FAP24

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RIVER SURVEY PROJECT

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Geomorphology and channel dimensions

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Acronyms and abbreviations

BWDB	:	Bangladesh Water Development Board
EC	:	The European Commission (formerly the Commission of the European Communities)
FAP	:	Flood Action Plan
FPCO	:	Flood Plan Coordination Organization
ISPAN	:	Irrigation Support Project for Asia and the Near East
MPO	:	Master Plan Organisation
RSP	:	The River Survey Project (= FAP24)
SPARRSO	:	Space Research and Remote Sensing Organisation
WARPO	:	Water Resources Planning Organisation (under the Ministry of Water Resources)

1 Introduction

The River Survey Project (RSP, or FAP24) was initiated in June, 1992, and was completed after 4 years. The project was executed by the Flood Plan Coordination Organisation (FPCO), today merged with the Water Resources Planning Organisation (WARPO), under the Ministry of Water Resources (formerly the Ministry of Irrigation, Water Development and Flood Protection). Funding was granted by the European Commission. The Consultant was DELFT-DHI Joint Venture in association with Osiris, Hydroland and Approtech. Project supervision was undertaken by a Project Management Unit with participation by WARPO/FPCO, a Project Adviser, and a Resident Project Adviser.

The objective of the project was to establish the availability of detailed and accurate field data as a part of the basis for the FAP projects, as well as adding to the basis for any other planning, impact evaluation and design activities within national water resources and river engineering activities.

The project consisted of three categories of activities:

- A survey component, comprising a comprehensive field survey programme of river hydrology, sediment transport, and morphology;
- a study component, comprising investigations of processes and effects within river hydrology, sediment transport and morphology; and
- a training component.

The study programme of the project was developed in a close dialogue with the Client and the Project Adviser. Objectives and scope of the programme were gradually identified and adjusted, and were eventually summarised in a Study Programme submitted to the Client in February 1995.

The present report was prepared within this programme, subject 3: Planform characteristics and channel dimensions, topic 3.1: Planform classification, and meandering and braiding characteristics. Related monographs are *RSP Special Report 6: 'Flodplain level and bankfull discharge', RSP Special Report 20: 'Joint BWDB/RSP measurements, morphology'*, and *RSP Special Report 24: 'Morphological processes in Jamuna River'*. For a general presentation of the findings of the morphological studies of the project, please refer to *RSP Final Report Annex 5: 'Morphology'*.

The study was been carried out and reported by Mominul Haque Sarker.

The present report was first submitted in November, 1995, as *RSP Study Report 7: 'Channel dimensions and geomorphological control'*. It was reviewed on behalf of WARPO by the PA, prof. J. J. Peters, and by prof. J. U. Chowdhury, BUET. To the extent practical, the comments received have been incorporated in the present edition. Some more far-reaching professional questions raised by the reviewers have been addressed elsewhere in the final reporting of the RSP.

The author wishes to thank the reviewers for good advice and valuable comments.

2 Background

A river responds to a number of independent variables as can be expressed by a number of dependent variables. The roles of the variables depend on the time scale, which determine whether a variable plays the role as an independent or a dependent variable. In an engineering time scale, the independent variables are the time dependent discharge Q_t, the yearly average sediment discharge S, the grain size D, the valley slope i_v, bed and bank material characteristics, etc. The dependent variables are the bank-full discharge Q_b, the bank-full width B, the depth h, the flow velocity v, the sinuosity p, the slope i, the total width B_t, etc.

The channel dimensions can be described by the dependent variables such as the bank-full width, the corresponding depth, the velocity, the slope, etc. In the present study, emphasis is given to the bank-full width and depth, which can serve as key parameters of the channel dimensions. First, an attempt is made to derive a regime type of relation to determine these two parameters as a function of the bank-full discharge, which is another dependent variable. Next, the result is examined and verified against the geomorphological conditions of the rivers. The regime type of relations can of course be applied only if the river is in an equilibrium.

The regime relations hide the influence of the other independent variables, such as S, D, i_v, etc. The role of S, D and i_v in determining the channel dimensions is well recognised. For the main rivers, Jamuna, Ganges and Padma, the magnitude of the above three variables certainly differ from each other, within a range of a factor of two.

Another factor, the bed and bank material characteristics, is a function of the geology of the basin. Geological factors control the morphology of a channel to a certain extent. For example, a highly erosion-resistant bank can control the planform characteristics, also within a graded or engineering time-scale. Therefore, when studying the channel dimensions, especially the geomorphological controls, the equilibrium aspect of the channels is a subject of particular attention.

The present report outlines the relevant key factors of the geology of the Bengal Basin. The morphology of the main rivers is discussed briefly. The data analysis is summarised, as a basis for a discussion of the significance of different parameters to the channel dimensions. Finally, conclusions and recommendations are presented.

3 Objectives

The objectives of the present study are as follows:

- To determine the channel dimensions of the Jamuna, Ganges and Padma Rivers as a function of an independent variable, the discharge (by regime equations);
- to estimate the influence of geomorphological controls on the channel dimensions; and
- to establish a common relation among the rivers with respect to their channel dimensions and geomorphological characteristics.

4 Study area

The channel dimensions are studied for the Jamuna, Ganges and Padma Rivers. The study is mainly based on BWDB cross-section data, and is therefore is limited to those reaches of the rivers that are covered by the BWDB standard cross-section survey net-work, see Figure 1.

5 Geomorphology

5.1 Geology

The Bengal Basin is bounded to the west by the pre-Cambrian rocks of the Indian Shield, and to the north by the Shilong Block of cetaceous and tertiary shelf sediments footed on a pre-Cambrian basement. The eastern boundary of the basin is framed by the N-S tending fold zones of the neogene phase of the Indo-Burma Orogeny. The east-west Dauki Fault separates the Shilong Block from the subsiding Surma Basin, see Figure 2. There is a number of faults and folds, which tectonically subdivide the Bengal Basin into crustal blocks. These, with their differential movements, produce uplifts and areas of subsidence, for example the Shilong Plateau, the Madhupur High, the Barind High, the Faridpur Trough, the Dhaka Trough, etc. (MPO 1987). The highly active tectonics of this region might have influenced the river courses and their shifting nature. Please refer to Morgan and McIntire (1959) for details on this subject.

The Bengal Basin is floored by the quaternary sediments deposited by the Ganges, Brahmaputra, and Meghna Rivers, and by their numerous tributaries and distributaries. It has been established that the basin is an area of subsidence, which is balanced by the deposition of sediments supplied by its river systems. The sediment deposits exhibit an almost complete sequence from cretaceous to recent alluvium. The thickness of the sediment over the pre-Cambrian basement varies in the range of a few hundred meters to about 16 km from place to place, see Figure 3.

For the present study, the quaternary sediments are of particular interest, and especially the most recent sediments. A schematic diagram of the quaternary sediment is shown as Figure 4. Barind and Madhupur are the two main pleistocene sediments in Bangladesh, which constitute the flood-plain deposits of the earlier Ganges and Brahmaputra Rivers. Pleistocene sediments are elevated relative to the recent flood-plain and can easily be recognised by their tone and texture. The recent sediments are typically dark, loosely compacted and with high water contents and appreciable quantities of organic components. Pleistocene sediments are reddish in colour, highly oxidised, compacted, and contain less water.

The physical classification of recent sediments is shown in Figure 5. Here, the characteristics of all types of sediment will not be discussed. Only sediments found near the present courses of the Jamuna, Ganges and Padma Rivers are briefly discussed below, with their notation as applied in Figure 5.

Alluvial sand (asd)
Light to brownish grey, coarse sand to fine silty sand. Sand constitutes the channel bars and the levee deposits along the rivers and the large tributaries. The Jamuna River sand ranges in size from coarse to fine, while the Padma River sand is medium to fine. At the downstream part of the Ganges and Padma Rivers, strips of these deposits are quite narrow, see Figure 6. Probably, the boundaries of the alluvial sand represent the oscillating boundaries of the rivers. However, the narrow neck upstream of the confluence of the Jamuna is confusing, as this river, in recent years, does not have such a narrow oscillation space.

Alluvial silt (asl)
Light to medium grey, fine sandy to clayey silt, normally poorly stratified; the average grain size decreases with distance from main channels. It is chiefly deposited in the flood basins and in inter-stream areas. The deposits include small backswamp deposits and varying amounts of thin, interstratified sand, deposited during episodic or unusual large floods. Artefacts between 500 to 6000 years old occur in the upper 4 m. These silt deposits surround the alluvial sand strips of the Jamuna River and are only found at the left banks of the Ganges and Padma Rivers.

Alluvial silt and clay (asc)
Medium to dark-grey silt to clay; the colour grows darker as the organic material increases. The boundary of 'asc' includes flood-basin silt, backswamp silty clay, and organic rich clay in sag ponds and large depressions. These sediments are located close to the boundary of the active corridor of the Jamuna River for a few km at the left bank and a few stretches of the Ganges and Padma Rivers at their left banks.

Marsh and clay peat (ppc)
These are paludal deposits that consist of grey to bluish grey clay, black peat, and yellowish-grey silt. Alternating beds of peat and peaty clay are common in beels and large structurally controlled depressions. These are possibly subsiding areas and occur near the left bank of the Ganges and Padma Rivers.

Deltaic sand (dsd)
Light to yellowish-grey, fine to silty sand, deposited mostly during floods in channels and floodplains, including channel bars and point bars. They are found on the right bank of the Ganges and Padma Rivers, and clearly identify the existing and old off-takes.

Deltaic silt (dsl)
Light-grey to grey, fine sandy silt to clayey silt, deposited in flood basins. They are over-bank sediments from the river or from its distributaries, and are found almost all over the right bank of the Ganges and Padma Rivers. The deltaic silt areas vary with respect to the period of deposition. At the upstream reach of the Ganges, the deposition is older than the deposition at the downstream part of the Padma River. Its cohesiveness depends on the age of deposition.

The above description of the recent sediments along the main rivers is based on the Geological Map of Bangladesh, 1990. This is a macro-scale description, and is mostly based on a generalisation of micro-scale variations.

FAP1 carried out a systematic geomorphological survey of the right bank of the Jamuna River, and found distinct zones of different predominant material characteristics, ranging from almost pure sand to thin strata of relatively cohesive material. But as all the materials are highly erodible, FAP1 suggested to consider the bank materials as being effectively uniform with respect to resistance to erosion (FAP1, 1993).

The floodplain of the three main rivers consist of recently deposited sediments. One feature common to these rivers is that the oscillation zone consists of alluvial sand, and is aproned by alluvial silt or deltaic silt. It is expected that alluvial and deltaic silts would be cohesive to some extent, and would also exert a higher resistance against erosion than the alluvial sand. Certainly, the extent of cohesion depends on the clay and mineral contents, and on the age of the deposition. Huizing (1971) found carbonate minerals in the Ganges floodplain, which are absent in the Brahmaputra-Jamuna floodplain. During the analysis of physical properties of river sediments, FAP24 found that the sediment of the Ganges contain a significant amount of carbonate, a mineral which is almost absent in the sediments of the Jamuna River. This relates to the findings of Huizing. The source of carbonate is the limestone of the Himalaya and the pleistocene soil in northern India. Due the presence of carbonate minerals, the cohesion and the resistance to erosion of the alluvial or deltaic silt along the Ganges River (and to some extent the Padma River) are expected to be higher, as compared with the alluvial silt along the Jamuna River.

5.2 Morphology

The basins of both the Ganges and Jamuna Rivers are bounded by the tectonically highly active Himalayas mountain ranges. These young Alpine ranges are subject to severe erosion, yielding the heavy sediment load in the Ganges and Jamuna Rivers.

A large number of geomorphic scratches on the recent alluvial or deltaic deposits, which are clearly visible from aerial or satellite images, give evidence that the rivers of Bangladesh are quite rapidly shifting in nature, probably due to the active tectonic nature of the basin. The role of tectonics on the river processes is beyond the subject of the present study, but the understanding of the shifting nature of the rivers is important for the river morphology. The morphology of the main rivers is discussed briefly in the following.

Jamuna River

Jamuna/Brahmaputra River originates in Tibet on the north slope of the Himalayas and drains an area of about 550,000 km^2, extending over China, Bhutan, India, and Bangladesh. Its traverse path is about 2,740 km before meeting with the Ganges River at Aricha. The mean annual discharge is 20,000 m^3/s, the maximum discharge recorded till now is 100,000 m^3/s (in 1988), and the bankfull discharge is about 48,000 m^3/s. The slope of the river within Bangladesh decreases in the downstream direction and is $8.5*10^{-5}$ at the upstream end, and $6.5*10^{-5}$ near the confluence with the Ganges. The bed material sizes also decrease from the upstream towards the downstream part and range from 0.22 mm to 0.16 mm.

The present river course is the result of shifting of the previous course from the eastern side of the Madhupur, mainly due to the recent faulting (Khan 1991). The present river course is bounded by the Barind and Madhupur pleistocene terrace.

Jamuna River is a braided river with a braiding index that varies spatially as well as with time. In general, the braiding index and the overall width are larger at the upstream part than further downstream, probably due to the effects of higher slope and grain sizes. The overall width of the river exhibits an increasing trend, and there is tendency of shifting westwards, especially at the upstream part of the river within Bangladesh (FAP1, 1993). The widening can be attributed to an advancing alluvial fan or to the not yet completed adaptation process after the shift to its new course (FAP24, Study Report 3, 1994).

Bristow (1987) proposed a classification of river channels into different orders. The entire channel is the first-order channel and comprises a number of second-order channels, which in turn have smaller channels. The second-order channels have slightly different characteristics, such as slightly different slopes, different water and sediment carrying capacities, and as a result, they behave differently. For the study of channel dimensions, the second-order channels are of main interest.

The shifting characteristics of the river can be divided according to the order of the channel, thus the shifting of the first-order channel and the second-order channel, respectively. The shifting rate of the first-order channel of the Jamuna River is 75 m to 150 m per year. The second-order channels change continuously, large channels being abandoned, and new ones developing in a few years only (Klaassen and Masselink, 1992). A bank erosion rate of the second-order channels of 250 m to 300 m/year is common, and in extreme cases, it can be more than 800 m/year (Klaassen and Masselink, 1992).

Ganges River

The river rises from the southern flanks of the Himalayas in India and breaks through the Indian shield. Before meeting with the Jamuna, the river travels about 2200 km, draining an area of about 1,000,000 km^2. The mean annual discharge is about 11,000 m^3/s and the bank-full discharge is about 43,000 m^3/s. The average water surface slope of the Ganges in Bangladesh is estimated by FAP24 at about $5.0*10^5$. The average bed material size is 0.14 mm, and the rate of downstream fining is approximately 0.03 mm/100 km (FAP24 findings).

About 500 years ago, the river swung to the east along recent multiple faults between Rajmahal Hills and Dinajpur Shield, to enter Bangladesh at Godagari (Khan, 1991). Until then, the course had coincided with the present Hoogly River. A hydraulic flow regime analysis of the Ganges by FAP4 shows that it is now a in dynamic equilibrium. However, it also shows that the sinuosity of the river is decreasing (Hossain, 1991, and FAP4, 1993), and that the river, especially the part downstream of Hardinge Bridge, is behaving as a wandering river, changing its planform between meandering and braiding (FAP4). FAP4 identified the active corridor of the Ganges, within which the risk of bank erosion is high, and also identified some embayment and nodal points along the river, in between which the river wanders.

The bank erosion rate of the Ganges River is quite high. ISPAN (1993) analyzed satellite imagery of 1984 and 1993, and found almost similar values as for the Jamuna River. The erosion rate is considerably reduced when the river attacks the highly erosion-resistant boundary of the corridor.

Padma River

The combined flows of the Jamuna and Ganges Rivers constitute the flow of the present Padma River. Before the avulsion of the Jamuna River, the flow was a continuation of the Ganges River only, and Rennel's map shows that the river passed further south than the present course. The annual mean discharge is 28,000 m^3/s, and the bank-full discharge is about 75,000 m^3/s (FAP24 findings). The average size of the bed material is about 0.10 mm.

Geomorphologically, the river is still young. A flow regime analysis by FAP4 shows that it is now in a dynamic equilibrium. A reach of about 90 km is almost straight and the planform of the river is a combination of the meandering and braiding type, indicating a wandering river. The meandering, sweeping bend and the braided belt swing within an active corridor. ISPAN (1993) found that both banks of the river often attack the active corridor boundary, probably still widening its active corridor.

The variation of the total width of the river is quite high, ranging from 3.5 km to 15 km. FAP9B related this phenomenon with the existence of cohesive bank material at the constricted reach, on the other hand FAP4 attempted to relate the width constriction with the high bank elevation. The present analysis shows that the explanation of FAP9b is more likely, though no detailed bank material data are available.

The bank erosion rate studied by ISPAN (1993) shows that the rate (in the period of 1984 to 1993) is quite high, and even higher than for the Jamuna River. The braiding intensity of the river is low, and typically, there are only two parallel channels in the braided reach. Channel shifting processes are quite rapid.

