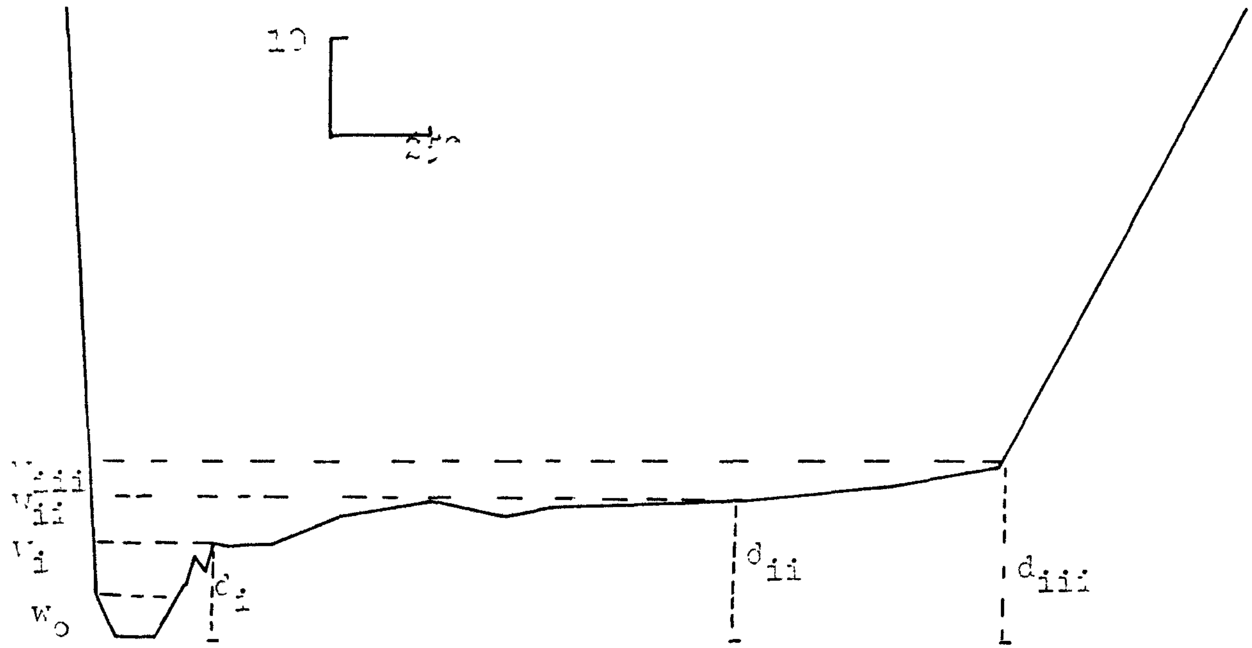
Cross section #20 in the Upper Reach.

