STUDY ON HYDRAULIC GEOMETRY OF THE GANGES

Submitted by

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In partial fulfillment of the requirements for the degree of Master of Engineering (Water Resources)

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May 1992

CERTIFICATE

This is to certify that this work has been done by me and neither this report nor any part thereof has been submitted elsewhere for the award of any degree or diploma.

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May 30, 1992

We hereby recommend that the project work prepared

by

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entitled "STUDY ON HYDRAULIC GEOMETRY FOR THE GANGES" be accepted as fulfilling this part of the requirements for the degree of Master of Engineering (Water Resources)

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ABSTRACT

A study on hydraulic geometry was conducted for the Ganges from Indo-Bangladesh Boarder to Aricha confluence covering a reach-length of about 125 km. In this connection cross-sectional data, discharge and water level data and rating curves were collected and analyzed for various years.

Analysis of cross-sectional data revealed that cross-sectional area and width varied very widely and randomly. The analysis also showed that cross-sectional area at the upper portion of the study reach were lower and higher in the lower reach in the year 1988-89 compared to 1967-68 and 1975-76. Linear relationships between width, area and hydraulic radius were developed. These relationships indicated that cross-sectional area increases but hydraulic radius decreases with the increase of width.

At-a-station hydraulic geometry was studied for the Ganges at Hardinge Bridge during the period 1970 to 1990. Correlations were developed between width, depth and velocity with discharge. From the developed relationships it may be observed that discharge was well correlated with velocity, width and depth. The exponents for width, depth and velocity were 0.172, 0.246 and 0.575 respectively .

Area-elevation curves were plotted for nine sections in the study reach. It was found that the area-elevation curves rise sharpely with high gradients near the channel bottom and bocome flatter with increase of depth towards top, which indicates faster increase of width in the upper elevation.The area-elevation curves gave a direct indication of aggradation or degradation at various sections of the study reach.

Thalweg for the year 1967-68, 1975-76 and 1988-89 were plotted for the study reach. It was found that in most of the sections thalweg of 1988-89 were shallower than other years. This gives an indication that in recent times more aggradation has taken place. It was also observed that from section G-1-1 to G-8,thalweg showed a leftward (N-E) movement.

Mean bed level was plotted in the study reach for the year 1967-68 and 1988-89. It was observed that in almost all the sections mean bed level rises except at G-6 and G-16 between the period 1967-68 to 1988-89. Maximum rise in mean bed level was about 2.2m at G-11 during 21 years.

Specific gauge analysis was carried out for the year 1968-69 to 1990-91. The analysis however did not show any significant trend of rise in water level especially at higher discharges. But at lower discharges rising a trend in the water level was obtained. It was also interesting to note that the trend of curve followed a sinuous form, which is the usual characteristics of an alluvial river.

ACKNOWLEDGEMENT

The author expresses sinceremost gratitude to Dr. Monowar Hossain, Supervisor, for his constant moral support, advice, guidence and understanding throughout this study. Dr. Hossain took personal interest in all the major and minor details of this research work and offered a helping hand whenever needed.

The author also wishes to express his sincere thanks to Dr. M.K. Alam, Professor and Head of the Department of Water Resources Engineering, Dr. Ainun Nishat, Professsor and Dr. Abdul Matin, Assistant Professor of the Department of Water Resources Engineering who were member of the Board of Examiners for their helpfull comments.

Thanks are also due to the organizations of Institute of Flood Control and Drainage Research (IFCDR), Bangladesh Water Development Board, and Master Plan Organization (MPO) for providing all the necessary data.

Sincere appreciations are expressed to Mr. A. K. Azad, Mr. Abdul Mannan Khan, Mr. M. Mofser Ali and Mr. Bahauddin Bhuiyan for their help and cooperation to prepare this project.

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NOTATIONS AND ABBREVIATIONS

A	cross-sectional area of the stream
a	constant
b	exponent
c	constant
D	average flow depth
f	exponent
f_s	seepage force in the bed of the stream
g	acceleration due to gravity
k	constant
m	exponent
Q	water discharge
R	hydraulic radius of the cross-section
Rc	radious of curvature of bend
r	coefficient of correlation
S	energy slope of the stream
S_c	shape factor of the cross-section of the stream
S_p	shape factor of the particles
s_R	shape factor of the reach of the stream
V	average flow velocity
W	channel width
γ	specific weight of water
ρ	density of water sediment mixture
ρ_s	density of sediment particles
ν	kinematic viscosity
δ	means of size distribution of bed materials

BWDB	Bangladesh Water Development Board
EPWAPDA	East Pakistan Water and Power Development Authority
MPO	Master Plan Organization

CHAPTER-1

INTRODUCTION

1.1 GENERAL

Rivers have played a dominant role in the history of civilization of various country of the world. The most ancient trade and commerce had developed through the routes of water ways and most prestigious cities developed along its banks. Bangladesh is a land of rivers interlaced by numerous tributaries and distributaries of the three great river systems: the Ganges-Padma, the Brahmaputra-Jamuna and the Meghna. The Ganges is an international river with its basin spreading over China, Nepal, India and Bangladesh.

The Ganges carries massive discharge and huge sediment load. In the lean flow periods there is a tendency of silting up of the bed. As a result there are changes in cross-section, width depth, slope, thalweg etc. of the river. These alltogether cause significant change to geomorphic and other hydraulic parameters of the rivers. Thus a study on the hydraulic geometry is extremely important in connection with the river bank stabilization, navigation, flood control and also for the development of any water resources project. Hence in this study an attempt was made to investigate changes of cross-sectional area, width, depth, discharge etc. of the Ganges from Indo-

Bangladesh Boarder to Aricha confluence. The study reach was about 125 km and is shown in Figure 1.

1.2 OBJECTIVE

The objectives of the study are:

i. To study the variation of hydraulic geometry of the Ganges in terms of area, width, depth and discharge and develop correlations.

ii. To study stage discharge curves at Hardinge Bridge for all available years from 1967-68 to 1990-91 and test the trend at the selected discharge levels.

CHAPTER-2

REVIEW OF LITERATURE

2.1 THE GANGES SYSTEM

The source of the Ganges is at Gangotri in the Uttar Khashi district of india and is located at an elevation of 7010 metre. The Ganges is one of the major and most important river of Bangladesh. The Ganges is not known by this name either at the begining or at the end. In India it is mostly known as the Ganges and in Bangladesh the river is known as the Padma. But in many literature it is called as the Ganges upto its confluence with the Brahmaputra (Jamuna) near Aricha and from there upto its confluence with the Meghna is known as the Padma.

After traversing through seven states of India (Uttar Pradesh, Himachal, Punjab and Hariana, Rajastan, Madhya Pradesh, Bihar and West Bengal) the Ganges enters Bangladesh at Lalgola, 18 km downstream of the Farakka Barrage. Then the river travels along the common border of Indo-Bangladesh for a distance of about 100 km to Jalangighat and then for a further distance of 125 km from Jalangighat to Aricha where it meets the Brahmaputra (Jamuna). The river known as the Padma travels further downstream to meet the Meghna near Chandpur and the combined discharge finally fall into the Bay of Bengal through a number of estuary channels.

The total length of the Ganges from its source to outfall into the sea measured along the Hooghly is about 2525 km and along the Padma-Meghna is about 2650 km (Rao, 1979). The drainage area of the Ganges upto Goalundo confluence is approximately 977044 sq.km. of which about 7 percent (67395 sq.km) lies above the Goalundo confluence and bounded by the Bhagirathi-Hoogly on the west and the Ganges-Meghna in the east.The Ganges river basin is shown in fig.2.1

2.2 PREVIOUS STUDIES

Except the recent Ganges-Kobadak(G-K) Project (EPWAPDA 1960) and the Hardinge Bridge (Gales 1917-18 after Inglis 1949), no significant water resources development project or construction have been under taken on the Ganges within Bangladesh. However, innumerous studies on the Ganges relating hydrology, morphology and sediment transport have been undertaken and some of these studies are described in the following section.

2.2.1 Hydrologic Study

Bangladesh Water Development Board (BWDB) normally collects hydrologic data and they published it in different reports like 'water level and discharge observation records', 'Water level records' and 'Gauge and discharge observation' under water supply Papers. More over, the hydrological year book of Bangladesh Water Development Board contain hydrological data including rainfall and evaporation.

Some of the available data was analyzed during the feasibility study and planning and designing of the major projects on the Ganges such as Ganges-Kobadak Project; survey of Faridpur Barisal scheme and Ganges Barrage, 1963; Ganges Barrage Design Project; Vol. I and II, 1970, and so on. Moreover, the consultant of EPWAPDA (i.e. IECO 1964) has compiled the hydrological data for master plan. Recently Master Plan Organization (MPO, 1984) and its consultants have done some studies while evaluating surface water availability of Bangladesh. Alam and Ahmed (1980) has conducted flood frequency analysis for the Ganges using mean monthly and annual maximum discharge at Hardinge Bridge for the years 1935 to 1959. Hossain(1987) had studied the maximum and minimum discharges of the Ganges at Hardinge Bridge before and after the construction of the Farraka barrage in India at 18km upstream of Indo-Bangladesh boarder. He conducted his study taking the data from 1956 to 1986. He found that average peak discharge had increased by about 12% compared to the average peak flow before 1976. On the other hand the average of the annual lowest discharge had decreased by about 60% compared to the average annual lowest flow after 1976.

2.2.2 Morphological studies

BWDB, morphology division collects morphological data. Historical maps for banklines of the Ganges was studied by the Water Investigation Directorate of BWDB for the year 1780, 1855 and 1868 for this reach (BWDB 1978).

Dad (1977) studied the course shifting pattern of the reach of the Ganges from the point of its entry into Bangladesh upto Goalundo. According to his investigation, study reach showed predominantly irregular and flat meandering pattern. The simusity of the river is getting flatter and the river has a tendency to develop brading in some of its meandering reaches. He also stated that the shifting of bank line is erratic and gradual and it is due to the frequent shifting of thalweg in different years. The shifting of thalweg is due to the movement of sand bars, mid-channel islands and aggradation.

Rahman (1978) had studied 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 for the river Padma from Ganges-Brahmaputra confluence to Padma-Meghna confluence. He stated that the frequent wandering of the thalweg from position to another is due to the great magnitude of discharge during flood and movement of sand bars and mid-channel islands. He also stated that the shifting of the banklines is erratic and due to aggradation of the channel bed and the movement of the thalweg. He found that 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.

Hossain (1989) studied the erosion-deposition pattern, shifting characteristics and rate of change of cross-section and thalweg movement, including sediment transport of the Ganges.

Hossain stated that bankline migration are very erratic in nature and varies very widely from bend to bend as well as from year to year. The analysis also show that the Ganges is becoming more sinuous in the upper reaches and less sinuous tending to straight-braided pattern in the lower reaches. The study reveals that there is a trend of rise in mean bed level in the upper reach and fall in the lower reach and net volume of material deposited during 1967-68 to 1979-80 within the study reach was about 4.26×10^{8} m^{3}. The short term migration of the bends were erractic in nature and varied very widely from about 20 m per year to as much as 645 m per year which corresponds to a minimum shift of 0.25 km at one bend and a maximum shift of 9 km at other bend during 1973 to 1897 period. The trend of the migration rate with Rc/W for the Ganges showed a general agreement with the trend of bend migration found in the case of another river. The mean gradient of the river bed had increased from 5.18 cm/km in 1967-68 to 7.14 cm/km in 1979-80 within the study reach. He also developed some meander relationships.

2.2.3 Sediment Transport Study

Bari (1978) has analysed the sediment data of the Ganges river at kalikapur for the year 1970, 1972 and 1973. He concluded that colby and Engelund-Hansen formula yield a result which may be comparable with the measured. He also developed rating curves for the Ganges at this station.

Alam and Ahmed (1980) have analysed the sediment data at kalikapur for the year from 1969 to 1972. They also compared the measured sediment flow with those predicted by the various sediment transport equation and Colby's equation was found to be the best.

BWDB had analysed the suspended sediment data of the Ganges at Goalundo utilizing the data of 1966 to 1969 (BWDB, 1972). Accoriding their analysis the total annual suspended load was found to vary from 421 million tons to about 675 million tons with a mean value of 451 million tons. The average daily minimum and maximum concentration was reported to be about 67 ppm and 2344 ppm respectively. According to coleman (1969) the suspended sediment load varied from 257 million tons to about 735 million tons per year estimated on the basis of data from 1958 to 1962. Khan and Matin (1986) found that the Ganges carries about 30 percent of the suspended load as sand load, whereas, 90 percent of the suspended load of the Brahmaputra is sand. Hossain (1989) studied that the annual suspended flow through the Ganges which may be taken to vary from 181 million tons to 304 million tons. The total annual sediment load was found to vary from 220 million tons to 368 million tons. Hossain (1991) also found that the total annual sediment flow of the Ganges at Hardinge Bridge was found to vary between 350 to 600 million tons. The highest and lowest daily sediment flow was found to be 10 million tons and 9000 tons respectively.

2.2.4 Hydraulic geometry study

The development of quantitative relationships for river geometry has been attempted by numerous investigators, notably by Leopold and Maddock, Leopold and Wolman, Blench, Langbein and Engelund and Hansen (after Lane, 1957). Regime formulas for rivers in the most general form were given as functions of the discharge as follows:

$$W = aQ^b \; ; \; D = cQ^f \; ; \; V = kQ^m \; ;$$

in which W = channel width ; D = mean channel depth ; V = mean flow velocity ; Q = discharge a, c, k are constants ; and b, f, m are exponents. From the continuity consideration $b+f+m = 1$. Coefficients and exponents were found to vary depending on the river data used; no unique relationship has been determined. For an alluvial channel, the necessary and sufficient condition for equilibrium is when the stream power is a minimum. Hence, an alluvial channel with given water discharges and sediment flow tends to establish its width, depth and slope such that the stream power is a minimum.

Stream channels vary in form; the mean form has been described in literature under the term "hydraulic geometry". This emperically described mean must fulfil the necessary hydraulic laws but in addition, a river channel tends toward equal distribution among velocity, depth, width and slope in accomodating a change in stream power (Langbein, 1964). These two principles are explained by the use of three examples. The first example is that of the response to changes in flow over a sand bed between the fixed walls of a circulating flume at constant slope. The flow has one degree of freedom the liberty to adjust its roughness. The second example is that of the accomodation of a river channel at a given cross-section to changing discharge. Here, too, there is only one degree of freedom. The third example is that of a river in a humid region with liberty to adjust its profile, velocities, depths and widths, to accomodate the downstream increase in discharge. There are three degrees of freedom. Langbein (1964) used the techniques introduced by Leopold and Maddock and to relate channel properties to bankfull discharge, Q in the following manner: velocity Q^m ; depth Q^f ; width Q^b The results of 'at-a-station' hydraulic geometry indicates that the velocity should increase as the 0.35 power of the discharge, depth as the 0.42 power, and width as the 0.23 power. For downstream hydraulic geometry considering bankfull or mean flood discharge, the exponents are: b = 0.53; f = 0.37 and m = 0.10.

In different geographical regions, Leopold and others (1964) found that the exponent in the hydraulic geometry relations varied with regions and they gave the mean values of indices shown in the table 5.6 (after Shen, 1971).

Nixon (1959) correlated the width, depth, area and velocity of non-tidal rivers in England and Wales with their bankfull discharge and obtained:

$$W = 2.67 \quad Q^{0.5}$$

$$D = 0.545 \quad Q^{0.333}$$

$$V = 1.112 \quad Q^{0.16}$$

Parker (1979) studied the downstream hydraulic geometry taking field data of GS-type streams. He obtained b = 0.50 ; f = 0.42 and m = 0.085.

At-a-station flow geometry reflects the general cross-sectional shape, which is it slelf dependent on material properties (Richards 1982). In homogeneous non-cohessive sand, a broadly parabolic shape occurs with concave banks steepening to the angle of repose at bankful water level; adjustment of these mobile sediments occurs in each significant flood. The resulting exponent set approximates to b = f = m = 0.33. Examples in cohessionless sediments have been described from semiarid (Leopold and Miller, 1956), humid tropical (Lewis, 1969) and proglacial (Fahnestock, 1963) environments. Stable cohessive silty bank sediments sustain rectangular or trapezoidal sections with low width exponent (b = 0.05; Wolman, 1955) and f and m exponents dependent on the roughness and registance to scour of the bed material. The velocity exponent is high when roughness decreases rapidly with increasing discharge, which is characteristics of straight cobble bed reaches with considerable skin registance (Knighton 1975 after Richards 1982). Carlston (1969) studied downstream hydraulic geometry in Mid-West American rivers and amended the exponents to b = 0.46 ; f = 0.38 and m = 0.16 after a regression analysis. The more rapid downstream increase of width compared to that of depth implies an adjustment of width-depth ratio, and hence a scale-related change in channel shape, with large rivers being slightly wider relative to their depth than small streams (Carlston 1969 after Richards 1982).

Petts (1983) studied downstream hydraulic geometry of the river Hodder, UK and the relationships obtained were as follows:

$$W = 0.284\ Q^{0.55}\ ;\ D = -\ 0.491\ Q^{0.34}\ \text{and}\ V = 0.207\ Q^{0.11}$$

Here it can be seen that velocity infact changes very little along the river as demonstrated by a low exponent of 0.11, and that the increase of channel capacity downstream is primarily associated with an increase of channel width as shown by relatively large exponent of 0.55.

Goudie (1985) pointed out that at-a-station flow geometry varies between rectangular sections with steep cohessive banks in humid areas, and parabolic sections in sandy sediments in semi-arid regions. In the former, $b = 0.05$; $f = 0.45$ and $m = 0.50$, and in the latter, $b = f = m = 0.33$. Downstream the adjustment of width and depth accomodates more of the increase in discharge, and $b = 0.50$; $f = 0.40$ and $m = 0.1$ (Richards 1982 after Goudie 1985). Downstream exponents vary according to the trends in roughness and long-profile slope, but their general similarity reflects the tendency of all rivers to create forms which allow equal dissipation of energy and minimize total work.

Myers (1991) studied the influence of Geometry on discharge capacity of open channels in the laboratory. He made the following conclusions:

a) The cross-sectional shape of an open channel influences its discharge capacity because of the occurence of secondary circulation.

b) A wide rectangular section has been shown to carry as much as 80% less than a narrow channel, and as much as 25% less than a compound section of the overall width, at the same cross-sectional area in each case.

c) Friction factors in wide rectangular sections are as much as 45% greater than narrow sections, and as much as 25% greater than friction factors in compound sections of the same overall width, at the same cross-sectional area in each case.

d) These findings show the dangers of neglecting shape effects in open channels and underline the need for a systematic investigation of the influence of cross-sectional shape on discharge capacity of open channels.

CHAPTER-3

DERIVATION OF NON-DIMENSIONAL PARAMETER FOR GEOMETRY ANALYSIS

3.1 FACTORS INFLUENCING RIVER MORPHOLOGY

The factors that govern the geometry and roughness of an alluvial river are numerous and inter-related. Their nature is such that, it is not possible to isolate and study the role of an individual variable. Thus, if one attempts to evaluate the effect of increasing channel depth on average velocity, additional related variables respond to changing depth, similarly, not only will the velocity respond to 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 study of the machanics of flow in alluvial channels and the response of channel geometry has been the subject of study by many investigators at various time.

There are several variables which influence the geometry of alluvial rivers. Some of the most important variables are (Simon 1971)

$$V, D, S, \rho, \mu, g, d, \sigma, \rho_s, S_p, S_R, S_c, f_s, C_T$$

where

V = velocity

D = depth

S = slope of energy grade line

ρ = density of water-sediment mixture

μ = apparent dynamic viscosity of the water sediment mixture

g = acceleration due to gravity

d = grain size of the bed materials

σ = measure of size distribution of bed materials

ρ_s = density of sediment

S_p = shape factor of the particles

S_R = shape factor of the reach of stream

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

f_s = seepage force in the bed of the stream

C_T = concentration of the bed material discharge.

The role of the variables on resistance and bedform have been discussed by Simons and Richardson (1962). Their importance on the geometry has also been partially explained by Simons (1971).

3.2 NON-DIMENSIONALIZATION OF VARIABLES

Non-dimensional analysis is a process whereby the variables pertinent to a physical problem are systematically organized into dimensionless groups. Such organization effectively reduce the number of unknown quantities and generalize a problem in a way that eliminates the need for specifying any particular system of units. Since so many factors influence the geometry of alluvial rivers, these factors are extremely difficult to incorporate into any mathematical formulations, the analysis are necessarily idealized. Thus the study for alluvial stream is potentially dependent on extensive use of different non-dimensional parameters originating from theoritical analysis and choosing the combinations which yield acceptable results. That is why the non-dimensional parameters of the dominating variables for alluvial rivers have been used in the present study.

The variables that govern the geometry of the alluvial channel can be written functionally as follows:

$$\phi(V, D, S, \rho, \mu, g, d, \delta, \rho_s, S_p, S_R, S_c, f_s, C_T) = 0 \qquad (3.4)$$

Applying method of dimensional analysis to equation (3.4) and the non-dimensional parameters obtained thus can be written functionally as follows:

$$\phi\left(VD/\nu, V/(gD)^{1/2}, d/D, fs/(VD)^2, S, \delta, \frac{\rho_s}{\rho}, s_p, S_R, S_c, C_T\right) = 0 \qquad (3.5)$$

In equation (3.4) if V be replaced by Q, the discharge, and those variable which practically govern the alluvial river geometry are considered, then, the resulting functional equation is,

$$\phi(Q, B, D, d, S, g, \nu) = 0 \qquad (3.6)$$

Where, B is the width of the river and ν is the ratio of μ/ρ, the kinematic viscosity. Application of dimensional analysis to equation (3.6) yield,

$$(D/d,\ D/B,\ S,\ [Q^{2/5}/(Sg)^{1/5}]/D,\ D/[\nu^{2/3}/(Sg)^{1/3}],\ (Q/\nu)/[\nu^{2/3}/(Sg)^{1/3}]$$

These are the list of non-dimensional parameters which are important in the study of alluvial river characteristics. In the present study shape factor (W/D), Froude number $V/(gD)^{1/2}$ and discharge parameter $[Q^{2/5}/(sg)^{1/5}]/D$ are chossen . Correlation among these three non-dimensional parameter will be discussed in the subsequent articles.

CHAPTER-4

DATA COLLECTION AND TECHNIQUE OF ANALYSIS

4.1 DATA COLLECTION

Data collected for the present study were cross-sectional map, rating curve, discharge and water level and observed discharge data. Cross-sectional data for the year 1967-68 and 1975-76 was collected from IFCDR, BUET and for the year 1988-89 from SWMC, MPO, Dhaka. Rating curve, discharge and water level data was collected for the year 1967-68 to 1990-91 from the Directorate of Hydrology, BWDB, Dhaka. Observed discharge data was also collected for the year 1969 to 1990 from the Directorate of Hydrology, BWDB, Dhaka.

4.2 Data analysis

In the present study nine number of cross-sections were selected out of eighteen number cross-sections of the Ganges for the years 1967-68, 1975-76 and 1988-89. All the X and Y co-ordinate obtained from each section was entered in the MIKE11 Package Program. Then cross-sectional area, hydraulic radius and width of the section was computed for different elevation using MIKE11. From these processed data relationships were developed between cross-sectional area and width, width and hydraulic radius for the year 1967-68, 1975-76 and 1988-89.At-a-station hydraulic geometry was studied for the station at Hardinge Bridge taking the data of 1970 to 1990. Area elevation relationships were also developed for the year 1967-68 and 1988-89, which will be discussed latter. Non-dimensional analysis for hydraulic and geometric parameter were done for the year 1970 to 1990. For the computation of average depth, the flow area was divided by the water width. Average slope of the river was taken to be 1:25000 and acceleration due to gravity was taken to be 9.81 m/sec^2. Non-dimensional parameter selected were shape factor W/D, Froude number $V/(gD)^{1/2}$ and discharge parameter $Q^{2/5}/[(sg)^{1/5}]/D$ and relationships were established between these parameter. It is to be noted here that all the parameter was calculated for each hydrological year covering lean flow period to peak flow period. Regression analysis was developed between W/D and $V/(gD)^{1/2}$, W/D and $Q^{2/5}/[(sg)^{1/5}]/D$ and $V/(gD)^{1/2}$ and $Q^{2/5}/[(sg)^{1/5}]/D$.

Mean bed level (MBL) was computed for the selected sections for the year 1967-68 to 1988-89 to determine the extent of change of mean bed level for the respective section over the 21 years period. The mean bed level of an equivalent rectangular cross-section having width and area equal to the width and area respectively of that particular section were computed such that the net erosion below and deposition above this level remain unchanged for a hydrological year. This level was measured from a fixed reference line at each section. This procedure is correct when the channel is wide, i.e., the width depth ratio is greater than 20 and for the case of the Ganges for the selected year the value of width-depth ratio was much higher.

Stage-discharge curves were analysed for the station at Hardinge Bridge from 1968-69 to 1990-91 and for discharge levels of 5000, 10000, 20000, 35000 and 50000 m^3/s.The trend of water level change was studied from these figures.

CHAPTER-5

RESULTS AND DISCUSSION

5.1 Variation of cross-section

All the cross-sections were plotted in a same scale and for each section it was plotted in one figure for the selected years to visualize the variation of cross-sectional shape, width, thalweg and its movement shown in the figure from 5.2 to 5.10. Cross-sectional area in different years for different sections were plotted and shown in figure 5.1. From the figure it was evident that cross-sectional area varies widely and randomly for each section as well as in different sections of the reach. At section G-6 and G-3, the value of cross-sectional area was found about twice and half for the year 1988-89 in comparison to 1967-68 and 1975-76 respectively. This value was found to vary between 18045 to 45865 square meter for the selected sections. G-16 was the widest (10345m) section and G-4 was the narrowest (3506) section observed in the year 1988-89 and 1967-68 respectively. It was also observed that the value of cross-sectional area in the upper reaches at G-18, G-11, G-9 & G-8, were lower and in the lower reaches at G-4 & G-6, were higher for the year 1988-89 than that of the year 1967-68 & 1975-76. This gives an indication that aggradation in the upper reaches and degradation in the lower reaches had been taken place. An exceptional deepest section was found at section G-16 in 1967-68. It was about 38 metre deep section. Variation of cross-sectional area, width and hydraulic radius in different years was shown in the table 5.1

5.2 Relationship between area and width

From the processed data relationships were developed between cross-sectional area (A) and width (w) for the year 1967-68, 75-76, 88-89 . Plotting of data of area and width for the year 1967-68, 75-76 and 88-89 were shown in figs. 5.12, 5.13 and 5.14 respectively. Best fit lines were drawn for these data. From the figures it was observed that width increases with the increase of area. The value of coefficient of corelation was found to vary between 0.70 to 0.80. Fig.5.15 shows the correlation between width and area considering all the data. A regression equation was developed for this case also. This was as follows:

$$W = 1080 + 0.185\ A, \quad r = 0.70$$

where 'W' is the width of the river and 'A' is the cross-sectional area of the river,'r' coefficient of correlation.It is aparent from the plot that area is well correlated with width for the Ganges in the study reach.

5.3 Relationship between width and hydraulic radius

Relationships were established between width and hydraulic radius of the Ganges for the year 1967-68, 75-76, 88-89 and were shown in figs.5.16, 5.17 and 5.18 respectively. From the linear relationship developed in each case, it was observed that hydraulic radius decreases with the increase of width of the river. Relationship was also developed taking three years data (1967-68, 75-76, 88-89) as shown in fig.5.19 and the form of the equation was found similar to that of the individual year but with different exponent and coefficients. The equation was as follows:

$$R = 9.58 - 0.00038\ W\ ;\ r = -\ 0.61$$

Where, 'R' is the hydraulic radius,
It is interesting to note that the cross-sectional area increases but hydraulic radius decreases with the increase of the width of the river. This is justified for an alluvial river like Ganges which carries large amount of discharge and sediment load, though the geometry of the river is influenced by a large number of other variables.

5.4 VARIATION OF HYDRAULIC CHARACTERISTICS AT A SECTION

Most rivers experience a wide range of flows. At different discharges the observed mean velocity, mean depth, and width of flowing water reflect the hydraulic characteristics of the channel cross-section. Relationships of these three parameters as functions of discharge at the cross-section constitute a part of what Leopold and Maddock (1953) called the hydraulic geometry of stream channels.

Significant contributions in the field of hydraulic geometry have been made by Maddock (1953) and Leopold, Wolman and Miller (1964). Two types of relationship have been presented: one describes the response of a river at a particular cross-section as discharge increases ('at-a-station' hydraulic geometry). The other describes channel geometry in relation to a dominant discharge which increases in the down stream direction as the area of contributing catchment increases.

Hydraulic geometry may be expressed in terms of a set of equations. These equations represent relationships between width (W), depth (D), velocity (V) and a characteristics discharge (Q). Leopold and Maddock (1955) described these relation in the form of simpler power functions. These forms were:

$W = aQ^b$; $D = cQ^f$; $V = kQ^m$

and since BHV = Q, it follows that

$b+f+m = 1$ and $ack = 1$

At-a-station hydraulic geometry was studied for the Ganges at Hardinge Bridge taking observed data from 1970 to 1990. The relationships between the width (W), depth (D), velocity (V) and area (A) with the discharge shown in Fig. 5.55, 5.56, 5.57 and 5.58 Regression equations for W, D, V and A with Q had also been established using regression technique. These were as follows:

$W \propto Q^{0.172}$

$D \propto Q^{0.246}$

$V \propto Q^{0.595}$ ..... (a)

$A \propto Q^{0.414}$

The coefficients for the above equations were 271.5, 0.742, 0.0052 and 212.34 respectively. It was observed from the analysis that with increasing discharge at a given cross-section, the width, mean depth and mean velocity each increases as power function. It was also found that discharge was primarily associated with velocity and less effect on width. From figure 5.55 it revealed that width increases gradually with the increase of discharge upto around 9000 cumecs. Beyond that discharge abrupt increase in width was observed and then it followed a gradual increasing trend. This phenomenon may be due to the change in registance or due to the change in flow regimes, i.e., from lower flow regime to upper flow regime. It may be worth while to mention that the flow Froude No. of the data sets used in this study varied from 0.01 to 0.30. For Laboratory situation the lower flow regime Froude No. varies from 0.17 to 0.44. But for natural situation to more degree of freedom this range may be different. That is why flow registance due to change of flow regime may be responsible for such abrupt change. Moreover when the flow remains within the main channel, width increases with the increase of discharge and registance to flow will decrease with ripple bed form upto bankfull stage. And when the flow just overtops the bank and flow through the flood plain, resistance to flow increases as wetted perimeter increases and abrupt increase in width occurs. Beyond that no significant increase in width with the increase of discharge was observed. It may be noted that the station from where these data were obtained for analysis was restricted due to protection works.

Leopold and Maddock had also studied at-a-station hydraulic geometry and the relationships obtained were as follows:

$$W \propto Q^{0.18}$$
$$D \propto Q^{0.58} \qquad \ldots\ldots (b)$$
$$V \propto Q^{0.30}$$

Their relationships on the concept of a representative discharge taking the data from American streams were

$$W \propto Q^{0.26}$$
$$D \propto Q^{0.40} \qquad \ldots\ldots (c)$$
$$V \propto Q^{0.30}$$

From Lacey's regime concept the relationships were:

$$W \propto Q^{0.5}$$
$$D \propto Q^{0.333} \qquad \ldots\ldots (d)$$
$$V \propto Q^{0.167}$$

It is to be noted here that discharge in equation (a) & (b) indicates varying discharge, but in eqn, (c) & (d) it indicates a characteristic discharge (i.e. bankfull or dominant discharge). In the present study, the variations of the exponent for 'at-a-station' hydraulic geometry was compared with that studied by Leopold and Maddock (1953), Langbein (1964) and Goudie (1985). The comparison is shown in table 5.7. It may be worth mentionable that the data used by Leopold and Maddock (1953), Langbein (1964) and Goudie (1985) were obtained from different hydroclimatological region and as such liable to vary from the present investigations which utilizes large alluvial river data.

5.5 Non-dimensional correlation between shape (W/D) and flow Froude no. $[V/(gD)^{1/2}]$

Use of non-dimensional parameters in the study of alluvial river phenomena has already been explained before. It may however be emphasised to state that flow through an alluvial stream incorporates a good number of variables and that is why dominant variables were chosen to form non-dimensional parameters to describe the alluvial river behavior. In the present study width depth ratio (W/D) and flow Froude number $[V/(gD)^{1/2}]$ were calculated for different years at Hardinge Bridge.

Graphical ralationships showing the variation of width depth ratio with flow Froude number were shown in the figures from 5.28 to 5.34 for the years 1983-87 and 1989. The value of width depth ratio and flow Frude number was found to vary from 56 to 395 and 0.01 to 0.33 respectively. From these plots it may be observed that Froude number decreases with the increase of width depth ratio and there exists very good correlation between them for all the years. All data were then plotted in one figure (fig. 5.34) and the form of the equation was similar as follows:

$$Y = 41774X^{-2.47}, \quad r = -0.86$$

where $Y = V/(gD)^{1/2}$, $X = W/D$ and r = coefficient of correlation.

If may be worthwhile to mention here that a similar type of study was conducted by Hossain (1989) for the same river. His study was done considering the data of all available cross-sections in different years. He found similar trend of decreasing flow Froude number with the increase of shape factor in power form. The form of general equation Hossain established was as follows:

$$F = 0.18\ (W/D)^{-0.08},\ r = -\ 0.70$$

where 'F'= $V/(gD)^{1/2}$ and 'r' coefficient of correlation.

The difference between the coefficients and constants are due to utilization of data volume. In the present study data covering lean flow and flood flow had been considered. But Hossain's study dealt with the lean flow data only. Therefore the present correlation is more general and applicable to rivers flowing in alluvium. Summary of correlation between W/D and $V/(gD)^{1/2}$ were shown in the table 5.3.

5.6 Non dimensional correlation between shape factor (W/D) and discharge Parameter $[Q^{2/5}/(sg)^{1/5}]/D$

Non-dimensional relationships were also developed between shape factor and discharge parameter and plottings are shown in the figure from 5.35 to 5.41 for the year 1983-87 and 1989 respectively. Power type regression equation were developed between the shape factor and discharge parameter shown in the table 5.4. From power type regression equation it was observed that discharge parameter decreases with the increase of shape factor and correlation exists between them were quite good. It may be infered from the plots that shape of alluvial river is closly related to discharge, slope and flow depth. General equation was also developed taking all the data together (fig. 5.41) which could be expressed as:

$$Y = 563X^{-0.598}; \; r = -0.73$$

where $Y = [Q^{2/5}/(sg)^{1/5}]/D$, $X = W/D$

5.7 Non-dimensional correlation between Froude number $(V/(gD)^{1/2}$ and discharge parameter $[Q^{2/5}/(sg)^{1/5}]/D$

Non-dimensional correlation was also developed between Froude number and discharge parameter for the Ganges at Hardinge Bride in different years. Powertype regression analysis was done and shown in the table (5.5). It was revealed from the analysis that very good correlation exists between the Froude number and discharge parameter. Discharge parameter increases with the increase of Froude number. It means that Froude number increases with higher discharges for a particular section. Graphical representation between the two parameters are shown in the figure from 5.42 to 5.52 for the years 1970, 74, 75, 80, 83-87 and 89 respectively. A general equation was developed considering all the data and the trend was similar to that of individual year. The trend of the general equation could be expressed as follows,

$$Y = 52.83X^{0.336};\ r = 0.91$$

where $Y = [Q^{2/5}/(sg)^{1/5}]/D$; $X = V/(gD)^{1/2}$

It is noted here that these two parameters have positive trend, whereas the previous two had negetive trend.

