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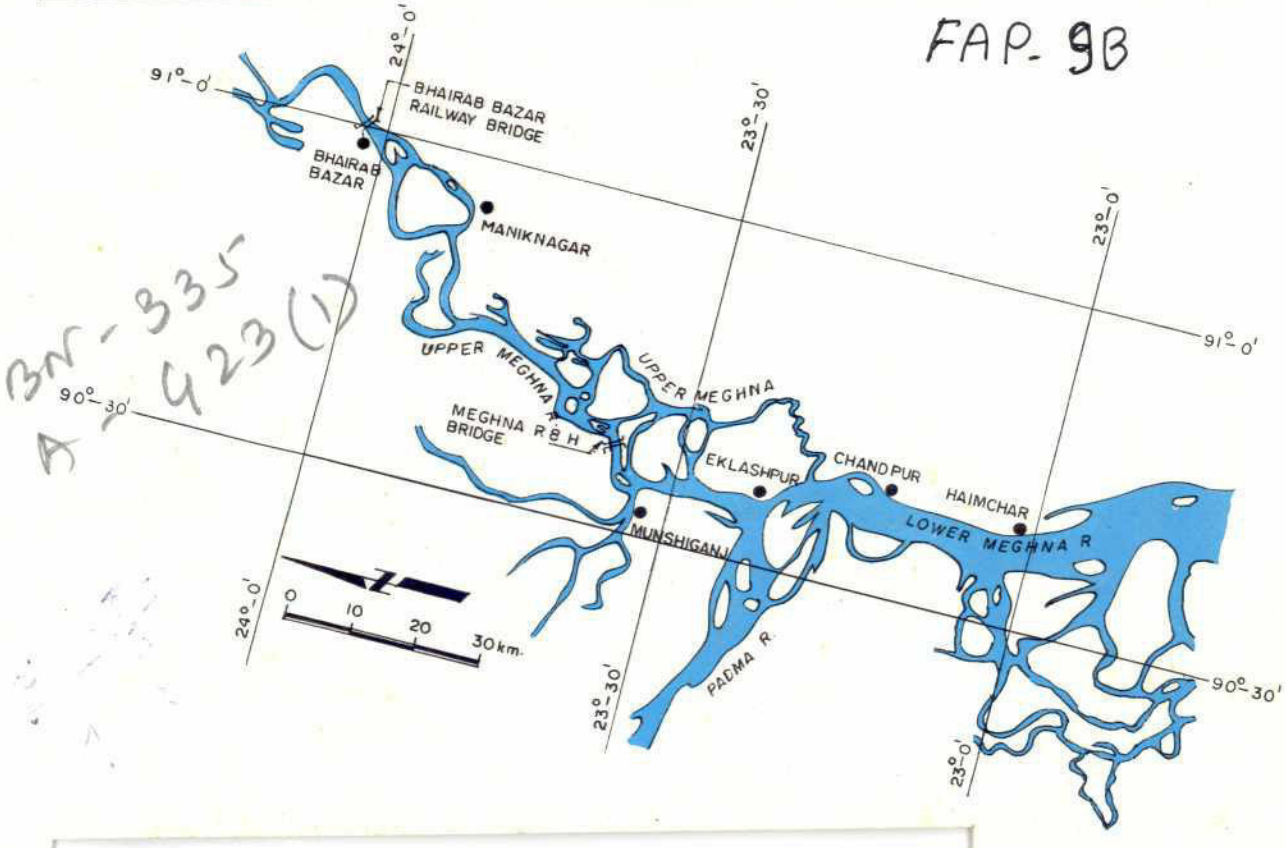
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BANGLADESH WATER DEVELOPMENT BOARD

MEGHNA RIVER BANK PROTECTION
SHORT TERM STUDY

IDA Credit 1870 BD (Part D), March 1990

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FINAL REPORT

VOLUME II

ANNEX: A HYDROLOGY

ANNEX: B RIVER MORPHOLOGY AND GEOMORPHOLOGY

February 1992

HASKONING, Royal Dutch Consulting
Engineers and Architects

in association with:

DELFT HYDRAULICS
BANGLADESH ENGINEERING & TECHNOLOGICAL SERVICES LTD.

PREFACE

The Meghna, one of Bangladesh' major rivers, flows through the eastern part of Bangladesh and discharges into the Bay of Bengal.

Like other rivers in Bangladesh the Meghna erodes it banks in many points and this erosion has assumed an alarming magnitude since the severe floods of 1987 and 1988. Consequently, a number of locations requires prompt attention to prevent further damage or even events of a catastrophic nature.

This Final Report describes the surveys, studies, designs, cost estimating and economic evaluation carried out during 1990-1992 as part of the Short Term Study (FAP-9B) for Meghna Bank Protection.

The Report consists of seven volumes comprising a Main Report and nine Annexes A to I. Some Annexes are accompanied by a series of APPENDICES containing detailed information or supporting data relevant to them.

Vol I			Main Report
Vol II	Annex	A :	Hydrology
		B :	River Morphology and Geomorphology
Vol III	Annex	C :	Geotechnical Investigations
Vol IV	Annex	D :	Scale Model Studies
		E :	Mathematical Model Studies
Vol V	Annex	G :	River Bank Protection
Vol VI	Annex	F :	Economics of Protection Works
Vol VII	Annex	H :	(not used)
		I :	Environmental Impact Assessment.

INTRODUCTION TO THE PROJECT

1. Background

There are three major rivers in Bangladesh; the Ganges, the Brahmaputra and the Meghna. Originating form Assam in India, the Meghna River flows through the eastern part of Bangladesh and discharges into the Bay of Bengal. The Meghna River drains an area of 77,000 km^2, of which about 46,500 km^2 is located in Bangladesh. The major contributors to the river upstream of Bhairab Bazar are the Boulai, the Surma and the Kushiyara rivers, covering an area of 62,960 km^2. The Ganges joins the Brahmaputra near Aricha and thereafter takes the name of the Padma. The Padma joins the Meghna at Chandpur. The Lower Meghna River conveys the melt and rain water form the Ganges and Jamuna basins, combined in the Padma River, and from the Upper Meghna basin to the sea. The total catchment area is about 1,637,000 Km^2. Maximum flows can be as high as 160,000 m^3/s. The major contribution of the discharge originates from the Jamuna River (annual average 19,642 m3/s) and the Ganges River (annual average 10,874 m^3/s).

The reach of the Meghna River from Bhairab Bazar to Haimchar is about 160 km in length. Width of the river varies from 1 km to more than 10 km. The river channel is more or less well defined upstream of its confluence with the Padma and is braided in the reach downstream of Chandpur. The river is considerably deep all along and the depth ranges to 35 m in the bends. The river bed and banks consist mainly of clayey-silt which is often loosely packed and is susceptible to liquefaction at some places. Of the three major rivers, the Meghna carries relatively less sediment. The velocity of flow of the river is high during monsoon. The river banks are also subjected to heavy wave action at some points.

Like other rivers in Bangladesh, the Meghna erodes its banks in many points. Erosion at the Meghna since the severe flood of 1988 has assumed an alarming proportion at the following locations which require prompt attention.

- The Railway bridge at Bhairab Bazar;
- Bhairab Bazar Township along the right bank;
- Maniknagar; along the left bank, falling within the proposed Gumti - Phase II Project;
- Meghna R & H Bridge;
- Eklashpur (near Meghna-Dhonagoda Project);
- Chandpur Town;
- Haimchar (adjacent to Chandpur Irrigation Project);

The Dhaleswari River, a tributary of Meghna, has been eroding its right bank at Munshiganj for quite some time and has threatened the existence of Munshiganj Town.

2. Meghna River Bank Protection -Short term Study

The study of possible bank protection works at critical locations along the Meghna river commenced officially in September 1990 when BWDB, Bangladesh Water Development Board commissioned HASKONING, Royal Dutch Consulting Engineers and Architects in association with DELFT HYDRAULICS and BETS, Bangladesh Engineering and Technological Services, to carry out the Meghna River Protection Short Term Study, financed under Credit IDA BD-1870, Part D.

The objectives of the study are:

- to provide short term measures for protection against erosion for seven locations on the Meghna river and one location on the Dhaleswari;

- to gradually implement a coherent and phased programme of works, aiming at the control of erosion on the defined stretches of the rivers Meghna and Dhaleswari. The protection of the locations indicated above should logically fit in this programme.

The Inception Phase started in November, 1990 with the mobilisation of the Expatriate Consultants. During the Inception Phase, the inter-action between this study and Flood Action Plan (FAP) Components was identified and maintained as far as possible.

The Meghna River Bank Protection Short Term Study, is now one of the **main components** of the Flood Action Plan for Bangladesh (FAP-9B. MEGHNA LB PROTECTION PROJECT), as included in the Review Report FPCO, December, 1990.

It has been recognised that during the Inception Phase, due to the internal and international situation during November 1990 to February 1991, delays were experienced, hampering the normal development of the activities planned. Therefore, activities in the critical path of the study were delayed (i.e, hydrometric surveys, geotechnical investigations, model investigations at RRI).

Furthermore, during the first phase of the project it became more and more clear that the inclusion of the flood season in the survey would considerably improve the designs of the protection works, the Consultants were supposed to submit at the end of the Study. Moreover, strengthening of the relation with the studies of the Bangladesh Action Plan for Flood Control (FAP) would also have a positive contribution to the outcome of this project. Therefore the BWDB instructed the Consultants to review and update the work plan taking note of the flood season of 1991 and the aforementioned studies of FAP.

As part of the Study a priority ranking was established. Accordingly, it was decided:

- to carry out a feasibility study, detailed designs and tender documents for bank protection works at the following locations:

    - Bhairab Bazar Township and Railway Bridge;
    - Munshiganj Town located on the Dhaleswari River;
    - Chandpur Town;

- to carry out a full feasibility study only for bank protection works in the following locations:

    - Eklashpur;
    - Haimchar;

- and pre-feasibility study for:

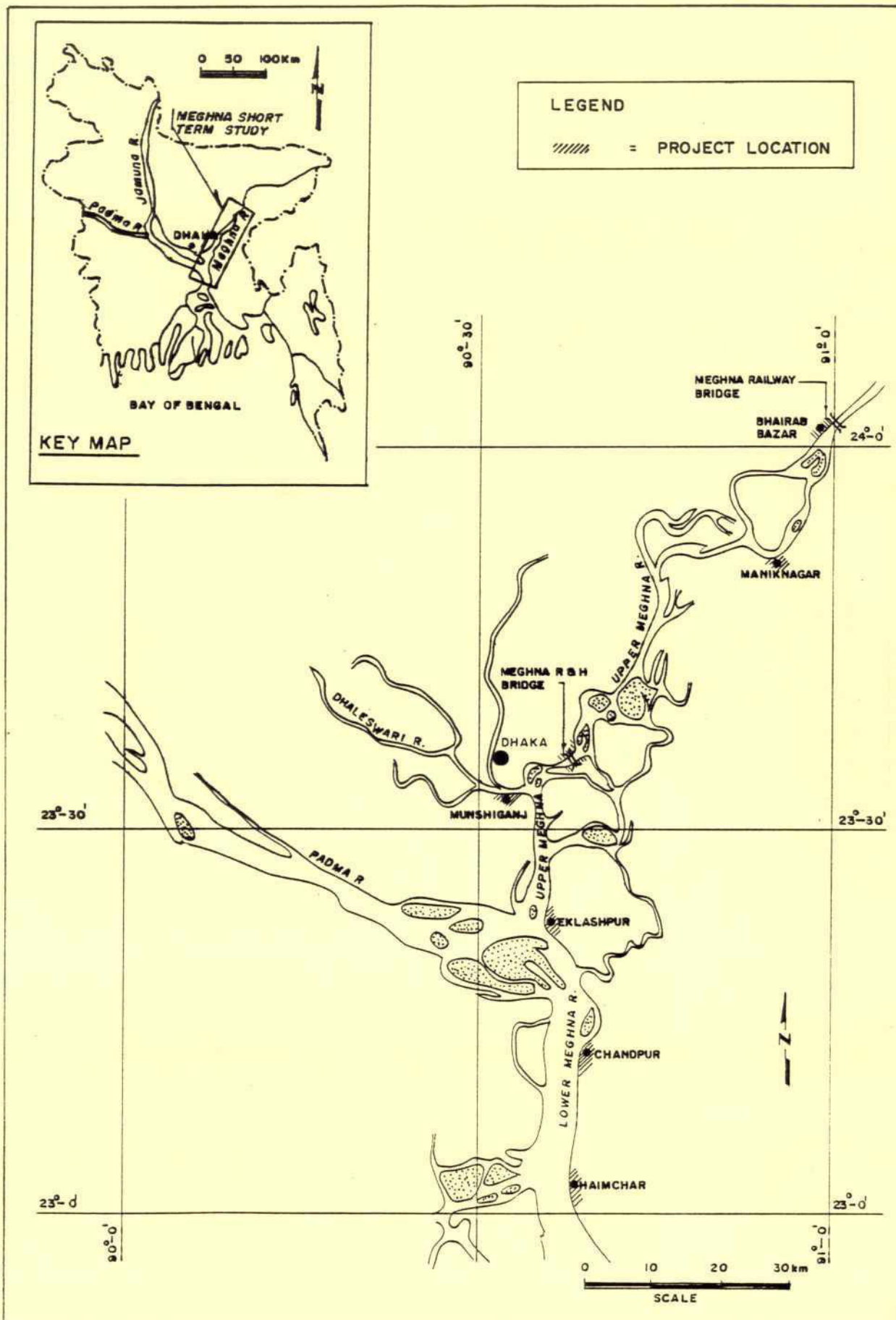
    - Meghna Roads & Highways Bridge;
    - Maniknagar, part of Gumti Phase II Project.

This Final Report submitted in accordance with the (Revised) Terms of Reference comprises all Feasibility studies carried out as well as the detailed designs for bank protection works at the three locations mentioned above.

ABBREVIATIONS AND GLOSSARY OF TERMS

ADB	Asian Development Bank
BCSIR	Bangladesh Council for Scientific and Industrial Research
BBS	Bangladesh Bureau of Statistics
B/C	benefit cost ratio
BCL	Bangladesh Consultants Limited
BETS	Bangladesh Engineering and Technological Services Ltd
BH	Bore hole
BIWTA	Bangladesh Inland Water Transport Authority
BIWTC	Bangladesh Inland Water Transport Corporation
BOD	Biological Oxygen Demand
BR	Bangladesh Railway
BS	British Standards
BUET	Bangladesh University of Engineering and Technology
BWDB	Bangladesh Water Development Board
^{0}C	degree Celsius
CIF	Cost, insurance and freight
CPT	Cone Penetration Test
Crore	10,000,000
DH	Delft Hydraulics (Netherlands)
Dollar (US)	taken at an exchange rate of Tk.36 for the Study
EIA	environmental impact assessment
EIRR	economic internal rater of return
FAO	Food and Agricultural Organization (United Nations)
FAP	Flood Action Plan
F/C	foreign currency
Fig(s)	figures(s)
FML	fortnightly mean water level
FPCO	Flood Plan Coordination Organization
g	acceleration due to gravity
GL	ground level
ha	hectare(s)
hr	hour(s)
IBRD	International Bank for Reconstruction and Development
IDA	International Development Association
IRR	internal rate of return
IWTA	Inland Water Transport
JICA	Japan International Cooperation Agency
kg	kilogramme(s)
km	kilometre(s)
Km^2	square kilometre(s)
km/h	kilometre per hour
Kn	kilonewton

Lakh	100,000
L/C	local currency
LWL	Low water level
m	metre(s)
MAT	Manual and automatic tidal gauge
MCA	multi-criteria analysis
m/s	metre(s) per second
m^2	square metre(s)
m^3	cubic metre(s)
m^3/s	cubic metre(s) per second (cumecs)
MG	Metre Gauge
mm	millimetre(s)
MMSS	Mica schist silty sand
MN	meganewton
MPO	Master Plan Organization
MSL	mean sea level
N	Newton
NEDECO	Netherlands Engineering Consultants
NMC	natural moisture content
N-value	standard penetration test value
ODA	Overseas Development Agency
OECF	Overseas Economic Cooperation Fund
OMC	optimum moisture content
p.a	per annum
PDB	Power Development Board
PDF	Probability density function
PWD	Public Works Department (datum)
RC	reinforced concrete
RHD	Roads and Highways Department
RPT	Rendel, Palmer & Tritton Limited
RRI	River Research Insititute
RTW	river training works
s,sec	second
SHW(L)	standard high water (level
SLW(L)	standard low water (level)
SOB	Survey of Bangladesh
SPT	standard penetration test
SWMC	Surface Water Modelling Centre
sq.km	square kilometre(s)
t(tons)	metric tons
Tk	taka
TOR	Terms of Reference
US$(or$)	US dollar(s)
USCS	Unified soil classification system
WB	World Bank



INDEX MAP SHOWING PROJECT LOCATIONS FOR THE MEGHNA SHORT TERM STUDY

ANNEX - A

HYDROLOGY

MEGHNA RIVER BANK PROTECTION
SHORT TERM STUDY

ANNEX - A

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A.1 INTRODUCTION

A.1.1 General

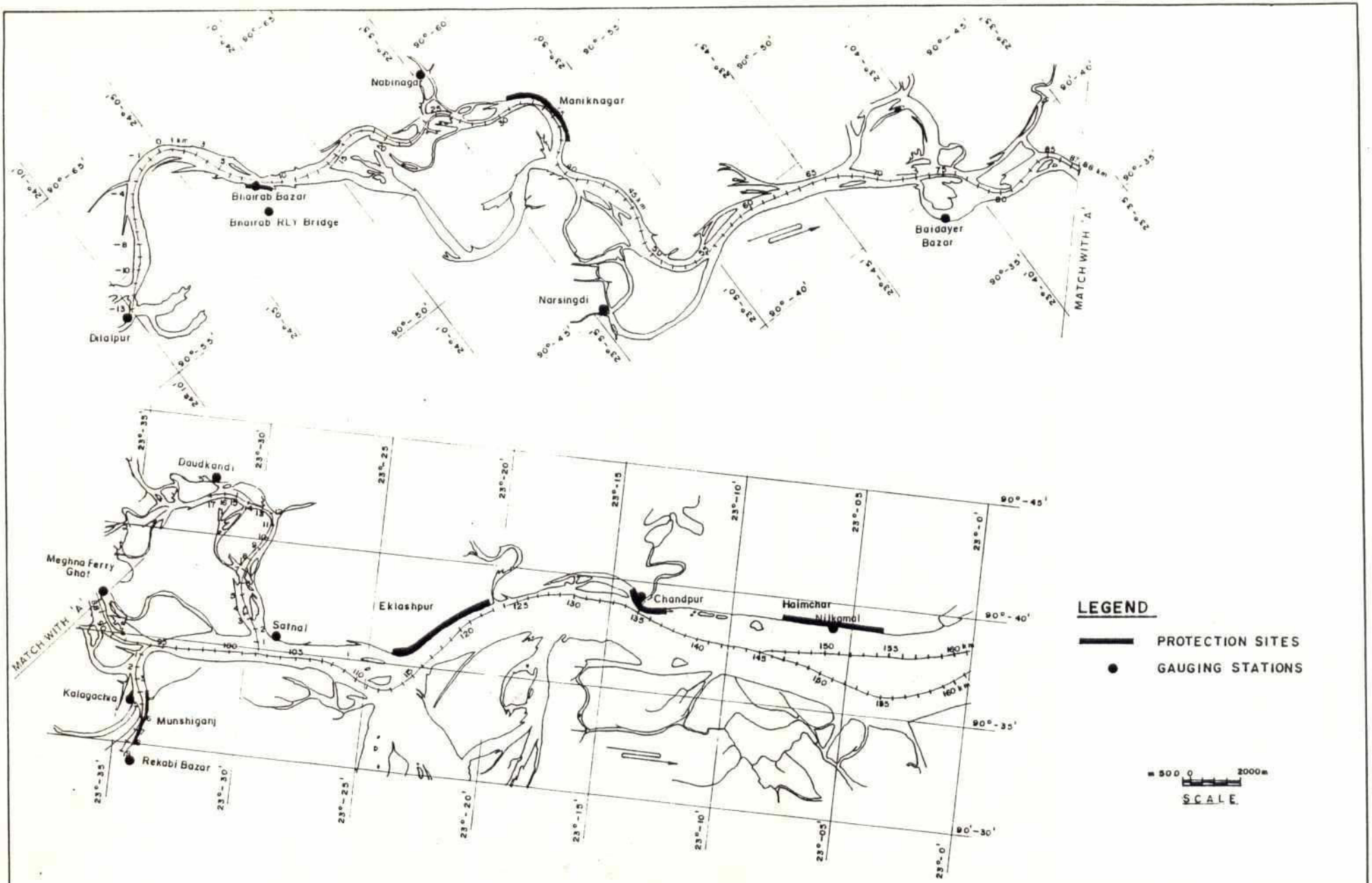
The hydrological study in the Meghna River Bank Protection Short Term Study aims at deriving the hydrological boundary conditions for the design of the bank protection at the following sites, see Figure A.1.1:

- Bhairab Bazar,
- Maniknagar,
- Meghna Road and Highway Bridge,
- Munshiganj,
- Eklashpur,
- Chandpur, and
- Haimchar.

The hydrological boundary conditions include:

1. flood levels having return periods up to 100 years,
2. water level range,
3. hydraulic head difference across the bank protection,
4. maximum flow velocities near the bank protection, and
5. wind speed and direction and wave data.

In this Annex the hydrological boundary conditions 1, 2, 4 and 5 are presented; reference is made to the Annex C, Geotechnical Investigations for condition 3. In the next chapters first of all a description is given of the hydrological characteristics of Meghna River Basin. In Chapter A.3 the data collected for the Study are summarized. Subsequently, the procedures used to validate the retrieved information are described. The results of the various analyses are presented in the Chapters A.5 to A.8.



MEGHNA RIVER BANK PROTECTION — INDEX MAP

FIGURE NO. A .1.1

A.2 HYDROLOGICAL CHARACTERISTICS IN THE PROJECT AREA

A.2.1 General

The hydrological conditions in the Project Area are determined by:

1. river flows, i.e. the Upper Meghna River for the sites Bhairab Bazar up to Munshiganj, whereas the conditions for the Lower Meghna sites are predominantly controlled by the Padma River flows, draining the Brahmaputra and Ganges Basins, with some contribution of the Upper Meghna River, see Figure A.2.1.;

2. the tide: periodic oscillations of the water levels at sea due to gravitational attraction forces from the moon and the sun, for major part represented by the semidiurnal M2 and S2 harmonic constituents with approximate 12 hours periods, and a fortnightly constituent MSf with a period of 15 days, corresponding with the variations in the spring and neap tides;

3. atmospheric pressure: the low pressure during the monsoon season and high pressure in the winter season generating a seasonal variation of the mean sea level, which creates above average levels during the monsoon and below average levels in winter;

4. wind: set-up and waves are created due to the friction at the air water interface; their magnitude depend on wind velocity and direction, fetch length and flow depth. This phenomenon is partly seasonal: due to the prevailing wind directions of the monsoon, set-up coincides with low pressure and hence increases the water levels.

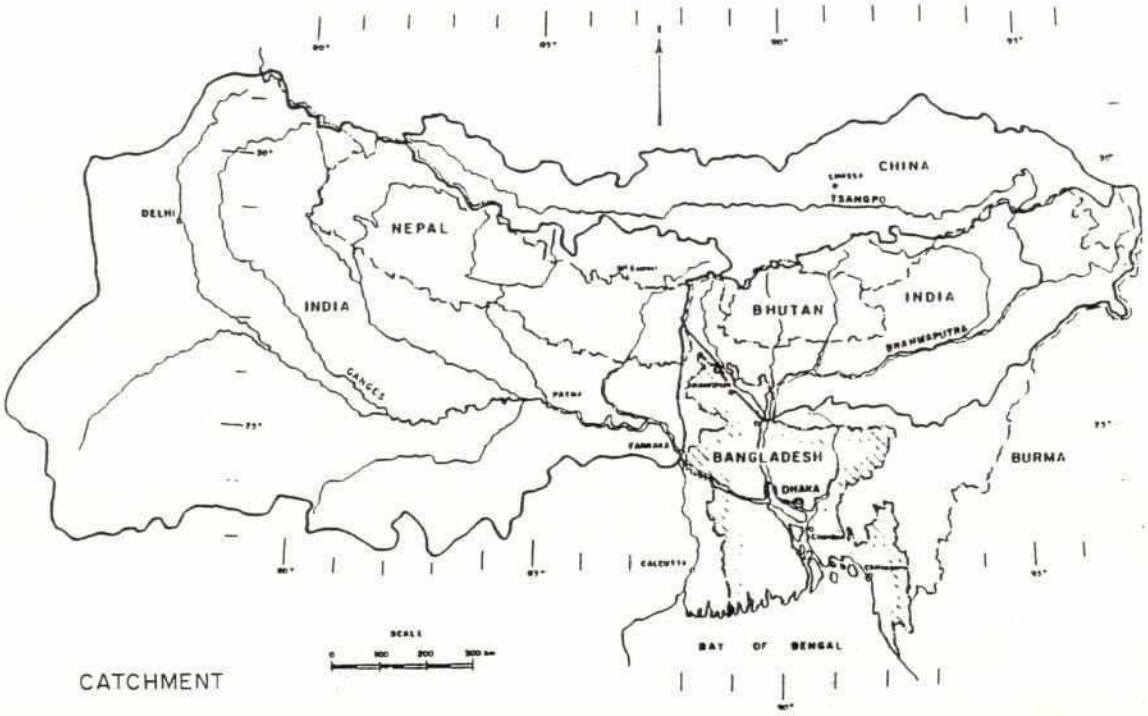
A.2.2. The Upper Meghna River Basin

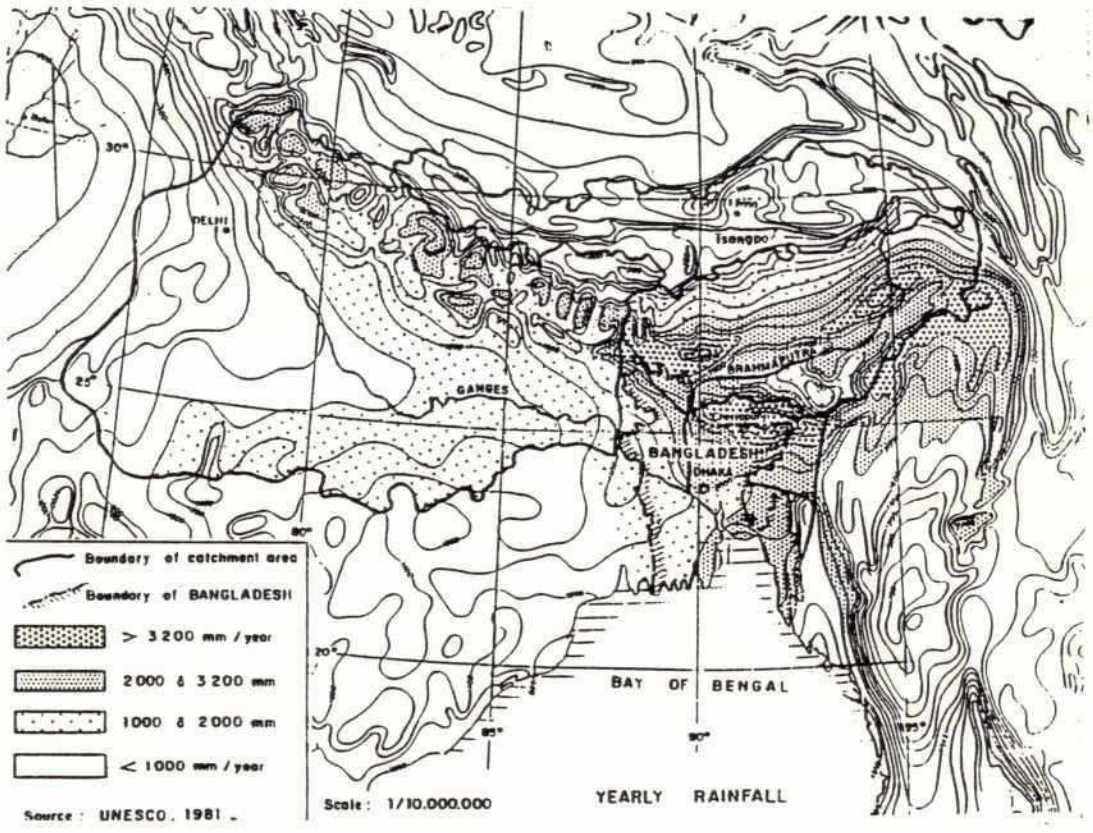
The Meghna River drains an area of 77,000 km^2, of which about 46,500 km^2 is located in Bangladesh. The major contributors to the river upstream of Bhairab Bazar are the Boulai, the Surma and the Kushiyara rivers, covering an area of 62,960 km^2, see Table A.2.1. Between Bhairab Bazar and the confluence with the Padma river the flows increase considerably by left bank spill from the Jamuna, when the river is in flood, and local drainage via the Old Brahmaputra, Lakhya, Arjam and Dhaleswari rivers.

Table A.2.1 DRAINAGE AREAS OF THE MAIN RIVERS

Station	River	Drainage area (km^2)
Bahadurabad	Jamuna	536,000
Hardinge Bridge	Ganges	907,000
Baruria Transit	Ganges-Jamuna confl.	1,490,000
Mawa	Padma	1,560,000
Bhairab Bazar	Upper Meghna	62,960
Eklashpur	Upper Meghna	77,000
Chandpur	Lower Meghna	1,637,000

Source: [1], [5]





THE DRAINAGE BASINS OF GANGES, JAMUNA AND MEGHNA RIVERS AND THE ANNUAL ISOHYETS

FIGURE NO. A.2.1

The rainfall is mainly experienced in the Monsoon period from June till September. Extreme high rainfall is reported for the upper regions of the Surma river, with annual totals of about 5000 mm. Typical values for Dhaka are an annual rainfall total of about 2000 mm of which near 70% falls during the monsoon months.

The annual average discharge at Bhairab Bazar is approximately 4,800 m^3/s, see Table A.2.2, which is equivalent to some 2500 mm runoff. The maximum flow occurs generally around mid August with values up to 19,800 m^3/s (1988).

Model computations by the Surface Water Modelling Centre for 1988 indicate that the contribution downstream of Bhairab Bazar from the right bank tributaries can even be higher, with flows up to 28,000 m^3/s. This contribution is mainly due to spill from the left bank of the Jamuna river. When these rivers are in flood vast areas are inundated and a substantial part of the water is conveyed overland. This explains the apparent inconsistency with the sum of maximum recorded discharges of those tributaries, adding up for 1988 to less than 10,000 m^3/s.

The contribution of the left bank tributaries Titas and Gumti is comparatively small.

In the low flow period the river is tidal up to past Markuli, far upstream of Bhairab Bazar. During high flow the tidal influence is strongly reduced, but still some tidal influence is felt as far upstream as Baidyer Bazar.

A.2.3 The Jamuna River

The river takes its rise on the north slopes of the Himalayas as Tsang-Po river. It runs first eastward, north of Bhutan, until it falls through a number of gorges, whereafter at the 95th degree meridian it changes its direction first south and then south-west through Assam as Brahmaputra and finally turns south-ward near the Bangladeshi border, see Figure A.2.2. In Bangladesh, before the Jamuna meets the Ganges, the right bank tributaries Teesta and Atrai rivers increase the Jamuna flow, whereas the left bank tributaries Old Brahmaputra, Arjam and Dhaleswari rivers divert part of the water from the Jamuna to the Upper Meghna river. The total river length is 2,880 km. The catchment area upstream of Bahadurabad amounts to 573,500 km^2.

The river starts rising in March due to the melting of the snow in the Himalayas, which causes a first peak in May, early June. Subsequent and largest peaks occur in July-August in quick response to heavy monsoon rains in Assam and Bangladesh, see Table A.2.3. In 1988 the peak flow was almost 100,000 m^3/s. The average annual discharge at Bahadurabad for the period 1964-1988 amounted to 19,462 m^3/s, which is equivalent to a runoff of about 1150 mm annually.

Table A.2.2 ANNUAL AVERAGE AND PEAK FLOWS OF MEGHNA RIVER AT BHAIRAB BAZAR

Year	average discharge m^3/s	maximum discharge m^3/s	date of max. days from 1/7
1964	4,365 *	12,300	38
1965	4,310	12,100	61
1966	5,080	14,400	65
1967	3,680	12,700	25
1968	4,130	13,300	29
1969	3,740	11,500	63
1970	5,070	16,400	41
1972	3,560	11,500	41
1973	5,340	12,400	46
1974	6,040	19,500	38
1975	4,228 *	12,700	36
1976	5,345 *	16,700	15
1981	4,183 *	11,200	37
1982	4,584 *	13,500	38
1983	5,752 *	16,000	74
1984	5,090	13,600	29
1985	4,410	14,300	33
1986	3,980	11,100	115
1987	4,950	15,200	44
1988	6,850	19,800	11
1989	5,566	15,500	34
Average	4,774	14,081	43
St. Dev.	850	2,518	23

*) estimated by: Qann.av = -359 + 0.464 * (Qav,Jul+Aug+Sep)/3
(St. error = 316 m^3/s)

Note: years 1971,1977,1978,1979 and 1980 are missing

Table A.2.3 FLOW CHARACTERISTICS OF PADMA RIVER AT BARURIA TRANSIT JAMUNA AT BAHADURABAD AND GANGES AT HARDINGE BRIDGE

Year	Qmean Baruria	Qmax Baruria	date	Qmax Bhahad.	date	Qmax Har.Br.	date
1966	24,400	81,300	64	68,900	57	41,900	63
1967	22,600	63,600	25	69,600	12	50,800	79
1968	24,500	80,200	30	62,300	25	45,200	60
1969	24,700	72,700	61	56,000	22	55,200	58
1970	28,100	84,200	31	75,000	28	48,700	85
1972	24,600	76,600	36	66,600	32	38,200	70
1973	30,200	90,900	44	67,300	40	50,700	52
1974	33,500	113,000	39	91,100	37	50,700	64
1975	30,300	93,300	36	52,200	28	51,100	60
1976	25,800	83,500	59	65,600	5	65,400	86
1977	29,800	81,800	54	66,600	53	51,100	45
1978	29,000	80,400	53	56,600	-2	67,900	52
1979	-,-	-,-	-	66,100	104	36,900	33
1980	31,300	109,000	52	61,200	50	57,800	52
1981	26,100	88,200	35	66,500	7	47,900	61
1982	27,400	89,600	84	55,900	30	61,600	72
1983	29,300	101,000	81	56,500	78	60,000	84
1984	31,600	107,000	82	77,000	81	56,500	78
1985	31,500	90,500	31	63,800	29	50,600	60
1986	27,600	81,500	37	43,100	21	53,500	38
1987	30,500	113,000	50	74,000	43	76,000	81
1988	33,600	132,000	63	98,600	61	72,400	64
1989	29,500	80,000	20	71,100	10	-,-	-
Average	28,450	90,605	48	66,591	37	54,095	64
Stdv.	3,114	15,969	19	11,943	26	10,126	15

Note: Dates refer to number of days counted from 1 July till the maximum occurred. (year 1971 is missing)

A.2.4 Ganges River

The Ganges originates on the southwestern slopes of the Himalayas through a number of tributaries enclosed between Delhi and Katmandu. It flows in south-easterly direction until it is joined by the Jamuna river at Goalundo. From this confluence onward it flows on for 130 km as Padma river to meet the Meghna river at Chandpur. The total length of the river from its westernmost sources to Chandpur is 2,600 km. The total drainage area is slightly over 900,000 km^2.

The river starts rising gradually in May-June and attains its peak on average early September. Peak flows up to 76,000 m^3/s (1987) have been reported, see Table A.2.3. Although the peak flows on the Ganges are experienced on average about one month later than on the Jamuna, given the range in the occurrence of the peak flows, particularly on the Jamuna, there is a high probability that both phenomena coincide. The average flow at Hardinge Bridge of 10,874 m^3/s (1964-1988) implies a runoff of 380 mm, which is considerably less than that of the Meghna and Jamuna rivers.

A.2.5 The Lower Meghna

The Lower Meghna river conveys the melt and rain water from the Ganges and Jamuna basins, combined in the Padma river, and from the Upper Meghna basin to the sea. The total catchment area is about 1,637,000 km^2. Maximum flows can be as high as 155,000 m^3/s. The major contribution of the discharge originates from the Jamuna river (annual average 19,462 m^3/s) and the Ganges river (annual average 10,874 m^3/s).

Studies on regional rainfall in the Ganges-Brahmaputra basin indicate an east-west alternation: droughts over central and northwest India take place in years of excess rainfall over northeast India/Bangladesh and vice versa, [7]. A weak southwest monsoon, which is responsible for drought in central and northwest India, seems to coincide with the El Niño anomaly off Peru. The alternation makes Bangladesh a continuous flood prone area.

A.2.6 Southern Sea-Boundary

The water levels at the lower boundary of the Project Area are strongly affected by the tide. The latter originates in the Indian Ocean and travels past the deep Bay of Bengal, where it reaches Hiron Point and Cox's Bazar almost concurrently [2], [3]. Extensive shallowness and partial reflection along the north eastern bay increase the range of tide, while bottom friction, due to decrease of depth, distorts it. Flow friction and river flow decrease the tidal effect land inward. The tide in Bangladesh is predominantly semidiurnal with slight diurnal inequalities. The solar annual and solar semi-annual constituents describing seasonal variation in the mean level play an important role in the raising of the mean sea level during the monsoon.

A.2.7 Project Area

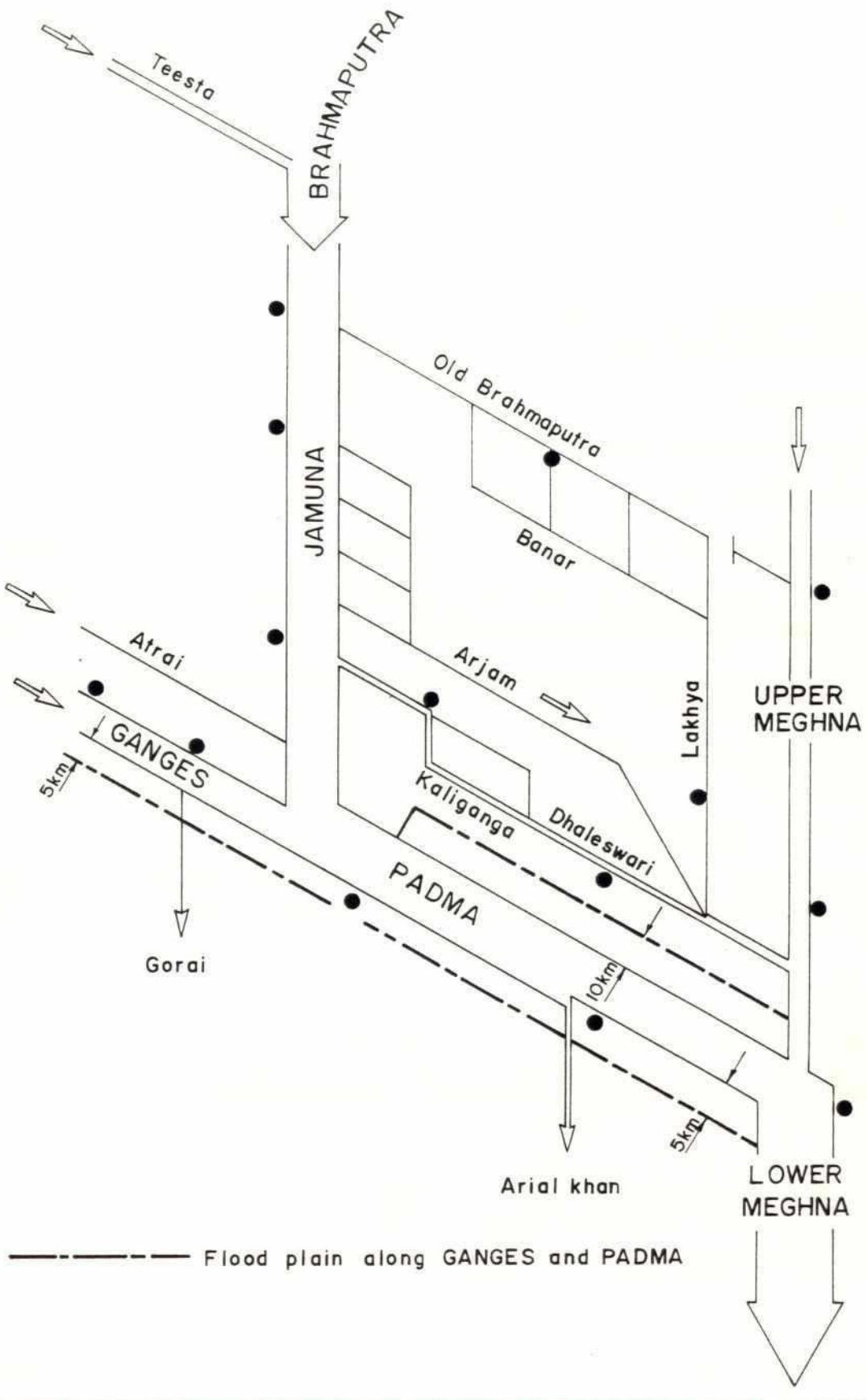
The system of rivers affecting the flow and hence stages in the Project Area is clearly depicted in the schematic lay-out in Figure A.2.3.

