A THESIS

A STUDY ON THE EROSION OF THE RIVER PADMA

Submitted by
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WE HEREBY RECOMMEND THAT THE THESIS PREPARED BY KAZI SAYEDUR RAHMAN ENTITLED A STUDY ON THE EROSION OF THE RIVER PADMA BE ACCEPTED AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN ENGINEERING (WATER RESOURCES).

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ABSTRACT

This study is concerned with the erosional characteristics of the river Padma from the confluence of the rivers Ganges-Brahmaputra at Goalundo to the confluence of the Padma-Meghna near Chandpur with a reach length of 65 miles.

Field data collected by Bangladesh Water Development Board have been studied, analysed and prominent morphological features have been found out.

It has been observed that the Ganges-Brahmaputra confluence has substantially migrated upstream. The width of the river Brahmaputra has also increased four times during a period of eight years from 1968-76.

The thalweg sinuosity of the reach is gradually decreasing from year to year. The reach concerned thus has a tendency of approaching towards braiding characteristics. The bed slopes are getting steeper, the thalweg meander shapes, ML/MB are increasing and the thalweg meander sizes MB/W are decreasing.

The frequent wandering of the thalweg from one position to another is due to the great magnitude of discharge during flood and movement of sand bars and mid-channel islands.

The shifting of the banklines is erratic and due to aggradation of the channel bed and the movement of the thalweg. The left bank is mainly under erosional activities while the right bank experiences both erosion and deposition. The maximum rate of erosion is about 1100 ft per year and the maximum rate of deposition is about 850 feet per year, both occuring on the right bank.

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LIST OF SYMBOLS

Symbol	Definition	Units
D	Average Depth	L
G	The river Ganges	-
g	Gravitational acceleration	LT^{-2}
J	The river Jamuna (Brahmaputra)	-
LR	Length along river	L
LV	Straight length chord	L
MB	Thalweg meander width	L
ML	Thalweg meander length	L
m	Weighted mean diameter	L
t	Time	T
V	Velocity	LT^{-1}
W	Surface width	L
ν	Kinematic viscosity	L^2T^{-1}
ρ_s	Density of sediment	ML^{-3}
ρ	Density of water sediment mixture	ML^{-3}
μ	Apparent viscosity of water sediment mixture	$ML^{-1}T^{-1}$

Chapter I

INTRODUCTION

General

From ancient times to the present days alluvial rivers have been playing a major role in human activities. The river flood plains were the early agricultural efforts and human habitation. The river routes for travel and trade are as old as civilization. The present civilization probably is making more of its uses than any in the past, either in the form of irrigation, generation of power, domestic water supply, transportation of goods to market or refuse to the sea.

However, alluvial rivers also cause tremendous problems to man. An occassional flooding of the lowlands refertilizes the soil and may be beneficial under pristine conditions, but such floodings frequently bring disastrous loss of crops, destruction of engineering works, and loss of life. As a result attempts are made to control the rivers so that flood damages are reduced and dependable navigation channels are maintained. However, before a river can be controlled it should be studied in sufficient detail so that its response to the controls can be anticipated.

Rivers flowing in alluvial materials, under a given set of climatic, hydrologic, geologic, and geomorphic conditions, exhibit a similarity of pattern and shape that implies cause and effect relations. It is of course, very important to understand the behaviour of rivers under diverse conditions and to identify the complex and interdependent variables which are responsible for the geomorphic and hydraulic character of a stream. However, the nature of a change of river character may be clearly apparent to the trained observer the reasons therefore often are obscure or, if suspected can not be proved. This is because there are many interdependent variables influencing a river and rarely can one be isolated and its effects studied. For example, Lane (1957) stated that "There is nearly infinite variety in stream forms, if considered in details. No stream is exactly like any other stream and no part of any stream is like any other part of the same stream". This is because stream channel forms are the result of a great many factors and the same combination of these factors is never exactly repeated. However, stream channel forms and shapes are the result of physical laws and if the conditions controlling the shape of any part of a stream were exactly reproduced, the same form of a stream would result.

Variabl s Affecting Alluvial Rivers

A great many factors affect stream channel forms some affect the form directly, and others affect it because of their influence on the directly affecting variables.

According to Lane (1957), the most important variables affecting alluvial streams are: (1) stream discharge, (2) slope, (3) sediment load, (4) resistance of banks and bed to movement, by flowing water, (5) vegetation, (6) temperature, (7) geology, and (8) works of man. Undoubtedly, other factors are involved, but Lane believed these eight to the major. They are not all independent, however, as many depend to a great or less extent on the others. The interrelation between slope, sediment load. and resistance of the banks and bed to movement is particularly close and complex.

Simons (1970) stated that "variables affecting alluvial channel forms are numerous and inter-related. Their nature is such that, unlike rigid boundary hydraulic problems, it is not possible to isolate and study the role of an individual variable". For example, if one attempts to evaluate the effect of increasing channel depth on the average velocity, additional related variables respond to the changing depth. Similarly, not only will the velocity respond to the change in depth but also the form of bed roughness, the position and shape of alternate, middle and point bars, the shape of cross-section, the magnitude of sediment discharge, and so on. Consequently, the mechanics of flow in alluvial channels and the response of channel geometry is not as well understood and explained as many other areas of fluid mechanics and hydraulics.

Simons (1970) gave the list of most important variables which influence the geometry of river channels. That list includes the following variables:

$$\varphi\left[V, D, S, \rho, \mu, g, d, \sigma, \rho_s, S_p, SD, S_c, f_s, C_T\right] = 0 \qquad (1)$$

in which

V = Velocity,

D = depth,

S = slope of energy grade line,

ρ = density of water-sediment mixture,

μ = apparent viscosity of water-sediment mixture,

g = gravitional constant,

d = representative fall diameter of the bed material,

σ = gradation of bed material,

ρ_s = density of sediment,

S_p = shape factor of the particles,

S_R = shape factor of the reach of the stream,

S_c = shape factor of the cross section of the stream,

f_s = seepage force in the bed of the stream, and

C_T = Concentration of bed-material discharge.

The majority of these variables were discussed in the analysis of forms of bed roughness by Simons and Richardson (1962).

Using V.D and ρ as the repeating variables and applying the Pi-theorem

$$\varphi_1 \left[S, \frac{VD}{\mu}, \frac{V}{\sqrt{gD}}, \frac{d}{D}, \alpha, \frac{\rho_s}{\rho}, S_p, SR, S_c, \frac{f_s}{\rho V^2}, C_T \right] = 0 \quad (2)$$

Equation 2 gives the list of the nondimensional parameters which are important in the study of alluvial river characteristics.

<u>Objectives</u>

This study attempts to know the probable behaviour of the river reach of the Padma for a reach length of 65 miles from the confluence of the Ganges-Brahmaputra at Goalundo to the confluence of the Padma-Meghna near Chandpur. The erosional pattern of the river reach, its migrating tendency and direction of movement, formation and movement of sand bars and mid-channel islands on its bed, has been studied and analysed. This type of systematic study for the prediction of the morphological behaviours of rivers is very important for rivers like Padma. The river influences greatly the socio-economic pattern of life of the country. It is not only one of the typically great rivers of Bangladesh but also one of the major rivers of the world.

The main objectives of this research are as follows:

a. to investigate the shifting and erosional characteristics of the river Padma.

b. to study the morphological changes of the river from year to year.

c. to study the morphological behaviours of the Ganges-Brahmaputra at the confluence.

Chapter II

RIVER PATTERNS

By river pattern is meant the configuration of a river as viewed on a map or from the air. River patterns are normally classified conveniently as straight, meandering and braided.

Straight rivers are those which have, at the bank-full stage, a negligible sinuosity over a distance ten times the channel width.

Meandering rivers show more or less regular inflections in the directions of the channel and are quite sinuous in plan.

Braided rivers are those marked by successive divisions and rejoinings of the flow around alluvial islands.

It should, however, be borne in mind that all channel forms in the field are not covered by these three categories and this classification is not comprehensive. For example, the distinguishing characteristic of a braided stream is the interlacing of its multiple channels. On the otherhand, the distinguishing characteristic of a meandering channel is a sinuous alignment. Thus, whereas the terms straight and meandering refer to direction, braiding refers to multiplicity of channels.

Straight River

A straight river is one that does not display a sinuous course. Leopold and Wolman (1957) pointed out that very few streams are completely straight for any appreciable distance. Although a stream may have relatively straight banks, its thalweg, is usually sinuous, Fig. IB. Thus there is no simple distinction between a straight river and a meandering river.

The ratio of channel length to down valley distance is often used as a basis for distinguishing between meandering and straight rivers. This ratio, called sinuosity, varies in rivers from a value of unity to a value of about 3 or more. Leopold, Wolman and Miller (1964) arbitrarily used a sinuousity of 1.50 as the division between meandering and straight rivers. Nevertheless a river with a sinuosity of sinuosity of 1.25 or greater would be considered to be meandering by most observers.

Braided River

A braided river is generally wide with poorly defined and unstable banks, and is characterized by a steep, shallow course with multiple channel divisions around alluvial islands, Fig. IA. Braiding was studied by Leopold and Wolman (1957) in a Laboratory flume, and they concluded that braiding is one of the many patterns which can maintain quasiequilibrium among discharge, sediment load and transporting ability. They also stated that braiding does not necessarily indicate an excess of total load. Lane (1957) concluded that there are two primary causes that may be r responsible for the braided condition: (1) over loading i.e., the stream may be supplied with more sediment that it can carry and part of it may be deposited, and (2) steep slopes causing a wide, shallow channel, in which bars and islands readily form.

Either one of these two causes alone may be responsible for the braiding pattern, or they may both be acting to cause it. If the channel is overloaded with sediment, deposition occurs, the bed aggrades, and the slope of the channel increases in an effort to maintain a graded condition. As the channel steepens, the velocity increases, multiple channels develop and cause the overall channel system to widen. The multiple channels, which form when bars of sediment accumulate within the main channel, are generally unstable and change position with both time and stage.

Another cause of braiding is easily eroded banks. If the banks are easily eroded, the river widens at high flow and at low flow bars form which become stabilized, forming islands. In general, then, a braided channel has a steep slope, a large bed material load in comparison with its suspended load, and relatively small amounts of silts and clay in the bed and banks. The braided river is difficult to work with in that it is unstable, changes its alignment rapidly, carries large quantities of sediment, is very wide and shallow even at flood flow and is in general unpredictable.

Meandering River

A meandering stream is one that consists of alternating bends, giving an S-shape appearance to the plan view of the river, Fig. IC. More precisely, Lane (1957) concluded that a meandering stream is one whose channel alignment consists principally of pronounced bends, the shapes of which have not been determined predominantly by the varying nature of the terrain through which the channel passes. The meandering river consists of a series of deep pools in the bends and shallow crossings in the short straight reach connecting the bends. The thalweg flows from a pool through a crossing to the next pool forming the typical S-curve of a single meander loop.

As shown schematically in Fig. IC, the pools tend to be somewhat traingular in section with point bars located on the inside of the bend. In the crossing the channel tends to be more rectangular, widths are greater and depths are relatively shallow. At low flows the local slope is steeper and velocities are larger in the crossing than in the pool.