5.8 Variation of deep water channel (Thalweg)

From the cross-sectional map thalweg movement was studied in different sections. It was observed that thalweg moves randomly from year to year and it shows leftward movement from section G-1-1 to G-8. According to Dad (1977), the movement of thalweg is due to the movement of sand bars, mid channel islands and aggradation. Deepest point of each section in different years were plotted along the stream shown in the figure 5.11. In most of the section the thalweg of 1988-89 was shallower than that of 1967-68. This is due to the long term effect of channel bed aggradation.

5.9 Area elevation relationship

Area elevation relationships were established in different sections for the year 1967-68 and 1988-89 to observe the variation of cross-sectional area in different elevation with respect to PWD datum. For this purpose raw data were entered and processed with the help of mikell package program. As a result cross-sectional area was obtained in different elevation, which was plotted and shown in the figure from 5.20 to 5.27. It may be observed from the plots that the cross -sectional area increases with the increase of elevation in power from and there was very good correlation between them. Summary of area-elevation relationship were shown in the table 5.2. This type of analysis was done with a view to observe the effect of siltation on cross-sectional area. This phenomenon was very distinct at G-9 & G-11. From figure 5.24 & 5.25, it was observed that same area was obtained with higher elevation in 1988-89 compared to 1967-68. This is the result of siltation or aggradation. In the remaining sections except G-3, it was found that for lower area, area elevation curve for the year 1988-89 lies above the curve of 1967-68. It indicates that channel bed is rising due to siltation.

5.10 Variation of mean bed level

Mean bed level (MBL) at different sections were computed and plotted for the year 1967-68 and 1988-89 shown in the figure 5.53. Change in MBL during 1967-68 to 1988-89 was also shown. Procedures applied for the computation of MBL in different sectins were as follows: (i) average depth was calculated dividing the cross-sectional area by the width of the river, (ii) then average depth was deducted from the bank level with respect to PWD datum. As a result MBL for the respective section was obtained. This analysis was conducted with a view to observing the effect of erosion and deposition on MBL at the selected sections during a long period between 1967-68 to 1988-89. Due to limitted data it was not possible to quantify the total amount of erosion or deposition throughout the reach, but an idea was obtained. It was obvious from the figure 5.53 that MBL rises in almost all the sections except at G-6 and G-16 during twenty years with respect to the MBL of 1967-68. So effect of deposition was dominant throughout the reach. Maximum rise in MBL was observed about 2.2m at G-11. However Hossain (1989) observed that MBL showed a general trend of rise in the upper reaches and fall in the lower reaches.

5.11 SPECIFIC GAUGE ANALYSIS

For the analysis of medium to long term behaviour of the river, a specific gauge analysis can be used to determine if there are any trends with time in the elevation of the water surface corresponding to a given discharge. The analysis must be based on historical stage-discharge records for a gauging station with an open river section. In the present study, stage discharge curves at Hardinge Bridge during the period 1968-69 to 1990-91 was taken. The analysis was based on discharge levels of 5000, 10000, 20000, 35000 and 50000 m^3/s and the corresponding water stages from the rating curves for the available years. Water stages were then plotted against the year of observation for a particular discharge shown in the figure 5.54. In some cases, it was observed that there were two curves; one is rising stage, another is falling stage. In that case the average value of the two was taken. It may be noted that from the analysis although no significant trend was observed but slight increase in the curve was noticeable. It is also interesting to note that the trend of the curve follows a sinuous form, which is the general characteristics of a mobile bed channel. From sinuous form of the curve it may be concluded that this behaviour indicates the movement of the bed forms (dunes, sandbars etc.), which is taking place across the gauging stating from year to year, even in the same year. But at lower discharge levels of 5000 and 10000 m^3/s, it shows slightly rising trend.

CHAPTER-6

CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

The following conclusions may be drawn in the present study:

Cross-sectional area was found to vary randomly in the present study from section to section and from year to year. The value of cross-sectional area in most of the sections in the upper reaches was observed lower and in the lower reaches higher for the year 1989 than that of the year 1967-68 and 1975-76.

Deepest point (Thalweg) in each section for the respective year was analysed and plotted to show the variation in different year. It was observed that the deepest point in 1967-68 was higher with respect to the year 1988-89 in almost all the sections, which indicates a depositing tendency.

Linear relationships were established between area and width of the river and it shows that area increases with the increase of width. Linear relationships were also developed between width and hydraulic radius of the river and it was observed that hydraulic radius decreases with the increase of width.

At-a-station hydraulic geometry was studied for the Ganges at Harding Bridge taking the data of 1970 to 1990. From the relationship it was observed that the width, mean depth and mean velocity each increases as power function. The variations in exponents in the present study may be due to the data used from different hydroclimatological region.

Power type area elevation relationships were developed for the year 1967-68 and 1988-89 and very good correlation was found.

Non-dimensional correlation between shape factor and flow Froude no shows that Froude number decreases with the increase of width depth ratio. Power type regression equation between W/D and $[Q^{2/5}/(sg)^{1/5}]/D$ were developed which also showed that discharge parameter decreases with the increase of width depth ratio. Non-dimensional relationship was also established between $V/(gD)^{1/2}$ and $[Q^{2/5}/(sg)^{1/5}]/D$ and it was found that Froude number increases with the increase of discharge parameter.

MBL was calculated in the selected sections for the year 1967-68 and 1988-89. It was found from the analysis that siltation was found to occur in almost every section except at G-6 and G-16 during 21 years. Maximum rise in MBL was observed 2.2m at section G-11.

Specific gauge analysis was carried out for the selected discharge levels but no significant trend was observed except at low discharges, though all the curves showed sinuous form.

6.2 RECOMMENDATIONS FOR FUTURE STUDIES

i) In the present study the reach considered was from Indo-Bangladesh Boarder to Aricha. Hydraulic geometry and specific gauge analysis was done in this study. Similar type of studies should be carried out in the upper and lower part of the same river as well as in different rivers, for the verification of relationships obtained in this study.

ii) Cross-sectional data in most of the sections (mainly in the upper reaches) in different years were discontinuous. Continuous data for a long period should be studied for better prediction of the river behaviour. Simultaneously sediment related study could be done.

iii) The break in the plot of discharge vs. width may be further investigated for difinite identification of the reasons with more new data sets.

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TABLE 5.1

Variation of cross-sectional area, width and hydraulic radius for the Ganges

Section no.	Year	Cross-sectional area (m^2)	Hydraulic radius(m)	Width(m)
G-18	1967-68	34261	7.26	6250
	1975-76	34377	8.90	6402
	1988-89	39894	5.81	9301
G-16	1967-68	31965	6.10	8993
	1975-76	44572	6.76	9756
	1988-89	39196	5.59	10345
G-11	1967-68	30908	8.47	5530
	1975-76	32236	8.20	5030
	1988-89	23422	5.30	6846
G-9	1967-68	31386	6.80	7926
	1975-76	28085	6.78	8231
	1988-89	23220	6.54	6873
G-8	1967-68	24715	6.93	4573
	1975-76	29437	6.57	6859
	1988-89	20862	6.03	4545
G-6	1967-68	20175	13.91	4573
	1975-76	31216	6.26	7012
	1988-89	42214	6.59	8975
G-4	1967-68	21277	10.07	3506
	1975-76	18045	8.81	3506
	1988-89	23514	7.76	4049
G-3	1967-68	29133	6.03	7149
	1975-76	45865	8.37	7012
	1988-89	27435	7.68	7060
G-1-1	1967-68	22419	6.81	4420
	1975-76	23467	7.88	4420

TABLE 5.2

Relation between cross-sectional area and elevation for the Ganges

Section no.	Regression equation	Coefficient of correlation	Data used for the years
G-3	$E = 0.183\ A^{0.396}$	0.998	1967-68
	$E = 0.024\ A^{0.608}$	0.983	1988-89
G-4	$E = 1.88*10^{-3}A^{0.878}$	0.998	1967-68
	$E = 0.304\ A^{0.359}$	0.98	1988-89
G-6	$E = 2.74*10^{-6}\ A^{1.577}$	0.94	1967-68
	$E = 1.028\ A^{0.23}$	0.964	1988-89
G-8	$E = 0.275\ A^{0.382}$	0.995	1967-68
	$E = 2.406\ A^{0.143}$	0.91	1988-89
G-9	$E = 0.155\ A^{0.434}$	0.997	1967-68
	$E = 0.645\ A^{0.299}$	0.988	1988-89
G-11	$E = 0.174\ A^{0.428}$	0.999	1967-68
	$E = 1.22\ A^{0.251}$	0.999	1988-89
G-16	$E = 0.75\ A^{0.301}$	0.998	1967-68
	$E = 3.717\ A^{0.131}$	0.995	1988-89
G-18	$E = 1.047\ A^{0.273}$	0.999	1967-68
	$E = 1.83\ A^{0.216}$	0.999	1988-89

where, A = cross-sectional area

E = Elevation

TABLE 5.3

Non-dimensional correlation between shape factor (W/D) and flow Froude no $(V/(gD)^{1/2}$ for the Ganges at Hardinge Bridge.

Regression equation	Coefficient of correlation	Data used for the years
$Y = 1100X^{-1.73}$	- 0.95	1983
$Y = 13.18*10^6X^{-3.58}$	- 0.96	1984
$Y = 99.63*10^4X^{-3.12}$	- 0.96	1988
$Y = 12.43*10^3X^{-2.26}$	- 0.93	1986
$Y = 43.71*10^6X^{-3.85}$	- 0.92	1987
$Y = 629.3*10^6X^{-4.22}$	- 0.93	1989

where $Y = V/(gD)^{1/2}$

$X = W/D$

TABLE 5.4

Non-dimensional correlation between shape factor (W/D) and dishcarge parameter ($Q^{2/5}(sg)^{1/5}$) for the Ganges at Hardinge Bridge

Regression equation	Coefficient of correlation	Data used for the years
$Y = 150.23X^{-0.327}$	- 0.82	1983
$Y = 4615X^{-1.001}$	- 0.93	1984
$Y = 2637.87X^{-0.916}$	- 0.91	1986
$Y = 297.42X^{-0.48}$	- 0.827	1986
$Y = 9573.97X^{-1.16}$	- 0.89	1987
$Y = 21971.82X^{-1.265}$	- 0.91	1989

where $Y = [Q^{2/5}/(sg)^{1/5}]/D$

$X = W/D$

TABLE 5.5

Non-dimensional correlation between Froude no $(V/(gD))^{1/2}$ and discharge parameter $[Q^{2/5}/(sg)^{1/5}]/D$ for the Ganges at Hardinge Bridge

Regression equation	Coefficient of correlation	Data used for the year
$Y = 69.99X^{0.451}$	0.969	1970
$Y = 99.89X^{0.653}$	0.97	1974
$Y = 72.31X^{0.497}$	0.955	1975
$Y = 59.89X^{0.395}$	0.908	1980
$Y = 41.72X^{0.208}$	0.95	1983
$Y = 47.52X^{0.286}$	0.99	1984
$Y = 46.60X^{0.301}$	0.987	1985
$Y = 41.40X^{0.234}$	0.969	1986
$Y = 48.53X^{0.309}$	0.995	1987
$Y = 51.77X^{0.306}$	0.994	1989

where $Y = [Q^{2/5}/(sg)^{1/5}]/D$

$X = V/(gD)^{1/2}$

TABLE 5.6

Variation of the exponents in the hydraulic geometry in various region (Leopold and others 1964 after Shen 1971)

	At-a-station relations			Average downstream relations (bankful or mean annual flow)		
	b	f	m	b	f	m
Average values mid westerm united states	0.26	0.40	0.34	0.50	0.40	0.10
Brandy wine creek Pennsylvania	0.04	0.41	0.55	0.42	0.45	0.05
Ephemeral streams in semiarid united states	0.29	0.36	0.34	0.50	0.30	0.20
Appalachian streams				0.55	0.36	0.09
Average of 158 gauging stations, united states	0.12	0.45	0.43			
Ten gauging stations on Rohine river	0.13	0.41	0.43			

Note: $W = a\,Q^b$; $D = cQ^f$; $V = kQ^m$

TABLE 5.7

Comparison of the hydraulic geometry exponents for the present study with Leopold and Maddock (1953), Langbein (1964) and Goudie (1985)

At-a-station hydraulic geometry

	b	f	m
Leopold and Maddock (1953) (sencca creek at Dawnsonville Maryland)	0.18	0.58	0.30
Leopold and Maddock (1953) (River sections in the Mid West USA)	0.26	0.40	0.35
Langbein (1964) (Laboratory study)	0.23	0.42	0.35
Goudie (1985) (In humid areas)	0.05	0.45	0.50
Present study (Ganges at Hardinge Bridge)	0.172	0.246	0.595