Downstream of Bhairab Bazar the discharge in the Upper Meghna is increased by left bank spill from the Jamuna and local drainage. The spill from the Jamuna is conveyed upstream of Bahadurabad by the Old Brahmaputra and downstream by the Arjam and Dhaleswari rivers. The major part of the Old Brahmaputra flow, increased by local drainage, runs off via the Lakhya river, which joins the Dhaleswari and Arjam rivers just upstream of the Dhaleswari-Upper Meghna confluence.

Furthermore, the Titas and Gumpti rivers contribute to the Upper Meghna runoff between Bhairab Bazar and the confluence with the Padma river.

As far as the Jamuna river is concerned, from Bahadurabad to the Jamuna-Ganges confluence near Baruria there is, apart from the left bank outflow, also an inflow from the Atrai river.

In the Ganges, from Hardinge Bridge onwards, the discharge is reduced by the Gorai river.
Finally, between Baruria and Chandpur upstream and downstream of station Mawa, some Padma river water is spilled southward through the Arial Khan before the river meets the Upper Meghna.



SCHEMATIC LAYOUT OF THE RIVER SYSTEM AROUND THE PROJECT AREA

FIGURE NO. A.2.2

A.3. DATA COLLECTION

A.3.1 General

Various sources have been consulted to obtain a consistent data set for the hydrological analyses, including:

1. The Bangladesh Water Development Board, Surface Water Hydrology,
2. Master Plan Organization, Hydrology Section
3. Surface Water Modelling Centre,
4. Bangladesh Inland Water Transport Authority, and
5. Interconsult A/S.
6. Flood Hydrology Study, FAP 25
7. Meteorological Department

The information comprised:

1. reports of hydrological studies carried recently, see list of References,

2. river maps and cross-sections,

3. gauge particulars of the gauging stations in and nearby the Project Area, see Section A.3.2,

4. water level and discharge data of the relevant stations in and nearby the Project Area, in tabular form on paper and ASCII files, see Section A.3.3,

5. discharge measurements for analysis of prevailing velocities and accuracy of rating curves, see Section A.3.4, and

6. wind data, see Section A.3.5

A.3.2 Gauge Station Particulars

Gauge particulars were retrieved from BWDB sources [4) and yearbooks. A summary of the BWDB gauging stations in and nearby the Project Area used in the analyses is given in Table A.3.1 and Figure A.3.1.

All stations of BWDB are manual gauges, read at 3 hours intervals during daytime only. Recording gauges are only in operation with the BIWTA. Summaries of gauging stations operated by BIWTA can be found in [3] and those inside the Project Area are presented in Table A.3.2.

Table A.3.2 BIWTA GAUGING STATIONS IN THE PROJECT AREA

Station name	River name	Station nr	Type of gauge
Char Ramdaspur	Lower Meghna	1620	MAT
Nalmuri	Lower Meghna	1630	MAT
Chandpur	Lower Meghna	1640	MAT
Narsingdi	Upper Meghna	1650	MAT

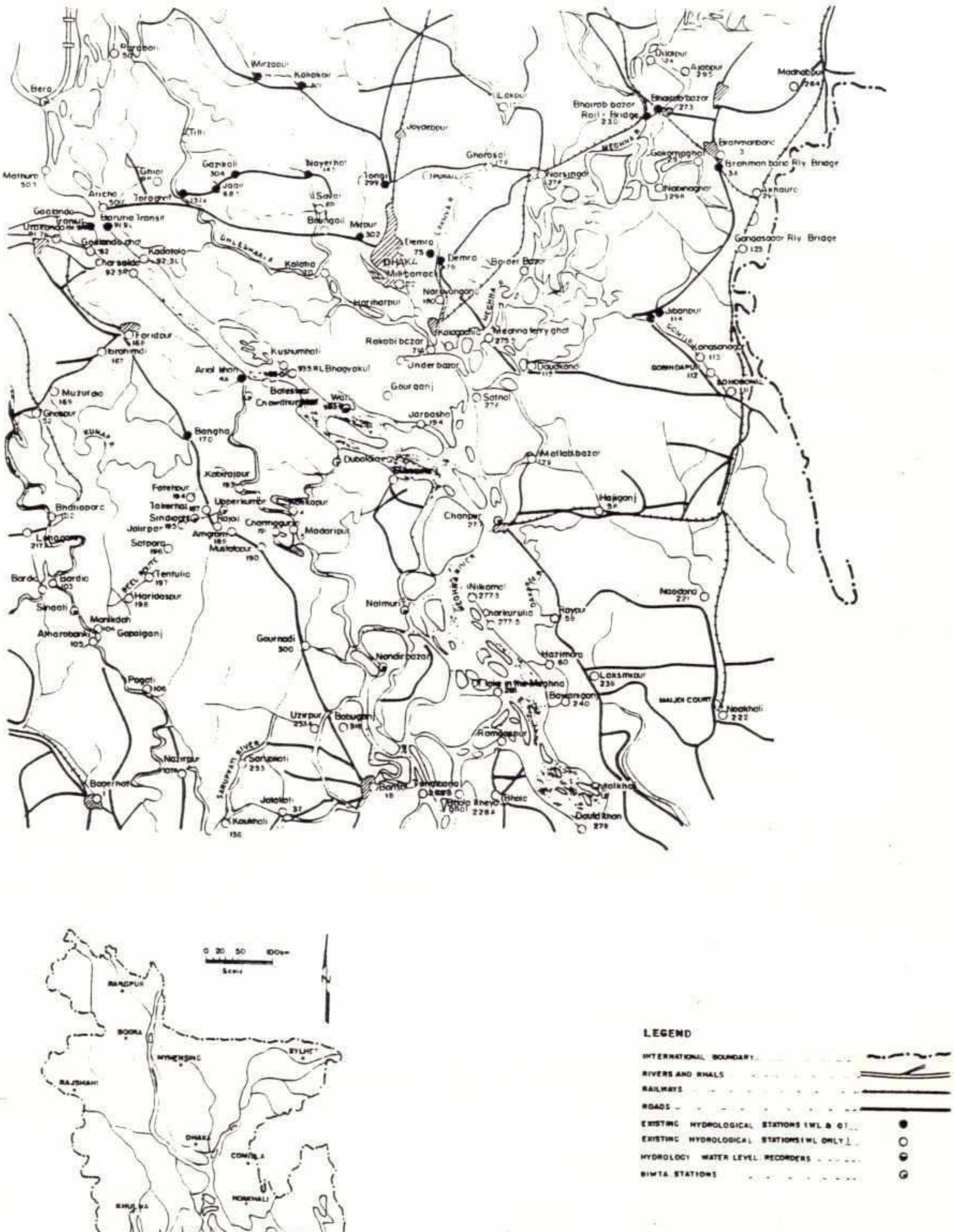
Source: [3]
Note: MAT = manual and automatic tidal gauge

Table A.3.1 SUMMARY OF BWDB GAUGING STATIONS USED IN THE ANALYSES

Name of River	No. Of station	Name of station	Nature of Observation	Date of installation	Date of Discontinuation	Tidal or Non tidal	Nearest B.M & its elevation, ft (PWD)	Hydrological Sub-Division Unit
Bangshi	14.5	Nyarnat	G.D	11.6.63	-	T	WAPDA BM 14.5 31.32	
Brahmaputra Jamuna	46.9L	Banaourabad	G.D.S	16.6.63	-	N.T	TBM	Mymensingh
Dhaleswari	68.5	Jagir	G.D.S	13.6.63	-	N.T	TBM	Dhaka
Dhaleswari	71	Kalagachia	G	15.6.45	-	T	WAPDA BM 71. 17.82	Dhaka
Dhaleswari	71.A	Rekabi Bazar	G	16.12.65	-	T	WAPDA BM 71A 21. 60	Dhaka
Dhanu-Boulai Ghorutra	74	Dilalpur	G	19.5.45	-	T	WAPDA BM 74 25.96	Brahmanbaria
Dhanagoda	79	Matlab Bazar	G	21.5.59	-	T	WAPDA BM 79 17.10	Comilla
Ganges	90	Hardinge Bridge	G.D.S	1934	-	N.T	WAPDA BM 90 62.18	Pabna
Ganges	91.9L	Baruria Transit	G.D.S	1.8.63	-	S.T	WAPDA BM 91.9L 29.38	Faridpur
Ganges	93.5L	Mawa (Bhagyakul)	G.D.S	1.6.65	-	S.T	WAPDA BM 93.5L 20.75	Bhagyakul
Ganges	94	Tarpasa	G	1.8.22	-	S.T	WAPDA BM 94 20.73	Bhagyakul
Ganges	95	Sureswar	G	25.3.53	-	S.T	WAPDA BM 95. 17.61	Bhagyakul
Gumti-Burinadi	115	Daudkandi	G	1.6.45	-	T	WAPDA BM 115 18.08	Comilla
Kaliganga Bethua	137.A	Taraghat	G.D	13.7.63	-	N.T	TBM	Dhaka
Lakhya	179	Demra	G.D	18.5.45	-	S.T	WAPDA BM 24.05	Dhaka

Table A.3.1 SUMMARY OF BWDB GAUGING STATIONS USED IN THE ANALYSES (Continuation)

Name of River	No. Of station	Name of station	Nature of Observation	Date of installation	Date of Discontinuation	Tidal or Non tidal	Nearest B.M & its elevation, ft (PWD)	Hydrological Sub-Division Unit
Old Brahmaputra	230.1	Bhairab Rly. Bridge	G.D	21.7.64	-	T	WAPDA BM 230.1 32.33	Brahmanbaria
Surma-Meghna	273	Bhairab Bazar	G.D.S	Nov. 1948	-	T	WAPDA BM 273 24.15	Brahmanbaria
Surma-Meghna	274	Narsingdi	G	Jan/1948	-	ST	WAPDA BM 274 22.35	Dhaka
Surma-Meghna	275	Baoyar Bazar	G	14.7.59	-	T	WAPDA BM 275 19.40	Comilla
Surma-Meghna	275.5	Meghna Ferryghat	G	25.9.655	-	T	WAPDA BM 275.5 24.05	Comilla
Surma-Meghna	276	Satnal	G	9.6.45	-	T	WAPDA BM 276 16.57	Comilla
Surma-Meghna	277	Chandpur	G	25.7.47	-	T	TBM 18.98	Comilla
Surma-Meghna	277.3	Nilkamal	G	April/1965	-	T	WAPDA BM 277.3 15.10	Comilla
Surma-Meghna	277.5	Char-kurulia	G	April/1965	1.11.79	T	WAPDA BM 277.5 13.15	Comilla
Surma-Meghna	278	Daulatkhan	G	7.7.47	-	T	TBM	Barisal
Tentulia	288	Off take in Meghna	G	20.8.57	-	T	WAPDA BM 288. 11.46	Barisal
Tista	298	Nabinagar	G	Nov./1947	-	T	WAPDA BM 298 20.90	Brahmanbari



LOCATION OF BWDB GAUGING STATIONS

FIGURE NO. A.3.1

A.3.3 Water Level and Discharge Data

A.3.3.1 Datum

All levels used in this report are given relative to PWD-datum, which is 0.4599 metre below New Mean Sea Level, see [3], page 4.
This reference is also in use with the BWDB.

A.3.3.2 Water Level Data

Daily extreme and annual extreme water level data of the BWDB gauging stations in and nearby the Project Area were collected from BWDB hydrology, MPO and FAP- 25. A summary of the available water level data is presented in Table A.3.3.

For a number of stations the data were provided on diskette by MPO, FAP-25 and SWMC, where data from SWMC comprised results from the General Model of the main rivers of Bangladesh.

Although BWDB has a large number of data computerized, these could not be made available on diskette due to incompatibility of data storage media. These problems can be overcome in the future by transferring the data by means of a communication program.

A.3.3.3 Discharge Data

Daily and annual extreme discharges have been collected for the relevant stations from BWDB, MPO and FAP 25 sources as well as from recent reports [1], [3]. Like the water level time series these data are partly in tabular form and some could be made available on diskette. A summary of the data availability is given in Table A.3.4.

A.3.4 Flow Velocity and Stage-Discharge Data

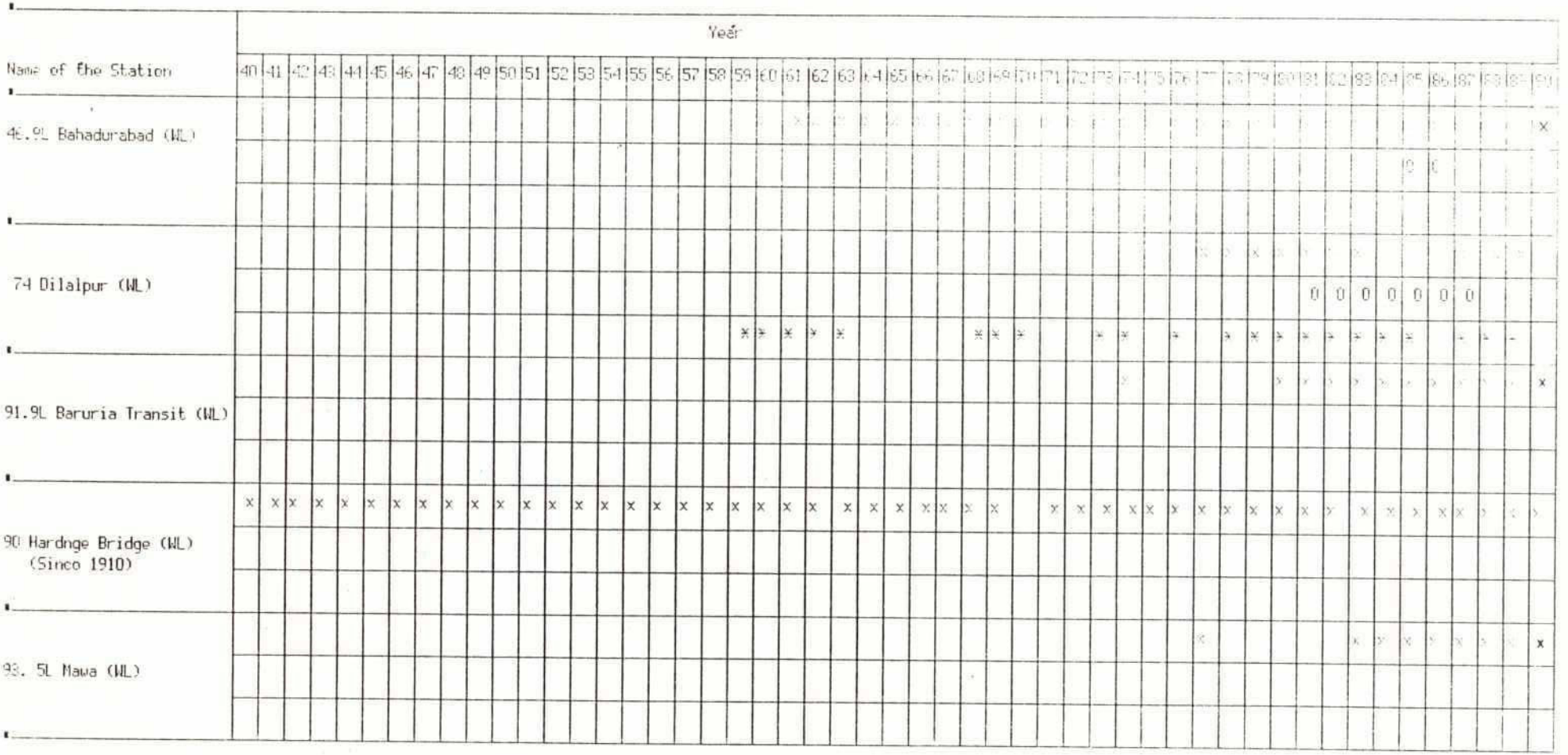
To determine the variation of the flow velocity in the cross-sections and to investigate the changes in and the reliability of the discharge rating equations results of discharge measurements and cross-sections have been collected. Most of the discharge data were in the form of condensed current metering results with only overall or cross-section averaged figures. In Table A.3.5 a summary is given of the available data.

A.3.5 Wind and Wave Data

Wind speed and wind direction data for the Project Area were retrieved from the Meteorological Department in Dhaka, from the Meghna-Gumti Bridges Construction Project [5], carried out in 1985, from the MPO Technical Report no 11 [6] and from the Jamuna Bridge Project [8]. The availability of the data comprise monthly maximum and prevailing wind speed and wind direction data of a number of stations in and around the Project Area. A summary of the available data is given in Table A.3.6.

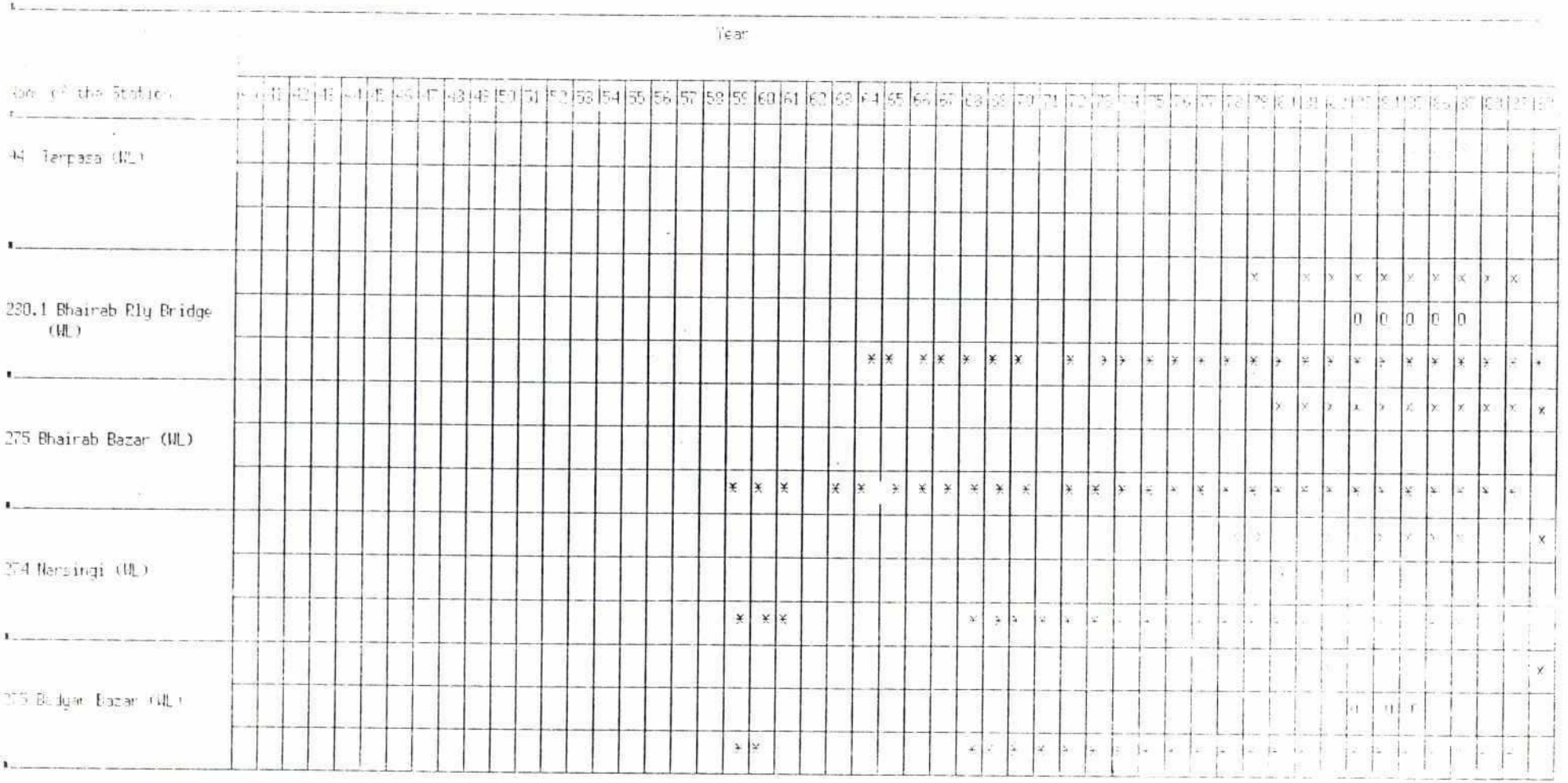
Data on waves appeared not to be available.

Table A.3.3/1 AVAILABILITY OF WATER LEVEL TIME SERIES AND WATER LEVEL EXTREMES



X - WL Collected in print from hydrology
O - WL Collected in diskette from MPO
* - Only H.W.L

Table A.3.3/2 AVAILABILITY OF WATER LEVEL TIME SERIES AND WATER LEVEL EXTREMES



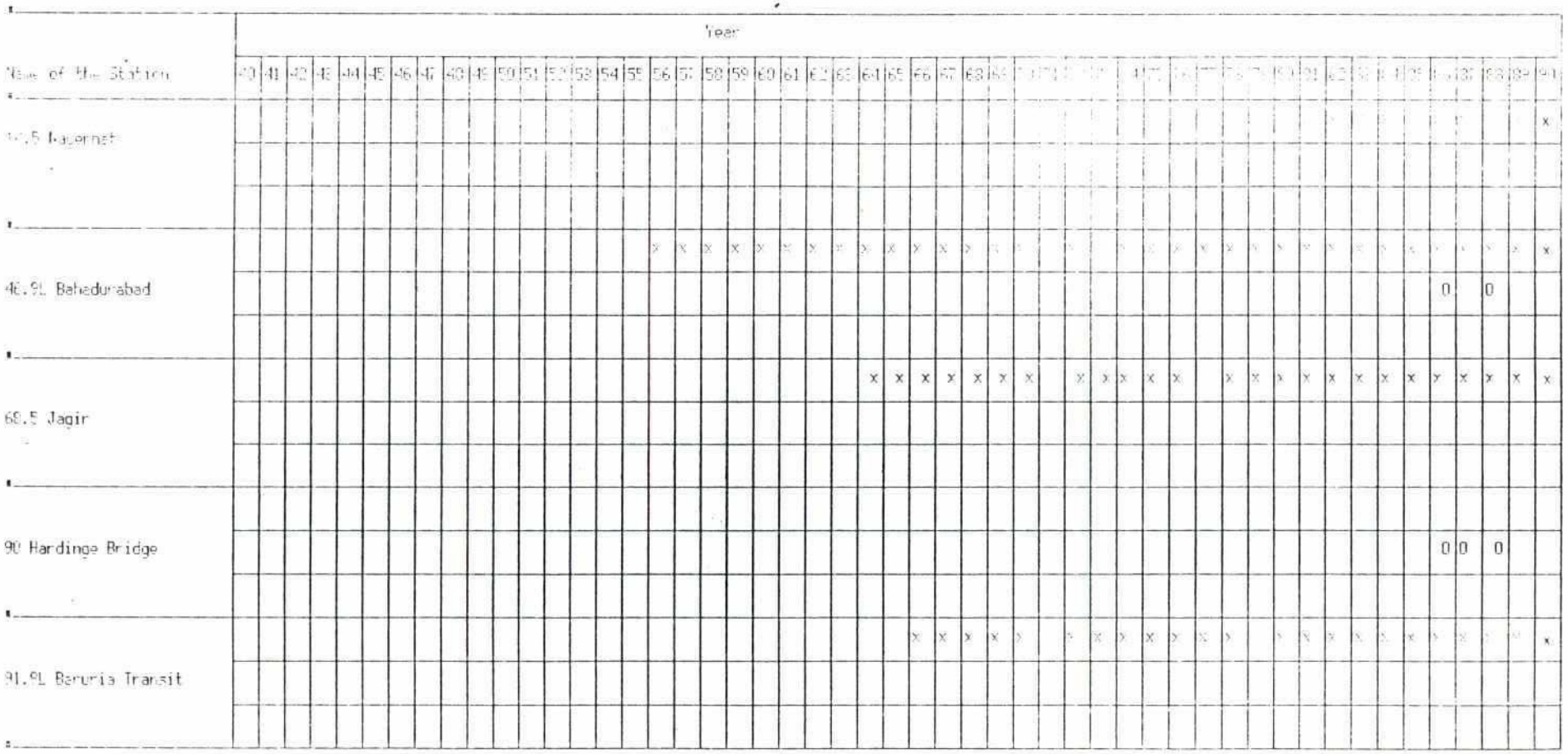
X - WL Collected in print fro. hydrology
O - WL Collected in diskette from MPO
* - Only H.W.L

Table A.3.3/3 AVAILABILITY OF WATER LEVEL TIME SERIES AND WATER LEVEL EXTREMES

Name of the Station	Year																																																		
	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90
275.5 Meghna Ferry Ghat (WL)																																						X				X	X	X				X	X	X	X
																																												0	0	0	0	0			
																														*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	
276 Satnal (WL)																																										X	X	X				X	X	X	X
																																												0	0	0	0	0			
																				*	*	*							*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	
277 Chandpur (WL)																																	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
							*	*	*	*	*	*	*	*	*	*	*	*	*	*	*								*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	
277.3 Nilkamal (WL)																																										X	X	X				X	X	X	X
																																												0	0	0	0				
																													*	*	*		*	*	*	*	*	*	*			*	*	*	*	*	*	*	*	*	
278 Daulatkhan (WL)																																												X				X	X	X	X
																																												0	0	0	0				

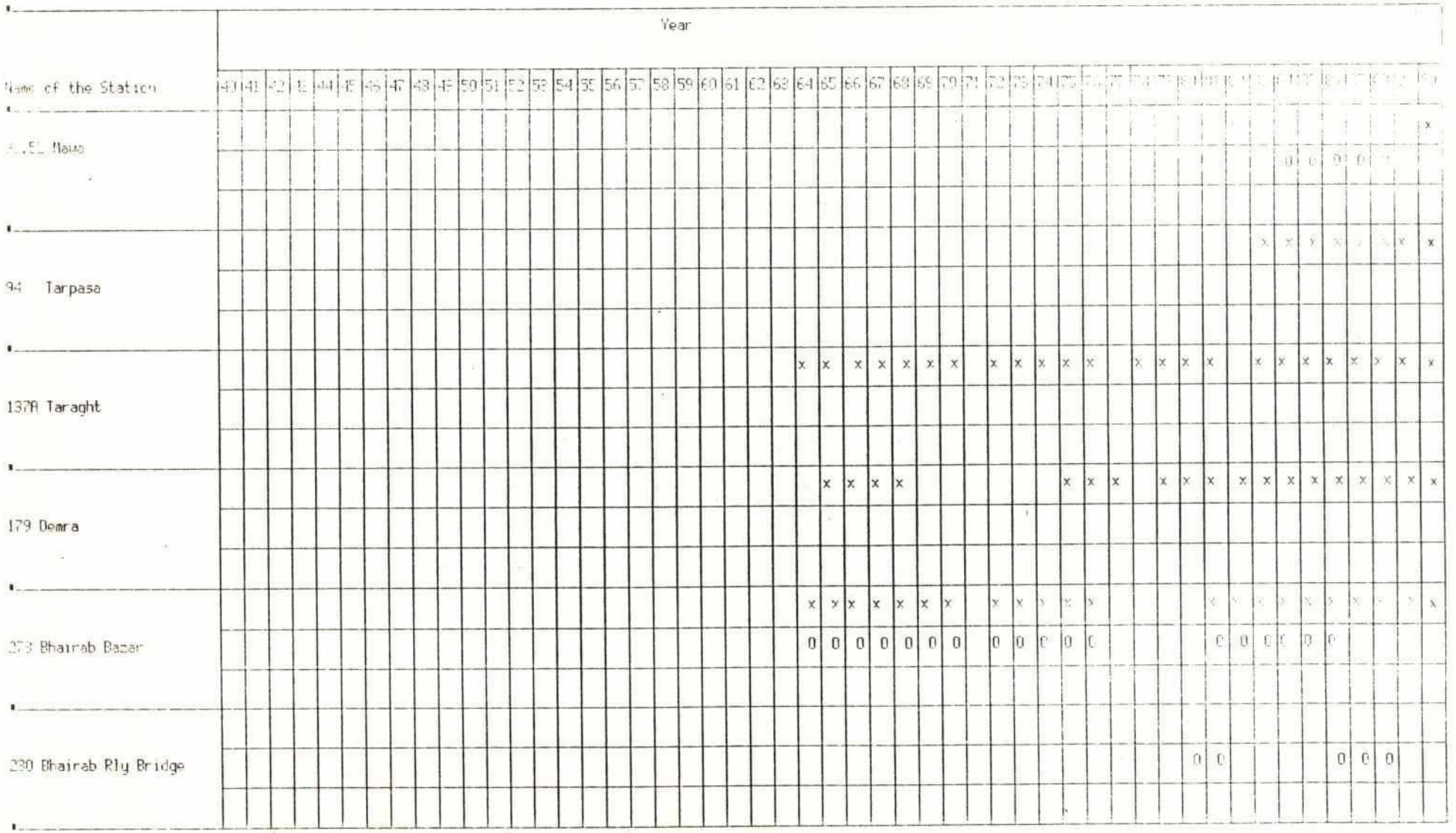
X - WL Collected in print from hydrology
0 - WL Collected in diskette from MFO
* - Only H.W.L

Table A.3.4/1 AVAILABILITY OF DISCHARGE TIME SERIES AND DISCHARGE EXTREMES



X - Discharge Collected in print from hydrology
0 - Discharge Collected in diskette from MFO

Table A.3.4/2 AVAILABILITY OF DISCHARGE TIME SERIES AND DISCHARGE EXTREMES



X - Discharge in print from hydrology
0 - Discharge Collected in diskette from MPO

Table A.3.5 AVAILABILITY OF DISCHARGE MEASUREMENT DATA

Name of the Station	Year																								
	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90
46.9L Bahadurabad		x		x	x	x		x	x	x	x	x	x	x				x	x	x	x	x	x	x		x
90 Hardinge Bridge		x		x	x	x		x	x	x		x				x	x		x	x	x	x	x	x		
93.5L Mawa						x													x	x	x	x	x	x	x	x
273. Bhairab Bazar											x	x		x		x	x		x	x	x	x	x	x	x	x

Table A.3.6 AVAILABILITY OF WIND DATA

Year	B.BARIA	BHOLA	CHANDPUR	COMILLA	DHAKA	MAJDEE
1948	10.	-.-	-.-	9.	-.-	-.-
1949	20.	-.-	-.-	24.	-.-	-.-
1950	14.	-.-	-.-	19.	-.-	-.-
1951	9.	-.-	-.-	24.	-.-	-.-
1952	10.	-.-	-.-	18.	-.-	9.
1953	-.-	-.-	-.-	50.	26.	24.
1954	20.	-.-	-.-	88.	90.	20.
1955	12.	-.-	-.-	9.	30.	31.
1956	10.	-.-	-.-	50.	90.	25.
1957	23.	-.-	-.-	51.	30.	13.
1958	12.	-.-	-.-	21.	69.	13.
1959	9.	-.-	-.-	18.	90.	19.
1960	70.	-.-	-.-	91.	30.	90.
1961	50.	-.-	-.-	43.	72.	90.
1962	60.	-.-	-.-	19.	50.	31.
1963	30.	-.-	-.-	-.-	51.	44.
1964	32.	-.-	-.-	19.	52.	19.
1965	50.	-.-	-.-	53.	50.	19.
1966	30.	51.	40.	25.	25.	37.
1967	30.	31.	52.	19.	25.	30.
1968	13.	91.	20.	26.	52.	50.
1969	60.	51.	70.	35.	30.	13.
1970	50.	25.	37.	19.	51.	37.
1971	10.	31.	31.	25.	19.	13.
1972	-.-	31.	-.-	34.	51.	13.
1973	-.-	46.	13.	35.	70.	19.
1974	-.-	38.	32.	40.	-.-	25.
1975	-.-	23.	13.	53.	25.	23.
1976	-.-	92.	13.	30.	25.	-.-
1977	-.-	33.	54.	36.	37.	-.-
1978	-.-	17.	-.-	-.-	37.	31.
1979	-.-	-.-	32.	96.	52.	22.
1980	-.-	33.	-.-	80.	21.	24.
1981	-.-	15.	19.	25.	19.	10.
1982	-.-	17.	19.	20.	19.	80.
1983	-.-	9.	16.	9.	23.	14.
1984	-.-	12.	35.	30.	15.	21.
1985	-.-	30.	25.	28.	28.	80.
1986	-.-	20.	31.	19.	18.	25.
1987	-.-	23.	31.	20.	24.	20.
1988	-.-	82.	35.	20.	37.	56.
1989	-.-	20.	12.	35.	18.	20.
1990	-.-	-.-	-.-	-.-	21.	-.-

A.4. DATA VALIDATION

A.4.1 General

Available data were where possible thoroughly checked on their consistency with surrounding stations. The most effective validation procedures include graphical techniques. These type of techniques have been applied to the computerized data.

Visit to some gauging stations was made to assess the quality of the gauge setting, gauge operation and measuring procedures. The following BWDB stations in the Project Area were visited in September 1991:

- Bhairab Bazar,
- Meghna Ferryghat,
- Kalagachia,
- Rekabi Bazar,
- Chandpur.

During these visits the field data sheets, gauge settings and benchmark were inspected. At all stations the gauge setting was doubtful. It appeared that at none of the stations a fixed staff gauge existed. The gauge planks were generally attached to a bamboo pole with a horizontally winded wire without proper vertical fixation. Gauges are replaced as soon as the water level is about to exceed the gauge range. Then a new gauge plank is installed and the new reference level is determined from the simultaneous reading at the old and the new gauge. Records showed that often when, at a later date, the gauge was levelled to the benchmark, adjustments had to be applied. Adjustments up to 0.20 m were noticed. The adjustments are then applied as from the date the new gauge plank is read. However, it could well be that before or after this moment the shift occurred.

During the field trips checks were made on the maximum water level of 1988. Local people were asked about the flood level, which was subsequently compared with the level of the benchmark. In all cases the indicated level was within a few decimeters from the recorded maximum water level in the BWDB files!.

The FAP 9B (started in November 1990) has used data collected and preliminarily processed by FAP 25 (started in October 1990). However, the FAP 9B hydrological study necessarily had to be completed at a time (viz. September 1991) the Flood Hydrology Study (FHS) had not yet produced substantial results. Some discrepancies between results of both studies could not be avoided. Differences have been assessed by RMC - FAP 25, and appear to be of minor importance, in particular in view of the results of the FAP 9B project as a whole.

In the event of a continuation of FAP 9B, a full copy of the FAP 25 hydrological data base for the Meghna rivers will be requested. This can easily be implemented since both projects use DELFT HYDRAULICS' data base system HYMOS. At short notice, this system will also become available in Surface Water Hydrology Directorate 2 of BWDB.

FAP 9B appreciates and fully supports the efforts undertaken by FAP 25 to unify and consolidate the hydrological data bases, analysis procedures and design criteria used in the various FAP studies, for the benefit of the FAP as a whole. The need for and benefits of such genuine efforts is highly valued.
The issue of the effects of nation-wide flood protection schemes on design conditions for the projects to be designed by FAP 9B has indeed not been addressed sofar. Useful results of the FHS are not yet available at this stage, while the issue was also not included in the TOR. Consultants agree, however, that this aspect is important and should be addressed at some stage in the Long-Term Strategic Plan for the Meghna River.

A.4.2 Water levels

The validation included the following procedures:

1. plotting of time series to compare the hydrographs and annual extremes of neighbouring stations;

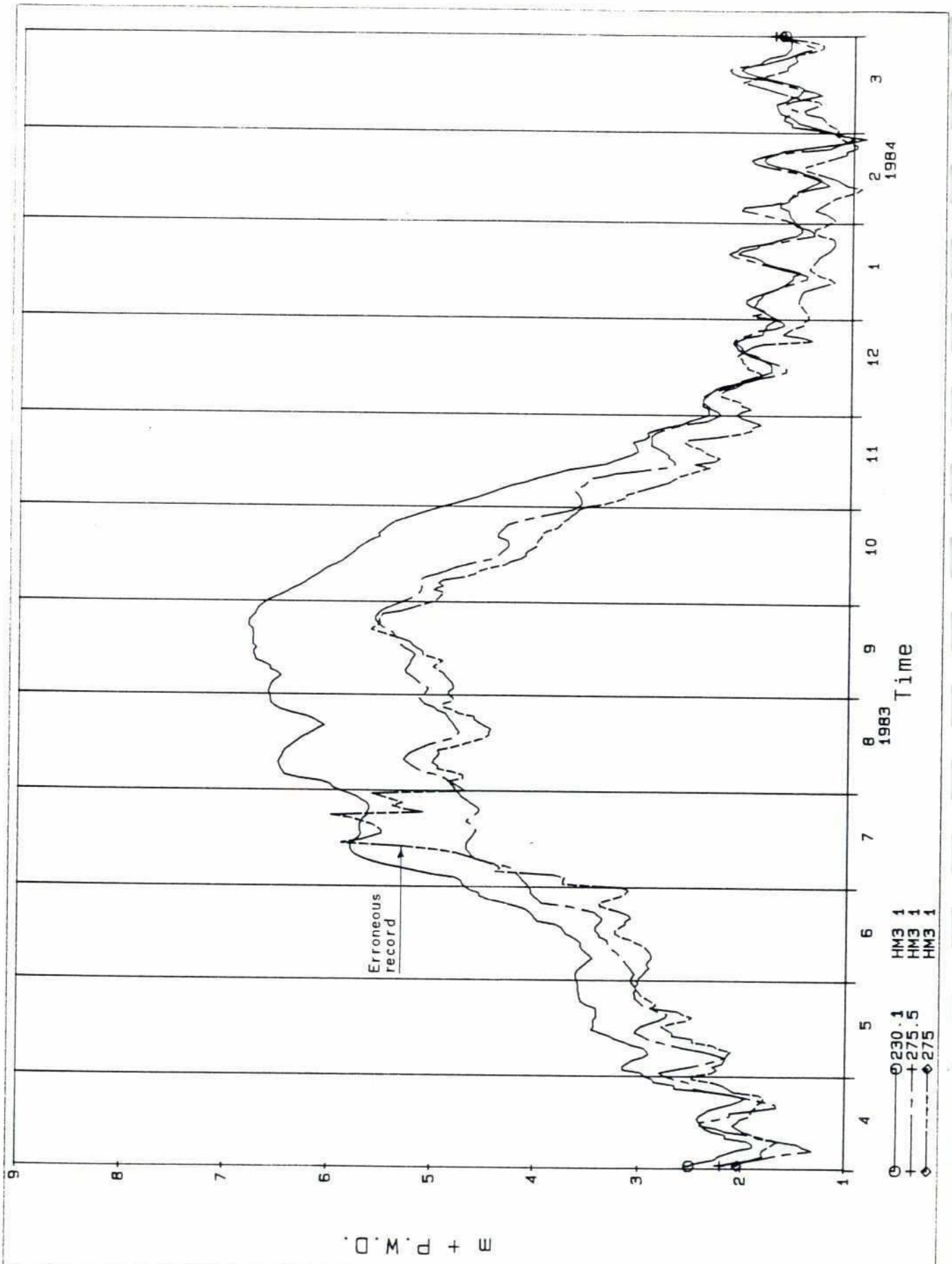
2. plotting of relation curves for successive years to investigate the stability of the relation and to detect possible gauge shifts;

3. double mass analysis in combination with regression analysis on annual extremes to check the consistency of the relation; breaks in the double mass curves indicate gauge or bottom shifts at one of the locations.

Since at all BWDB stations a sampling interval of 3 hours is only applied during daylight hours, a full reproduction of the water level fluctuation is not possible and some information on extremes is lost. Moreover, from inspection of the original field data sheets it was learned that considerable gauge shifts take place, with no gradual adjustment of the data, (see above). The effects of these shifts are obscured by the reading procedure (at 3 hour intervals) in combination with the tidal variation. Inconsistencies due to these shifts can only be clearly visualized when continuous records would be available.
Nevertheless, clear inconsistencies at some locations were detected in the hydrographs, see e.g. Figure A.4.1, as well as in the annual extremes values. The original sources were subsequently consulted to eliminate possible transcription errors. In case no satisfactory answer could be found the data were eliminated from the data base and from the analysis.

A.4.3 Discharges

In addition to time series plotting an efficient way of validating discharge data is to make continuity checks and water balance computations. The latter technique is cumbersome in the Project Area as only one discharge station exists on the Upper and Lower Meghna. Stage-discharge measurements have therefore been evaluated particularly with regard to the fit of the rating equation and the range of the flow measurements in comparison to the range of water levels.



Validation of Water Level Data by Comparison of Hydrographs

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FIG. A.4.1

A.5. FLOOD LEVELS

A.5.1 General

For the determination of the top level of the bank protection water levels having return periods up to 100 years are required: a design frequency of 50 years is applied for rural areas and one of 100 years for urban and industrial areas.

The extreme water levels having a particular return period have been derived from frequency analysis on the series of annual maximum water levels at the gauging sites. The following procedure has been applied:

1. Annual maximum water levels were retrieved from the annual reports of the BWDB on daily maximum water levels;

2. The annual maximum water levels have been validated by comparison with extremes at surrounding stations;

3. Unreliable data have been eliminated and missing data have been filled in to arrive at series of comparable length and years for reasons of mutual consistency;

4. Various frequency distributions have been fitted to the data, viz: Pearson-III, Log-Pearson-III and Lognormal-3 distributions;

5. The water levels for return periods of 5, 10, 25, 50 and 100 years have been derived from the selected distribution;

6. The values for the specific return periods at the various stations have been interconnected to obtain a longitudinal profile of flood levels along the river axis.

Annual maximum water levels of the stations summarized in Table A.5.1 have been used in the analysis.