$d_o = 4.2$ $w_o = 200.0$

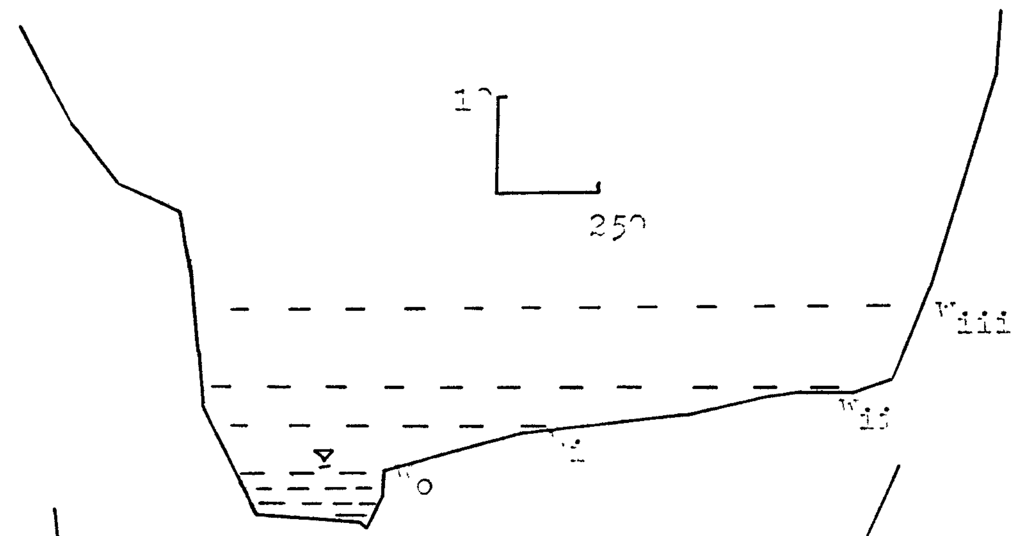
$d_i = 9.2$ $w_i = 310.0$

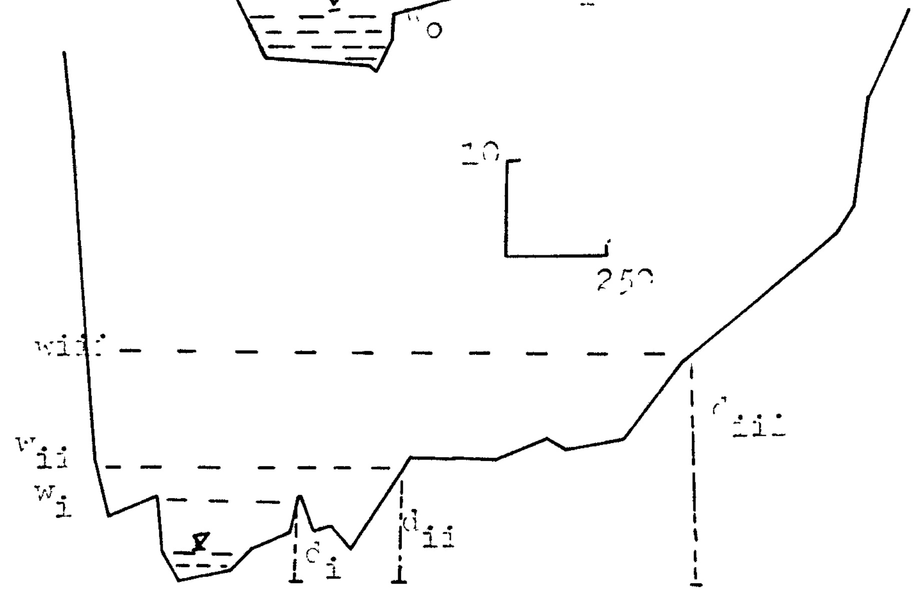
$d_{ii} = 14.0$ $w_{ii} = 1650.0$

$d_{iii} = 18.1$ $w_{iii} = 2350.0$



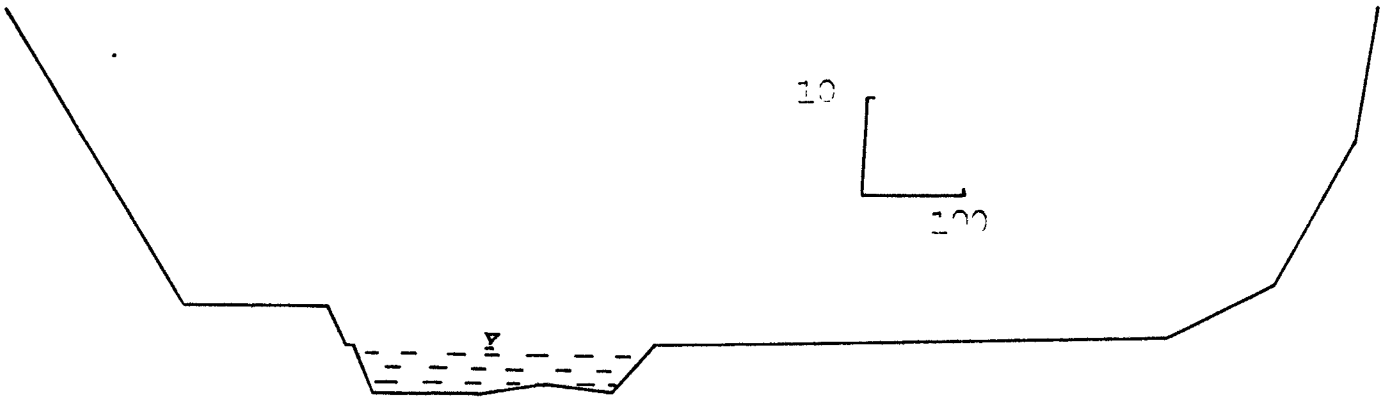
Cross section # 89 in the Upper Reach.