Note: $W = aQ^b$; $D = cQ^f$; $V = kQ^m$

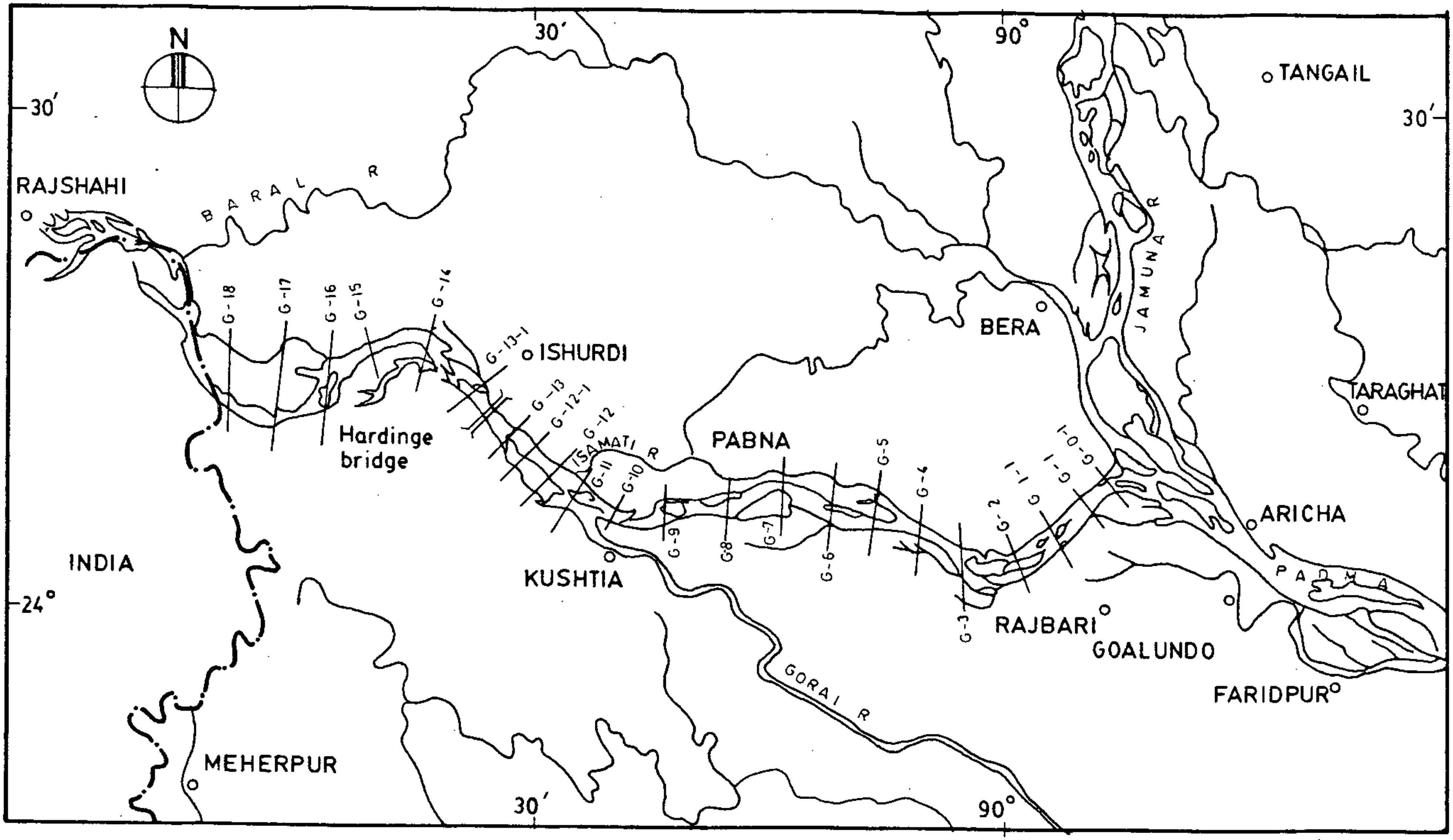

FIGURE 1.1 GANGES RIVER FROM INDO BANGLADESH BORDER TO BRAHMAPUTRA CONFLUENCE

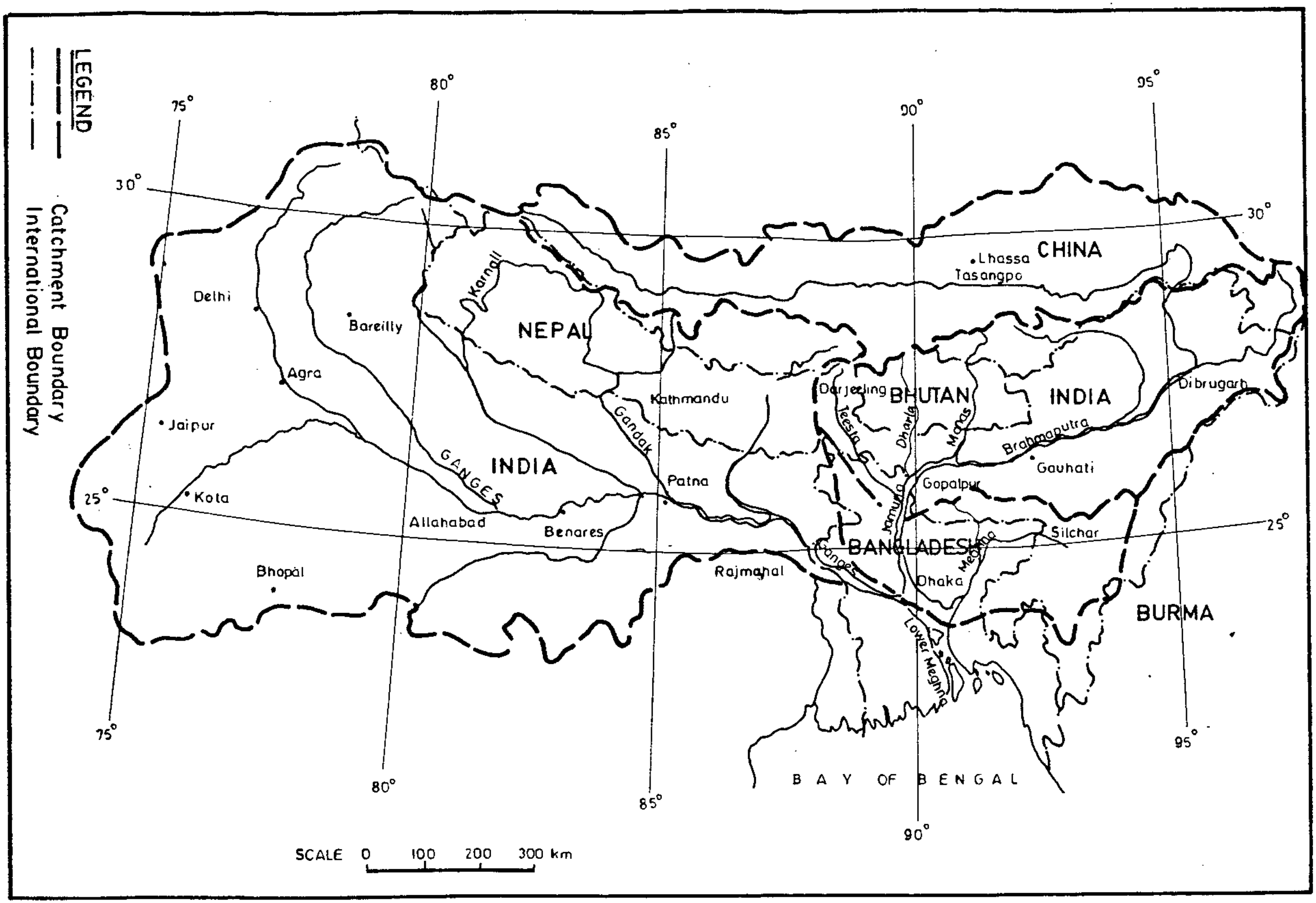

FIG. 2.1 THE GANGES BASIN

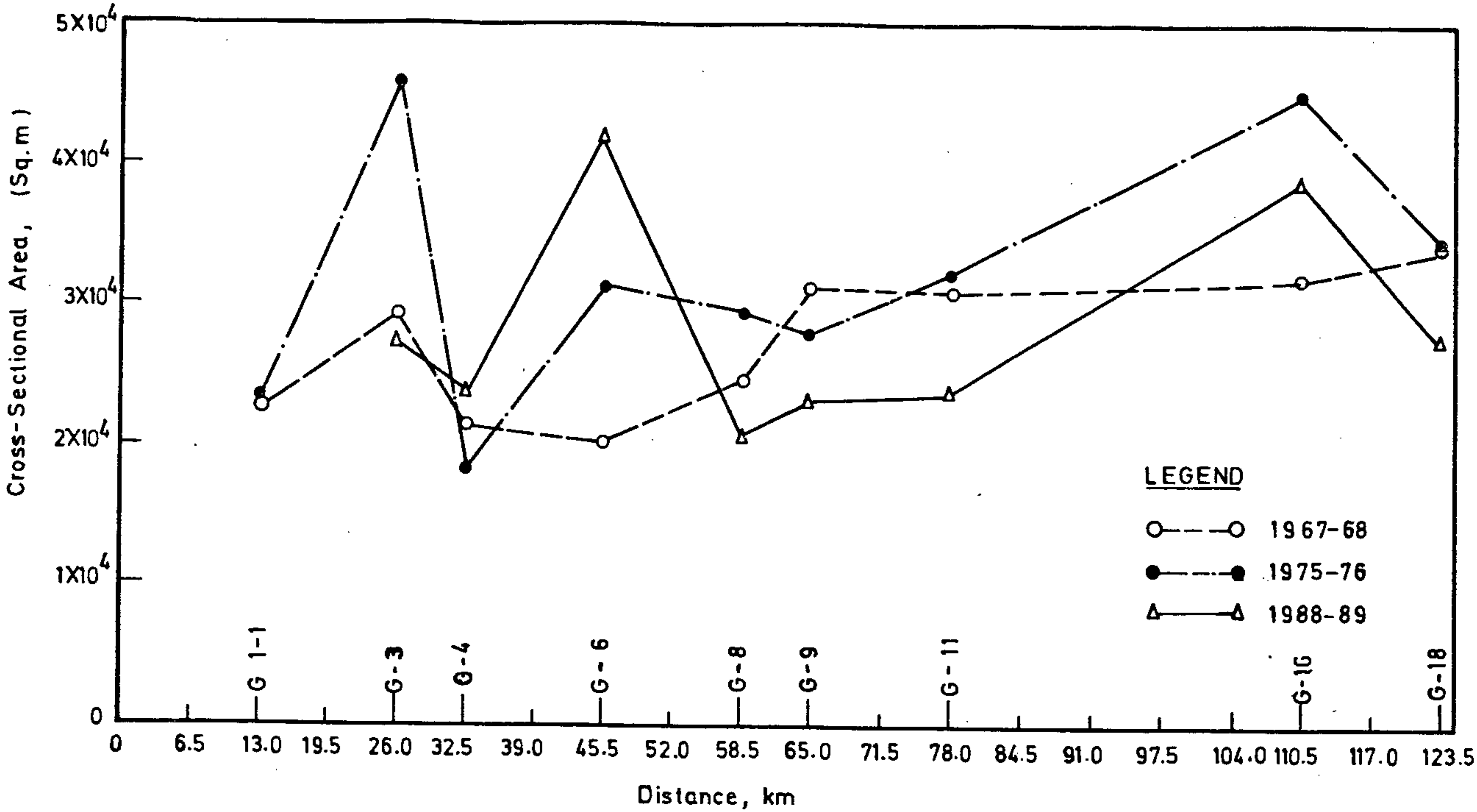

FIG. 5.1 VARIATION OF CROSS SECTIONAL AREA FOR THE GANGES ALONG THE STREAM

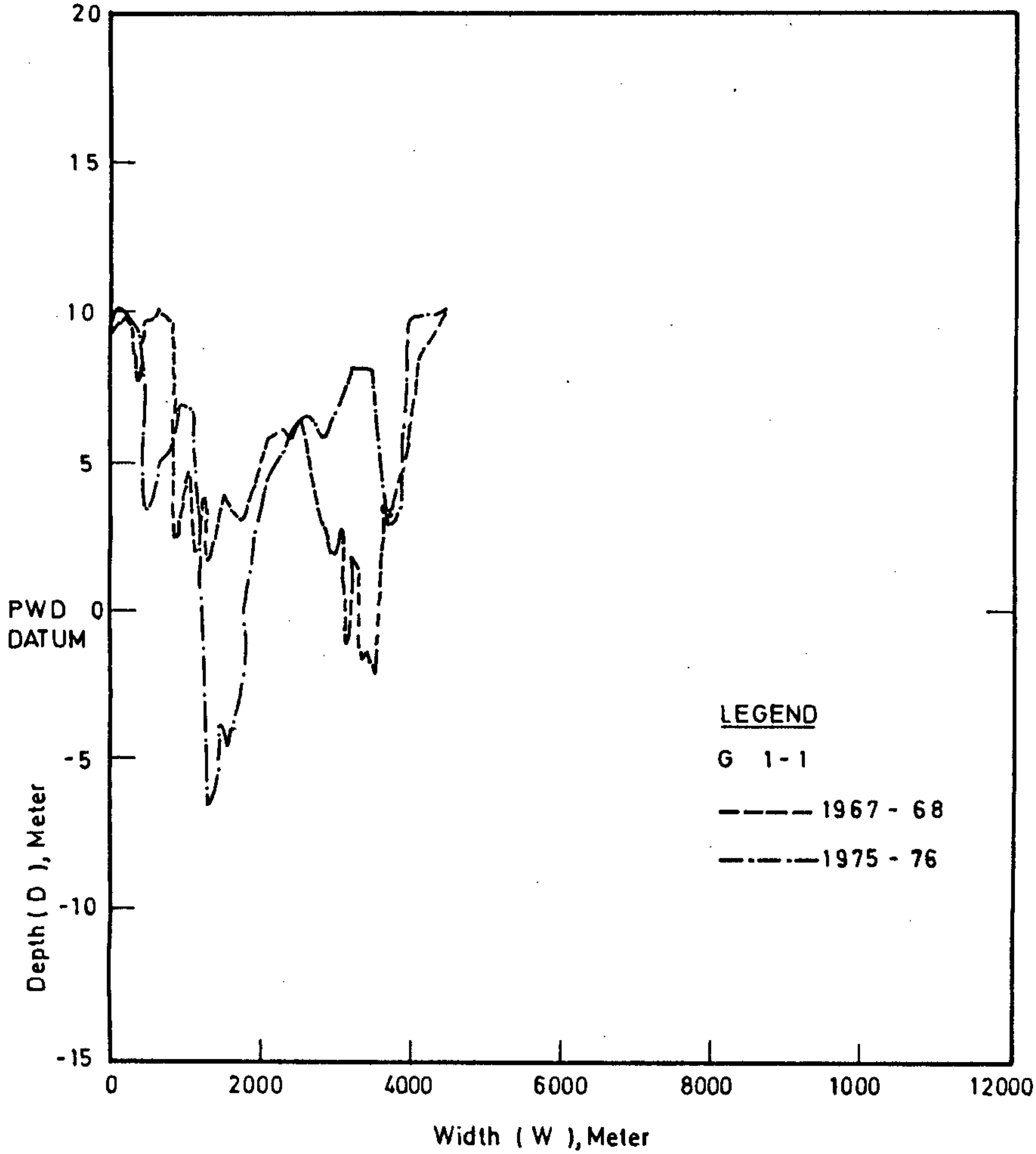

FIG. 5.2 VARIATION OF CROSS SECTIONAL AREA FOR THE GANGES AT G-1-1

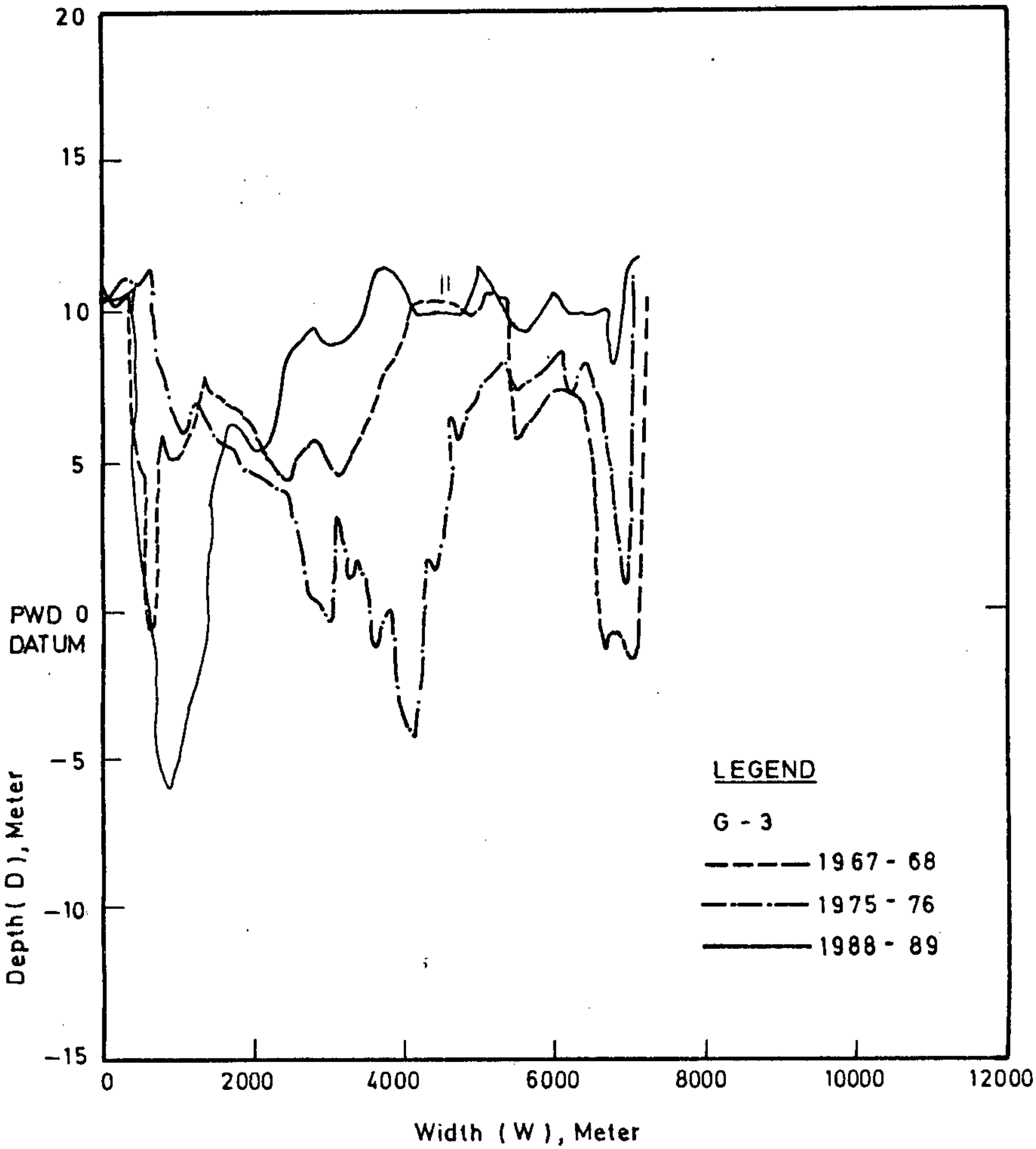

FIG. 5.3 VARIATION OF CROSS SECTIONAL AREA FOR THE GANGES AT G-3

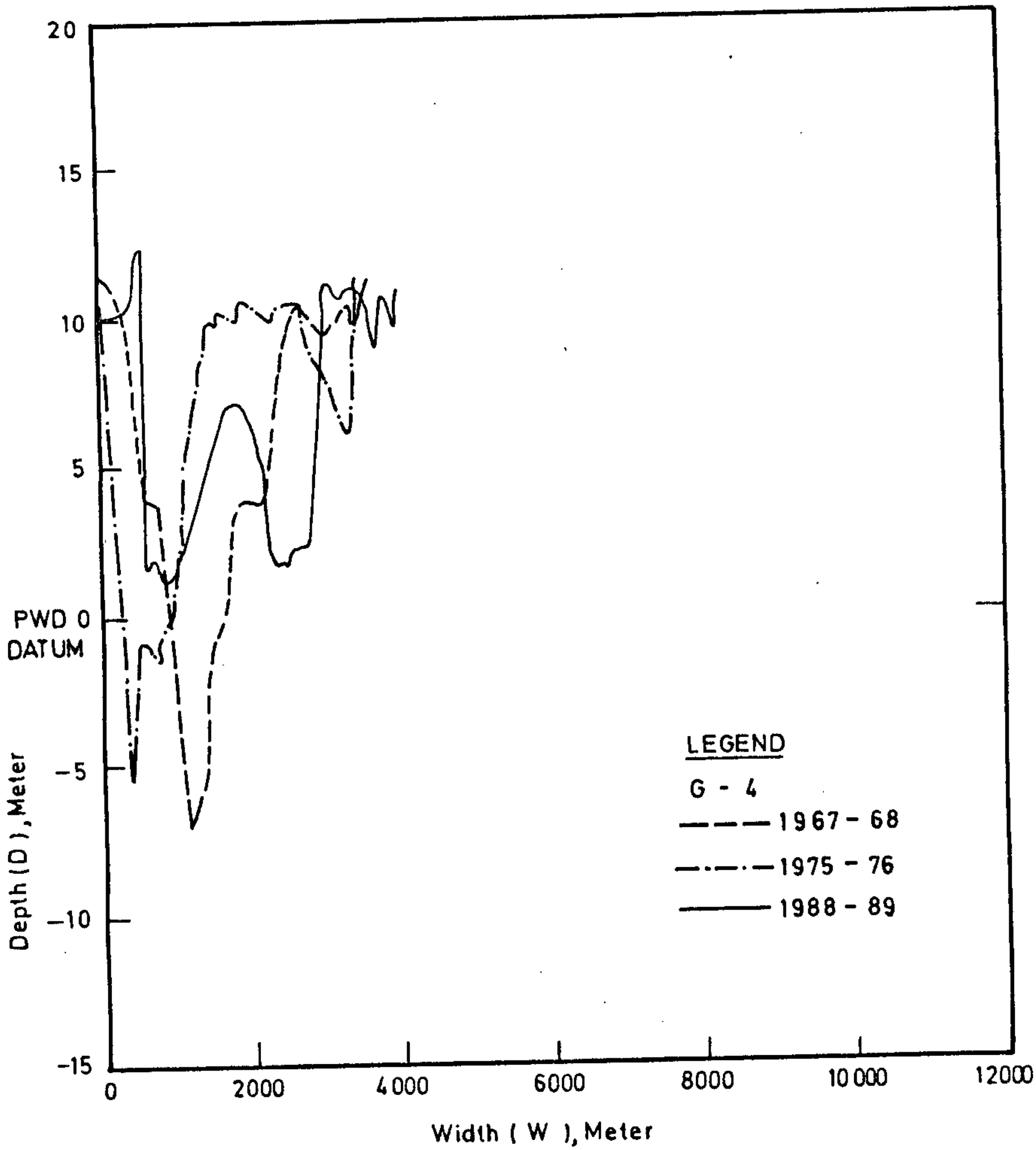

FIG. 5.4 VARIATION OF CROSS SECTIONAL AREA FOR THE GANGES AT G-4

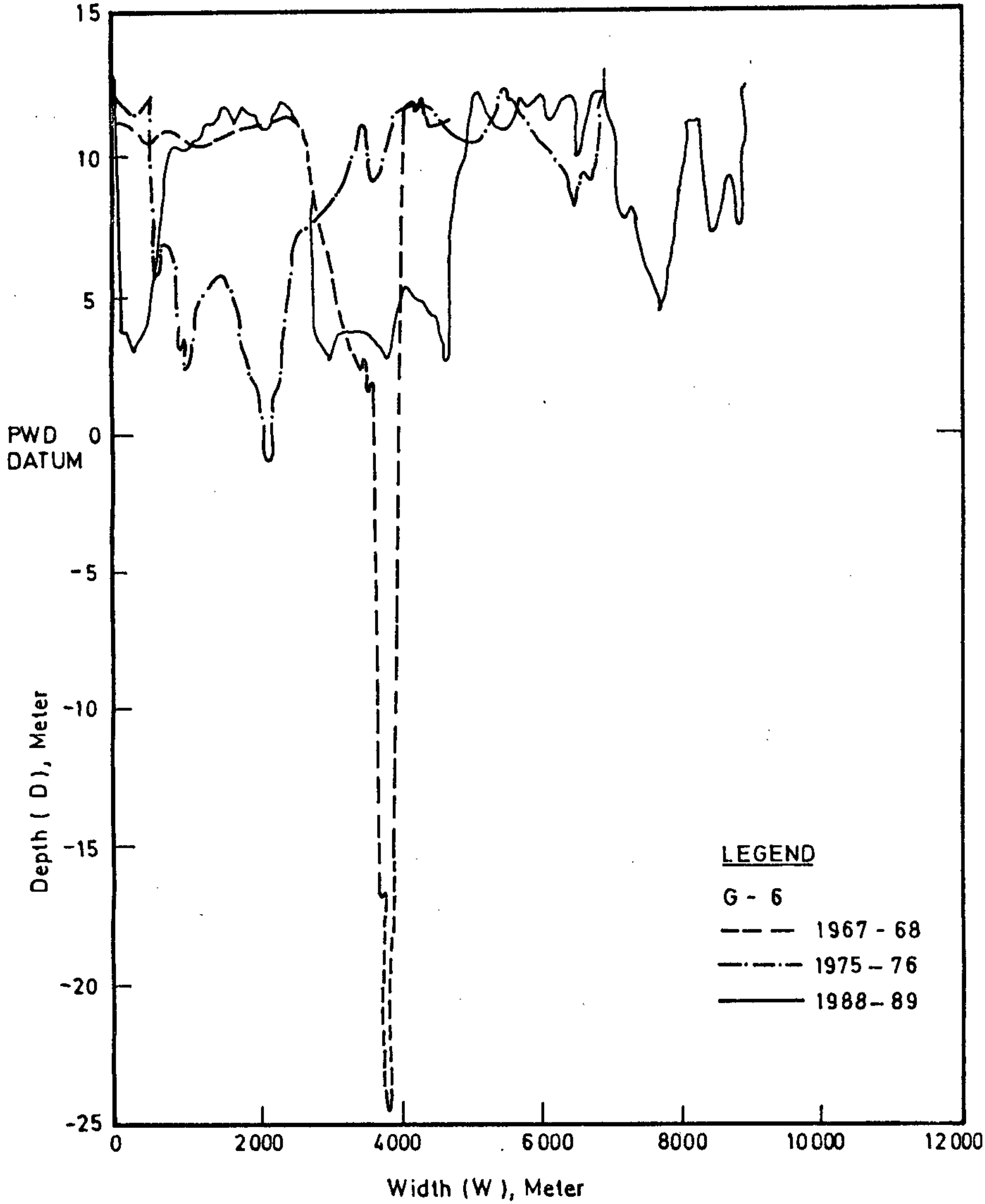

FIG. 5.5 VARIATION OF CROSS-SECTIONAL AREA FOR THE GANGES AT G-6

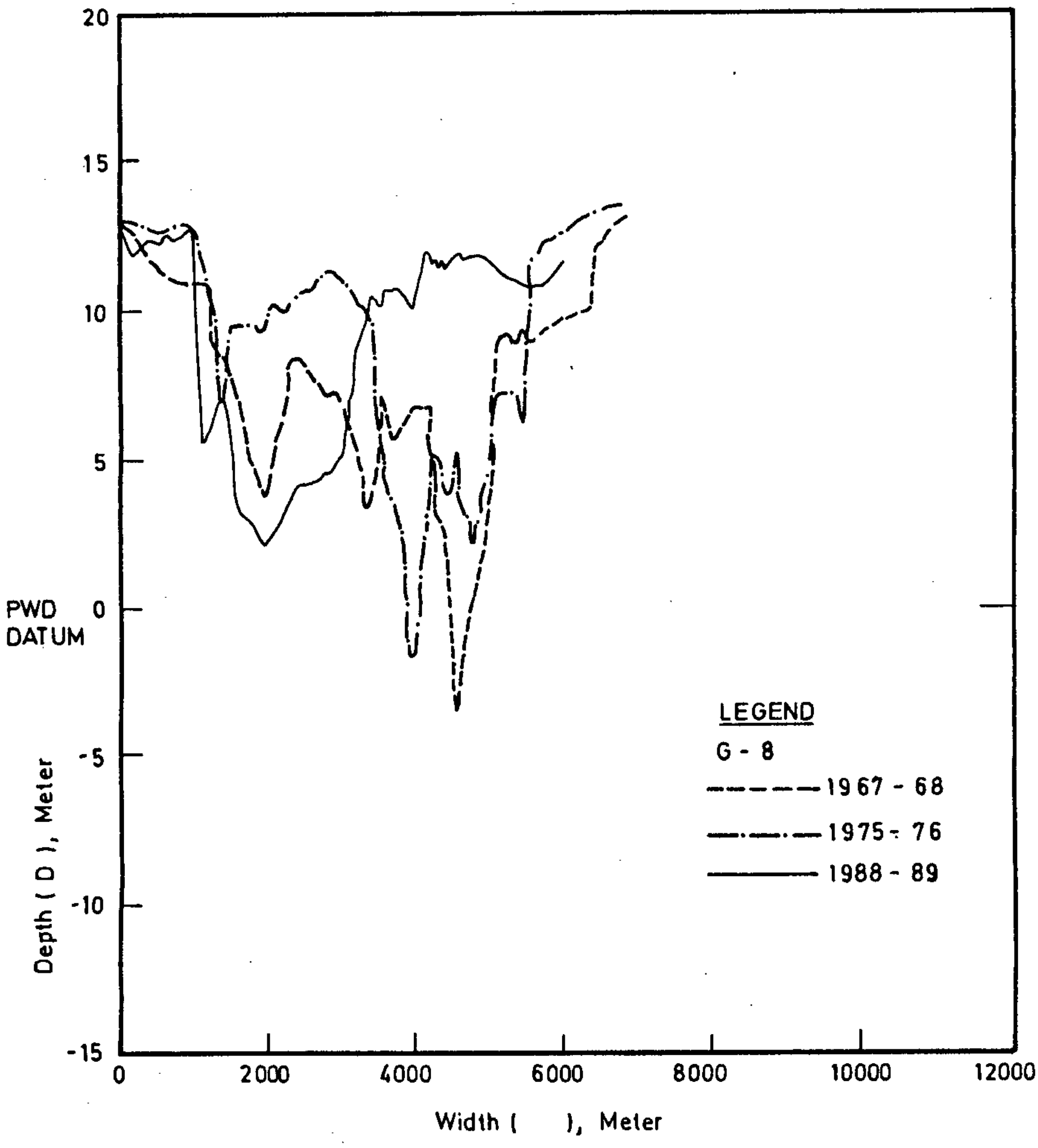

FIG. 5.6 VARIATION OF CROSS SECTIONAL AREA FOR THE GANGES AT G-8

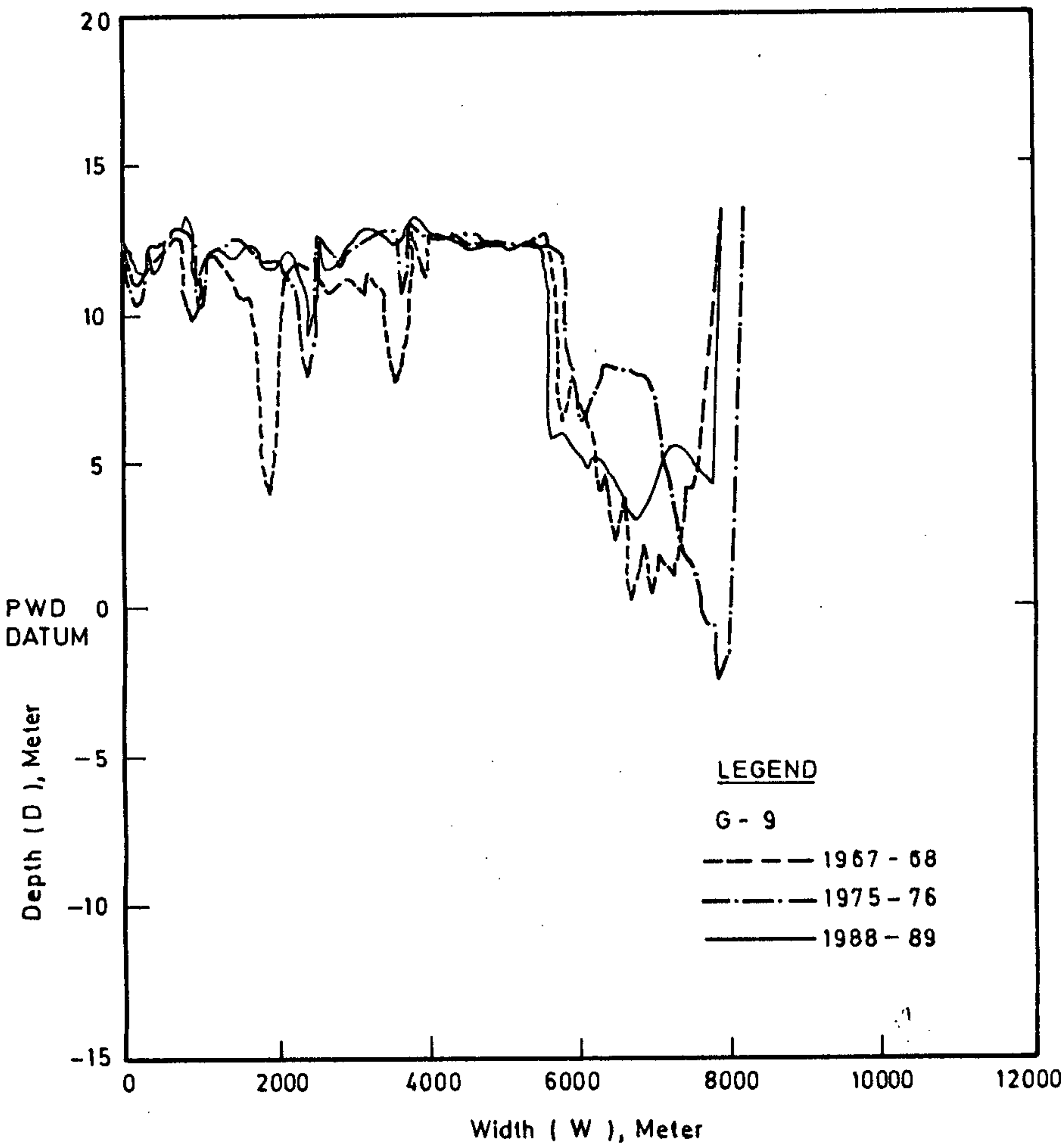

FIG. 5.7 VARIATION OF CROSS SECTIONAL AREA FOR THE GANGES AT G - 9

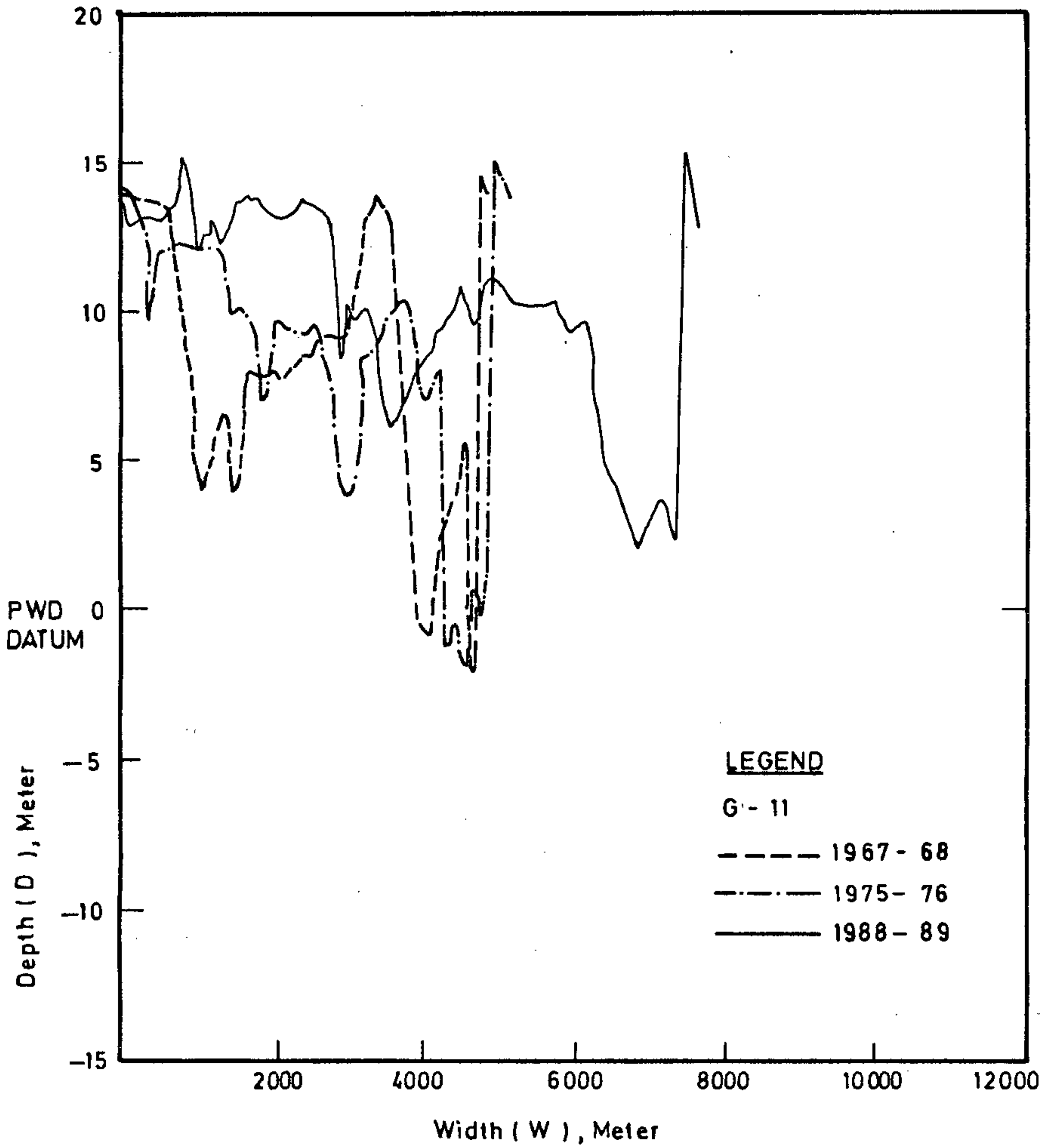

FIG. 5.8 VARIATION OF CROSS SECTIONAL AREA FOR THE GANGES AT G - 11

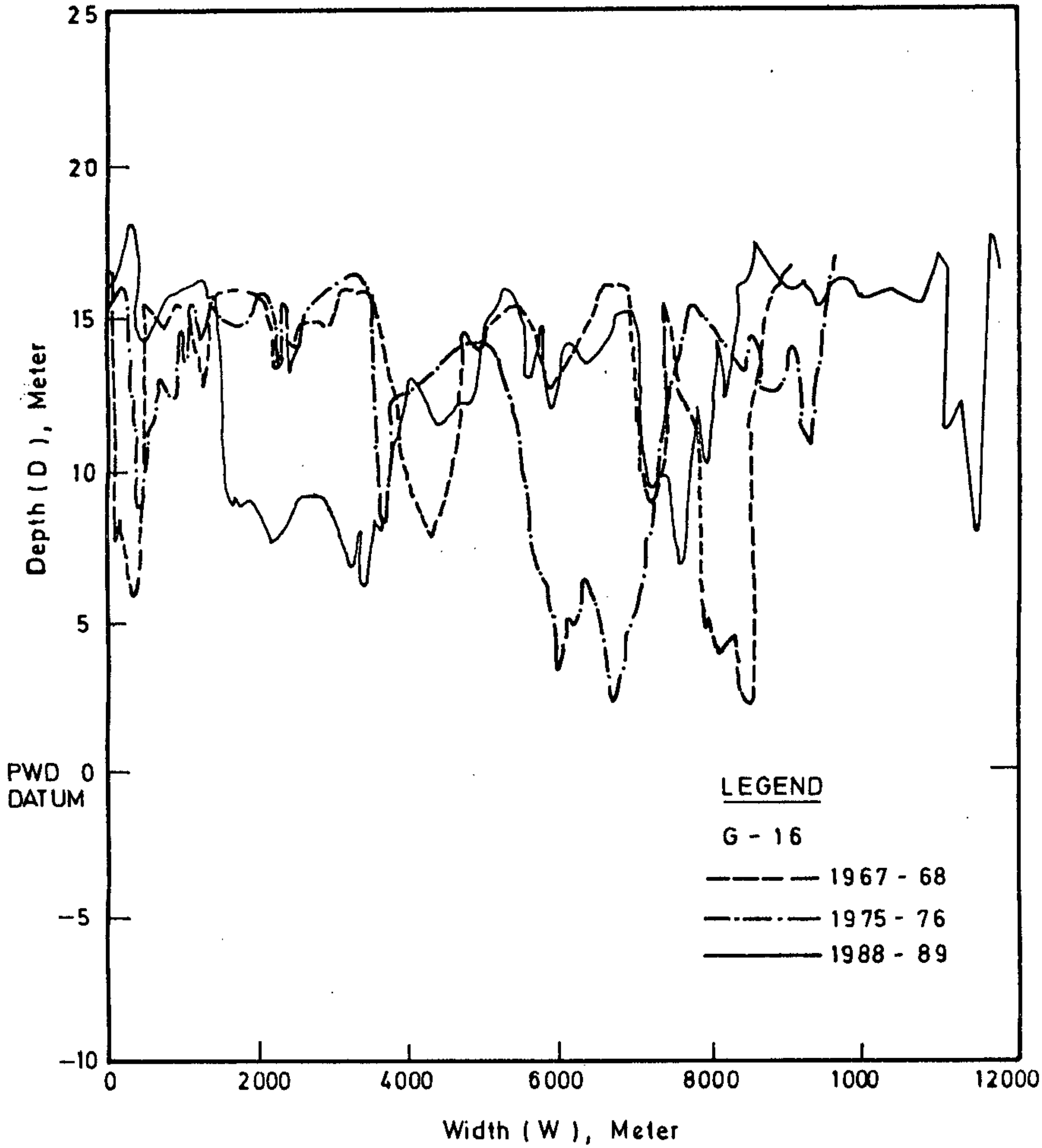

FIG. 5.9 VARIATION OF CROSS-SECTIONAL AREA FOR THE GANGES AT G-16

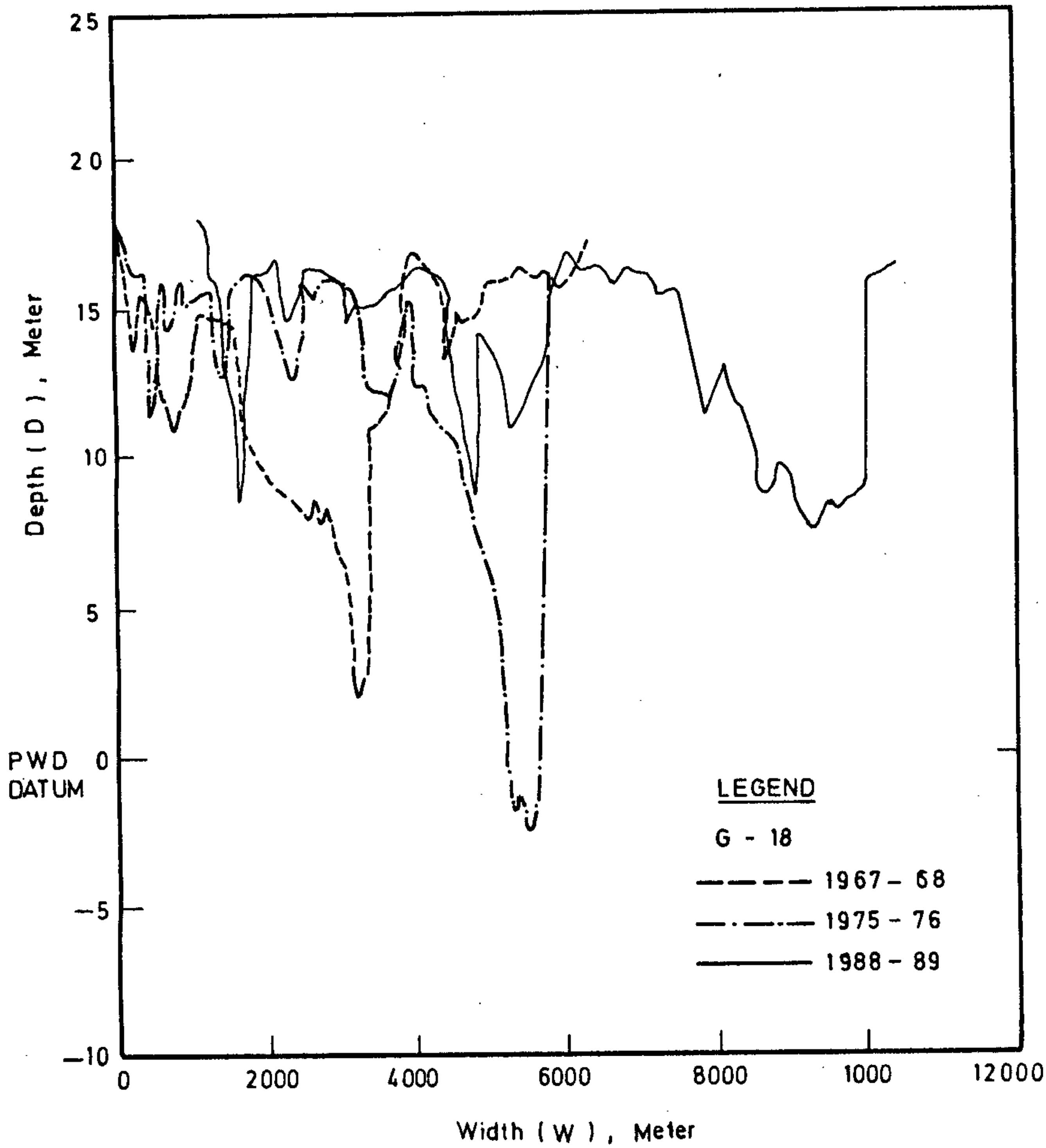

FIG. 5.10 VARIATION OF CROSS-SECTIONAL AREA FOR THE GANGES AT G -18

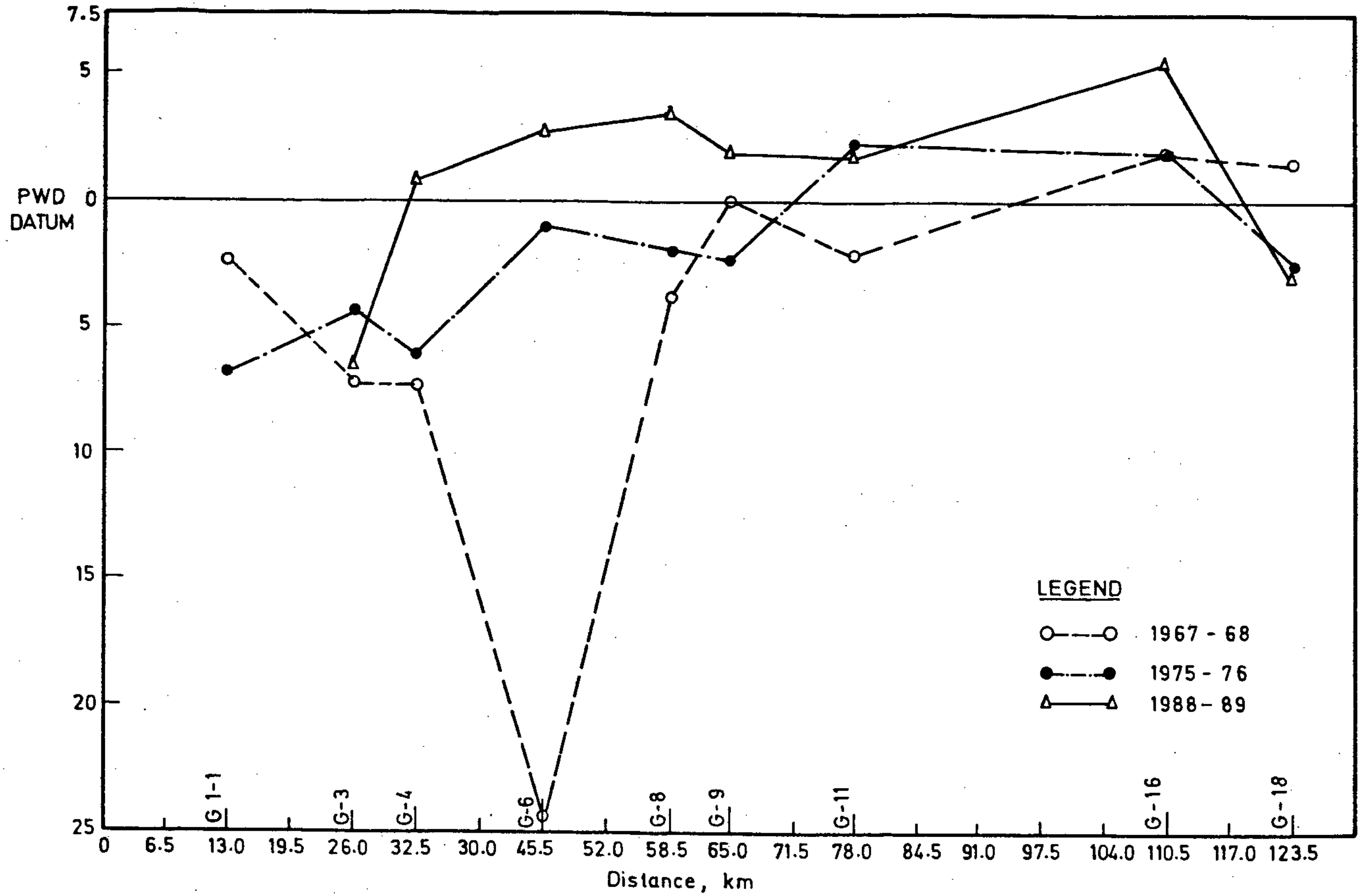

FIG. 5.11 VARIATION OF DEEP WATER CHANNEL FOR THE GANGES

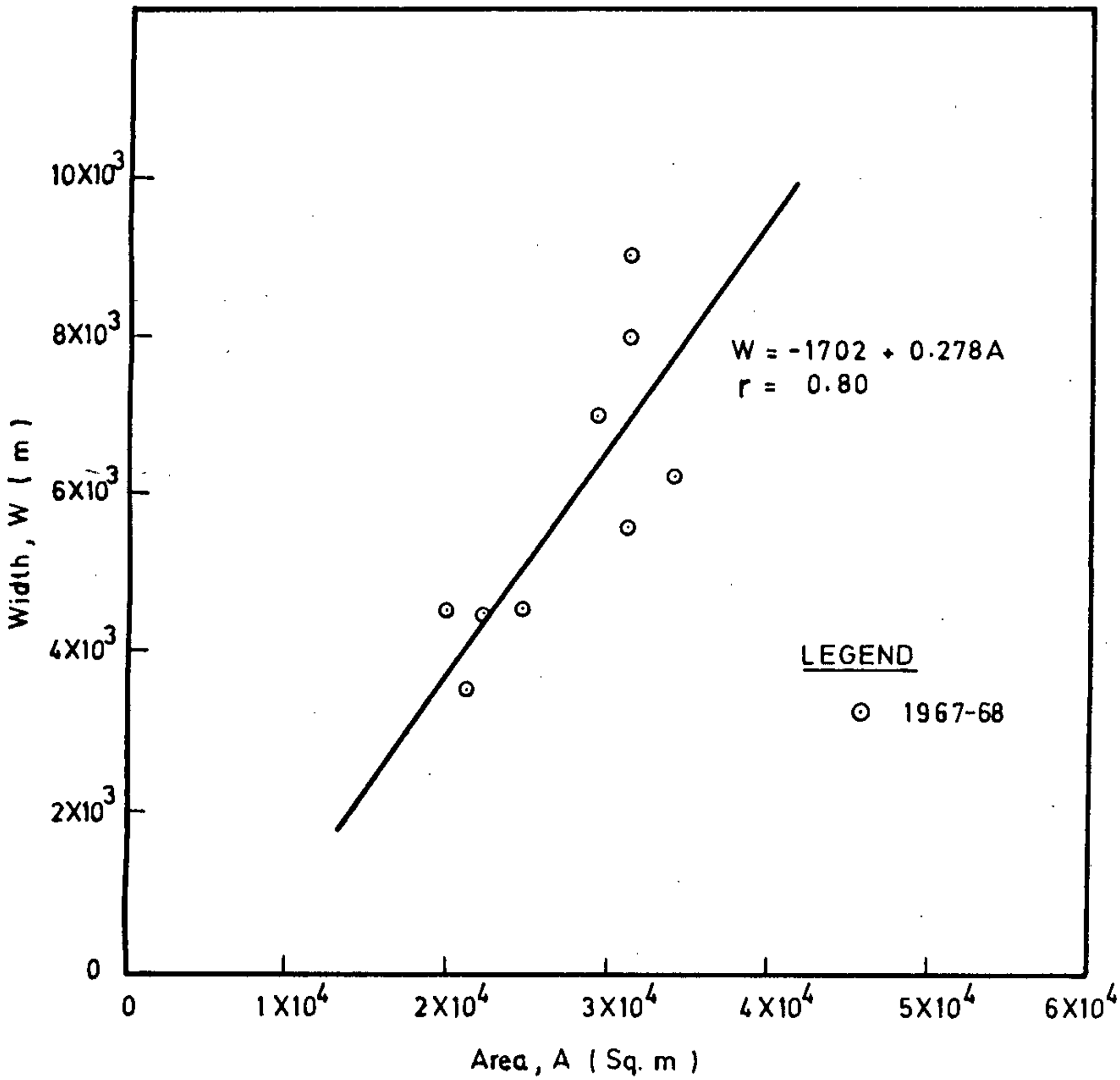

FIG. 5.12 RELATIONSHIP BETWEEN WIDTH AND CROSS-SECTIONAL AREA OF THE GANGES RIVER (1967 - 68)

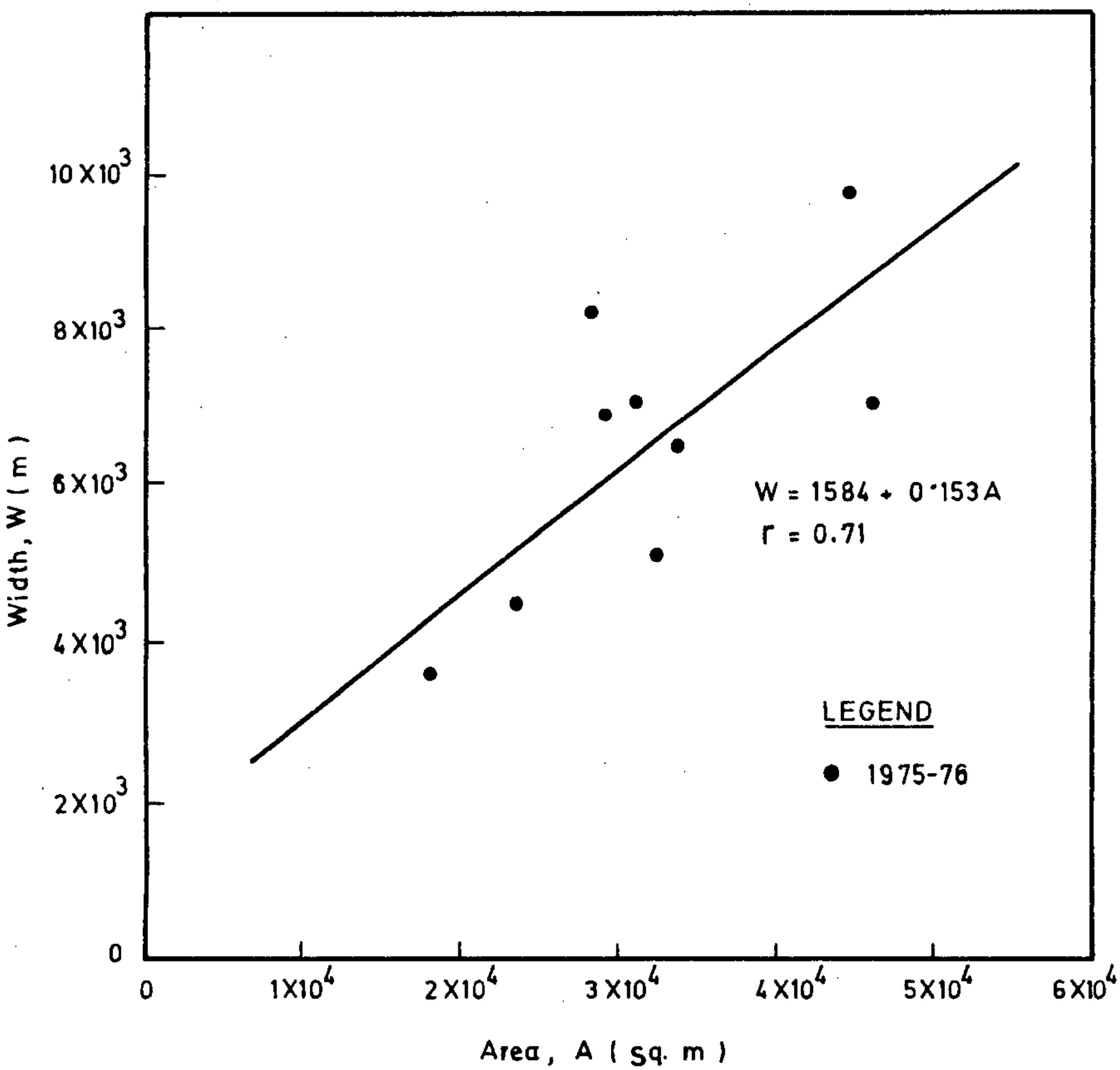

FIG. 5.13 RELATIONSHIP BETWEEN WIDTH AND CROSS-SECTIONAL AREA OF THE GANGES RIVER (1975-76)