The Continuum of River Patterns

Because of the physical characteristics of straight, braided and meandering streams, all natural channel patterns intergrade. Although braiding and meandering patterns are strikingly different, they actually represent extremes in a continuum of channel patterns. On the assumption that the pattern of a stream is determined by the interaction of numerous variables whose range in nature is continuous, one should not be surprised at the existence of a complete range of channel patterns. A given reach of a river, then, may exhibit both braiding and meandering, and alteration of the controlling parameters in a reach can change the character of a given stream from meandering to braided or vice-versa.

A number of studies have quantified this concept of a continuum of channel patterns. Khan (1971) related sinuosity, slope and channel pattern, Fig. 2. Any natural or artificial change which alters channel slope such as the cutoff of a meander loop, can result in modifications to the existing river pattern. A cutoff in a meandering channel shortens channel length, increases slope, and tends to move the plotting position of the river to the right on Fig. 2. This indicates a tendency to evolve from a relatively tranquil, easy to control meandering pattern to a braided patterns that varies rapidly with time, has high velocities, is subdivided by sand bars, and carries relatively large quantities of sediment. Conversely, a slight decrease in slope could change an unstable braided river into a more stable meandering pattern.

Lane (1957) investigated the relationship among slope,, discharge and channel pattern in meandering and braided stream, and observed that an equation of the form

$$SQ^{\frac{1}{4}} = K \qquad (3)$$

fits a large amount of data from meandering sand streams. Here S is the channel slope, Q is the water discharge, and K is a constant. From his plots, it is seen that when

$$SQ^{\frac{1}{4}} = .0017 \qquad (4)$$

a sand bed channel will tend toward a meandering pattern. Similarly, when

$$SQ^{\frac{1}{4}} = .01 \qquad (5)$$

a river tends toward a braided pattern. Slopes for these two extremes differ by a factor of almost six.

Chapter III

DATA COLLECTION

Sources of Data

All the cross-sections of the river Padma from the confluence of the Ganges-Brahmaputra at Goalundo to the confluence of the Padma-Meghna and a few cross-sections of the rivers Ganges and Brahmaputra around the confluence have been collected from the Directorate of River Morphology, Research and Training of Bangladesh Water Development Board, Dacca.

Stage-discharge and discharge hydrograph data were procured from the Directorate of Surface Water Hydrology, Division II, BWDB, Dacca.

Methods Used by BWDB for Data Collection

Discharge Measurement - The measurement involves measuring of velocity (at a number of points) and width of water surface at the measuring station . At the measuring station, the section consists of water surface width at the top and the bedcontour at the bottom.

Velocity Measurement by Current Meter - The principles are as follows (1). If 80 percent of depths are 5.0 ft or greater, set meter at 1.0 ft above bottom of weight.

a) Depths 5.0 ft. or greater, read velocity at 0.2 and 0.8 depth.

b) Depths 2.5 to 5.0 ft. read velocity at 0.6 depth.

c) Depths 2.0 to 2.5 ft. read velocity at 0.5 depth and apply co-efficient of 0.95 to get mean velocity in vertical.

d) Depths below 2.0 ft, read surface velocity and supply co-efficient of 0.86 to get mean velocity in the vertical.

2. If 80 per cent of depths are less than 5 ft. set meter 0.6 foot above bottom of the weight.

a) Depths 3 ft. or greater, read velocity at 0.2 and 0.8 depths.

b) Depths 1.5 to 3.0 ft. read velocity at 0.6 depths.

c) Depths 1.2 to 1.5 ft. read velocity at 0.5 depth and apply co-efficient of 0.95 to get mean velocity in vertical.

d) Depths below 1.2 ft. read surface velocity and apply 0.86 co-efficient to get mean velocity in vertical.

3. Measurements with wading rod, on measurement in section with low velocity (less then about 0.5 ft.) where the meter can be suspended at the bottom of the hanger bar without a weigth.

a) Under these conditions the meter can be pleased at 0.2 and 0.8 depth for depths 1.5 ft. or greater.

b) For depths 0.8 to 1.5 ft, set meter at 0.6 depth.

c) For depths 0.6 to 0.8 ft. read velocity at 0.5 depth and apply 0.95 co-efficient.

d) For depths upto 0.6 ft. read surface velocity and apply 0.86 co-efficient.

In taking the verticals care should be taken such that discharge between any two vertical must not exceed 10 per cent and preferably not more than 5% of the total discharge.

From site, gauge readings time distance from initial point to the edge of water, (Initial point may be permanent or temporary pillar), sounding that notes depth, and 08 of the total depth of the same vertical line etc. are taken.

If the direction of flow is not perpendicular to the line of measuring section, it will be necessary to correct observed velocities in order to obtain the perpendicular component. For this, measure the horizontal angle of flow i.e., the angle between the direction of flow and perpendicular to the section line, by some convenient method. The cosine of the horizontal angle is to be multiplied by the observed velocity to give the correct velocity.

Horizontal angle can be determined by (1) Magnetic campass (II) Instruments like sextant. Theodolite etc. or (III) by the use of a circular paper disc graduated in degrees.

From the meter rating table the velocity is taken. For each vertical that necessary informations are taken. This is mainly the field observations.

For discharge measurement average velocity is taken for each vertical. Correction if necessary for depth, angle are also made, two verticals make a pocket whose width, mean velocity and area can be calculated, Hence discharge for each pocket is calculated whose total some is the total discharge. When total discharge is divided by total area gives the mean velocity.

This is the main principle adopted by the Hydrology, BWDB, which is followed throughout the year.

Measurements are taken throughout the year. For daily discharge rating curves are drawn, from where peak discharge is taken.

Cross-Section Measurement - The distance between two cross-sections are fixed according to the requirement of a particular project or programme. However, the usual measurements are taken at an approximate interval of 4 miles. For locating one cross-section generally three permanent monoments (1'-0" x 1'-0") R.C.C. Pillars are placed.

The monuments and pillars are fixed in such places which are considered safe from being eroded. Two of these are placed on one bank and the third on the other bank. The location of these pillars are transferred on mouza maps and the particulars of the owners of land are recorded. The lines are also drawn with important features. The pillars are placed in a line having the same bearing of cross-section line. The Mouza maps along with the location of pillars are reduced with the help of pentagraph to the scale of Thana maps. From the thana maps the latitude and longitude of pillars are computed. The top of the monuments or pillars are connected with bench mark. These values a are used in future survey.

The survey starts from one pillar at one end of cross-section. The bearing recorded is followed and gnerally Theodolite is used to maintain the measurement in alignment. Levelling instrument is used to find out the elevation of land on cross-section. This process is continued upto the river bank. The same procedure is followed for the other bank of the river.

The survey on river proper requires the help of vessels. Launches are used in big rivers while country boats are adopted in small rivers. Echo sounder is generally used for measuring the depths of water in major rivers while the lead and rope are used for the same purpose in small streams.

The survey thus conducted in a particular year hardly coincides with that performed in previous years. This is due to personal and instrumental errors and terrestrial effects. When the variation is excessive, the correction is made by proportionate distribution. Then the corrected cross-sections are plotted in a special profile paper. In the profile paper the location of pillars or monoments, plan of cross-section, and profile of cross-sections are plotted. The plotting is done, keeping the left bank at the left edge of the paper.

Chapter IV

RESULTS AND DISCUSSIONS

As mentioned in chapter I, this study concerns mainly with the river reach of Padma. Padma is the combined flow of the Ganges and Brahmaputra from Goalundo to Chandpur. It is, therefore, necessary to get some information of the Ganges-Brahmaputra confluence at Goalundo before studying the actual reach. This chapter is therefore, divided in two parts such as

1) the Ganges-Brahmaputra confluence at Goalundo.
2) the Padma from Goalundo to Chandpur.

The Ganges-Brahmaputra Confluence at Goalundo

Fig. 4 represents the plan of the Ganges-Brahmaputra confluence at Goalundo. The rivers in the figure are represented from approximately 7 miles upstream of their courses. The original figure showed the banklines of the rivers only for 1956 and 1976. Thalweg movement was drawn only for the year 1976. The positions of sand bars and mid-channel islands of 1956 and 1976 were also shown. Detailing, such as banklines and thalweg movement for the years 1968 and 1969 have been superimposed from the cross-sectional details for the present study.

The Brahmaputra Upstream Confluence - From Figure 4 it is seen that in 1956, the river maintained predominantly a single channel from the downstream of section J-2, and met the confluence as a single channel. There existed a small mid-channel island in the middle of the course at section J-2, Figure 4 and it was nearly 4 miles upstream of the present confluence. Gradually this mid-channel island developed fully and seperated the main river in two channels-left and right. In 1968, the mid-channel island was further developed and was about 2.69 miles upstream from the present confluence position. In 1969, the island grew in size and moved downstream. In 1976, the downward shifting continued with an average rate of about 1800 ft. per year. In 1968, the divided channels formed a single channel at section J-1 and cut the thalweg of the Ganges approximately 1.5 miles upstream of section P-7 as shown in Figure 4. In 1969 due to the extension of mid-channel island, the formation of single channel was 2.50 miles more downstream of 1968 position. But on the contrary the thalweg this time met the thalweg of the Ganges 3 miles upstream of the previous year. In the year 1976, the two divided channels could no longer form a single course but flowed independently and met the thalweg of the Ganges at two different points, keeping a distance of approximately 4.5 miles between them. So far the thalweg of the river is concerned, it follows along the right channel and met the thalweg of the Ganges upstream of the meeting point of the left channel. From the cross-sectional details, Figure 14 through 18, it can be said that the right channel is growing wider and deeper than its counterpart in most of its cources. This channel also meets the thalweg of the Ganges upstream of the whalweg meeting point of the left channel. The phenomenon is quite clear. The Brahmaputra is a over-loaded river. Every year during rising stage, there is a huge flow of sediment from the upstream catchment area. But during falling stage, the river can not carry this load, depositing mainly on the bed, forming sand bars and islands and braiding characteristics is getting more prominent from year to year. From engineering point of view, a braided channel is not wanted and unstable in nature than a meandering channel. Study of sediment control is therefore a very important factor for the Brahmaputra.

The Ganges Upstream Confluence - Figure 19 through Figure 21, are the cross-sectional details of the river, at sections, G-1-1, G-1 and G-0-1. The Ganges at present predominantly flows leftwards and meets the Brahmaputra on its extreme right.

In 1956, the river course was different from the present position. The river flowed mainly in two courses. Deposition occurred greatly on the right bank and at the middle.

In 1968, banklines were changed. The river was divided in two channels at section G-1-1 but there were three channels at sections G-1 and G-O-1. Great changes took place of the sand bars that were present in 1956, namely char Brhabanipur, Rakhatgachhi, Majhail, Bethun etc. and some of them shifted towards left as a whole as shown in Figure 4. The thalweg alignment follows a meandering pattern and swings from right to left. In 1969, the river was divided in four branches in sections G-1 and G-O-1. The thalweg alignment did not follow the path to that of 1968. The sand bars between sections G-1 and G-O-1 were eroded on the left side. The sinuosity of the thalweg increased and met the thalweg of the Brahmaputra upstream of 1968 position.