The slope and the bed material sizes of the rivers vary within a range of 8.5 to 5 cm per km, and 0.20 to 0.10 mm, respectively. Bankfull discharges are within the range of 43,000 m^3/s to 75,000 m^3/s. With respect to planform, Jamuna is distinctly a braided river, while the Ganges and Padma Rivers fall in between braided and meandering rivers, i.e. wandering rivers. The bank erosion rates of the rivers are almost the same. However, there is a difference between the Jamuna River on the one hand and the Ganges and Padma Rivers on the other. The bank erosion rates of the former are invariably similar, while the flow attacks any of its banks. The bank erosion of the Ganges and Padma River resembles the Jamuna River within the active corridor only. Unlike the Jamuna River, the rate is reduced significantly at the boundary of the active corridor. The corridor consists of alluvial/deltaic silt deposits, while the floodplain outside of it is more resistant to erosion, probably due to the presence of carbonate, as discussed in the previous chapter.

6 Previous studies

Lacey (1929) introduced empirical regime equations for finding the proper width of a sand bed irrigation canal. By analysing irrigation canals in Punjab, Lacey determined the wetted perimeter and the hydraulic radius as a function of the discharge. For a wide river with a uniform depth, the wetted perimeter can be treated as the width, and the hydraulic radius as the average depth. Converting the equations into S.I units, Lacey's regime relations read:

$$B = 4.81\ Q^{1/2} \qquad (1)$$

$$h = 0.47\ (Q/f)^{1/3} \qquad (2)$$

where Q = bank-full discharge (m^3/s), B = bank-full width (m), h = average depth (m), and f = silt factor, defined as

$$f = 1.59\ D_{50}^{\ 1/2} \qquad (3)$$

where D represents the grain size.

After Lacey, a number of attempts were made to apply the regime equations for natural rivers. The problem encountered in this connection is that the discharge of a natural rivers often varies widely, while the canal discharge is almost fixed by its design discharge. However, the bankfull discharge is usually used as the channel forming discharge with respect to channel geometry (Chang, 1987). Klaassen et. al. (1988) derived regime equations for the Jamuna River, as a function of bank-full discharge, as follows:

$$B = 16.1\ Q^{0.53} \qquad (4)$$

$$h = 0.23\ Q^{0.23} \qquad (5)$$

In order to determine the channel dimensions of the Jamuna, Ganges and Padma Rivers, the bankfull discharge is used in the present study, like Klaassen et. al. (1988).

The limitation of the regime type equations is that they hide the influences of other independent variables, notably the influence of slope, grain sizes, bank materials, vegetation, etc. Hey and Thorne (1982) derived regime equations for gravel bed rivers and found different coefficients depending on the vegetation on the banks. However, for wide rivers like Jamuna, Ganges and Padma, the effect of the vegetation can safely be neglected. This is demonstrated by the study of bank erosion of the Jamuna River by Klaassen and Masselink (1992), which shows that the rate of erosion is independent of the vegetation on the banks.

There is no broad consensus regarding the link between bank characteristics and regime hydraulic geometry (Thorne, 1988). Thorne (1988) linked the bank material characteristics with the fluvial activity at the bank toe through the state of basal end point control, which he proposed can influence on the channel geometry. During the analysis, it was also observed that the channel dimensions are probably influenced by the characteristics of the bank materials.

In addition to the empirical approaches, there are several theoretical approaches for determining the channel dimensions, such as tractive force, stability, and optimisation. A few of those have been discussed by FAP21/22 (1992, for details please refer to the Draft Final Report, Planning Study, vol. II). In general, the results of their application on the Jamuna River were not encouraging. No such theoretical approaches were attempted during the present study.

7 Data used and quality checking

BWDB cross-section survey data along the three rivers from 1966 to 1993 were employed for the purpose of the present study. Vertical control checking of the BWDB cross-section survey data was done by FAP24. The horizontal control for a few years was checked by comparing with satellite images and, apart from that, by bench mark histories. Only data that were both horizontally and vertically consistent were used in the analysis. The types and sources of cross-section data utilised in the present study are shown in Table 1. After quality checking, the data listed in Tables 2, 3 and 4 were used.

River	Source and type of data	Year
Jamuna	BWDB - cross-section	1965-66, 1978, 1980, 1985, 1989 and 1992
	FAP24 - routine gauging and bathymetric survey	1993 and 1994
	SPARRSO-LANDSAT images FPCO-SPOT images	1978, 1980, 1985, 1989 and 1992
Ganges	BWDB - cross-section	1965-1966, 1972, 1973, 1974, 1980, 1981, 1982, 1989, 1991 and 1993
	SPARRSO-LANDSAT images FPCO-SPOT images	1973, 1981, 1989, 1991 and 1993
Padma	BWDB - cross-section	1965-1966, 1972, 1973, 1974, 1980, 1981, 1982, 1989, 1991 and 1993
	SPARRSO-LANDSAT images FPCO-SPOT images	1973, 1981, 1989, 1991 and 1993

Table 1: Type, source and year of the data used

The BWDB cross-section surveys follow a fixed alignment for each standard cross-section. Hereby, an oblique cross-section profile is often retained, which differs from the direction perpendicular to the flow of the river. Those BWDB cross-sections that are nearly perpendicular to the alignment of the main channel were used. A perpendicularity correction of those sections were made by comparing with the satellite images mentioned in Table 1. Cross-sections were not analyzed if they deviated significantly from the perpendicular direction (see for example section J#5 in Figure 2), or if they were located at bifurcations or in a strongly curved bend. Also in the case of the FAP24 routine gauging surveys, only nearly perpendicular sections were considered for the analysis.

When BWDB began to survey the river cross-sections in the mid sixties, the cross-section alignment was fixed nearly perpendicular to the river. Therefore, the oldest BWDB cross-section survey data, i.e. the data from 1965-66, have been assumed to be perpendicular to the channel direction, and those data were analyzed without comparing with any maps.

Section	Year
J#2_1	1966, 1978, 1989, 1992
J#4	1965, 1978, 1980, 1985, 1989
J#5	1965, 1985, 1989, 1992
J#6	1978, 1980, 1985, 1992
J#6_1	1966, 1980
J#7	1965, 1985, 1992
J#8	1980
J#10_1	1980, 1992
J#11	1965, 1978, 1989, 1992
J#12_1	1966, 1980, 1985, 1989, 1992
J#13	1965, 1980, 1985, 1989, 1992
J#14_1	1966, 1978, 1980, 1989, 1992
J#15	1965, 1978, 1989
J#16	1965, 1978, 1985, 1992
J#17	1965, 1992

Table 2: BWDB cross-sections in the Jamuna River used in the study

Section	Year
G#2	1972, 1973, 1974, 1981, 1989, 1991, 1993
G#300	1967, 1989, 1991, 1993
G#4	1967, 1972, 1973, 1974, 1980, 1981, 1981, 1989, 1993
G#5	1974, 1981, 1982, 1989, 1991
G#7	1967, 1972, 1980, 1981, 1982, 1989, 1993
G#8	1967, 1972, 1973, 1974, 1980, 1981, 1982, 1989, 1991, 1993
G#9	1967, 1972, 1973, 1974, 1980, 1991, 1993
G#10	1967, 1972, 1973, 1974, 1980, 1981
G#11	1967, 1980, 1981, 1982, 1989, 1991
G#12	1967, 1980, 1981, 1982, 1991, 1993
G#13	1967, 1981, 1982, 1989, 1991, 1993
G#15	1967, 1981, 1982, 1989, 1991, 1993
G#16	1967, 1980, 1981, 1982, 1989, 1991, 1993
G#17	1967, 1980, 1981, 1982, 1993

Table 3: BWDB cross-sections in the Ganges River used in the study

Section	Year
P#1	1966, 1980, 1981, 1993
P#1_1	1972, 1989, 1993
P#2	1965, 1972, 1973, 1980, 1981, 1989
P#2_1	1966, 1972, 1973, 1980, 1982, 1989
P#3	1981, 1982, 1989
P#3_1	1965, 1974, 1980, 1981, 1989, 1993
P#4	1965, 1974, 1980, 1981, 1989, 1993
P#4_1	1989, 1993
P#5	1965, 1972, 1973, 1980, 1981, 1982, 1989, 1993
P#6	1972, 1973, 1974, 1980, 1981, 1982, 1989, 1993
P#6_1	1966, 1974, 1981, 1982, 1993
P#7	1965, 1980, 1981, 1982, 1993

Table 4: BWDB cross-sections in the Padma River used in the study

In order to determine the channel dimensions, cross-sections perpendicular to the flow are relevant. During the screening of the data, the perpendicularity of the cross-sections can only be checked against the channel geometry as observed from the satellite imagery. However, the flow direction does not always coincide with the direction of the channel, especially in a large braided river like Jamuna. This is one limitation of the data used.

8 Data analysis

The BWDB cross-sections are the main data for determining the channel dimensions of the Jamuna, Ganges and Padma River. For at-a-station relations of the Jamuna River, also FAP24 data were analyzed. After quality checking, the data were processed and analyzed. During the analysis, results were compared with previous findings and were evaluated against the planform and the geological characteristics of the river.

8.1 Processing the data

Near bank floodplain levels are evaluated in Study Report 6 of FAP24. The average bank level for each cross-section was marked on the BWDB cross-sections for the three rivers. As a basis for at-a-station relations of the Jamuna River, two additional levels were marked, corresponding to the mean annual discharge (20,000 m^3/s) and lean season average discharge (6,000 m^3/s), see Figure 7. As the next step, the water surface width of each second-order channel, the average depth, and the relative Chezy conveyance factor of each second-order channel were determined. hereby, the total discharge was distributed among the second-order channels according to their relative conveyance factors. For details about the applied procedure, please refer to FAP24, 2° Interim Report.

8.2 Type of analysis

Regime type relations were established by plotting the width and depth against the bankfull discharge of the second order channels of the rivers in a logarithmic scale. The best fit regression lines yield the relations of width and average depth as a function of discharge. In this regression analysis, the best fit line can be defined by a coefficient and an exponent of the independent variable, i.e the discharge. Hereby, it is observed that the coefficient is very sensitive to changes of the exponent. For almost similar values of width and average depth, and within a certain range of discharges, a 20 % variation of the exponent of the discharge will change the coefficient by nearly 100 %. So, when comparing regime relations of different rivers, it must be kept in mind that the best fit exponents and coefficients can be rather different, even for regression lines that resemble each other closely.

8.3 Results and evaluation

Results of the regression analysis were compared with the previous findings, evaluated in the light of the geomorphological setting of each river.

Unlike the Jamuna River, the regime relations of the Ganges and Padma Rivers were not directly determined for the whole stretches (where data were available). As mentioned earlier, the Ganges and the Padma are wandering rivers, where the planform characteristics change from stretch to stretch and also with time. Also, it was observed that the channel width varies considerably from one river stretch to another, as well as with time. Therefore, an attempt was made to separate the stretches of the rivers with respect to their geomorphological settings and the channel geometry.

The following sections present the results of the analysis, together with a comparison and evaluation.

Jamuna River

The river exhibits a braided planform for the total reach covered by the study, although the braiding index varies considerably. The bank material characteristics of the river in a macro-scale are seen in the geological map of Bangladesh (1990) (see Figure 6). Previous studies show that the bank material along the river is fine sand and almost uniform with respect to flow resistance (FAP1, 1993). Therefore it was considered that the erodibility of the banks along this river is almost constant.

Regime type relations are shown in Figure 8. In this figure, the width and depth relations are shown at bankfull discharge, together with their correlation coefficients. These relations indicate a width which is less than according to similar regime equations derived by Klaassen and Vermeer (1988). This is partly because a new value of the bank-full discharge has been introduced, and partly due to the perpendicularity corrections of the cross-sections. The discharge-depth relation of the present analysis is almost the same as the one of Klaassen and Vermeer, which shows that for the depth, the change of the value of the bank-full discharge and the perpendicularity corrections balance each other. Lacey's equation give a width that is four times less than the present results, and a depth which is about two times higher. In fact, most natural rivers have a higher width and a smaller depth than according to Lacey. Probably, the discharge pattern and the sediment load of natural rivers differ significantly from the irrigation canals investigated by Lacey.

At-a-station relations for width and depth have been derived for the Jamuna River, for two reasons. One is to see the river response to different discharges, and another is to asses the accuracy of the results that are based on BWDB cross-section data. This is done by comparing the at-a-station relations derived from BWDB cross-sections with the ones derived from the FAP24 survey data. The comparison shows that the at-a-station relations based on BWDB data give slightly higher values for width and depth than the regime relations, see Figure 9. The difference varies from 0 m to 150 m for the width, and from 0.25 m to 0.50 m for the depth, which is not significant, considering the size of the Jamuna River. In other words, the at-a-station relations yield almost similar channel dimensions as the ones derived from the regime relations. This confirms the statement of Klaassen and Vermeer (1988), that the Jamuna River is a quickly responding river, adjusting its dimensions with the variation of discharges.

The at-a-station relations based on FAP24 data show a less width and a higher depth as compared with values based on BWDB data, see Figure 10. The difference in width is from 150 m to 400 m, and in depth from 0.50 m to 0.80 m. There may be three possible reasons for these differences: (i) the inaccuracy of the BWDB cross-section data; (ii) FAP24 discharge measurements are done at some selected and particularly well suited sections, where submerged bars do not impede the navigation; (iii) the time dependency of the cross-sections, i.e. the dry season cross-section data (of BWDB) differ from the monsoon geometry. The existence and magnitude of errors due to the first and the third reason could not be determined, but there is definitely some influence by the second one. If it is assumed that the difference between the results is due to a combination of the possible three reasons, then only a part of the difference is related to the probable inaccuracy of the BWDB data, and this inaccuracy is not very significant for the regime relations. It can be stated that regime relations derived for the Jamuna River by using BWDB data are fairly reasonable.

Ganges River

The planform of the river varies within the study reach of the river, as shown in Figure 11. Multiple channels are observed in the large sweeping bend, and three single thread channel stretches are prominent at the crossings of the bends: One is in the vicinity of Hardinge Bridge, and the other two are downstream of Hardinge Bridge. Apparently, these two stretches are crossings of the meandering bend. Figure 12 shows that the channel widths are different from one of these regions to another. The width of single channels, that carry more than 80 % of the discharge where the river is braided, are plotted in Figure 12. (This analysis could not be made for the Jamuna, where it is difficult to find a single channel carrying more than 85 % discharge in bankfull condition).

A plot of the channel width of the single thread stretches against the discharge shows that the data are concentrated in the range between 2,000 and 3,000 m, see Figure 13. Width and depth of the braided sections of the river are shown against the discharge in Figure 14. The corresponding regime relations are also presented in this figure. The regime width of the Ganges River is similar to the one of Jamuna River, and the depth is 0.25 m to 0.35 m less than for Jamuna River. The overall impression of Figure 14 is that the regime relations of the braided reaches of the Ganges River are similar to the ones of Jamuna River. The planform and the geomorphological factors, which influence the channel dimensions, are examined in the following.

ISPAN (1993) has compared four historical maps, covering a part of the Ganges River and the Padma River, with SPOT imagery of 1993, see Figure 15. The comparison shows that the Ganges River has been much more sinusoidal than today. In region 1 (Figure 15), the river was probably never located to the right of its present course, and in region 2, it has not been located to the left of its present course since 1860. During the processing of the BWDB cross-sections it was noticed that the right bank of cross-sections G#8 and G#9 (in region 1) almost remain at the same position, indicating the existence of high-resistant bank materials at the right bank, which may well influence the channel dimensions as well as the planform of that region. It was also observed that, in the sixties, the river was a multi-thread stretch in this region.

BWDB cross-sections G#2, G#3 and G#4 are located in region 2 (Figures 15 and 16). It was noticed that the river at sections G#2 and G#4 remained within a width of less than 3,500 m and maintained a single thread channel from the mid sixties to 1993, which is not a common feature for a river like the Ganges (except near Hardinge Bridge, where the bank is artificially fixed). Figure 16 also shows that the width of the strip of alluvial sand is narrow in this region. However, section G#3, which is in between sections G#2 and G#4, behaves differently. Here, at the end of the sixties and in the early seventies, the stretch was a multi-thread braided reach with a total width of about 7,000 m, see Figure 16. In the eighties, the river abandoned its right bank channels and started to flow near the left bank as a single thread channel. At the same time, the river reduced its bank-full width from about 6,000 m to about 2,500 m, see Figure 17. The length of the channel stretch from section G#2 to G#4 is about 13 km. Sections G#2 and G#4 were acting as nodal points, see Figure 16. So, the changing of the planform at section G#3, as well as of the upstream boundary condition of section G#4, could not shift the channels from their confined corridor. This is an indication of a boundary of cohesive materials near both banks of sections G#2 and G#4, which feature is probably the controlling factor of the planform as well as the channel geometry of that reach of the Ganges.