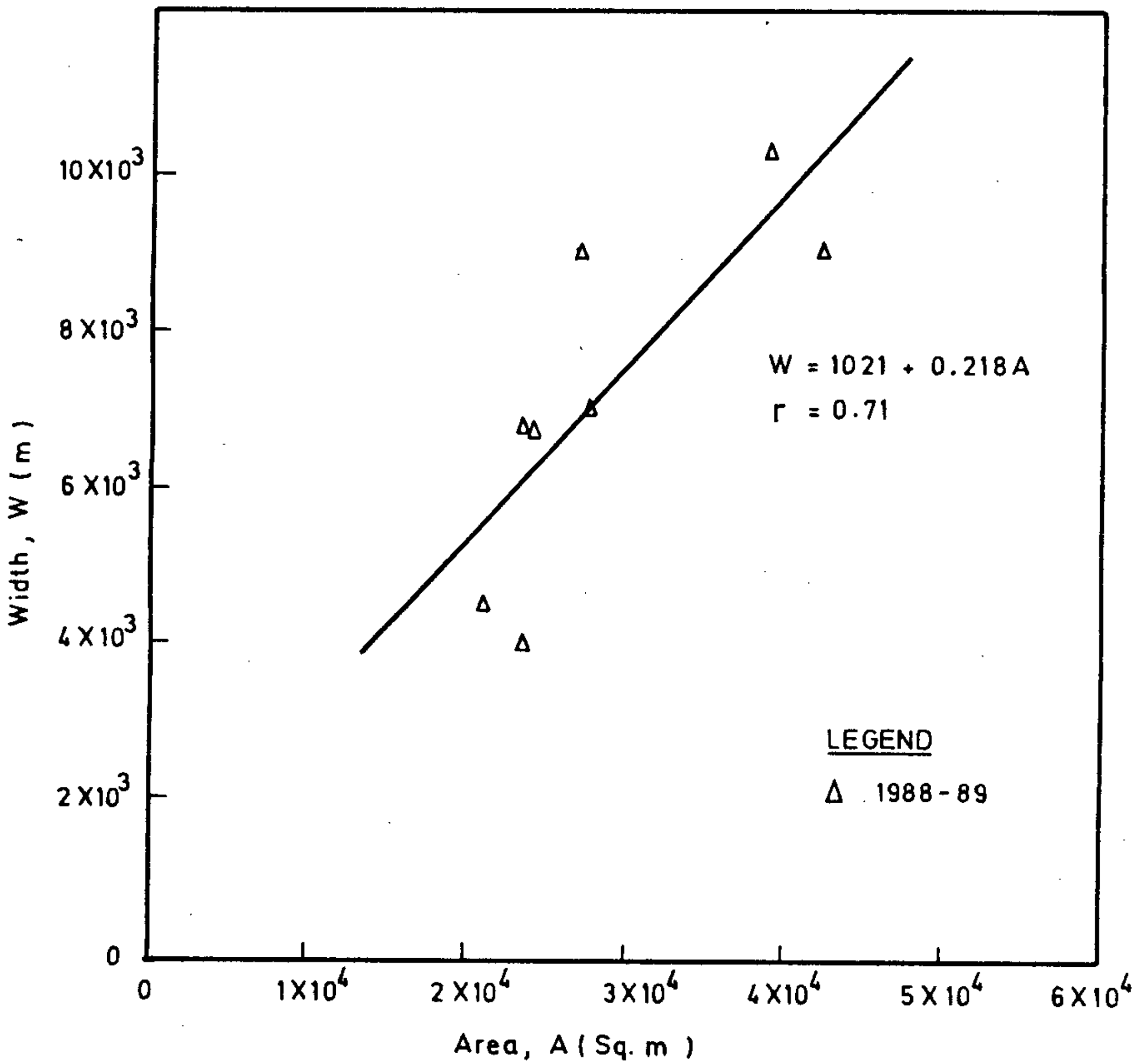

FIG. 5.14 RELATIONSHIP BETWEEN WIDTH AND CROSS SECTIONAL AREA OF THE GANGES RIVER (1988-89)

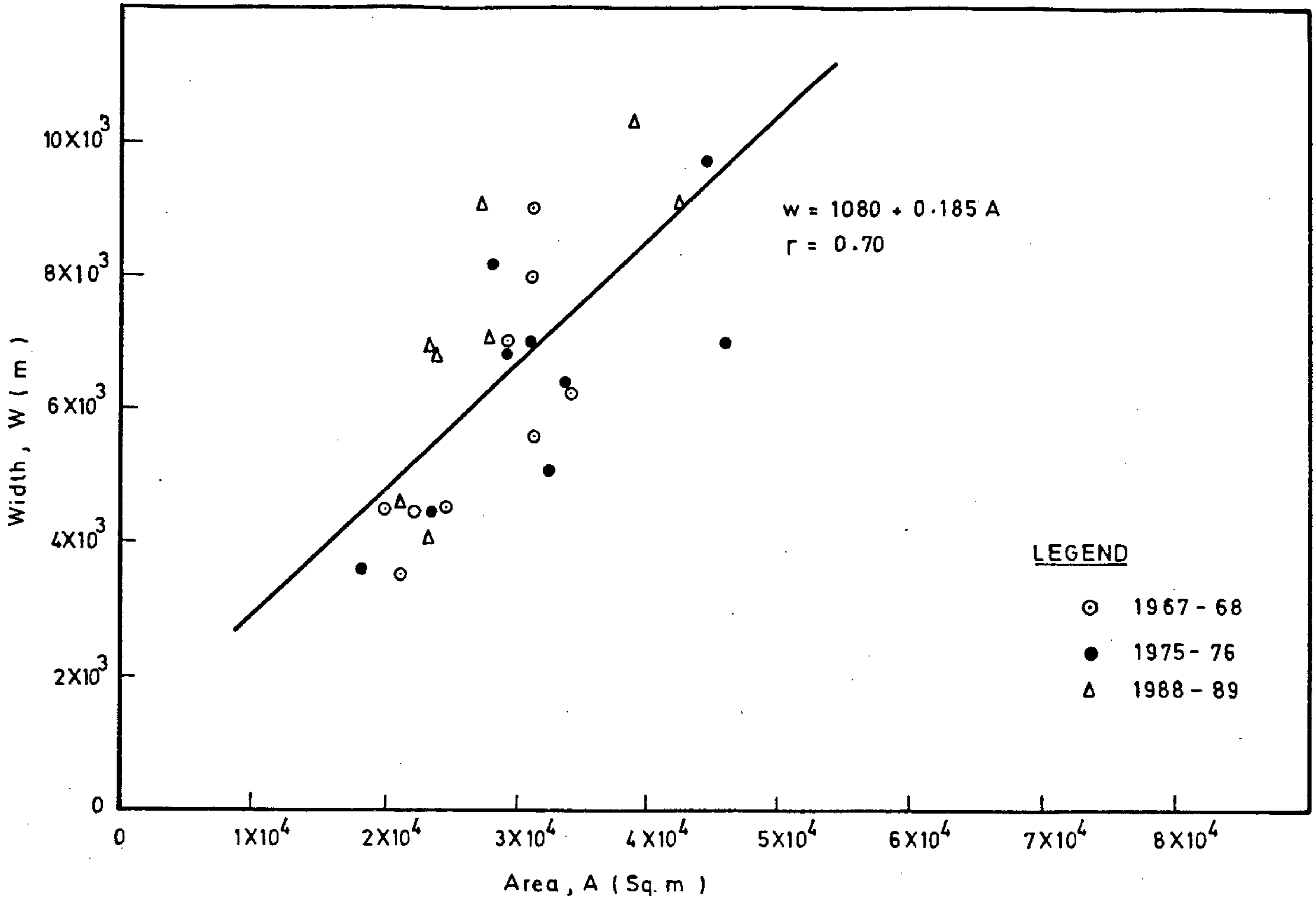

FIG. 5.15 RELATIONSHIP BETWEEN WIDTH AND CROSS-SECTIONAL AREA OF THE GANGES RIVER(1967-68, 75-76, 88-89)

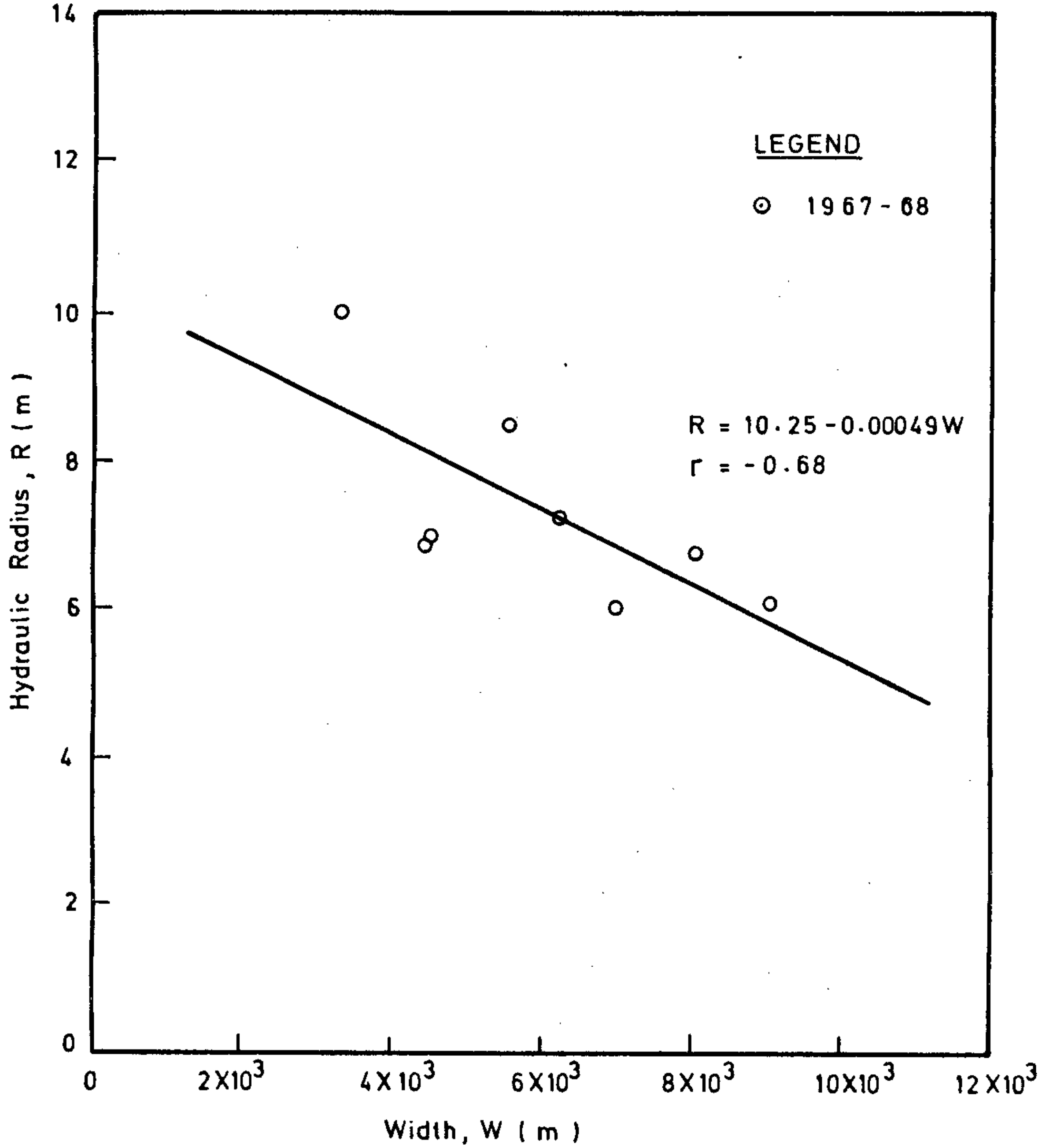

FIG. 5.16 RELATIONSHIP BETWEEN WIDTH AND HYDRAULIC RADIUS FOR THE GANGES (1967-68)

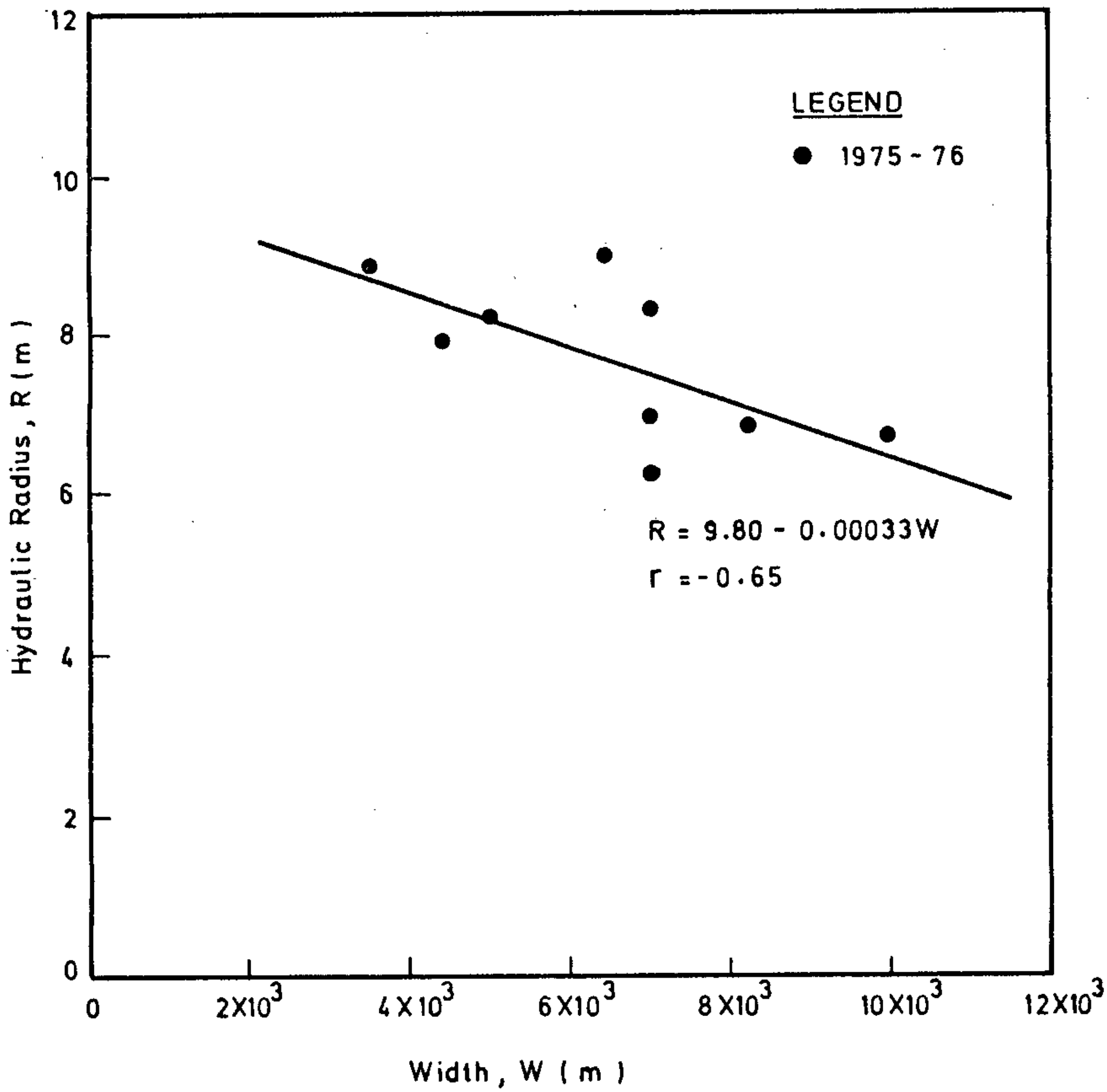

FIG. 5.17 RELATIONSHIP BETWEEN WIDTH AND HYDRAULIC RADIUS FOR THE GANGES (1975 - 76)

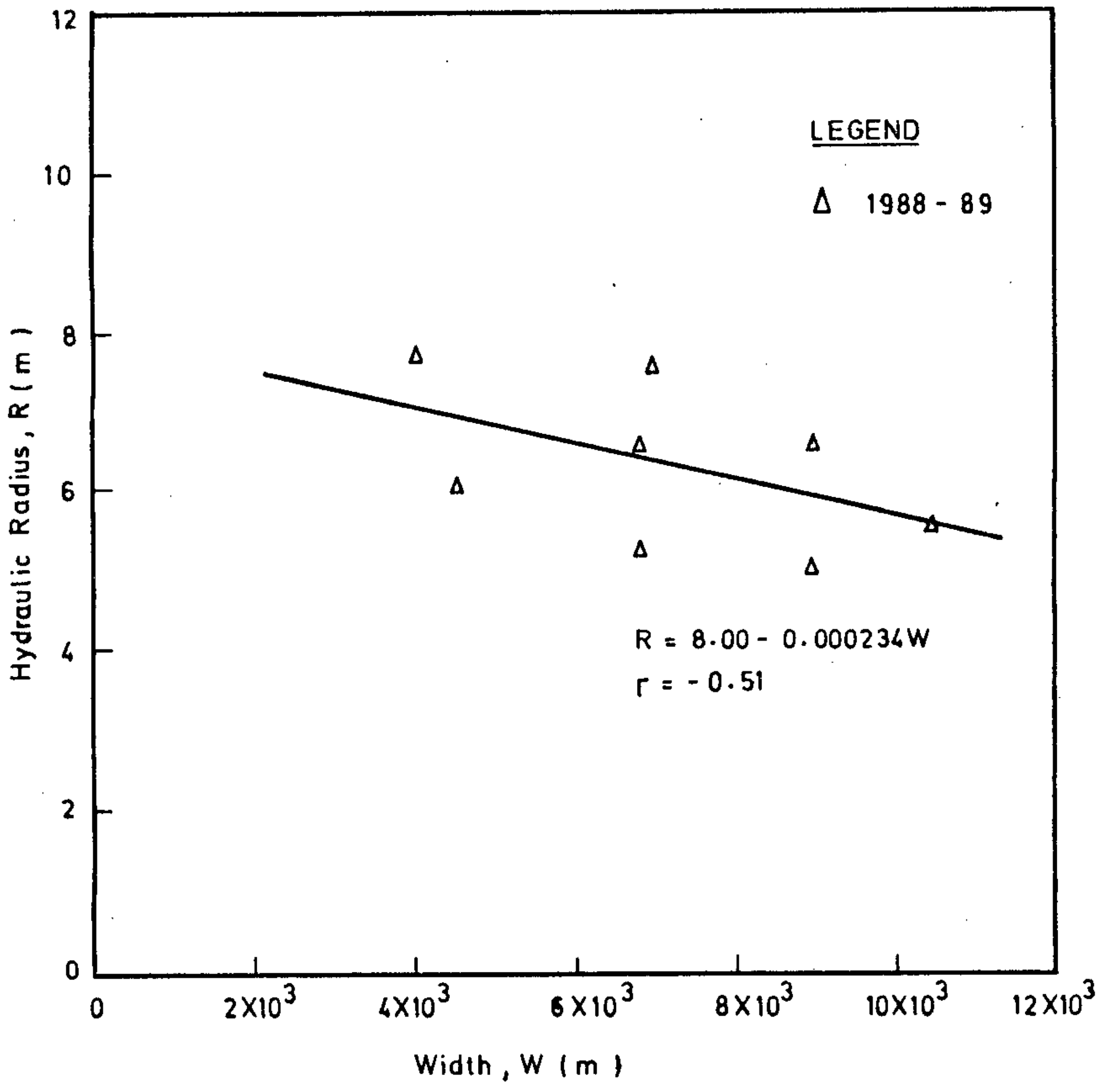

FIG. 5.18 RELATIONSHIP BETWEEN WIDTH AND HYDRAULIC RADIUS FOR THE GANGES (1988-89)

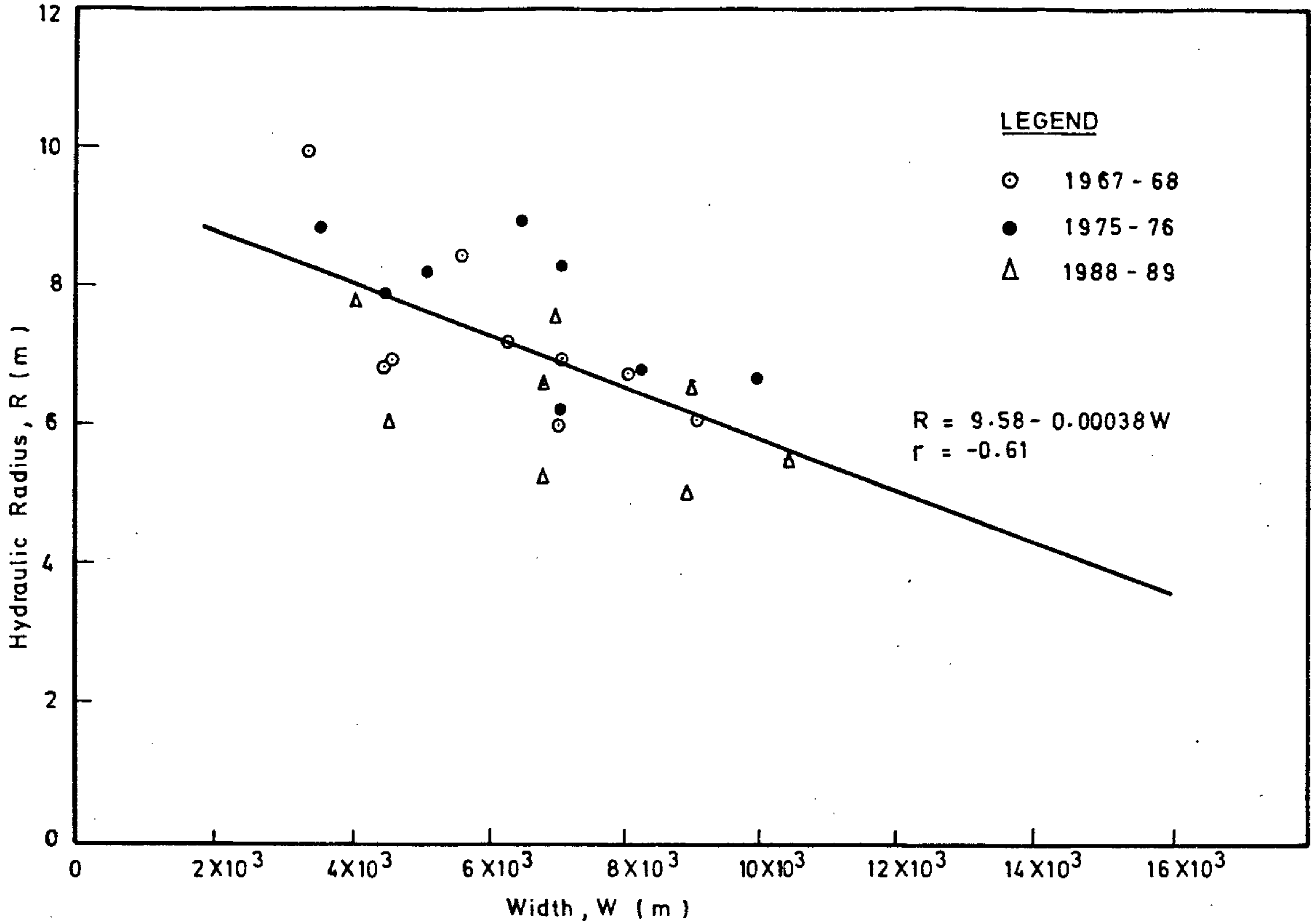

FIG. 5.19 RELATIOSHIP BETWEEN WIDTH AND HYDRAULIC RADIUS FOR THE GANGES (1967-68, 75-76, 88-89)