Table A.5.1 SUMMARY OF STATIONS USED IN ANALYSIS OF ANNUAL MAXIMUM WATER LEVELS

Station	River	Code	Chainage km
Dilalpur	Dhanu	74	-13.6
Bhairab Bazar	Upper Meghna	273	7.9
Bhairab B. Rly Bridge	Old Brahmaputra	230.1	9.4
Nabinagar	Titas	288	3.0 u/s 25.0
Narsingdi	Upper Meghna	274	50.0
Bayder Bazar	Upper Meghna	275	76.0
Meghna Ferryghat	Upper Meghna	275.5	88.0
Kalagachia	Dhaleswari	71	4.2 u/s 94.0
Rekabi Bazar	Dhaleswari	71A	9.5 u/s 94.0
Daudkandi	Gumpti-Burinadi	115	17.0 u/s 102.0
Satnal	Upper Meghna	276	103.4
Tarpasa	Padma	94	35.0 u/s 113.0
Chandpur	Lower Meghna	277	135.0
Nilkamal	Lower Meghna	277.3	150.8
Off-take in Meghna	Lower Meghna	288	184.0

A.5.2 Validation

Annual maximum water levels of the stations listed in Table A.5.1 were mutually compared for their consistency with the extremes at upstream and downstream stations. A number of extremes appeared to be inconsistent and was eliminated from the analysis, a summary of which is presented in Table A.5.2.

Table A.5.2 SUMMARY OF YEARS ELIMINATED FROM ANALYSIS

Station	code	years
Dilalpur	74	1968
Narsingdi	274	1959
Bayder Bazar	275	1982, 1983, 1985, 1986, 1987 1988, 1989
Kalagachia	71	1973
Daudkandi	115	1986, 1987
Nilkamal	277.3	1968, 1969, 1970, 1972, 1973 1974, 1975

In addition to this it is noted, that series 275 (Bayder Bazar) in general is consistently lower than series 275.5 (Meghna Ferryghat), although the former one is upstream. Because of the clear errors in the data (Table A.5.2) together with the aforementioned inconsistency Bayder Bazar was not taken as a basic station in the final analysis.

The records of Nilkamal prior to 1976 deviated considerably from those of Chandpur and Tarpasa and were therefore eliminated.

An overview of the annual extreme water levels which passed the various tests is presented in Appendix A/1 Tables A/1.1 and A/1.2 (Upper Meghna) and Table A/1.3 (Padma and Lower Meghna).

A.5.3 Series completion

To arrive at series with comparable lengths at the various sites missing values were filled in for the stations considered in the construction of flood lines, viz:

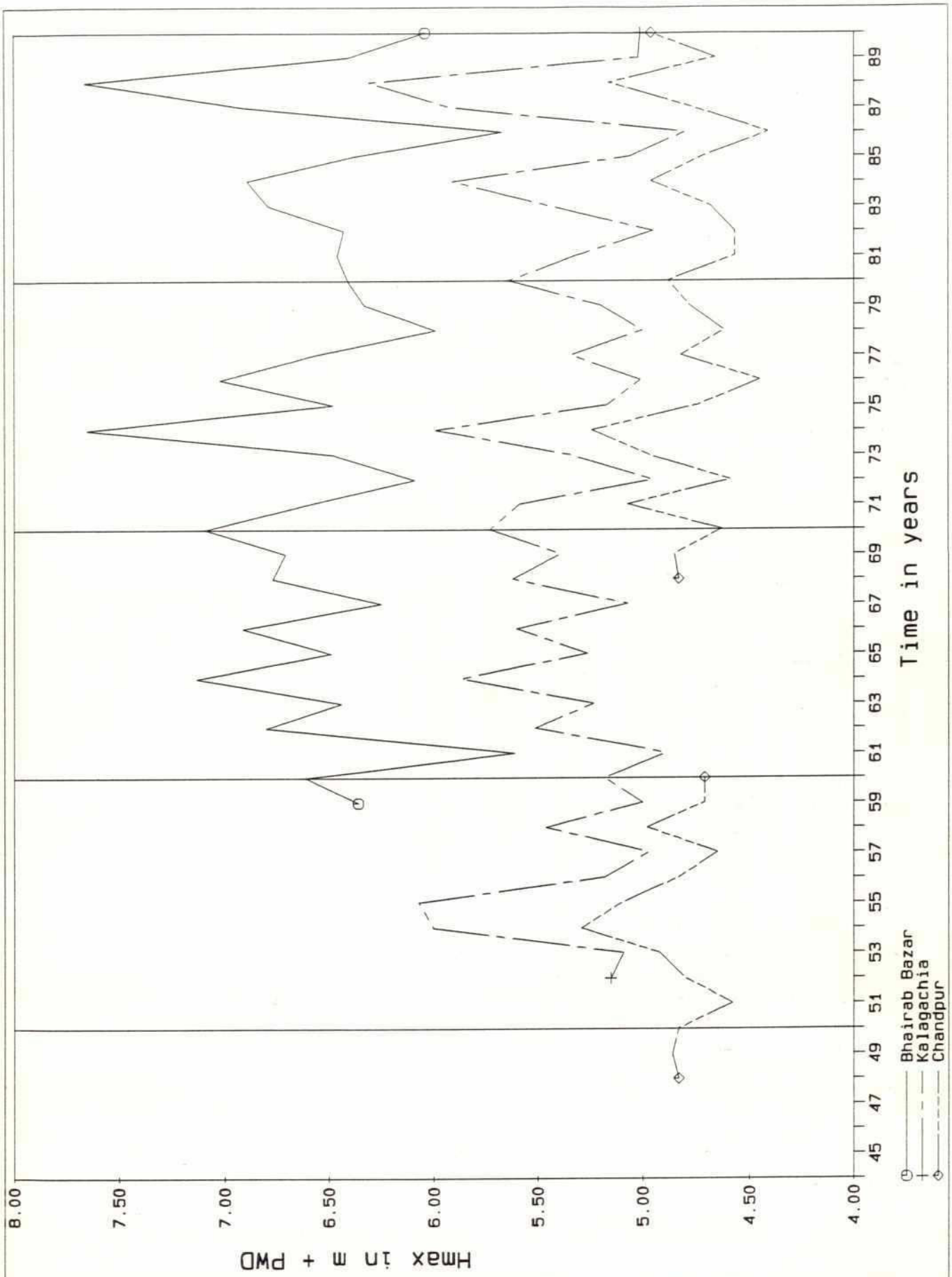
- Bhairab Bazar (273),
- Nabinagar (298),
- Narsingdi (274),
- Meghna Ferryghat (275.5),
- Kalagachia (71),
- Rekabi Bazar (71A),
- Satnal (276),
- Chandpur (277),
- Nilkamal (277.3), and
- Off take in Meghna (288).

It was found, that, based on the availability of data and existing correlations, a consistent set of data could be created for the Upper Meghna for the period 1959-1990. For the Lower Meghna the record of Chandpur was taken as a basis to establish the water level extremes.

Simple and multiple linear and parabolic regression equations have been applied to fill in the missing data. These regression equations are summarized in Appendix A/2. For those stations, where more than one equation is presented, preference was given to the one with the lowest standard error of estimate. From the Appendix it is observed that in general very accurate relationships exist, in particular for the flood period tidal-free stations.

The resulting completed series are shown in Appendix A/3, Table A/3.1. Note that for the Lower Meghna no completion of series has been carried out as the Chandpur record is much longer than the other series.The relations established between, on the one hand, Nilkamal and Off-take in Meghna and, on the other hand, Chandpur will therefore be used to transform the Chandpur extremes for particular return periods to these sites.

The completed series were subsequently subjected to trend and correlation tests to investigate the homogeneity. None of the homogeneity hypotheses were rejected, hence the conditions for application of frequency analysis are fulfilled.



Annual maximum water levels
Meghna stations: Bhairab Bazar, Kalagachia and Chandpur

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FIG. A.5.1

A.5.4 **Frequency analysis**

To determine the water levels for various return periods a number of frequency distributions have been fitted to the data, viz:

- Pearson-III distribution
- Log-Pearson-III distribution
- 3-parameter log-normal distribution
- 2-parameter log-normal distribution

All distributions, except the 2-parameter log-normal distribution, fit well and their difference is rather small as is shown in Table A.5.3. The results of the base line study of FAP 25 with respect to the most appropriate frequency distribution for annual maximum water levels became only available in January 1992. It recommends the use of the 3-parameter log-normal distribution, though the Pearson-III distribution showed equal performance. This is fully in line with the results shown in Table A.5.3.
FAP 25 preferred the former distribution only because of its computational ease in application on a wide scale in Bangladesh. Hence, there is no factual discrepancy between both studies.
The Pearson-III distribution was finally selected by the Consultants.

Table A.5.3 COMPARISON OF EXTREME WATER LEVELS AT SELECTED SITES DERIVED FROM VARIOUS FREQUENCY DISTRIBUTIONS PERIOD 1959-1990

Station	Return Period	prob(xi<x)	P-III	LP-III	LN-3	LN-2
273	2	.50000	6.54	6.56	6.56	6.51
	5	.80000	6.95	6.95	6.95	6.95
	10	.90000	7.18	7.16	7.17	7.19
	25	.96000	7.45	7.40	7.41	7.47
	50	.98000	7.62	7.56	7.56	7.66
	100	.99000	7.79	7.70	7.71	7.84
298	2	.50000	6.27	6.26	6.28	6.28
	5	.80000	6.67	6.67	6.67	6.67
	10	.90000	6.89	6.90	6.88	6.88
	25	.96000	7.15	7.17	7.10	7.11
	50	.98000	7.32	7.36	7.26	7.27
	100	.99000	7.48	7.59	7.39	7.41
71	2	.50000	5.29	5.28	5.29	5.34
	5	.80000	5.64	5.63	5.63	5.66
	10	.90000	5.86	5.86	5.85	5.83
	25	.96000	6.13	6.14	6.12	6.01
	50	.98000	6.32	6.36	6.33	6.14
	100	.99000	6.51	6.57	6.54	6.26
277	2	.50000	4.79	4.79	4.79	4.80
	5	.80000	4.97	4.97	4.97	4.98
	10	.90000	5.08	5.08	5.07	5.07
	25	.96000	5.20	5.21	5.19	5.17
	50	.98000	5.29	5.30	5.27	5.24
	100	.99000	5.37	5.39	5.35	5.30

Note: 1. P-III = Pearson-III distribution
LP-III = Log-Pearson-III distribution
LN-3 = 3-parameter lognormal distribution
LN-2 = 2-parameter lognormal distribution

2. All levels are in m+ PWD

It is noted, that application of frequency distributions to extreme river stages, with extrapolation beyond the measured range, is basically incorrect as sudden changes in the cross-sectional profile determine to a high degree the behaviour of the water level at the very high stages; these physical aspects are not incorporated in the frequency analysis. Starting off from discharges is the correct procedure. In this case, however, with significant annual variation in the stage-discharge relations this is cumbersome, (see also Chapter A.7), and the used procedure is the only feasible one provided that the extrapolation beyond the observed maximum is limited.

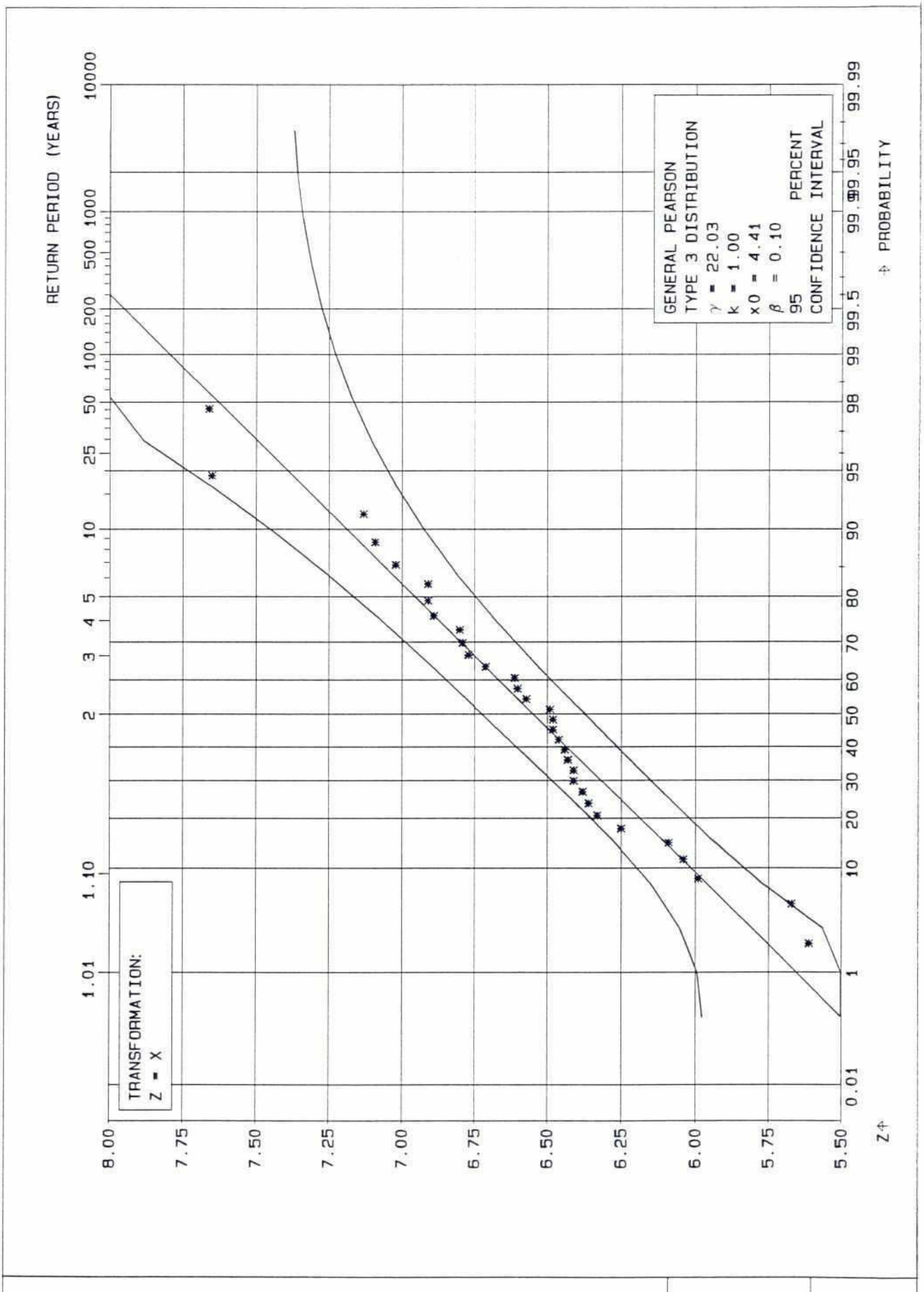
In the series applied most filling-in was carried out for the period 1959-1967. After 1967 the series are rather complete. It appears that the results of the frequency analysis are somewhat dependent on the length of the series, due to the fact that they include two outliers, 1974 and 1988. The effect of taking the longer series 1959-1990 rather than the shorter 1968-1990 is shown in Table A.5.4. The shorter series is seen to produce values which are about 0.10 to 0.14 m higher than the longer ones.

Table A.5.4 EFFECT OF SERIES LENGTH ON RESULTS OF FREQUENCY ANALYSIS SHOWN FOR BHAIRAB BAZAR (273), NABINAGAR (298) AND KALAGACHIA (71)

Station	Return Period	prob(xi<x)	59-90	68-90	Hextr(59-90) - Hextr(68-90)
273	2	.50000	6.54	6.55	-0.01
	5	.80000	6.95	6.98	-0.03
	10	.90000	7.18	7.24	-0.06
	25	.96000	7.45	7.53	-0.08
	50	.98000	7.62	7.74	-0.12
	100	.99000	7.79	7.93	-0.14
298	2	.50000	6.27	6.28	-0.01
	5	.80000	6.67	6.70	-0.03
	10	.90000	6.89	6.95	-0.06
	25	.96000	7.15	7.23	-0.08
	50	.98000	7.32	7.42	-0.10
	100	.99000	7.48	7.60	-0.12
71	2	.50000	5.29	5.31	-0.02
	5	.80000	5.64	5.68	-0.04
	10	.90000	5.86	5.92	-0.06
	25	.96000	6.13	6.21	-0.08
	50	.98000	6.32	6.41	-0.09
	100	.99000	6.51	6.61	-0.10

All levels are in m + PWD

The results of the frequency analysis applying the Pearson-III distribution are presented in the Tables A.5.5 and A.5.6 and an example of the fit is shown for Bhairab Bazar in Figure A.5.2.



Pearson-III frequency distribution
Annual maximum water levels
Meghna at Bhairab Bazar, 1959-1990

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FIG. A.5.2

In Table A.5.5 the parameters of the Pearson-III distribution as estimated from the 1959-1990 series (Upper Meghna) and from the 1948-1990 series (Chandpur) are presented.

Table A.5.5 PARAMETERS OF THE PEARSON-III FREQUENCY DISTRIBUTION

Station name	code	Beta	Gamma	X0	n
Bhairab Bazar	273	0.098	22.029	4.414	32
Nabinagar	298	0.087	27.335	3.912	32
Narsingdi	274	0.140	8.609	4.677	32
Meghna Ferryghat	275.5	0.176	3.998	4.820	32
Rekabi Bazar	71A	0.237	2.528	4.843	32
Kalagachia	71	0.205	3.374	4.663	32
Satnal	276	0.159	4.248	4.542	32
Chandpur	277	0.061	11.292	4.114	36

Note: Beta, Gamma and X0 = parameters of Pearson-III distribution

The extreme water levels for the 5, 10, 25, 50 and 100 years return period at the selected locations are shown in Table A.5.6.

Table A.5.6. FLOOD LEVELS ALONG THE UPPER AND LOWER MEGHNA RIVER FOR DISTINCT RETURN PERIODS

Station name	Code	Chainage km	Return Period (yrs) 5	10	25	50	100
Bhairab Bazar	273	9.4	6.95	7.18	7.45	7.62	7.79
Nabinagar	298	25.0	6.67	6.89	7.15	7.32	7.48
Narsingdi	274	50.0	6.20	6.42	6.68	6.86	7.03
Meghna Ferry	275.5	88.0	5.79	6.00	6.25	6.42	6.59
Rekabi Bazar	71A	94.0	5.71	5.95	6.23	6.44	6.64
Kalagachia	71	94.0	5.64	5.86	6.13	6.32	6.51
Satnal	276	103.4	5.47	5.66	5.89	6.05	6.21
Chandpur	277	135.0	4.97	5.08	5.20	5.29	5.37
Nilkamal	277.3	150.8	4.71	4.78	4.87	4.94	5.00
Offtake Meghna	288	184.0	3.40	3.46	3.54	3.61	3.67

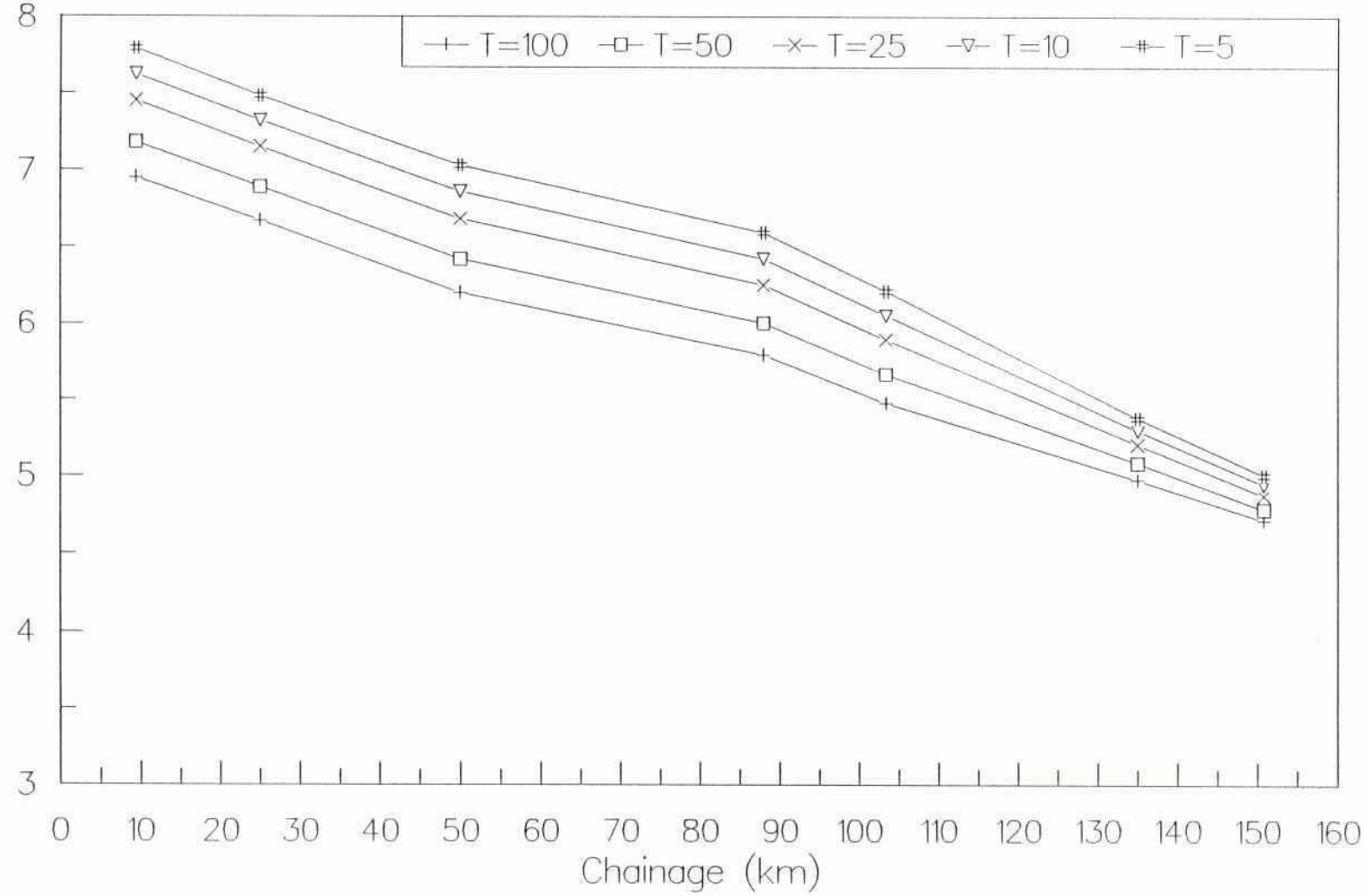
Note: All levels are in m+PWD

The resulting flood levels along the Upper and Lower Meghna are obtained by linear interpolation between the stations and are presented in Figure A.5.3.

Flood levels along Meghna River for various return periods

FIG. A.5.3

T=return period in years



A.5.4 Flood levels at the protection sites

The flood levels having a return period of 50 and 100 years at the proposed protection sites, which are to be used in the design, are summarized in Table A.5.7. The levels are obtained from Table A.5.6 by linear interpolation between surrounding gauging stations. As the sites extend generally over several kilometers, values for the upstream and for the downstream ends are presented.

Table A.5.7 FLOOD LEVELS AT THE PROTECTION SITES FOR 50 AND 100 YEARS RETURN PERIODS

Site	Chainage km	Return Period			
		50 years		100 years	
		u/s	d/s	u/s	d/s
Bhairab Bazar	7.5 - 9.0	7.66	7.62	7.83	7.79
Maniknagar	31.0 - 37.0	7.22	7.10	7.39	7.27
Meghna R&H Bridge	88.0 - 88.0	6.42	6.42	6.59	6.59
Munshiganj (Dlswri)	8.0 - 4.0	6.41	6.32	6.60	6.51
Eklashpur	114.0 - 123.0	5.80	5.58	5.93	5.69
Chandpur	134.0 - 137.0	5.31	5.25	5.40	5.32
Haimchar	147.0 - 154.5	5.02	4.86	5.09	4.91

All levels are in m+PWD

The maximum water levels on the Meghna occur in the months July, August and September and occasionally in October, see Chapter A.2.

Only design levels as shown in Table A.5.7 for Maniknagar, Eklashpur and Haimchar were obtained by linear interpolation between surrounding gauging stations. The interpolated 100-year levels differ respectively only 0.2, 0.3 and 0.1 m from the related levels at the nearest stations. The suggestion that perhaps a better interpolation could be obtained through the results of the General Model (GM) is, therefore, rather academic. With such small differences in levels no physically realistic interpolation technique, as for example the GM can provide results significatively deviating from those obtained through linear interpolation.

However, as soon as the General Model has been recalibrated its results should be used to the maximum possible extent during an eventual extension of the FAP 9B project. This holds in particular when nation-wide flood protection schemes would affect the design conditions in the project region.Meanwhile, results of the GM were used in FAP 9B as needed and appropriate.

A proper picture of the variation of stages and the occurrence of extreme high water levels can be obtained from the frequency curves displayed in the next chapter.

A.6. FREQUENCY AND DURATION CURVES

A.6.1 General

The variation of water levels and discharges through the year can be obtained from frequency curves, where each curve indicates the magnitude of the quantity for a specific probability of non-exceedance. Related to this are duration curves. From these curves the most suitable period in the year for construction can be obtained as well as the corresponding likely river stages.
Duration curves of discharges are useful for the computation of the bed scour.

Frequency curves are established in the following way. Given a record covering many years of data, for each date in the year a cumulative frequency distribution is made and the values for specified non-exceedance probabilities are determined, e.g. at 10, 50 and 90 percent probability. By connection of values with equal non-exceedance probabilities for the successive dates frequency curves of given probabilities of non-exceedance are obtained. Hence the curves have only a meaning for specific dates. Note that the curves do not provide information on possible succession of low or high water levels or discharges.

Duration curves for given non-exceedance probabilities are ranked representations of the frequency curves.

The average duration curve gives the average number of occasions a given value was not exceeded in the years considered. Note that this curve differs from the 50 percent non-exceedance duration curve!

A.6.2 Water levels

Frequency, duration and average duration curves have been established of daily average water level series and for the protection sites.

Computational procedure
The daily average water level series were derived, where necessary, from the daily maximum and minimum water levels, available on diskette through MPO and FAP 25 for the following stations:

- Bhairab Bazar (273)
- Bhairab Bazar Railway Bridge (230.1)
- Bayder Bazar (275)
- Meghna Ferryghat (275.5)
- Satnal (276)
- Chandpur (277)
- Nilkamal (277.3)

Validation of the data revealed clear inconsistencies in the data sets of Bayder Bazar and Nilkamal for the period 1983-1987. The data of Bayder Bazar were ignored, whereas for Nilkamal only use was made of the most recent data, i.e. 1990-1991.

Based on the available station data, records or relations were created for the protection sites in the following way:

- Bhairab Bazar : record of station Bhairab Bazar,

- Maniknagar : series created by linear interpolation according to distance between Bhairab Bazar and Meghna Ferryghat

- Meghna Ferryghat : record of station Meghna Ferryghat

- Munshiganj : levels are represented by station Kalagachia; since no historical data were available on diskette for this station use was made of a relation curve with Meghna Ferryghat based on computed water levels by the General Model, see equation (6.1)

- Eklashpur : series created by linear interpolation according to distance between Meghna Ferryghat and Chandpur

- Chandpur : record of station Chandpur

- Haimchar : levels are represented by station Nilkamal; data were derived from station Chandpur based on a relation curve between the two stations for 1990-1991, see equation (6.2)

The water level relation curves for Munshiganj as a function of Meghna Ferryghat and of Haimchar as a function of Chandpur are well represented by following linear regression equations:

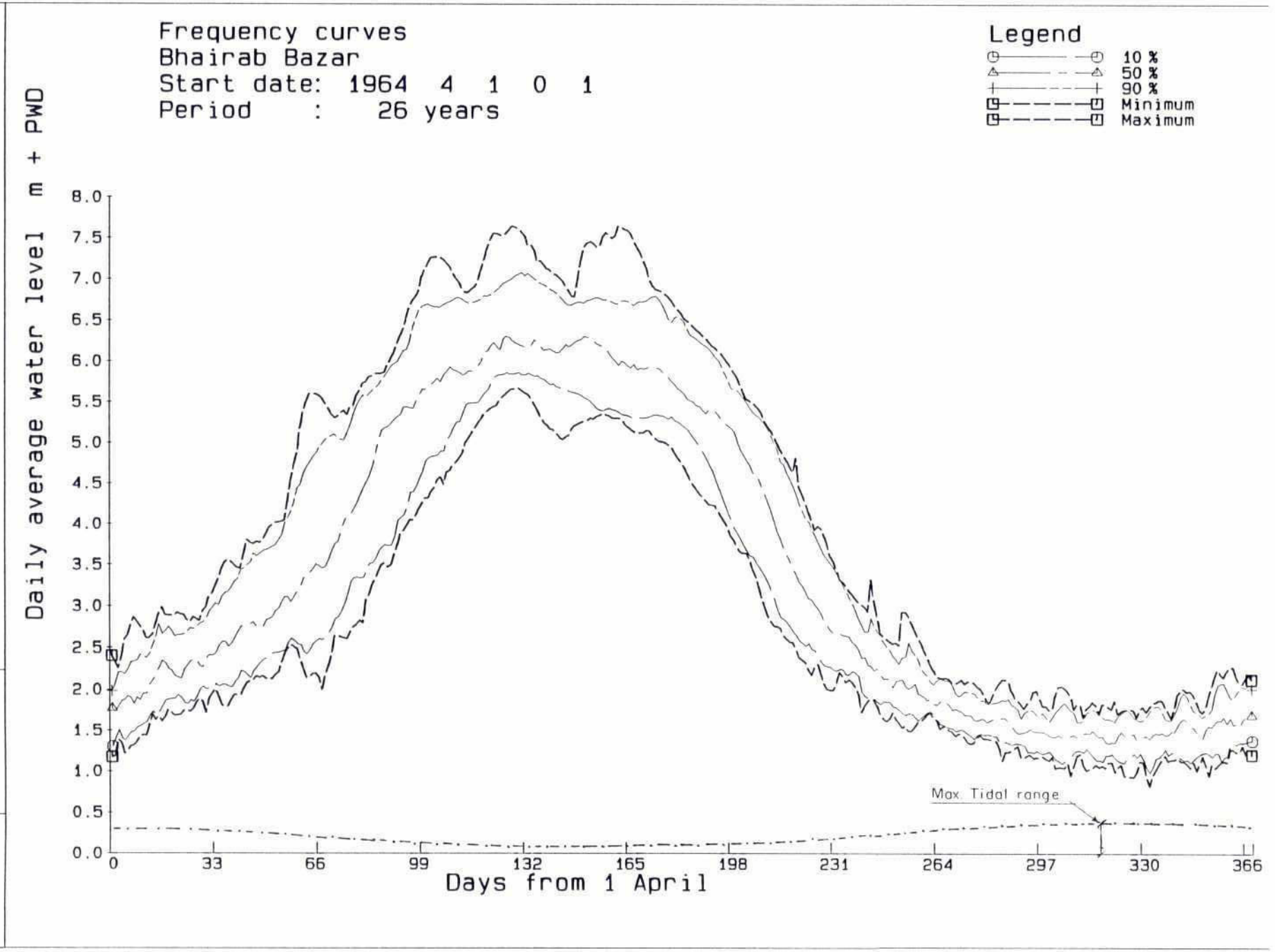
HMunsiganj = 0.043 + 0.962 * HMeghna Ferryghat (6.1)

HHaimchar = -0.062 + 0.9116 * HChandpur (6.2)

Results for daily average water levels

Figures A.6.1 to A.6.5 show the frequency and duration curves for the various protection sites, except for Munshiganj and Haimchar; for these stations the curves for respectively Meghna Ferryghat and Chandpur should be used in combination with the relations (6.1) and (6.2). In Appendix A/4 the average duration curves are presented in tabular form.

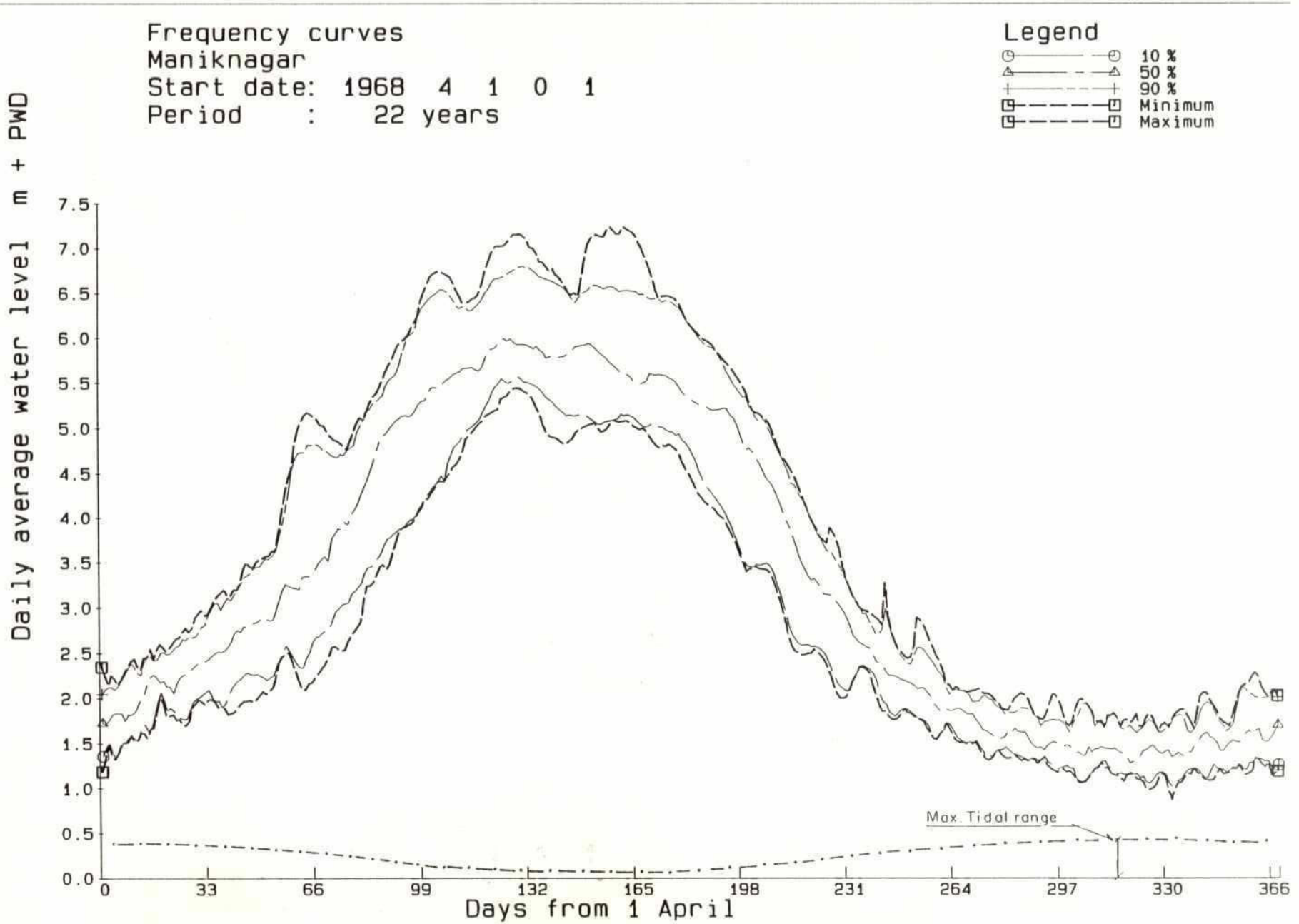
To determine the most acceptable period for construction of the embankment protection assuming an implementation period of 0.5 year, the level, which is on the average not exceeded during 183 days, was selected from the average duration curve and from the frequency curves it was determined when the non-exceedance is most likely. For the 10, 50 and 90 percent curves these periods have been presented in Table A.6.1



Frequency curves daily average water levels at Bhairab Bazar
Period 1964 - 1989

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FIG. A.6.1



Frequency curves daily average water levels at Maniknagar
Period 1968 - 1989

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FIG. A.6.2

Frequency curves daily average water levels at Meghna Ferryghat Period 1968 - 1989

HASKONING - DELFT HYDRAULICS - BETS

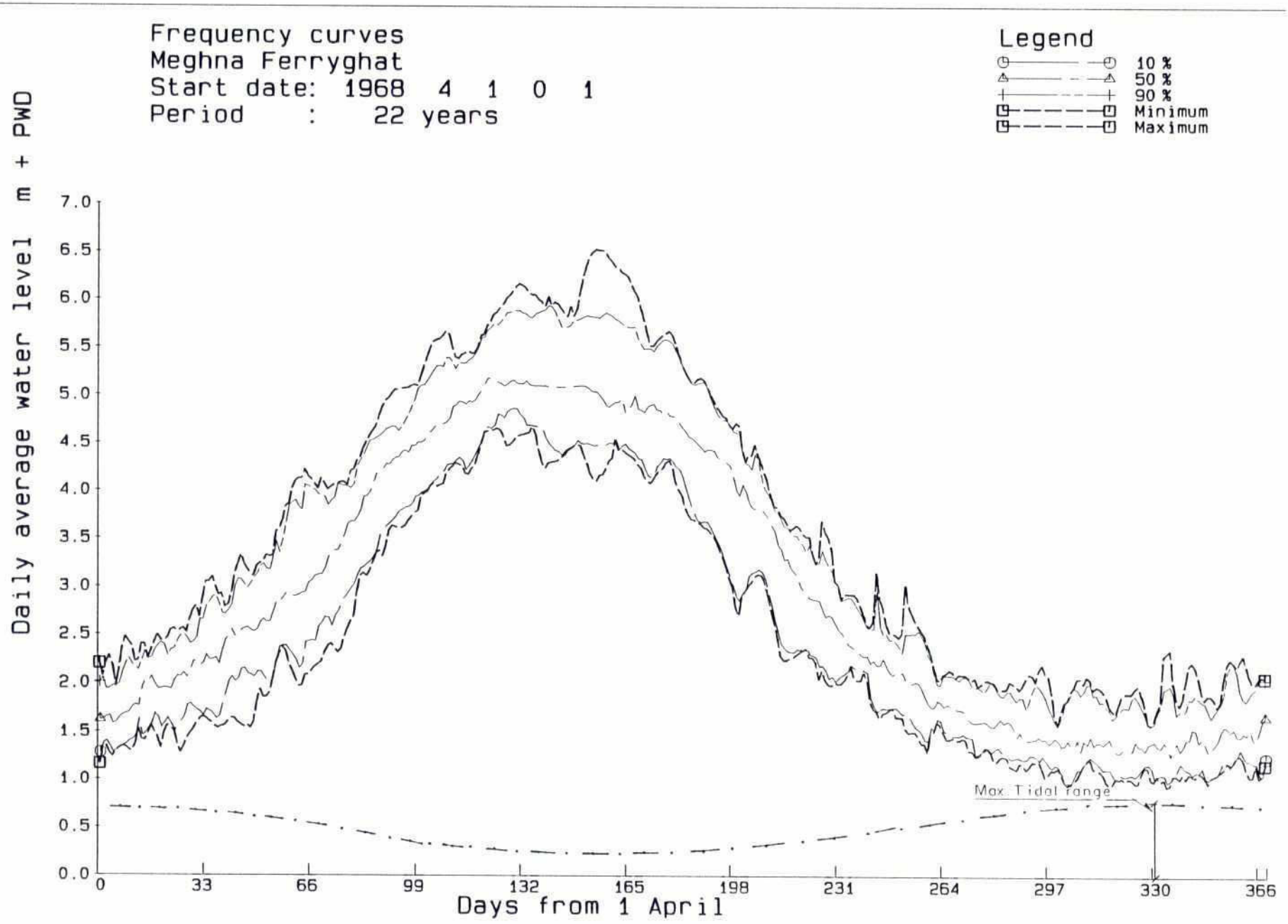
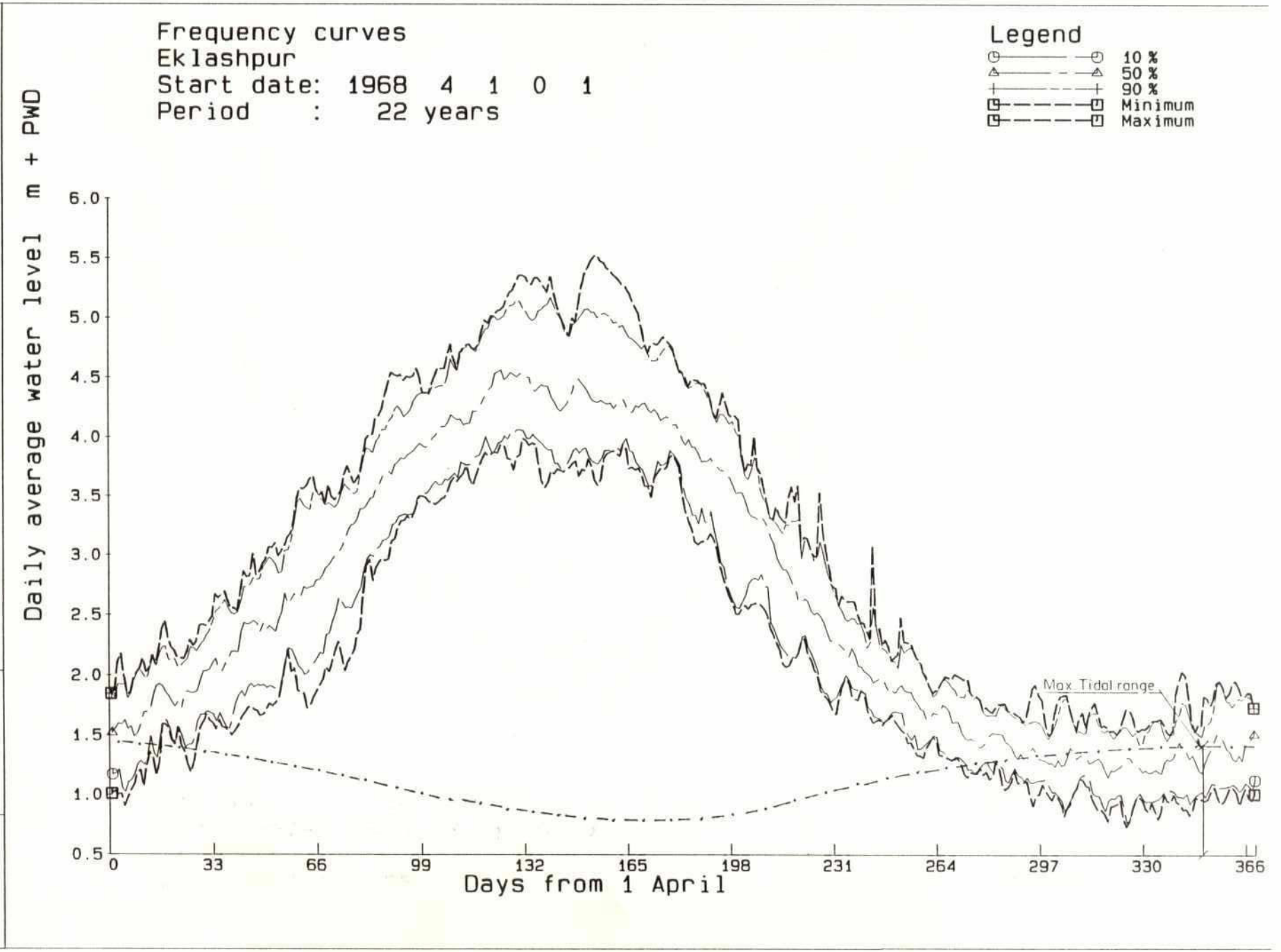