Padma River

The river is almost straight, showing a braiding tendency with a low braiding intensity, see Figure 18. The downstream part, near Mawa River, is constricted and proceeds as a straight single thread channel. Figure 18 shows that the shifting of the banks at the constricted reach is moderate in the period of 1984-1993. A comparison with historical maps shows that the left bank has never been further to the left than today, which indicates the existence of erosion-resistant cohesive bank material. Figure 18 shows that in region 3, the river has been somewhat further to the right as compared with its present bank, while recent maps and satellite imagery show that at Mawa, the river has remained constricted for many decades. Probably, fine sediment deposits over the old course of the river form pockets with a comparatively higher erosion resistance. Like the Ganges River, the width differs between the constricted and the braided parts, see Figure 19. The bank-full width of the single channel at section P#3 near Mawa is distinctly less than for the sections of the river, and the straight single thread reach downstream of Mawa has a single channel bank-full width that is less, as compared with the braided part of the river. Regime relations for the braided reach of the Padma River are shown in Figure 20. Like it is the case for the Ganges, the relations are almost similar to the ones of the Jamuna.

FAP4 attempted to relate the width variation of the Padma River to the bank level. According to this analysis, a higher bank level causes a constricted reach of the river, see the FAP4 Final report, volume 3, 1993. In contrast, Figure 19 shows that there is probably no relation in between constricted reach and relative height of the bank level.

9 Discussion

It appears that a number of factors influence the regime relations. The significance of the planform and of the bank material characteristics was noted in the analysis described in the previous chapters. Below, a discussion is given of aspects related to the regime relations.

9.1 Regime aspects

During the course of time, the river itself adjusts its valley slope, planform, and hydraulic geometry, in accordance with the independent variable characteristics. Recent studies, for example by FAP1 and FAP4, found that the Jamuna, Ganges and Padma Rivers are in a dynamic equilibrium, so that on the average, the rivers convey their sediment loads without any aggrading of degrading trends. Deviating opinions are also offered, pointing at the widening and the westward shifting tendency of the Jamuna (FAP1), and the braiding tendency of the Ganges, as indications that these rivers are probably still in the process of approaching an equilibrium.

The shifting characteristics and the bank erosion rates of these rivers show that the adjustment time of their second-order channels is very small. For the Jamuna River, it is as little as 3 to 4 years in some cases, see Klaassen and Masselink, 1992. Within a short period of time, the second order channel develops, reaches its full grown size, and dies again, and this type of process is continuing in the three rivers. All such phases of the second-order channels are included in the cross-section data. Moreover, the cross-sections used are nearly perpendicular to the channel direction, rather than the flow direction, which is another possible source of the scatter in Figures 8, 9, 14 and 20. Between them, these reasons are probably the main causes of the scatterness in those figures. Still another possibility, however, is the indirect method of estimating the bank-full discharge for the second-order channels.

The second order channels are probably not in an equilibrium or a regime condition, but still, the regime relations of this study reflect the average dimensions of the channels from their development to their decaying phase, and it is also interesting that the braided parts of the rivers have similar regime relations.

9.2 Controlling factors

The slopes and the bed material sizes of the Jamuna and the Ganges are within a range of 8.5 cm to 5.5 cm per km, and 0.20 mm to 0.14 mm, respectively. Also, the sediment transports and the bankfull discharges are similar. The two rivers can be distinguished by their age, the Jamuna being much younger than the Ganges. Another factor, though not verified in the field, is that the Ganges and Padma floodplains are partly composed of alluvial/deltaic silt, which is more cohesive than the material of the Jamuna floodplain. The finer sediments of the Ganges and Padma contain appreciable amounts of carbonate, which is possibly one of the factors of the higher flow-resistance of their banks, as compared with those of the Jamuna River.

Thorne (1988) showed that the width of a river is less in case of cohesive bank material than in case of non-cohesive bank material. Also, the planform of a channel depends on the bank material characteristics. For example, a braided planform is more likely in case of non-cohesive bank material. When the flow attacks a cohesive bank at the boundary of an active corridor, it does not hereby produce the abundant supply of sediments that is needed to form bars, and therefore, it cannot develop braided channels. Instead, it deepens its bed and reduces its width, as it is the case for region 1 and 2 in the Ganges, and region 3 in the Padma River.

On the other hand, the Jamuna River and the braided reaches of the Ganges and the Padma Rivers (though they change with time) have similar bank material characteristics. The material of those banks has been deposited recently (within the last one or two decades), and the loosely packed non-cohesive material results in similar regime relations.

From the above discussion, it appears that the bank material and the channel form have a definite influence on the channel dimensions. These two factors are again a function of the geomorphological characteristics of the river. Further studies, based on detailed data on bank material characteristics, are required in order to describe the relations between geomorphology and channel geometry.

9.3 Regime relations

The regime relations derived for the different rivers are almost similar. The combined data from all three rivers give the following relations (see also Figure 21):

$B = 10.34\ Q^{0.55}$
$h = 0.31\ Q^{0.29}$

The exponents are close to Lacey's values, though the present relations yield a much higher width and a smaller depth. Data from the Meghna River, as studied by FAP9b, are also shown in Figure 20. Both the width and depth relations for this river differ from the ones shown above, probably due to a different planform and different bank materials, and also due to a different state of the river, as discussed by FAP9B.

9.4 Flow regime and planform

As wandering rivers, the Ganges and Padma have different characteristics with respect to channel geometry. The variation of parameters, such as width (B), average depth (h), conveyance factor ($B*h^{3/2}$), average velocity (u), and roughness (C) are shown in Table 5 for each river and each type of planform.

River	Planform	B (m)	h (m)	$B*h^{1.5}$ ($m^{2.5}$)	u (m/s)	C ($m^{0.5}/s$)	u^5/C^3*B	i (cm/km)
Ganges	Braided	3718	6.50	61614	1.78	93	0.083	5.6
	Constricted	2476	6.90	44877	2.51	144	0.083	4.4
Padma	Braided	5200	7.78	106806	1.93	100	0..135	4.9
	Constricted	3867	8.00	87500	2.42	134	0.135	4.1

Table 5: Variation of different parameters with the changing of characteristics of the river stretches

An attempt has also been made to see whether the channel at bank-full condition could transport its sediment load without aggrading or degrading any channel reaches. Engelund-Hansen's sediment transport factor u^5/C^3 was used, where C is Chezy's roughness factor. The width (B) and the average depth (h) of the braided part were estimated from Figures 14 and 20 and of the constricted part from Figures 12, 13 and 19. The average velocity was estimated by a continuity condition at bank-full discharge. By assuming a constant sediment transport throughout the river, and by keeping 'u^5/C^3' constant, C and i can be estimated by iteration. It can be seen from Table 5 that the braided parts of the rivers need a higher slope than the constricted parts for transport of the same amount of sediments.

In both rivers, the roughness factor C of a straight reach is higher, and even higher than the Chezy value for the grains. Such a higher value of C is also found by FAP9b for the Padma River, which requires further analysis.

It is also of interest to know the relation between the channel dimensions and the planform characteristics of the river. There are a number of planform prediction methods based on stability analysis. Among those, three methods are compared in Figure 22: Fredsoe (1979), Struiksma and Klaassen (1988), and Blondeaux (1993). All these methods are based on the form ratio and the slope of the river. Estimated parameters for the prediction methods are shown in Table 6.

Figure 22 suggests that the Jamuna River and all stretches (within the study reaches) of the Ganges and Padma Rivers are in a braided or transition planform. It appears that the methods of Blondeaux (1993) and of Struiksma and Klaassen (1988) are applicable for the different stretches of those rivers.

River	Planform	Q_b (m^3/s)	B (m)	h (m)	i (cm/km)	u (m/s)	B/h	θ	F_r	θ'	λ_s/λ_w
Jamuna	Braided	48,000	4213	6.6	7.5	1.70	630	1.52	0.21	0.96	91
Ganges	Braided	43,000	3718	6.5	5.0	1.78	571	1.40	0.22	1.42	76
	Constricted	43,000	2476	6.9	5.0	2.51	357	1.5	0.30	2.8	27
Padma	Braided	75,000	5200	7.5	4.5	1.93	695	2.04	0.22	2.17	113
	Constricted	75,000	3867	8.0	4.5	2.42	483	2.15	0.27	3.4	56

Table 6: Parameters estimated for the rivers to classify the planform characteristics on the basis of Fredsoe (1979), Struiksma and Klaassen (1988), and Blondeaux (1993). Q_b= bankfull discharge (m^3/s), B= bankfull width (m), i= overall water surface slope, θ= shield stress, θ'= shield stress (modified for form roughness) and $\lambda_s/\lambda_w = (2g/\pi^2C^2)*(B/h)^2*f(\theta)$, where g= acceleration due to gravity (m/s^2), and $f(\theta) = 0.85\theta^{0.5}$

10 Conclusion and recommendations

On the basis of the analysis and the discussion in the previous chapters, the following conclusions can be drawn:

- In view of the geomorphology and the channel geometry, the rivers are probably not in a regime condition

- It appears that the channel dimensions of the Ganges and Padma Rivers are influenced by geomorphological control

- The braided reaches of the three major rivers have almost similar relations for width and depth at bank-full discharge

- The at-a-station equations of the Jamuna River are almost similar to the regime relations, which confirms that the Jamuna is a quickly responding river.

- The constricted stretches of the Ganges and Padma show a smaller width and roughness, a higher depth, and probably a smaller slope, as compared with those single channels of the braided stretches that carry more than 80 % of the discharge at bank-full condition

- The prediction method for planform classification by Struiksma and Klaassen (1988) seems to apply for these three rivers

In the present study, the channel dimensions and their geomorphological controls have been studied for the three main rivers only. The geomorphological controls have been assessed on the basis of cross-section analysis and macro-scale geological information. The following recommendations are given in order to further improve the understanding of the controls on the main river systems and other rivers:

- This type of study should be extended to cover other rivers

- Further studies are needed of the influence of geomorphological controls on the rivers, with a detailed examination of the bank material characteristics

- Also, further studies are recommended on the sensitivity of the channel dimensions to the sediment transport, the hydrological variability, and the slopes, as a basis for an improved understanding of the river processes

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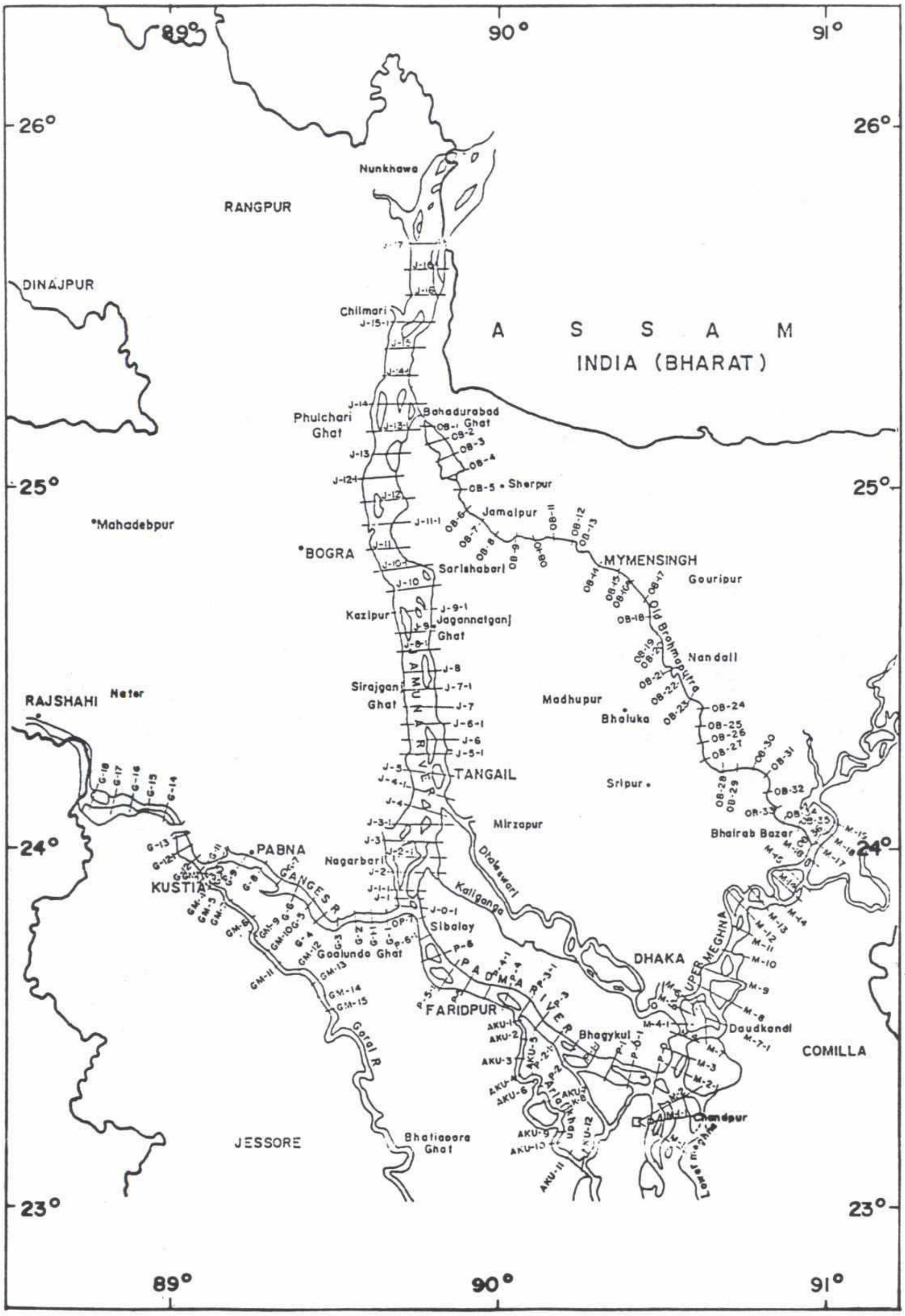