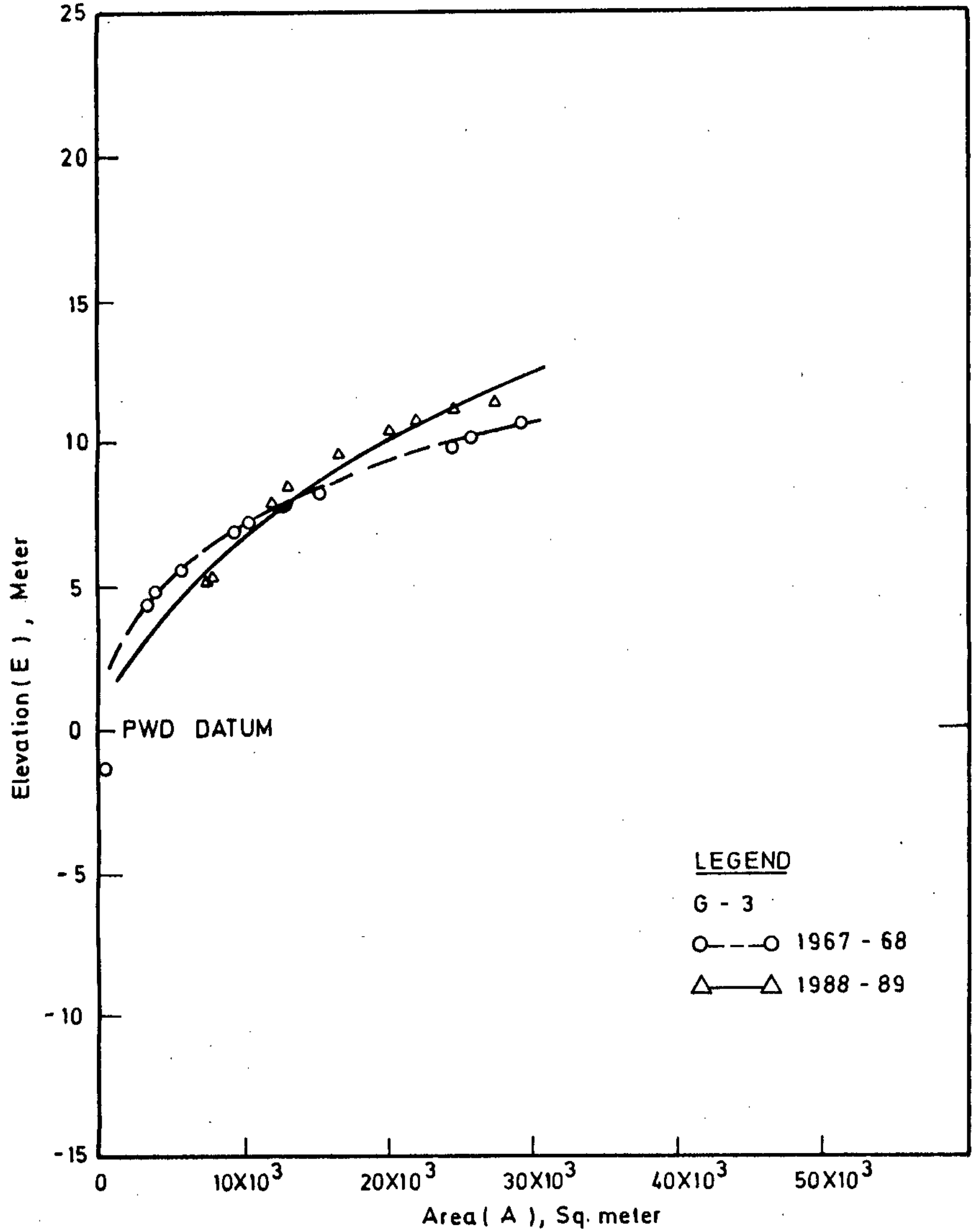

FIG. 5.20 RELATIONSHIP BETWEEN AREA AND ELEVATION FOR THE GANGES AT G-3

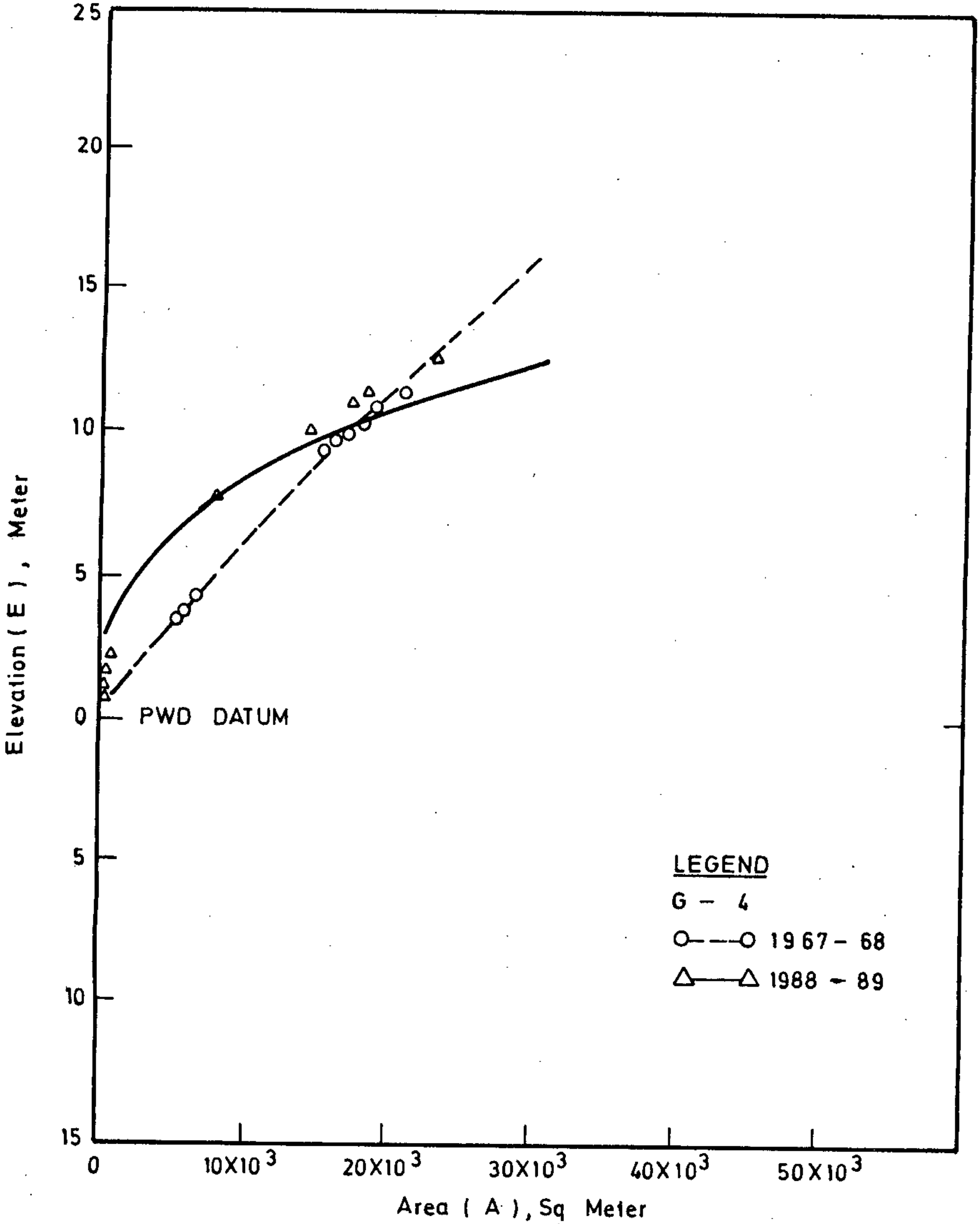

FIG. 5.21 RELATIONSHIP BETWEEN AREA AND ELEVATION FOR THE GANGES AT G-4

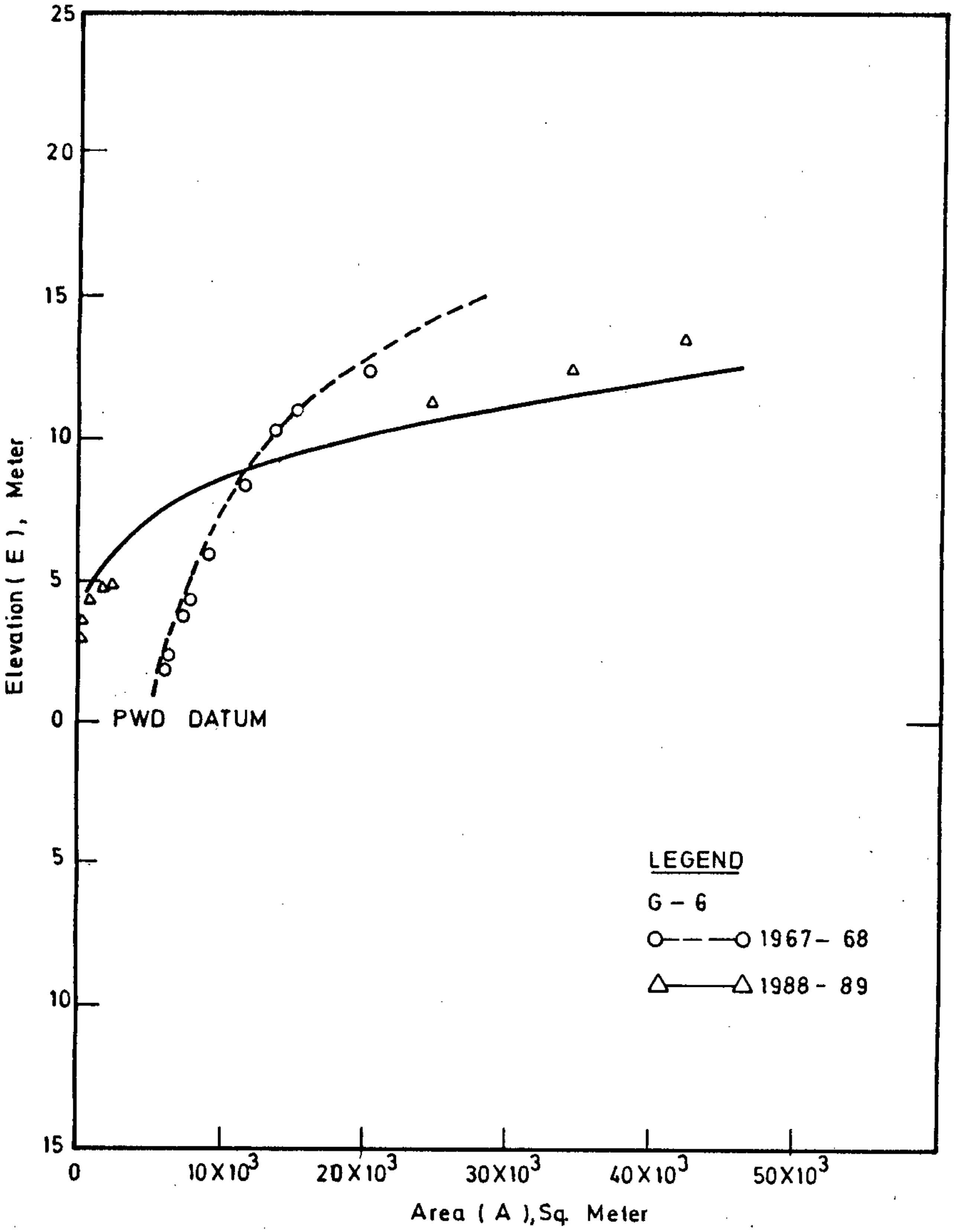

FIG. 5.22 RELATIONSHIP BETWEEN AREA AND ELEVATION FOR THE GANGES AT G-6

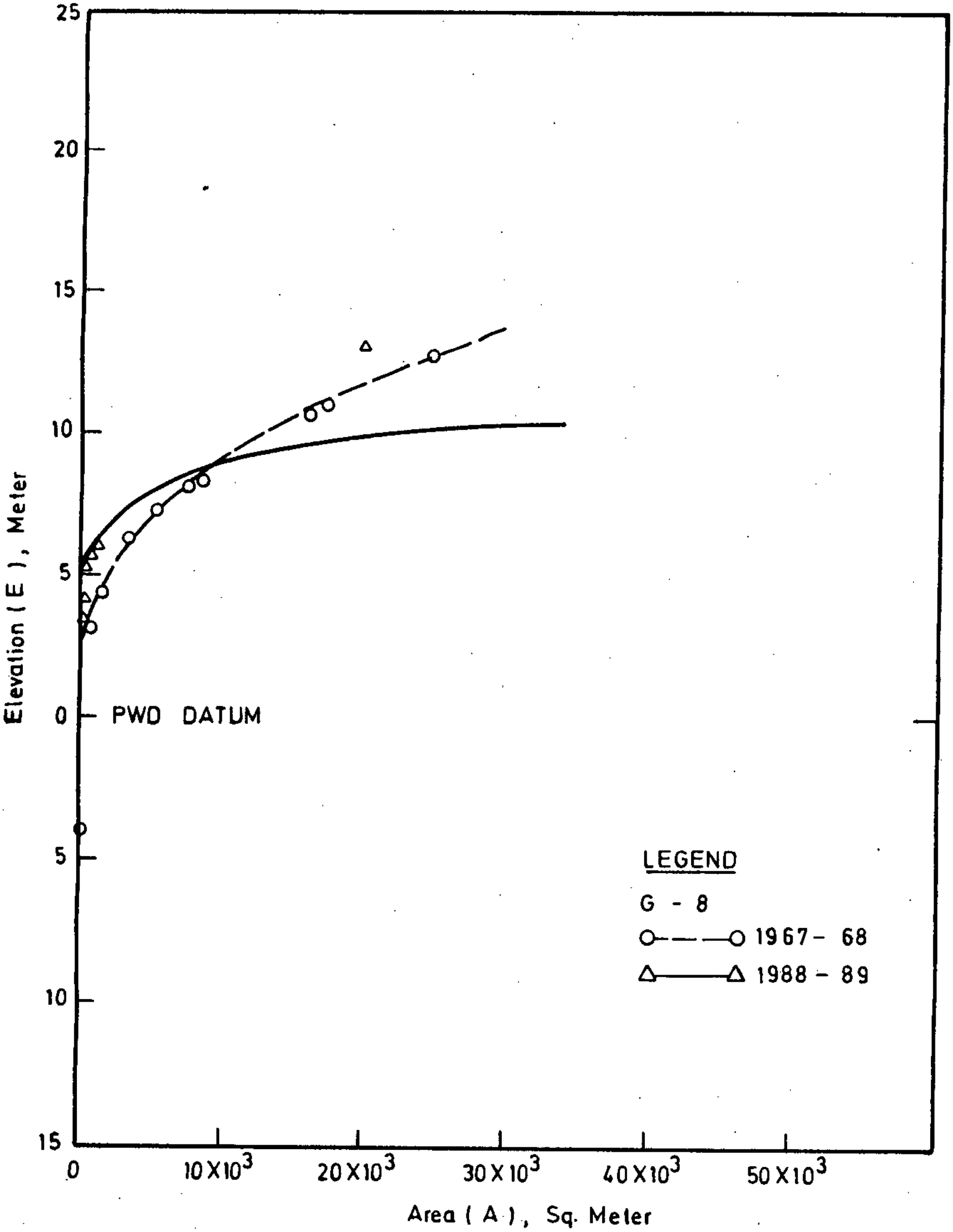

FIG. 5.23 RELATIONSHIP BETWEEN AREA AND ELEVATION FOR THE GANGES AT G-8

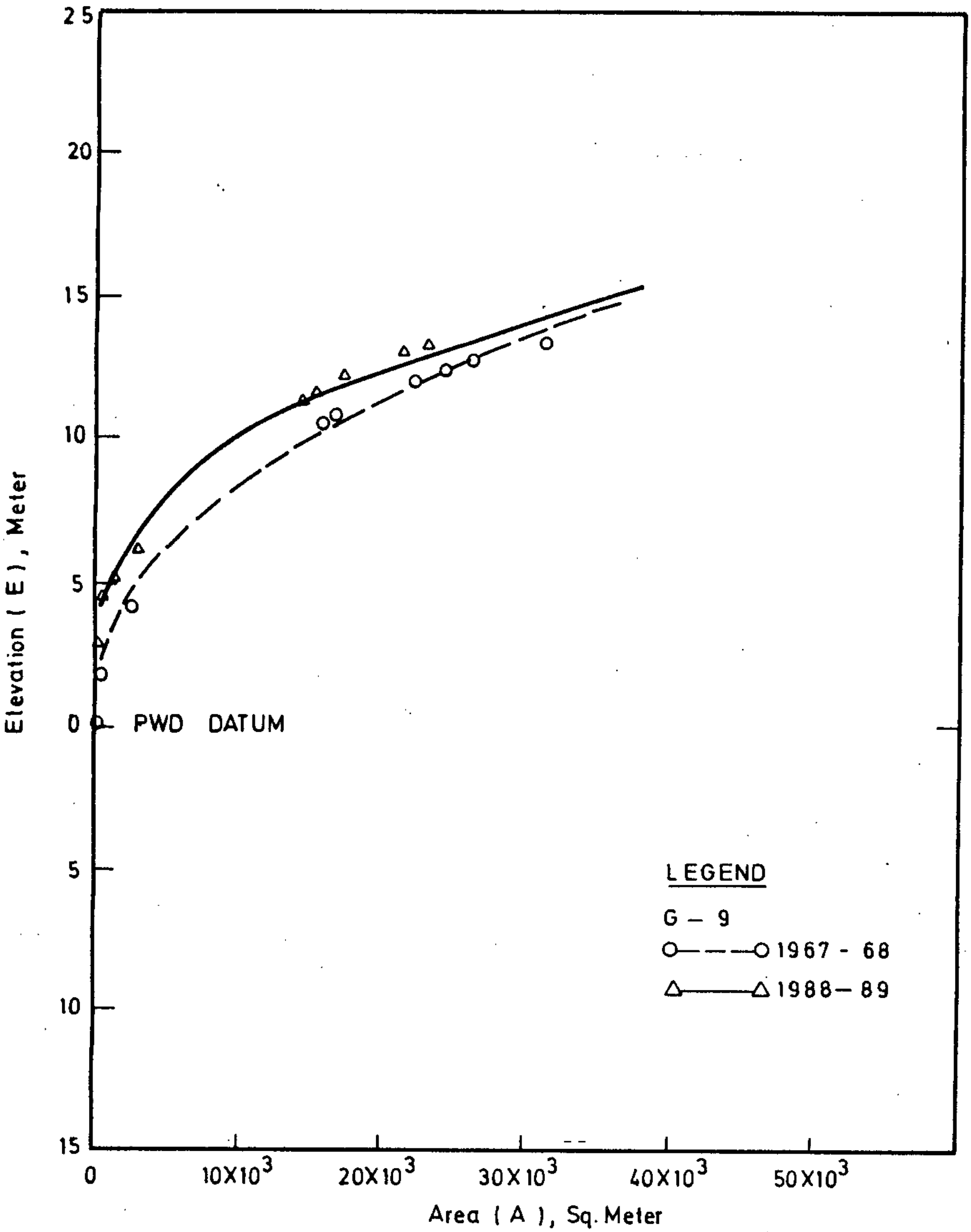

FIG. 5.24 RELATIONSHIP BETWEEN AREA AND ELEVATION FOR THE GANGES AT G-9

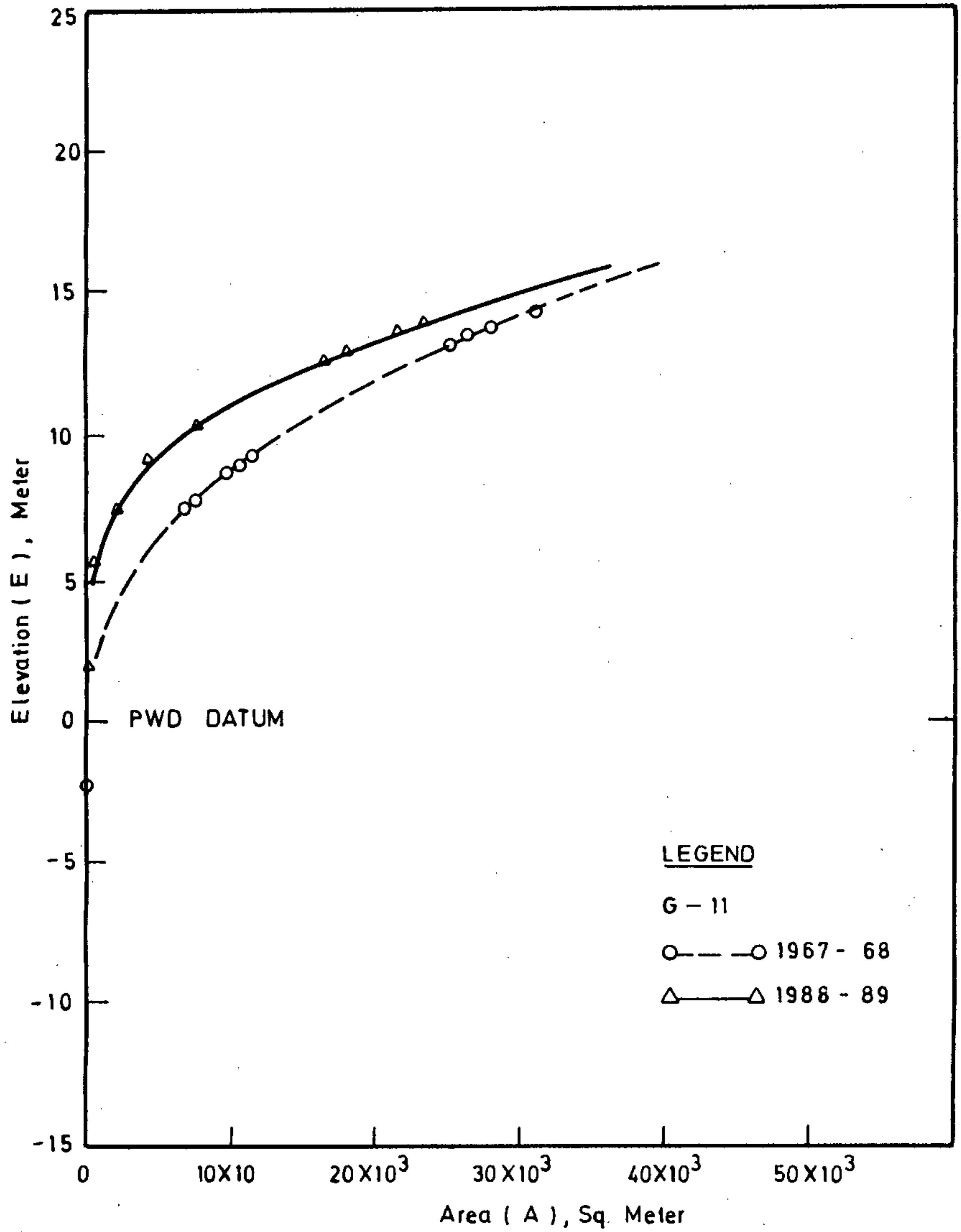

FIG. 5.25 RELATIONSHIP BETWEEN AREA AND ELEVATION FOR THE GANGES AT G-11

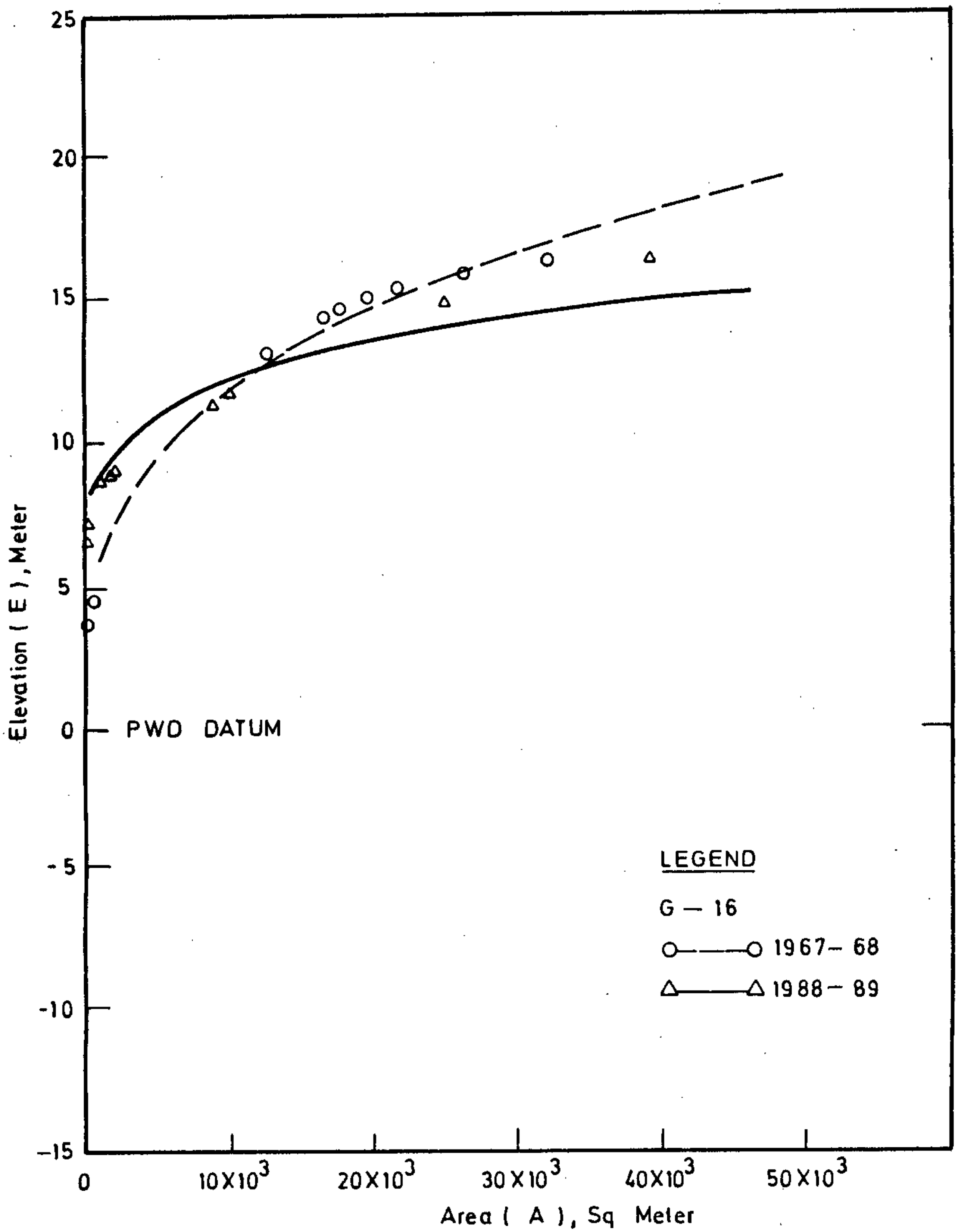

FIG. 5.26 RELATIONSHIP BETWEEN AREA AND ELEVATION FOR THE GANGES AT G-16

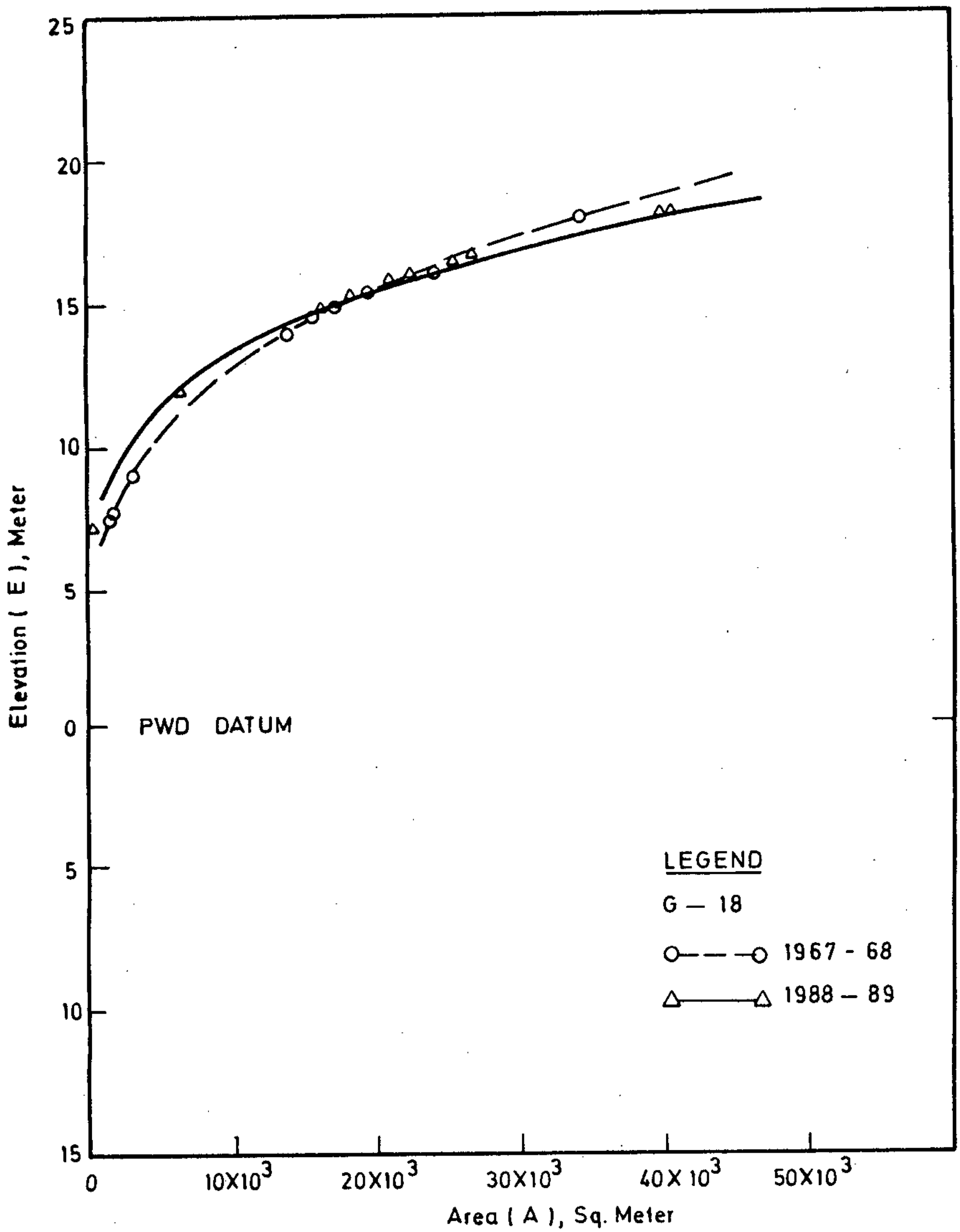

FIG. 5.27 RELATIONSHIP BETWEEN AREA AND ELEVATION FOR THE GANGES AT G-18

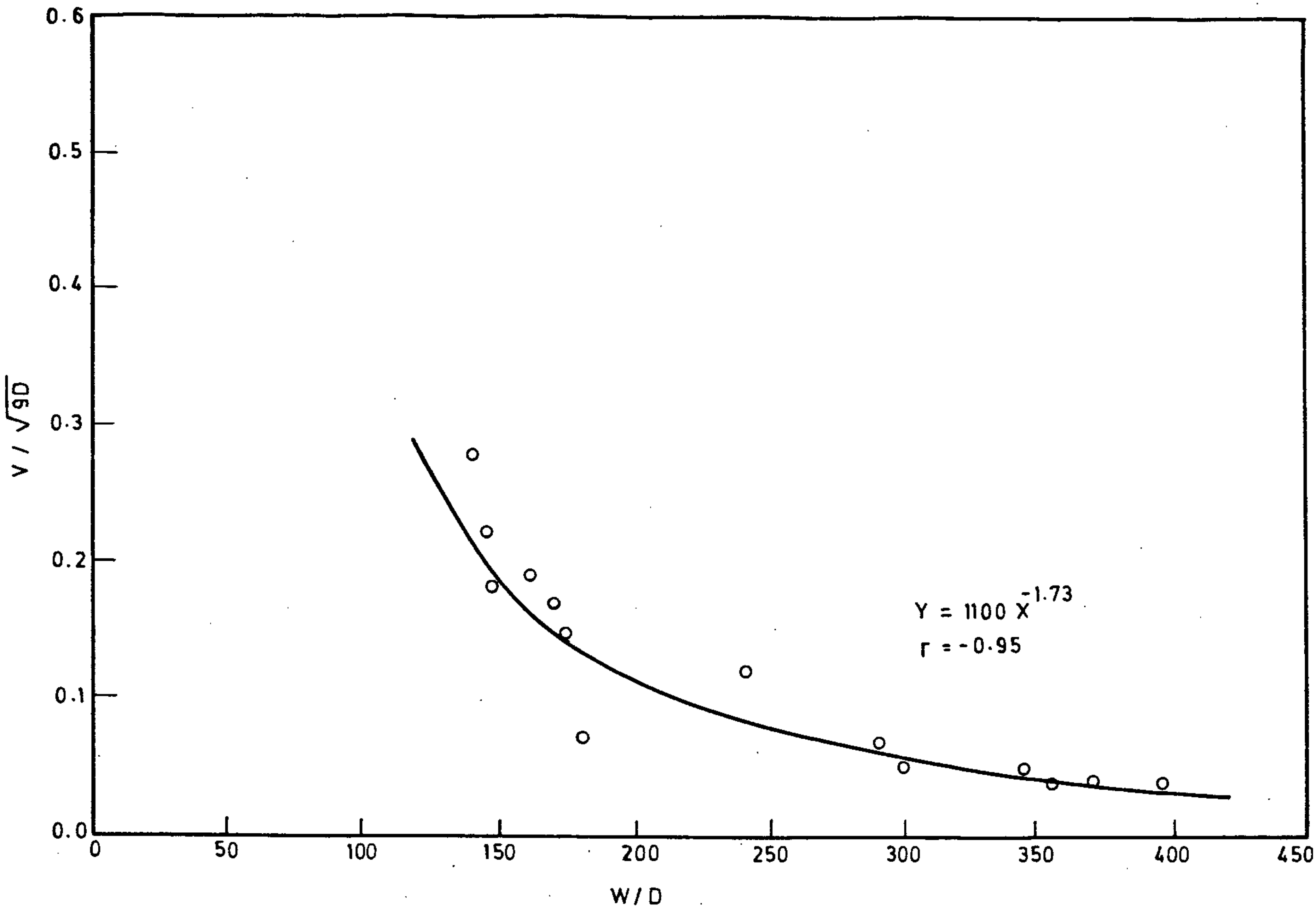

FIG. 5.28 RELATIONSHIP BETWEEN W/D AND $V/\sqrt{gD}$ FOR THE GANGES AT HARDINGE BRIDGE (1983).

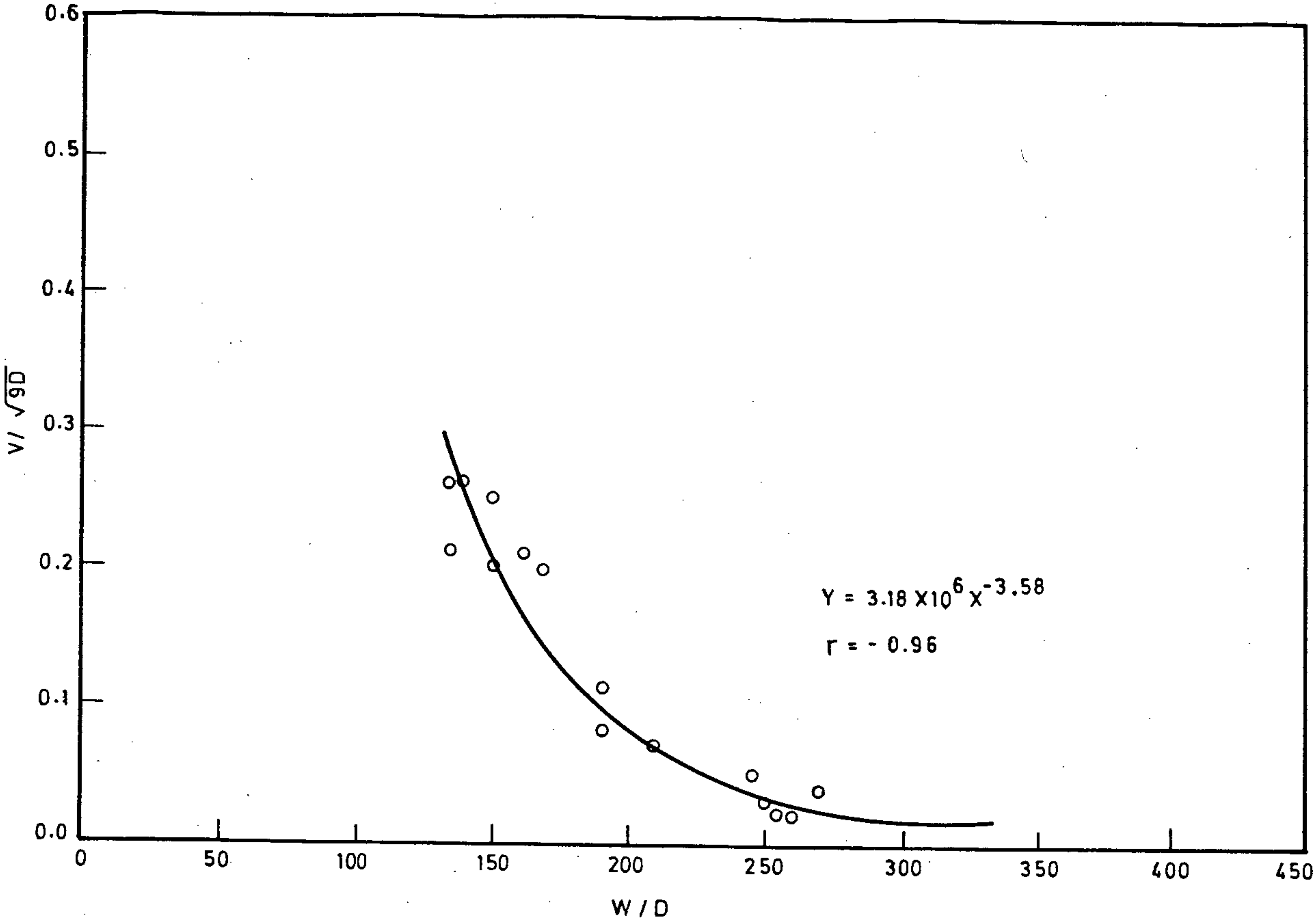

FIG. 5.29 RELATIONSHIP BETWEEN W/D AND $V/\sqrt{gD}$ FOR THE GANGES AT HARDINGE BRIDGE (1984).

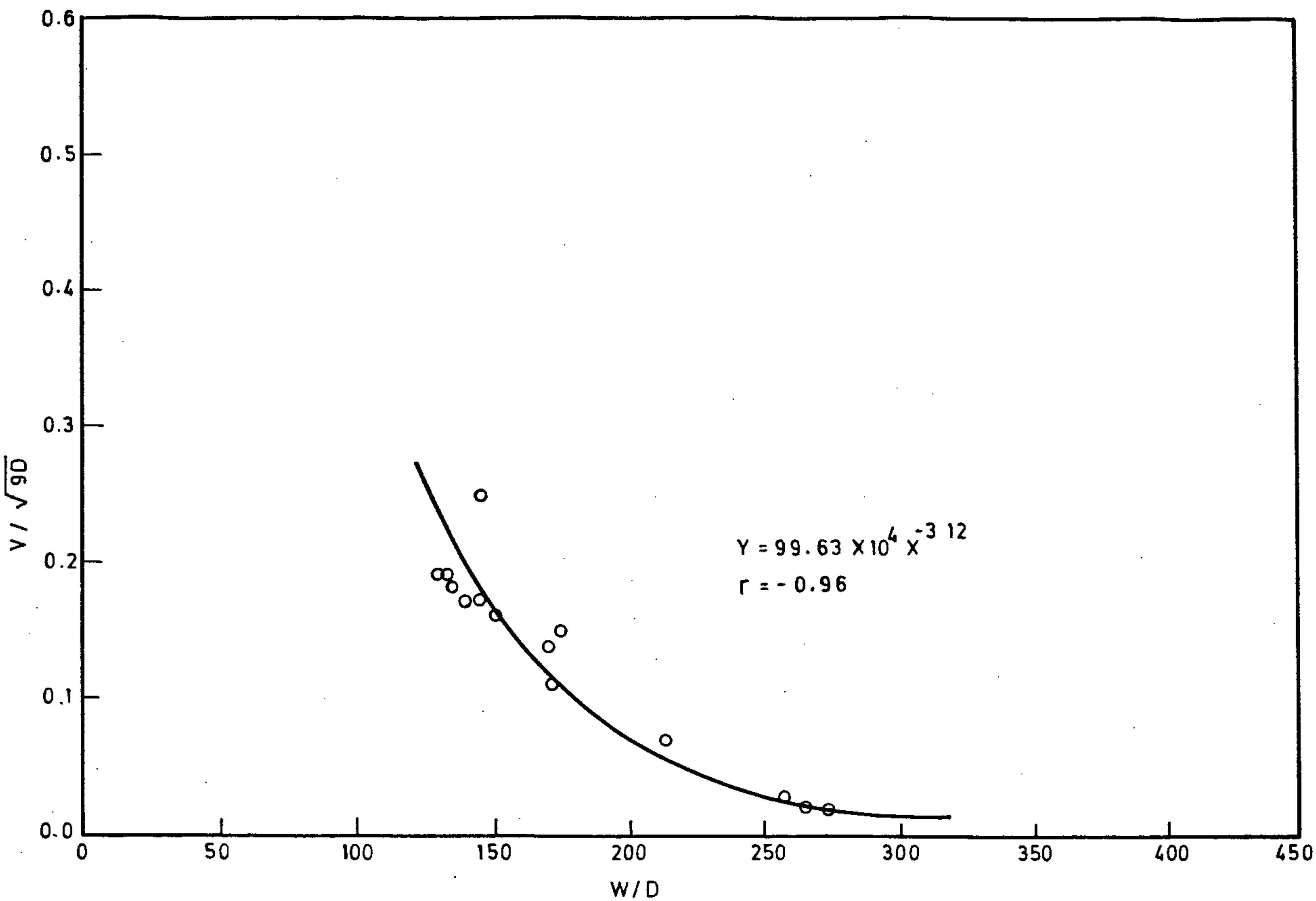

FIG. 5.30 RELATIONSHIP BETWEEN W/D AND $V/\sqrt{gD}$ FOR THE GANGES AT HARDINGE BRIDGE (1985).

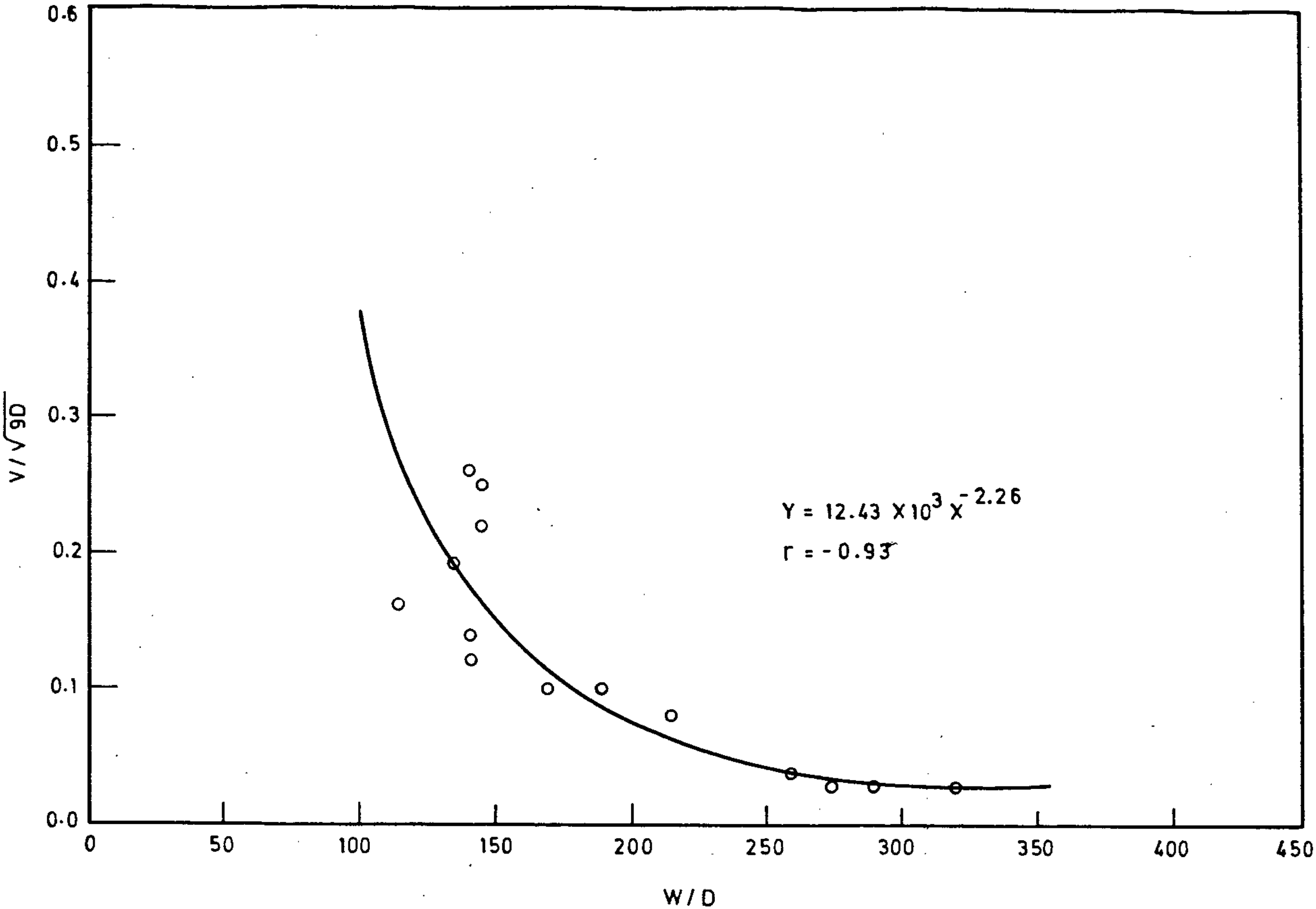

FIG. 5.31 RELATIONSHIP BETWEEN W/D AND V/√9D FOR THE GANGES AT HARDINGE BRIDGE (1986).