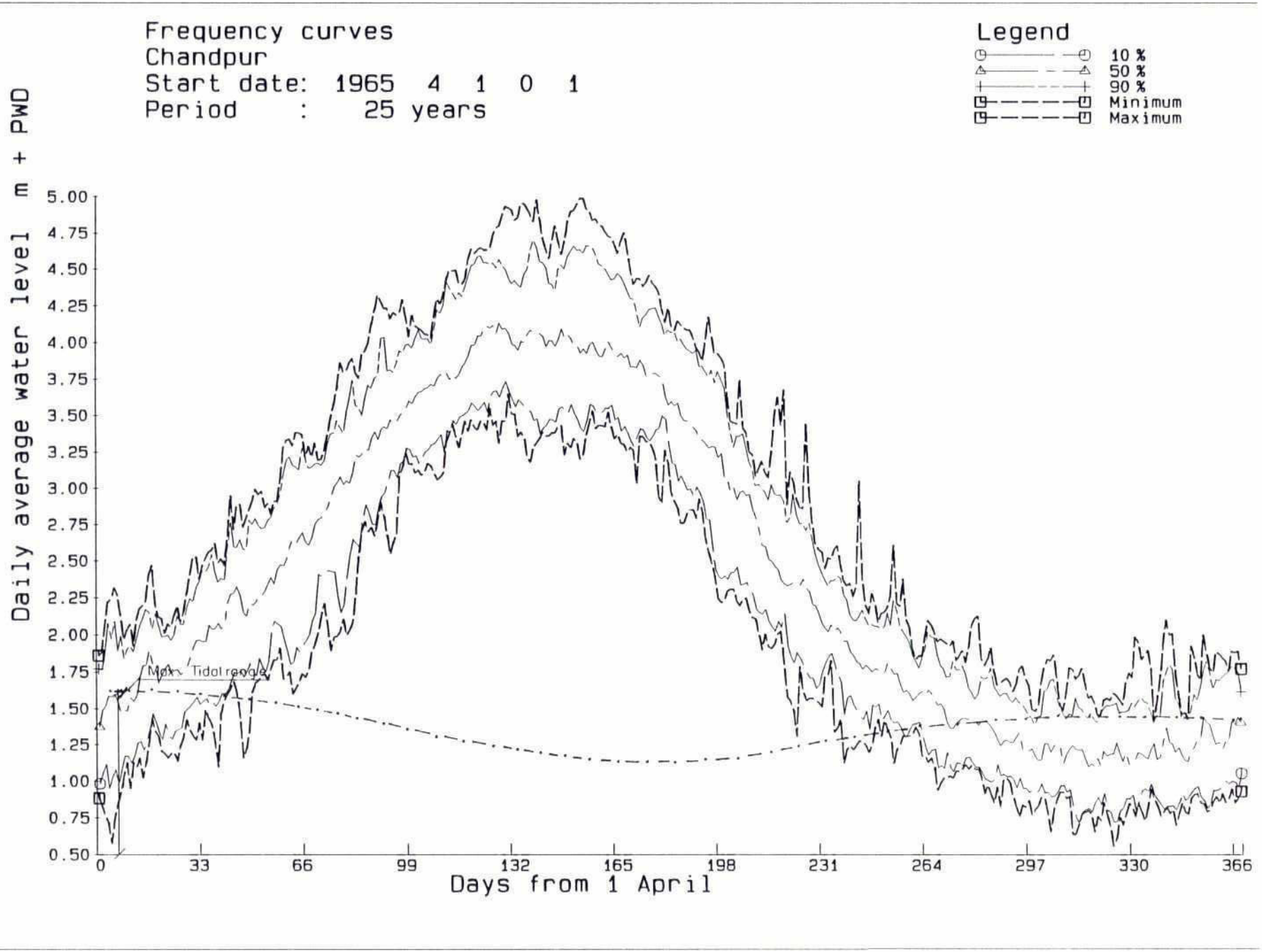
FIG. A.6.3



Frequency curves daily average water levels at Eklashpur Period 1968 - 1989

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FIG. A.6.4



Frequency curves daily average water levels at Chandpur
Period 1965 - 1989

HASKONING - DELFT HYDRAULICS - BETS

FIG. A.6.5

Table A.6.1 MEDIAN WATER LEVELS AT THE CONSTRUCTION SITES AND THEIR PERIOD OF NON-EXCEEDANCE IN A 10, 50, 90 PERCENT WET YEAR

Site	water level not exceeded 183 days/yr on average	Period during which the median level is not exceeded		
		10% year	50% year	90% year
Bh. Bazar	2.87	02/11-12/6	15/11-22/5	26/11-02/5
Maniknagar	2.78	02/11-10/6	20/11-15/5	02/12-01/5
Meghna Fght	2.55	30/10-07/6	19/11-11/5	02/12-01/5
Munshiganj	2.50	30/10-07/6	19/11-11/5	02/12-01/5
Eklashpur	2.35	30/10-08/6	16/11-11/5	02/12-01/5
Chandpur	2.19	28/10-09/6	16/11-11/5	27/11-29/4
Haimchar	1.93	28/10-09/6	16/11-11/5	27/11-29/4

Note: Levels in m + PWD

From Table A.6.1 it is observed that for a construction period of 0.5 year with lowest daily average water levels the period from mid November till mid May is most suitable for all sites.

(a) Comparison with Interconsult results

The range of water levels is also given in the study by Interconsult [3]. Their results are summarized in Table A.6.2, with within brackets the values from the average duration curve as derived above.

Table A.6.2. STANDARD LOW AND STANDARD HIGH WATER LEVELS AND 95 AND 5% EXCEEDANCE LEVELS EXTREMES

Station name	code	SLW	SHW	95%	5%
Bhairab Bazar	273	0.71	8.57	1.16(1.31)	7.44(6.50)
Nabinagar	298	0.65	7.63	1.09	7.08
Narsingdi	1650	0.62	7.11	0.88	6.71
Baidyar Bazar	275	0.59	6.49	0.92	6.12
Meghna Ferryghat	275.5	0.73	6.34	1.03(1.22)	5.96(5.38)
Satnal	276	0.55	6.04	0.90	5.60
Chandpur	1640	0.19	5.16	0.55(1.02)	4.59(4.22)
Nilkamal	277.3	0.73	4.79	0.95	4.09

Source: [3]

Note: SLW = FML95% -(1.1(M2+S2)-MSf) (Spring Tide)
SLW = FML95% -(1.1(M2+S2)+MSf) (Neap Tide)
SHW = FML 5% +(1.1(M2+S2)+MSf)
FML = Fortnightly Mean Level

There appears to be a clear difference between the results of the two studies, which cannot simply be attributed to the diurnal variation of the water level; e.g for Bhairab Bazar the tidal variation is nil during the flood period. The SHW-level as well as the 5% exceedance level for Bhairab Bazar as presented by Interconsult are rather strange; since the period of record the level never exceeded 7.66 m+PWD! Similar remarks can be made for Meghna Ferryghat and Chandpur.

(b) Semi-diurnal tidal variation

The average daily water level records do not include the semi-diurnal variation. To determine the possible variation of the levels at any moment in the year, in conjunction with the average daily water levels, also the range of the water levels (daily maximum-daily minimum) have been presented in the graphs. The curves are based on the records for the years 1983-1987. The results are also shown in the frequency curves mentioned above.

(c) Results for monthly average water levels

Similar to the average daily water levels frequency and duration analysis has been applied to monthly average water levels to eliminate the effects of the fortnightly variation. The results for 10, 50 and 90 percent curves for each month are shown for the protection sites in the Tables A.6.3 to A.6.9.

Table A.6.3 AVERAGE MONTHLY EXCEEDANCE LEVELS OF UPPER MEGHNA AT BHAIRAB BAZAR, PERIOD 1964-1989

Month	Non-exceedance Frequency Levels in m + PWD		
	.10	.50	.90
April	1.82	2.11	2.37
May	2.36	2.70	3.39
June	3.19	4.21	5.25
July	5.16	5.74	6.61
August	5.83	6.17	6.82
September	5.35	5.95	6.62
October	4.10	5.05	5.62
November	2.45	2.87	3.60
December	1.74	1.97	2.21
January	1.46	1.52	1.74
February	1.33	1.42	1.53
March	1.43	1.52	1.71

Table A.6.4 AVERAGE MONTHLY EXCEEDANCE LEVELS OF UPPER MEGHNA AT MANIKNAGAR, PERIOD 1968-1989

Month	Non-exceedance Frequency Levels in m + PWD		
	.10	.50	.90
April	1.87	2.06	2.24
May	2.28	2.79	3.23
June	3.11	4.07	4.89
July	4.62	5.44	6.17
August	5.39	5.88	6.55
September	5.07	5.61	6.38
October	3.77	4.90	5.38
November	2.37	2.99	3.38
December	1.73	1.98	2.21
January	1.42	1.50	1.76
February	1.34	1.41	1.54
March	1.41	1.53	1.77

Table A.6.5 AVERAGE MONTHLY EXCEEDANCE LEVELS OF UPPER MEGHNA AT MEGHNA FERRYGHAT, PERIOD 1968-1989

Month	Non-exceedance Frequency Levels in m + PWD		
	.10	.50	.90
April	1.63	1.90	2.07
May	2.13	2.59	2.86
June	2.99	3.52	4.12
July	4.19	4.73	5.07
August	4.70	5.18	5.74
September	4.43	4.85	5.55
October	3.24	4.21	4.53
November	2.21	2.72	2.98
December	1.64	1.91	2.18
January	1.34	1.44	1.78
February	1.21	1.38	1.64
March	1.27	1.46	1.76

Table A.6.6 AVERAGE MONTHLY EXCEEDANCE LEVELS OF DHALESWARI AT MUNSHIGANJ, PERIOD 1968-1989

Month	Non-exceedance Frequency Levels in m + PWD		
	.10	.50	.90
April	1.61	1.87	2.03
May	2.09	2.53	2.79
June	2.92	3.43	4.01
July	4.07	4.59	4.92
August	4.56	5.03	5.56
September	4.30	4.71	5.38
October	3.16	4.09	4.40
November	2.17	2.66	2.91
December	1.62	1.88	2.14
January	1.33	1.43	1.76
February	1.21	1.37	1.62
March	1.26	1.45	1.74

Table A.6.7 AVERAGE MONTHLY EXCEEDANCE LEVELS OF LOWER MEGHNA AT EKLASHPUR, PERIOD 1968-1989

Month	Non-exceedance Frequency Levels in m + PWD		
	.10	.50	.90
April	1.56	1.72	1.86
May	1.96	2.43	2.63
June	2.70	3.20	3.56
July	3.76	4.10	4.42
August	4.02	4.44	4.94
September	3.89	4.28	4.69
October	2.87	3.55	3.89
November	2.03	2.44	2.69
December	1.58	1.74	1.95
January	1.29	1.34	1.59
February	1.15	1.28	1.39
March	1.25	1.32	1.58

Table A.6.8 AVERAGE MONTHLY EXCEEDANCE LEVELS OF LOWER MEGHNA AT CHANDPUR, PERIOD 1965-1989

Month	Non-exceedance Frequency Levels in m + PWD		
	.10	.50	.90
April	1.45	1.67	1.79
May	1.89	2.18	2.51
June	2.46	3.02	3.26
July	3.41	3.69	4.07
August	3.68	4.03	4.41
September	3.55	3.89	4.31
October	2.70	3.18	3.55
November	1.91	2.18	2.51
December	1.42	1.61	1.85
January	1.18	1.28	1.49
February	1.04	1.17	1.31
March	1.10	1.26	1.40

Table A.6.9 AVERAGE MONTHLY EXCEEDANCE LEVELS OF LOWER MEGHNA AT HAIMCHAR, PERIOD 1965-1989

Month	Non-exceedance Frequency Levels in m + PWD		
	.10	.50	.90
April	1.26	1.46	1.57
May	1.66	1.93	2.23
June	2.18	2.69	2.91
July	3.05	3.30	3.65
August	3.29	3.61	3.96
September	3.17	3.48	3.87
October	2.40	2.84	3.17
November	1.68	1.93	2.23
December	1.23	1.41	1.62
January	1.01	1.10	1.30
February	0.89	1.00	1.13
March	0.94	1.09	1.21

A.6.3 Discharges

Frequency curves of the discharge at Bhairab Bazar and at Chandpur are presented in Figures A.6.6 and A.6.7 and as average duration in tabular form in Appendix V. The discharges were taken from the General Model, run for a 25 years period from 1965, exclusive of 1971. Typical values of the average duration curves are summarized in Table A.6.10.

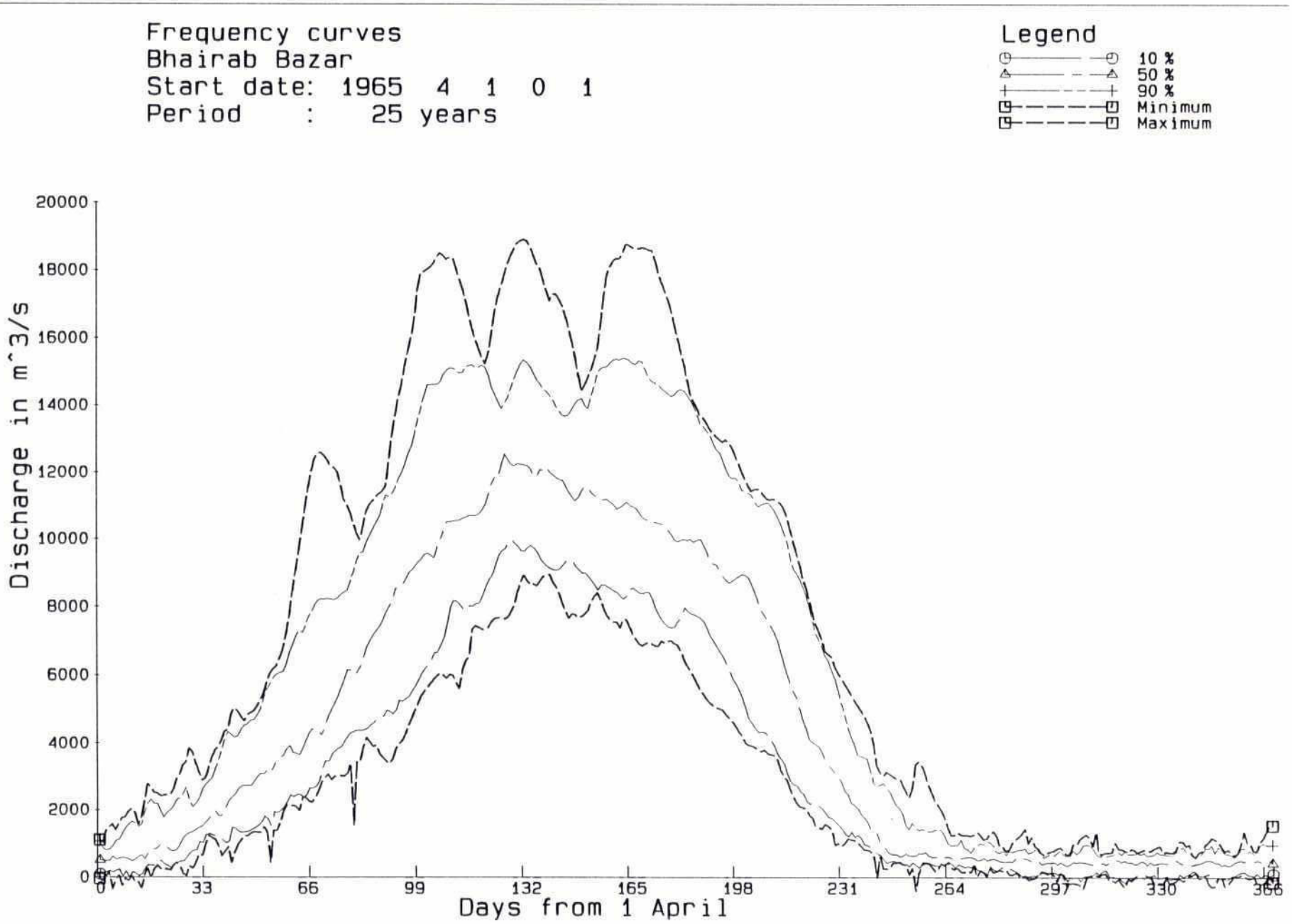
Table A.6.10 DISCHARGES OF MEGHNA RIVER AT BHAIRAB BAZAR AND CHANDPUR EXCEEDED 5, 10, 25 AND 50 PERCENT OF TIME

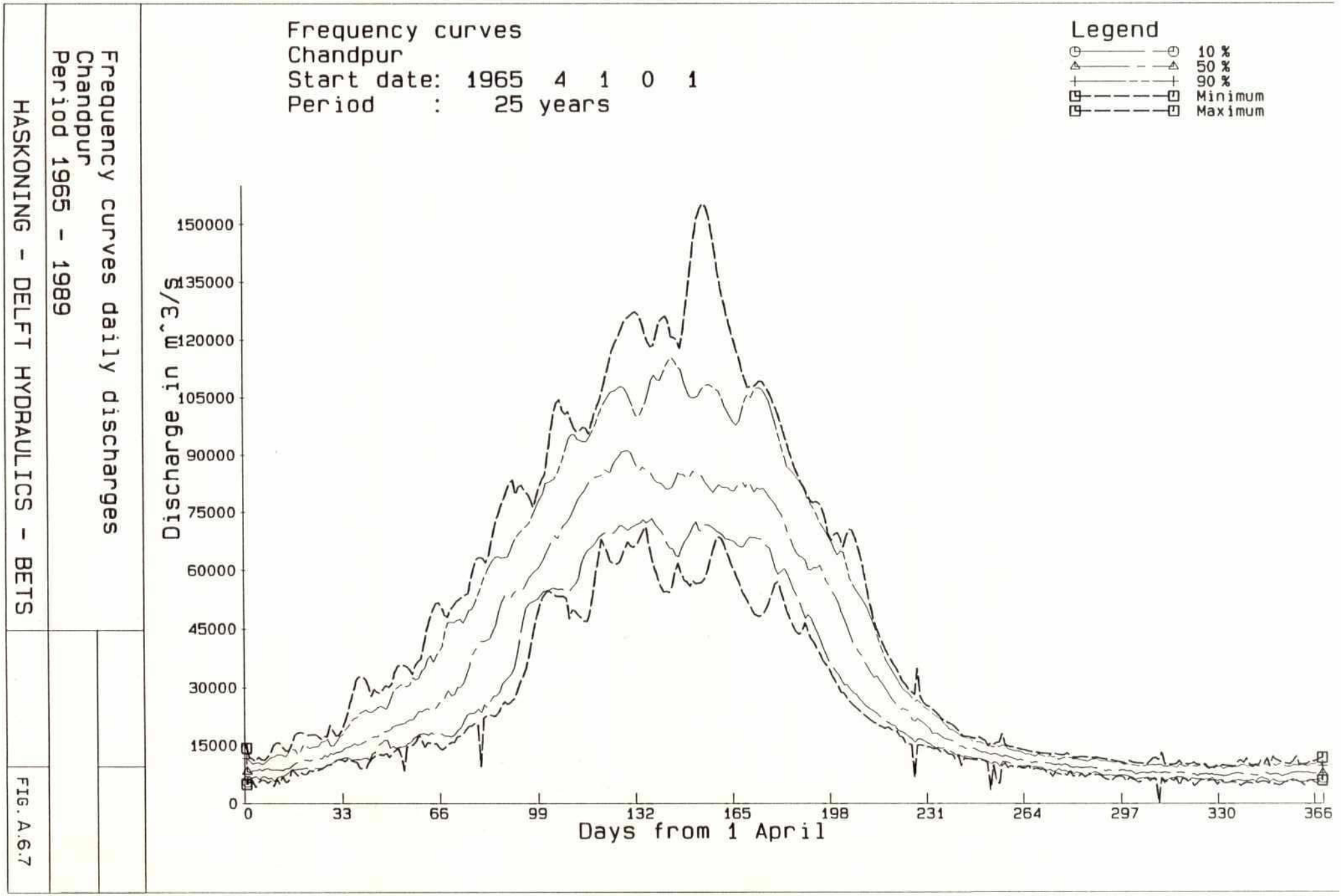
Location	Discharges in m3/s at exceedance levels			
	5%	10%	25%	50%
Bhairab Bazar	13,970	11,935	9,120	2,875
Chandpur	94,860	84,520	62,690	19,200

Frequency curves daily discharges
Bhairab Bazar
Period 1965 - 1989

HASKONING - DELFT HYDRAULICS - BETS

FIG. A.6.6





Frequency curves daily discharges
Chandpur
Period 1965 - 1989

HASKONING - DELFT HYDRAULICS - BETS

FIG. A.6.7

A.7 FLOW VELOCITIES

A.7.1 General

An important boundary condition for the design of the bank protection is the maximum flow velocity near the bank. However, despite its importance, actual flow measurements are not at a regular basis at protection sites. Therefore maximum velocities were computed.

Computational procedure

The velocity computations have been based on the Manning equation, stating that the velocity is proportional to the 2/3 power of the depth. For the application of this method it is assumed that the energy slope is constant throughout the section; the roughness may still vary in the cross-section.

Two procedures are discerned:

1. Water level and discharge are given and the velocity follows from:

$$K_M.\sqrt{S} = Q/\Sigma(h_i^{5/3}.B_i) \qquad (7.1)$$

and:

$$v_i = K_M.\sqrt{S}.h_i^{2/3} \qquad (7.2)$$

where: K_M = Manning coefficient for hydraulic resistance
S = hydraulic gradient
h = flow depth
Q = discharge
B_i = width of section i
v_i = velocity at location i

2. Hydraulic gradient and K_M are given and the velocity in the cross-section is computed from (A.7.2)

In practice actual flow velocities may deviate from the Manning equation due to helicoidal flow effects in river bends, which concentrates the flow towards the outer bend and due to lateral momentum transfer between fast and slow moving water bodies. In the first case the Manning equation will slightly underestimate the maximum flow velocity and hence a safety margin has to be added, whereas in the second case abrupt changes in velocity are smoothed out, and the Manning equation overestimates the actual velocities.

In this Section the results of the above outlined procedures, using the cross-sections at the locations shown in Figure A.7.1, are dealt with, applied to the following protection sites:

- Bhairab Bazar,
- Maniknagar,
- Meghna Ferryghat and
- Munshiganj.

For Eklashpur and Chandpur flow conditions are far too complicated to allow the approach outlined above. Two-dimensional depth-averaged mathematical hydraulic model computations and scale model test are required to estimate the design velocities. The flow velocities at Haimchar also follow from the model. In this Annex the boundary conditions for the model computations and scale model tests are elaborated.

Occurrence of maximum velocities

From computational results of the General Model completed with observed discharges and water level data it was revealed that at most sites maximum water level gradients occur at or near maximum discharge, whereas the latter coincides with near maximum water levels. Since the flow velocity is proportional to the 2/3 power of the depth and to the root of the hydraulic gradient it follows that maximum velocities occur near maximum discharge, provided that the hydraulic roughness does not decrease with increasing flow velocities. The latter is supported by calibration results of the General Model.

A.7.2 **Bhairab Bazar**

Discharge extremes

Maximum flow velocities at Bhairab Bazar coincide with near maximum discharge conditions as outlined in Section A.7.1.

Annual maximum discharge data are available from 1964 onward with some gaps, see Table 2.2. To obtain a set of data comparable with the water level extremes the series have been extended to the period 1959-1990. The missing data were partly filled in with data from the General Model (1977-1980) and, prior to 1964, from a relation between maximum annual discharges and the corresponding water levels. For the highest stages the discharges were estimated from the following stage-discharge relation:

$$Q = 3915*(H - 3.54)^{1.126} \qquad (7.3)$$

where: Q = annual maximum Upper Meghna discharge at Bhairab Bazar
H = corresponding maximum water level

The completed series are presented in Appendix VI.

Some frequency distributions have been applied to the series of extremes, see Table A.7.1.

Table A.7.1 DISCHARGES EXTREMES IN UPPER MEGHNA AT BHAIRAB BAZAR FOR VARIOUS RETURN PERIODS

Return Period years	P-III	LP-III	LN-3	Gumbel	P-III(H)
10	16,900	16,800	16,800	16,500	16,800
25	18,700	18,900	18,700	18,000	18,200
50	20,000	20,500	20,200	19,200	19,100
100	21,300	22,100	21,800	20,300	20,000

Note:1. P-III = Pearson-III distribution
LP-III = Log-Pearson-III distribution
LN-3 = 3-parameter lognormal distribution
P-III(H) = discharges from extreme water levels with return periods according to Pearson-III distribution from Table 5.5
2. discharges are in m^3/s

The various distributions give comparable results; Log-Pearson-III gives the highest and the Gumbel distribution gives the lowest values. In the last column also the discharges as computed from the water level extremes of Table 5.5, applying equation (A.7.3), are presented. Excellent resemblance is observed with the Gumbel estimates. Hence to get consistency between the extreme water levels and discharges basically the Gumbel estimates for the discharge and the Pearson-III estimates for the corresponding water level have to be used in the velocity computations.

Maximum velocities according to Procedure 1

The results of the velocity computations for cross-section M#18A in the most constricted part of the Meghna at the protection site are shown in Table A.7.2.

Table A.7.2 MAXIMUM FLOW VELOCITIES IN MEGHNA AT BHAIRAB BAZAR

Return Period years	Qmax (m^3/s)	Hmax m+PWD	vmax-Gumbel m/s
10	16,500	7.18	1.46
25	18,000	7.45	1.57
50	19,200	7.62	1.67
100	20,300	7.79	1.75

Note: max = maximum velocity in cross-section
v-Gumbel = velocities based on Gumbel estimates of Q_{max}

Table A.7.2 shows maximum velocities according to Gumbel of 1.75 m/s in the cross-section at a return period of 100 years.

From the computation a K_M value of 38.3 results, which leads to C-values up to 70 $m^{1/2}/s$. This compares well with a K_M-value of 40 calibrated for the General Model and the latter value is applied in the following for the Upper Meghna.

Maximum velocities according to Procedure 2

From the water level and discharge records of Bhairab Bazar and the water levels of Meghna Ferryghat maximum gradients appear to coincide with maximum discharge. During the flood of 1988 falls up to 2 m occurred, corresponding to a gradient of $2.5*10^{-5}$ at a water level of 7.20 m. This average gradient has to be corrected for constriction by a factor 0.8, see Annex B. Hence for this cross-section a maximum gradient of $2*10^{-5}$ applies. This gradient is slightly steeper than the one derived from the extreme water levels at Bhairab Bazar and Narsingdi at corresponding return periods, being $1.8*10^{-5}$. This is in accordance with the observation for 1988 that maximum gradients did occur below maximum stage. Note that the return period of the 1988 flood was between 50 and 100 years (depending on the frequency distribution applied), hence the conditions are representative for the design.
Consequently with this procedure design velocities are derived from (A.7.2) for:

- a water level of 7.2 m
- a gradient S = $2.0*10^{-5}$, and
- a Manning coefficient K_M = 40

Based on this analysis a maximum velocity of 1.90 m/s is to be expected in the cross-section at maximum depth of 34.60 m. This is 0.15 m/s higher than the velocity estimated by Procedure 1.

Rating curves

An analysis of the rating curves of station Bhairab Bazar for successive years showed that generally the range of the measurements had been satisfactory, and with a few exceptions also the fit of the rating curves was acceptable.

The stage-discharge relationship for successive years varies considerably. It means that a particular discharge corresponds with different levels year by year. This is illustrated in Table A.7.3, where the resulting water level relative to PWD for a 20 percent exceeded discharge (10,000 m^3/s) is presented. The range of water levels is seen to vary by about 1 metre.

Table A.7.3 WATER LEVELS AT BHAIRAB BAZAR CORRESPONDING TO A DISCHARGE OF 10,000 M_3/S

Year	Water Level	Qmax	Year	Water Level	Qmax
1979	5.60	13,800	1985	5.70	14,300
1980	6.00	11,300	1986	6.00	11,100
1981	6.20	11,200	1987	5.60	15,200
1982	5.60	13,500	1988	5.20	19,800
1983	5.50	16,000	1989	5.20	15,500
1984	5.60	13,600			

Note: levels are in m+PWD and discharges in m^3/s

From the table it is observed that the water level and hence the bottom level is high during low annual maxima and vise versa.

For the year 1988-1989 which nears the design conditions the following rating curve applies:

$$Q = 1170(H-1.0)^{1.49} \qquad (7.4)$$

A.7.3 Maniknagar

The Maniknagar site is located in a bend on the left bank of the left branch of the Upper Meghna between km 31 and 37. The flow distribution between the branches has been determined from cross-section M#14-1, which covers both branches, whereas the flow velocities were based on cross-section M#14. To estimate the maximum flow velocities near the protection site basically the same procedures as used for Bhairab Bazar were applied here.

Discharge extremes

The discharge at Maniknagar equals the discharge at Bhairab Bazar increased with flow from the Old Brahmaputra. Analysis shows that the Old Brahmaputra maximum coincides approximately with the maximum at the Bhairab Bazar, hence near maximum Old Brahmaputra discharges should be combined with the Upper Meghna extremes. A summary of the annual maximum discharges of the Old Brahmaputra at Bhairab Bazar Railway Bridge is presented in Table A.7.4. The average annual maximum is about 600 m^3/s.

Table A.7.4 ANNUAL MAXIMUM DISCHARGE OF OLD BRAHMAPUTRA AT BHAIRAB BAZAR RLY BRIDGE

Year	Qmax (m^3/s)	Year	Qmax (m^3/s)
1969	594	1980	569
1970	801	1981	367
1971	-	1982	595
1972	708	1983	408
1973	691	1984	629
1974	1190	1985	395
1975	788	1986	154
1976	-	1987	412
1977	937	1988	593
1978	496	1989	-
1979	399		

The extreme discharges at Maniknagar as applied in this Annex has been derived from the General Model run for the period 1965-1989 and adjusted to get results comparable with the 1959-1990 series of Bhairab Bazar. The results are shown in Table A.7.5

Table A.7.5 DISCHARGES EXTREMES IN UPPER MEGHNA AT MANIKNAGAR

Return Period years	Hmax m+PWD	Gumbel m^3/s	LP-III m^3/s
50	7.10	19,700	20,900
100	7.27	20,900	22,600

The discharge extremes at Maniknagar for 50 and 100 year return periods are seen to be 400 to 600 m^3/s higher than the values for Bhairab Bazar. This is about equal to the mean value of the annual extremes at the Railway bridge, which fits into the above observation on the occurrence of the maximas at the two sites.

Maximum velocities according to Procedure 1

From conveyance capacity computations it appeared that independent of the roughness ratio between river and flood plain the left branch takes about 52% of the total discharge under the assumed boundary conditions. The resulting design discharges according to Gumbel for the left branch are therefore respectively 10,250 and 10,850 m^3/s for the 50 and 100 years return period.

Subsequently, the velocities were computed for cross-section M#14 near the protection site by assuming that the flood levels match with the discharges at corresponding return periods, The velocities for various river-flood plain roughness ratios are presented in Table A.7.6.

Table A.7.6 MAXIMUM FLOW VELOCITIES IN LEFT MEGHNA BRANCH AT MANIKNAGAR

Return Period years	Qmax (m^3/s)	Hmax m+PWD	vmax1 m/s	vmax2 m/s	vmax3 m/s
50	10,250	7.10	0.73	0.96	1.26
100	13,850	7.27	0.95	0.99	1.32

Note: vmax1 = maximum velocity in cross-section for equal K_M of floodplain and river
vmax2 = -do-, but K_M-floodplain = 0.5 * K_M-river
vmax3 = -do-, but K_M-floodplain = 0.01* K_M-river

Given the local conditions on roughness vmax2 is most realistic with respect to roughness. Hence this procedure results in velocity estimates of 1 m/s.

Maximum velocities according to procedure 2

In Section A.7.3 design roughness and gradient values for the Upper Meghna between Bhairab Bazar and Meghna Ferryghat were determined at K_M = 40 and S = $2.5*10^{-5}$ for a water level at Maniknagar 0.60 m below the 100 year return period value of 7.27. This results into maximum velocities in the left branch at maximum depth 14.0 m of 1.16 m/s. It is noted that due to helicoidal flow the velocities will locally be slightly higher than presented and an increase of 15 percent is assumed leading to a maximum velocity of 1.35 m/s.

It is realized that both procedures are rather approximate but in absence of actual measurements at Maniknagar the latter velocity is to be considered in the design.

A.7.4 Meghna Road & Highway Bridge

The Meghna Road & Highway bridge is located at km 88. The protection site is at an outer eroding bend in the right branch of the Meghna river. The procedures applied for Bhairab Bazar have been used for this site also.

Maximum velocities according to Procedure 1

The discharge extremes have been determined from the General Model and is equal to the discharge extremes at Maniknagar, see Section A.7.3.

Cross-section M#7 and M#7-1 have been used to calculate the flow distribution between the branches and M#7 to estimate the flow velocities in the right branch of the Meghna for discharges of 50 and 100 year with water levels of the same return periods.
The results are presented in Table A.7.7. The values appear to be unrealistically low, even with a non-participating flood plain.

Table A.7.7 MAXIMUM FLOW VELOCITIES IN RIGHT MEGHNA BRANCH AT MEGHNA ROAD & RAILWAY BRIDGE

Return Period years	Qmax (m^3/s)	Hmax m+PWD	vmax1 m/s	vmax2 m/s	vmax3 m/s
50	19,700	6.42	0.90	1.07	1.31
100	20,900	6.60	0.92	1.10	1.36

Note: vmax1 = maximum velocity in cross-section for equal K_M of floodplain and river
vmax2 = -do-, but K_M-floodplain = 0.5 * K_M-river
vmax3 = -do-, but K_M-floodplain = 0.01* K_M-river

Maximum velocities according to Procedure 2

In Section A.7.3 design roughness and gradient values for the Upper Meghna between Bhairab Bazar and Meghna Ferryghat were determined at K_M = 40 and S = $2.5*10^{-5}$ for a water level at Meghna Ferryghat of 5.20 m+PWD. This results into maximum velocities in the right branch at maximum depth 22.25 m of 1.58 m/s. However, detailed bathymetric surveys from recent date indicate depth of over 35 m near the ferry landing. This results in maximum flow velocities of 2.15 m/s. The above indicates that large velocity variations can be expected near the bridge. Hence clearly not a design velocity should be given here but the above hydraulic parameters should be used in combination with the bottom topography.

Comparison with actual flow measurements

In 1984 flow measurements were carried out at the site (see (5)). Then, at a discharge of 9,020 m^3/s, the average velocity amounted 1.10 m/s and the maximum velocity was 1.54 m/s.
This value is about equal to the velocity resulting from M#7 profile but referring to a discharge half the one where the computation refers to.

A.7.5 Munshiganj

At Munshiganj erosion takes place at the right bank of the Dhaleswari River upstream and downstream of the ferry landing.
The protection site is enclosed by the gauging stations Rekabi Bazar and Kalagachia.

On the Dhaleswari discharges are being measured far upstream of the protection site in the branches. During high flow however these data will give only a partly impression of the total discharge because large parts of the flow will travel overland, not observed at the sites. Therefore the estimates on velocities as given in this sub-chapter have been based on the results of the simulation with the General Model. The model was run for daily averaged boundary conditions of the period 1965-1989 by the Surface Water Modelling Centre on request of FAP 25.

Most extreme in the simulated period were the conditions of 1988. At Munshiganj maximum hydraulic gradients occur at maximum water level. This gradient near the Dhaleswari mouth is well described by the following second order polynomial:

$$S = (6.0 - 2.79*H_{Kalagachia} + 0.386*H^2_{Kalagachia})*10^{-5} \quad (7.5)$$

For the flood levels at Kalagachia with a return period of 50 and 100 years, equal to respectively 6.32 and 6.51 m+PWD, this gives gradients of 3.8 to 4.2*10^{-5}. The resulting velocities, using a hydraulic roughness coefficient K_M of 40 equal to the value used for the Upper Meghna and which corresponds with the value used in the General Model, in the cross-sections 21 and 22 of 1989 with depths from nearly 12 to 27 m are presented in Table A.7.8.

TABLE A.7.8 EXTREME FLOW VELOCITIES IN DHALESWARI AT MUNSHIGANJ

Return Period years	Hmax m + PWD	Slope *10-5	vmax-S.21 m/s	vmax-S.22 m/s
50	6.32	3.8	1.26	2.21
100	6.51	4.2	1.34	2.33

The presented values show very large differences as a consequence of a the differences in maximum depth. Hence the used hydraulic parameters rather than the velocities are the design criteria and in absence of flow measurements these parameters are proposed to be applied to a particular cross-section.

It is emphasized here that one cannot blindly rely on the values produced by the model for a number of reasons:

1. The General Model doesnot include every flow detail; in particular near the junction Dhaleswari, Arjam and Lakhya rivers the model produces only a very schematic representation of reality;
2. No measurements are available on the diverted flows from the Jamuna River; by means of a water balance between Bahadurabad and Baruria one will not get an accurate picture of the diverted flow as the amount probably diverted is of the order of measuring inaccuracy at the two sites.

In summary field measurements will be required to get a final answer as to the design flow velocities at Munshiganj.

A.7.6 Eklashpur, Chandpur and Haimchar

The flow conditions at Eklashpur, Chandpur and Haimchar are determined by combined Meghna and Padma river flows and the tide and will result from the 2-dimensional model.

The required boundary conditions for the model studies can be retrieved from the General Model, run for the period 1965-1989. The runs indicate that for ordinary years extreme hydraulic gradients correspond with maximum discharge. However, for the two most extreme years in the series, 1974 and 1988 maximum gradients occurred discharges and water levels slightly below maximum conditions. The flood of 1988 produced the highest gradient of record; for Chandpur this occurred at a water level of about 1.0 m below maximum corresponding with a Lower Meghna discharge of 100,000 to 110,000 m^3/s, see Figures A.7.2 and A.7.3.

Discharge extremes

The return periods of the 1988 flood on the Padma (108,700 m^3/s), Upper Meghna (50,900 m^3/s) and Lower Meghna (155,300 m^3/s) are estimated from the extremes presented in Table 2.4 as computed by the General Model. The results for different frequency distributions are shown in Table A.7.9.

Table A.7.9 MAXIMUM DISCHARGE ON MEGHNA AND PADMA RIVERS FOR VARIOUS RETURN PERIODS

River	Return Period(yr)	LN-III	P-III	LP-III	Gumbel
U.Meghna	10	39,400	39,800	39,600	39,600
	25	43,400	44,000	44,100	44,100
	50	46,400	47,100	47,400	47,400
	100	49,300	50,000	50,800	50,700
Padma	10	88,700	89,600	89,100	89,200
	25	97,200	98,000	98,000	97,100
	50	103,800	104,100	104,900	102,900
	100	110,600	110,100	112,100	108,700
L.Meghna	10	123,300	124,900	124,000	124,600
	25	136,600	137,900	137,700	135,900
	50	147,400	147,500	148,600	144,300
	100	158,800	157,100	160,100	152,700

From Table A.7.9 it is observed that on the average the return period of the 1988 flood on each of the rivers was about 100 years.

Gradient extremes

The maximum gradient on the Lower Meghna in 1988 as derived from the General Model results amounted $2.48*10^{-5}$. To estimate its return period a similar analysis as for the discharges has been carried out for the annual maximum gradients on the Lower Meghna. Pearson-III and 3-parameter Lognormal distribution appeared to fit best. The results of the analysis are presented in Table A.7.10.