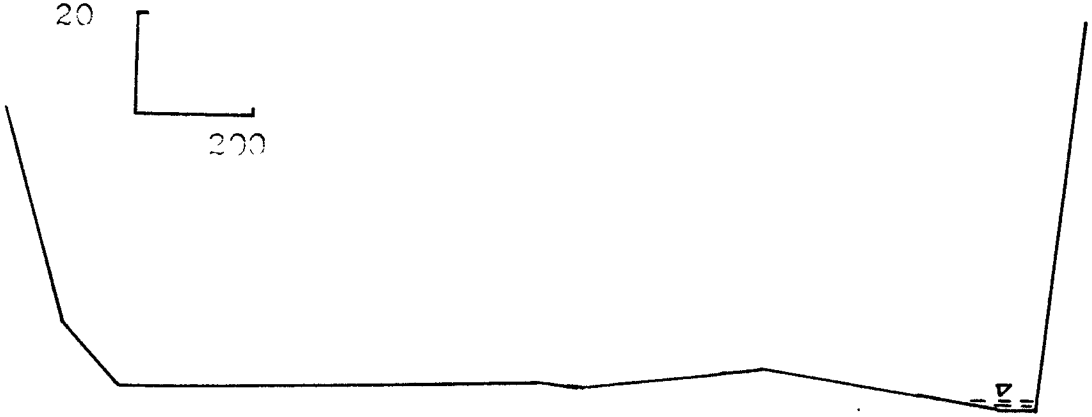


Cross section #97 in the upper reach.

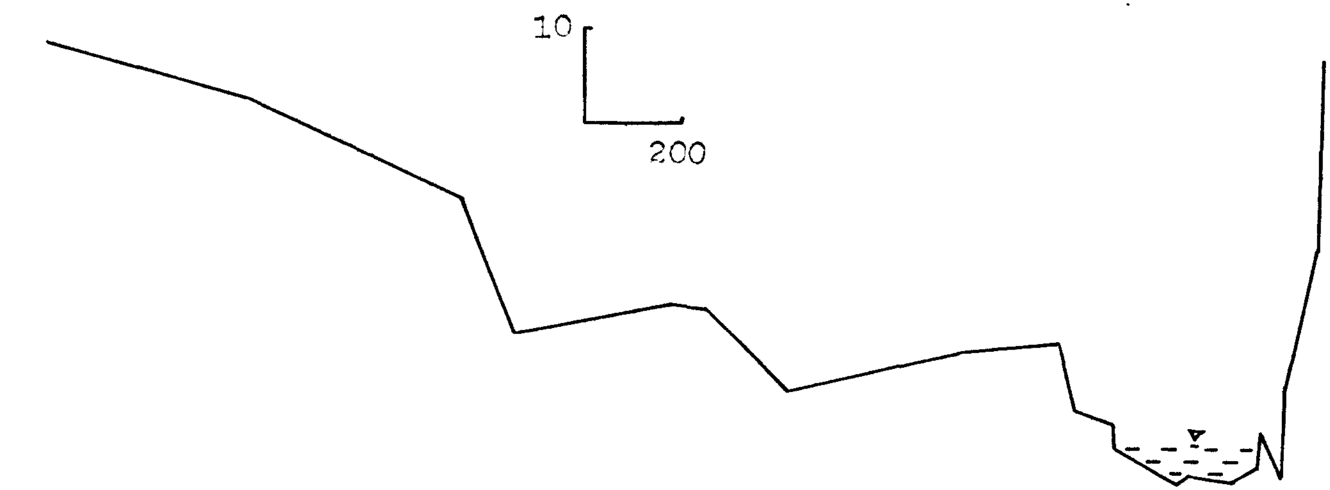
Cross section # 96 in the Upper Reach.

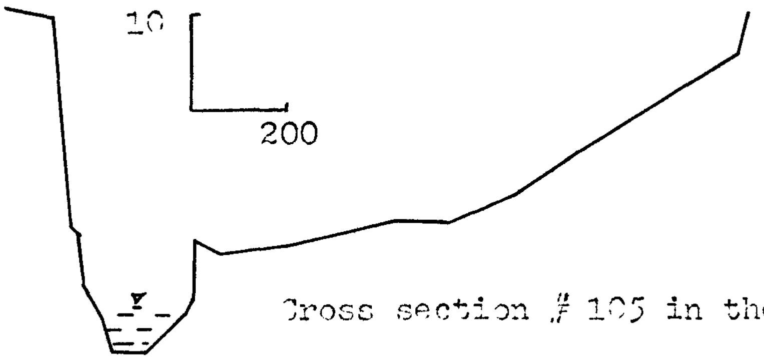


Cross section # 95 in the Upper Reach.