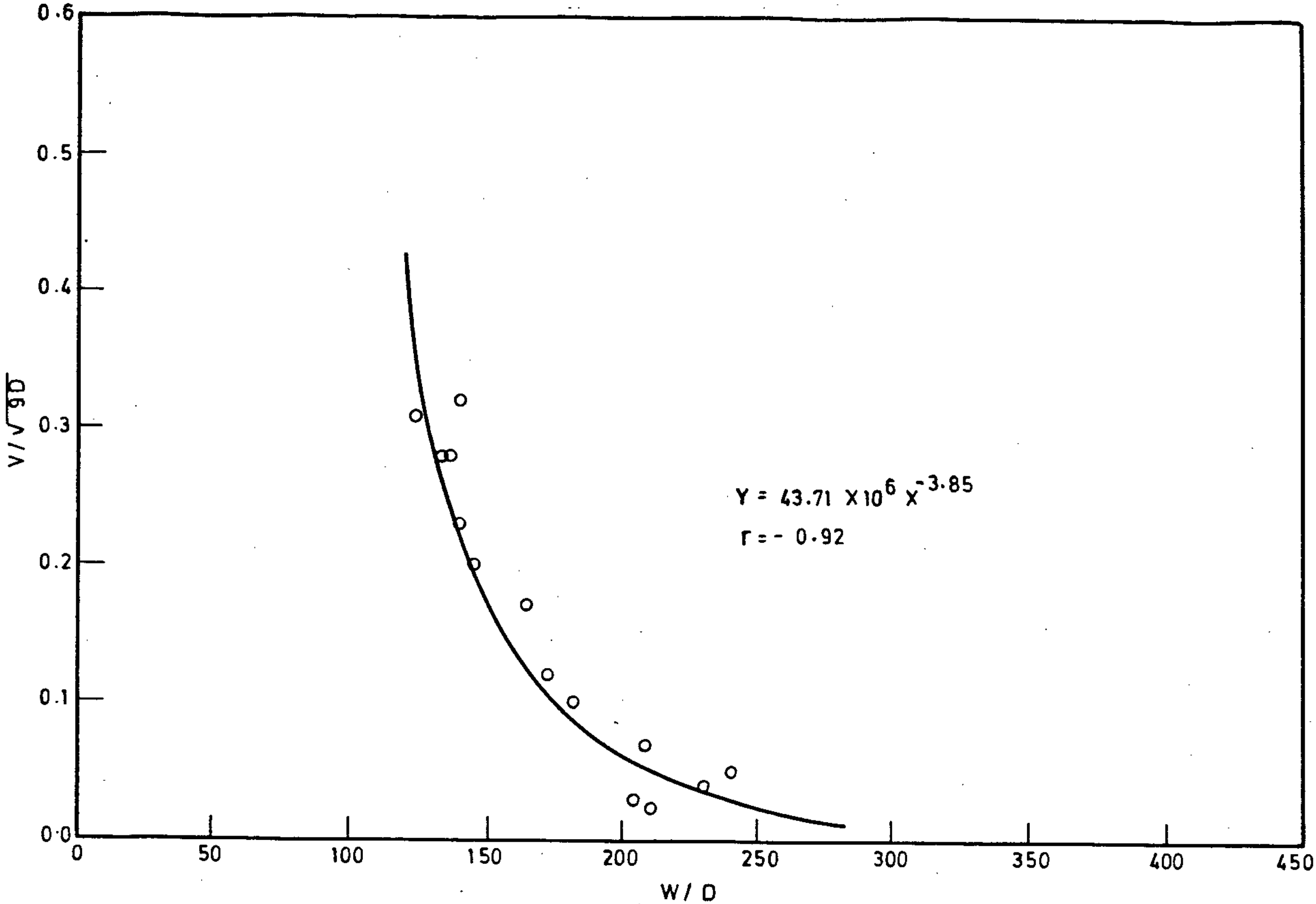

FIG. 5.32 RELATIONSHIP BETWEEN W/D AND $V/\sqrt{gD}$ FOR THE GANGES AT HARDINGE BRIDGE (1987).

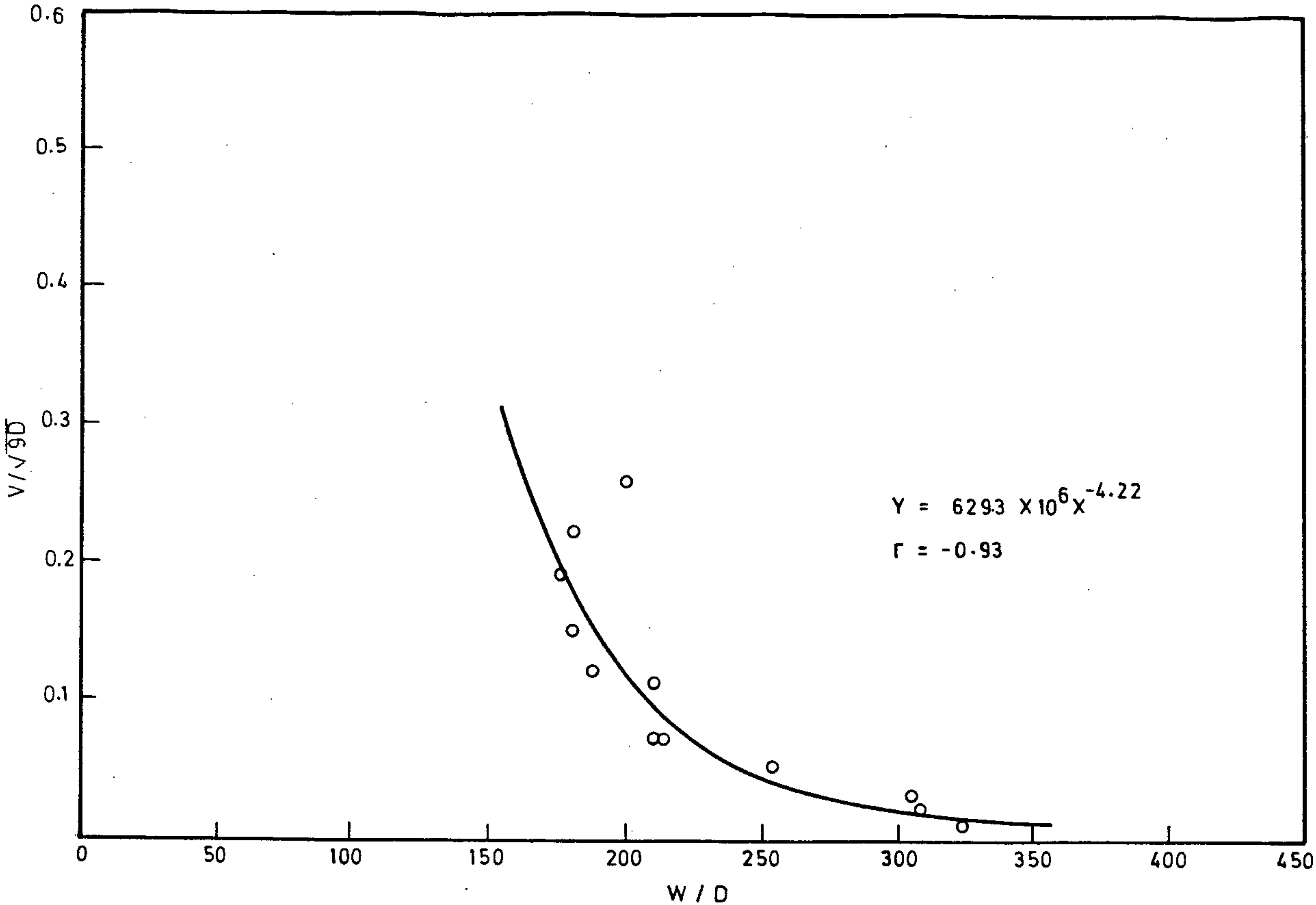

FIG. 5.33 RELATIONSHIP BETWEEN W/D AND $V/\sqrt{gD}$ FOR THE GANGES AT HARDINGE BRIDGE (1989).

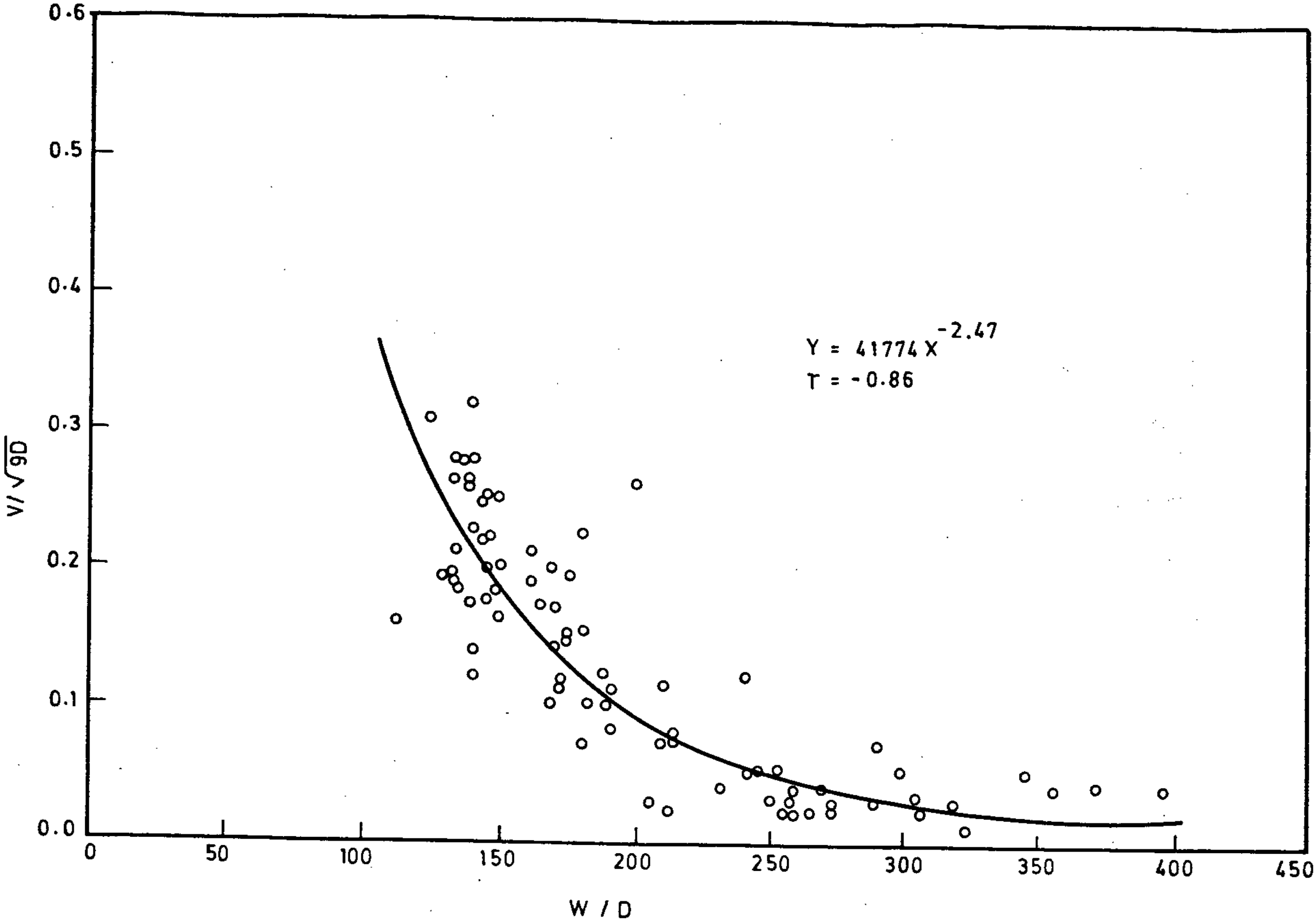

FIG. 5.34 RELATIONSHIP BETWEEN W/D AND $V/\sqrt{gD}$ FOR THE GANGES AT HARDINGE BRIDGE (1983-87, 89)

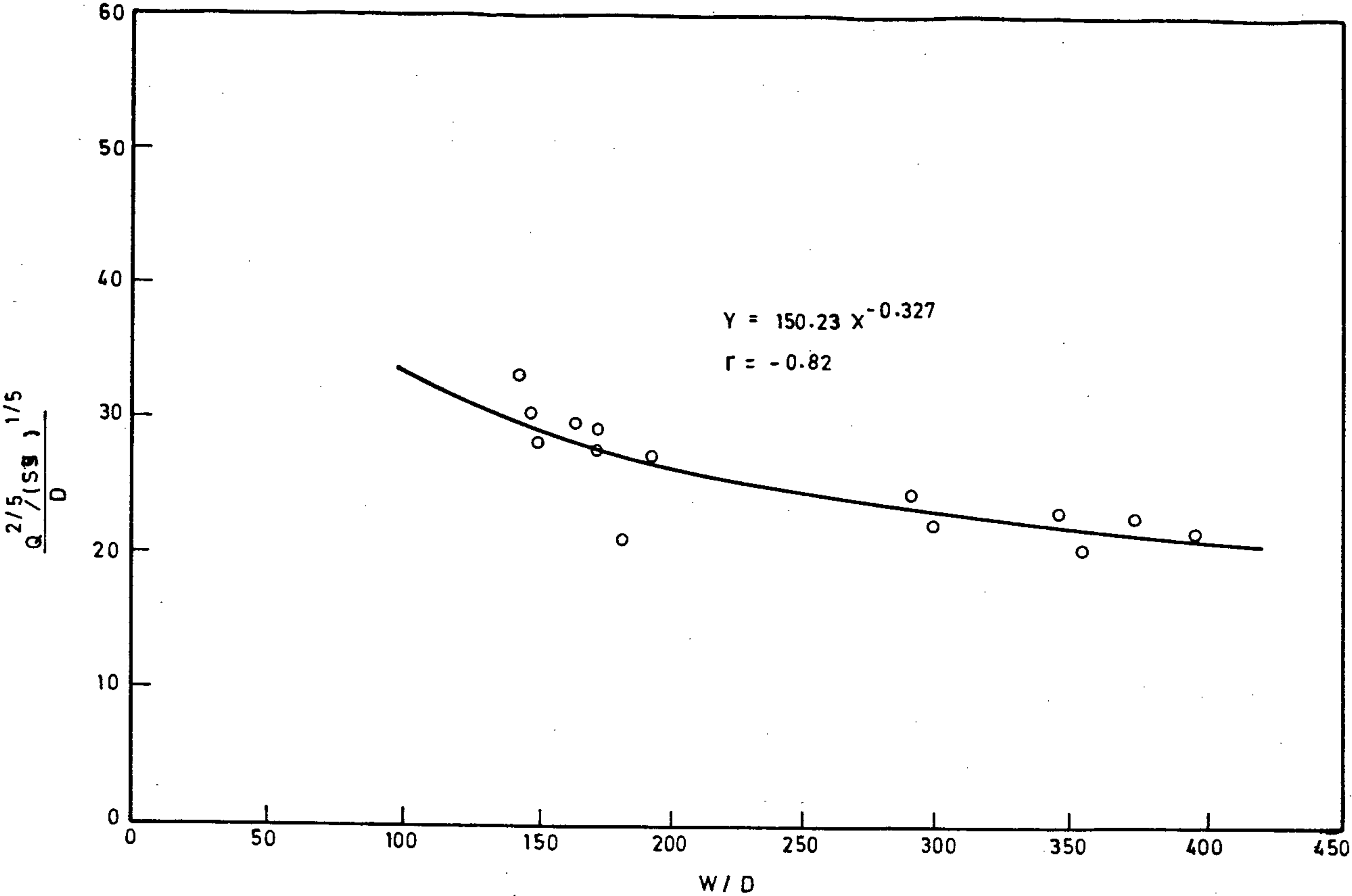

FIG. 5.35 RELATIONSHIP BETWEEN W/D AND $\frac{Q^{2/5}/(Sg)^{1/5}}{D}$ FOR THE GANGES AT HARDINGE BRIDGE (1983)

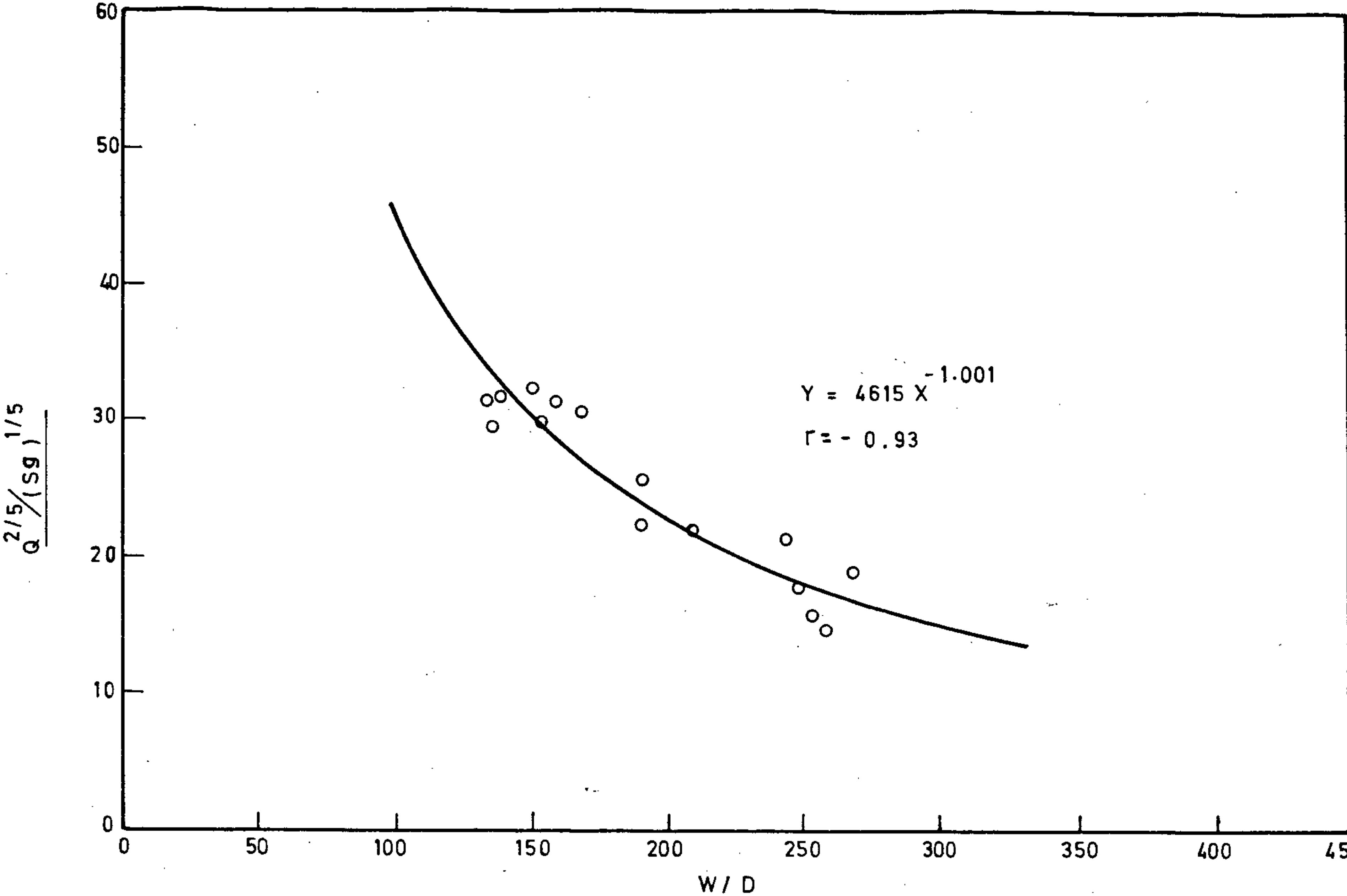

FIG. 5.36 RELATIONSHIP BETWEEN W/D AND $\frac{Q^{2/5}/(Sg)^{1/5}}{D}$ FOR THE GANGES AT HARDINGE BRIDGE (1984)

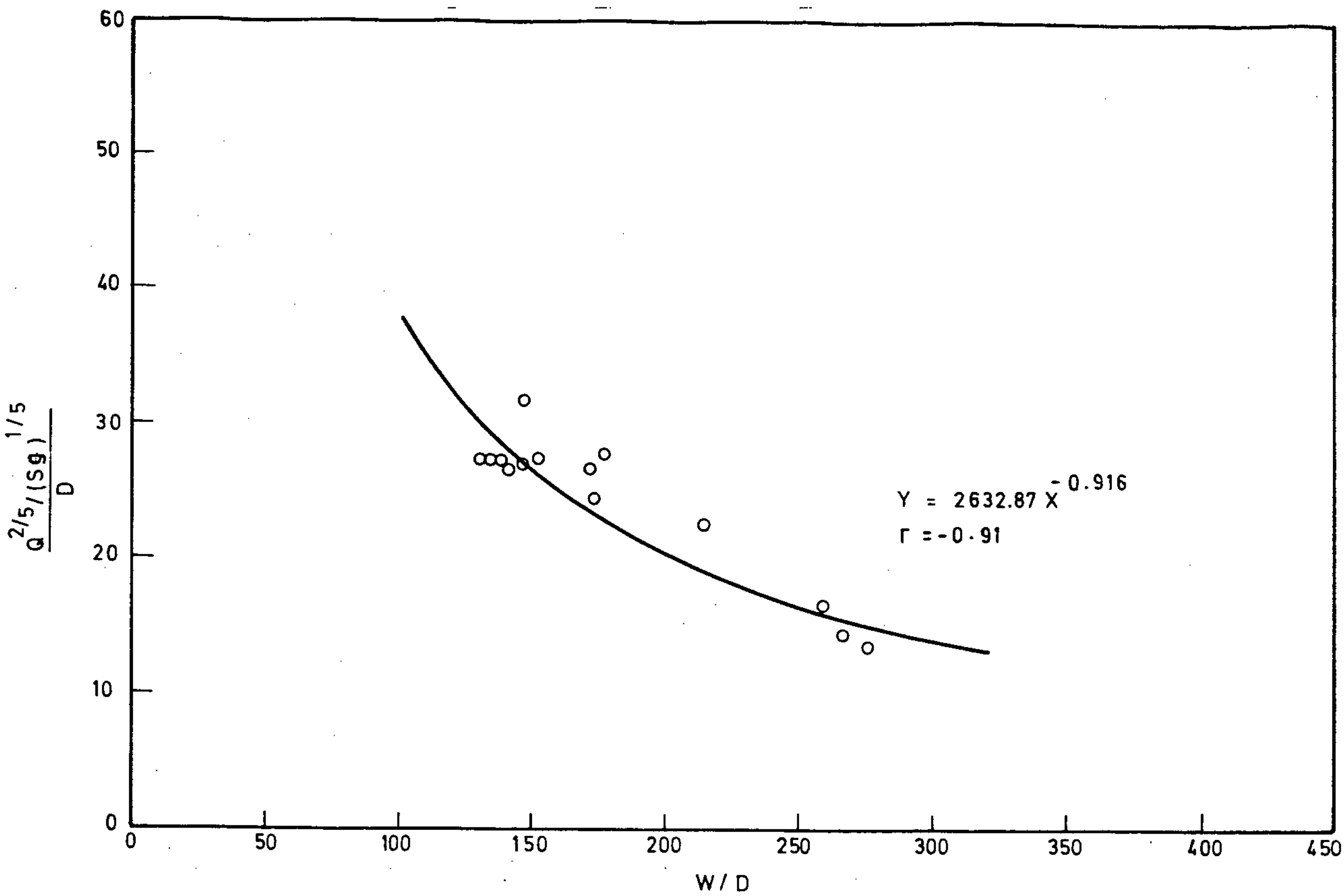

FIG. 5.37 RELATIONSHIP BETWEEN W/D AND $\frac{Q^{2/5}/(Sg)^{1/5}}{D}$ FOR THE GANGES AT HARDINGE BRIDGE (1985)

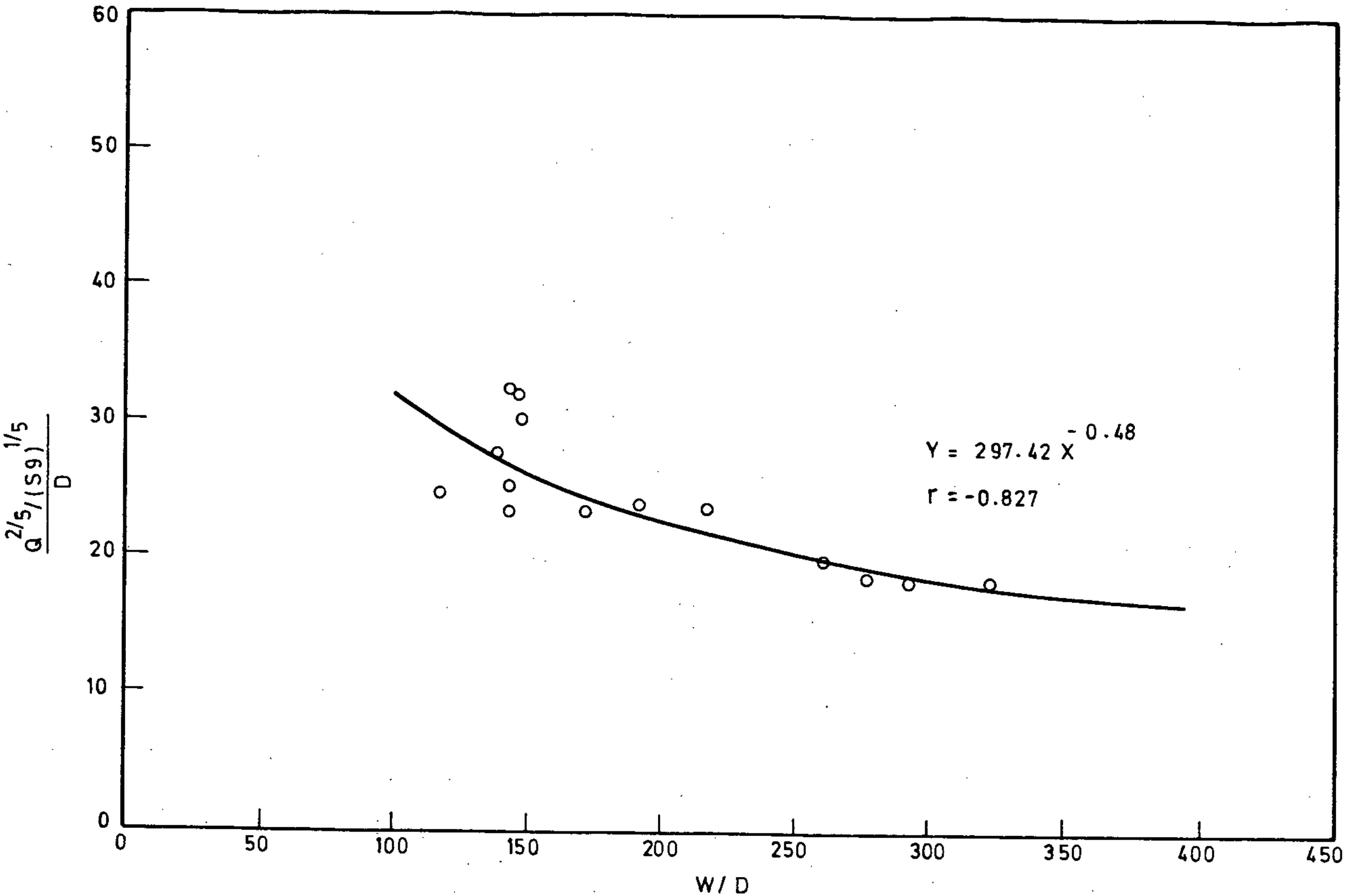

FIG. 5.38 RELATIONSHIP BETWEEN W/D AND $\frac{Q^{2/5}/(S9)^{1/5}}{D}$ FOR THE GANGES AT HARDINGE BRIDGE (1986)

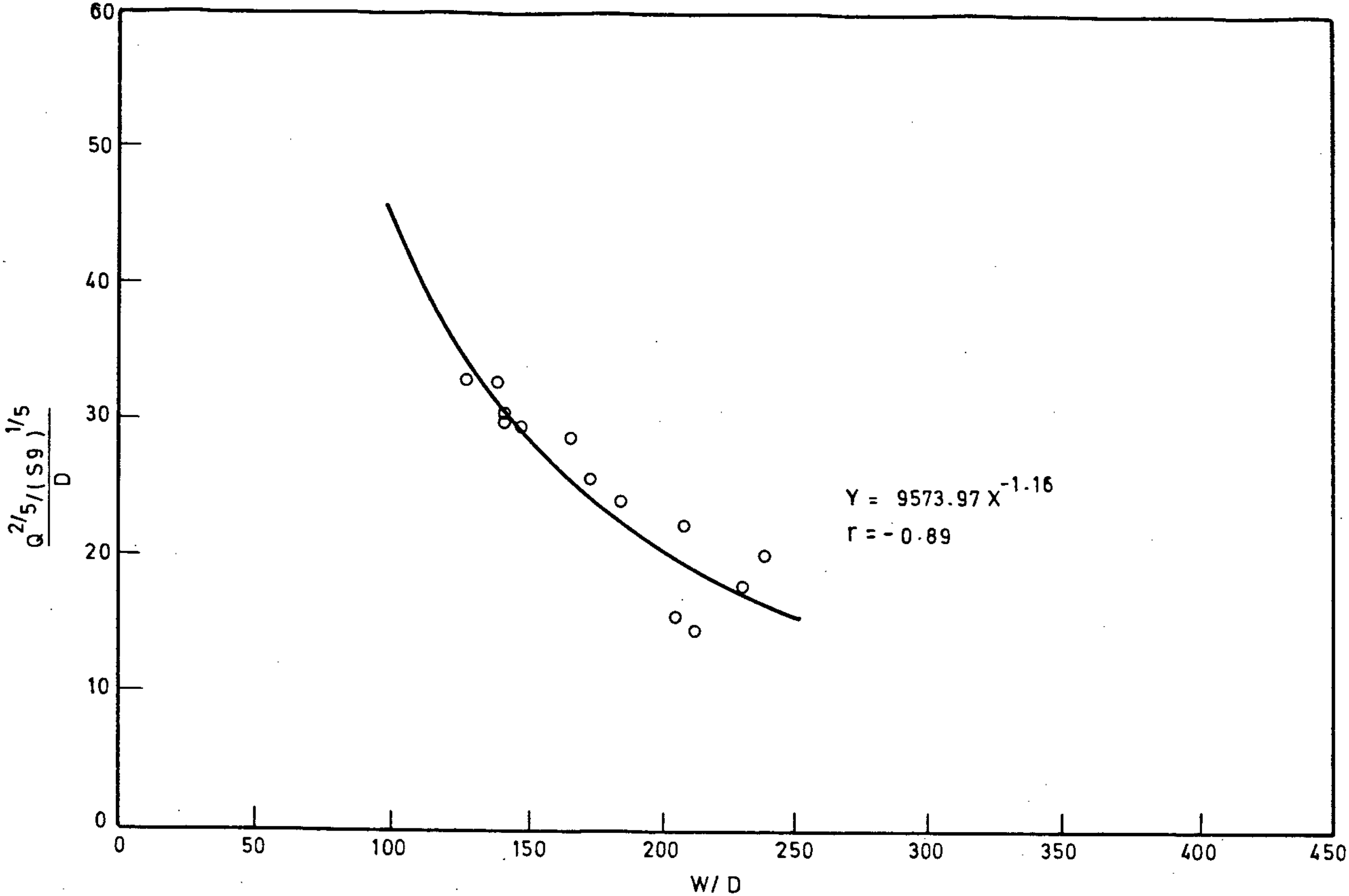

FIG. 5. 39 RELATIONSHIP BETWEEN W/D AND $\frac{Q^{2/5}/(S9)^{1/5}}{D}$ FOR THE GANGES AT HARDINGE BRIDGE (1987)

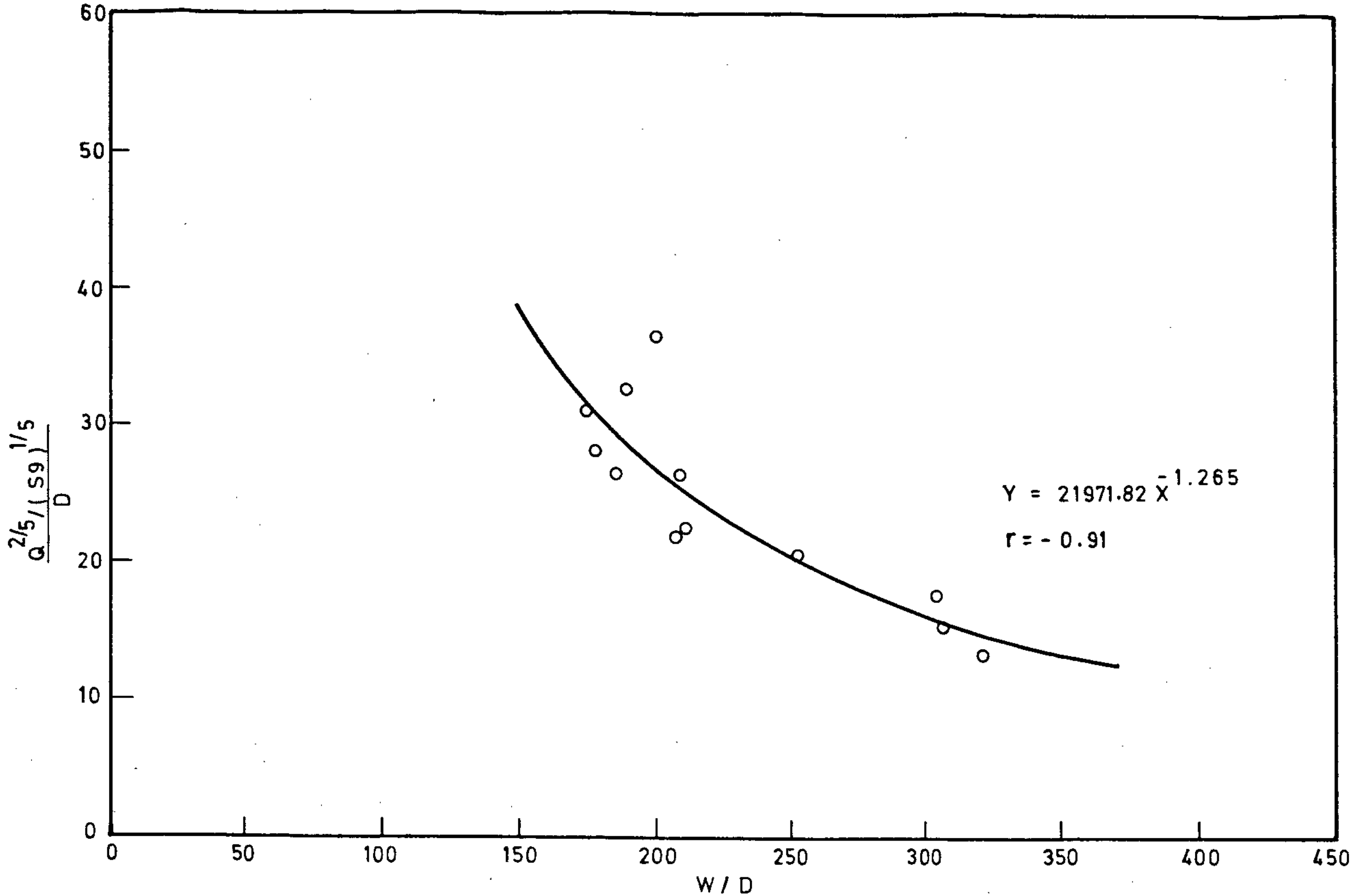

FIG. 5. 40 RELATIONSHIP BETWEEN W/D AND $\frac{Q^{2/5}/(S9)^{1/5}}{D}$ FOR THE GANGES AT HARDINGE BRIDGE (1989)