Table A.7.10 MAXIMUM WATER LEVEL GRADIENTS ON LOWER MEGHNA RIVER FOR VARIOUS RETURN PERIODS

River	Return Period(yr)	LN-III	P-III
L.Meghna	10	2.32	2.33
	25	2.39	2.40
	50	2.43	2.45
	100	2.47	2.50

Note: gradients * 10^{-5}

From the table it follows that the gradient of 1988 had a return period of about 100 years. Consequently the 1988 flood can be used as design condition.

Design conditions

The velocities for various discharges, corresponding water levels and water level gradients as derived from the General Model results are elaborated in Table A.7.11 for Chandpur. A Manning value of 60 is used in the computations.

Table A.7.11 DEPTH-AVERAGE FLOW VELOCITIES NEAR CHANDPUR FOR VARIOUS FLOW CONDITIONS

Q-Meghna (m^3/s)	H-Meghna (m+PWD)	Gradient * 10-5	Velocities (m/s) at bottom level (m+PWD) 0(m)	-5(m)	-10(m)	-20(m)	-30(m)
90,000	3.89	2.38	0.72	1.26	1.70	2.43	3.07
100,000	4.12	2.48	0.77	1.30	1.74	2.49	3.14
110,000	4.33	2.42	0.78	1.31	1.74	2.48	3.12
120,000	4.52	2.29	0.78	1.29	1.71	2.42	3.04
130,000	4.68	2.21	0.79	1.28	1.69	2.39	3.00
140,000	4.82	2.16	0.80	1.28	1.68	2.37	2.97
150,000	4.94	2.10	0.80	1.27	1.67	2.35	2.94

From Table A.7.11 it is observed that maximum flow velocities occur for Lower Meghna discharges in the range of 100,000 to 110,000 m^3/s, with a water level gradient of $2.48*10^{-5}$. However, the differences in velocities in a wider discharge range are rather small; for flows in the range of 100,000 to 130,000 m^3/s these differences are seen to be less than 5 percent.

It should be realized that the table is based on the rather approximate schematization of the Lower Meghna in the General Model; hence maximum velocities will likely deviate from the presented ones. The presentation of the table is only meant to identify the most critical boundary conditions. Accurate estimation of local extreme velocities can only be obtained from the 2-dimensional mathematical model and the scale model.

The most severe boundary conditions for each of the protection sites depend further on the flow distribution at the Padma-Meghna confluence:

1. the percentage of flow which is contributed by the Upper Meghna river, and

2. the distribution of the Padma flow over the northern and southern channel; due to the migration of a large char at the Padma-Meghna confluence the conveying capacity of the two channels vary; the northern channel pushes the water towards eastward and the southern channel south-eastward.

For Eklashpur the most severe boundary condition is created when a maximum amount of flow is conveyed through the northern channel in the Padma. This puts the river bank at Eklashpur under direct attack the Padma, which is not suppressed by the flow from the Upper Meghna provided that the latter is relatively low. A summary of maximum flows from the Padma for various Upper Meghna discharges is shown in Table A.7.12. In the range of flows of 100,000 to 110,000 m^3/s on the Lower Meghna from the table it is seen that the lowest realistic Q_{Meghna}/Q_{Padma} ratio is 0.26, i.e. Q_{Padma} = 74,000 to 81,400 m^3/s and Q_{Meghna} = 26,000 to 28,600 m^3/s.

Reversely, the most severe conditions for Chandpur and Haimchar occur if the Padma flow is mainly conveyed via the southern channel, with the same flow distribution between the Padma and Upper Meghna as above. For Chandpur also the effect of the Dakatia river has to be taken into account, to be estimated by mathematical model computations. High flow velocities are expected in the Dakatia mouth when the Meghna approaches ebb-tide. Discharge data of the Dakatia river are not available.

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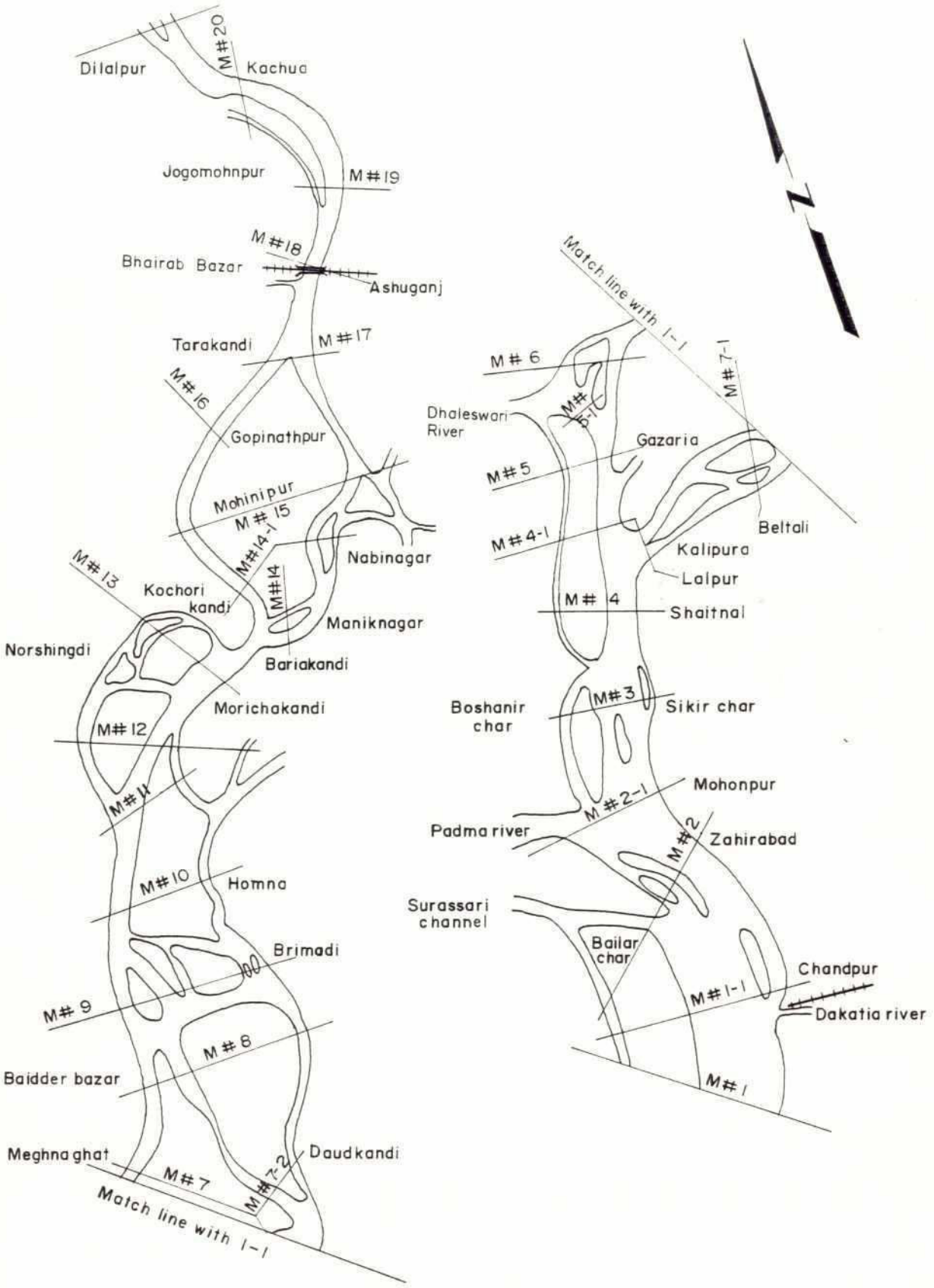
Tidal effect

The above results apply for daily averaged conditions, with the semidiurnal variation eliminated. However, preliminary runs with the General Model with a tidal boundary indicated that during high flows the tide hardly affects the velocity at Eklashpur and Chandpur; some effect was seen for Haimchar. However, the tidal amplitude as produced by the model appeared to less than reality. Hence, after a proper calibration of the model with tidal boundaries, additional runs with the General Model are required to get a good picture of the effect of the tide on the velocities.

Table A.7.12 MAXIMUM PADMA DISCHARGE FOR VARIOUS UPPER MEGHNA FLOWS

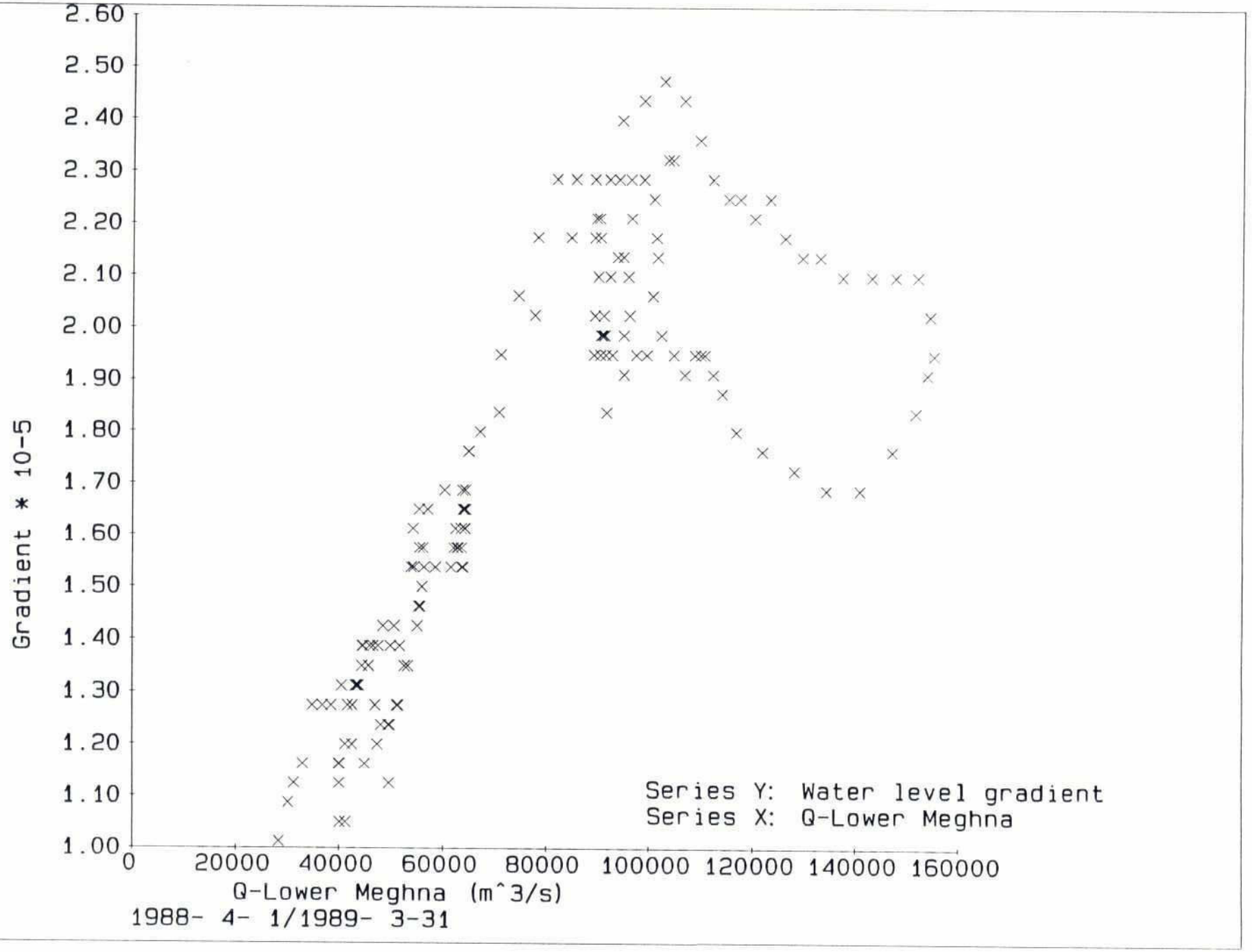
year	mm	dd	Q Padma	Q Meghna	Threshold	Ratio
1976	9	25	74597.	13352.	13500.	17.9
1978	9	17	75965.	15028.	15500.	19.8
1978	9	18	76177.	15978.	16000.	21.0
1980	7	25	76208.	20100.	20500.	26.4
1969	8	28	80476.	21254.	21500.	26.4
1969	8	29	80503.	21678.	22000.	26.9
1987	9	22	87596.	22948.	23000.	26.2
1980	8	19	91625.	25809.	26000.	28.2
1980	8	20	94308.	26078.	26500.	27.7
1980	8	21	95399.	26889.	27000.	28.2
1980	8	22	95779.	27816.	28000.	29.0
1988	8	27	99254.	28968.	29000.	29.2
1988	8	28	104772.	30080.	30500.	28.7
1988	8	29	108697.	32562.	33000.	30.0
1988	8	30	111810.	35729.	36000.	32.0
1988	8	31	114005.	39246.	39500.	34.4
1988	9	1	114020.	43026.	43500.	37.7

Note: 1. Ratio = $(Q_{Meghna}/Q_{Padma})*100\%$
Treshold = threshold on Q_{Meghna} not being exceeded
2. All discharges are in m^3/s



LOCATION OF AVAILABLE CROSS- SECTIONS

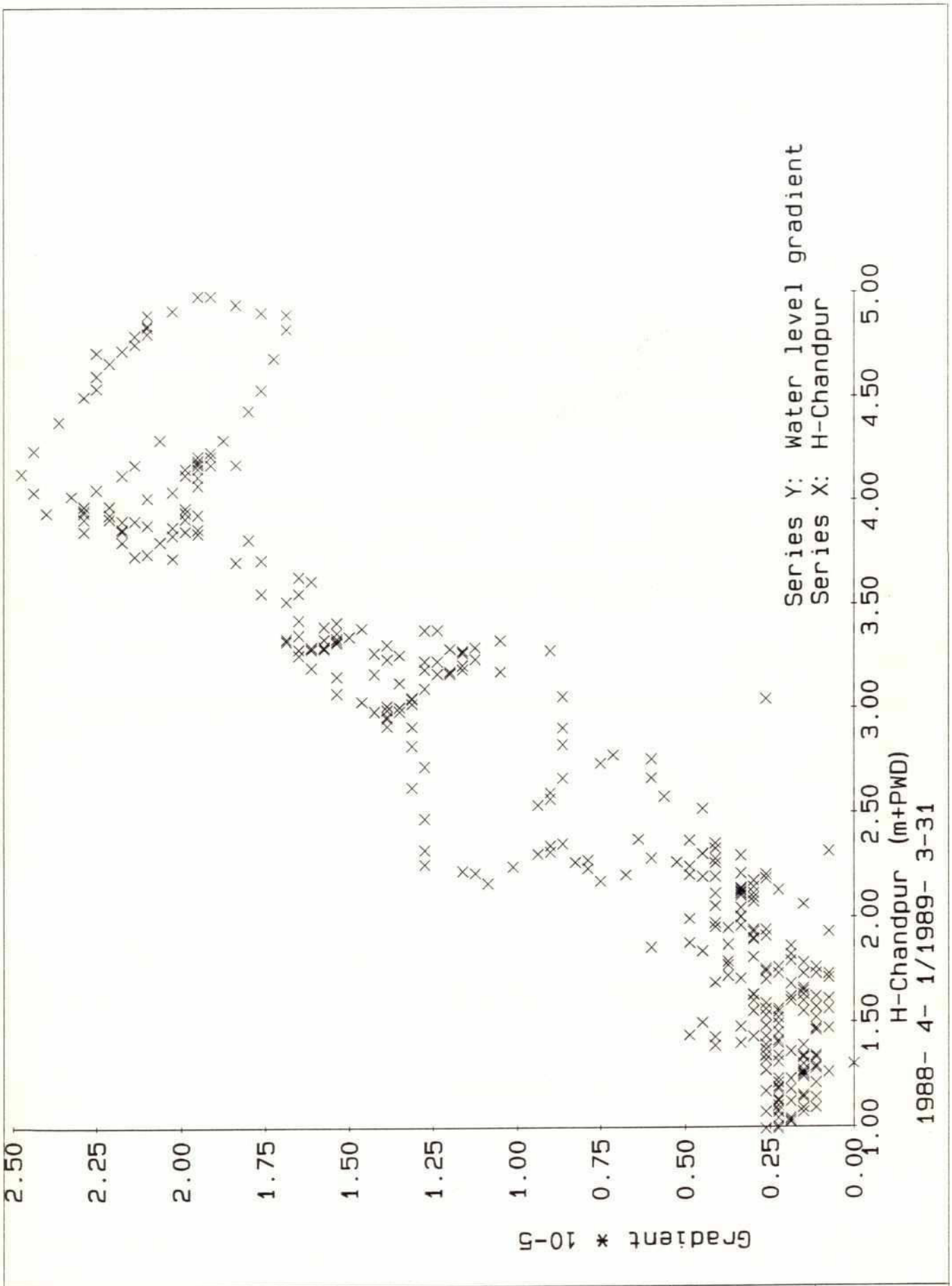
FIGURE NO. A.7.1



Discharge - gradient relation
Lower Meghna
Period 1988-1989

HASKONING - DELFT HYDRAULICS - BETS

FIG. A.7.2



Water level - gradient relation
Lower Meghna at Chandpur
Period 1988 - 1989

HASKONING - DELFT HYDRAULICS - BETS

FIG. A.7.3

A.8. WIND AND WAVES

A.8.1 General

In Bangladesh two wind systems generate extreme high wind velocities leading to the design windspeeds for the determination of design waves:

- 'Nor-Wester' thunderstorm squalls, and

- cyclones

High wind speeds in Bangladesh are most commonly associated with the 'Nor-Wester' thunderstorm squalls, generally occurring within the season April - June, though also possible between March and September. The classic pattern is a rapid rise in speed accompanied by a swing in direction, followed by a progressive decay over about half an hour. This is characterized by the event marked (1) on Figure A.8.1, which is a reproduction of the anemogramme of station Dhaka for 25/3/1985. There is, however, a range of variation; the higher speeds are probably associated with shorter durations (see [2], Figure A.8.1) but more complex events (see [3], Figure A.8.1), particularly at the lower speed levels do also occur.

However, very high winds may also occur as a result of the incursion inland of tropical cyclones from the Bay of Bengal, although these are rare events. Cyclonic storms occur in the pre- and post-monsoon period (i.e. April-May and October-November), with a general direction of the tracks South-East to South. The average number of cyclones affecting any part of Bangladesh is about three in any ten-year period, and each such cyclone will only cause very high winds over a small fraction of this area.

A.8.2 Data

Monthly extreme wind speed and direction have been collected for the following stations and years:

Station	Period
Brahmanbaria	1948 - 1971
Comilla	1948 - 1991
Chandpur	1966 - 1991
Noakhali	1952 - 1991
Bhola	1966 - 1991
Madaripur	1977 - 1991
Dhaka	1951 - 1991

Furthermore a list of occurrence of cyclonic storms, their wind speeds and tracks was collected.

From the Meteorological Department it was learned that:

1. Published wind extremes are the maximum 3 minute average windspeeds based on measurements taken every 8 hours during the day; mentioned per month in the data summaries.

2. 100 knots (Nautical miles/hour (= 185.2 km/h)) is the maximum wind speed that can be measured by an anemometer. For cyclones this is not always sufficient and the values above 100 knots are estimated from pressure differences. These values, however, do not appear in the standard records for the following reasons:

   - value is above the anemometer maximum,

   - extreme occurs in between the measurements.

A.8.3 Statistical analysis

The monthly wind extremes have been analysed by computing the number of occurrences of wind direction associated with a particular windspeed class. The extremes above 40 knots did not show any clear preference direction, hence no further selection was made on the wind direction.

Next, annual extremes were created ignoring the type of the storm. These data are presented in Appendix A/7. The 3-parameter Lognormal and the Gumbel type distributions were used to fit these annual extremes. In case of the Gumbel distribution only acceptable fits were obtained when the lowest extremes were censored out. The results are presented in Table A.8.1.

Table A.8.1 DESIGN WIND SPEEDS FOR VARIOUS STATIONS AROUND THE PROJECT AREA

Station	Return Period years	Wind speed (knots) Lognormal	Gumbel	design speed (m/s) 3 min	15 min
BBaria	50	89.3	81.8	44	22
	100	107.4	93.1	52	26
Bhola	50	105.8	102.5	54	27
	100	126.0	117.4	63	31
Chandpur	50	70.3	69.4	36	18
	100	79.4	77.7	40	20
Comilla	50	88.8	90.4	46	23
	100	103.9	103.6	53	27
Dhaka	50	87.8	91.4	46	23
	100	92.1	98.5	49	25
Majdee	50	100.3	101.8	52	26
	100	123.7	119.0	62	31

No preference was given to one of the distributions and the wind speeds presented in the one but last column in Table A.8.1 were computed as the average of the two.

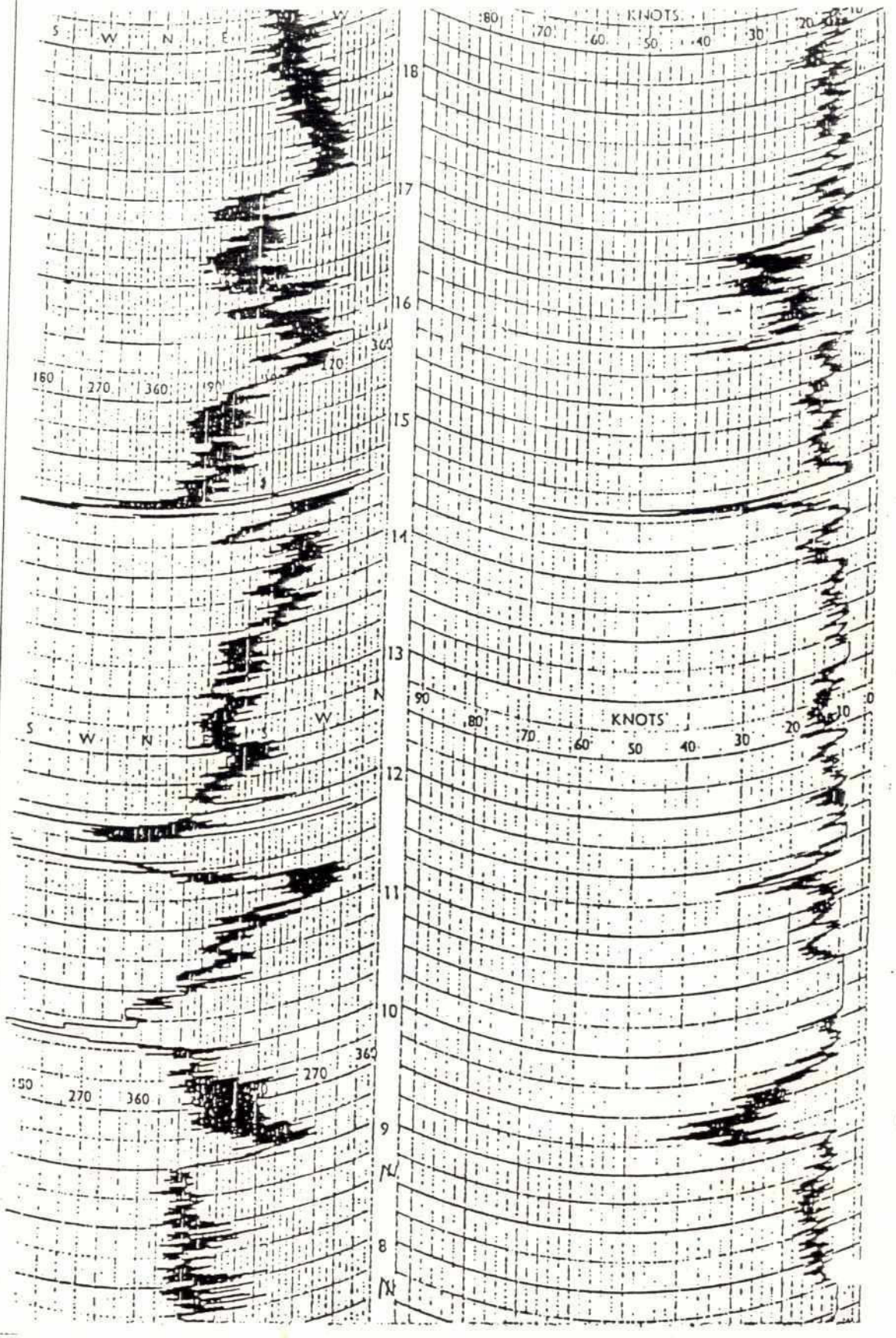
A period of fifteen minutes has been chosen as being the time required for the full growth of wind waves for design purposes. A reduction of 50 percent was applied to the three minute to account for the transformation of gust speeds into fifteen minute average wind speeds, shown in the last column of the table.

From Table A.8.1 it is observed that the extremes for Chandpur are the lowest of the selected stations. This location is apparently too far north to be under severe cyclonic influence and too far south to be affected strongly by the Nor-wester.

The design winds for the protection sites have been derived from Table A.8.1 by interpolation from the nearby stations. Hence the following design winds apply, see Table A.8.2.

Table A.8.2 DESIGN WIND SPEEDS AT THE PROTECTION SITES

Site	Design wind speed (m/s)	
	Return P=50 years	Return P=100 years
Bhairab Bazar	22	26
Maniknagar	22	26
Meghna R&H Bridge	23	25
Munshiganj	23	25
Eklashpur	21	23
Chandpur	18	20
Haimchar	21	23



EXTRACT FROM ANEMOGRAM FOR MARCH 25TH, 1985

FIG. A.8.1

A.9 SUMMARY OF DESIGN CONDITIONS

The design conditions as determined in the Sections A.5 to A.8 are summarized in this Section.

Bhairab Bazar, chainage: 7.5 - 9.0 km

(a) Flood level

- 50 years return period: 7.66 - 7.62 m+PWD (u/s resp. d/s)
- 100 years return period: 7.83 - 7.79 m+PWD (u/s resp. d/s)

Median water level = 2.87 m+PWD

Period of non-exceedance:

- 10 percent wet year: 02/11 - 12/06
- 50 percent wet year: 15/11 - 22/05
- 90 percent wet year: 26/11 - 02/05

(b) Flow velocities

Design velocities are to be derived from:

- water level: 7.2 m+PWD
- hydraulic gradient: $2.0*10^{-5}$
- Manning coefficient K_M: 40

Velocity at maximum depth of 34.60 m = 1.90 m/s

(c) Wind speed

Design waves to be derived from following wind speeds:

- 50 years return period: 22 m/s
- 100 years return period: 26 m/s

Maniknagar, chainage: 31.0 - 37.0 km

(a) Flood level

- 50 years return period: 7.22 - 7.10 m+PWD (u/s resp. d/s)
- 100 years return period: 7.39 - 7.27 m+PWD (u/s resp. d/s)

Median water level = 2.78 m+PWD

Period of non-exceedance:

- 10 percent wet year: 02/11 - 10/06
- 50 percent wet year: 20/11 - 15/05
- 90 percent wet year: 02/12 - 01/05

(b) Flow velocities

Design velocities are to be derived from:

- water level: 6.67 m+PWD
- hydraulic gradient: $2.5*10^{-5}$
- Manning coefficient K_M: 40
- helicoidal correction: 15 percent increase

Velocity at maximum depth = 1.35 m/s

(c) Wind speed

Design waves to be derived from following wind speeds:

- 50 years return period: 22 m/s
- 100 years return period: 26 m/s

Meghna R&H Bridge, chainage: 88.0 km

(a) Flood level

- 50 years return period: 6.42 m+PWD
- 100 years return period: 6.59 m+PWD

Median water level = 2.55 m+PWD

Period of non-exceedance:

- 10 percent wet year: 30/10 - 07/06
- 50 percent wet year: 19/11 - 11/05
- 90 percent wet year: 02/12 - 01/05

Flow velocities

Design velocities are to be derived from:

- water level: 5.20 m+PWD
- hydraulic gradient: $2.5*10^{-5}$
- Manning coefficient K_M: 40

Velocity at depth of 35 m = 2.15 m/s

Munshiganj, chainage: 8.0 - 4.0 km on Dhaleswari

Flood level

- 50 years return period: 6.41 - 6.32 m+PWD (u/s resp. d/s)
- 100 years return period: 6.60 - 6.51 m+PWD (u/s resp. d/s)

Median water level = 2.50 m+PWD

Period of non-exceedance:

- 10 percent wet year: 30/10 - 07/06
- 50 percent wet year: 19/11 - 11/05
- 90 percent wet year: 02/12 - 01/05

Flow velocities

Design velocities are to be derived from:

- for 50 years return period:
- water level: 6.32 m+PWD
- hydraulic gradient: $3.8*10^{-5}$
- Manning coefficient K_M: 40

Velocity at depth of 27 m = 2.33 m/s

- for 100 years return period:
- water level: 6.51 m+PWD
- hydraulic gradient: $4.2*10^{-5}$
- Manning coefficient K_M: 40

Velocity at depth of 27 m = 2.33 m/s

Wind speed

Design waves to be derived from following wind speeds:

- 50 years return period: 23 m/s
- 100 years return period: 25 m/s

<u>Eklashpur, chainage: 114.0 - 123.0 km</u>

Flood level

- 50 years return period: 5.80 - 5.58 m+PWD (u/s resp. d/s)
- 100 years return period: 5.93 - 5.69 m+PWD (u/s resp. d/s)

Median water level = 2.35 m+PWD

Period of non-exceedance:

- 10 percent wet year: 30/10 - 08/06
- 50 percent wet year: 16/11 - 11/05
- 90 percent wet year: 02/12 - 01/05

Flow velocities

Design velocities can best be derived from mathematical and scale model tests using following boundary conditions:

- $Q_{Lower\ Meghna}$: 100,000 m^3/s
- Q_{Meghna}: 26,000 m^3/s
- Q_{Padma}: 74,000 m^3/s, concentrated mainly in the northern channel

- $H_{Chandpur}$: 4.12 m+PWD
- hydraulic gradient: $2.48*10^{-5}$

Note that velocities for $Q_{Lower\ Meghna}$ up to 130,000 m^3/s will hardly deviate from the velocities for the above conditions.

Wind speed

Design waves to be derived from following wind speeds:

- 50 years return period: 21 m/s
- 100 years return period: 23 m/s

Chandpur, chainage: 134.0 - 137.0 km

Flood level

- 50 years return period: 5.31 - 5.25 m+PWD (u/s resp. d/s)
- 100 years return period: 5.40 - 5.32 m+PWD (u/s resp. d/s)

Median water level = 2.19 m+PWD

Period of non-exceedance:

- 10 percent wet year: 28/10 - 09/06
- 50 percent wet year: 16/11 - 11/05
- 90 percent wet year: 27/11 - 29/04

Flow velocities

Design velocities can best be derived from mathematical and scale model tests using following boundary conditions:

- $Q_{Lower\ Meghna}$: 100,000 m^3/s
- Q_{Meghna}: 26,000 m^3/s
- Q_{Padma}: 74,000 m^3/s, concentrated mainly in the southern channel
- $H_{Chandpur}$: 4.12 m+PWD
- hydraulic gradient: $2.48*10^{-5}$

Note that velocities for $Q_{Lower\ Meghna}$ up to 130,000 m^3/s will hardly deviate from the velocities for the above conditions.

Wind speed

Design waves to be derived from following wind speeds:

- 50 years return period: 18 m/s
- 100 years return period: 20 m/s

Haimchar, chainage: 147.0 - 154.5 km

Flood level

- 50 years return period: 5.02 - 4.86 m+PWD (u/s resp. d/s)
- 100 years return period: 5.09 - 4.91 m+PWD (u/s resp. d/s)

Median water level = 1.93 m+PWD

Period of non-exceedance:

- 10 percent wet year: 28/10 - 09/06
- 50 percent wet year: 16/11 - 11/05
- 90 percent wet year: 27/11 - 29/04

Flow velocities

Design velocities can best be derived from mathematical and scale model tests using following boundary conditions:

- $Q_{Lower\ Meghna}$:	100,000 m^3/s
- Q_{Meghna}:	26,000 m^3/s
- Q_{Padma}:	74,000 m^3/s, concentrated mainly in the southern channel
- $H_{Chandpur}$:	4.12 m+PWD
- hydraulic gradient:	$2.48*10^{-5}$

Note that velocities for $Q_{Lower\ Meghna}$ up to 130,000 m^3/s will hardly deviate from the velocities for the above conditions.

Wind speed

Design waves to be derived from following wind speeds:
- 50 years return period: 21 m/s
- 100 years return period: 23 m/s

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APPENDIX A/1

OBSERVED ANNUAL EXTREME WATER LEVELS

Table A/1.1 ACCEPTED AVAILABLE ANNUAL MAXIMUM WATER LEVELS
UPPER MEGHNA, PERIOD 1959-1990

Year	Dilalpur 74	Bhairab Bazar 273	B.B.Rly Bridge 230.1	Nabinagar 298	Narsingdi 274	Badyar Bazar 275
1959	6.83	6.36	-.-	6.05	-.-	-.-
1960	7.07	6.61	-.-	6.31	5.65	5.46
1961	6.18	5.61	-.-	-.-	5.15	4.91
1962	7.50	6.69	-.-	6.46	-.-	-.-
1963	7.04	6.37	-.-	6.13	-.-	-.-
1964	-.-	7.13	7.13	-.-	-.-	-.-
1965	-.-	6.49	6.49	-.-	-.-	-.-
1966	-.-	6.91	6.89	-.-	-.-	-.-
1967	-.-	6.25	6.25	-.-	-.-	-.-
1968	-.-	6.77	6.81	6.62	6.12	5.65
1969	7.21	6.71	6.71	6.43	6.00	5.49
1970	7.60	7.09	7.09	6.82	6.32	5.82
1971	-.-	-.-	-.-	6.34	6.11	5.64
1972	-.-	6.09	6.08	5.84	5.44	5.01
1973	7.00	6.48	6.45	6.18	5.82	5.43
1974	8.17	7.65	7.62	7.32	6.87	6.16
1975	7.00	6.48	6.46	-.-	5.75	5.30
1976	7.48	7.02	6.95	-.-	6.05	5.26
1977	6.98	6.57	6.50	-.-	5.87	5.41
1978	6.40	5.99	6.02	5.70	5.37	5.14
1979	6.83	6.33	6.26	6.02	5.62	5.27
1980	6.81	6.41	6.39	-.-	5.87	5.64
1981	6.95	6.46	6.49	6.24	5.70	5.43
1982	6.92	6.43	6.48	-.-	5.62	-.-
1983	7.30	6.79	6.78	6.49	6.04	-.-
1984	7.44	6.89	6.88	6.62	6.21	5.77
1985	6.88	6.38	6.36	6.10	5.67	-.-
1986	-.-	5.67	5.62	-.-	5.15	-.-
1987	7.38	6.91	6.90	-.-	6.27	-.-
1988	8.05	7.66	7.66	7.34	6.90	-.-
1989	6.91	6.41	6.41	-.-	-.-	-.-
1990	6.48	6.04	6.03	5.79	5.41	-.

Note: all levels in m + PWD

Table A/1.2 ACCEPTED AVAILABLE ANNUAL MAXIMUM WATER LEVELS
UPPER MEGHNA, PERIOD 1959-1990

Year	Meghna Ferryghat 275.5	Kalagachia 71	Rekabi Bazar 71A	Daudkandi 115	Satnal 276
1959	-.-	5.00	-.-	5.08	4.88
1960	-.-	5.18	-.-	5.30	4.97
1961	-.-	4.89	-.-	4.94	4.94
1962	-.-	-.-	-.-	-.-	-.-
1963	-.-	-.-	-.-	5.38	-.-
1964	-.-	-.-	-.-	5.93	-.-
1965	-.-	-.-	-.-	-.-	-.-
1966	-.-	-.-	-.-	-.-	-.-
1967	-.-	-.-	-.-	-.-	-.-
1968	-.-	5.62	5.75	5.25	-.-
1969	5.63	5.39	5.47	5.00	5.21
1970	5.87	5.73	5.85	5.60	5.46
1971	5.76	5.59	-.-	5.65	5.70
1972	5.11	4.95	5.00	5.07	4.82
1973	5.44	5.08	5.46	5.46	5.24
1974	6.19	5.99	6.07	6.05	5.79
1975	5.29	5.17	5.18	5.27	5.05
1976	5.32	5.01	-.-	5.14	4.83
1977	5.59	5.34	5.39	5.39	5.20
1978	5.12	-.-	-.-	5.30	4.94
1979	5.24	-.-	-.-	5.12	5.15
1980	5.82	5.64	5.61	5.75	5.49
1981	5.40	-.-	-.-	5.55	5.24
1982	5.19	-.-	-.-	5.20	4.82
1983	5.56	5.44	-.-	5.53	5.26
1984	5.73	5.91	-.-	5.52	5.62
1985	5.44	5.06	-.-	4.95	4.99
1986	5.03	-.-	-.-	5.44	4.71
1987	5.99	5.92	-.-	6.06	5.61
1988	6.55	-.-	6.43	6.34	6.04
1989	5.22	-.-	-.-	-.-	4.91
1990	5.29	5.01	5.14	5.10	4.98

Note: all levels in m+ PWD

Table A/1.3 ACCEPTED AVAILABLE ANNUAL MAXIMUM WATER LEVELS
PADMA AND LOWER MEGHNA, PERIOD 1948-1990

Year	Chandpur	Tarpasa	Nilkamal	Off-take in Meghna
	277	94	277.3	288
1948	4.83	5.85	-.-	-.-
1949	4.86	5.94	-.-	-.-
1950	4.83	5.88	-.-	-.-
1951	4.58	5.94	-.-	-.-
1952	4.80	5.97	-.-	-.-
1953	4.92	6.04	-.-	-.-
1954	5.29	6.43	-.-	-.-
1955	5.10	6.04	-.-	-.-
1956	4.83	5.97	-.-	-.-
1957	4.65	6.04	-.-	-.-
1958	4.98	6.25	-.-	-.-
1959	4.71	6.25	-.-	-.-
1960	4.71	5.88	-.-	-.-
1961	-.-	5.58	-.-	-.-
1962	-.-	-.-	-.-	-.-
1963	-.-	5.82	-.-	-.-
1964	-.-	5.97	-.-	-.-
1965	-.-	-.-	-.-	-.-
1966	-.-	-.-	-.-	-.-
1967	-.-	-.-	-.-	-.-
1968	4.83	5.97	-.-	3.17
1969	4.85	-.-	-.-	3.32
1970	4.63	6.13	-.-	3.29
1971	5.07	6.27	-.-	3.52
1972	4.59	5.46	-.-	3.24
1973	4.97	5.91	-.-	3.32
1974	5.24	6.23	-.-	3.58
1975	4.74	5.50	-.-	3.41
1976	4.45	-.-	4.16	3.17
1977	4.82	-.-	4.74	3.26
1978	4.62	-.-	4.42	3.20
1979	4.78	-.-	-.-	3.44
1980	4.88	5.87	-.-	-.-
1981	4.57	-.-	4.47	-.-
1982	4.57	-.-	4.27	-.-
1983	4.68	5.59	4.44	-.-
1984	4.96	5.77	4.61	-.-
1985	4.72	5.49	4.55	-.-
1986	4.41	5.42	4.49	-.-
1987	4.77	6.32	4.57	-.-
1988	5.16	6.72	4.76	-.-
1989	4.66	5.38	4.50	-.-
1990	4.96	-.-	4.85	-.-

Note: all levels are in m+ PWD

APPENDIX A/2

REGRESSION EQUATIONS FOR COMPLETION OF ANNUAL MAXIMUM WATER LEVELS

Regression Equations for completion of Annual maximum Water Levels

Following simple and multiple linear and parabolic regression equations (1) to (17) have been applied to fill in the missing data:

Bhairab Bazar

$H273 = 0.051 + 0.842*H298 + 0.175*H74$ See = 0.027 (1)

$H273 = 3.130 + 0.112*H298 + 0.0688*H298^2$ See = 0.042 (2)

Nabinagar

$H298 = -0.247 + 0.797*H273 + 0.183*H74$ See = 0.027 (3)

$H298 = -3.055 + 1.834*H273 - 0.0623*H273^2$ See = 0.042 (4)

Narsingdi

$H274 = 3.946 - 0.272*H273 + 0.0856*H273^2$ See = 0.104 (5)

Meghna Ferryghat

$H275.5 = 0.109 + 0.989*H275$ See = 0.081 (6)

$H275.5 = 0.936 + 0.251*H274 + 0.582*H71$ See = 0.105 (7)

$H275.5 = -0.065 + 0.489*H115 + 0.497*H274$ See = 0.115 (8)

$H275.5 = 0.696 + 0.821*H274$ See = 0.143 (9)

Kalagachia

$H71 = 0.326 + 0.930*H71.A$ See = 0.050 (10)

$H71 = -0.554 + 0.692*H276 + 0.417*H275.5$ See = 0.103 (11)

$H71 = -0.788 + 1.110*H275.5$ See = 0.110 (12)

Rekabi Bazar

$H71A = 0.095 + 0.998*H71$ See = 0.056 (13)

Satnal

$H276 = 0.348 + 0.165*H115 + 0.744*H71$ See = 0.106 (14)

$H276 = 0.341 + 0.884*H275.5$ See = 0.126 (15)

Nilkamal

$H277.3 = 1.112 + 0.723*H277$ See = 0.118 (16)

Off-take in Meghna

$H288 = 8.414 - 2.570*H277 + 0.314*H277^2$ See = 0.090 (17)