Figure 1: Standard BWDB cross-sections in the main river system

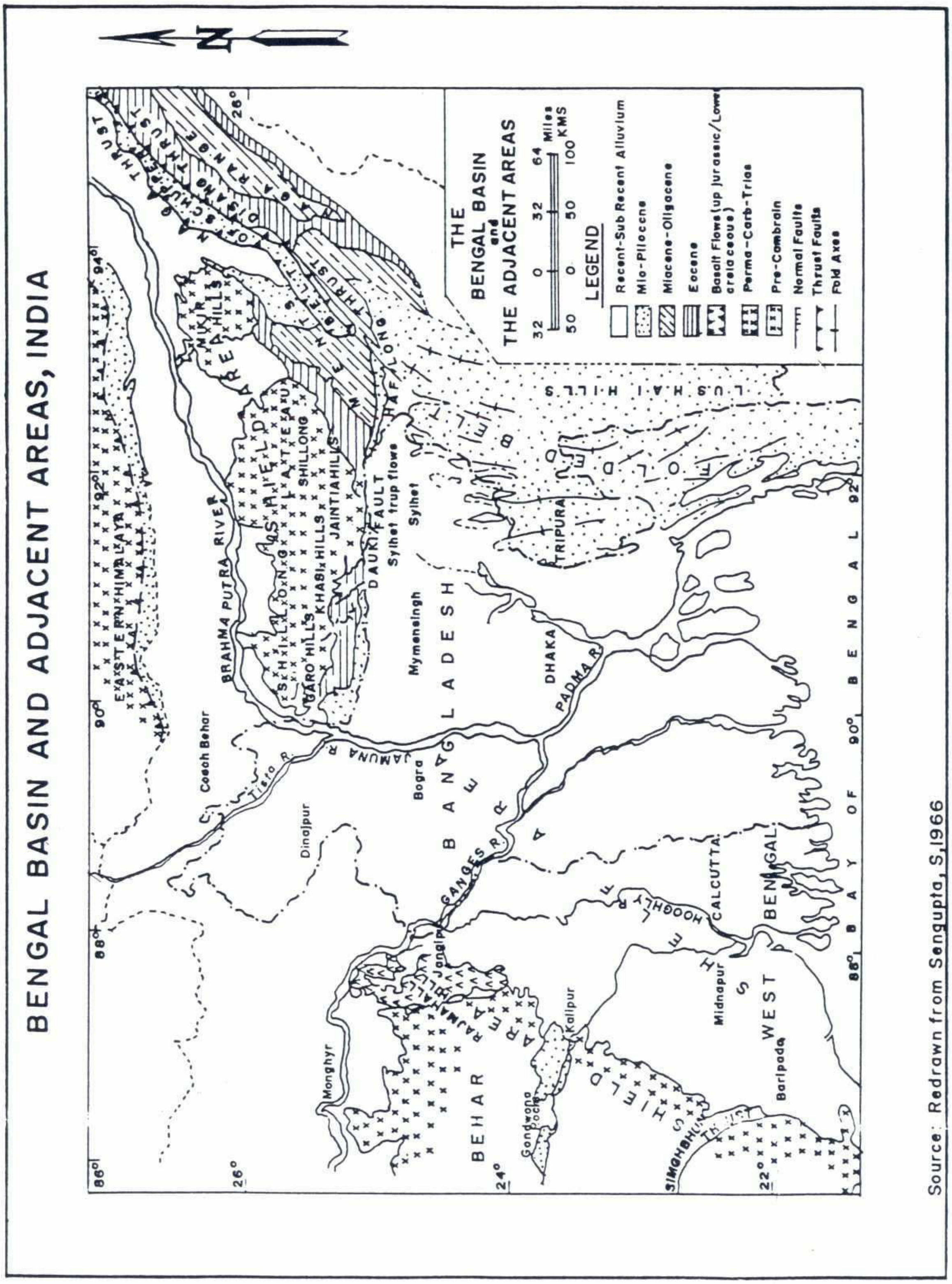


Figure 2: The Bengal Basin and its surrounding areas, after MPO, 1987

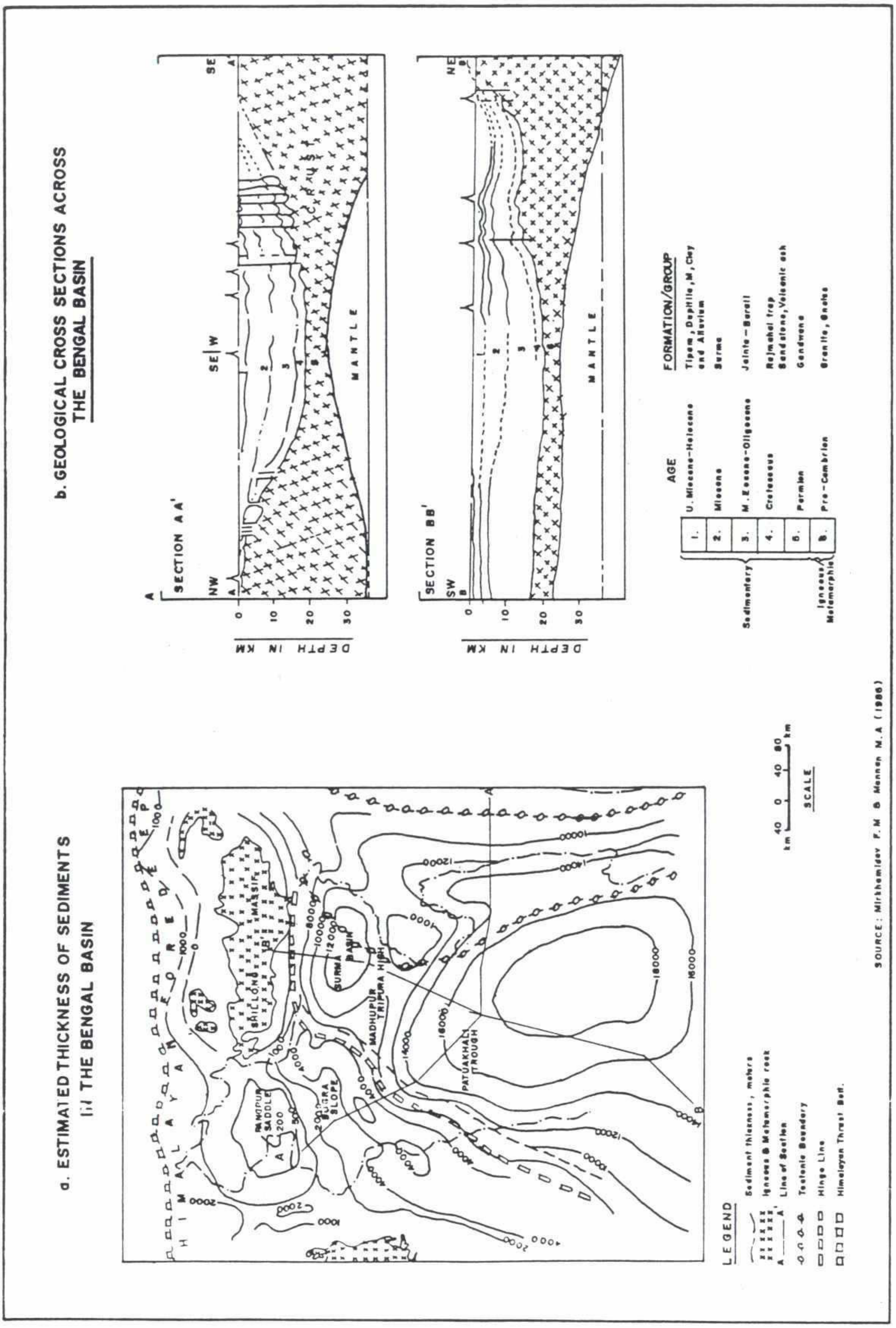


Figure 3: Thickness of sediments in the Bengal Basin, after MPO (1987)

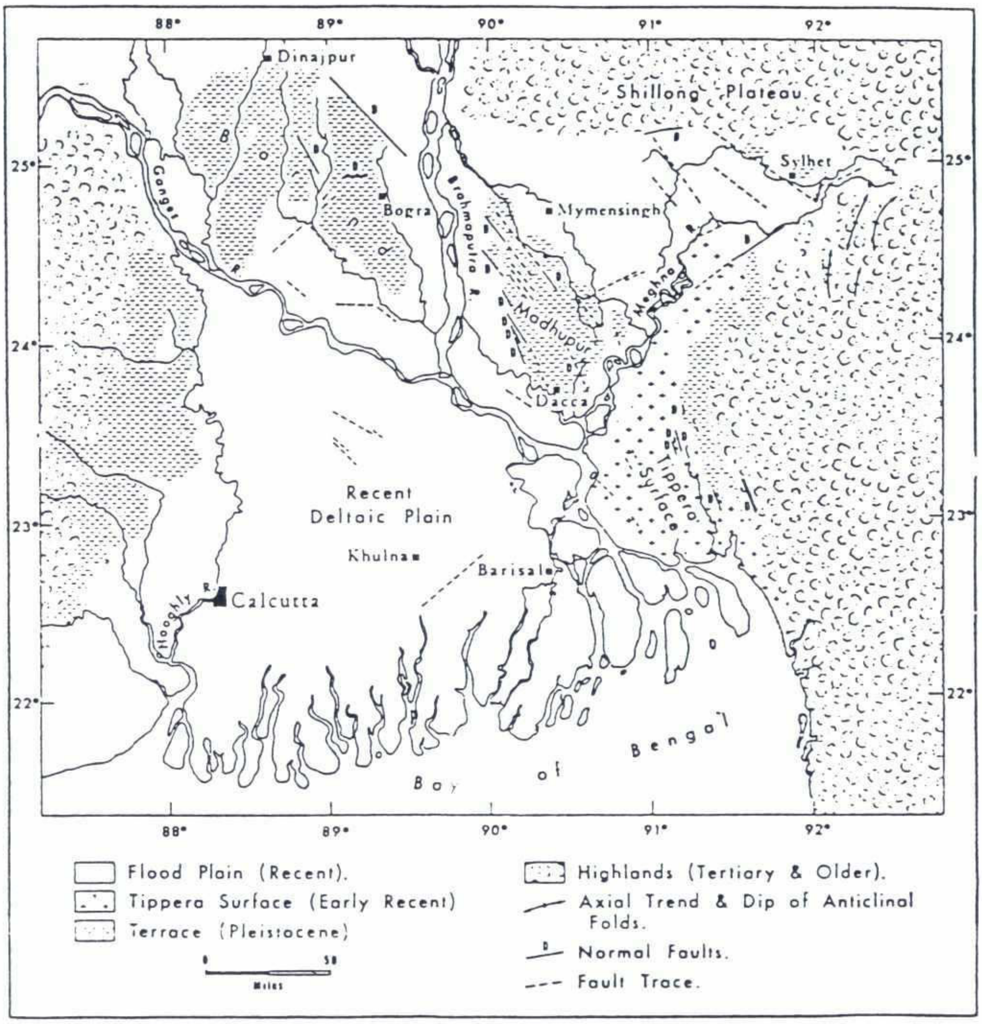
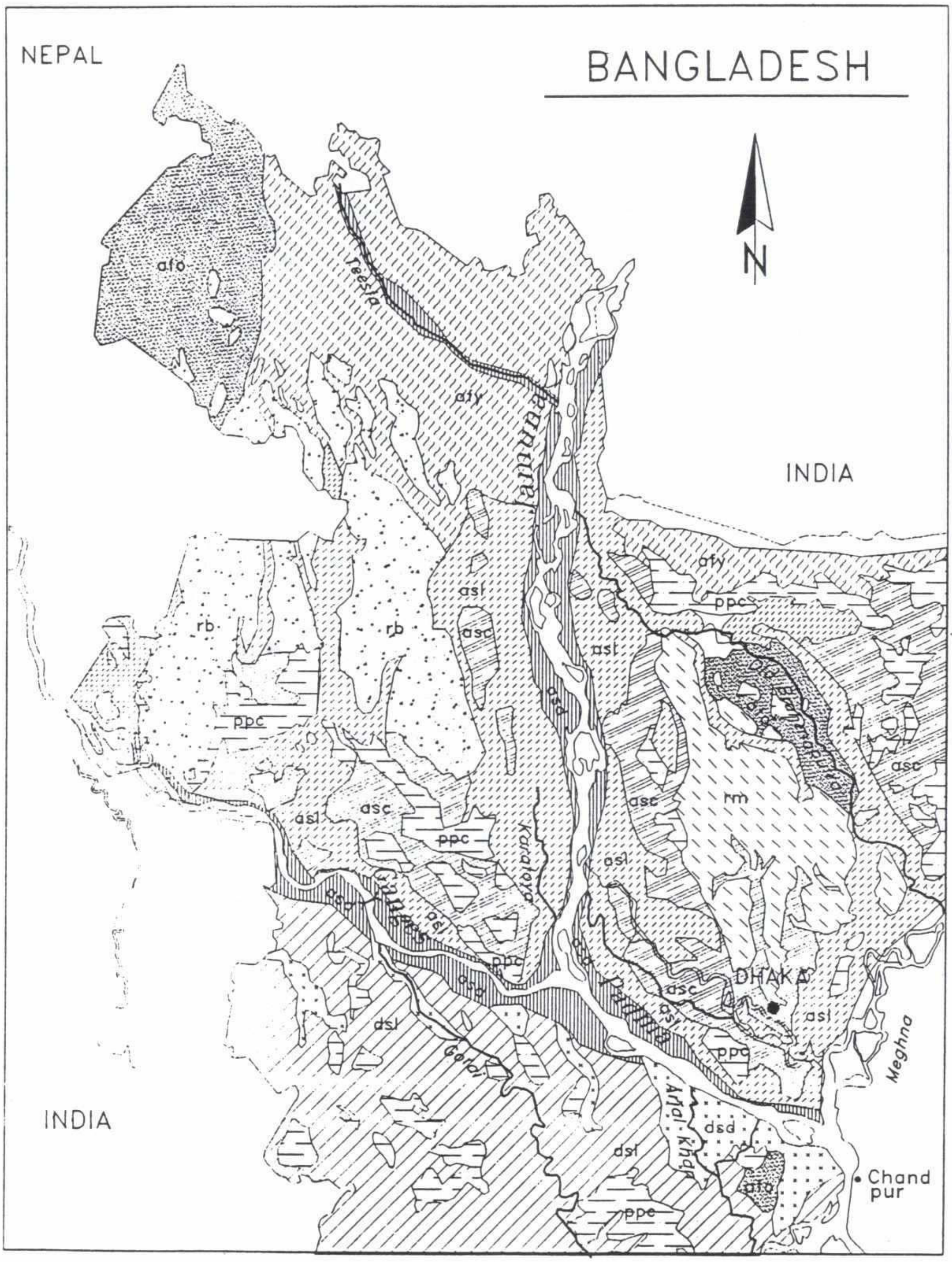


Figure 4: Quaternary geology of the Bengal Basin, after Morgan and McIntire (1959)



Redrawn from Geological map of Bangladesh, 1990

Figure 5: A part of the geological map of Bangladesh, showing the floodplains of the Jamuna, Ganges and Padma Rivers. Abbreviations are explained in Section 5.1