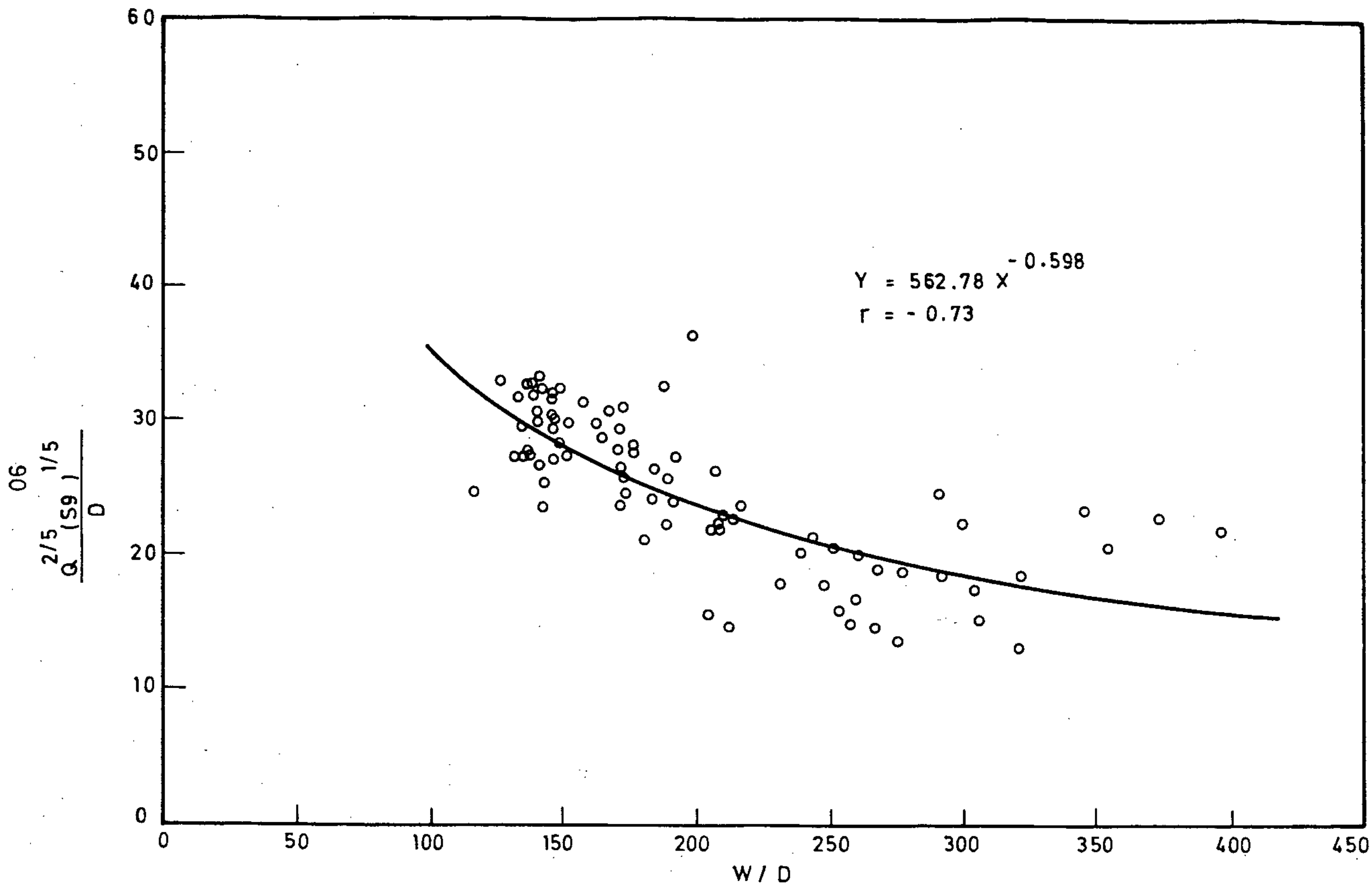

FIG. 5.41 RELATION BETWEEN W/D AND $\frac{Q^{2/5}/(Sg)^{1/5}}{D}$ FOR THE GANGES AT HARDINGE BRIDGE (1983-87, 89)

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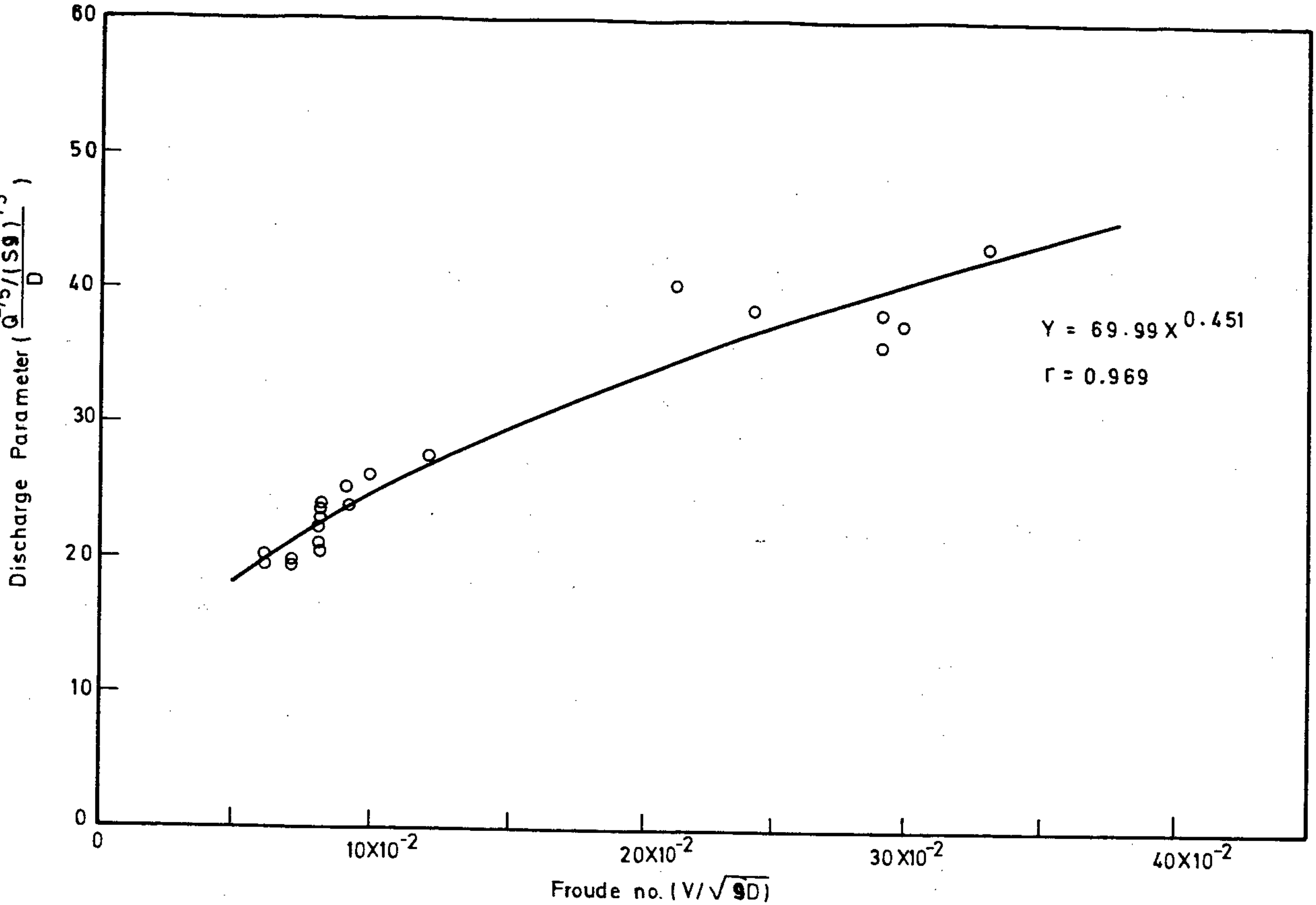

FIG. 5.42 RELATIONSHIP BETWEEN $V/\sqrt{gD}$ AND $\frac{Q^{2/5}/(Sg)^{1/5}}{D}$ FOR THE GANGES AT HARDINGE BRIDGE (1970

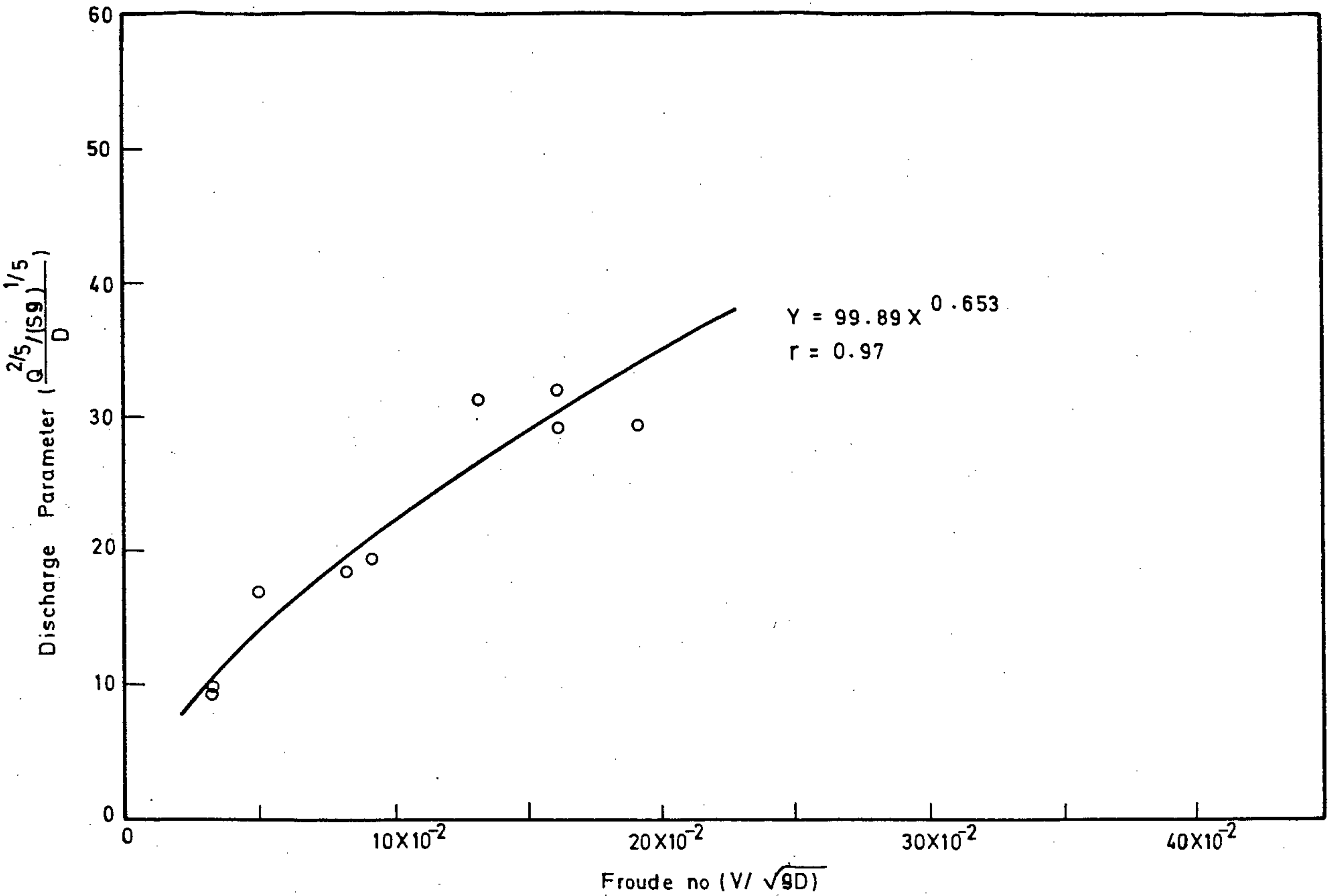

FIG. 5.43 RELATIONSHIP BETWEEN $V/\sqrt{gD}$ AND $\frac{Q^{2/5}/(Sg)^{1/5}}{D}$ FOR THE GANGES AT HARDING BRIDGE (1974)

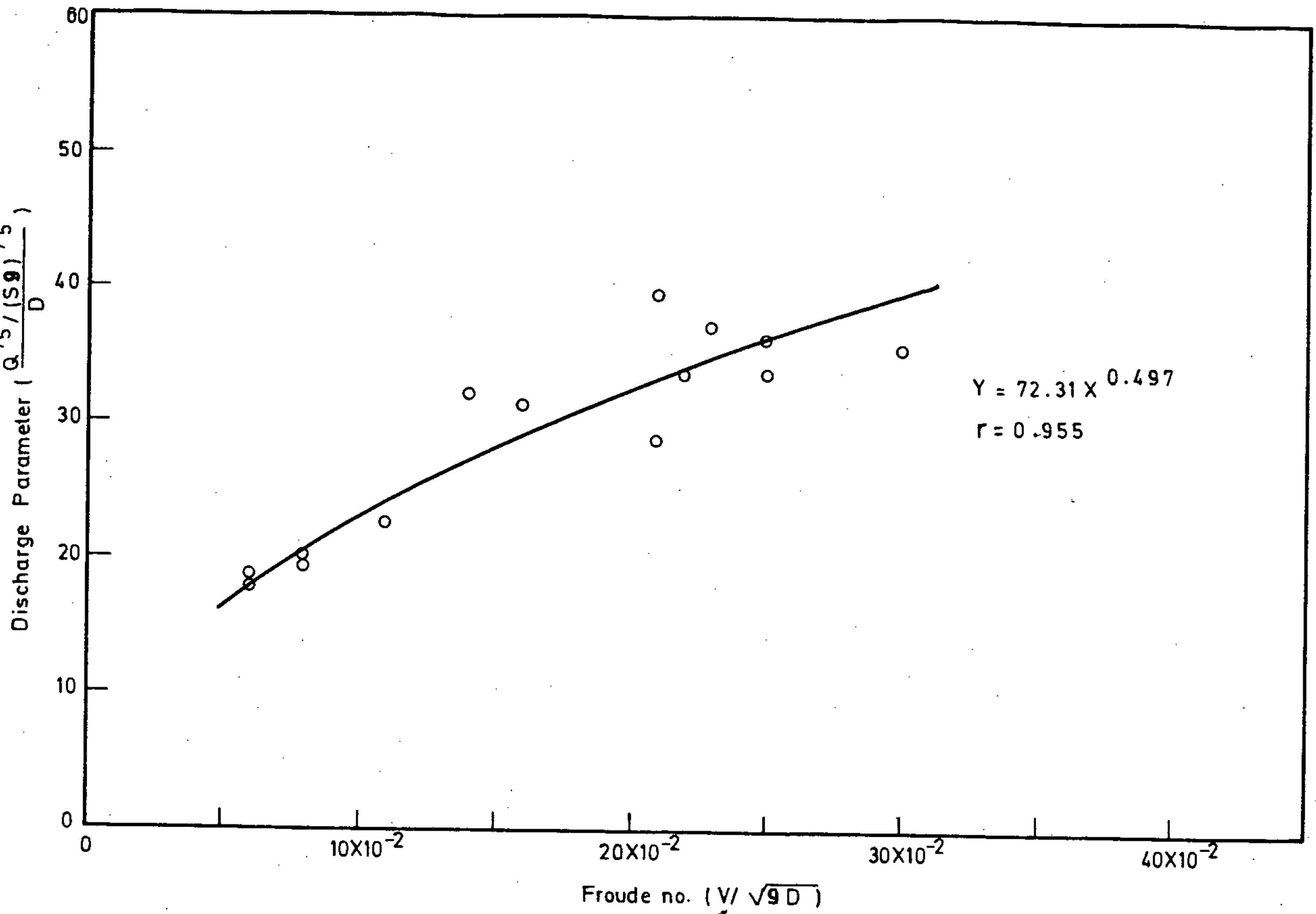

FIG. 5.44 RELATIONSHIP BETWEEN $V/\sqrt{gD}$ AND $\frac{Q^{2/5}/(Sg)^{1/5}}{D}$ FOR THE GANGES AT HARDING BRIDGE (1975)

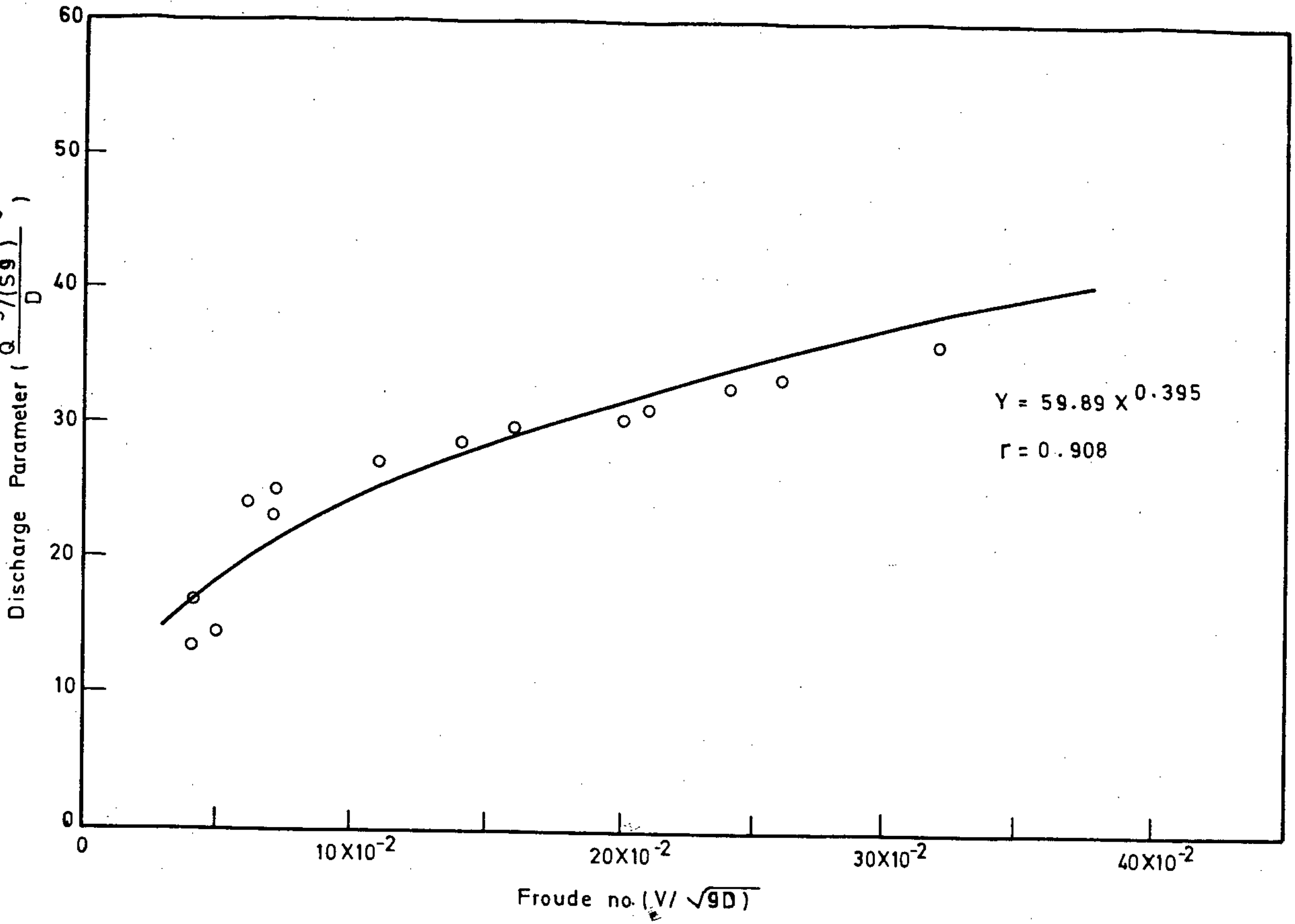

FIG. 5.45 RELATIONSHIP BETWEEN $V/\sqrt{gD}$ AND $\frac{Q^{2/5}/(Sg)^{1/5}}{D}$ FOR THE GANGES AT HARDING BRIDGE (1980)

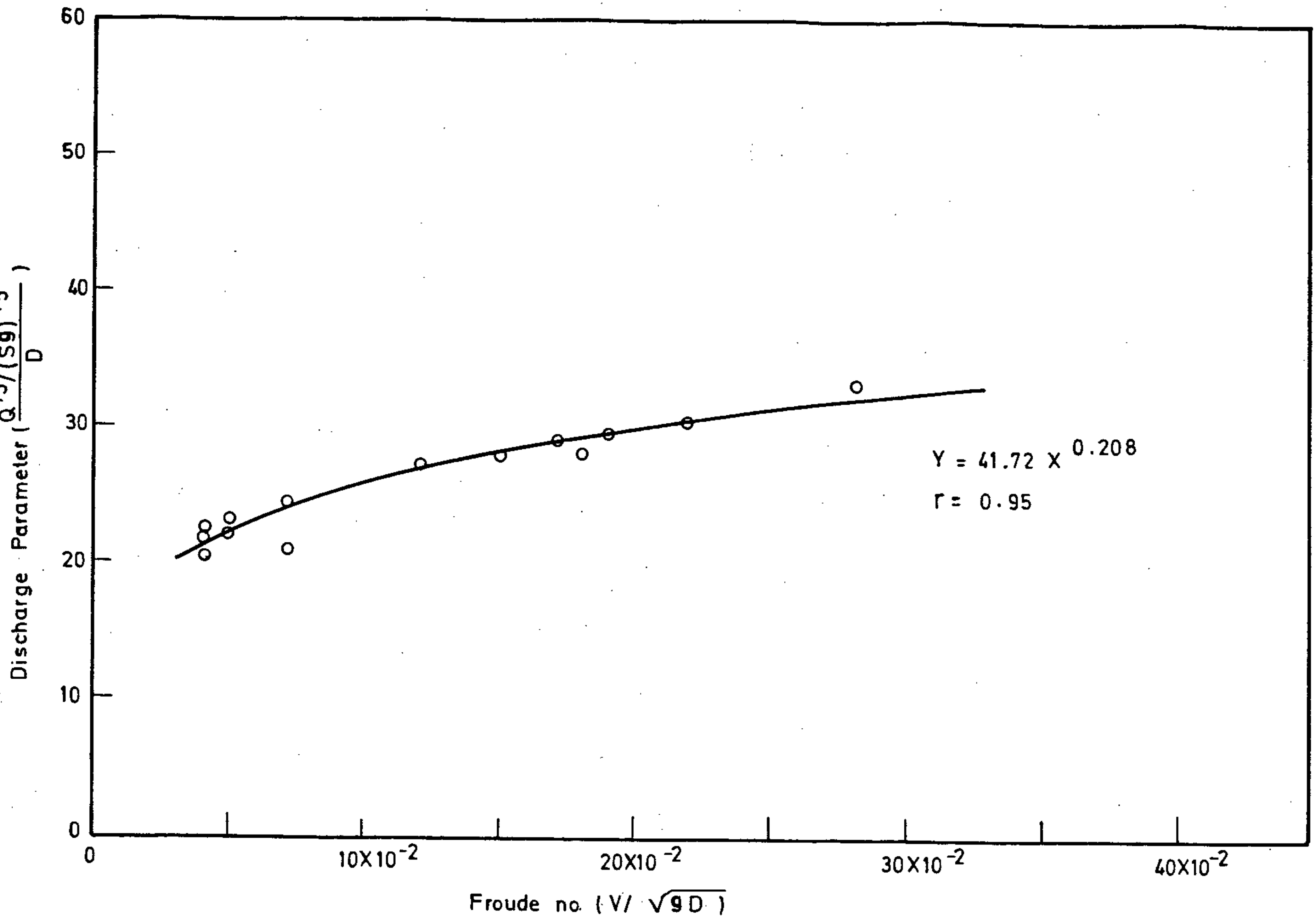

FIG. 5.46 RELATIONSHIP BETWEEN $V/\sqrt{gD}$ AND $\frac{Q^{2/5}/(Sg)^{1/5}}{D}$ FOR THE GANGES AT HARDING BRIDGE (1983)

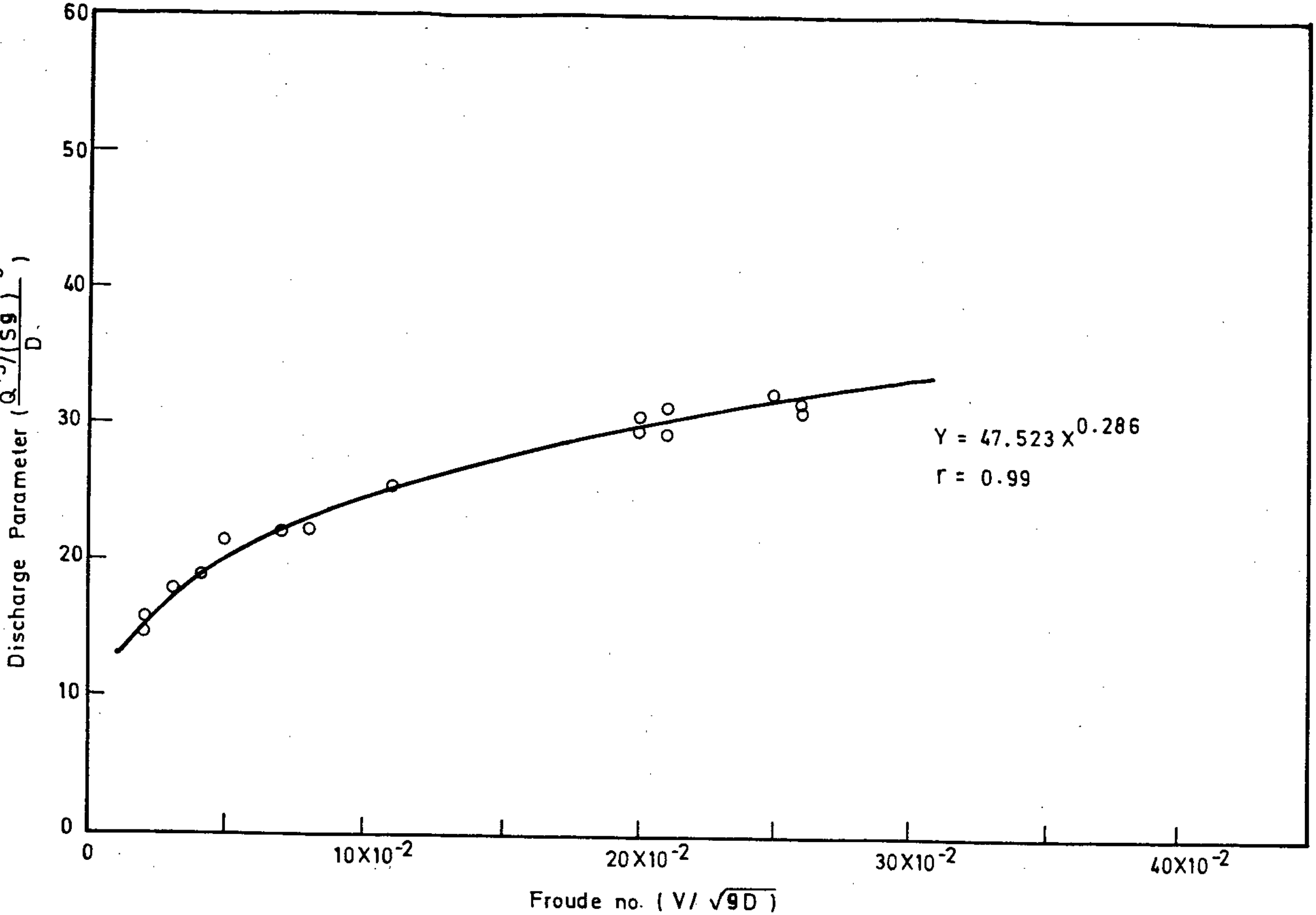

FIG. 5.47 RELATIONSHIP BETWEEN $V/\sqrt{gD}$ AND $\frac{Q^{2/5}/(S\,g)^{1/5}}{D}$ FOR THE GANGES AT HARDING BRIDGE (1984)

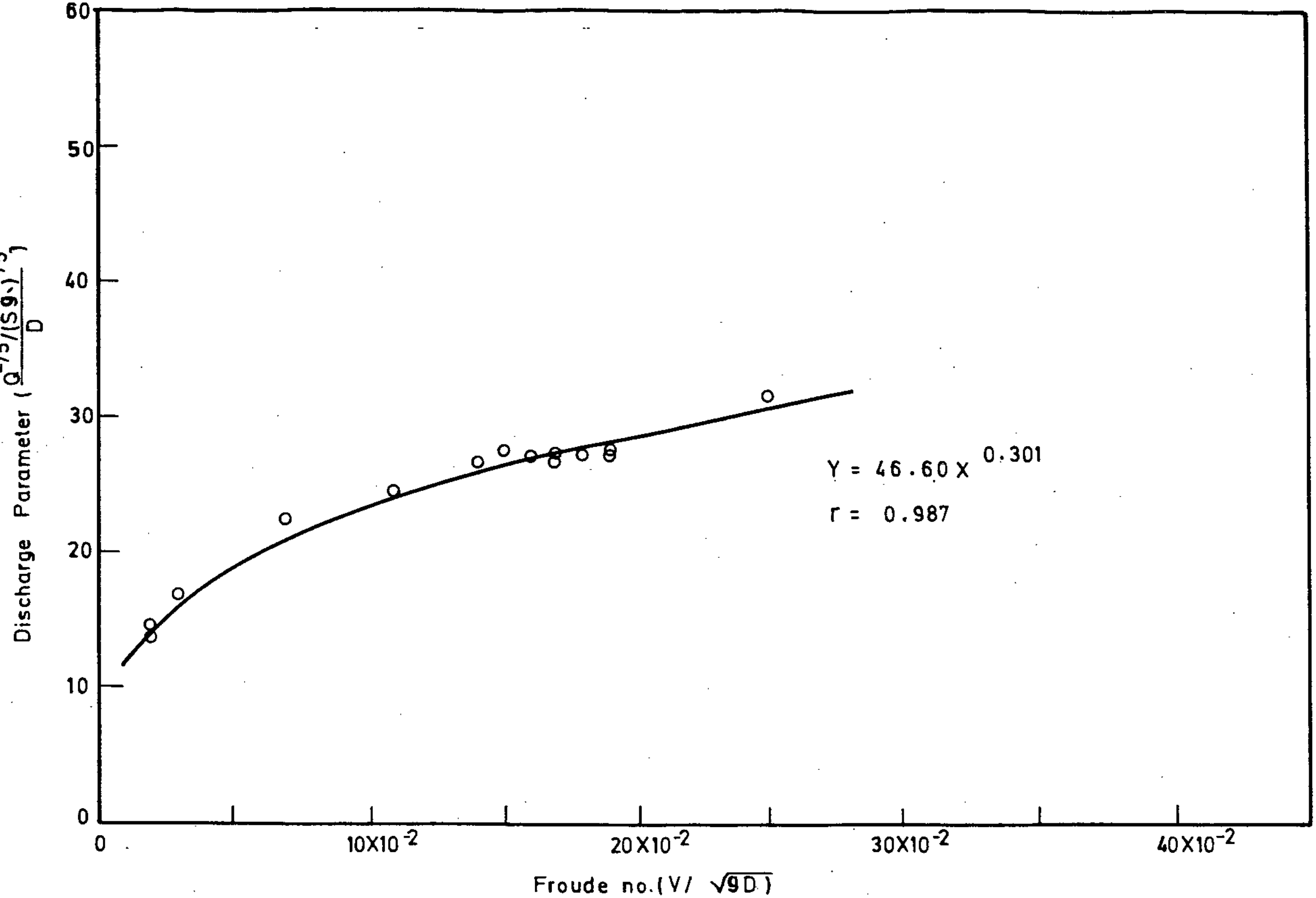

FIG. 5.48 RELATIONSHIP BETWEEN $V/\sqrt{gD}$ AND $\frac{Q^{2/5}/(Sg)^{1/5}}{D}$ FOR THE GANGES AT HARDING BRIDGE (1985)

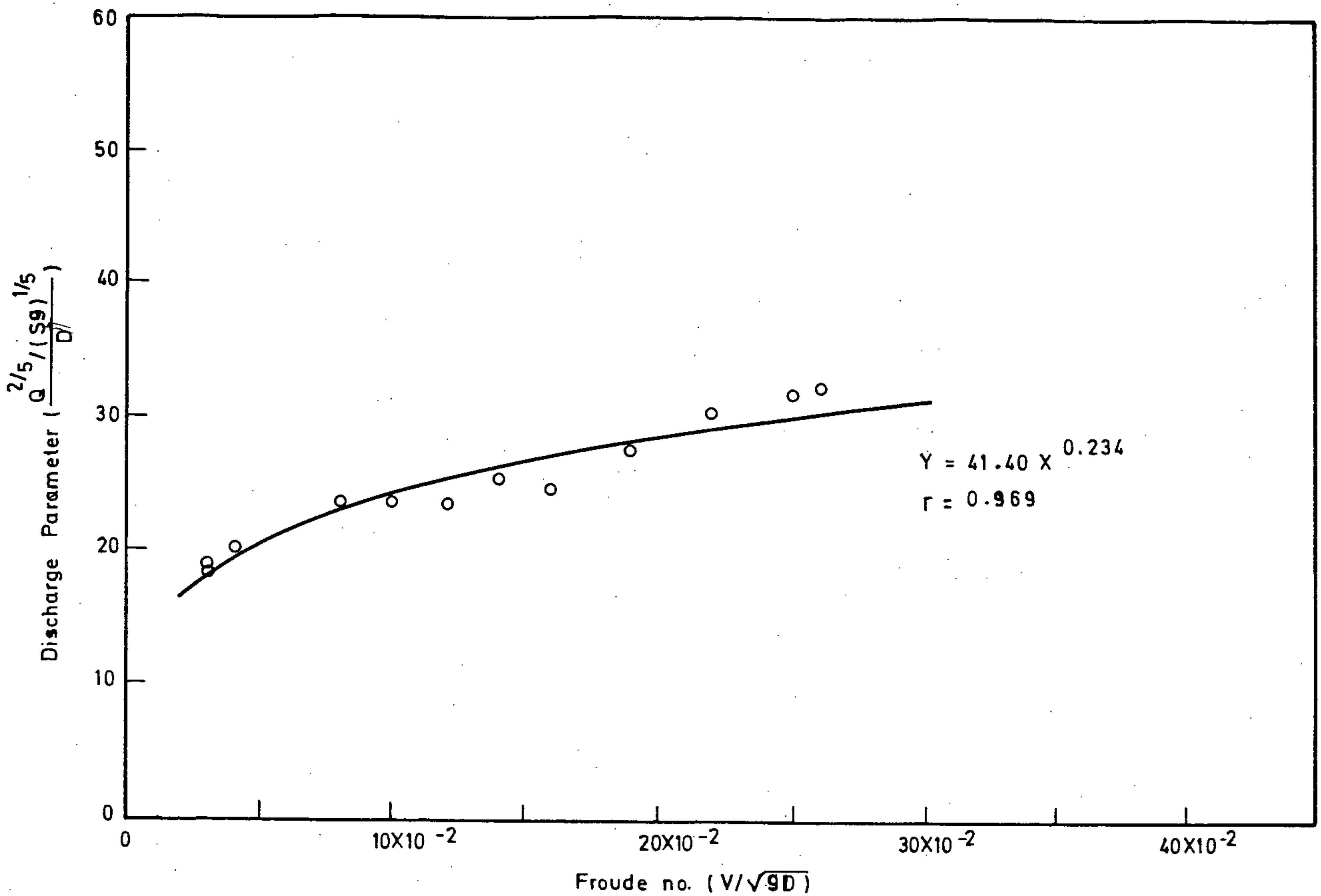

FIG. 5.49 RELATIONSHIP BETWEEN $V/\sqrt{gD}$ AND $\frac{Q^{2/5}/(Sg)^{1/5}}{D}$ FOR THE GANGES AT HARDING BRIDGE (1986)