APPENDIX A/3

COMPLETED ANNUAL MAXIMUM WATER LEVELS

Table A/3.1 COMPLETED ANNUAL MAXIMUM WATER LEVEL SERIES
UPPER MEGHNA, PERIOD 1959-1990

Year	Bhairab 273	Nabina. 298	Narsi. 274	Ferrygh. 275. 5	Rekabi 71A	Kalaga. 71	Satnal 276
1959	6.36	6.06	5.68	5.27	5.09	5.00	4.86
1960	6.61	6.31	5.65	5.51	5.27	5.18	4.97
1961	5.61	5.36	5.15	4.97	4.98	4.89	4.94
1962	6.69	6.46	6.06	5.67	5.60	5.51	5.35
1963	6.37	6.13	5.75	5.42	5.32	5.23	5.13
1964	7.13	6.85	6.36	6.00	5.96	5.87	5.69
1965	6.49	6.22	5.79	5.45	5.35	5.26	5.16
1966	6.91	6.64	6.16	5.75	5.69	5.60	5.42
1967	6.25	5.97	5.59	5.28	5.16	5.07	5.01
1968	6.77	6.62	6.12	5.70	5.75	5.62	5.40
1969	6.71	6.43	6.00	5.63	5.47	5.39	5.21
1970	7.09	6.82	6.32	5.87	5.85	5.73	5.46
1971	6.60	6.34	6.11	5.76	5.68	5.59	5.70
1972	6.09	5.84	5.44	5.11	5.00	4.95	4.82
1973	6.48	6.18	5.82	5.44	5.46	5.34	5.24
1974	7.65	7.32	6.87	6.19	6.07	5.99	5.79
1975	6.48	6.21	5.75	5.29	5.18	5.17	5.05
1976	7.02	6.72	6.05	5.32	5.10	5.01	4.83
1977	6.57	6.30	5.87	5.59	5.39	5.34	5.20
1978	5.99	5.70	5.37	5.12	5.09	5.00	4.94
1979	6.33	6.02	5.62	5.24	5.29	5.20	5.15
1980	6.41	6.11	5.87	5.82	5.61	5.64	5.49
1981	6.46	6.24	5.70	5.40	5.41	5.32	5.24
1982	6.43	6.15	5.62	5.19	5.04	4.95	4.82
1983	6.79	6.49	6.04	5.56	5.53	5.44	5.26
1984	6.89	6.62	6.21	5.73	6.00	5.91	5.62
1985	6.38	6.10	5.67	5.44	5.15	5.06	4.99
1986	5.67	5.34	5.15	5.03	4.97	4.80	4.71
1987	6.91	6.61	6.27	5.99	6.02	5.92	5.61
1988	7.66	7.34	6.90	6.55	6.43	6.31	6.04
1989	6.41	6.13	5.72	5.22	5.10	5.02	4.91
1990	6.04	5.79	5.41	5.29	5.14	5.01	4.98

Note: all levels are in m + PWD

APPENDIX A/4

AVERAGE DURATION CURVES OF DAILY AVERAGE WATER LEVELS AT THE CONSTRUCTION SITES

Table A/4.1 AVERAGE DURATION CURVE OF DAILY AVERAGE WATER LEVELS OF THE UPPER MEGHNA AT BHAIRAB BAZAR

Level m + PWD	Nr. of days of non-exceedance
.81	.04
1.04	.97
1.27	12.80
1.50	45.02
1.73	83.94
1.95	112.97
2.18	134.45
2.41	152.66
2.64	169.10
2.87	183.15
3.09	193.56
3.32	200.79
3.55	209.47
3.78	217.87
4.00	224.98
4.23	231.27
4.46	236.28
4.69	241.65
4.92	246.82
5.14	254.98
5.37	266.64
5.60	282.59
5.83	302.05
6.06	319.38
6.28	335.08
6.51	348.20
6.74	355.51
6.97	360.56
7.19	362.25
7.42	363.06
7.65	364.03

Table A/4.2 AVERAGE DURATION CURVE OF DAILY AVERAGE WATER LEVELS OF THE UPPER MEGHNA AT MANIKNAGAR

Level m + PWD	Nr. of days of non-exceedance
.87	.06
1.08	.94
1.29	14.83
1.51	49.30
1.72	85.02
1.93	113.05
2.14	134.76
2.36	152.34
2.57	170.24
2.78	181.56
2.99	192.20
3.21	199.39
3.42	209.53
3.63	218.66
3.84	224.67
4.05	231.24
4.27	236.56
4.48	242.81
4.69	249.82
4.90	258.52
5.12	271.09
5.33	288.05
5.54	304.94
5.75	320.95
5.97	334.03
6.18	346.86
6.39	354.99
6.60	360.25
6.82	361.87
7.03	362.75
7.24	364.25

Table A/4.3 AVERAGE DURATION CURVE OF DAILY AVERAGE WATER LEVELS OF THE UPPER MEGHNA AT MEGHNA FERRYGHAT AND THE DHALESWARI AT MUNSHIGANJ

Level m + PWD		Nr. of days of non-exceedance
Ferryghat	Munshiganj	
.94	.94	.06
1.12	1.12	7.12
1.31	1.30	27.53
1.49	1.48	57.98
1.68	1.66	90.14
1.87	1.84	116.07
2.05	2.01	137.31
2.24	2.20	158.44
2.43	2.38	175.17
2.61	2.55	186.98
2.80	2.74	197.19
2.99	2.92	206.98
3.17	3.09	218.13
3.36	3.28	225.67
3.55	3.46	231.25
3.73	3.63	238.72
3.92	3.81	245.85
4.11	4.00	254.92
4.29	4.17	265.07
4.48	4.35	280.38
4.67	4.54	296.28
4.85	4.71	311.59
5.04	4.89	324.53
5.22	5.06	339.72
5.41	5.25	349.22
5.60	5.43	355.62
5.78	5.60	360.37
5.97	5.79	362.21
6.16	5.97	363.16
6.34	6.14	363.58
6.53	6.32	364.17

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Table A/4.4 AVERAGE DURATION CURVE OF DAILY AVERAGE WATER LEVELS OF THE LOWER MEGHNA AT EKLASHPUR

Level m + PWD	Nr. of days of non-exceedance
.74	.06
.90	1.43
1.06	8.79
1.22	28.75
1.37	57.82
1.53	87.32
1.69	111.58
1.85	133.66
2.01	153.19
2.17	169.59
2.33	181.63
2.49	192.85
2.65	202.65
2.81	212.06
2.97	221.48
3.13	229.34
3.29	237.01
3.45	246.37
3.61	255.97
3.77	268.39
3.93	283.42
4.09	301.32
4.25	316.54
4.41	330.70
4.57	343.36
4.73	352.78
4.89	358.39
5.05	361.44
5.21	362.26
5.37	363.63
5.53	364.19

Table A/4.5 AVERAGE DURATION CURVE OF DAILY AVERAGE WATER LEVELS OF THE LOWER MEGHNA AT CHANDPUR AND HAIMCHAR

Level m + PWD		Nr. of days of non-exceedance
Chandpur	Haimchar	
.56	.45	.04
.71	.59	.54
.86	.72	5.36
1.00	.85	16.21
1.15	.99	35.44
1.30	1.12	61.25
1.45	1.26	86.47
1.59	1.39	111.11
1.74	1.52	132.22
1.89	1.66	151.13
2.04	1.80	169.08
2.18	1.93	182.08
2.33	2.06	195.09
2.48	2.20	206.14
2.63	2.34	215.04
2.78	2.47	224.76
2.92	2.60	233.36
3.07	2.74	241.84
3.22	2.87	252.43
3.37	3.01	264.48
3.51	3.14	278.74
3.66	3.27	293.36
3.81	3.41	309.90
3.96	3.55	324.86
4.10	3.68	339.20
4.25	3.81	350.08
4.40	3.95	356.56
4.55	4.09	360.06
4.69	4.21	362.17
4.84	4.35	363.17
4.99	4.49	363.92

APPENDIX A/5

AVERAGE DURATION CURVES OF UPPER MEGHNA DISCHARGE AT BHAIRAB BAZAR AND OF LOWER MEGHNA DISCHARGE AT CHANDPUR

Table A/5.1 AVERAGE DURATION CURVE OF DAILY DISCHARGES OF THE UPPER MEGHNA AT BHAIRAB BAZAR

Discharge m^3/s	Nr. of days of non-exceedance
0	.04
226	20.24
870	129.48
1,514	154.01
2,158	168.85
2,803	181.73
3,447	192.83
4,091	203.39
4,735	212.66
5,380	221.84
6,024	229.37
6,668	236.27
7,312	243.08
7,956	252.39
8,601	262.83
9,245	276.67
9,889	289.64
10,533	302.36
11,178	316.95
11,822	327.63
12,466	337.82
13,110	345.55
13,755	351.99
14,399	355.77
15,043	358.27
15,687	360.10
16,331	360.97
16,976	361.63
17,620	362.22
18,264	362.88
18,908	364.04

Table A/5.2 AVERAGE DURATION CURVE OF DAILY DISCHARGES OF THE LOWER MEGHNA AT CHANDPUR

Discharge m^3/s	Nr. of days of non-exceedance
0	.04
5,167	.83
10,345	106.60
15,522	163.24
20,699	191.04
25,876	208.83
31,053	222.42
36,231	231.35
41,408	238.58
46,585	246.39
51,762	253.71
56,939	263.06
62,117	273.24
67,294	284.63
72,471	296.97
77,648	311.85
82,826	325.69
88,003	337.03
93,180	345.80
98,357	351.66
103,534	357.10
108,712	360.84
113,889	361.76
119,066	362.42
124,243	362.96
129,420	363.50
134,598	363.63
139,775	363.67
144,952	363.75
150,129	363.84
155,307	364.04

APPENDIX A/6

COMPLETED ANNUAL MAXIMUM DISCHARGES
OF THE UPPER MEGHNA AT BHAIRAB BAZAR

Table A/6.1. ANNUAL MAXIMUM DISCHARGE OF UPPER MEGHNA AT BHAIRAB BAZAR

Year	Qmax (m^3/s)	
1959	12,600	*
1960	13,800	*
1961	11,500	*
1962	14,300	*
1963	16,500	*
1964	12,300	
1965	12,100	
1966	14,400	
1967	12,700	
1968	13,300	
1969	11,500	
1970	16,400	
1971	-,-	
1972	11,500	
1973	12,400	
1974	19,500	
1975	12,700	
1976	16,700	
1977	14,800	*
1978	12,400	*
1979	13,800	*
1980	11,300	*
1981	11,200	
1982	13,500	
1983	16,000	
1984	13,600	
1985	14,300	
1986	11,100	
1987	15,200	
1988	19,800	
1989	15,500	
1990	12,100	*

Note: values marked with * are estimated

APPENDIX A/7

ANNUAL MAXIMUM WIND SPEED AT VARIOUS STATIONS IN AND AROUND THE PROJECT AREA

Table A/7.1 ANNUAL MAXIMUM WIND SPEED IN KNOTS AT VARIOUS LOCATIONS IN AND NEAR THE PROJECT AREA

Year	B.BARIA	BHOLA	CHANDPUR	COMILLA	DHAKA	MAJDEE
1948	10.	-.-	-.-	9.	-.-	-.-
1949	20.	-.-	-.-	24.	-.-	-.-
1950	14.	-.-	-.-	19.	-.-	-.-
1951	9.	-.-	-.-	24.	-.-	-.-
1952	10.	-.-	-.-	18.	-.-	9.
1953	-.-	-.-	-.-	50.	26.	24.
1954	20.	-.-	-.-	88.	90.	20.
1955	12.	-.-	-.-	9.	30.	31.
1956	10.	-.-	-.-	50.	90.	25.
1957	23.	-.-	-.-	51.	30.	13.
1958	12.	-.-	-.-	21.	69.	13.
1959	9.	-.-	-.-	18.	90.	19.
1960	70.	-.-	-.-	91.	30.	90.
1961	50.	-.-	-.-	43.	72.	90.
1962	60.	-.-	-.-	19.	50.	31.
1963	30.	-.-	-.-	-.-	51.	44.
1964	32.	-.-	-.-	19.	52.	19.
1965	50.	-.-	-.-	53.	50.	19.
1966	30.	51.	40.	25.	25.	37.
1967	30.	31.	52.	19.	25.	30.
1968	13.	91.	20.	26.	52.	50.
1969	60.	51.	70.	35.	30.	13.
1970	50.	25.	37.	19.	51.	37.
1971	10.	31.	31.	25.	19.	13.
1972	-.-	31.	-.-	34.	51.	13.
1973	-.-	46.	13.	35.	70.	19.
1974	-.-	38.	32.	40.	-.-	25.
1975	-.-	23.	13.	53.	25.	23.
1976	-.-	92.	13.	30.	25.	-.-
1977	-.-	33.	54.	36.	37.	-.-
1978	-.-	17.	-.-	-.-	37.	31.
1979	-.-	-.-	32.	96.	52.	22.
1980	-.-	33.	-.-	80.	21.	24.
1981	-.-	15.	19.	25.	19.	10.
1982	-.-	17.	19.	20.	19.	80.
1983	-.-	9.	16.	9.	23.	14.
1984	-.-	12.	35.	30.	15.	21.
1985	-.-	30.	25.	28.	28.	80.
1986	-.-	20.	31.	19.	18.	25.
1987	-.-	23.	31.	20.	24.	20.
1988	-.-	82.	35.	20.	37.	56.
1989	-.-	20.	12.	35.	18.	20.
1990	-.-	-.-	-.-	-.-	21.	-.-

ANNEX - B

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LIST OF SYMBOLS

Symbol	Description	Unit
A	area of cross-section	m^2
B	width of river	m
B_s	width of scour	m
C	Chezy roughness coefficient	$m^{\frac{1}{2}}/s$
c	concentration (usually by volume)	-
D	grain size	m
D_*	dimensionless grain size $D^* = D(\Delta g/\nu^2)^{1/3}$	-
D_{90}	median grain size	m
Fr	Froude number, defined via $Fr = U/(gh)^{0.5}$	-
f	Darcy-Weisbach friction factor	-
f	Lacey silt factor	-
g	acceleration due to gravity	m/s^2
H	total energy head, head loss	m
h	water depth	m
k_s	equivalent roughness height (Nikuradse)	m
n	Manning coefficient	-
q	discharge of water per unit width	m^2/s
Q	discharge of water	m^3/s
R	hydraulic radius	m
R	radius of curvature	m
Re	Reynolds number	-
S	discharge of sediment (volume of grains)	m^3/s
s	sediment transport per unit width	m^2/s
U	depth-averaged flow velocity	m/s
U_c	average flow velocity at initiation of sediment motion	m/s
u_*	shear velocity	m/s
u_{*c}	shear velocity at initiation of sediment motion	m/s
w	fall velocity of sediment	m/s
h_r	regime depth	m
h_s	scour relative to river bed	m
z	bed level	m
α	angle of attack	-
Δ	$(\rho_s - \rho)/\rho$	-
κ	relative density Von Kármán constant	-
λ	wave length, meander length	m
λ_s	relaxation length of sediment	m
λ_w	relaxation length of water	m
μ	dynamic viscosity	Ns/m^2
υ	kinematic viscosity	m^2/s
ρ,	density of water, sediment	kg/m^3
ρ_s	density of sediment	kg/m^3
σ_g	geometric standard deviation of the grain size distribution	-
τ_0	bed shear stress	N/m^2
τ_c	bed shear stress at initiation of motion	N/m^2
θ	dimensionless shear stress, defined via $\theta = hi/\Delta D$	-

B.1 INTRODUCTION

This Annex deals with geomorphological aspects and the river morphology of the Upper and Lower Meghna River. A careful analysis of these aspects is very important for the understanding of the processes taking place in these large rivers and for any prediction of how they will develop over time. This understanding in turn is an key factor for the proper design of the emergency and the short-term bank protection works.

Due to the time and budget constraints of the present project, the analysis underlying this Annex is a first attempt only to understand the processes occurring in the Upper and Lower Meghna. It is imperative to study the geomorphology of the area and the river morphology of both rivers in much more detail when a long term strategy for bank protection works has to be developed. Nevertheless, Consultants feel that within the limited frame work available, they have managed to deepen the understanding of the relevant processes allowing to better cope with the present bank erosion problems along the Upper and Lower Meghna Rivers.

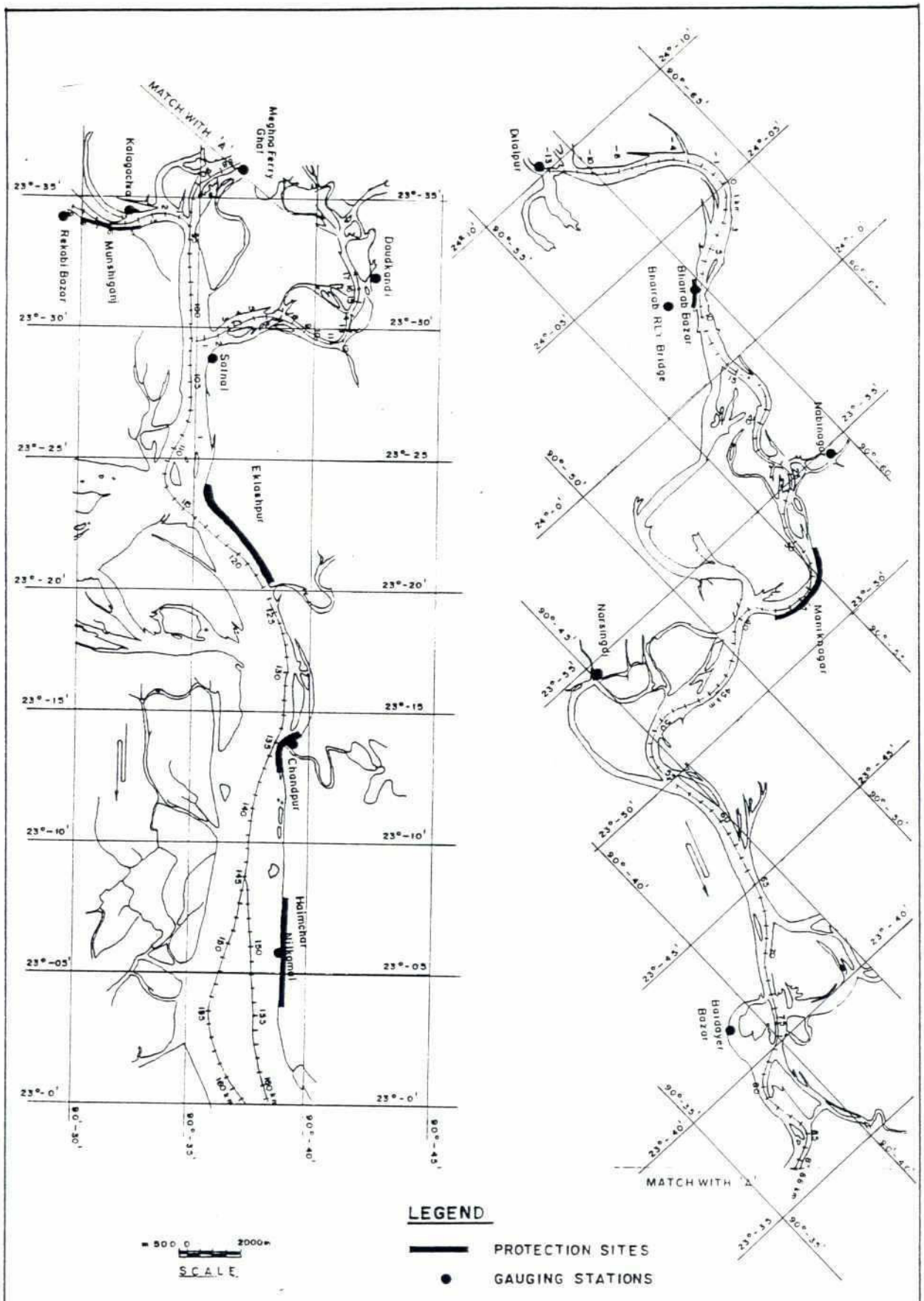
A very essential point to stress here is that the Upper and the Lower Meghna River are two completely different rivers. In the past, when the Brahmaputra River still followed its old (Old Brahmaputra River) course, the Lower Meghna River could be viewed as the downstream reach of the Upper Meghna River. The more so, because the Ganges River at that time had a different outlet to the Bay of Bengal. Nowadays, however, the Upper Meghna is just a smaller tributary to the Ganges/Jamuna-Padma-Lower Meghna Rivers system. Hence, very often in this annex, the Upper and the Lower Meghna have been treated separately. This implies also that, for an understanding of the processes in the Lower Meghna one should include an analysis of the river processes in the Padma River, rather than consider the Upper Meghna in this respect. This explains why in the following Chapters often the lower reach of the Padma River has been included in the analysis too.

The structure of this Annex is as follows. In Chapter 2 of this Annex the **approach** adopted in the present study is described. Chapter 3 provides an overview of the **available data**, that were identified during the inception phase and that were subsequently acquired. During the inception phase the need for a number of additional data became clear, and these additional data collected during subsequent surveys are also presented. In Chapter 4 an analysis of the available data on the Upper Meghna, the Lower Meghna and (in line with what is stated in the previous paragraph) also the lower reach of the Padma River is given. The analysis yields a fair insight in the **river characteristics** of the Upper and Lower Meghna.

In the Chapters 5 and 6 **bank line changes** of the Upper and Lower Meghna River are dealt with. In Chapter 5 historical changes in river alignment and planform are discussed for the Upper and Lower Meghna Rivers separately, while a more detailed analysis of bank line changes at the problem locations listed in the Terms of Reference is also presented in this Chapter. It is attempted to relate these bank lines to the alignment of the rivers and to the movement of the system of bars and channels in the Padma / Lower Meghna River system. The understanding obtained in Chapter 5 is subsequently used in Chapter 6 for making predictions for the movement of the Upper and Lower Meghna Rivers at the problem locations. Also the effect of river training works is assessed in some depth.

The Chapters 7 and 8 deal with **scour** and the prediction of the maximum scour depth in the future at the problem locations. In Chapter 7 the available knowledge on scour phenomena is reviewed against the background of the conditions in the Upper and Lower Meghna Rivers. A distinction is made between the various types of scour and for some of the problem locations it is indicated which types are most important. "Dedicated" prediction methods for scour along the Upper and Lower Meghna Rivers are developed. Also here an attempt is made to connect planform development and the likely changes in the bar and channel system to the magnitude of the various types of scour. In Chapter 8 the different prediction methods are applied to assess the likely future maximum scour depths at some problem locations for which designs for short term bank protection works have to be made within the present project.

In most cases the theory underlying the analyses carried out by Consultant could only be indicated briefly. An extensive list of **references** is added to this report for readers interested in more details.



Upper and Lower Meghna Rivers	B.1.1

B.2 APPROACH

This Chapter describes Consultants' approach to the geomorphological and river morphological study, reported upon in the present Annex. This approach can be characterised by a number of steps that were taken during the subsequent stages of the project. These steps are described hereafter in some detail.

B.2.1 Inception phase

In the inception phase the bank erosion problems experienced along the Upper and the Lower Meghna Rivers were reviewed and possible causes were identified on the basis of field visits, discussions, and a review of the easily accessible data and these observations were cross-checked against Consultants knowledge of and experience with bank erosion problems along similar rivers (like the Jamuna River, the Mekong River, etc.). Based on this the approach to be followed in the present project was determined and the need for more data was established. A review of these additional data (which was divided in data already existing but not yet collected, and measurements still to be done) was given in the Inception Report.

B.2.2 Data collection phase

In this phase the available ("historical") data were collected and some surveys were done to do additional measurements. The collected data consisted of maps, satellite images, soundings, sediment transport data in addition to the hydrological data (for the latter see Annex A). Additional measurements were done during surveys in February and September of 1991. During these surveys mainly soundings were made for use for the mathematical modelling, but these data were also useful for the present study as they provided quite detailed information. In addition bed samples were taken during these surveys and these samples were subsequently analyzed at RRI (River Research Institute) in Faridpur. Due to a number of reasons this data collection phase extended to September 1991.

B.2.3 Data analysis phase

In the data analysis phase the already available and the additionally collected data were (further) processed. This processing aimed at three goals:

(1) to get insight in the characteristics of the Upper and Lower Meghna Rivers, important to understand the phenomena observed in the other parts of the study,
(2) to understand the planform and bank line changes, especially in relation to the geomorphology of the area, ultimately with the aim to make predictions of the future bank line changes; and
(3) to improve the understanding of the scour occurring in various reaches of the two rivers, to allow for the prediction of the maximum scour depths and their probabilities of occurrence at those reaches of the river where bank protection works are being considered.

The data analysis consisted of a number of partly separate and partly integrated activities, notably:

(a) compilation and interpretation of the results of the bed sampling campaign;
(b) analysis of soundings etcetera to derive river characteristics like channel dimensions, planform characteristics, and dimensionless parameters like the Shields parameter, the suspension parameter, etc.;
(c) analysis of maps, satellite images and soundings to study planform changes in time and to identify systematic changes, if any;
(d) interpretation and analysis of the different scour phenomena active in the Upper and Lower Meghna River, aiming at deriving prediction methods for maximum scour depths.

In the process extensive use was made of the understanding obtained during previous but similar studies, notably the investigations for the river training works for the Jamuna Bridge.

The data analysis phase covered the period March through October 1991. There was a substantial overlap in time with the data collection and the modelling phase, but this could not be avoided considering the tight time schedule for the present study.

B.2.4 Modelling phase

To arrive at optimal designs for the short-term bank protection works, use was made of models, both mathematical models and physical scale models. For these models boundary conditions had to be generated. The required boundary conditions relate to:

- the bed topography in the surroundings of the bank protection works.
- the downstream water levels, and
- the upstream distribution of the water over the width of the model.

Both the bed topography and the upstream water distribution are determined by the position of the channel and bar pattern in the Padma/Lower Meghna River system. Within the frame-work of the geomorphological and river morphology study a prediction was made of the future conditions at the sites to be protected. Use was made of the understanding obtained in the data analysis phase. The potentially most serious attack on the river training works was identified and guestimates were made of the corresponding channel and bar pattern, and the bank erosion over the coming decades. These were fed into the mathematical model of the flow field (see Annex C?), which in turn was used to generate boundary conditions for the physical scale models. The results of the physical scale modelling, providing in particular scour relations (see Annex E), were again used in the assessment of the scour depths to be expected in front of the bank protection works.

The modelling phase covered the period March through and including November 1991. Again there was an overlap, in this case with the data analysis phase, necessitating more computations and model tests to be done than would had a longer time span would have been available for the project.

B.2.5 Preliminary design and feasibility phase

In the preliminary design phase first estimates were made of the design scour depths in front of the bank protection works. These estimates were based on the field data available, on the experience from a.o. the Jamuna Bridge Appraisal Study and on "theoretical" predictors. In addition estimates were made of bank erosion to be expected over the next decades if no bank protection works were to be carried out. The latter was needed for the economic analysis of the bank protection projects. These predictions of the bank line changes were based on the understanding of the bank erosion of the Meghna River obtained during the data analysis phase. The effect of the possible bank protection works was also taken into account and estimates were made of the areas of land (distinguishing between urban area and agricultural land) that were safeguarded by the bank protection works. These figures were essential for the economic analysis (see Annex F).

This phase covered roughly the period June through and including September 1991.

B.2.6 Detailed design phase

In this period the detailed designs of the bank protection works were made. For this it was needed to predict accurately the scour depths to be expected in front of the bank protection works. To provide these, extensive use was made of the results of the analysis of the geomorphological and river morphological conditions in the Upper and Lower Meghna Rivers. Also the results of the physical models

(hence implicitly of the mathematical models also) were used in determining in particular the local scour to be expected near the bank protection works. The other contributions to the total scour (like constriction scour, bend scour, confluence scour, protrusion scour, etc.) were evaluated on the basis of the results of the present geomorphological and river morphology study.

This last phase covered the period September through and including December 1991.

From the description above it will have become clear that the investigation was carried out under extreme time constraints. Nevertheless the results are well balanced and it is felt that within the time and budget available, the optimum result has been obtained.

B.3 DATA USED

B.3.1 Introduction

This Chapter deals with the data used during the present study. A distinction can be made between the data already available and data to be measured additionally. The former are discussed in Section 3.2, whereas the latter are described in Section 3.3. Also the processing of the primary data and the subsequent analysis is discussed in this Chapter, notably in Section 3.4.

B.3.2 Existing data

B.3.2.1 Introduction

For the present study different types of data were obtained from different sources. The type of data can be listed as follows:

- hydrological data;
- maps;
- satellite images;
- soundings;
- bed material sampling;
- sediment transport data;
- literature.

These different types of data are reviewed hereafter, whereby the emphasis is on listing the data used.

B.3.2.2 Hydrological data

Hydrological data were needed for different parts of the present geomorphological and river morphological study, in particular for the determination of the river characteristics, for the evaluation of the scour phenomena and the estimate of the future conditions. Annex A of the present report discusses the hydrological data, their availability and their accuracy in detail. Also the processing and the further analysis of the hydrological data is described in Annex A.

Here only the results of these analyses were used, in particular:

- the slopes of the different river reaches,
- water levels, especially during low flow conditions when the satellite images were obtained, and the frequency distribution of the water levels at the different stations,
- discharges: absolute values and frequency distributions.

No additional data were needed for this study.

B.3.2.3 Maps

Old maps can be used to determine the location and the planform of a river, and provided that they are made during low flow they can also be used for determination of the channel pattern inside the main course. It may be anticipated, however, that the channel patterns of wide rivers is not always correctly drawn on old maps, simply because the methods were lacking to determine accurately the actual pattern. Another problem with old maps is that in the 19th century the longitude was corrected, when the exact longitude of Calcutta with respect to Greenwich was determined. This makes the use of the map of 1776 less quantitative appropriate for comparisons.

Old maps of the **Upper Meghna** were obtained for the years 1776, 1860, 1953, 1960 and 1964. The scales of these maps are listed hereafter:

Year	Scale
1776	1: 1,000,000
1860	1: 253,400
1953	1: 253,400
1960	1: 250,000
1965	1: 250,000

Old maps of the **Lower Meghna** are available of the following years: 1770, 1860, 1952 and 1960. The scales are similar to the maps of the Upper Meghna of the corresponding years (see above).

B.3.2.4 Satellite images

Satellite images are a useful instrument to get insight in the yearly changes in channel pattern, and in the yearly erosion and sedimentation of the Lower Meghna. For the present study a number of prints of satellite images were obtained from SPARRSO, Dhaka. Here it concerns prints from negatives, hence there are different sources of inaccuracy:

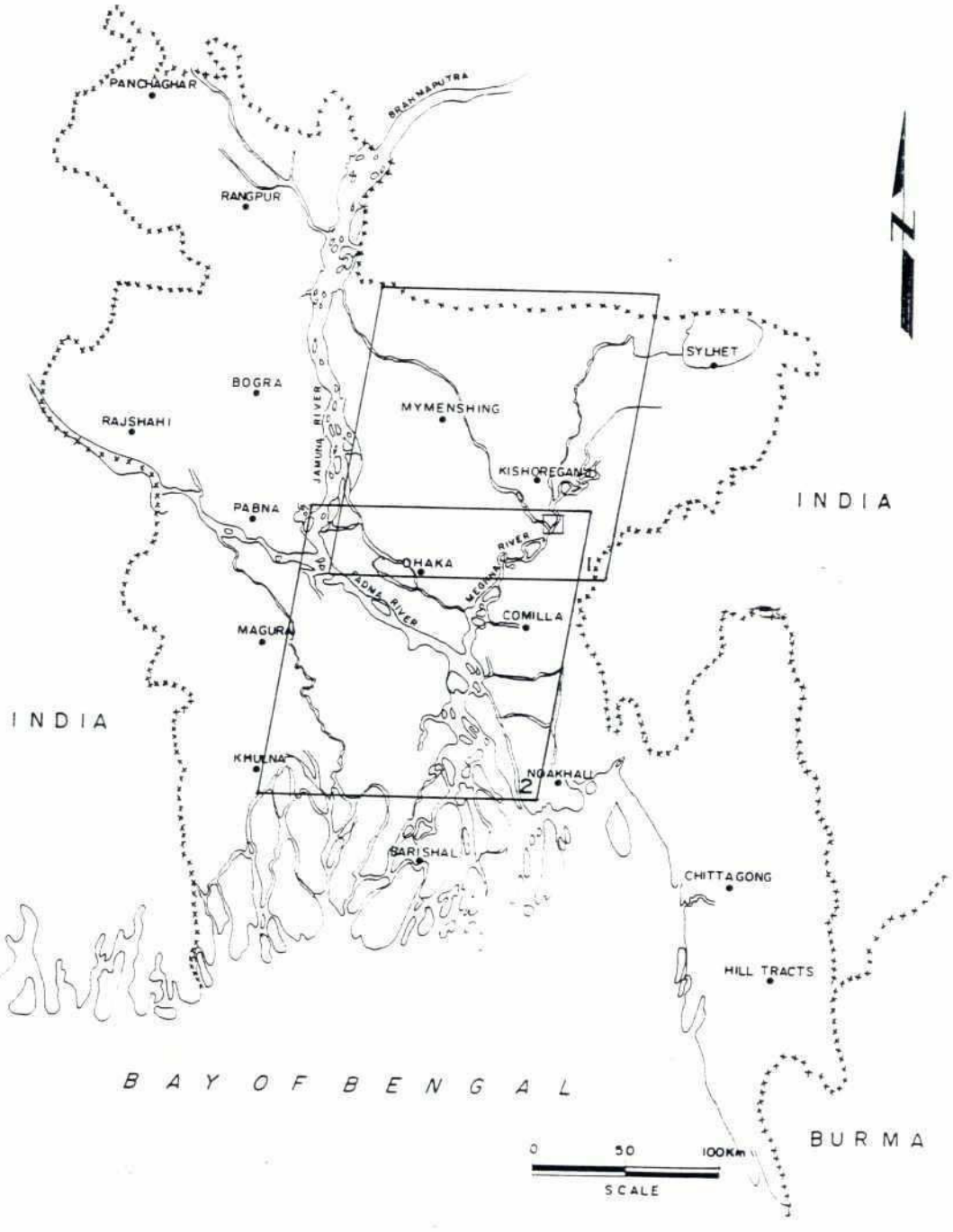
(1) The satellite images could not be selected with regard to the date (as was e.g. done during the Jamuna Bridge Appraisal Study), because only images available in Bangladesh could be used. It is preferable to use images with approximately the same stage as only then the bank-line changes will not be mixed up with changes due to a different stage. In the below tables with satellite images used also the water level is added to allow for a check on this aspect.

(2) The satellite images were not corrected geometrically as was done during the Jamuna Bridge Study, hence observed changes could also be due to the incorrect geometry (at least partly).

(3) The prints that were made by SPARRSO were not at exactly the same magnification. This necessitated a correction which might have induced another error.

Satellite images used were LANDSAT images. Two different scenes were required to cover the Upper and the Lower Meghna Rivers. The coverage of these two scenes is indicated in Figure B.3.1. Available satellite images with the corresponding dates and water levels are listed in Table B.3.1.

As can be observed from an inspection of Table B.3.1, during the making of the satellite images the HWL (High Water Level) at Chandpur varied between 0.90 m and 1.85 m+PWD, and the LWL (Low Water Level) between 0.40 and 1.15 m+PWD. A more accurate indication of the water level at the exact moment the satellite image was made could not be obtained.



1 LANDSAT AI-001105 (1988)

2 LANDSAT AI-001106 (1988)

Coverage of LANDSAT scenes used	Figure B.3.1

TABLE B.3.1 OVERVIEW OF SATELLITE IMAGES USED IN THE PRESENT STUDY

Year	Date of scene		Water level at Chandpur (m+PWD)	
	Upper Meghna	Lower Meghna	HWL	LWL
1973	January 15	January 15	1.62	0.98
1973	February 2	----[1])	----	----
1976	March 21	March 21	1.85	0.84
1977	February 8	February 8	1.52	0.59
1980	----	January 15	0.90	0.40
1980	February 2	----	----	----
1984	March 10	March 10	1.83	0.89
1987	----	February 16	1.76	0.89
1988	March 11	March 11	1.34	0.94
1989	February 5	February 5	1.84	1.15
1990	January 7	January 7	1.35	0.91

----[1]) = no image or no information on the water level available

Although the water level was not constant for the different images the water level variation was only minor. In this respect is it worth mentioning that especially the erosion rate is of interest and because this in usually connected with steep banks it may be assumed that the influence of the water level variation is small only.

In addition to the 1989 mentioned LANDSAT images also SPOT images of the year 1990 were available. These images were at a scale of 1:50,000. They were used for the analysis of the bend characteristics of the Upper Meghna and for the study of the channel and bar patterns in the Padma/Lower Meghna River system.

B.3.2.5 **Soundings**

Two sources of information on the bed topography of the Upper and the Lower Meghna River were identified, notably (1) cross-sectional soundings carried out regularly by the Bangladesh Water Development Board (BWDB), and (2) soundings carried out by Bangladesh Inland Water Transport Authority (BIWTA).

(i) BWDB cross-sections

The cross-sections sampled by BWDB are usually some 5 km apart and they are measured once every few years. For their location reference is made to Figure B.3.1. It is noticed that not all of these cross-sections are perpendicular to the river axis. This holds especially for the Upper Meghna River, where different parallel channels may be present. What makes the cross-sections very interesting is that they cover the full width of the river (the BIWTA soundings cover only a part).

The cross-sections are connected to benchmarks which are located on both sides of the cross-sections. These benchmarks are known in location and level.

For the Upper Meghna River cross-sectional data were obtained from BWDB for 21 cross sections for the years 1982, 1986, 1987 and 1990. These cross-sections (M#20 through M#3) cover the whole reach of interest for the present study from upstream of Bhairab Bazar down to the confluence with the Padma River.

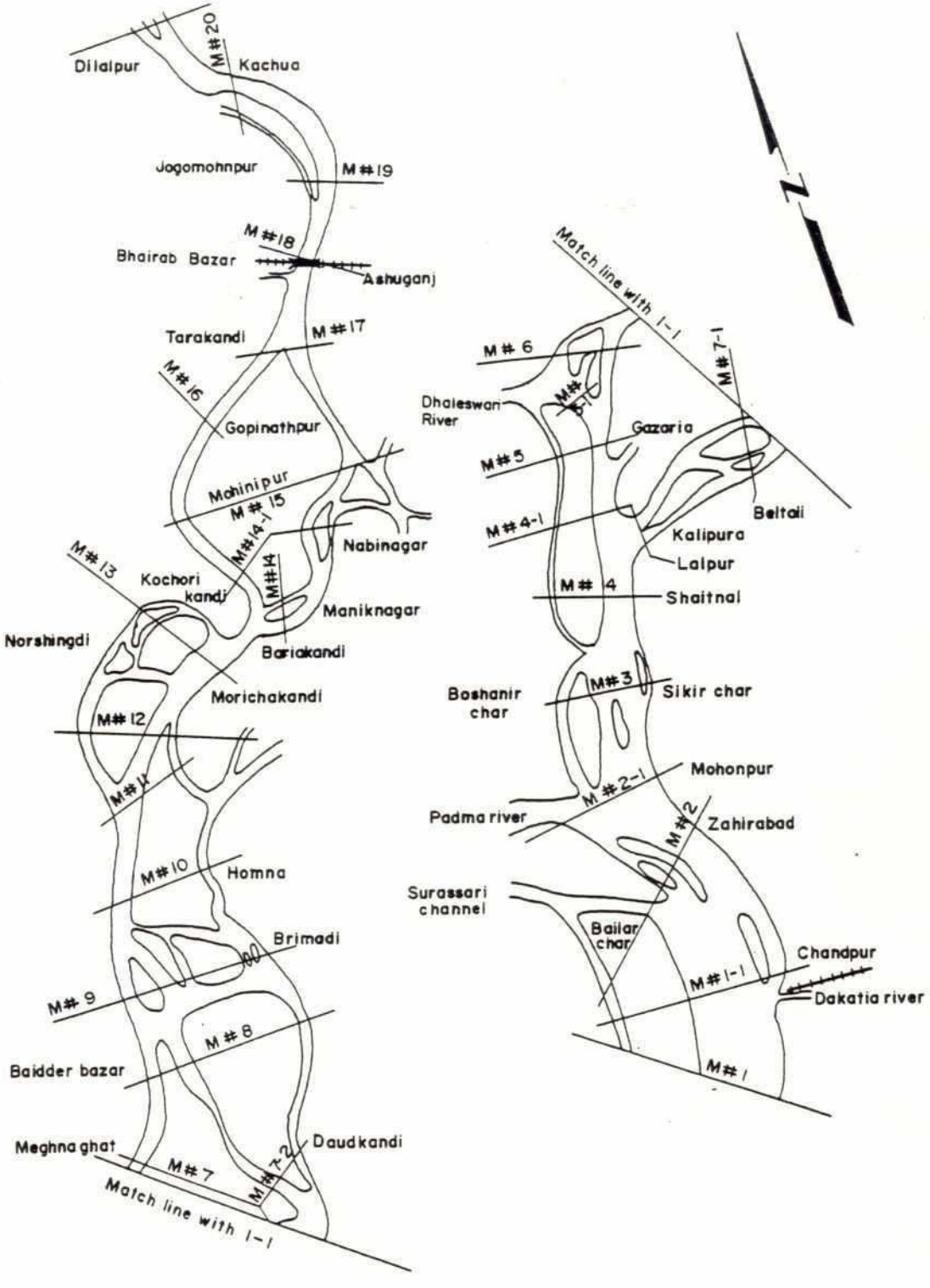
Along the Lower Meghna River cross-sectional data were obtained from the Bangladesh Water Development

Board for 4 cross sections (M#2-1 through M#1) for the years 1982, 1986, 1987 and 1990. No cross-sections have been measured in the river reach more downstream.