The river moved leftward considerably in 1976, deep water channel proceeds along the left bank with greater meandering loop than that of 1968 and 1969 and meets the thalweg of the Brahmaputra upstream of 1969 position, Figure 4. Heavy deposition of sediment load took place and the the mid channel islands extended from section G-1-1 to down-stream of G-O-1 with a length greater 14 miles. The average width of the mid-channel island was more than two miles. There existed a shallow and narrow channel of the right of these island throughout the length.

The Confluence - As discussed above, the Brahmaputra-Ganges confluence is choked with sand bars. The meeting point is shifting upstream along the Brahmaputra from year to year with total shift of nearly 10.5 miles during 1968 to 1976. The migration may be considered due to the movement of the Ganges towards left. The confluence was much narrower in 1956-68 but there has been an abrupt increase in width of the river Brahmaputra during the period 1968-76 from 1.50 miles to 7.50 miles affecting an increase of 400 per cent during a span of 8 years.

The Padma from Goalundo to Chandpur

A survey of the available cross-section shows that the complete set of data were available only for the year 1967, 1969, and 1977. Figure 5 represents the banklines and the deep water channels of the reach for the above years. These data were superimposed (Figure 5) which originally represented the banklines of the river, the positions of sand bars and mid-channel islands for 1956 only, and Figure 6 which shows the erosional and depositional features of the banks and thalweg movements, has been derived from this figure. The shifting of the banklines in Figure 6, has been shown with respect to the banklines of 1956.

Shifting of Deep Water Channel - Looking to Figure 6, it is evident that deep water channel did not follow the same path every year, It is shifting continuously to the left at sections P-7, P-6 , P-4-1, and P-1 as shown in Figure 6. At other sections there is no systematic trend. The left-ward movement is maximum at section P-7 and P-1 with an average rate of movement being 2700 ft. and 2250 ft.per year respectively.

In an alluvial river like Padma, the wandering of thalweg may be considered due to the movement of sand bars and mid-channel islands. From the discharge hydrograph at Bhagyakul as shown in Figure 7, it can be said on general basis that the flow in the Padma has the capacity of shifting sand sand bars and mid-channel islands. In the low-water stage, prior to the passage of the flood, the observation says that the river is subdivided into several channels, with one of them generally serving as the main channel and carrying a larger portion of the flow. This channel is commonly situated near one of the river bank and is slightly curved. With the onset of the flood, as it happened in the Brahmaputra (Coleman, 1969), the initial reaction of the river is to seek a course with a little curvature. This may be the reason of the movement of the thalweg towards the inside portion of the curvature. During the flood stage which is quite rapid as shown in Figure 7, the channel naturally may try to widen and deepen to accomodate the large increase in discharge, As a rule, the bank erodes, slumping occurs and the thalweg migrates in transverse direction.

As flood water subsides, velocities diminish and this may cause deposition of excess sediment in one location, resulting a corresponding change in flow direction and deepending by scour in another location. This way the thalweg in alluvial rivers tends to wander continuously from one position to another within the river banklines.

Lateral Movement of Bank - Comparing bank lines of 1977 with those of 1956, it is found that the movement varies from section to section. The river is shifting towards left at sections P-7, P-5, P-4-1, P-2-1, P-2 and P-1 while it is migrating towards right at sections P-6-1, P-5-1 and P-0 as shown in Figure 6. The overall situation shows that the river is oscillating left and right within a bend of nearly 80000 feet. The right bank has the maximum rate of erosion of 1090 feet per year at section P-6-1 and maximum rate of deposition of 853 feet per year at section P-2. On the left bank, these values are 732 feet per year and 21 feet per year respectively at section P-1 and P-0. In most of the sections while one bank is eroding, the other is depositing. But at sections P-6, P-4 and P-1-1, the channel is getting wider, signifying erosion on both the banks.

Various factors are responsible for the lateral migration of the river. The major factor is the aggradation of the channel bed. When the total amount of sediment provided by the catchment of the river far exceeds the ability of the flow to carry the sediments, there is general aggradation of the channel bed which causes the channel to become wider abd shallower. The aggradation constantly naturally causes the main current to seek better gradients, new alignment and paths of least resistance. A new channel thus formed is at first narrow and deep. With time, however, it, too, will begin to aggradate and the whole process is repeated. In this manner, the channel is in a state of constant migration, eroding and redepositing sediment of its own making as well as older deposits of previous channels. High susceptivility to erosion of the bed material, the large variability of the flow and abrupt rise and fall of the river stage may also have strong bearing on the migration pattern. The constant shifting of the thalweg also adds to the magnitude and complexity of deposition and erosion patterns. Sudden flood events, lack of bank stability and permanence of vegetation and improper flood plain land use are also responsible for the shifting of the course.

Thalweg Sinuosity

The thalweg sinuosity of the whole reach are calculated from Figure 5 for the available years and are presented in table 5. The values are found to be 1.30, 1.23, and 1.12 for the years 1967, 1969 and 1977 respectively. When plotted these thalweg sinuosities against year in normal scale as in Figure 8, a decreasing trend of the sinuosity with time is noticed. This may be explained due to the development of braiding tendency of the channel.

Development of braiding in the Padma may generally be stated due to the deposition of sediment load on its bed and banks forming bars and islands which flattens the bed slope upstream the reach and increases the value downstream the reach. Velocity increases and the river may have a tendency to follow more or less shorter course forming multiple channels. In a recent study of alluvial river morphology in the laboratory, Khan (1971) also observed this fact of braiding development.

<u>Thalweg Sinuosity and Bed Slope</u> - Table 5 also shows values of sinuosities calculated at different points of the reach. These are plotted against bed slope in Figure 9 on a semi-log paper. Slope is determined in this plot on the basis of the difference of elevation of the two deepest points at two sections. No systematic trend line or curve is drawn but it can b can be said that sinuosity decreases gradually and the channels attain steeper slopes.

<u>Thalweg Sinuosity and Channel Shape (W/D)</u> - The relationship between thalweg sinuosity and channel shape is shown in Figure 10. It is seen from the curves that with the lowering of thalweg sinuosity, the value of W/D (the ratio of surface

width to average depth) is increasing i.e., the channels are becoming wider and shallower. In a paper presented to American Society of Civil Engineers, Chitale (1970) has also observed the above facts. His study included field data for about 35 Indian rivers and 7 other rivers of America, Canada, Combodia, Africa and Pakistan. He also drew conclusions that higher sediment load and coarser bed material are associated with wider, shallower and steep channels. Padma in the present case also confirms this conclusion.

Thalweg Sinuosity and Thalweg Meander Shape, ML/MB

Measurements of meander lengths i.e., wave length, ML and widths of meander belt, MB are taken from the thalweg drawn for different years, in Figure 5 and these data are plotted in Figure 11. The plot shows that an increase of thalweg meander shape, ML/MB is associated with decrease of thalweg sinuosity. In other words, the thalweg of Padma is getting flatter from year to year, the meander length, ML is increasing and the width of meander belt, MB is decreasing. The observation seems to be similar to that of Chitale (1970).

Thalweg Sinuosity and Thalweg Meander Size, MB/W - Plot of thalweg sinuosity, LR/LV against thalweg meander size, MB/W is shown in Figure 12. On general basis the figure represents that decrease of thalweg sinuosity causes decrease of thalweg size MB/W verifying Chitale's (1970) general observations.

From the figure it can also be said that thalweg meander size may remain same from year to year but this does not mean that sinuosity will also have a constant value,rather the value is on decreasing trend. The rate of decrease of thalweg sinuosity is higher between 1967 and 1969 where it is much lower during 1969-77.

Thalweg Meander length ML and Average Width of the Channel

Figure 13 shows the relation between thalweg meander length and average width of the channel in log scale. Leopold and Wolman's observation that meander length varies directly with the width of the channel seems to be valid here. Small increase in the average width of the channel causes a very rapid increase in meander length. However, the rate of increase of thalweg meander length is different for different years. In 1967, from the figure, it can be said that the rate of increase in thalweg meander length is about 6.0 times to that of the rate of increase of the average width of the channel. For the plotted points for 1969, the river does not show any systematic trend. Data of this period may be considered of more or less to that of transition type. As the sinuosity of the thalweg goes on reducing, the rate of increase of meander length is also increasing from year to year as shown in the figure for 1977. The rate of increase of meander length for this year is about 10 times to that of the average width. In short it can be said that the river is getting wider and the meander length is increasing.

Stage-Discharge Curves at Bhagyakul

There is only one discharge measuring station throughout the river reach under study and it is at Bhagyakul. Bhagyakul is in between sections P-3-1 and P-3 i.e., downstream of section P-3-1 and upstream of section P-3. Theleft bank in both the sections is almost stable whereas the right bank is unstable. Changes in the section P-3-1 are erratic. In section P-3, the right bank is eroding since 1967. It is seen from the cross-section, Fig. 23 that the deep water channel in section P-3 is shifting continuously towards the right due to the movement of sand bars and mid-channel islands.

The curves shown in Figure 24 for the years 1966-67, 1968-69 and 1976-77 are more or less similar in nature i.e., an increase of discharge causes the corresponding increase of stage.

Chapter V

CONCLUSIONS

The following conclusions can be drawn from the present study:

1. The Ganges-Brahmaputra confluence at Goalundo has substantially migrated upstream. The thalweg meeting point of the two rivers has shifted nearly 10.5 miles during 1968-76. The average rate of migration is approximately 6880 feet per year.

2. There has been an abrupt increase in the width at the confluence from 1.50 miles to 7.50 miles affecting an increase of 400 per cent duering a span of 8 years (1968-76).

3. Near the confluence, the river Ganges moves leftward considerably in 1976, deep water channel proceeds along the left bank with greater meandering loop and meets the thalweg of the Brahmaputra upstream of 1969 position.

4. The thalweg sinuosity of the reach is gradually decreasing from 1.30 in 1967 to 1.12 in 1977 indicating that the river has a tendency to develop braiding.

5. The frequent wandering of the thalweg is due to great magnitude of discharge during flood and movement of sand bars and mid-channel islands.

6. The shifting of banklines is erratic and it is due to aggradation of the channel bed and frequent movement of the thalweg within the river banklines. The maximum rates of erosion and deposition are 1100 and 850 feet per year respectively, both on the right bank.

7. The bank to bank distance is getting wider with formation of mid-channel islands and brs at the middle. This causes shallowing of the river depth from year to year.

8. An increase of thalweg meander shape, ML/MB is associated with decrease of thalweg sinuosity. This observation seems to be similar to that of Chitale (1970).

9. A decrease of thalweg sinuosity causes decrease of thalweg meander size, MB/W confirming Chitale's general observation on natural channels.