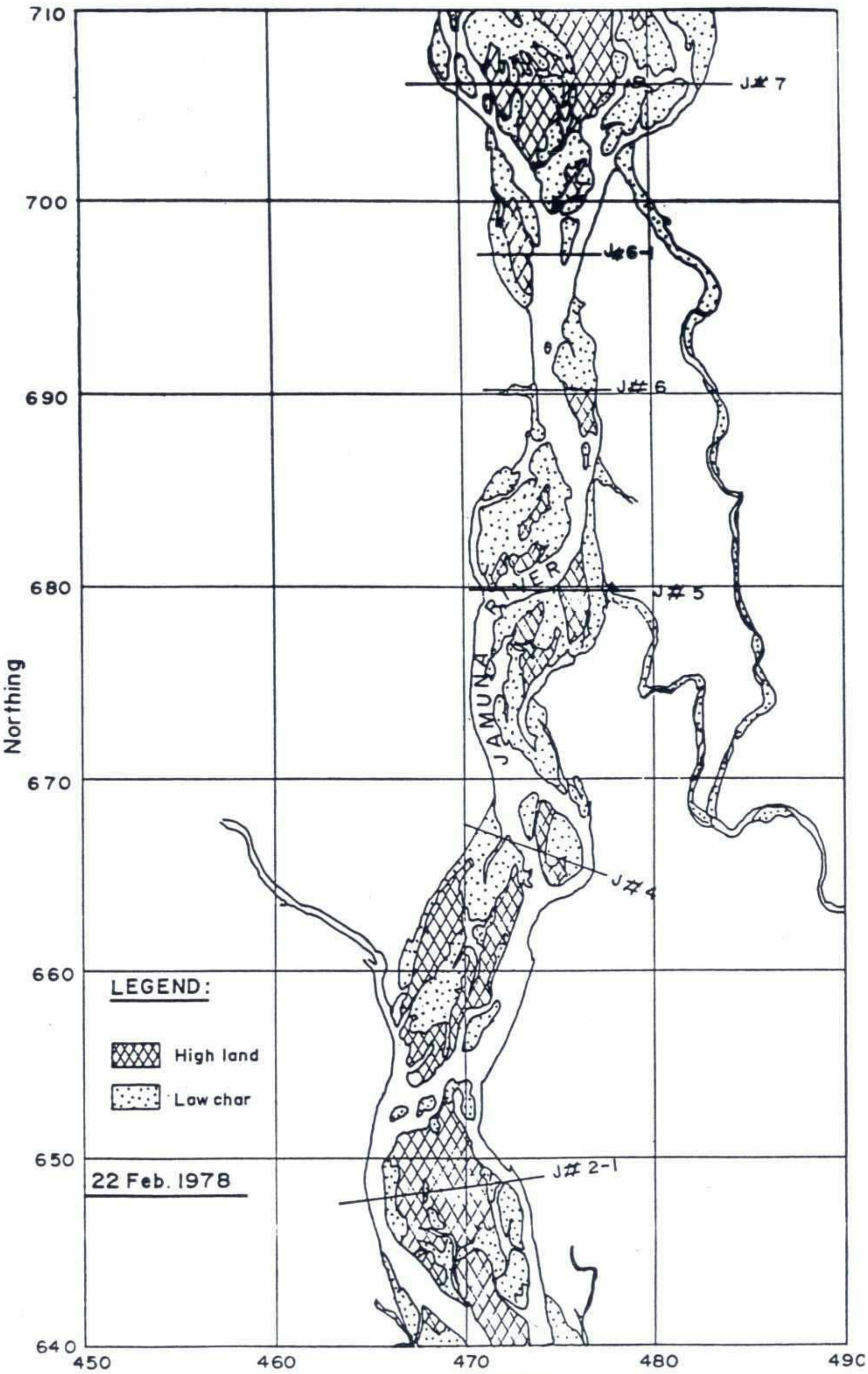


Figure 6: A part of the Jamuna River, based on LANDSAT imagery, 1978

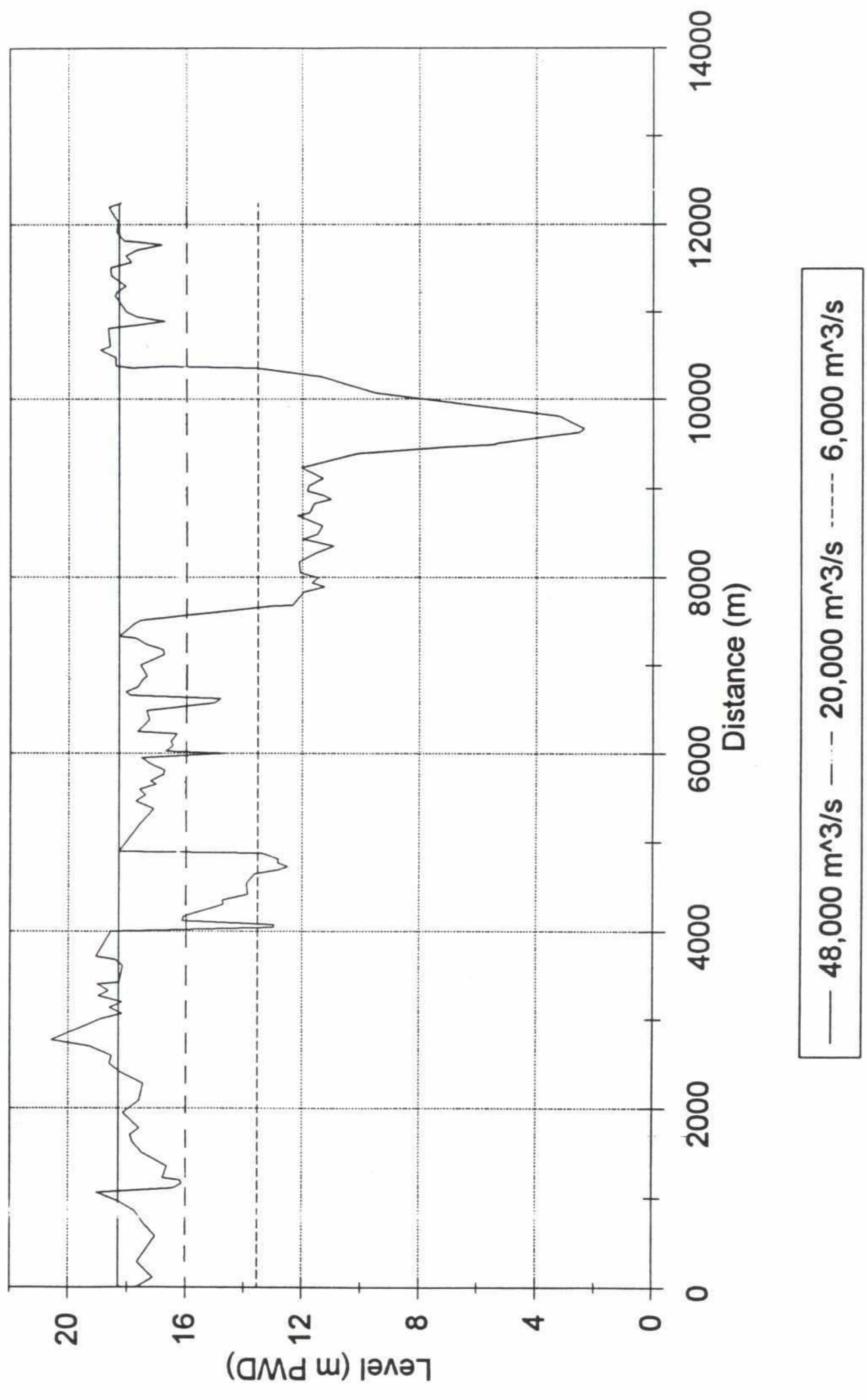
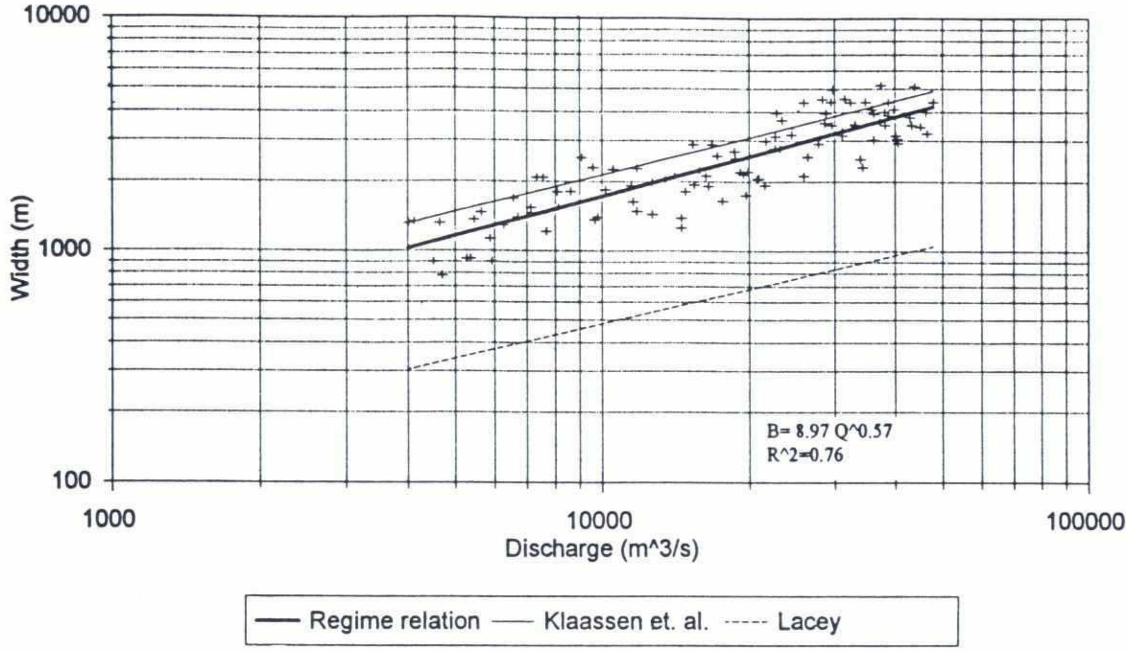
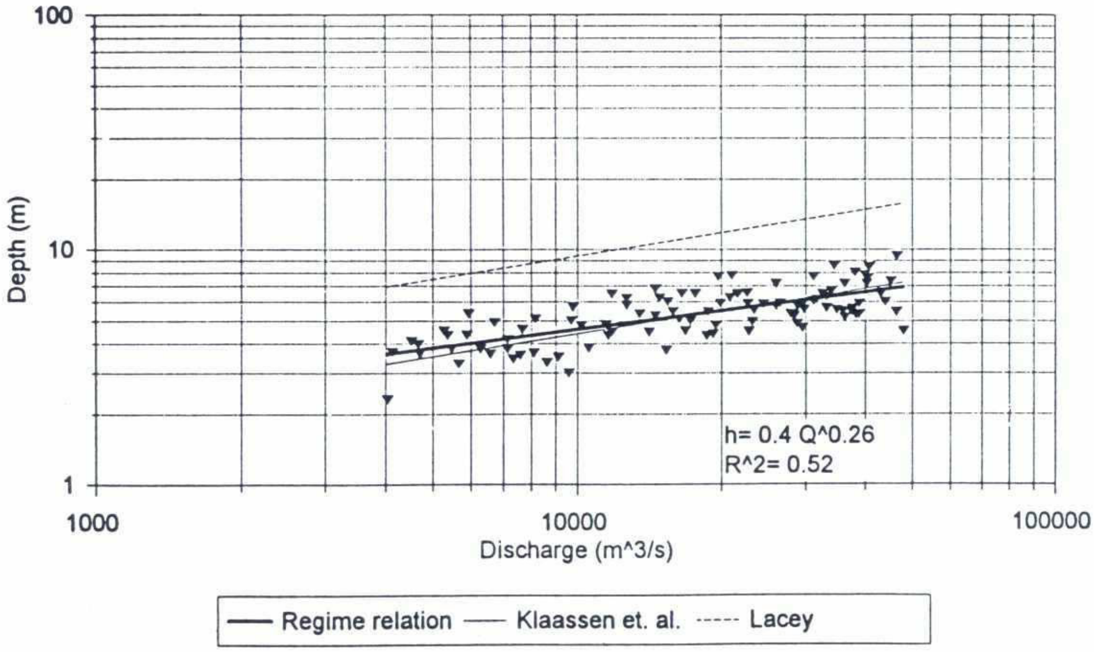


Figure 7: A BWDB cross-section of the Jamuna River showing the different levels for different discharges

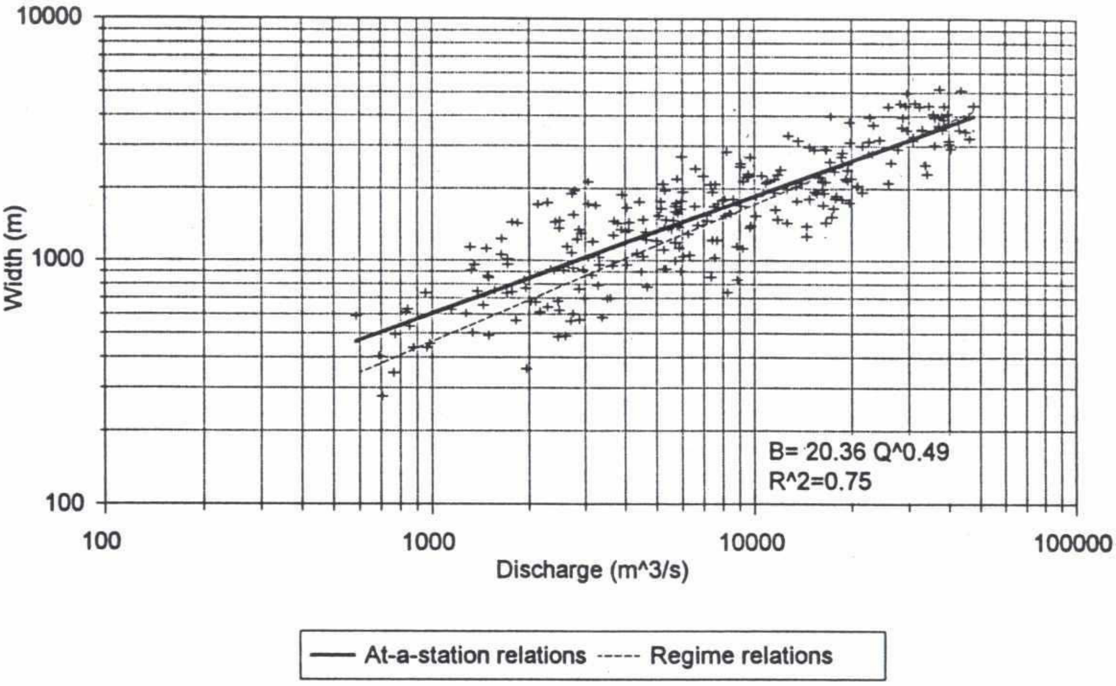


a. Width relation to bankfull discharge

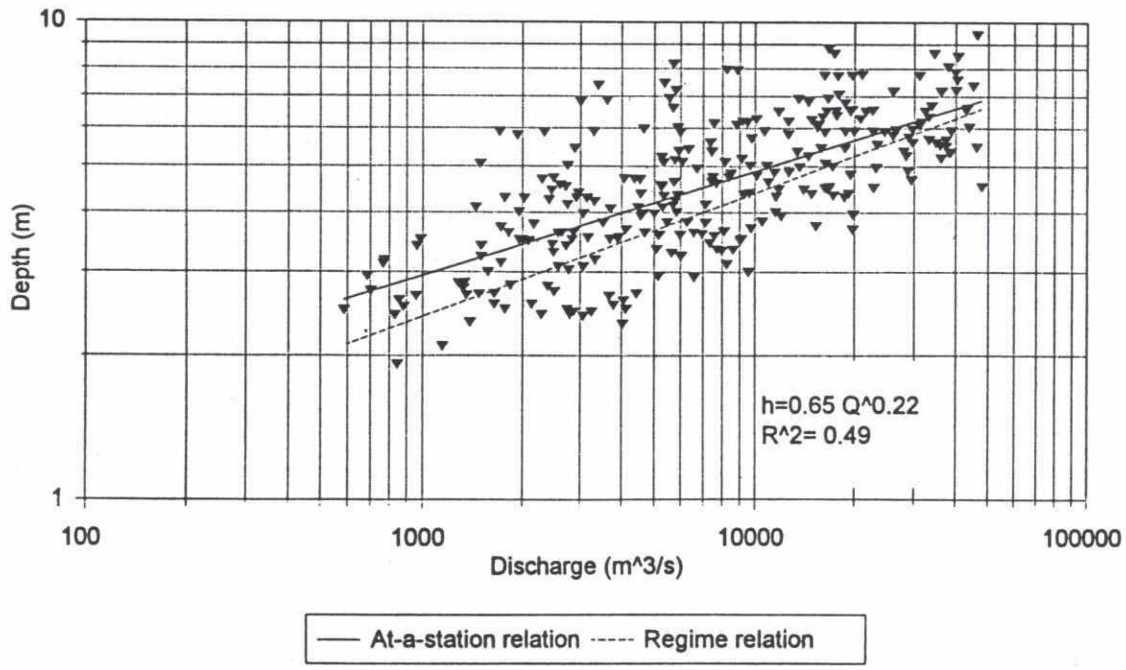


b. Depth relation to bankfull discharge

Figure 8: Regime relations at bank-full discharge (48,000 m^3/s) of channels of the Jamuna River

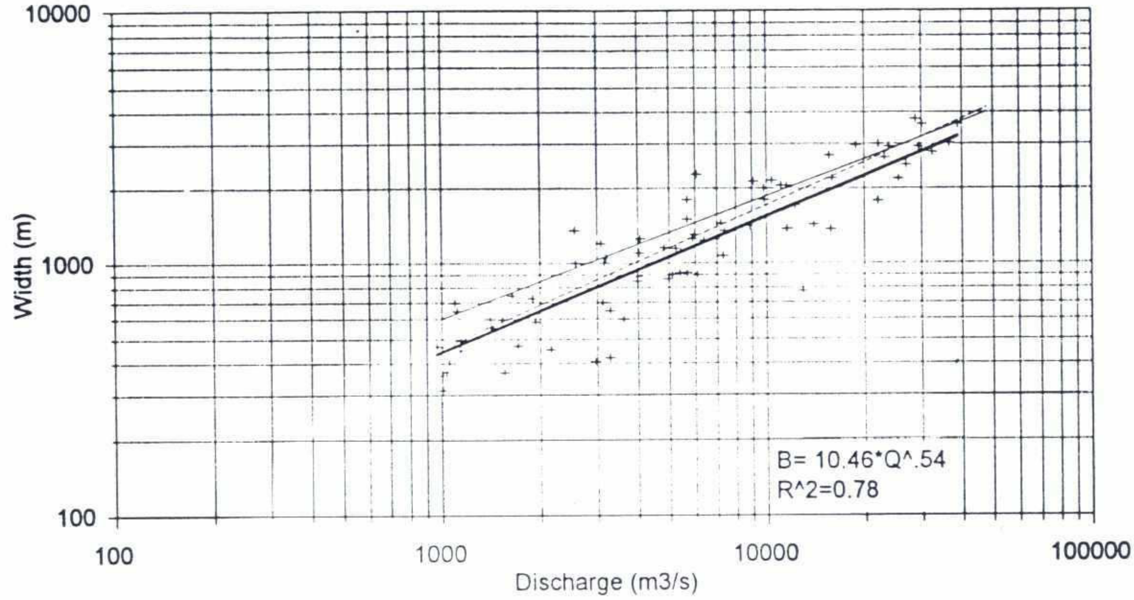


a. Width relation to discharges



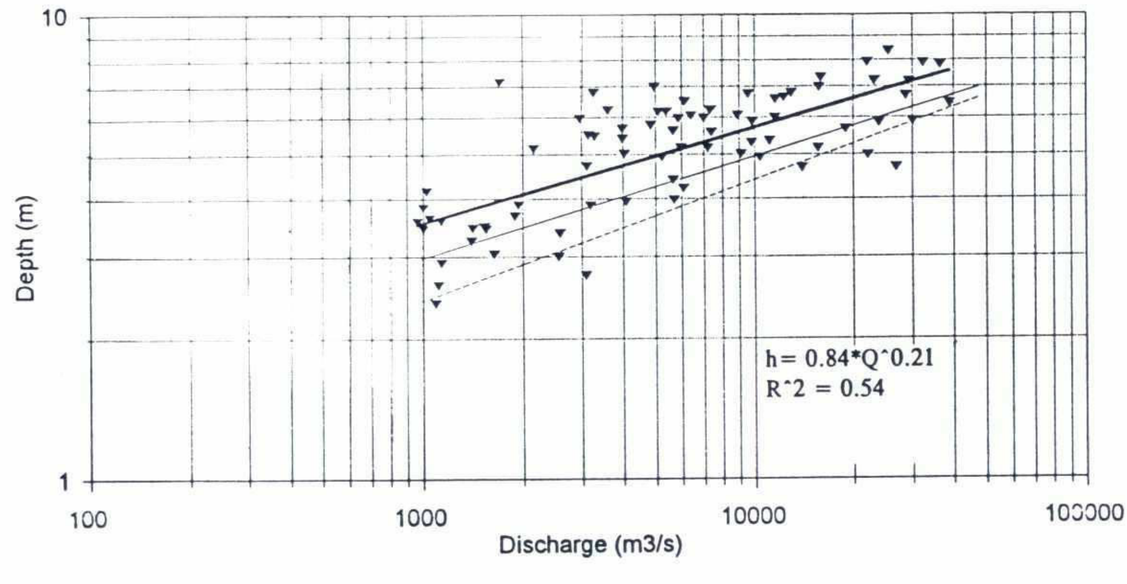
b. Depth relation to discharges

Figure 9: At-a-station width and depth relations (at different discharges) of channels of the Jamuna River (using BWDB cross-section data)