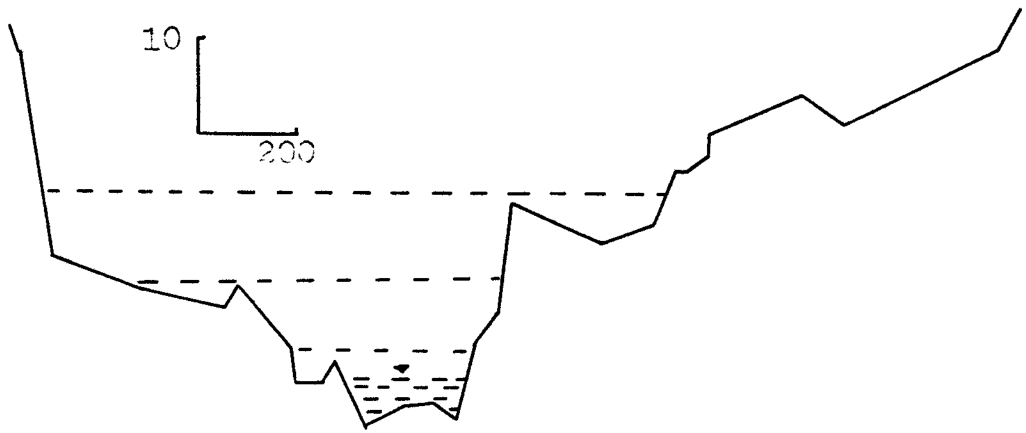


Cross section # 97 in the Upper Reach.





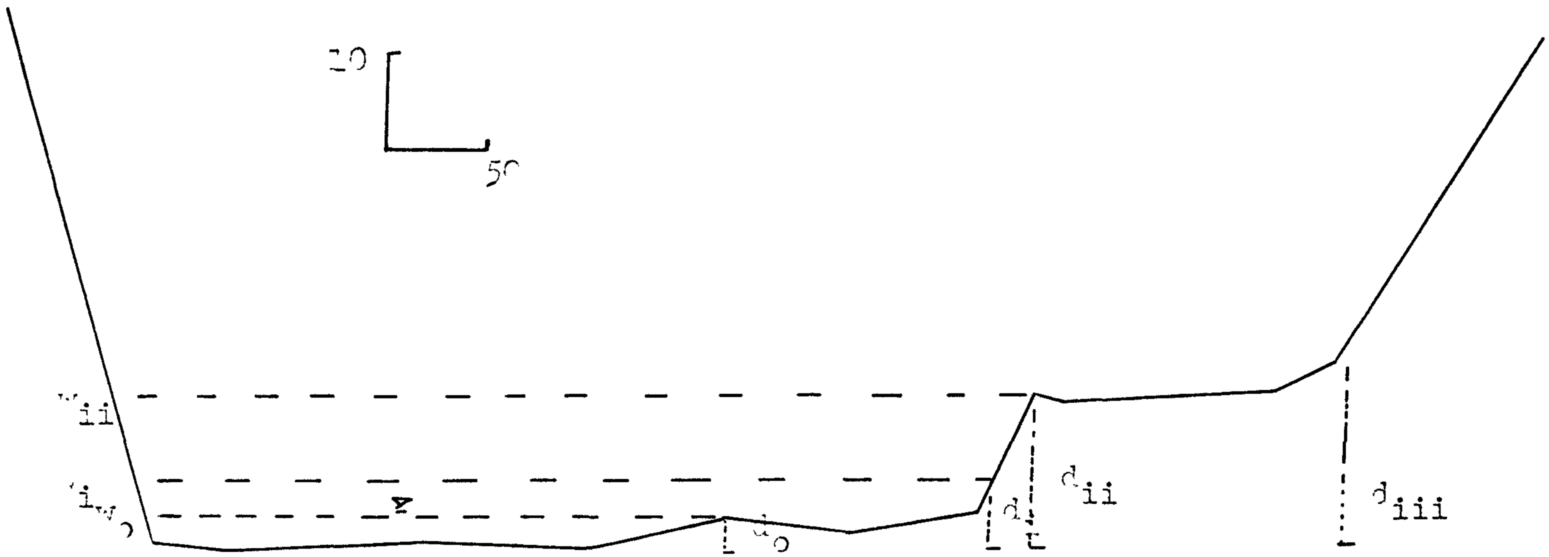
Cross section # 105 in the Upper Reach.