10. With small increase in the average width of the channel, there is a great increase of thalweg meander length, ML.

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A P P E N D I X - A

Figures

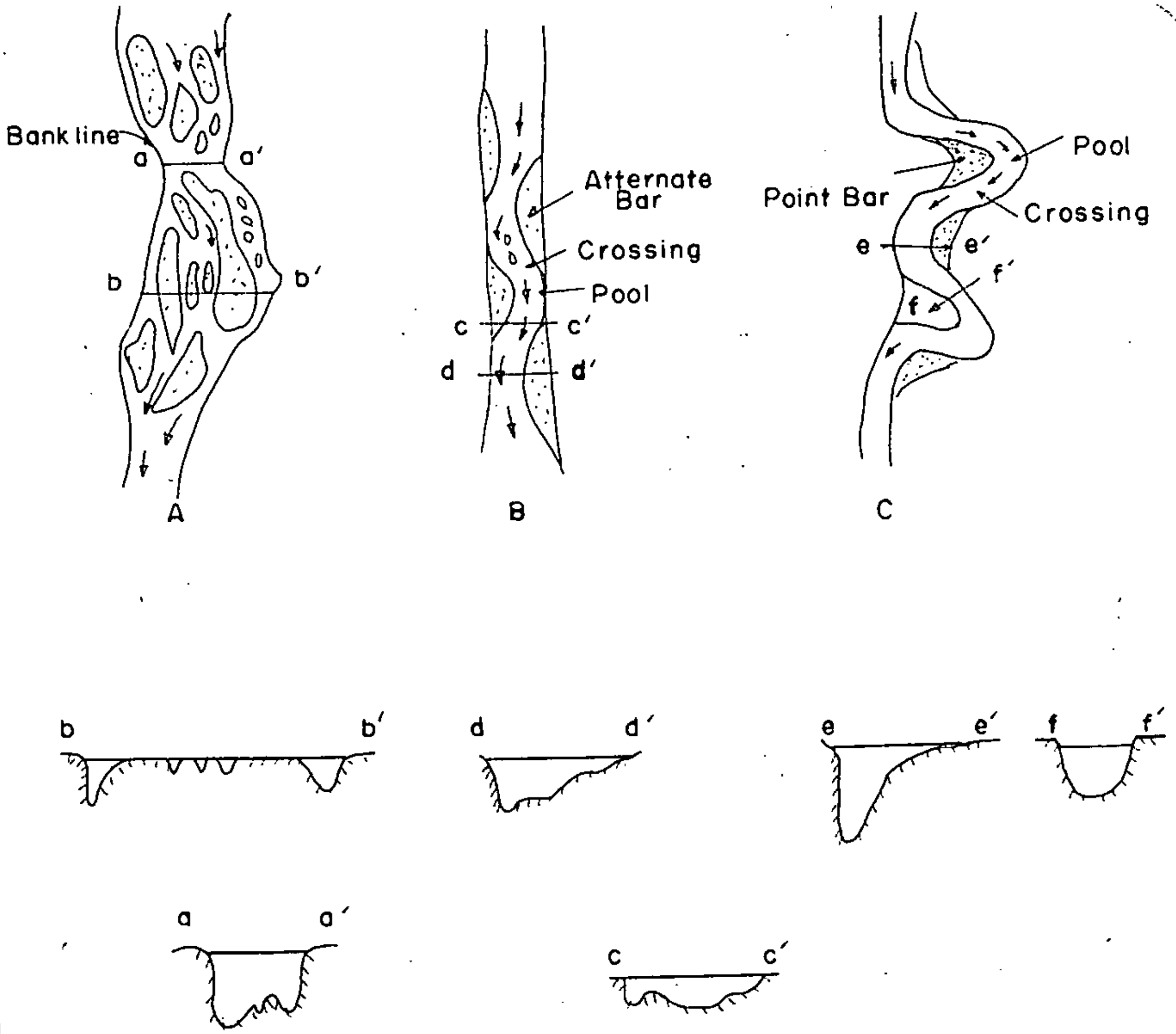
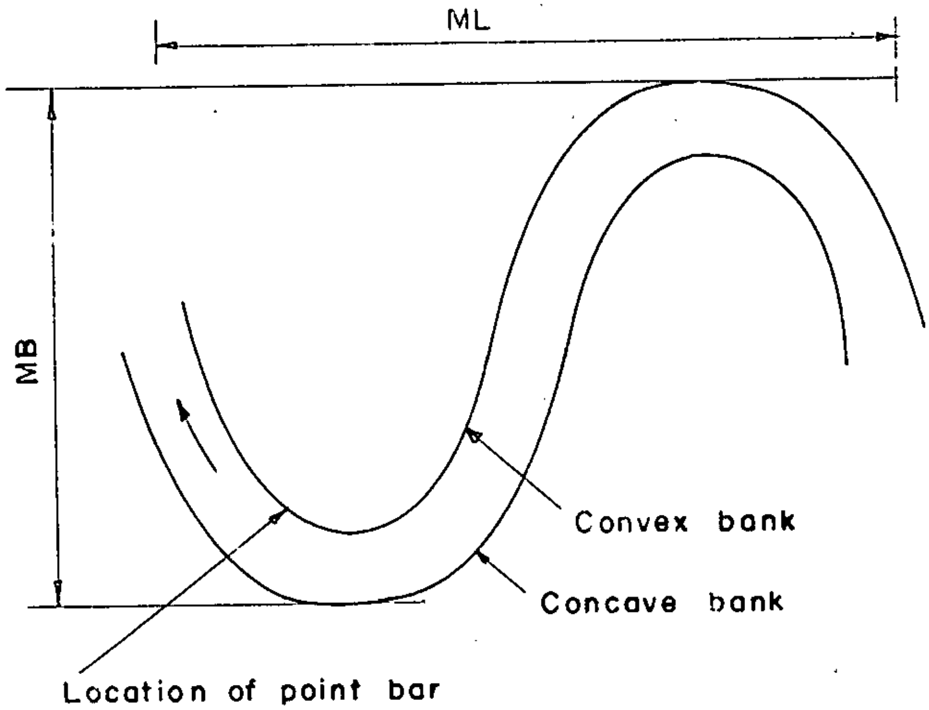


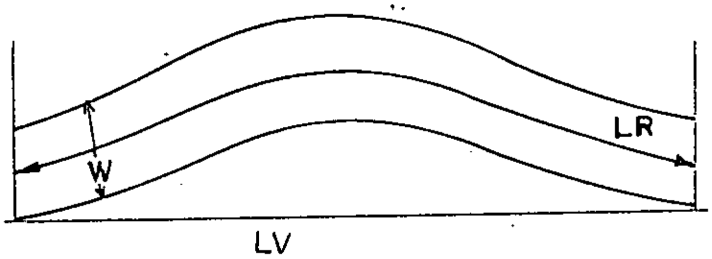
Fig. 1. River channel pattern and typical cross-sections
A. Braided B. Straight C. Meandering
(after Leopold, 1957.)



MB = Width of meander belt.

ML = Meander length (wave length)

[(a) after leopold, 1957]



LR = Length along river bend

LV = Straight length along chord

W = Surface width of channel

[(b) after chitale, 1970]

FIG. 3 DEFINITION SKETCH FOR MEANDERS.

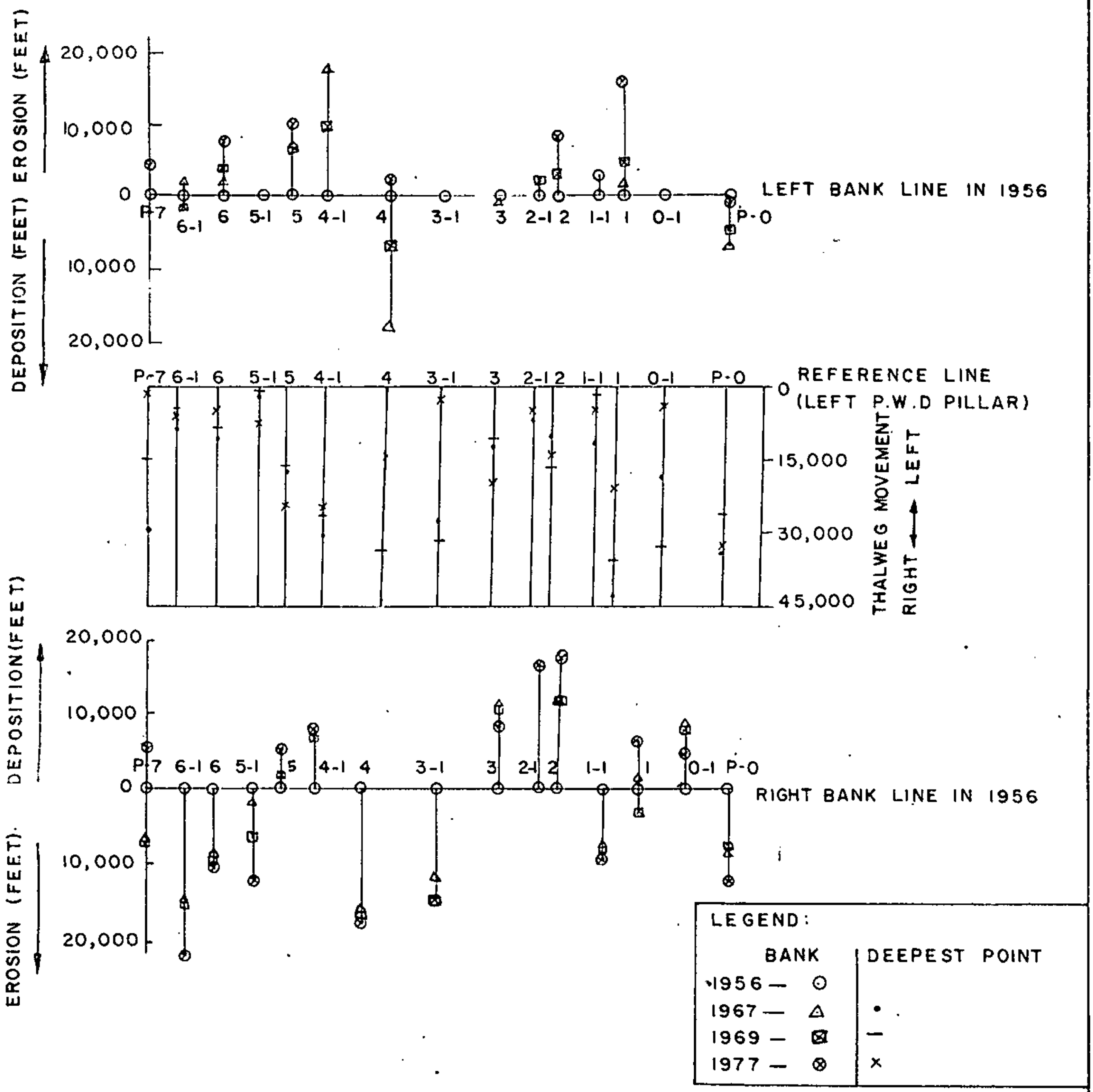


FIG. 6 PRESENTATION OF EROSION & DEPOSITION OF BANKS WITH REFERENCE TO THE BANK LINES OF 1956 & THALWEG MOVEMENT FOR THE YEARS 1967, 1969 & 1977.