— At-a-station, FAP24 data Regime relation — At-a-station, BWDB data

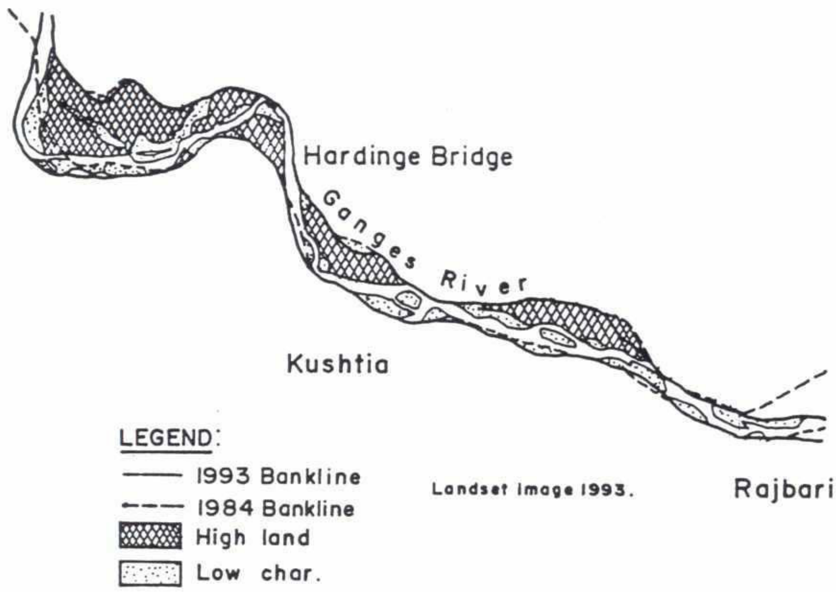
a. Width relation to discharges



— At-a-station, FAP 24 data ----- Regime relations — At-a-station, BWDB data

b. Depth relation to discharges

Figure 10: At-a-station width and depth relations (at different discharges) of channels of the Jamuna River (using FAP24 survey data)



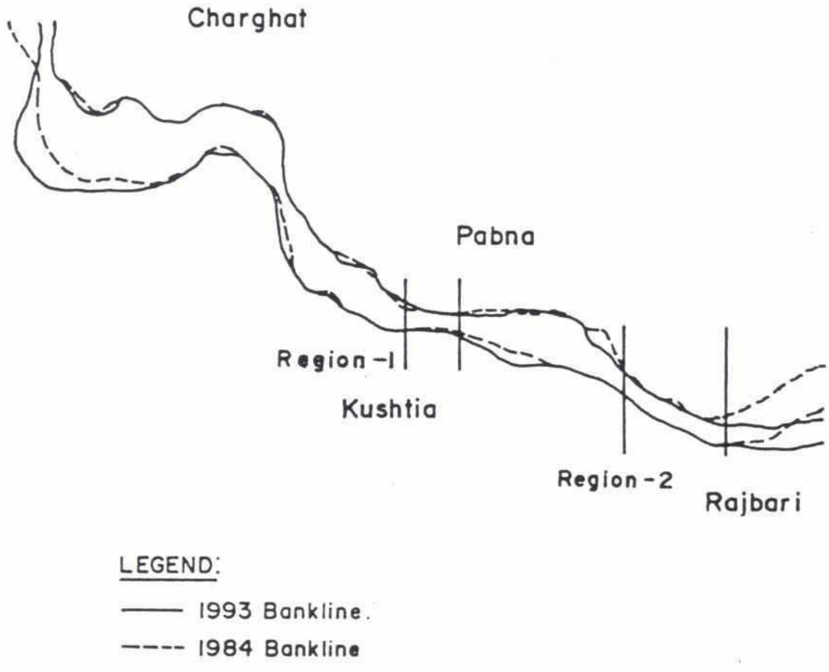


Figure 11: Bankline movement of the Ganges River (1984-1993), after ISPAN (1993)

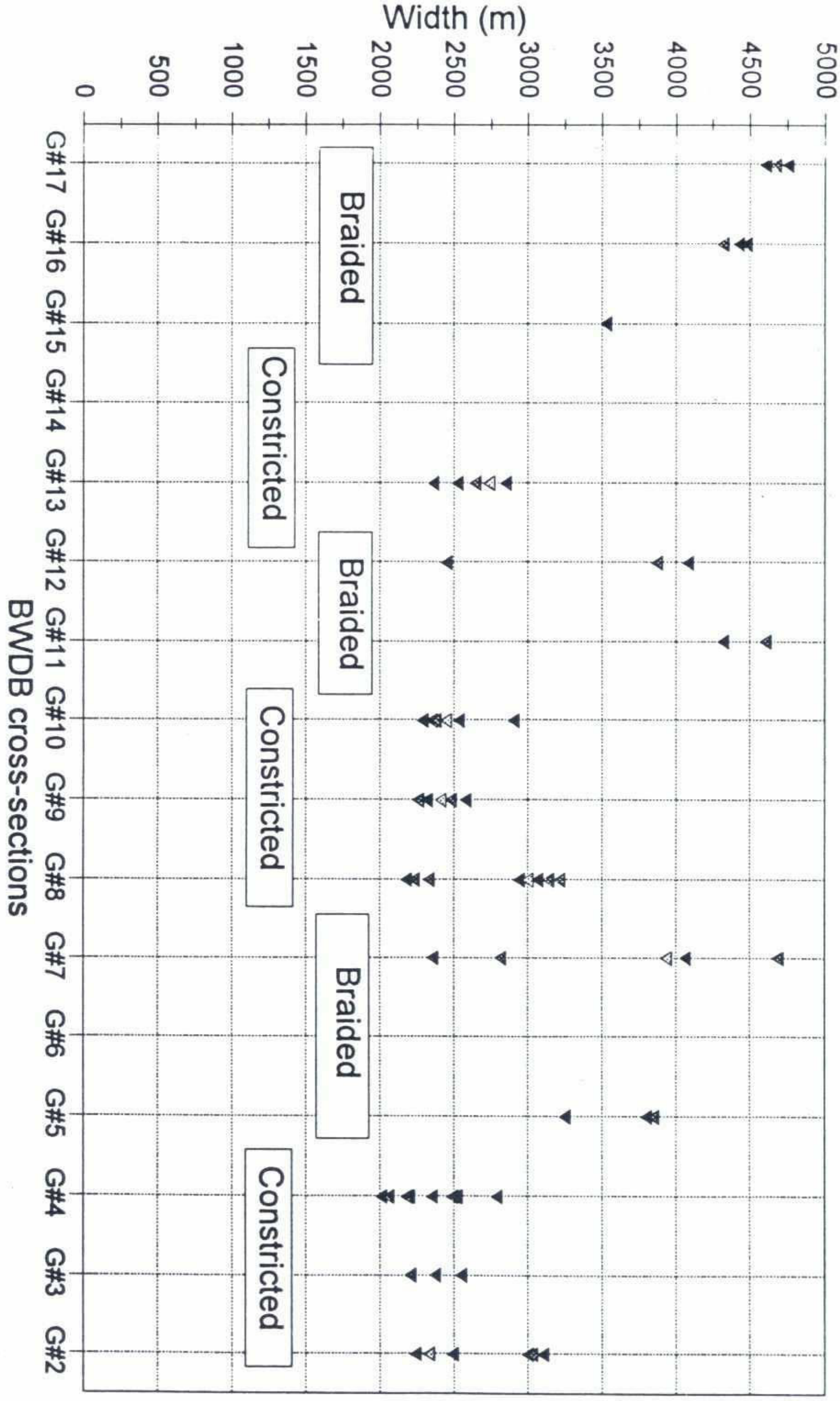
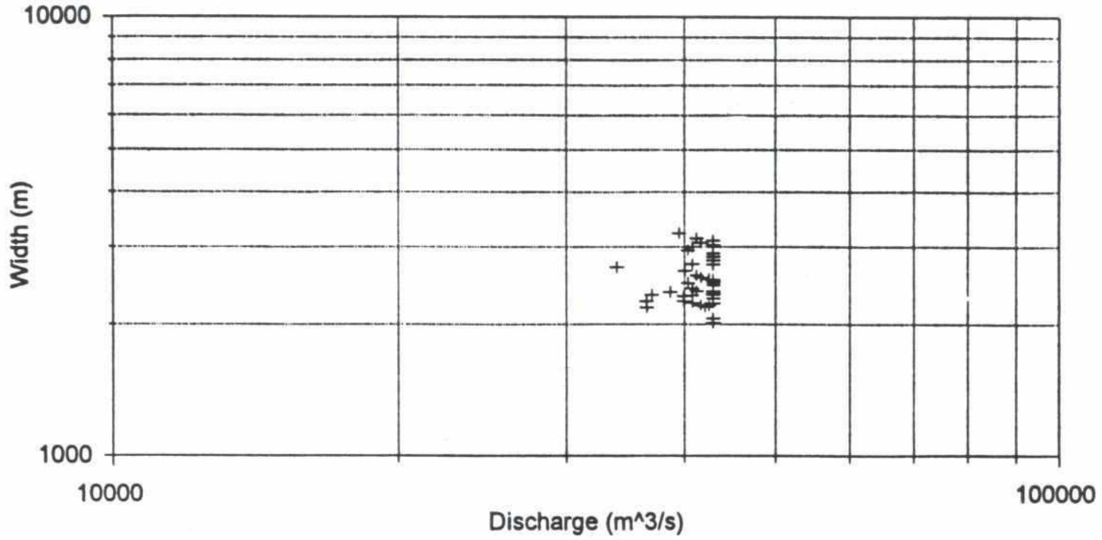
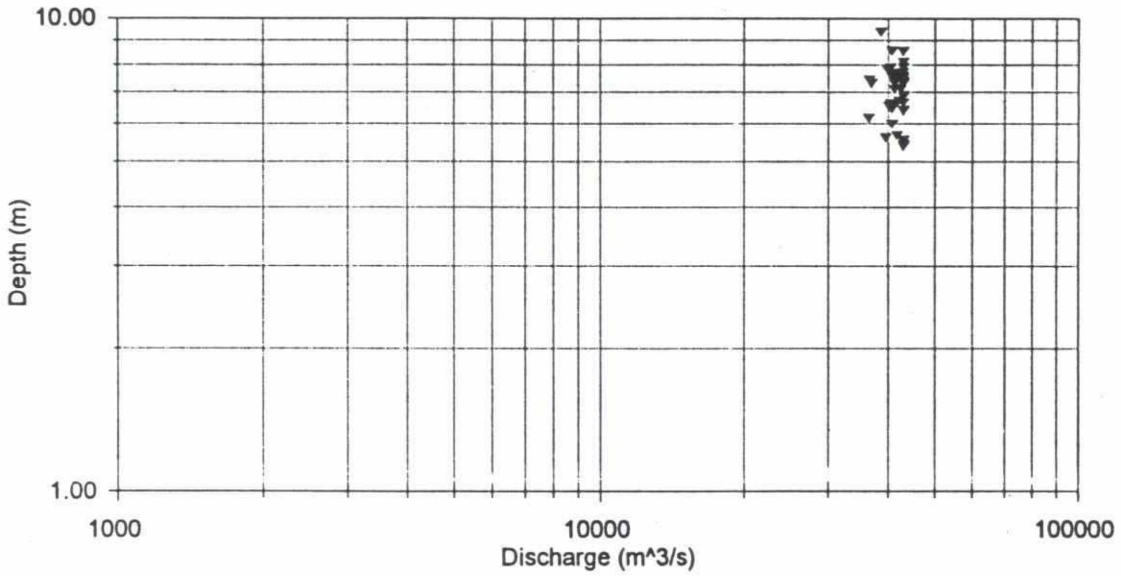


Figure 12: Width of channels, Ganges River (conveyance more than 85% at bankfull discharge)

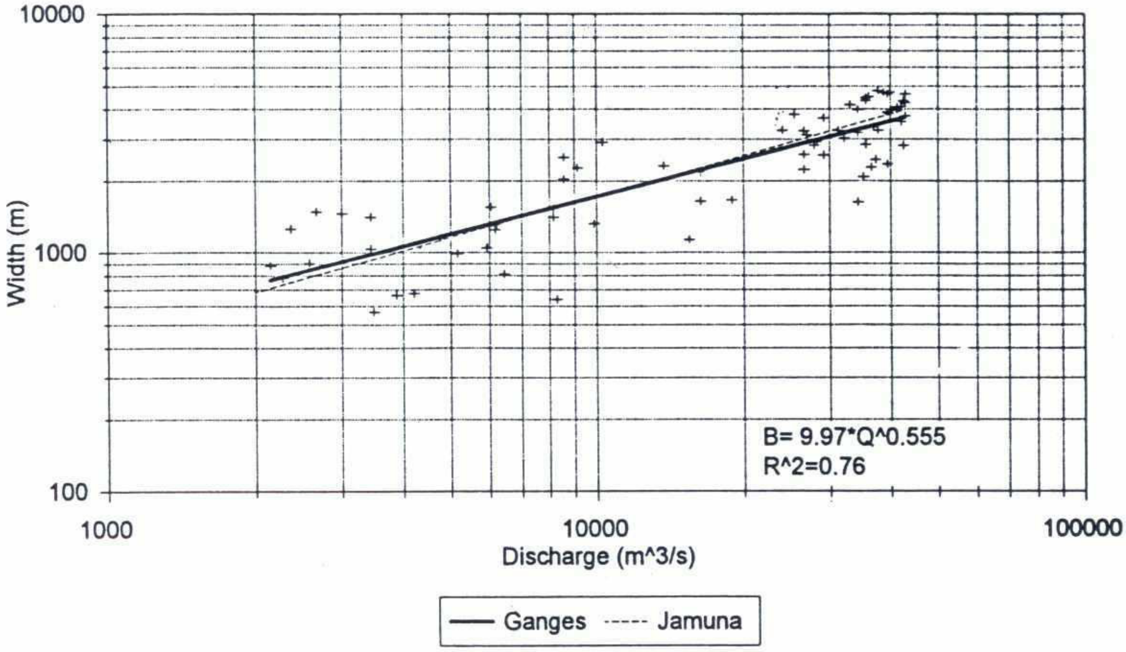


a. **Width relation to bankfull discharge**

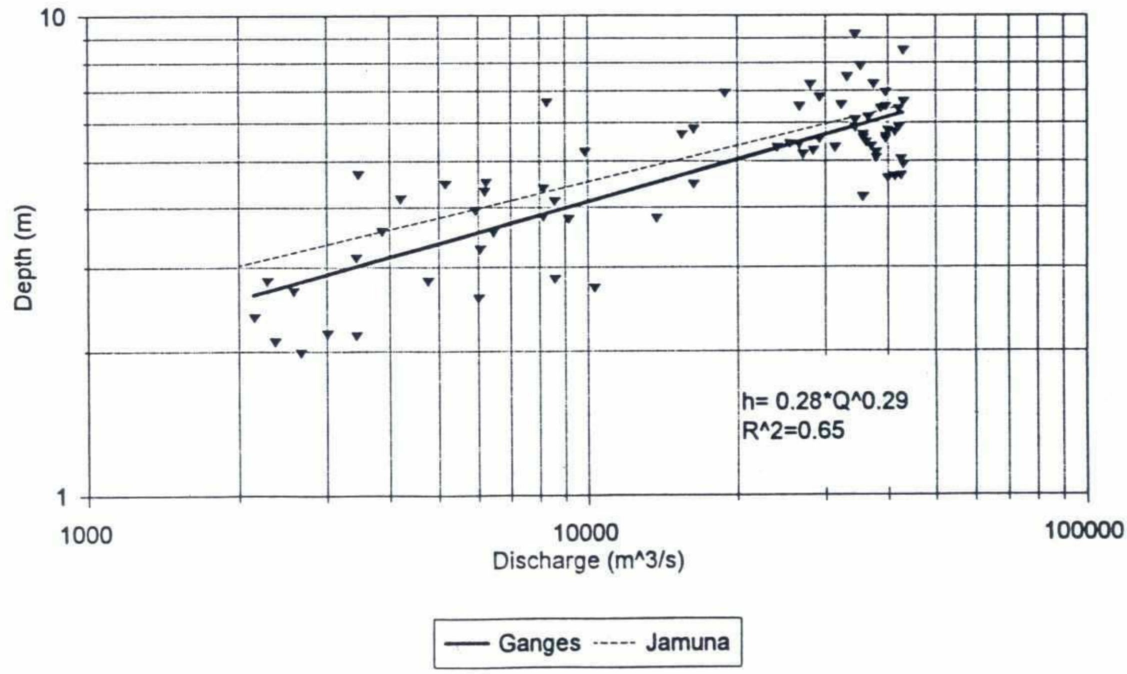


b. **Depth relation to bankfull discharge**

Figure 13: Regime relations at bankfull discharge (43,000 m^3/s), the constricted part of the Ganges River



a. Width relation to bankfull discharge



b. Depth relation to bankfull discharge

Figure 14: Regime relations at bankfull discharge (43,000 m^3/s), the braided part of the Ganges River