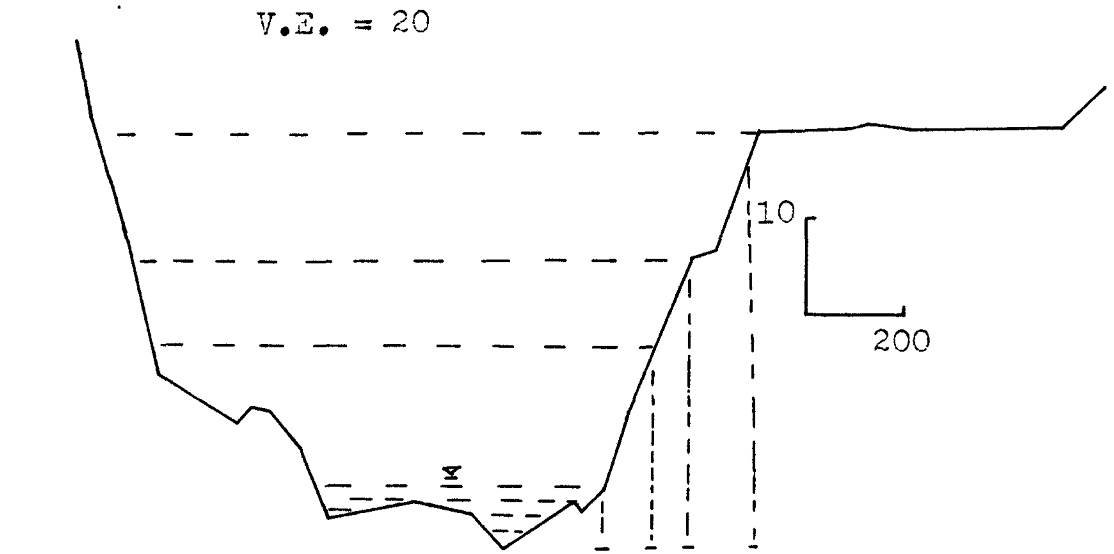
Cross section # 93 in the Upper Reach.

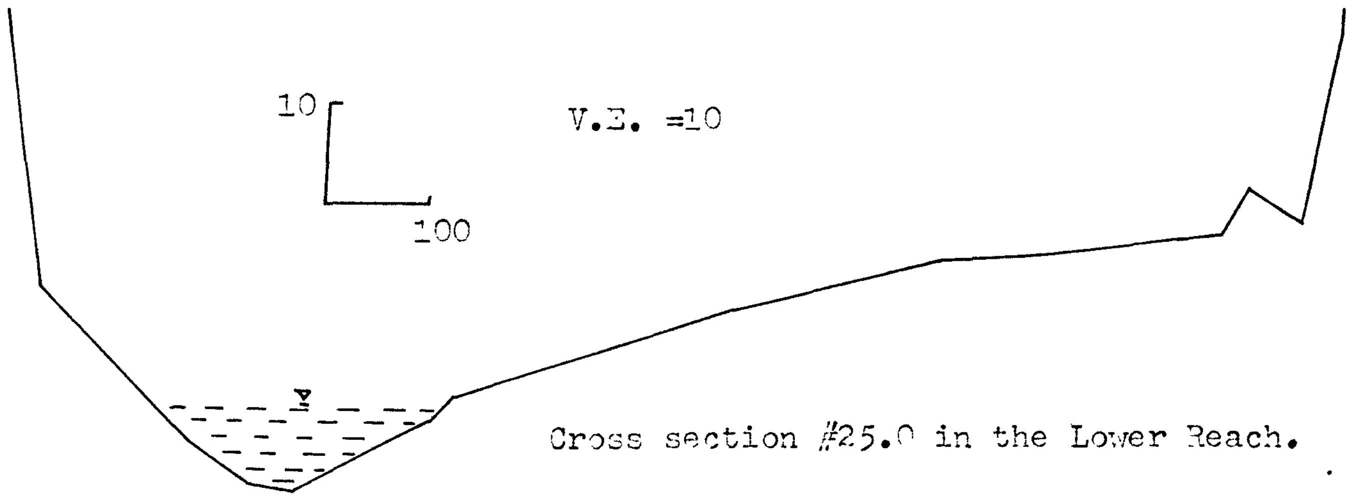
Cross section # 10 in the Lower Reach.

V.E. =5



Cross section # 20 in the Lower Reach.





Cross section #25.0 in the Lower Reach.