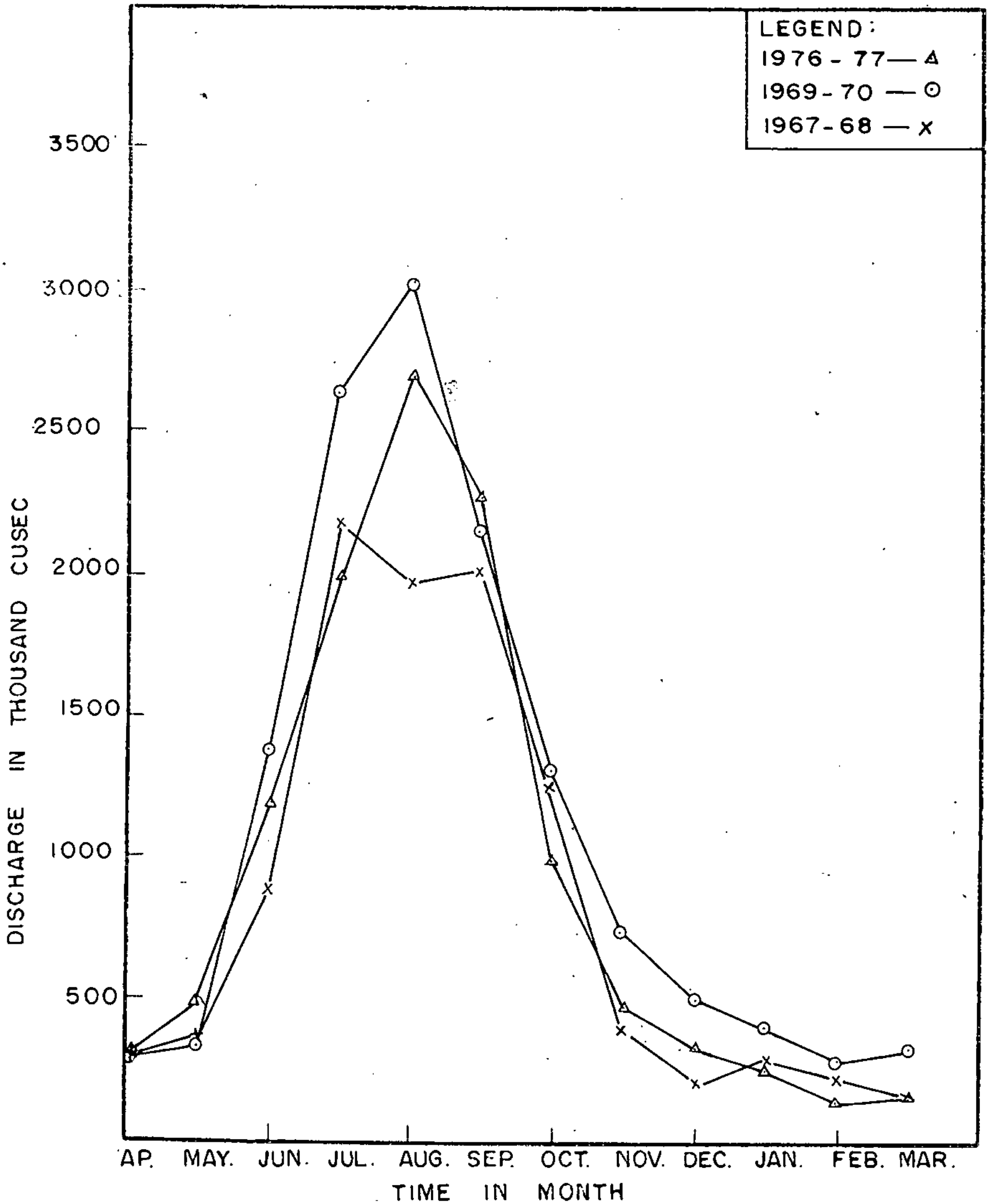


Fig. 7 Discharge hydrograph at Bhayyakul for the years 1967 - 68, 1969 - 70 & 1976 - 77.

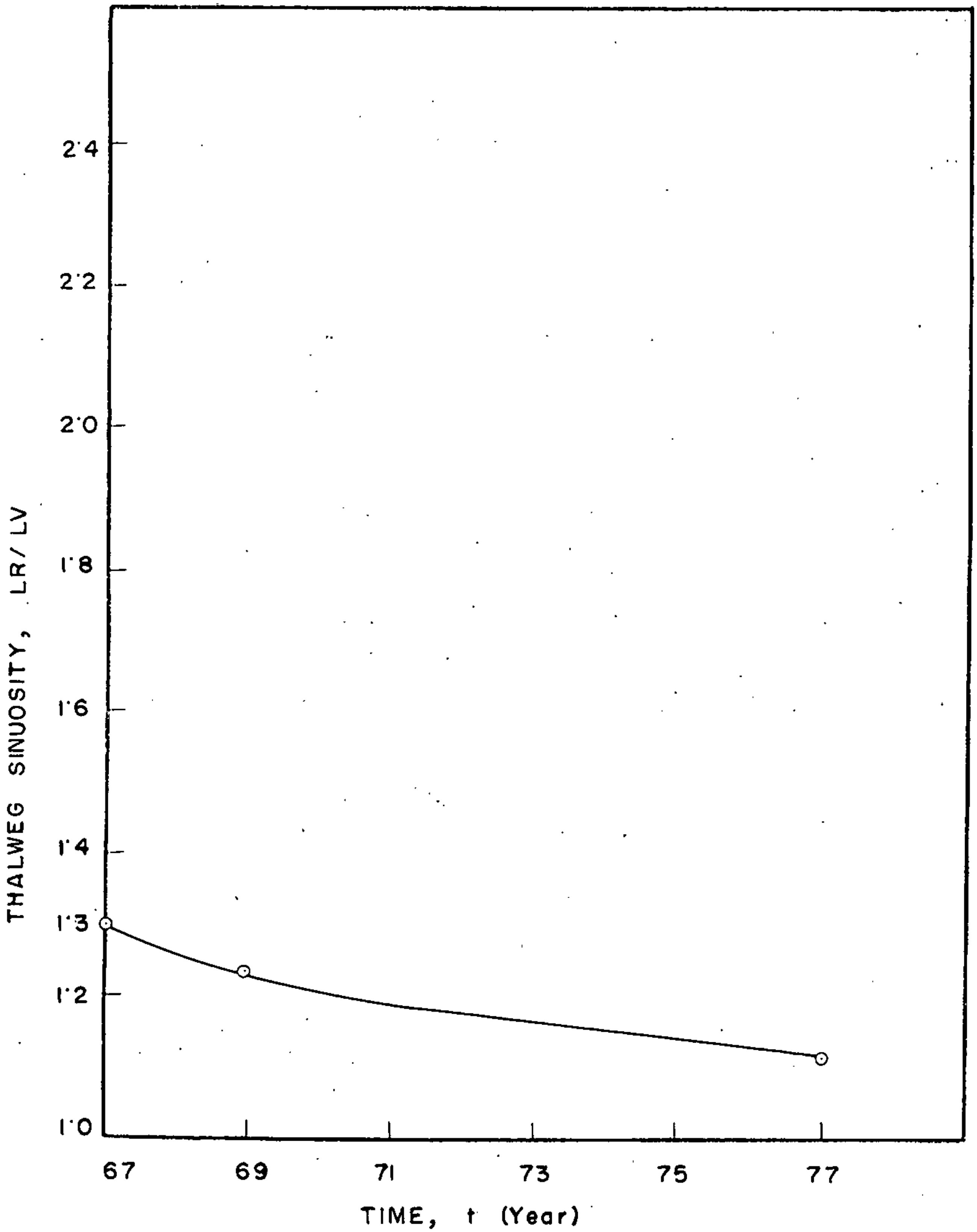


Fig. 8 Relationship between thalweg sinuosity and time.

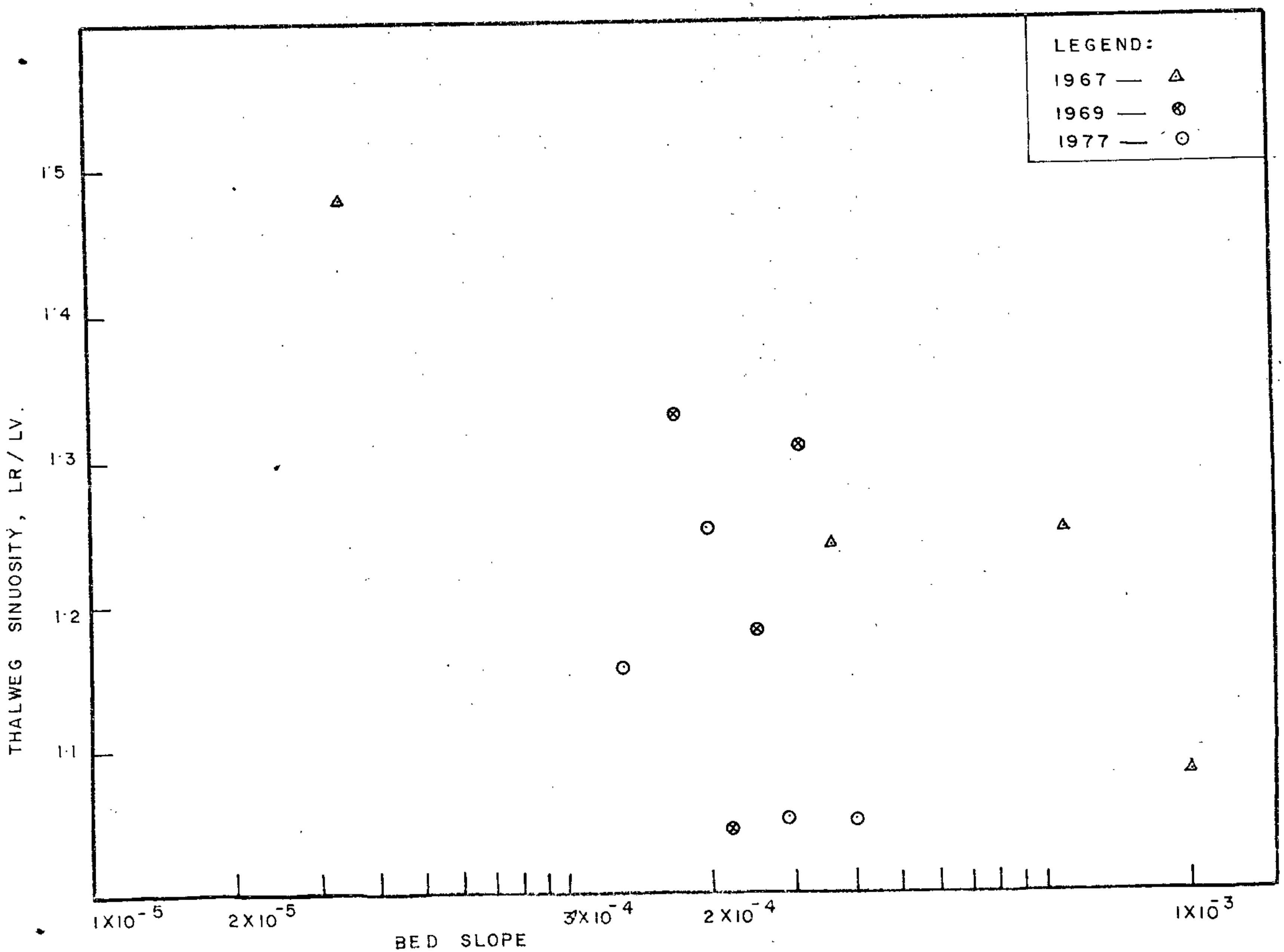


FIG. 9. RELATION BETWEEN THALWEG SINUOSITY AND BED SLOPE FOR THE YEARS 1967, 69 AND 1977.