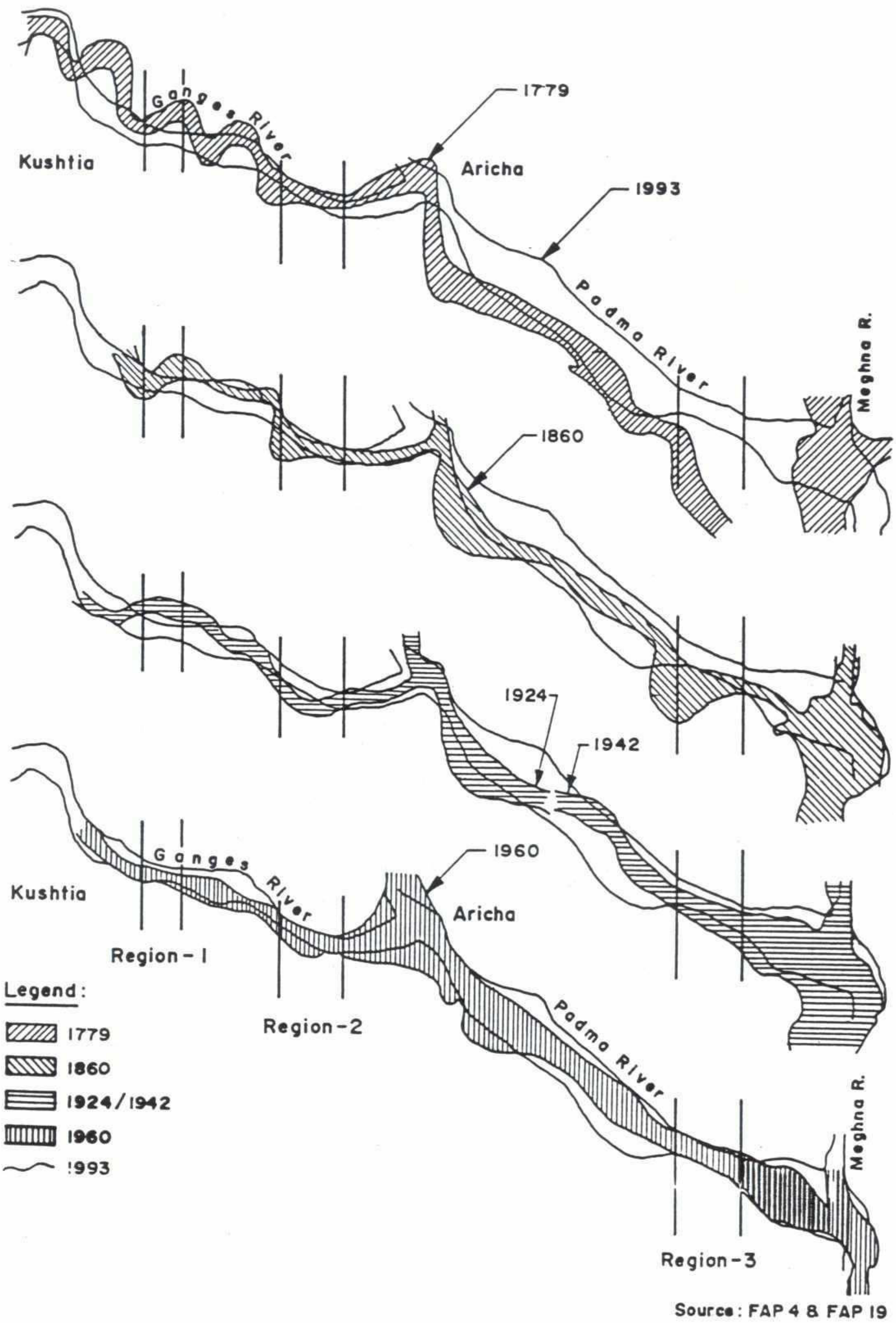


Figure 15: Historical bank line positions of the Ganges and Padma Rivers, as compared with the 1993 bank line position, after ISPAN (1993)

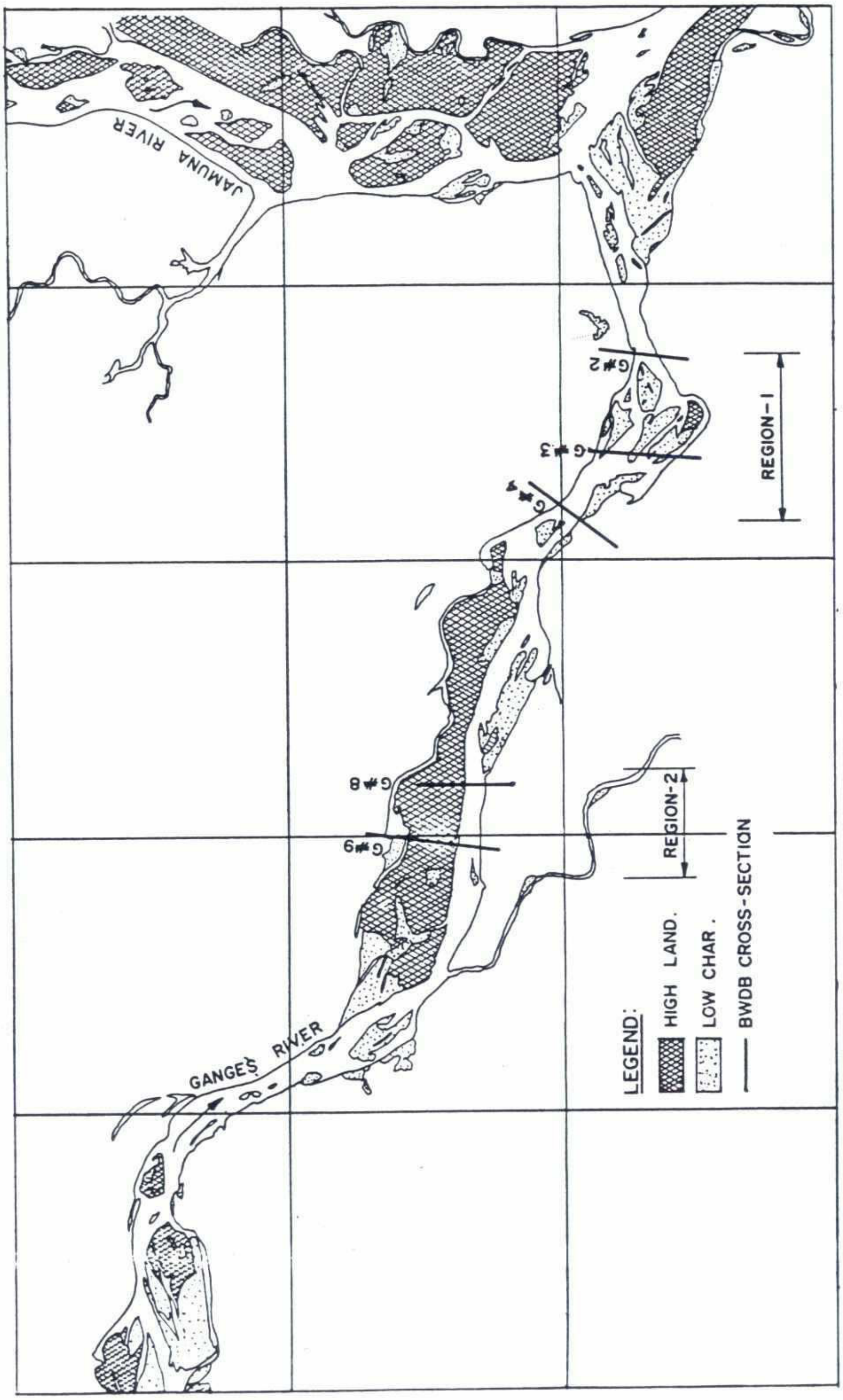


Figure 16: Ganges River, based on LANDSAT imagery, January, 1973

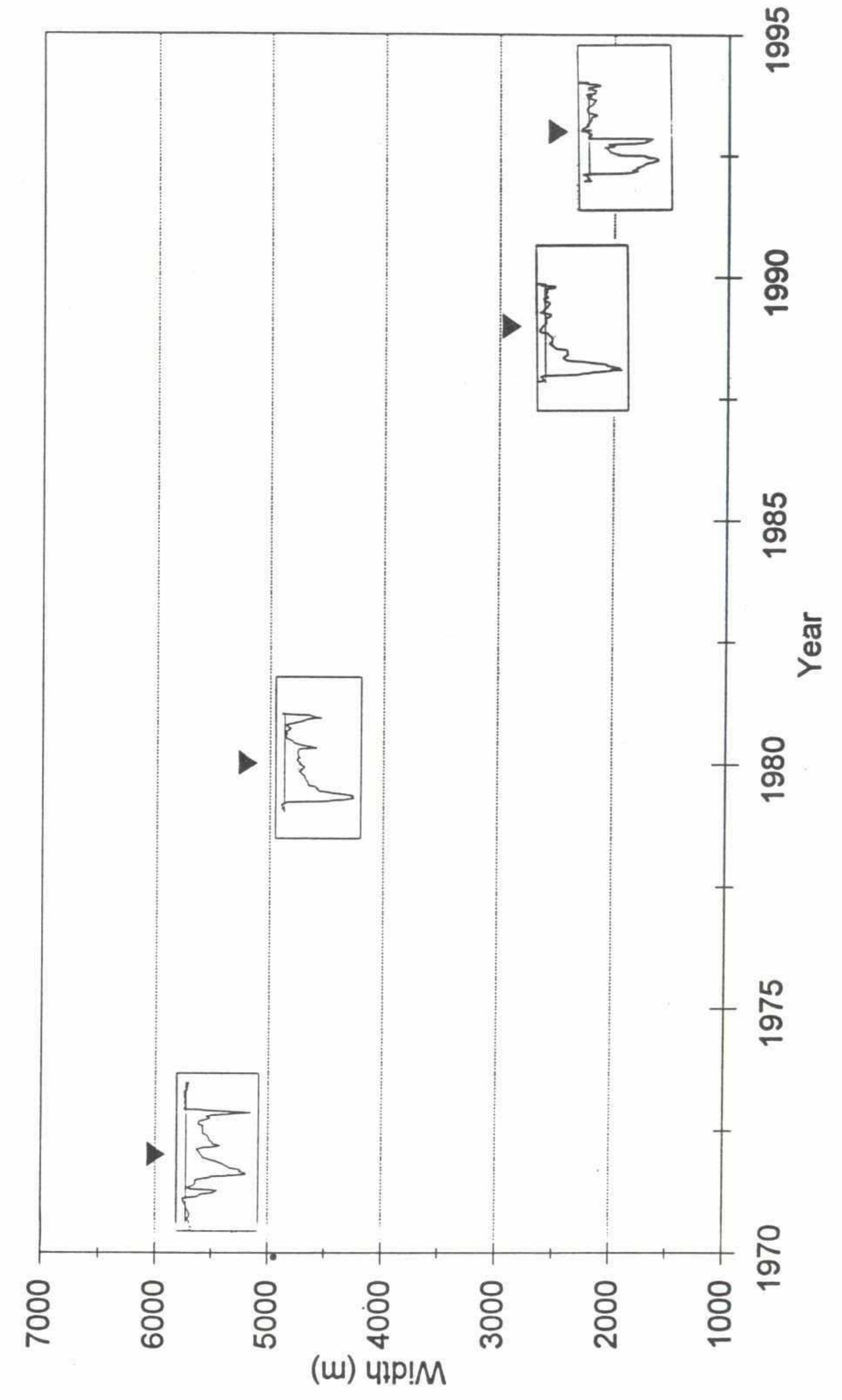


Figure 17: Width of channel at BWDB cross-section G#3 as a function of time and planform

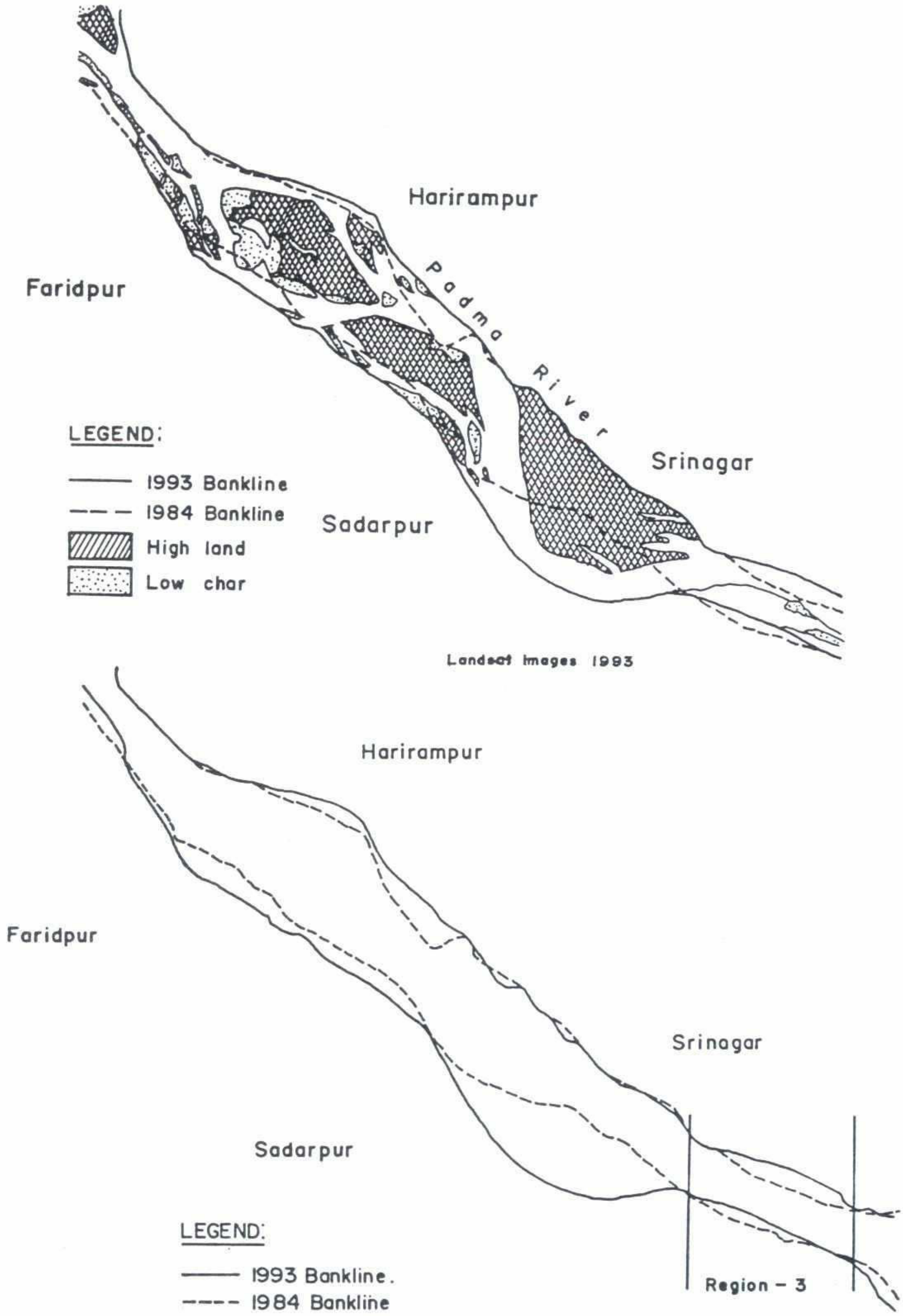


Figure 18: Bankline movement of the Padma River (1984-1993), after ISPAN (1993)