The data were obtained in graphical form. In due time also digitized data were obtained in processed form. These data however became only available in a late stage of the project and for a few cross-sections only (M#20, M#19, M#18 and M#17 for the Upper Meghna, and M#2-1, M#2, M#1-1 and M#1 for the Lower Meghna River), so they could not be used anymore in the analysis.

(ii) BIWTA Soundings

The Bangladesh Inland Water Transport Authority is doing regular soundings of many river reaches in Bangladesh. These soundings are done for navigational purposes mainly so they concern major shipping routes and reaches where ferries are sailing. The advantage of the BIWTA soundings is that they give a full coverage of the river bed, most of the time with a relatively dense network varying from some 50 m of some reaches in the Upper Meghna to some 250 m in the Lower Meghna River. Hence these

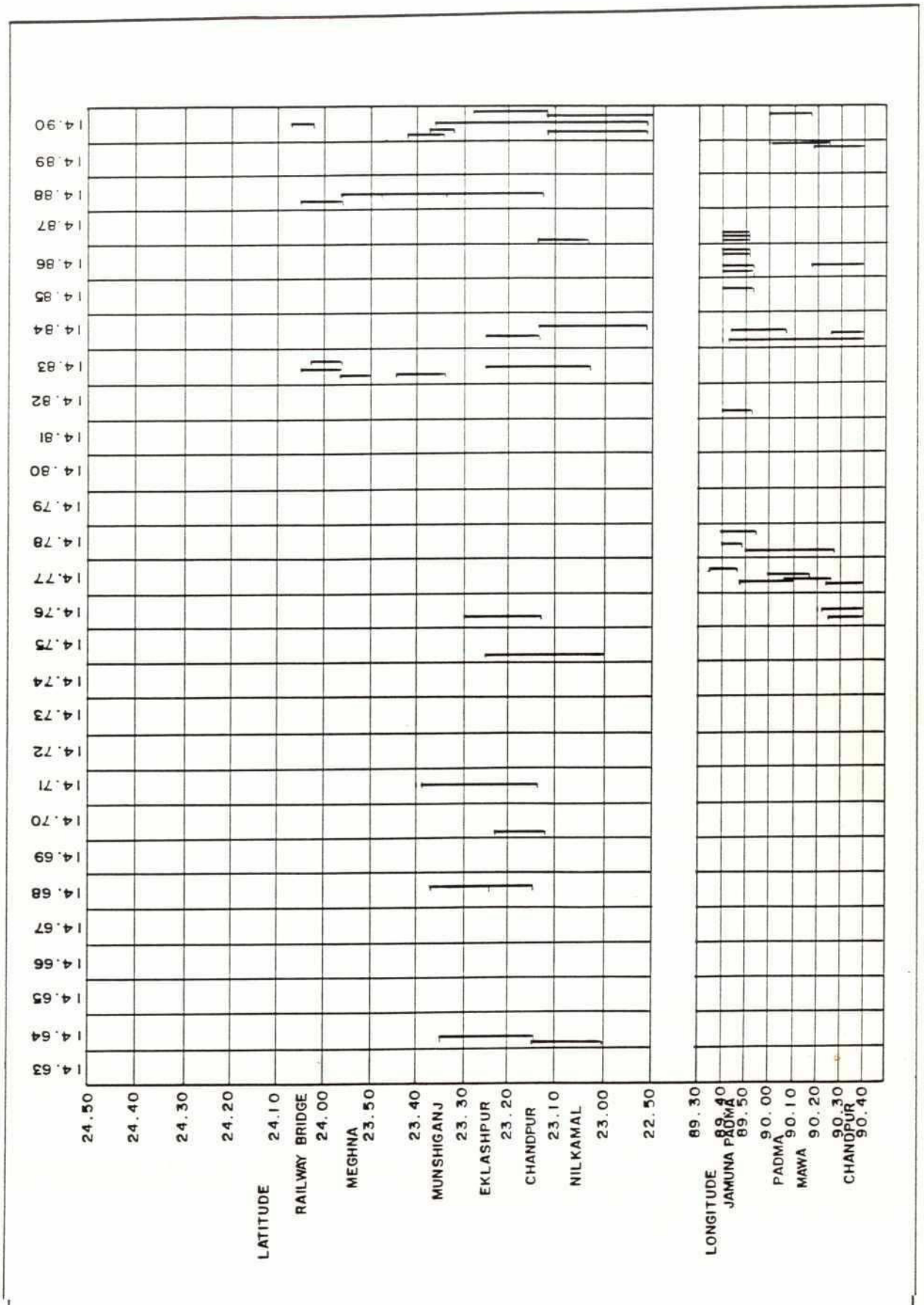


Location of BWDB cross-sections	Figure B.3.2

soundings give a much better image of e.g. the deepest scour holes than the cross-sections of the BWDB. The horizontal position of the measuring vessels is determined with the Decca system under operation in Bangladesh. Although the absolute position of this measuring system is not so high, it is very well suited for comparative results.

A disadvantage of the BIWTA soundings is that they are concerned with the deepest sections only, hence they provide no information on the levels of the bars between the channels. For the study of extreme scour holes these BIWTA soundings are however extremely suited. Also the channel characteristics can be derived from these soundings.

For the present study soundings from both the Upper and the Lower Meghna Rivers were used. Furthermore soundings from the Padma River were also studied (as stated before) for a study of the river processes in the Lower Meghna the conditions in the Padma River have to be considered too. Figure B.3.3 provides an overview of the availability of soundings of the Upper, Lower and Padma Rivers.



Overview of BIWTA soundings used

Figure B.3.3

Soundings of the Padma / Lower Meghna were available during the short-term study for the following years:

Year	Scale
1968	1: 25,000
1975	1: 50,000
1976	1: 50,000
1977	1: 50,000
1983	1: 50,000
1984	1: 50,000
1988	1: 50,000
1990	1: 50,000

B.3.2.6 Bed material

Hardly any information is available on the bed material present in the Upper and Lower Meghna Rivers. Some data are provided in NEDECO (1967), notably D_{50} and D_{90} values of some bed material samples in both rivers. Only the location of these samples is indicated, no information is provided where they were taken in the river and at what depth. These data are of limited use only.

Information on the bed material of the Padma River is not known either, but some data can be used from studies of the Ganges (NEDECO, 1983) and the Jamuna Rivers (RPT/NEDECO/BCL, 1087). It may be assumed that the bed material in the Padma River is at least slightly smaller than the average composition of the bed material of these two rivers. This leads to a first estimate of some 0.15 mm.

B.3.2.7 Sediment transport

Only a limited number of results of suspended load measurements in the Upper Meghna River are available. These measurements have been carried out in 1970 at Bhairab Bazar. Only data for the "coarse" fraction (with $D > 0.07$ mm) were used in the present study. No information is available how these measurements were done. For the time being it is assumed that they were collected in the same way as the sediment transport measurements in the Jamuna River at Bhadurabad. No suspended measurements are available for the Lower Meghna River. Data on the sediment transport in the Padma River are discussed by the China - Bangladesh Joint Expert Team (1991).

B.3.2.8 Literature

For the geology and geomorphology of the Upper and Lower Meghna River the most important literature are the articles by Morgan and MacIntyre (1959) and Coleman (1969). Furthermore, recently a book (Haroum et Rashid, 1991) become available, that provides relevant information.

In the past some more studies have been carried out of the Meghna river, like NEDECO (1967), Galay (1980) and Kalam (1983). These previous studies are to some extent useful in gaining understanding of the processes that take place in the Lower Meghna River.

B.3.3 Additionally collected data

B.3.3.1 Introduction

In the preceding Section an overview is given of the available data on the Upper and Lower Meghna Rivers and on the Padma River. In the inception phase it was decided that still some data were missing that were considered as essential for the present study. This related in particular to the bed configuration in the river reach near Chandpur but also to some other reaches (Munshiganj). Furthermore it was felt necessary to collect some more data on the bed material of the Upper and Lower Meghna Rivers and of the Padma River. In this Section the collection of the additional data is described.

B.3.3.2 Soundings

Soundings were made of the Padma and the Lower Meghna River during two periods. The first measuring campaign was in March 1991. The second measuring campaign was in August 1991.

The first campaign (of March 1991) covered the whole reach of the Padma and the Lower Meghna River between Mawa and Haimchar. Char levels were measured only to a limited extent due to the fact that the river was flowing at rather low levels.

The campaign of August 1991 covered only the Lower Meghna River from its confluence with the Upper Meghna River down to Haimchar. During both measurements the same procedure was applied as used for the BITWA soundings (a grid of some 250 m and positioning with the help of the Decca positioning system).

B.3.3.3 Bed samples

Bed samples were taken from the Upper and Lower Meghna Rivers over the whole reach of interest. Also samples were taken from the Padma River between the Mawa and the confluence with the Upper Meghna River. The bed samples were collected approximately every 5 km at three locations in each cross-section (left, middle and right).

B.3.3.4 Miscellaneous

During the August 1991 measuring campaigns also some velocity measurements were done to verify the computations with the 2-dimensional mathematical model (see Annex C). These measurements could be used to check the roughness coefficients applied in these model computations.

B.3.4 **Processing and analysis**

In this section a summarized description is given of the processing and analysis of the available and additionally collected data. This description deals with:

(1) the satellite images and the maps;
(2) BWDB soundings;
(3) BIWTA soundings;
(4) bed samples.

Re (1) Satellite images and old maps

To identify morphological changes in the Upper and Lower Meghna Rivers and in the Padma River, satellite images of the available years were mutually compared. To do this, the different images had to be on the same scale while ideally also the water levels should be equal.

The water levels in the Upper Meghna were not available at the time of the analysis. Water level data of the Lower Meghna River are listed in Table B.3.1. As can be deducted from that Table, all satellite images were obtained with approximately the same (low) water level.

Since all available images are at a slightly different scale an attempt was made to make all images at the same scale. An overlay was made for every satellite image and a few control points were marked. These control points were small lakes and confluences of small rivers which position not changing over the years. With a photocopier with the possibility of enlarging and reducing in horizontal and vertical direction independently, the overlays were brought to approximately the same scale (which is approximately 1:250.-000). For the maps of the Lower Meghna River for the years 1938/49 - 1952/53 - 1960 and 1963 the same procedure was followed. Because the accuracy that could be obtained in this way is limited, and because the images were not geometrically corrected, the multi-temporal comparison of the different images is done by considering only small reaches of the river at a time. If larger reaches were compared at a time, the scale differences became too large and the comparison became inaccurate.

The bank erosion which can be deduced from the satellite images of different years is used to predict the future developments of the different problem sites. Due to scale differences and differences in water level the estimated erosion and thus the predicted erosion rate is not very reliable. It should be considered as an estimate only of the magnitude of the local bank erosion. All the problem sites along the Upper Meghna are situated at outer bends so for all sites some erosion is expected even for sites where satellite images show no difference. The erosion rates, however, are quite different for the various problem sites.

Re (2) BWDB cross-sectional data

An analysis of some of the cross-sectional data was made to compare these cross-sections for different years. The measurements have been carried out during low stage, and it was assumed that the flood stage morphology did not differ significantly from the low flow stage. Hence the bankfull water level was used as the relevant level for which the river characteristics could be determined.

Each cross section was analyzed for four years, notably 1982, 1986, 1987 and 1990. For each cross-section the following characteristics were estimated in order to identify any systematic changes in the cross-sections over the years:

- distance of the 50% conveyance point to the right bank;
- average bed level of the individual channels;
- maximum depth in the cross-section;
- distance of maximum depth to the right bank;
- average level of all channels and bars;
- width of the main channel;
- average depth of the main channel.

The above analysis was carried out for the following cross-sections: M#20, M#19, M#18, M#14 of the Upper Meghna River, and M#3, M#2, M#2-1 M#1-1 and M#1 of the Lower Meghna River.

Re (3) BIWTA soundings

The BIWTA soundings were mostly used for the determination of the river characteristics, as supporting information on the channel and bar patterns in the Padma and Lower Meghna River and for the analysis of the scour phenomena in the Upper and Lower Meghna River.

For the determination of the river characteristics of the Upper and Lower Meghna Rivers selected cross-sections were analyzed as far as their widths and the average depths is concerned. All data were related to the bankfull level.

The channel and bar pattern and its changes through the years could be derived from the satellite images. The actual channel dimensions and their changes could be derived from the BIWTA soundings. This provided additional information about the river morphological processes and was used in defining the worst cases for the 2-dimensional flow computations and the local scour models.

The scour at the different sites where bank erosion was occurring could also be studied on the basis of the BIWTA sounding maps. The detailed information on the bed topography in the eroding reaches allowed for the identification of the scour phenomena responsible for the bank erosion. Also this interpretation was mostly done "by hand", so without the use of data processing programs apart from simple spread sheet programs.

Re (4) Bed samples

The bed samples taken in the Upper and the Lower Meghna Rivers and in the Padma River were analyzed for their size distribution at the River Research Institute (RRI) at Faridpur. This was done by a combination of sieving (for sand down to 0.07 mm) and hydrometer tests (for the finer fractions). Next the results were processed by means of spread sheet programs and ultimately the average bed material characteristics of the three river reaches were derived. In doing this is was assumed that the decrease in size of the bed material (usually occurring due to a combination of abrasion and longitudinal sorting) was negligible over the short reaches considered here.

B.4 RIVER CHARACTERISTICS

B.4.1 Introduction

This Chapter discusses the characteristics of the Upper and Lower Meghna Rivers. As discussed before (in Chapter 1) the Upper and the Lower Meghna Rivers have quite different characteristics. The Lower Meghna River is more the continuation of the Padma rather than the lower course of the Upper Meghna River. This explains also the structure of this Chapter. After Section 4.2 with a brief description of the geological and historical setting of the Meghna River (including the Ganges and Brahmaputra Rivers), the Upper Meghna River is discussed first. This is done in Section 4.3. Section 4.4 deals with the Lower Meghna River, but because of the importance of the Padma River for the Lower Meghna River, also the characteristics of the Padma River are taken into account. Hence, the river system discussed in Section 4.4 is referred to as the Padma/Lower Meghna River system.

The river characteristics discussed here are similar for both river systems. Subsequently the following is dealt with:

- short description of the river and its basin;
- hydrology;
- planform characteristics;
- channel dimensions;
- hydraulic parameters;
- bed material; and
- sediment transport.

This description is based on the data available on the two river systems, as listed in Chapter 3.

In the last Subsection ("Synthesis") an attempt is made to interpret the river characteristics of each of the two river systems in an integrated way. This is a first step towards the overall understanding of the rivers and their behaviour, a "must" for the interpretation of the historical bank line changes and for the prediction of the future bank line developments, and also a "must" for the specification of design boundary conditions for any bank protection works.

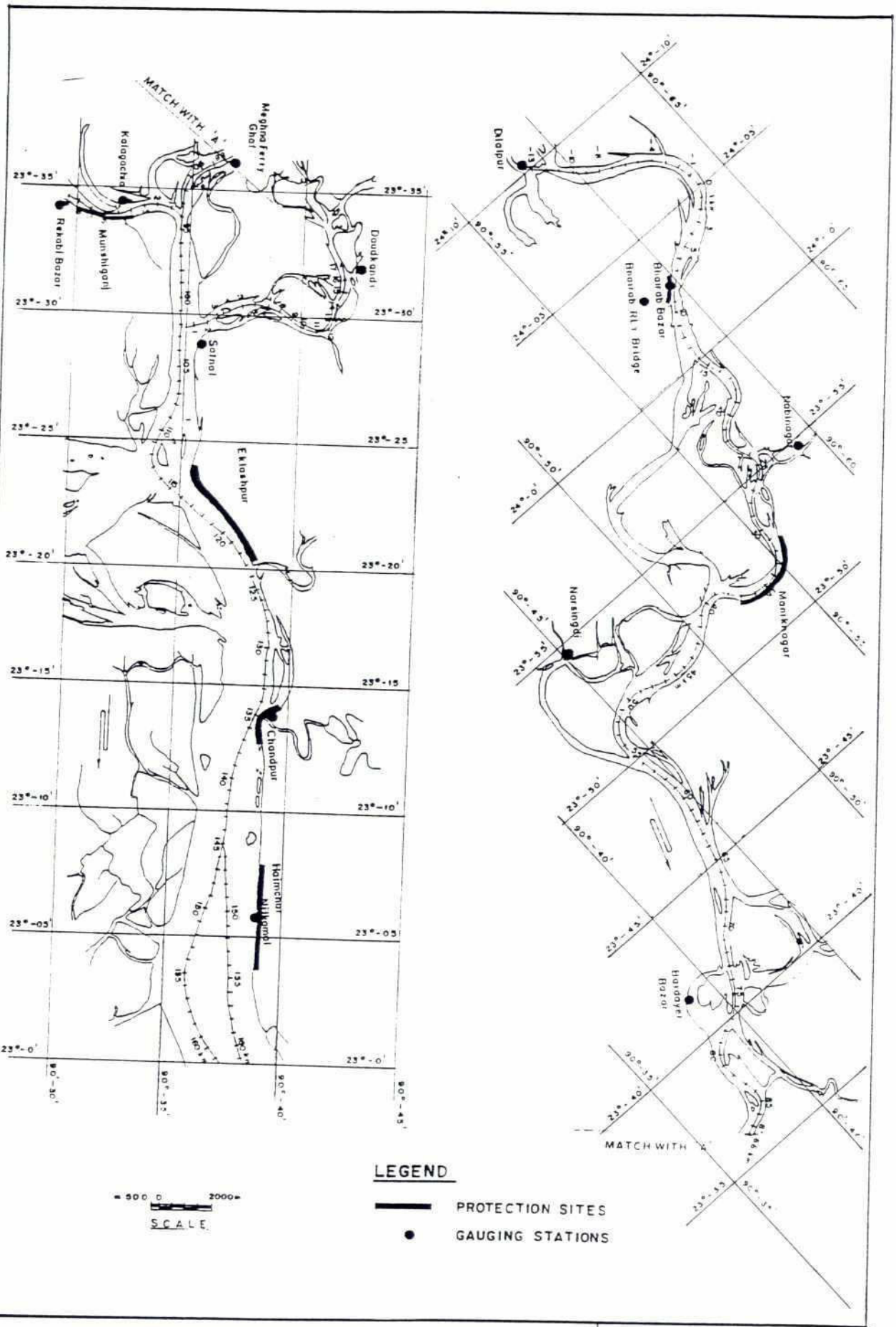
For a description of the river characteristics it is convenient to use a chainage along the river reaches as many of the river parameters vary along the river. No formal chainage has been established along the river reaches under consideration. Hence a tentative chainage was established. This chainage is indicated in Figure B.4.1. It starts along the Upper Meghna with Cross-section M#20 as km 0, the confluence with the Padma River at approximately km 110 and it continues along the Lower Meghna until Haimchar as km 150. Along the Padma River the chainage starts at Mawa with km 0 and its continues to the confluence with the Upper Meghna River as approximately km 35. The indicated chainage is only approximate, and is of course affected by changes in the courses of the rivers. Therefore it is not meant to be authorative, but should be considered only as a help in presenting some data on the rivers under consideration.

The chainage of some important stations is indicated hereafter:

Station	River	Chainage (km)
Bhairab Bazar	Upper Meghna River	8
Meghna Ferry ghat	Upper Meghna River	88
Confluence Upper Meghna River-Padma River	Upper Meghna River	about 115
Mawa	Padma River	0
Confluence Padma River -Upper Meghna River	Padma River	about 35
Chandpur	Lower Meghna River	135
Haimchar	Lower Meghna River	about 150

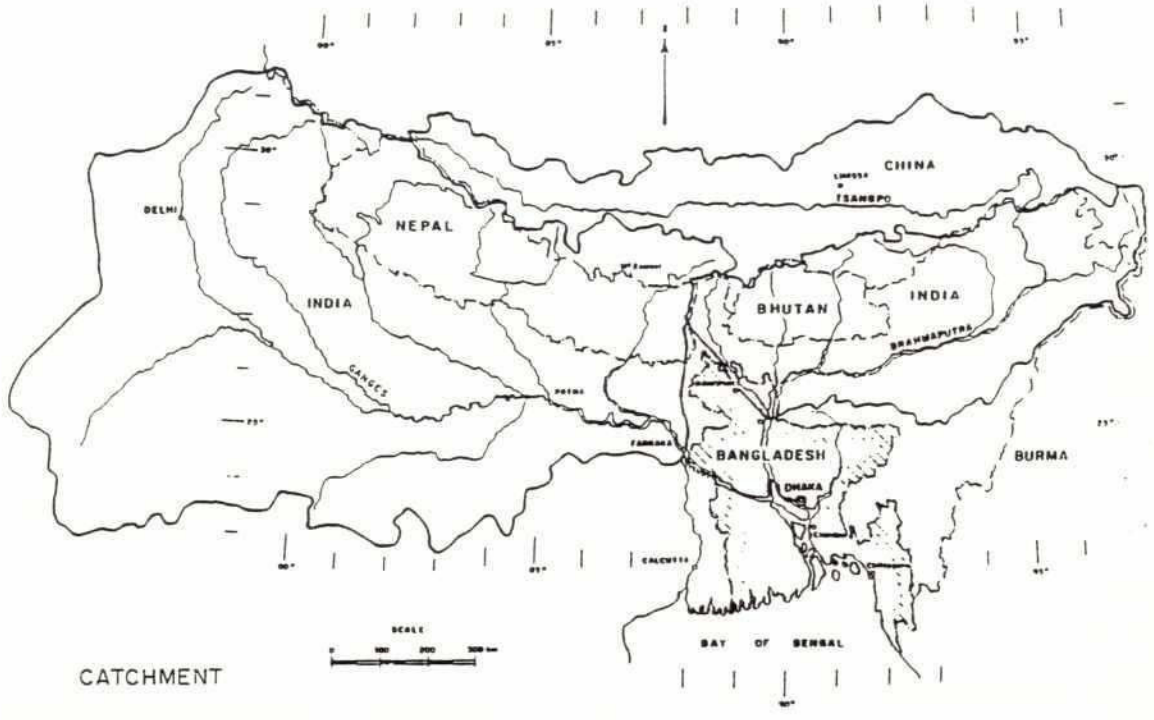
B.4.2 **Geological and historical setting**

The (Lower) Meghna River flows through the lower part of the Bengal Basin and it carries the combined discharge of the Ganges, Brahmaputra and the Meghna Rivers. The drainage basins of these rivers is shown in on Figure B.4.2; their total area amounts to some 1,637,000 km^2. The combined rivers drain a considerable part of the Himalayas. The Brahmaputra River originates on the northern slopes as the Tsang-Po River. It runs first eastward until it breaks as the Dihang River through the Himalayan range in southern direction. Next it flows as Brahmaputra River in south-western direction through Assam and finally turns south near the Bangladesh border. In Bangladesh south of the offtake of the Old Brahmaputra River it is called the Jamuna River. In Assam and in Bangladesh some tributaries of the Brahmaputra River (like the Manas, Gadhadhar and the Teesta Rivers) drain part of the southern slopes of the Himalayas. The Ganges River drains the more western parts of the southern slopes of the Himalayas and collects the discharge of many large tributaries (like the Ghaghara, Gandak and Kosi Rivers).



Tentative chainage of Meghna Rivers

Figure B.4.1



Drainage basins of the Brahmaputra, Ganges and Meghna Rivers

FIGURE B.4.2

The drainage area of these three rivers is located in one of the geologically most active areas of the world. The plain of the north east Indian sub-continent is bounded to the north by the Himalayas and to the east by the range of mountains running North-South through Burma. On a geological time scale the northern Indian plate structure is sliding under the South-East Asian Plate (see Figure B.4.3), forming the Himalayas and in doing so undergoes considerable warping and shearing. On the East the two plates are rubbing against each other. Hence the Bengal Basin and its adjacent area is an active tectonic area. Morgan & McIntyre (1959) suggested that compressional and shear forces may have influenced the Padma and Lower Meghna courses. Furthermore it has been suggested by the same authors that there may be a major fault at depth or a subsiding trough along the axis of the Jamuna-Meghna River system.

The Bengal Basin has been in filled by sediments washed down from the surrounding mountains, especially from the Himalayas, where the slopes are deeper and the rocks are not so consolidated. It is estimated that the depths of sediments may be some 8 km. These sediments are underlain by very old rocks. North of the Upper Meghna River these old rocks crop up as the Meghalaya Plateau.

Haroun et Rashid (1991) divides Bangladesh in a number of sub-regions and units, and presents details as to the tectonic movements of the different units. This information is summarized in Figure B.4.4. For the present study the following observations are of interest:

(1) The upstream reaches of the Upper Meghna River are located in areas that are sinking away. Estimates of the rate of sinking of this Sylhet basin (also called Hoar area) are 9-12 m over the last two centuries (Morgan and McIntyre, 1959) and 0.9-1.5 m over the last 50 years (Haroun et Rashid, 1991).

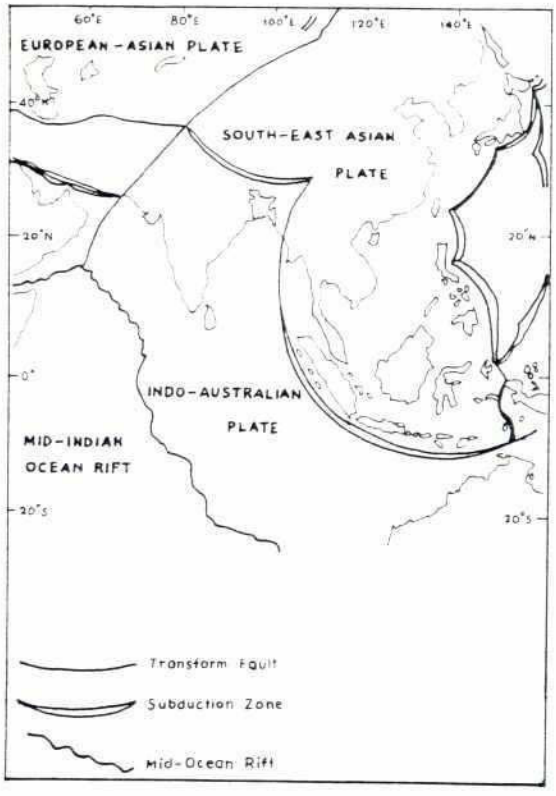


Figure B.4.3 Tectonic plates

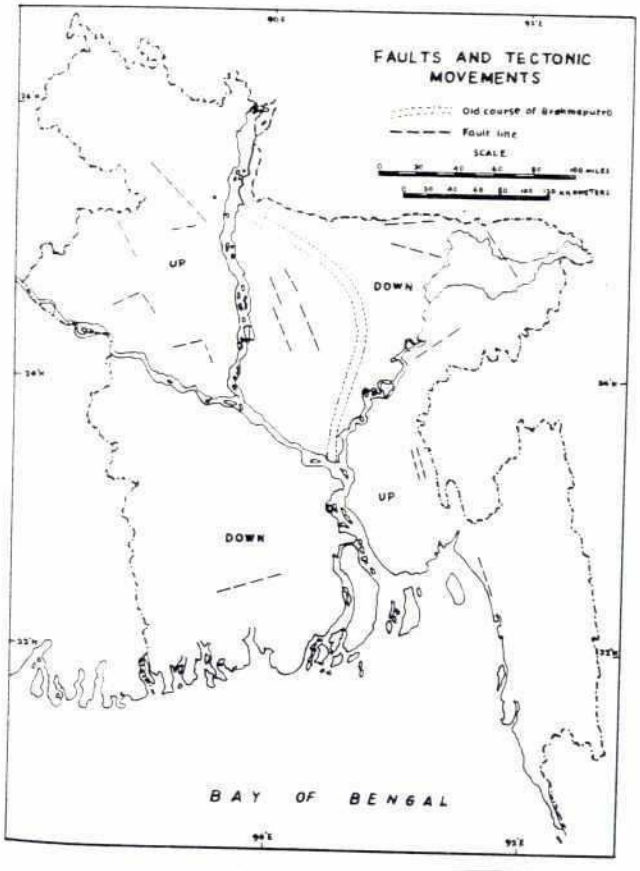


Figure B.4.4 Faults and tectonic movements

Note:
These two figures were taken from Haroun et Rashed (1991)

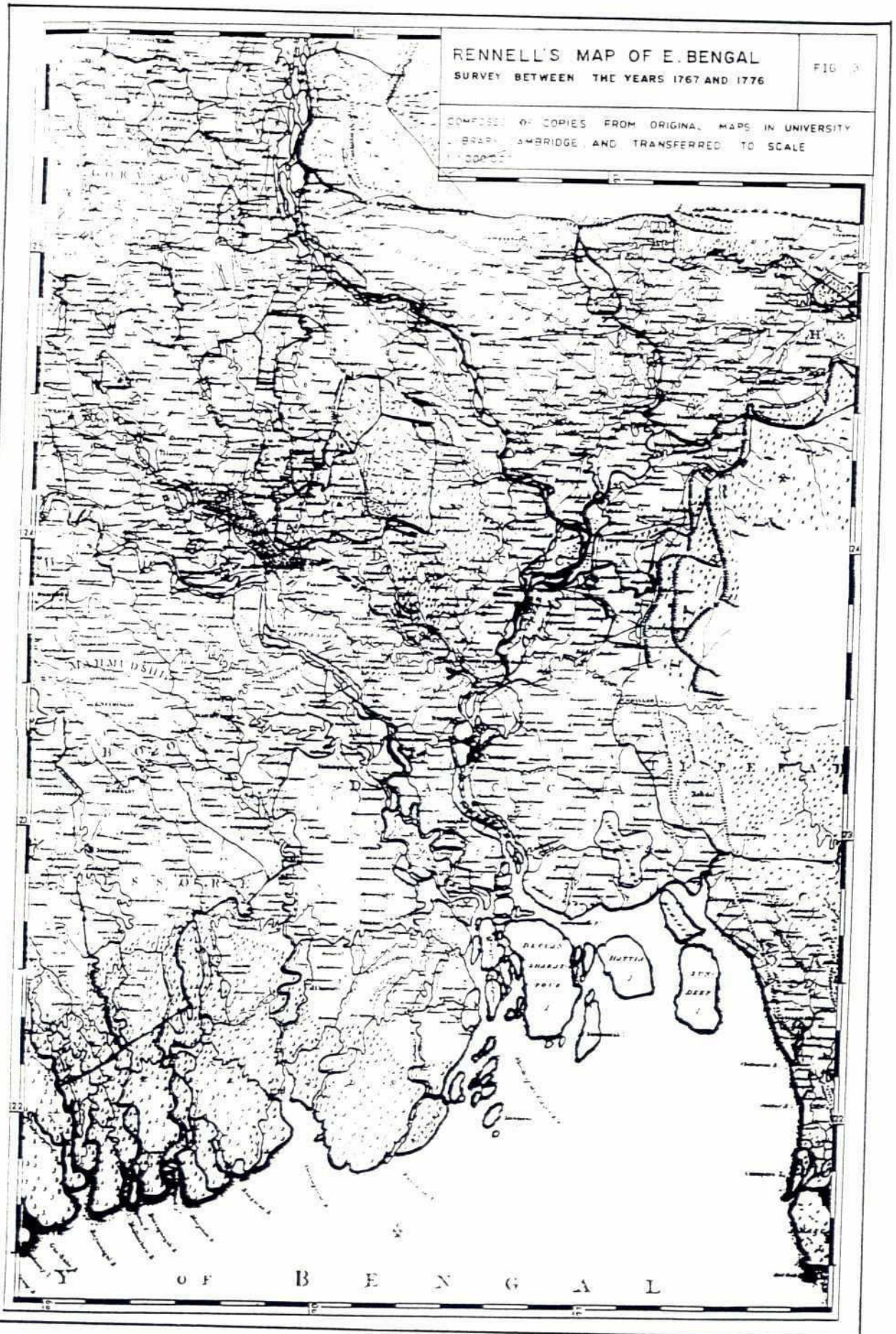
(2) The part of Bangladesh east of the Lower Meghna River is according to this Figure rising, but this seems contradictory to the movements of the Ganges river mouth over the last centuries (see hereafter).

Over the past centuries substantial changes have occurred in the location of the major rivers within the Bengal Basin. Here only a summary of these changes is given. For more details reference is made to Morgan and McIntyre (1959). Two aspects are particularly important:

(1) In the past (before 1780) the Brahmaputra river did not follow the present Jamuna course, but upstream of Bahadurabad it turned south-east ward following the course of the present Old Brahmaputra. The Brahmaputra river joined the Meghna River at Bhairab Bazar, so the Meghna River downstream of Bhairab Bazar carried also the discharge of the Brahmaputra. Hence, the present discharge of the Upper Meghna River is much less than before this major avulsion of the Brahmaputra. A comparison of the Rennell's map (surveyed between 1767 and 1776, see Figure B.4.5) and the present situation shows that the river which is presently called the Old Brahmaputra had much larger dimensions than the present river. There is no certainty as to the cause of the major avulsion of the Brahmaputra River. Some possible causes are discussed by Morgan and McIntyre (1967) and Coleman (1969).

(2) As can also be seen on the Rennell's map (Figure B.4.5) the mouth of the Ganges River was different from the mouth of the (in that time) Brahmaputra/Meghna river system. Since 1780 the mouth of the Ganges River, by then enlarged by the contribution of the Brahmaputra/Jamuna River, has shifted over quite some distance eastward. This was a continuation of the movement of the mouth of the Ganges River over the preceding centuries. It seems that this river and its mouth has gradually covered the area between Calcutta and its present course. A possible explanation of this would be the sinking away of the lower part of the Bengal Basin (see Figure B.4.4), which may have "attracted" the Ganges River. Another cause may be the sharp turn of the river towards the south which may have been subject to continued erosion (in fact the same process may still be active at present, see Chapters 5 and 6).

Summarizing the above discussion it may be stated that many changes in the river systems under consideration have occurred both in geological and historical times. It may therefore be anticipated that the rivers reaches under consideration have not stabilized in their present position and level. This will be discussed in more detail in the next Chapters. It is against this background that also the next description of the Upper Meghna River and Padma/Lower Meghna River systems has to be understood.



Rennell's map

Figure B.4.5

B.4.3 Upper Meghna River

B.4.3.1 Short description of the river

The upper Meghna River flows in the northeastern part of Bangladesh (see figure B.1). The Upper Meghna carries the combined flow of the Surma and the Kusiyara Rivers which originate in the Indian hills northeast of Bangladesh. The Surma River flows through the Sylhet area which is rapidly sinking away. A number of tributaries of the Surma originate from the Sisang hills in India and from piedmont areas. They bring quite some sediment (boulders, gravel, sand), that most probably settles in the Sylhet area.

Going in downstream direction, the Meghna River is joined by the Old Brahmaputra at Bhairab Bazar. The Dhaleswari is another tributary (and another distributary from the Jamuna system) and it joins the Meghna River at Munshiganj on the right bank. Some tributaries that originate from the Tripura hills join the Upper Meghna (and even the Lower Meghna) at the left bank. Although having some reaches with a system of various channels, the Upper Meghna River can be characterized as a river mainly meandering within a well defined high water bed and having flood discharges up to some 20.000 m3/s.

The Upper Meghna flows through probably, structurally, the most active part of the Bengal Basin, notably the Sylhet depression, that has subsided about 10 metres within the last several hundred years (see before). This subsidence may be a combination of compaction together with tectonic activity (related to the major fault system bounding the northern side of the area). Together with the compaction and the tectonic activity another factor affects the drainage of the Sylhet area. This deeply flooded area is in fact an area which is inundated by the backwaters of the Ganges and the Jamuna. Because of the high water levels in these rivers, the floods from the Sylhet area do not have sufficient slope to be rapidly evacuated to the Bay of Bengal. This "impeded drainage" causes the floodwaters to accumulate in the deeply flooded area, causing silting up, and so creating an enormous basin which only gradually drains into the Meghna. The prevailing morphological action in this upper catchment area is sedimentation rather than erosion (Hoar development reconnaissance study, 1986). See also Section 4.3.7.

B.4.3.2 Hydrology

The hydrological conditions (stages and discharges) in the Upper Meghna River are extensively discussed in Annex A. Here only those elements which are relevant for the morphological study are highlighted. The salient hydrological features of the upper Meghna River are:

(1) **Stages**
The average daily water levels at Bhairab Bazar vary between 0.81 m and 7.65 m (see Appendix IV of Annex A). The lowest figure demonstrates the small slope along the river during lowest discharges. A duration curve of the daily average water levels at Bhairab Bazar is provided in Appendix IV of Annex A.

(2) **Tidal influence**
The stages along the Upper Meghna are subjected to tidal influence. During low flows in the Upper Meghna River the tidal range near the confluence with the Padma River is about 1 m, and under those conditions still a vertical tide of some 0.2 m is noticeable in Bhairab Bazar.

(3) **Discharges**
The maximum discharges at Bhairab Bazar are about 20,000 m^3/s (return period 100 years, see also Section 7.2 of Annex A). A duration curve for the daily discharges could be prepared by correlating the duration curve of the daily water levels at Bhairab Bazar with the rating curve of Bhairab Bazar. This duration curve is shown in Figure B.4.5.

These hydrological data are used in Section B.4.3.5 for the determination of the hydraulic conditions in the Upper Meghna River.

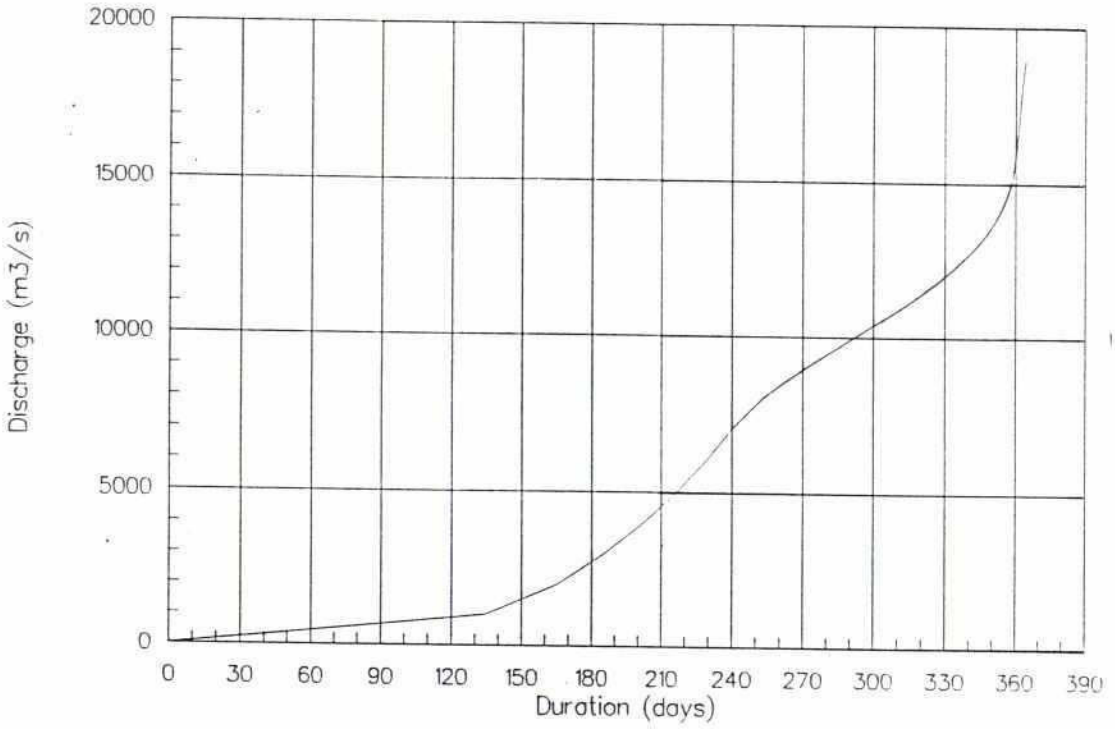


Figure B.4.6 Duration curves of the daily discharges at Bhairab Bazar

B.4.3.3 **Planform characteristics**

In this Chapter the planform characteristics of the Upper Meghna River are discussed. Subsequently the following aspects are dealt with:

(1) overall planform;
(2) differences in planform since the 18th century;
(3) characteristics of bends.

Recent changes in planform are discussed in Section B.5.2 of this Annex.

Re (1) **Overall planform**

Usually the overall planform of a river can be deduced from maps or satellite images. In the case of the Upper Meghna River, however, this information is misleading. Many reaches can be observed where the river has different parallel channels, so one would be tempted to classify the Upper Meghna River as a braided river. A closer inspection of all the available data reveals, however, that the Upper Meghna River can better be classified as a meandering river.

This can best be illustrated by inspecting the BWDB cross-sections of the Upper Meghna. From this inspection it becomes clear that the Upper Meghna consists mainly of one single channel and over two reaches over two parallel ones of almost similar importance. All the other channels which can be seen clearly on the satellite images carry too little water to be of any importance. The satellite images reveal also many "scars" of abandoned rivers or rivers which carry no water during the low flow season at the right bank and at the left bank of the Upper Meghna.

The explanation for this is probably that the Upper Meghna River flows in a bed that has been shaped by the Brahmaputra River and that the present river is still in the process of adapting its bed to the new ultimate conditions.

Figure B.4.6 presents a planform view of the Upper Meghna River. On it is indicated which channels can be considered as the main channel(s). This is to be considered as the "real" planform of the Upper Meghna River. This is much more a meandering river with maybe some anastomosing channels than the complete picture with many parallel channels.