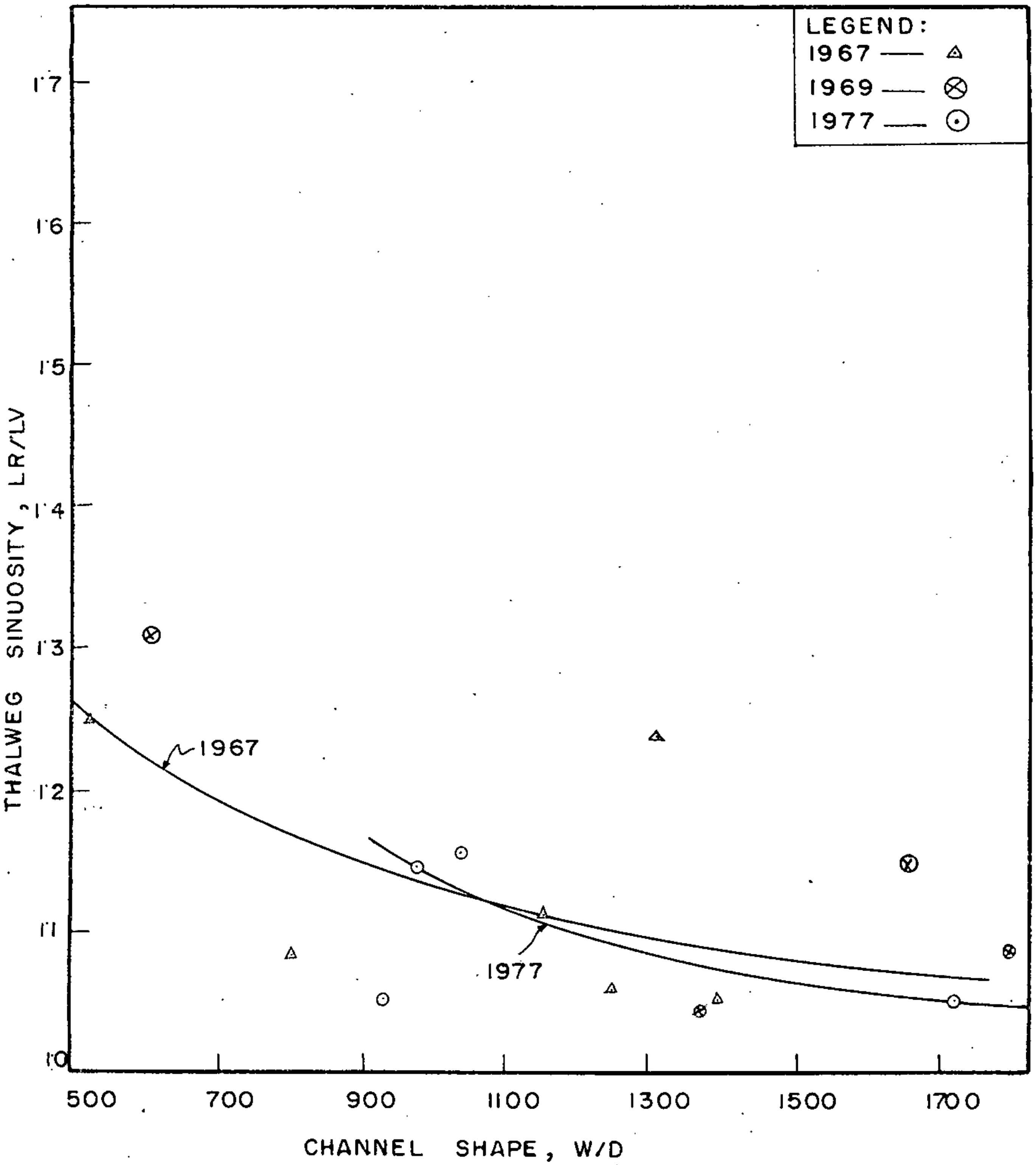


Fig. 10 Relation between thalweg sinuosity and channel shape for the years 1967, 1969 & 1977.

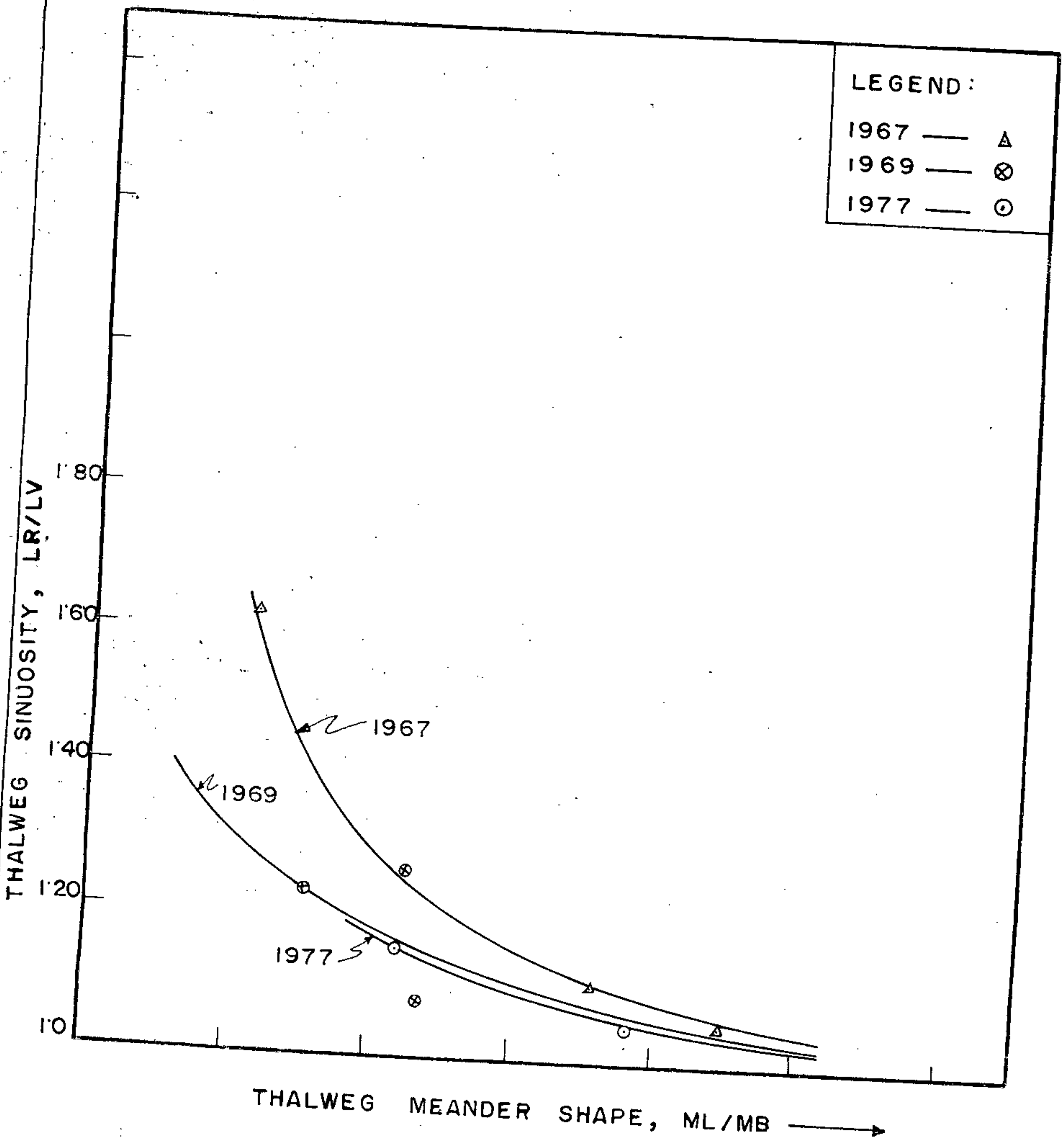


Fig. II Relation between thalweg sinuosity and thalweg meander shape for the years 1967, 1969 & 1977.

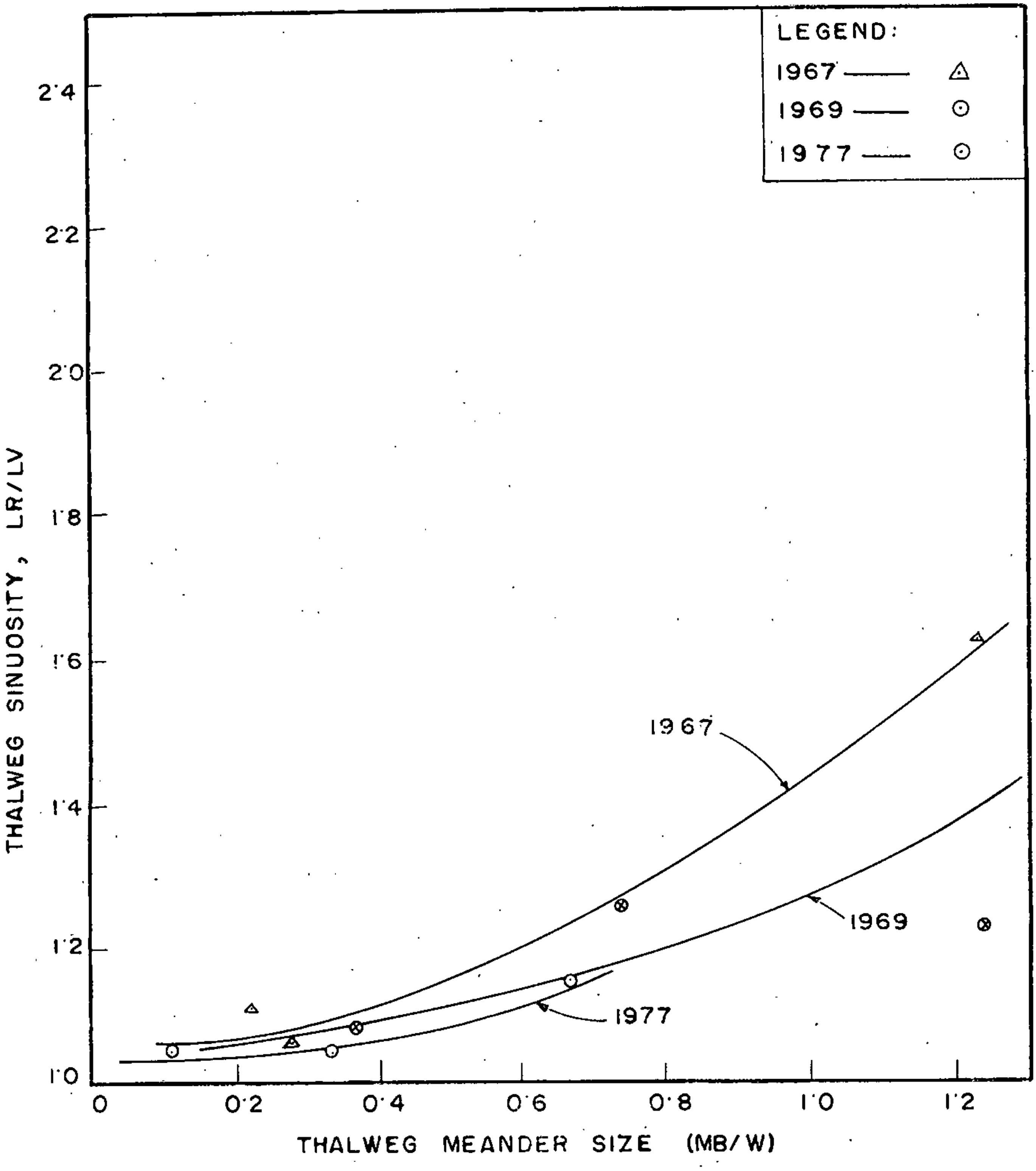


Fig. 12 Relation between thalweg sinuosity and thalweg meander size for the years 1967, 1969 and 1977.