APPENDIX 6

REGRESSION ANALYSIS OF THALWEG SLOPE AND WIDTH FOR THE UPPER REACH

Thalweg slope x10^{-3}	O-width	C-Width
1.0	133.0	240.4
.56	254.0	229.6
1.31	174.0	247.9
.036	246.0	216.7
1.56	200.0	254.1
1.33	284.0	248.5
.68	235.0	232.5
1.59	222.3	254.8
.54	177.0	229.1
1.13	186.0	243.6
.45	288.0	226.9
1.37	256.0	249.2
1.36	224.0	249.2
1.13	292.0	243.6
2.5	179.0	277.2
1.46	382.5	251.7
.57	185.5	229.8
1.14	387.0	243.8
1.18	258.0	244.8
1.03	184.0	241.1
2.46	205.0	276.2
.67	252.0	232.3
.52	234.0	228.6
3.78	418.0	308.[illegible]
1.85	224.0	261.2
1.07	323.0	242.1

APPENDIX 6 (cont....)

REGRESSION ANALYSIS OF THALWEG SLOPE AND DEPTH FOR THE UPPER REACH

Thalweg slope $\times 10^{-3}$	O- depth	C- depth
1.0	1.6	3.37
.56	1.9	3.47
1.31	3.7	3.31
.036	1.3	3.58
1.56	3.4	3.26
1.33	4.4	3.30
.68	8.8	3.45
1.59	3.2	3.25
.54	2.5	3.48
1.13	2.3	3.35
2.5	2.2	3.06
1.46	6.7	3.28
.57	5.1	3.47
1.14	3.0	3.35
1.18	3.3	3.34
1.03	5.0	3.37
2.46	2.0	3.07
.67	4.0	3.45
.52	3.4	3.48
3.78	3.3	2.78
1.85	2.8	3.20
1.07	2.8	3.36
.45	3.3	3.50
1.37	1.0	3.30
1.13	2.5	3.35
1.36	3.0	3.30

APPENDIX 6 (cont....)

REGRESSION ANALYSIS OF THALWEG SLOPE AND WIDTH-DEPTH RATIO FOR THA UPPER REACH.

Thalweg slope $\times 10^{-3}$	O-w/d ratio	C- w/d ratio
1.0	83.1	91.1
.56	133.7	89.8
1.31	47.0	92.0
.036	189.2	88.2
1.56	58.9	92.9
1.33	64.5	92.1
.68	26.7	90.1
1.59	69.5	92.9
.54	70.8	89.6
1.13	80.9	91.5
.45	180.0	89.5
1.37	156.0	92.2
1.36	74.7	92.2
1.13	116.8	91.5
2.5	81.4	9[illegible].6
1.46	61.4	92.5
.57	41.4	89.9
1.14	129.0	91.5
1.18	78.2	91.6
1.03	47.3	91.2
2.46	102.5	95.5
.67	69.6	90.1
.52	68.8	89.7
3.78	160.4	99.5
1.85	80.0	93.7
1.07	115.6	91.3

APPENDIX 6 CONTINUE

REGRESSION ANALYSIS OF SLOPE AND WIDTH OF THE LOWER REACH

THALWEG SLOPE X 10E-1	O-WIDTH	C-WIDTH
1.05	298.0	346.9
2.84	300.0	344.4
5.19	672.8	341.1
.94	332.6	347.1
.70	270.0	347.4
3.47	450.0	343.5
2.37	438.7	345.1
.33	269.0	347.9
3.82	355.0	343.0
1.78	430.5	345.9
.25	360.5	348.0
3.68	228.0	343.2
1.07	298.5	346.9
1.71	160.5	345.9
	212.5	329.4
1.63	312.3	346.1
2.67	391.0	344.6
1.81	316.0	345.8
.13	401.0	348.2
2.03	399.5	345.5