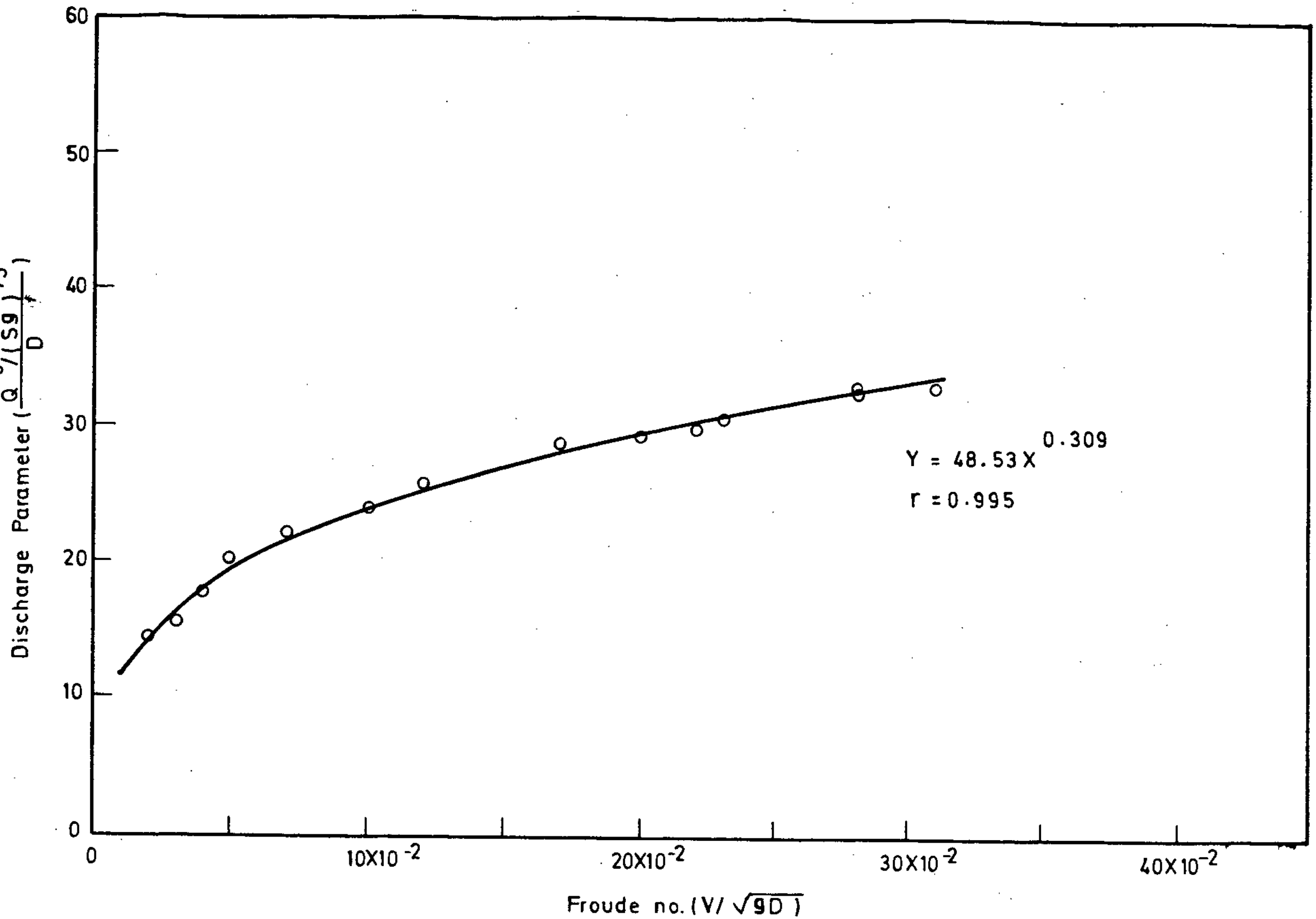

FIG. 5.50 RELATIONSHIP BETWEEN $V/\sqrt{gD}$ AND $\frac{Q^{2/5}/(Sg)^{1/5}}{D}$ FOR THE GANGES AT HARDING BRIDGE (1987)

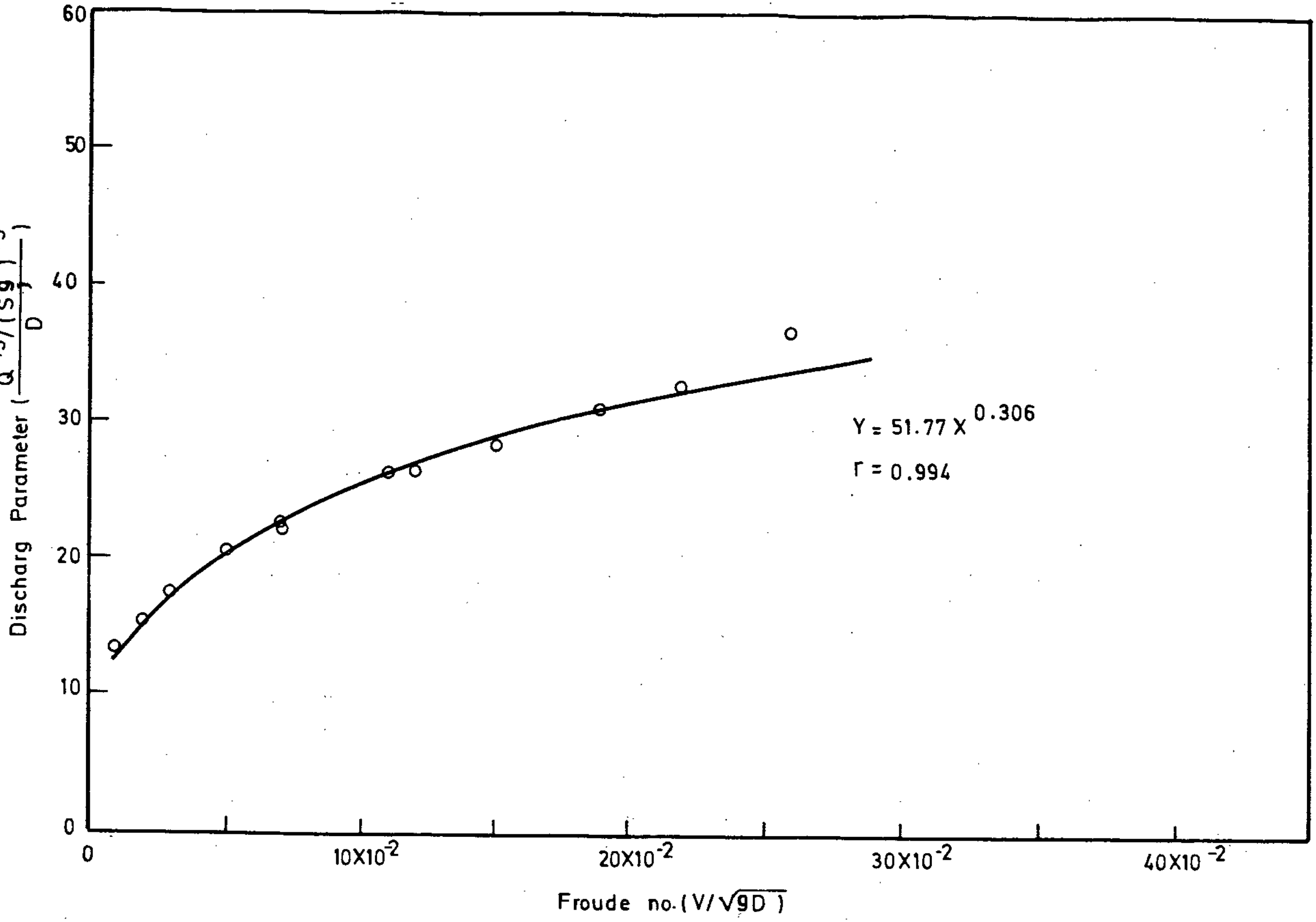

FIG. 5.51 RELATIONSHIP BETWEEN, $V/\sqrt{gD}$ AND $\frac{Q^{2/5}/(Sg)^{1/5}}{D}$ FOR THE GANGES AT HARDING BRIDGE (1989)

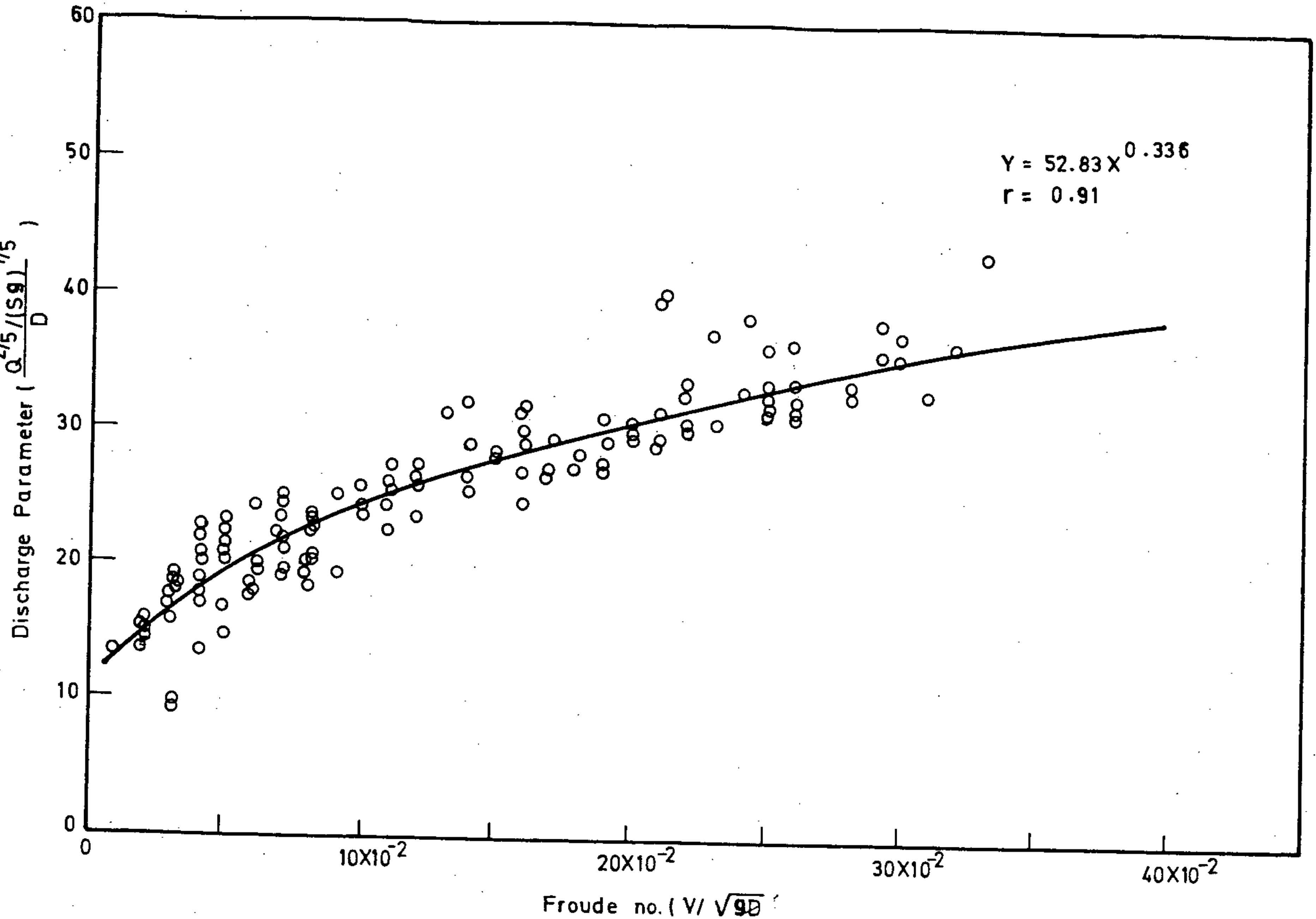

FIG. 5.52 RELATION BETWEEN $\frac{V}{\sqrt{gD}}$ AND $\frac{Q^{2/5}/(Sg)^{1/5}}{D}$ FOR THE GANGES AT HARDINGE BRIDGE (1970, 74, 75, 80, 83-87, 89)

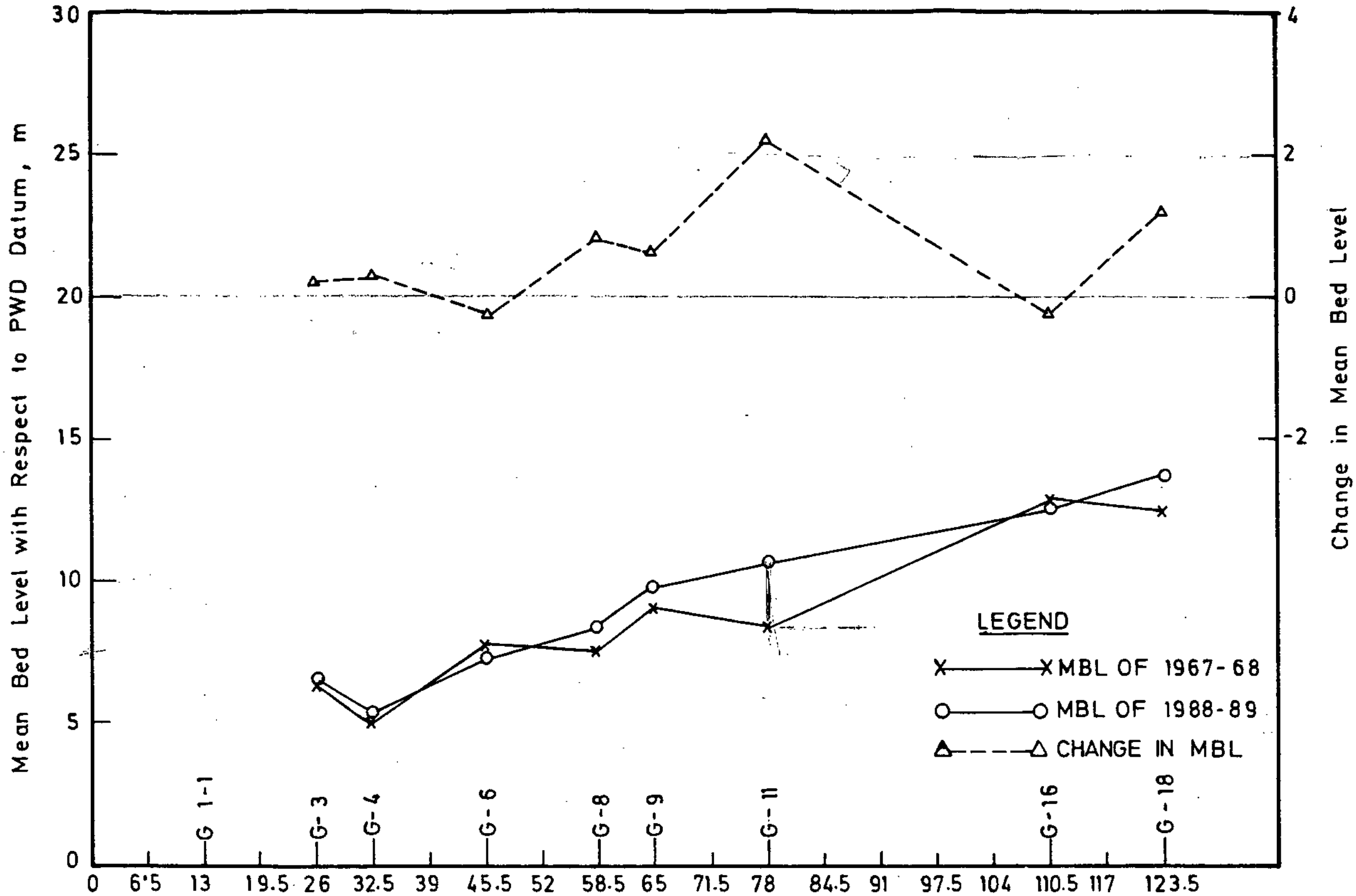

FIG. 5.53 VARIATION OF MEAN BED LEVEL (MBL) WITH DISTANCE FOR THE GANGES (1967-68 TO 1988-89)

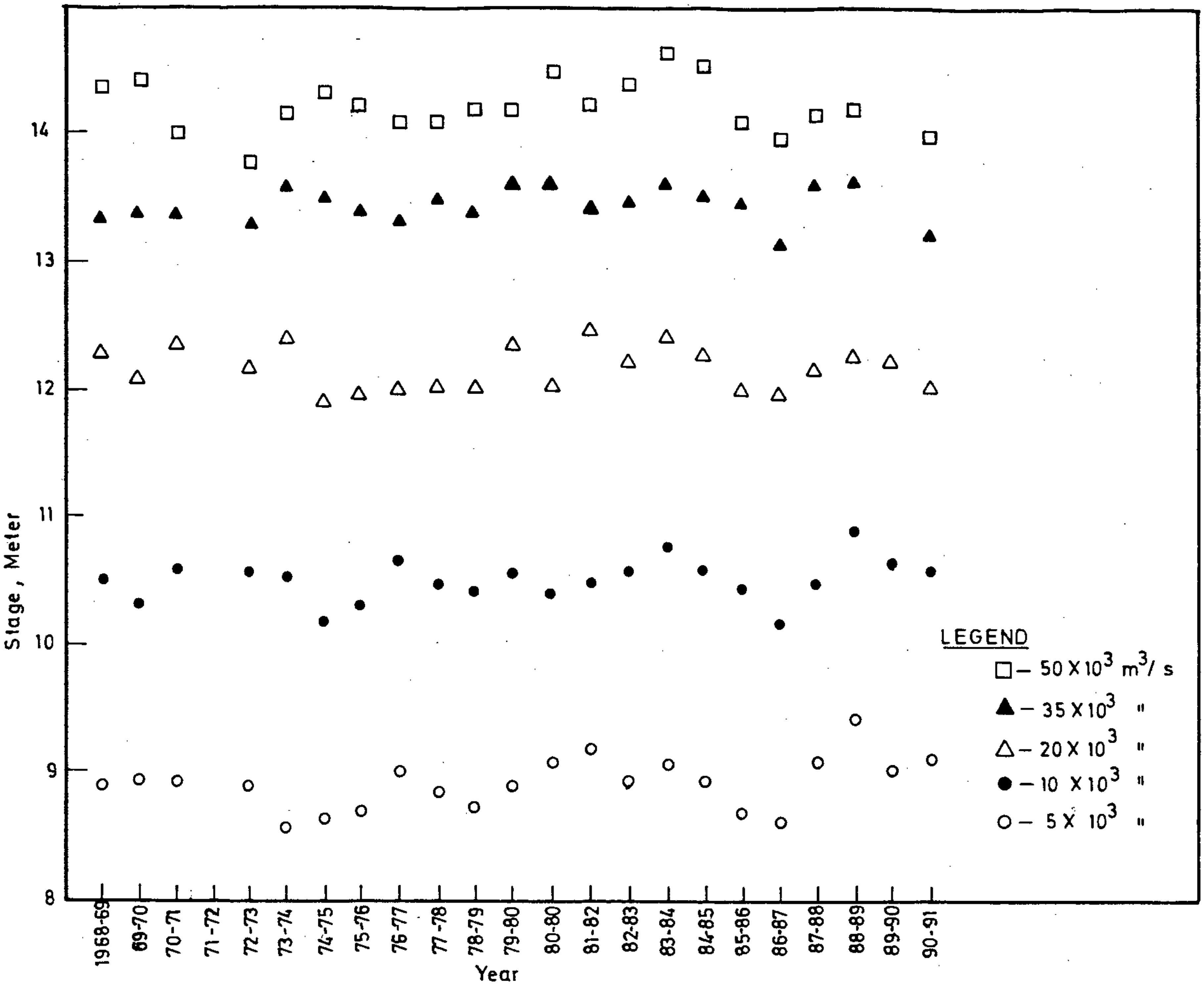

FIG. 5.54 VARIATION OF STAGE AT DIFFERENT DISCHARGE FOR THE GANGES AT HARDINGE BRIDGE

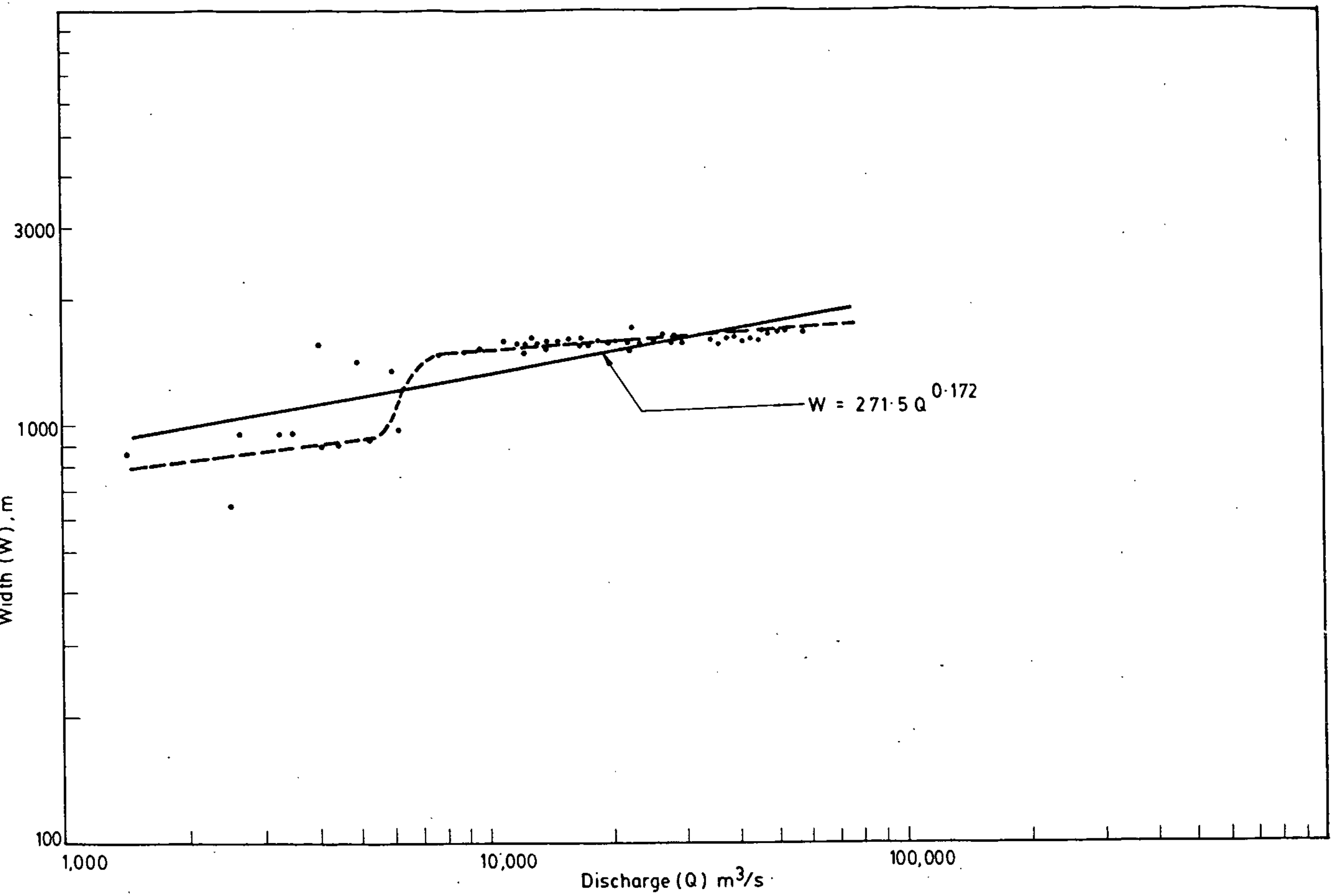

FIG. 5.55 CHANGES OF WIDTH WITH DISCHARGE AT HARDINGE BRIDGE (1970, 74, 75, 80, 83, 84, 85, 86, 87, 90)

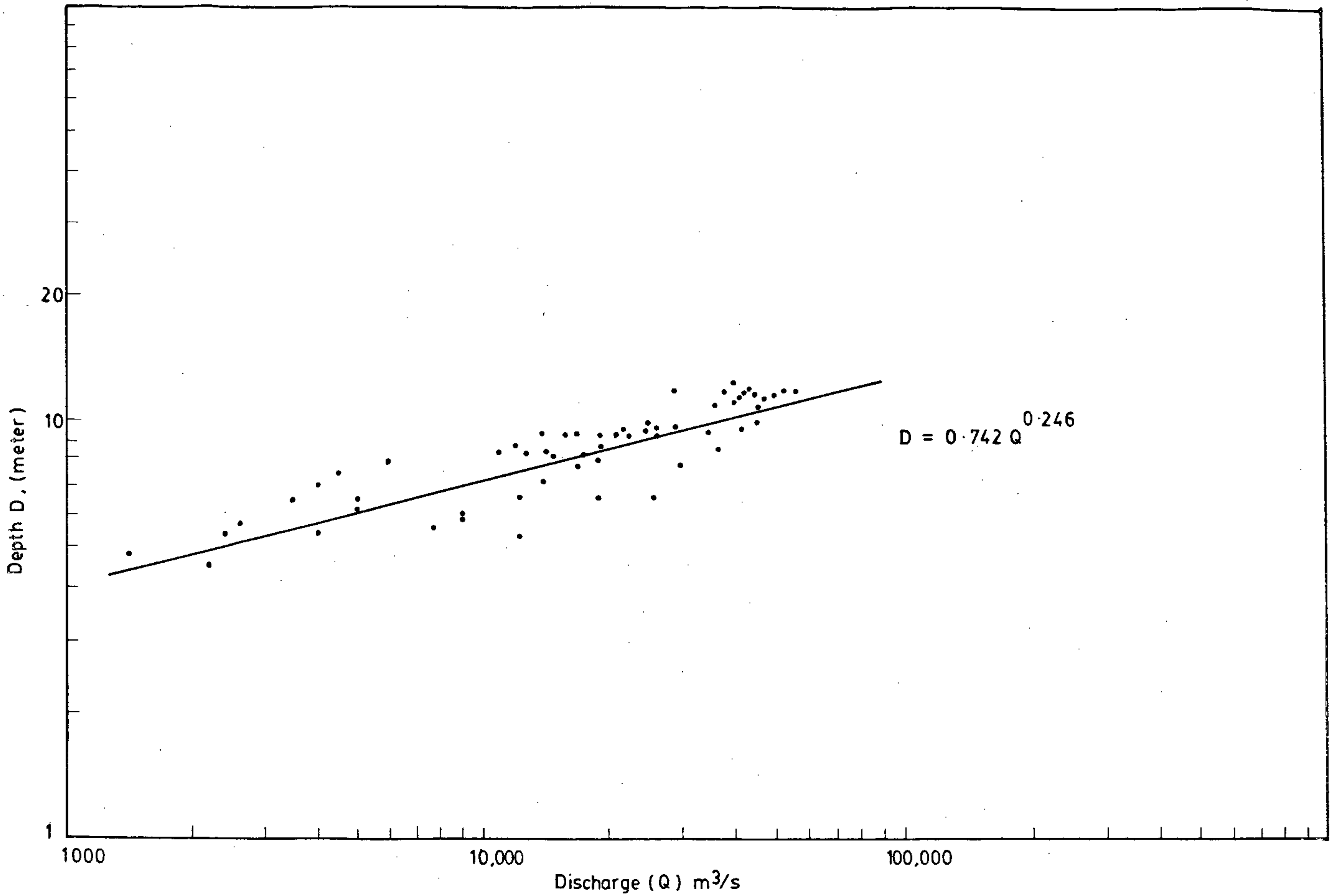

FIG. 5 . 56 CHANGES OF DEPTH WITH DISCHARGE AT HARDINGE BRIDGE (1970, 74, 75, 80, 83, 84, 85, 86, 87, 90)

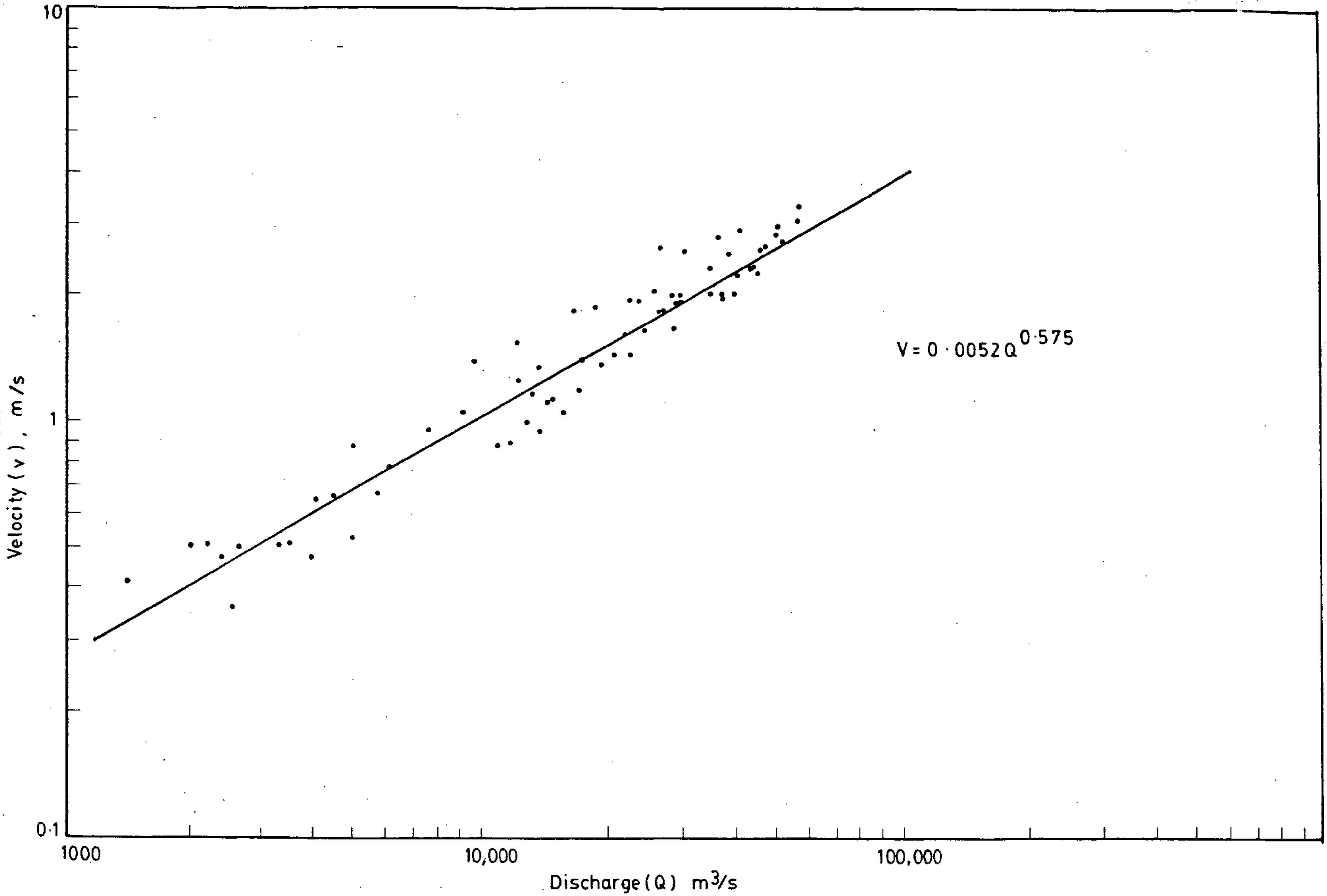

FIG. 5.57 CHANGES OF VELOCITY WITH DISCHARGE AT HARDINGE BRIDGE (1970, 74, 75, 80, 83, 84, 85, 86, 87, 90)

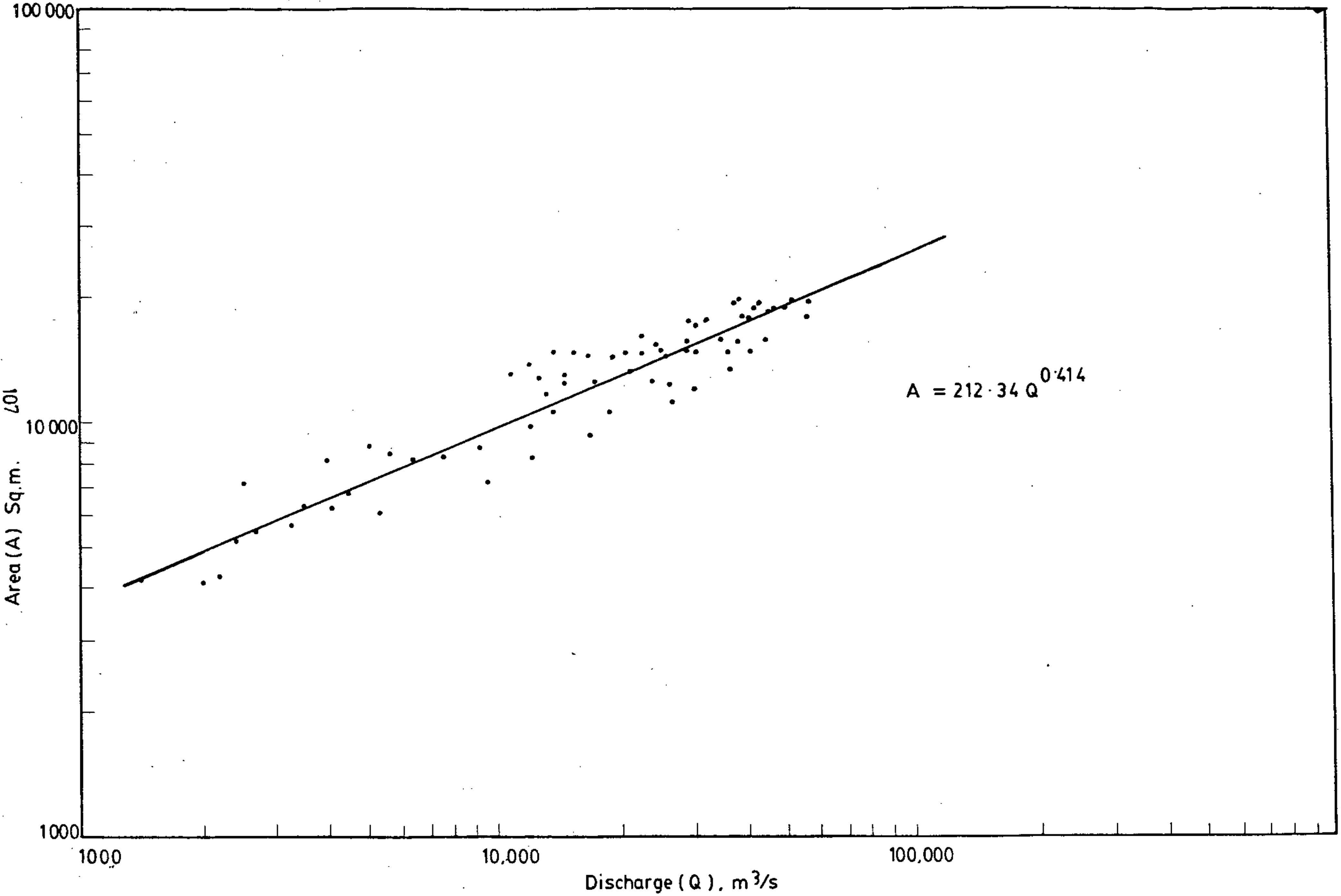

FIG. 5.58 CHANGES OF AREA WITH DISCHARGE AT HARDINGE BRIDGE (1970, 74, 75, 80, 83, 87, 90)