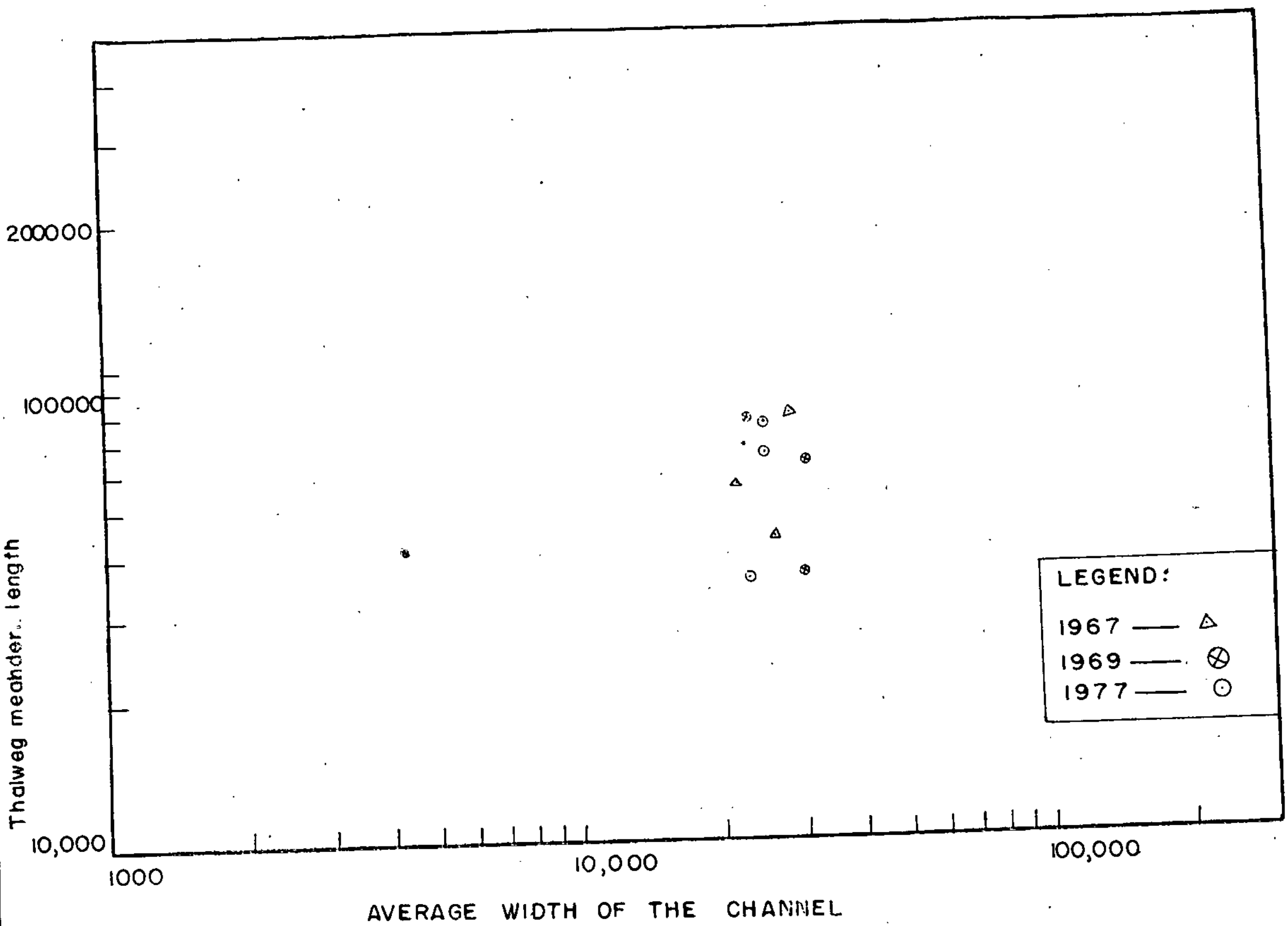


Fig. 13 Relation between thalweg meander length & average width of the channel for the years 1967, 1969 & 1977.

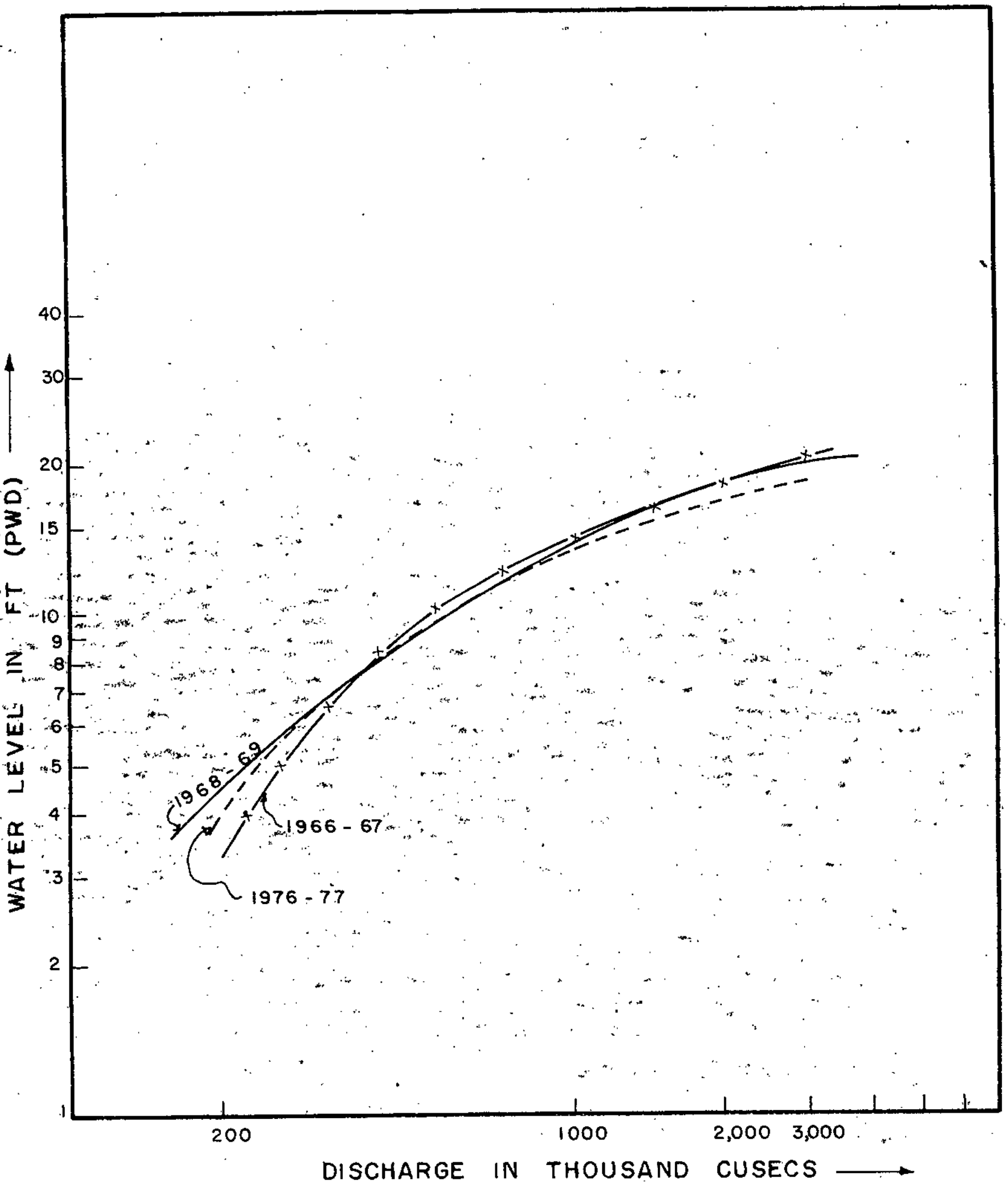


Fig. 24. Stage-discharge curves at Bhagyakul for the years 1966-67, 1968-69 and 1976 - 77.

A P P E N D I X - B

Tables

Table I

Section	Year	Distance of deepest pt from left B.M. pillar ft. ft.	Distance of left bank from left B.M.pillar ft.	Distance of right bank from left B. M. pillar ft.
P-7	1968	9000	5500	30500
G-0-1	1968	22000	700	34800
	1969	8000	500	34800
G-1	1968	11000	1500	25500
	1969	21500	1900	25100
G-1-1	1968	11300	800	14500
	1969	1200	200	13200
	1976	6300	600	100
J-0-1	1968	2400	1200	7400
	1969	1200	1100	7600
J-1	1968	22700	12000	30500
	1969	1200	1100	7600

There are two channels in the river Brahmaputra.