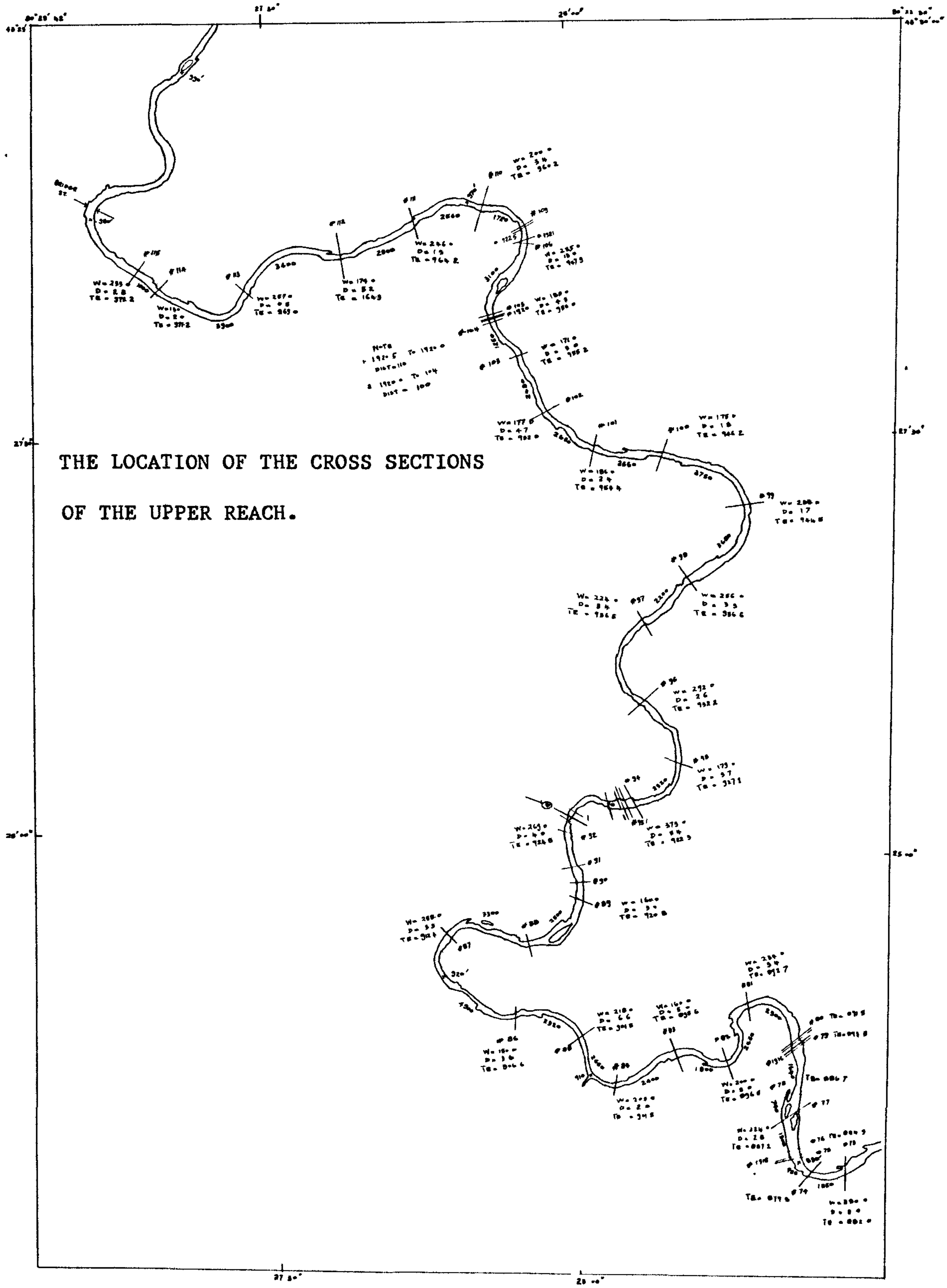
REGRESSION ANALYSIS OF SLOPE AND WIDTH-DEPTH RATIO OF THE LOWER REACH

THALWEG SLOPE X 10E-3	O-W/D RATIO	C-W/D RATIO
1.05	32.7	54.9
2.84	42.9	60.8
5.19	58.7	68.5
.94	64.2	54.5
.70	46.6	53.7
3.47	65.2	62.8
2.37	102.0	59.2
.33	35.4	52.5
3.82	78.9	63.9
1.78	68.3	57.3
.25	30.6	52.3
3.68	84.4	63.5
1.07	45.9	54.9
1.71	61.7	57.1
13.5	88.5	95.7
1.63	54.8	56.8
2.67	43.4	60.2
1.81	50.2	57.4
.13	70.4	51.9
2.03	71.3	58.1