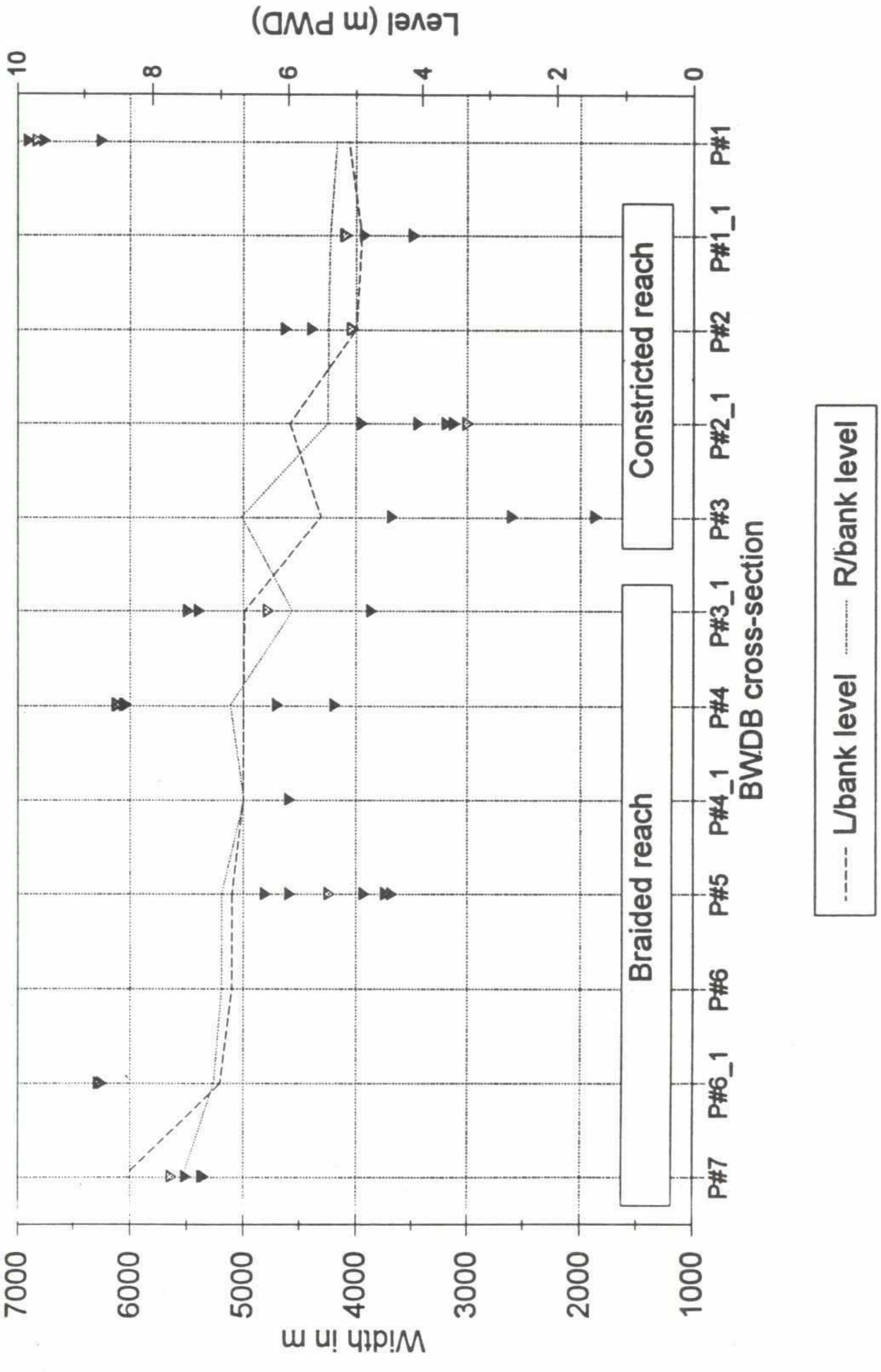
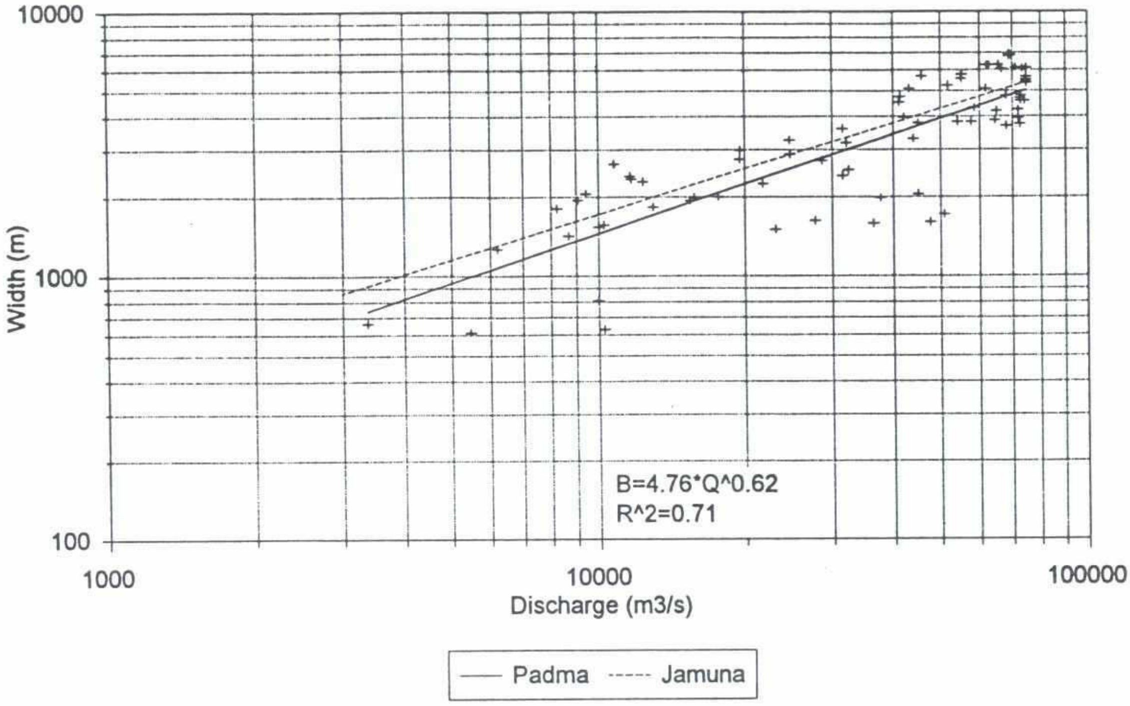
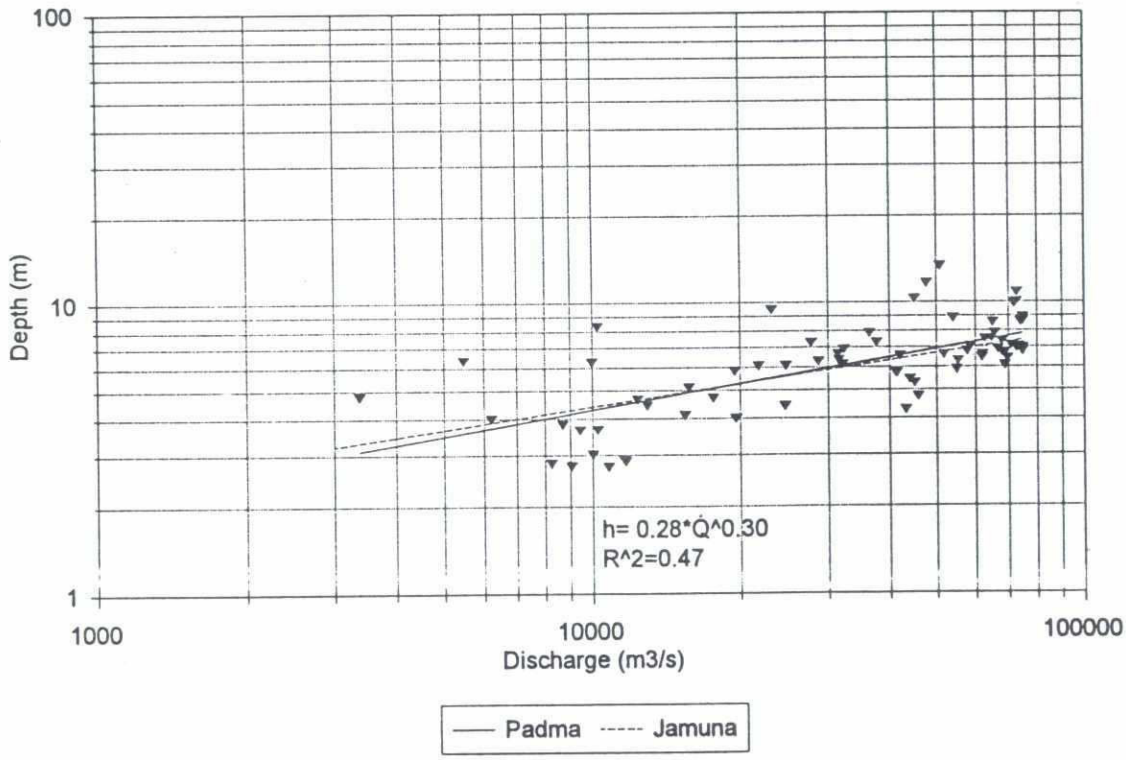


Figure 19: Width of channel (conveyance more than 85% at bankfull discharge) and bank elevation of the Padma River

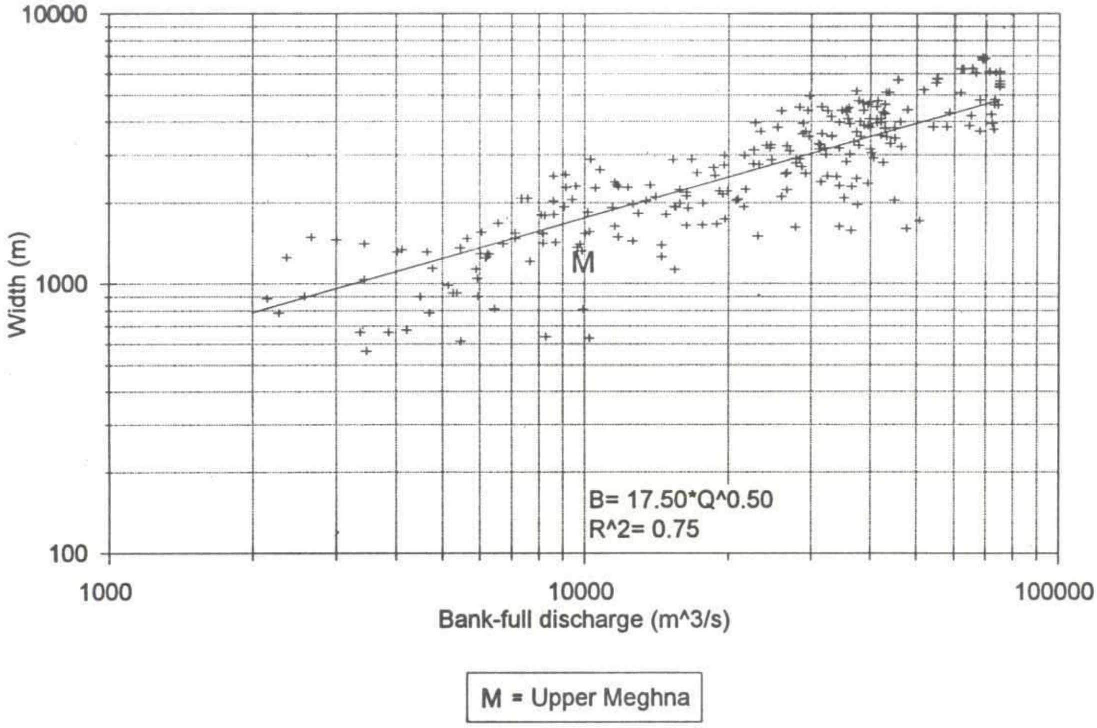


a. Width relation to bankfull discharge

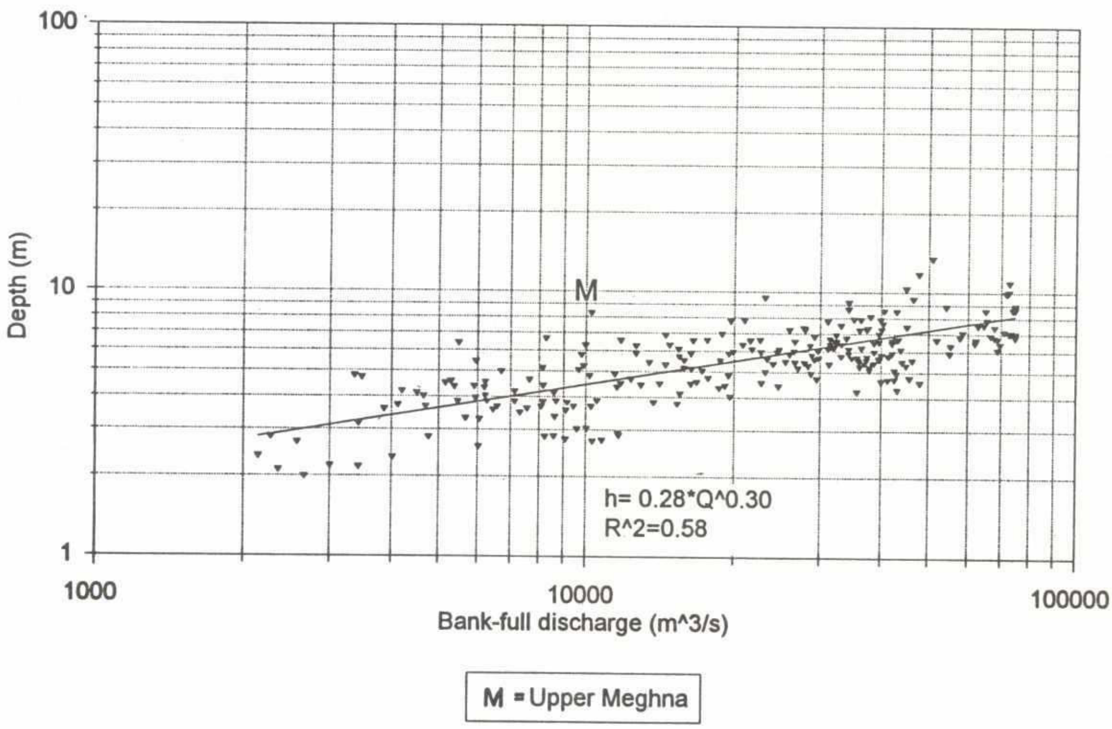


b. Depth relation to bankfull discharge

Figure 20: Regime relations at bankfull discharge (75,000 m^3/s) of channels in the braided part of the Padma River

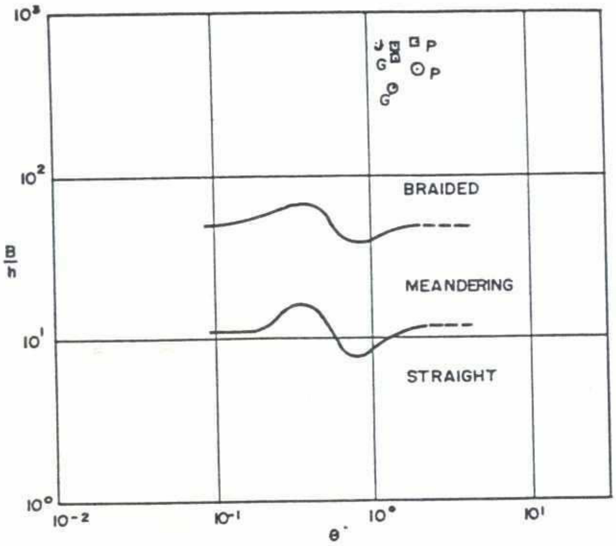


a. Width relation to discharges

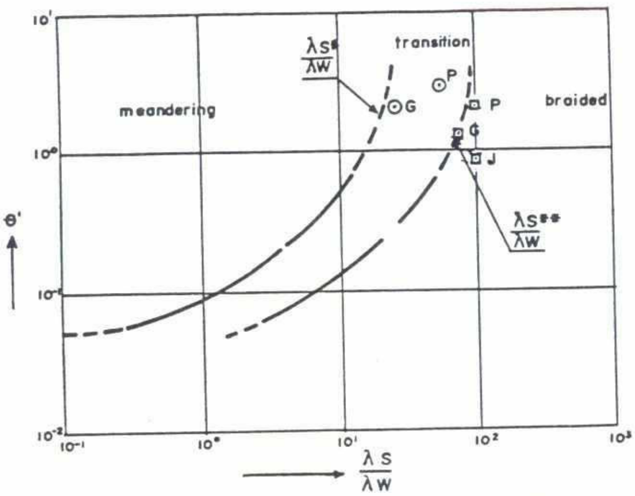


b. Depth relation to discharges

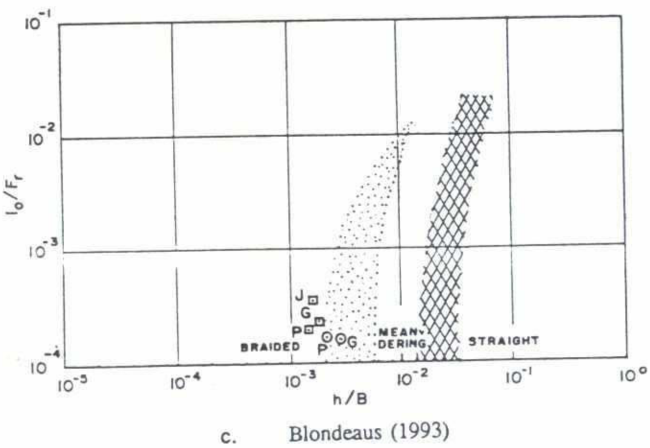
Figure 21: Regime relations at bankfull discharge of channels of the Jamuna River and the braided parts of the Ganges and Padma Rivers



a. Fredsoe (1979)



b. Struiksma and Klaassen (1988)



c. Blondeaus (1993)

LEGEND:

- ⊡ Braided stretches of river.
- ⊙ Constricted stretches of river.
- J Jamuna river.
- P Padma river
- G Ganges river

Figure 22: Position of the Jamuna River and different stretches of the Ganges and Padma Rivers on the different planform classification diagrams