Section	Years	Distince of deepest point from left B.M. pillar		Distance of left bank from left B.M.pillar, ft.	Distance right bank from left B.M.pillar ft.	Distance of left bank from left B.M. pillar ft.	Distance of right bank from left B.M. pillar ft.
		Left channel	Right channel				
J-1	1969	13100'	22800	11300	18000	19200	28500
J-1-1	1968	2800'	18500	2000	4500	12200	20000
	1969	2900'	20500	2100	3900	11800	21700
J-2	1968	20900'	30200	19500	21200	25700	34000
	1969	20200	31400	19200	21200	26000	35200
J-2-1	1968	12200	19500	6100	14000	17400	19900
	1969	8700	18500	5600	14500	17400	20100

Table 2

Section	Year	Elevation of deepest point (P.W.D. datum)	Distance of deepest point from the left B.M. pillar in ft.	Cumulative thalweg length starting from sec.p-7 in ft.	Distance of the left bank from left B.M.pillar in ft.	Distance of the right bank from left B.M.pillar in ft.
	1977	-43.2	2506		1000	18000
P-7	1969	-26.5	13835		5400	31000
	1967	-20.0	29500		3500	30200
	1977	-24.5	6416	16708	3000	41900
P-6-1	1969	-46.90	5480	18713	3700	35200
	1967	-23.5	9000	26320	1500	34000
	1977	-32.50	5848	36758	5300	37000
P-6	1969	-35.0	9792	38096	9300	35800
	1967	-26.0	11000	46060	10900	35000
	1977	-35.5	6450	63492	2500	25200
P-5-1	1969	-10.69	1169	64171	0	18200
	1967	-45.0	2506	68958	700	16200
	1977	-39.7	24563	80200	10400	25700
P-5	1969	-87.26	17077	91563	13200	29800
	1967	-46.5	18500	82645	13000	31500
	1977	-24.3	25566	98579	15800	31800
P-4-1	1969	-28.5	26401	113284	18300	49500
	1967	-14.0	30600	103964	10000	40000
	1977	-21.5	14036	119632	300	38200
P-4	1969	-33.5	35926	141689	9200	37000
	1967	-30.0	27500	126336	20400	36500

Table 2 (Continued)

Section	Years	Elevation of deepest point (P.W.D. datum)	Distance of deepest point from the left B.M.pillar in ft.	Cumulative thalweg length starting from sec. p-7 in ft.	Distance of the left bank from left B.M.pillar in ft.	Distance of the right bank from left B.M.pillar in ft.
	1977	-23.0	4010	148037	1100	31700
P-3-1	1969	-49.0	1114	176777	1100	32000
	1967	-57.5	28000	165026	1300	29300
	1977	-52.0	19650	169758	10200	20500
P-3	1969	-58.0	11465	206852	10000	17500
	1967	-107.65	12500	194768	10300	17000
	1977	-30.5	5581	193150	800	13500
P-2-1	1969	-47.5	5347	225565	900	32000
	1967	-34.0	7000	213192	700	31200
	1977	-22.4	13869	203843	1200	26200
P-2	1969	-47.5	17211	236927	8200	33000
	1967	-42.0	10600	227010	8200	33000
	1977	-28.0	5848	222556	1300	45000
P-1-1	1969	-34.3	2506	259316	2000	44000
	1967	-32.0	11200	245434	2500	43000
	1977	-37.0	21054	239659	800	40400
P-1	1969	-53.7	36427	282708	14500	50900
	1967	-37.0	44600	268464	14700	45500
	1977	-30.7	4946	26998	500	39700
P-0-1	1969	-34.3	33620	308439	500	36500
	1967	-45.0	18000	315050	800	35500
	1977	-21.5	33319	307680	24900	55644
P-0	1969	-53.7	26067	338514	25500	51000
	1967	-33.0	33800	355320	27500	51567

Table 3

		Right Bank			Left Bank		
Section	Year	Cumulative bank lengths (ft.) from p-7	Erosion (ft.)	Deposition (ft.)	Cumulative bank lengths from p-7	Erosion (ft.)	Deposition (ft.)
	1977	-	-	4913	-	4411	-
P-7	1969	-	7888	-	-	-	-
	1967	-	7319	-	-	-	-
	1977	-	22893	-	-	-	201
P-6-1	1969	-	16042	-	-	-	869
	1967	-	14772	-	-	1504	-
	1956	17108	~~17108~~	-	17108	-	-
	1977	-	10895	-	-	7520	-
P-6	1969	-	9625	-	-	3442	-
	1967	-	8823	-	-	2039	-
	1956	35532	~~35532~~	-	38164	-	-
	1977	-	12533	-	-	-	280
P-5-1	1969	-	5681	-	-	-	334
	1967	-	1872	-	-	-	1003
	1956	53956	-	-	60536	-	-
	1977	-	-	5681	-	9525	-
P-5	1969	-	-	1404	-	6684	-
	1967	-	234	-	-	6851	-
	1956	71064	-	-	73038	-	-
	1977	-	-	7185	-	9520	-
P-4-1	1969	-	10661	-	-	9592	-
	1967	-	1003	-	-	17546	-
	1956	87119	-	-	94620	-	-

Table 3 (Continued)

Section	Year	Right Bank: Cumulative bank lengths (ft.) from p-7	Right Bank: Erosion (ft.)	Right Bank: Deposition (ft.)	Left Bank: Cumulative bank lengths from p-7	Left Bank: Erosion (ft.)	Left Bank: Deposition (ft.)
P-4	1977	-	18481	-	-	1938	-
	1969	-	17278	-	-	-	7185
	1967	-	16810	-	-	-	18147
	1956	113702	-	-	128178	-	-
P-3-1	1977	-	14371	-	-	134	-
	1969	-	14772	-	-	201	-
	1967	-	12031	-	-	-	-
	1956	154498	-	-	156736	-	-
P-3	1977	-	-	7921	-	-	401
	1969	-	-	10862	-	-	469
	1967	-	-	11430	-	-	434
	1956	188056	-	-	183056	-	-
P-2-1	1977	-	-	16042	-	2507	-
	1969	-	2674	-	-	2507	-
	1967	-	1671	-	-	2406	-
	1956	211744	-	-	202138	-	-
P-2	1977	-	-	17913	-	8823	-
	1969	-	-	11363	-	2339	-
	1967	-	-	11496	-	2507	-
	1956	222272	-	-	213324	-	-
P-1-1	1977	-	9358	-	-	2339	-
	1969	-	8355	-	-	2005	-
	1967	243986	7352	-	233722	1170	-
	1956	-	-	-	-	-	-

Table 3 (Continued)

		Right Bank			Left Bank		
Section	Years	Cumulative bank lengths (ft.) from p-7	Erosion (ft.)	Deposition (ft.)	Cumulative bank lengths from p-7	Erosion (ft.)	Deposition (ft.)
P-1	1977	-	-	6183	-	15373	-
	1969	-	4010	-	-	5314	-
	1967	-	-	1337	-	1404	-
	1956	262410	-	-	251488	-	-
P-0-1	1977	-	-	4812	-	668	-
	1969	-	-	7687	-	668	-
	1967	-	-	7856	-	501	-
	1956	287414	-	-	276492	-	-
P-[illegible]	1977	-	12700	-	-	-	441
	1969	-	7954	-	-	-	4812
	1967	-	8690	-	-	-	6918
	1956	313734	-	-	306002	-	-

Table 4

Section	Right Bank Rates of Erosion	Right Bank Rates of Deposition	Left Bank Rates of Erosion	Left Bank Rates of Deposition
P - 7	-	234	210	-
6 - 1	1090(Max)	-	-	10
6	519	-	358	-
5 - 1	597	-	-	13
5	-	271	453	-
4 - 1	-	342	453	-
4	800	-	92	-
3 - 1	684	-	06	-
3	-	377	-	19
2 - 1	-	764	119	-
2	-	853(Max)	441(Max)	-
1 - 1	446	-	113	-
P - 1	-	294	720(Max)	-
P-0-1	-	229	3.2	-
P - 0	605	-	-	21

Table 5

Years	Range of sections over which measurements are taken	LR (cm)	LV (cm)	Thalweg sinuosity, =LR/LV	Thalweg length over the range (ft.)	Diff. of elevation (ft.)	Slope (ft/ft)	LR from p-7 to p-0 (cm)	LV from p-7 to p-0 (cm)	LR/LV
	P-7 to P-6	27.94	26.49	1.05	36758	10.7	2.9×10^{-4}			
	P-6 to P-4-1	49.53	42.86	1.15	61821	8.2	1.3×10^{-4}			
1977	P-3 to P-2-1	36.83	32.18	1.14	45113	6.5	1.4×10^{-4}	233.8	208.5	1.12
	P-2 to P-1	22.00	21.00	1.05	35816	14.6	4×10^{-4}			
	P-1 to P-0	50.00	40.00	1.25	61835	15.5	2×10^{-4}			
	P-5 to P-4-1	30.48	46.49	1.15	45113	78.19	1.7×10^{-3}			
1969	P-4-1 to P-3	73.66	56.18	1.31	93569	29.50	3.1×10^{-4}	257.0	208.5	1.23
	P-3-1 to P-2	44.45	41.24	1.07	60151	30.00	5×10^{-4}			
	P-2 to P-1	31.50	23.68	1.33	45782	7.70	1.7×10^{-4}			
	P-7 to P-5	47.80	38.70	1.24	68958	25.0	3.6×10^{-4}			
	P-4 to P-3	52.20	41.80	1.25	68432	77.65	1.1×10^{-3}	271.0	208.5	1.30
1967	P-3 to P-2	21.50	20.00	1.08	32242	65.65	2×10^{-3}			
	P-2 to P-0-1	65.00	43.80	1.48	88040	3.00	3.4×10^{-5}			

Table 6

Years	Range of sections over which measurements are taken	Thalweg sinuosity LR/LV	Average width of the channel, W, ft.	Average depth of channel the river D, ft.	Channel shape, W/D
1977	P-7 to P-6	1.05	24350	26.84	907.22
	P-6 to P-4-1	1.15	23850	23.34	1021.85
	P-3-1 to P-2-1	1.14	21650	22.69	954.16
	P-2 to P-1	1.05	32300	19.03	1697.32
1969	P-7 to P-6	1.04	26050	19.31	1349.04
	P-5 to P-4-1	1.15	24700	14.91	1656.60
	P-4-1 to P-3	1.31	19350	31.96	605.44
	P-3 to P-2	1.07	27850	15.25	1826.22
	P-7 to P-5-1	1.24	24175	18.48	1308.00
1967	P-6-1 to P-5-1	1.05	24000	17.50	1371.00
	P-5-1 to P-4-1	1.06	21333	17.38	1227.00
	P-4 to P-3	1.25	16933	33.29	508.00
	P-3 to P-2	1.08	20666	26.46	781.00
	P-3 to P-1-1	1.11	25625	22.41	1143,00

Table 7

Years	Range of sections over which measurements are taken	Thalweg sinuosity LR/LV	Thalweg meander length, ML, (Ft.)	Thalweg meander width, MB (ft.)	Average width of the channel (W) (ft.)	Thalweg meander shape ML/MB	Thalweg meander size MB/W
1977	P-7 to P-6	1.05	47508	6975	21451	6.80	0.33
	P-6-1 to P-4-1	1.15	73696	16845	25267	4.37	0.67
	P-2 to P-1	1.05	35786	2630	23012	13.60	0.11
1969	P-5-1 to P-3-1	1.23	85540	28162	22767	3.04	1.24
	P-3-1 to P-2-1	1.08	53430	11186	31387	4.78	0.36
	P-2 to P-0	1.26	84224	18424	25004	4.57	0.74
	P-6 to P-4-1	1.06	54482	6054	22000	9.0	0.28
	P-3 to P-1-1	1.11	42112	5922	26660	7.1	0.22
	P-2 to P-0	1.62	77644	34874	28350	2.22	1.23