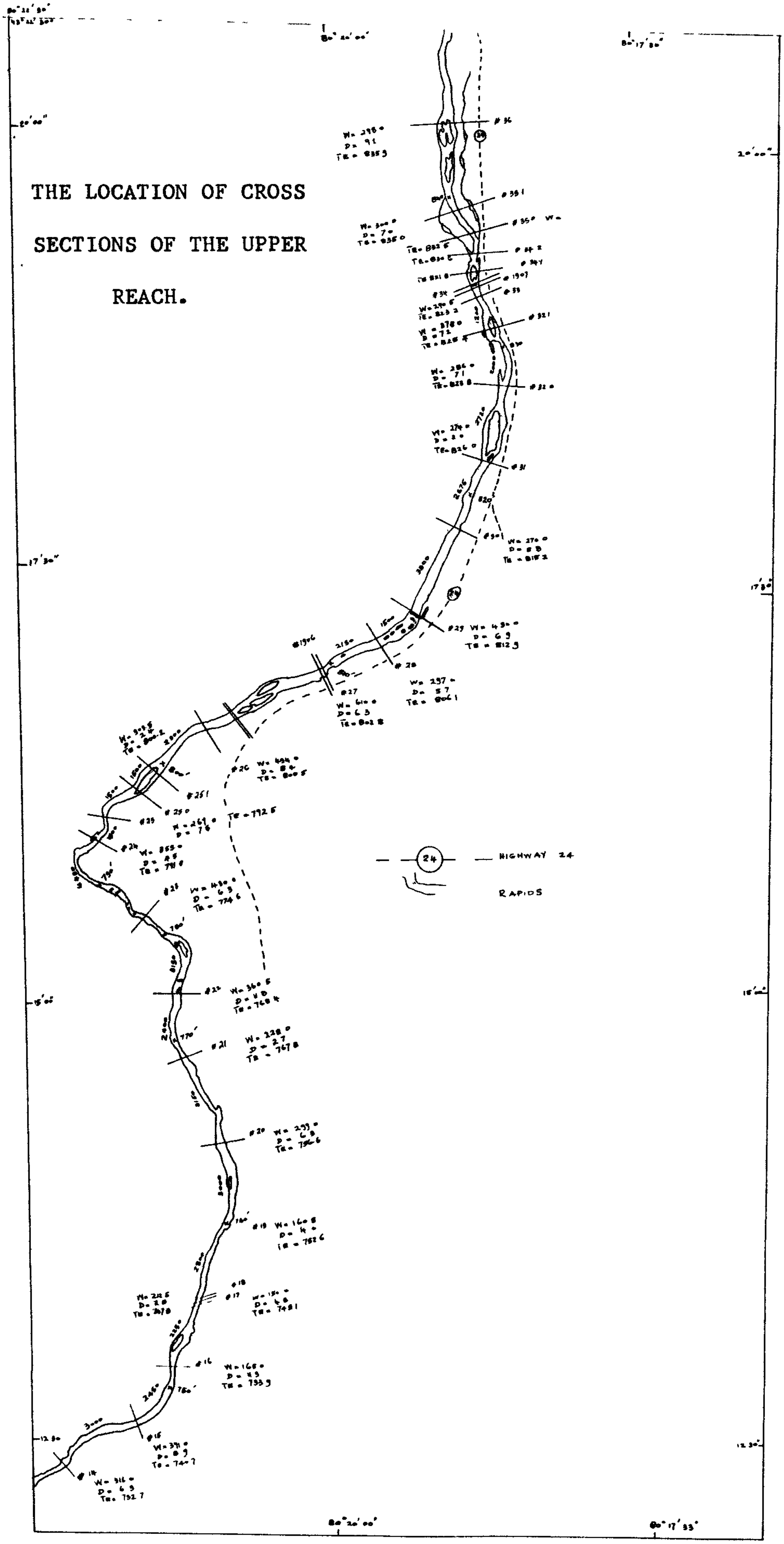
REGRESSION ANALYSIS OF SLOPE AND DEPTH OF THE LOWER REACH

THALWEG SLOPE X 10E-3	O-DEPTH	C-DEPTH
1.05	9.1	6.9
2.84	7.0	6.4
5.19	111.3	5.6
.94	5.7	6.9
.70	5.8	7.0
3.47	6.9	6.2
2.37	4.3	6.5
.33	7.6	7.1
3.82	4.5	6.1
1.78	6.3	6.7
.25	11.8	7.2
3.68	2.7	6.1
1.07	6.5	6.9
1.71	2.6	6.7
13.5	2.4	3.1
1.63	7.9	6.7
2.67	9.0	6.4
1.81	6.3	6.7
.13	5.7	7.2
2.03	5.6	6.6

APPENDIX 7



THE LOCATION OF THE CROSS SECTIONS OF THE UPPER REACH.


THE LOCATION OF CROSS SECTIONS OF THE UPPER REACH.
HIGHWAY 24
RAPIDS