Re (2) **Differences in planform since the 18th century**

Considering the above a logic step is to see whether the planform of the Upper Meghna has changed significantly since the 18th century (when the Brahmaputra abandoned its course to the present Jamuna course). This can be done by comparing the map of Rennell with a recent map. This is done in Figure B.4.7.

The following observations are made:

(1) Although there are clear changes, there seems to be some overall correspondence in the location of some of the channels.

(2) Also in 1776 the Upper Meghna consisted of several channels (in fact it was a braided river like the present Jamuna River is a braided river, see Klaassen and Vermeer (1988), but the 1776 channels were more straight. At present, the individual channels look more tortuous. This is also an evidence of the decreased discharge of the present Upper Meghna River. The present Upper Meghna River seems to flow in the old Brahmaputra bed, but with a much smaller discharge. According to Leopold et al (1964) the curves of the meanders scale with the discharge they carry.

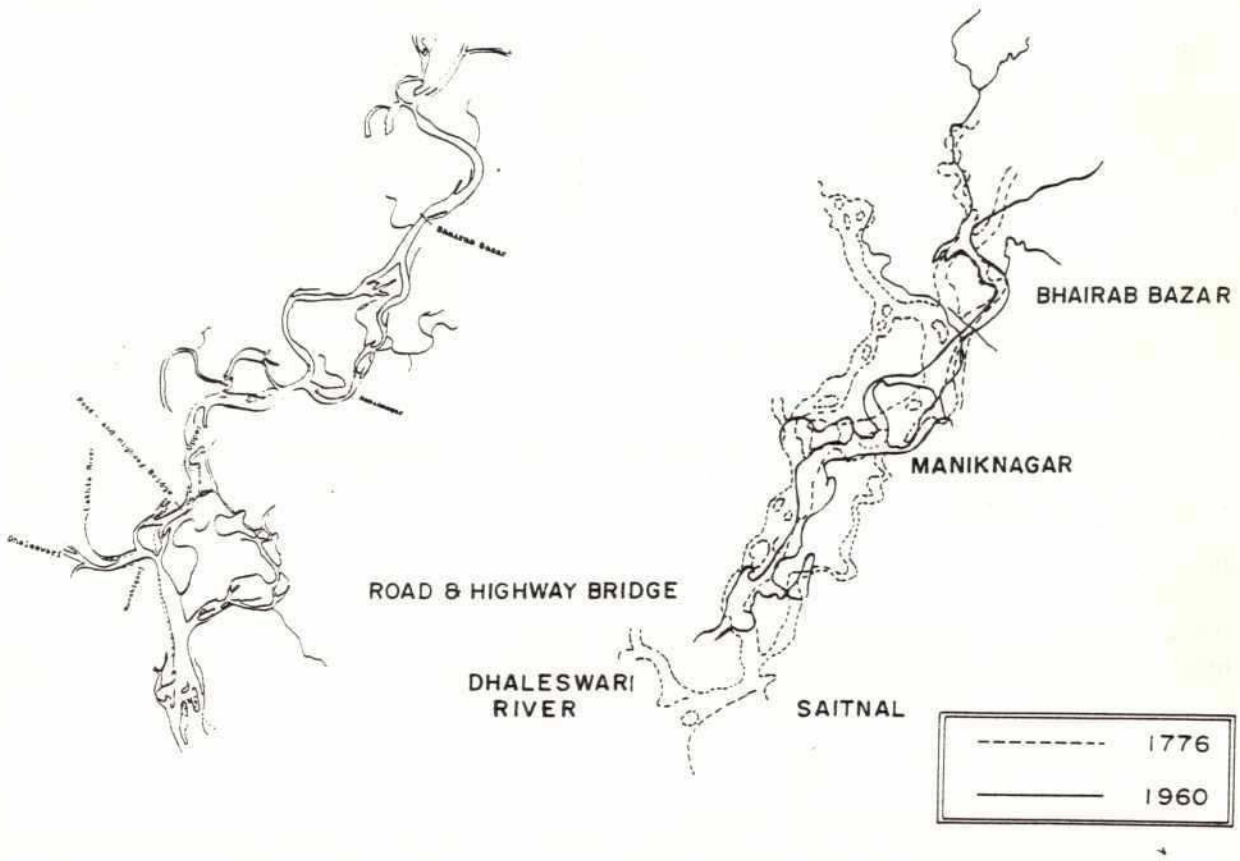


Figure B.4.7 Planform of the Upper Meghna River

Figure B.4.8 Comparison of Rennell's map and the 1960 map

Apparently, some of the curved channels have adapted their curvature to the new discharge conditions.

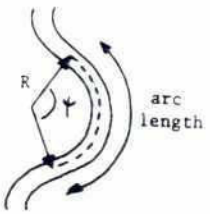
(3) The confluence with the Dhaleswari River was more to the south. The Lakhya river, which at present joins the Dhaleswari just upstream of the confluence with the Upper Meghna, used to flow at approximately the same location as nowadays.

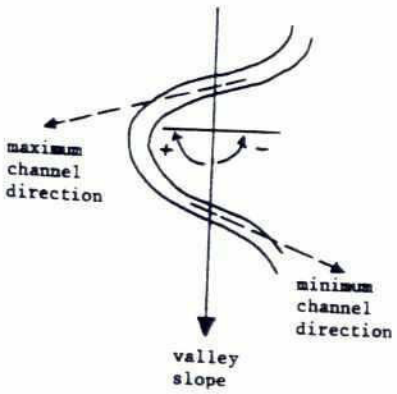
(4) A tributary of the Upper Meghna River in 1776, the Little Meghna, who flowed from Maniknagar to Satnal roughly, still carries water and can at present, although in a more tortuous form, still be identified.

Although the reliability of Rennell's map is of course not known, nevertheless it can be stated that some changes of the planform of the Upper Meghna have occurred, nevertheless the overall picture supports what was concluded under (1), notably that the Upper Meghna River is still in the process of adapting itself to the new conditions.

Re (3) **Characteristics of bends**

The bend characteristics are of interest for the estimation of the possible bed scour in the Upper Meghna River (see Chapter 7). Some bend characteristics were derived, notably the radius of curvature and the total arc length of the bend. Furthermore the derivation from the valley direction of the beginning and the end of the bend was determined, in accordance with the following notation:





If the beginning or end of the bend exceeds +90 or -90 degrees it implies that the river flows against the slope of the river. This is possible for meandering rivers.

In total 27 bends in the Upper Meghna River were studied using the SPOT images of the year 1989. The bends studied are indicated on Figure B.4.9. Most of the bends are located in reaches where only one channel is present; some of the bends are located in reaches where two channels of approximately the same importance are running "parallel". The characteristics of the river bends are presented in Figure B.4.9, notably:

Figure B.4.10 (a) Channel width versus radius of curvature;
Figure B.4.10 (b) Channel direction versus radius of curvature;
Figure B.4.10 (c) Radius of curvature versus arc length.

The following observations can be made:

(1) The radii of curvature of the main channel vary between 1,250 and 12,500 m, while the arc length varies between 40 and 140 degrees. The same values for the "secondary" channels are 250 to 1000 m, and 40 to 190 degrees.

(2) Regarding the plot of the radius of curvature versus the width of the channels, a comparison can be made with the relationships proposed by Leopold et al (1964). Leopold et al propose the following relationship between the meander length and the channel width and between the meander length and the radius of curvature:

$$\lambda = 6.6\ B^{0.99} \qquad \text{(B.4.1)}$$

$$\lambda = 4.7\ R^{0.98} \qquad \text{(B.4.2)}$$

where λ = meander length (m), B = width of river (m) and R = radius of curvature (m). From these two equations the meander length λ can be eliminated, which results in:

$$B = 0.71\ R^{0.99} \qquad \text{(B.4.3)}$$

This relation has also been drawn in Figure B.4.9. It appears that in comparison with this relationship most channels seem to have a too large radius of curvature. This may however be due to the fact that here the width during low flow conditions is used, while it should be the width during bankfull discharge. For a possible correction see Klaassen and Vermeer (1988).

(3) It can be observed that the deviation of the channel direction does hardly exceed 90 degrees, hence channels that flow opposite the valley slope hardly occur.

(4) There is a clear correlation between the radius of curvature and the arc length of the bends: a large radius of curvature results in (or may be better: allows only) a small arc length.

B.4.3.4 Channel dimensions

Channel dimensions of the Upper Meghna River were determined on the basis of the BWDB soundings. In total 18 cross-sections were analyzed. A complication is the fact that along two reaches two channels are running parallel. For the time being only the "main" channel was considered. From the soundings the following characteristics were obtained:

- cross-sectional area A_b (with a planimeter);
- width B_b (by measuring).

All measurements were done for bankfull level, hence the index b. All channels were approximately perpendicular to the direction of the main channel, hence no correction was needed to compensate for any deviation from the perpendicularity.

From the values of A_b and B_b the bankfull depth h_b can be derived via:

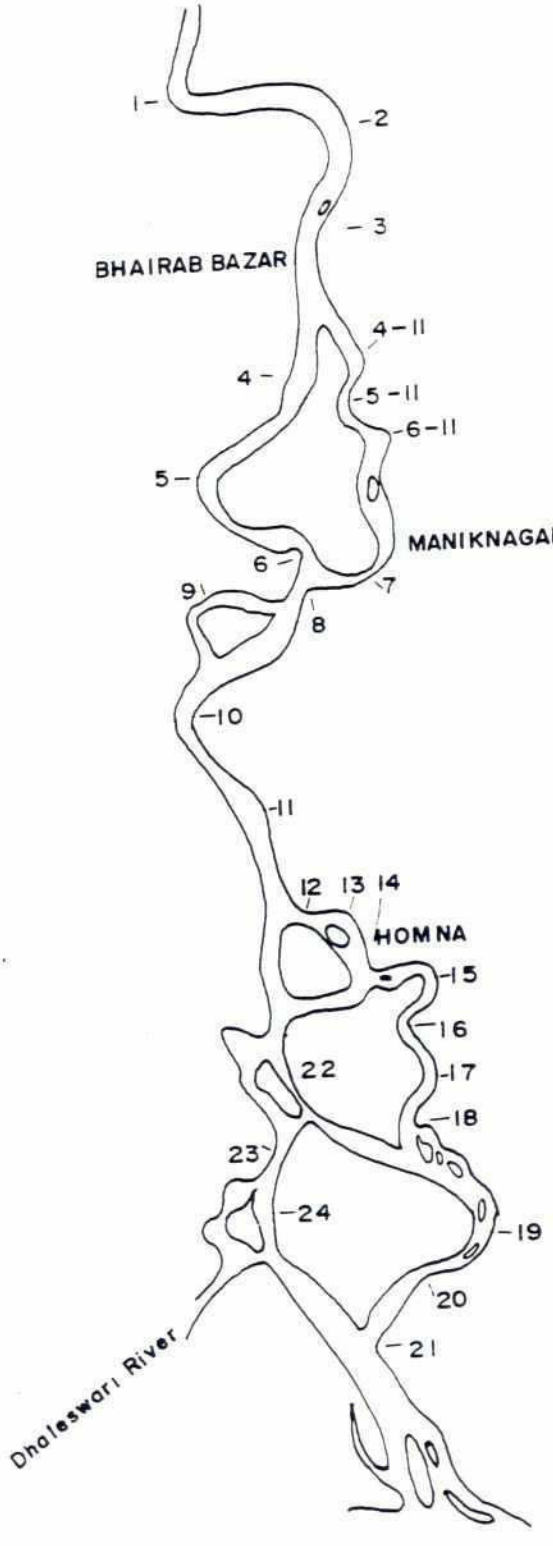
$$h_b = \frac{A_b}{B_b} \qquad \text{(B.4.4)}$$

The values of A_b, B_b and h_b are plotted versus the chainage in Figure B.4.10. From this Figure the following observations can be made:

(1) The average cross-sectional area at bankfull discharge is about 10,000 m^2 over the largest reach of the Upper Meghna River and it increases downstream of the confluence with the Dhaleswari River (km 100).

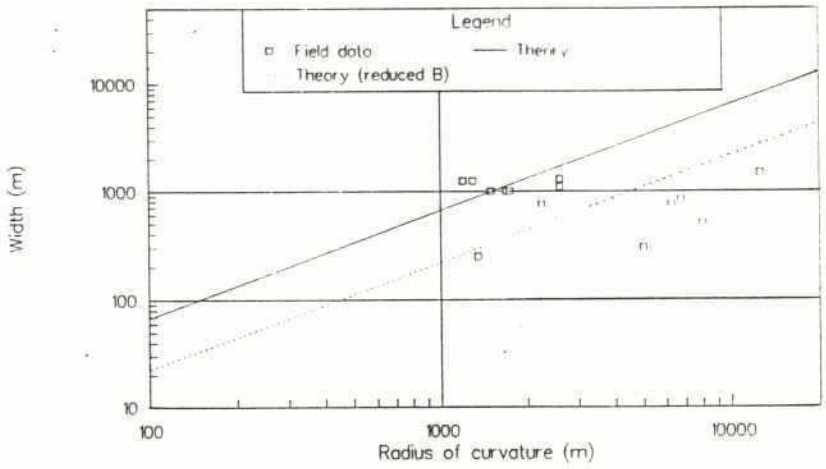
(2) The average bankfull width is some 1,200 m and it increases also downstream of km 100 to some 3,000 m.

(3) The bankfull depth varies between 7 and 14 m, with an average of about 10 m. There is no clear increase downstream of the confluence with the Dhaleswari River.

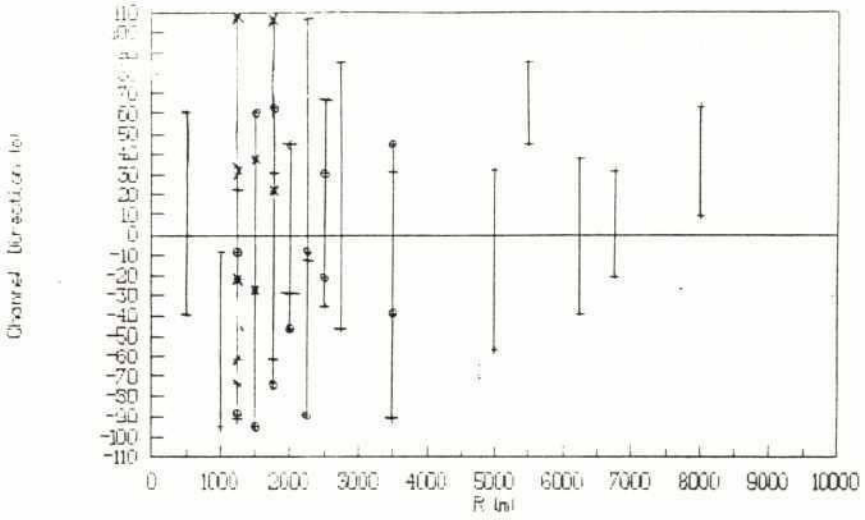


Bends studied

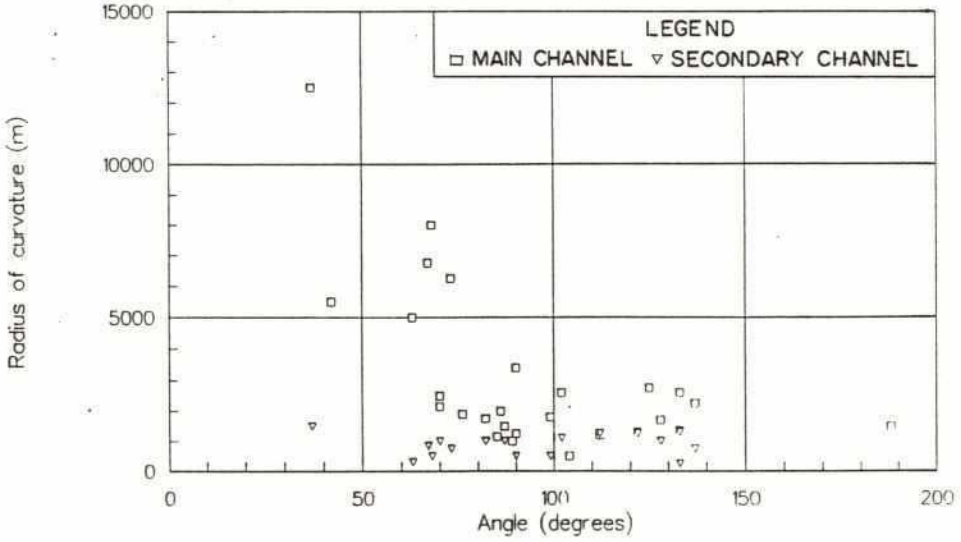
Figure B.4.9



(a) Width of bend versus radius of curvature



(b) Channel direction versus radius of curvature



(c) Radius of curvature versus arc length

Bend characteristics of the Upper Meghna River	Figure B.4.10

It is of interest to compare these channel dimensions with the regime equations which were derived for the Jamuna River and with the original regime equations proposed by Lacey (1947). The former read (Klaassen and Vermeer, 1988b) for the bankfull depth and the bankfull width as:

$$h_b = 0.23\ Q^{0.32} \tag{B.4.5}$$

$$B_b = 16.1\ Q^{0.53} \tag{B.4.6}$$

The regime equations proposed by Lacey (1947) read in SI-units as:

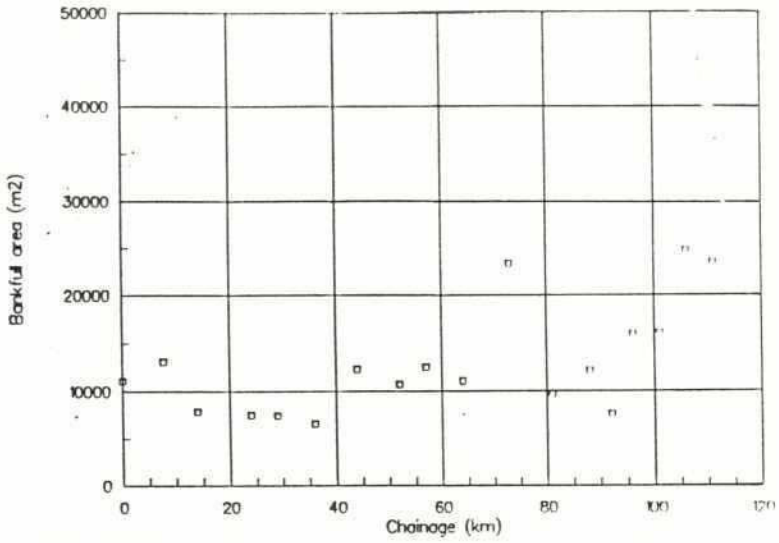
$$h_b = 0.47\ (\frac{Q}{f})^{0.33} \tag{B.4.7}$$

$$B_b = 4.81\ Q^{0.5} \tag{B.4.8}$$

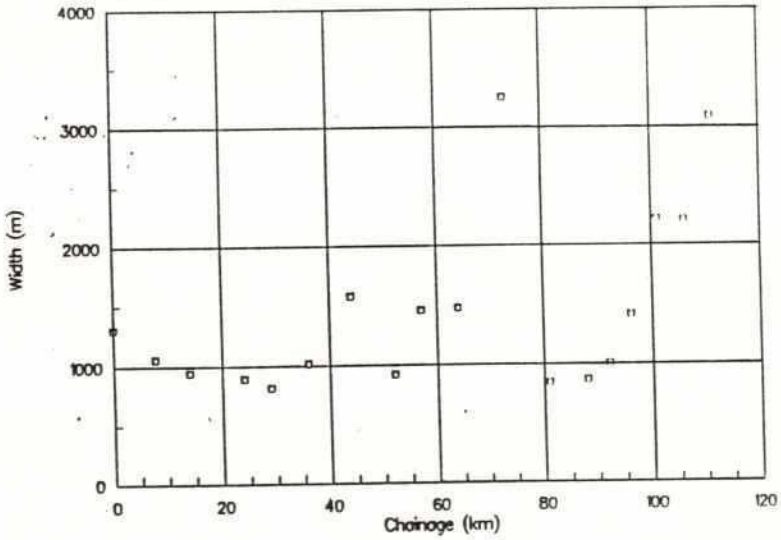
where the silt factor f is defined as:

$$f = 1.59\ D_{50}^{1/2} \tag{B.4.9}$$

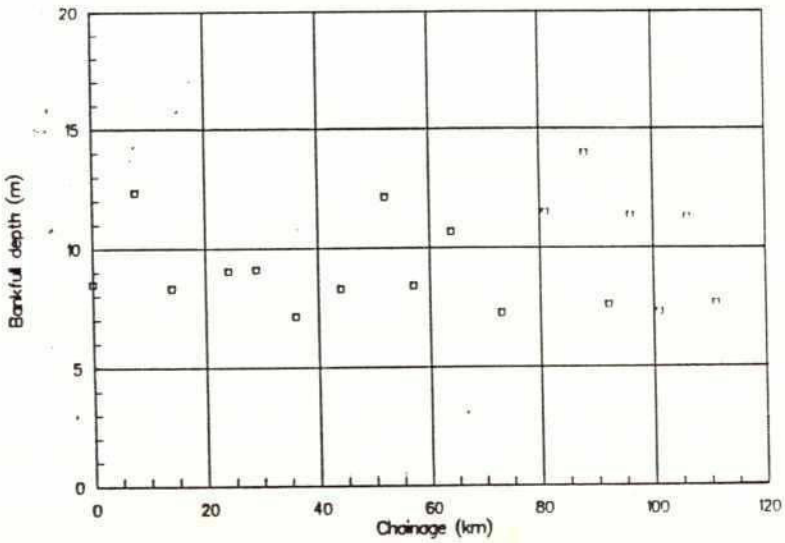
with D_{50} in mm. For the Upper Meghna River, with D_{50} = 0.14 mm (see Section B.4.3.6) f = 0.60.



(a) Bankfull area versus chainage



(b) Bankfull width versus chainage



(c) Bankfull depth versus chainage

Channel dimensions of the Upper Meghna River	Figure B.4.11

In the following Table a comparison is made between the observed and predicted channel dimensions, whereby as bankfull discharge both 8,000 and 11,000 m^3/s was used (see Section B.4.3.5):

TABLE B.4.1 PREDICTED CHANNEL DIMENSIONS UPPER MEGHNA RIVER

Predictor	Klaassen and Vermeer (1988b)		Lacey (1947)		Observed
Bankfull discharge (m^3/s)	8,000	11,000	8,000	11,000	
Bankfull depth (m)	4.08	4.52	10.8	12.00	10
Bankfull width (km)	1.89	2.23	0.43	0.50	1.2

It can be concluded that the observed channel widths in the Upper Meghna River are much smaller than the predicted by Klaassen and Vermeer (1986b), but about 2 times larger than predicted by Lacey (1947). The latter is commonly observed in meandering channels. The observed depths correspond fairly well to the Lacey depth and are much larger than found with the Jamuna predictor. Usually in meandering rivers a smaller bankfull depth is found than according to the Lacey depth. The possible reason for this is discussed in more detail in Section B.4.3.5.

B.4.3.5 **Hydraulic parameters**

Here the hydraulic conditions in the Upper Meghna are discussed as far as relevant for the understanding of the sediment transport phenomena and the river morphology. In particular the water levels will be compared with the bed levels and values for the slopes, water depths and Chezy coefficients are determined. This is done for a variety of discharges. For other hydraulic aspects reference is made to Annex A.

Water levels for different discharges are available for a number of stations along the Upper Meghna River. These water levels have been drawn versus the chainage in Figure B.4.11. For the Upper Meghna River only the reach upstream of km 110 is of interest. The data relate especially to the flood levels with recurrence intervals of 5, 10, 25, 50 and 100 years. From the analysis of the BWDB cross-sections the average bed level was determined together with the bankfull level. Also this information is plotted in Figure B.4.11.

The following observations can be made upon inspection of Figure B.4.11:

(1) Even for flood conditions the water level slopes in the Upper Meghna River are very small, notably in the order of 1.8 m per 100 km (corresponding to $0.2*10^{-4}$). This is much smaller than the present slope of the Jamuna River (in the order of $0.7*10^{-4}$), which occupied the valley of the Upper Meghna River until some 2 centuries ago.

(2) The flood levels are 3 to 4 m above the bankfull level, which is quite a large inundation depth.

An analysis of the level of the banks indicates that bankfull discharge in the Upper Meghna River corresponds to about 8,000 m^3/s, a value which is exceeded about 27 % of the year. This is extremely often.

The conditions at Bhairab Bazar have been considered in more detail. The average bed level (not considering the local constriction, see Section 8.2.2) have been combined with the water levels and slopes as a function of the discharges. The results are presented in Figure B.4.13. It is found that during low discharges the slope is even much smaller, while the Chezy coefficient increases from about 40 to 65 $m^{1/2}/s$. The latter value may be too large as the conveyance of the floodplains was not taken into account.

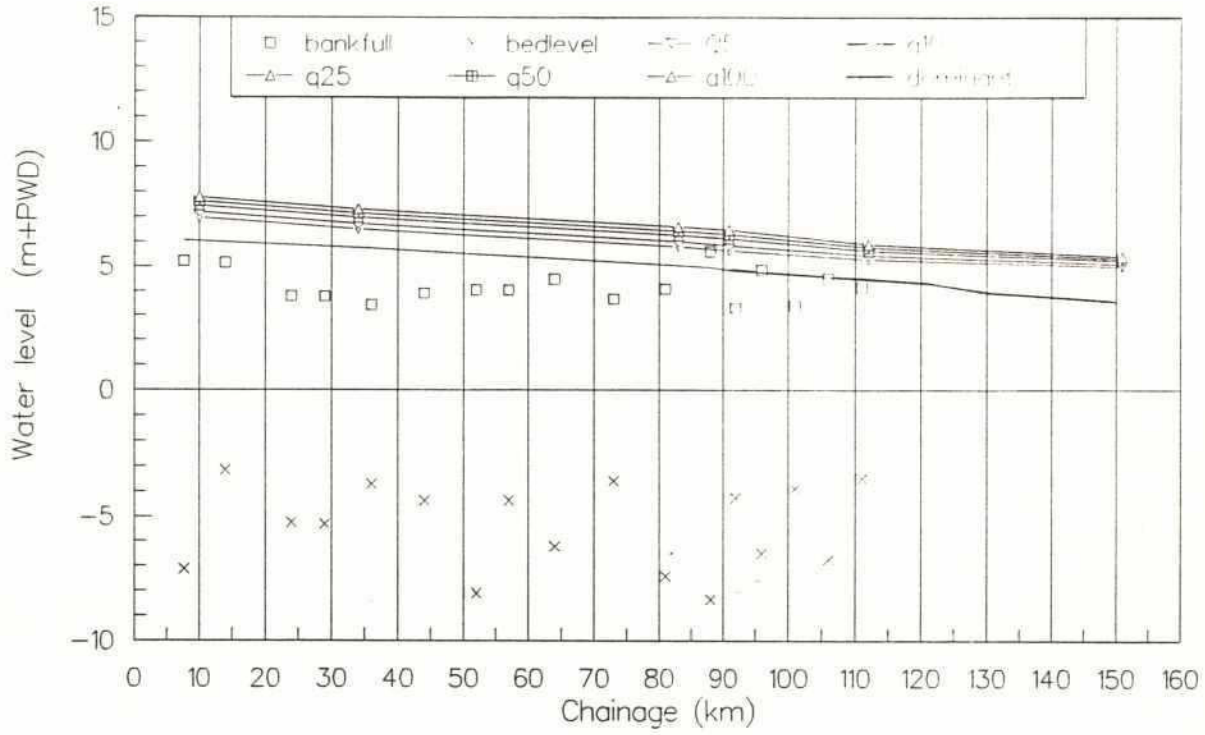


Figure B.4.12 Water levels in the Upper Meghna River

B.4.3.6 **Bed material**

Data on the bed material characteristics of the Upper Meghna River were obtained during the additional data collection phase. Figure B.4.13 presents the results after processing all available data, whereby in Figure B.4.13 (a) the results of the average of the right, middle and left sample is indicated. Figures B.4.13(b) presents the average particle size distribution over the whole reach of the Upper Meghna River.

The following observations are made:

(1) The characteristic particle sizes D_{16}, D_{50} and D_{84} do hardly vary with the chainage, implying that abrasion and longitudinal sorting are not noticeable over such short reaches.

(2) The average values of these characteristic particle sizes are:

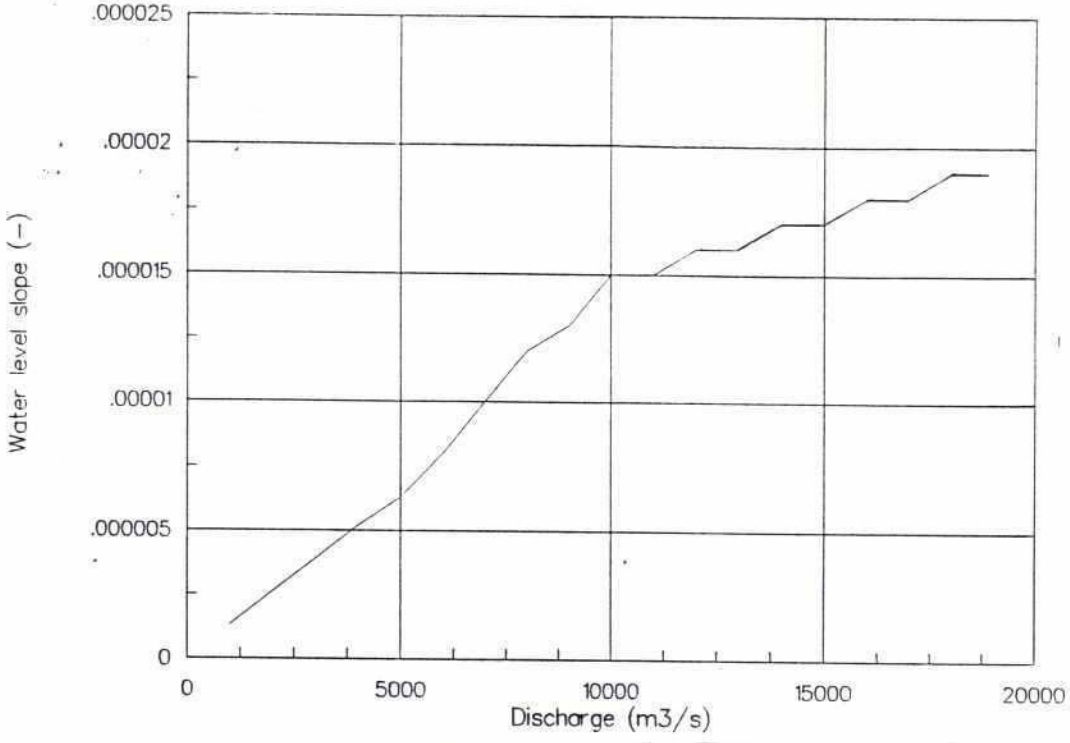
D_{16} = 0.037 mm,
D_{50} = 0.14 mm, and
D_{84} = 0.25 mm.

Hence the bed material of the Upper Meghna can be characterized as rather uniform and fine sand with a small fraction (some 20 %) of finer silt.

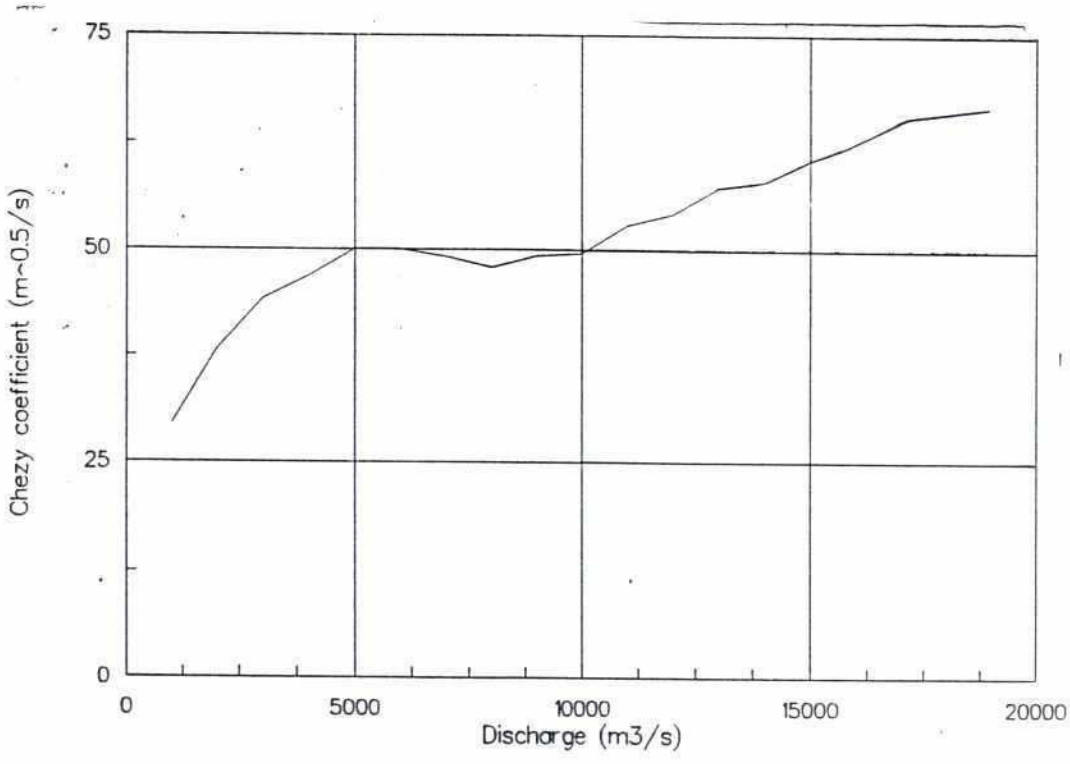
B.4.3.7 Sediment transport

The following aspects of the sediment transport of the Upper Meghna River are dealt with:

(1) Mode of transport
(2) Predicted and measured sediment transport rates
(3) Yearly sediment transport
(4) Dominant discharge

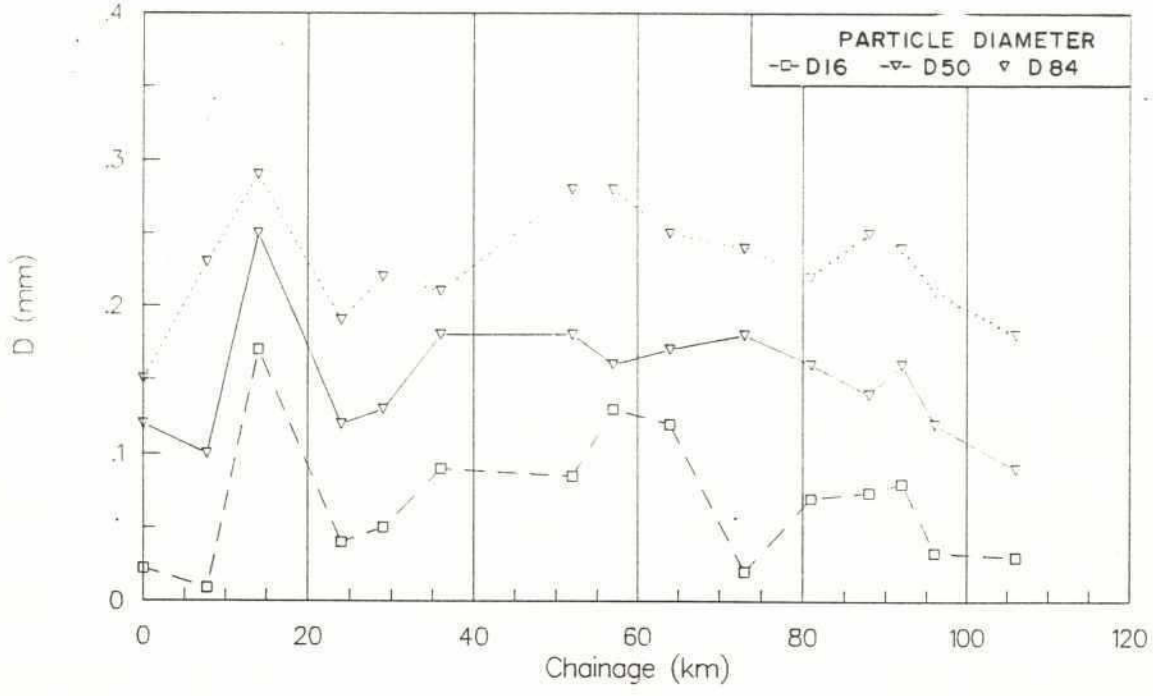


(a) Water level slope

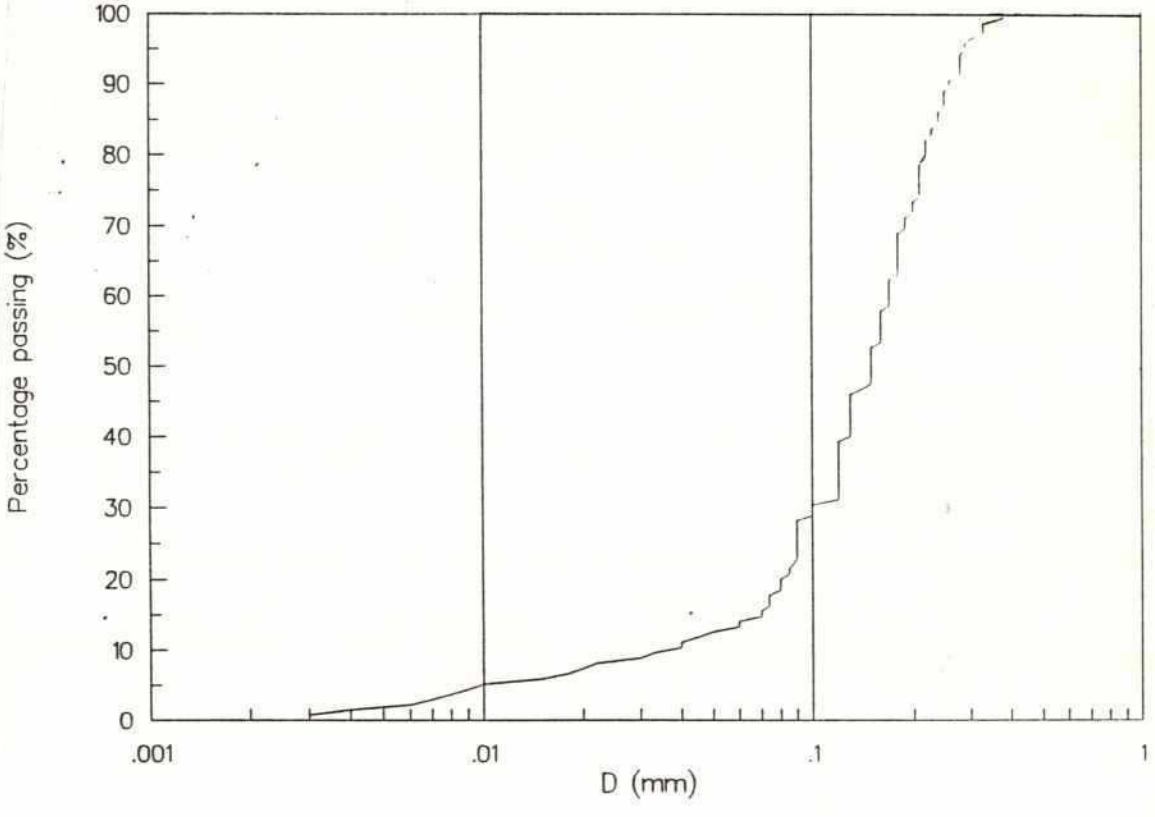


(b) Computed Chezy coefficient

Water level slope and computed Chezy coefficient at Bhairab Bazar as a function of the discharge	Figure B.4.13



(a) Variation of the D_{16}, D_{50} and D_{84} with chainage



Bed material characteristics of the Upper Meghna River	Figure B.4.14

Re (1) **Mode of transport**

The bed material is transported depending on the ratio of the hydraulic shear stresses and the resisting forces, being the bed material characteristics. Whether or not the bed material is in movement can be evaluated with the Shields parameter θ, which is defined as:

$$\theta = \frac{h\,i}{\Delta\,D} \qquad \text{(B.4.10)}$$

where h = water depth (m), i = slope (-), Δ = relative specific density (-), defined as $\Delta = (\rho_s - \rho)/\rho$, where ρ_s = density of sediment (kg/m^3) and ρ = density of water (kg/m^3), and D is a characteristic particle size. The so-called Shields diagram (see e.g. Graf (1971) or Jansen et al (1979)) indicates whether for a certain Shields parameter the bed material moves. If $\theta > 0.06$ then the bed material will move, independent of the particle size. The value of θ was determined for the Lower Meghna using D_{50} as characteristic particle size. The value of θ as function of the discharge Q is presented as Figure B.4.14. From inspection of this figure it follows that the bed material is always in movement.

Bed material can move in the suspended or the bed load mode. This is indicated by the suspension parameter u_*/w. Here u_* = shear stress velocity defined as:

$$u_* = \sqrt{\frac{\tau}{\rho}} = \sqrt{g\,h\,i} \qquad \text{(B.4.11)}$$

where τ = shear stress (N/m^2) and g = acceleration of gravity (m/s^2) and w = fall velocity of the particles (m/s). If $u_*/w > 1$, then most of the sediment is in suspension. The value of u_*/w as a function of Q is also indicated in Figure B.4.14. It may be concluded that u_*/w is well above 1 for almost all discharges, hence the dominant mode of transport is apparently suspended load.

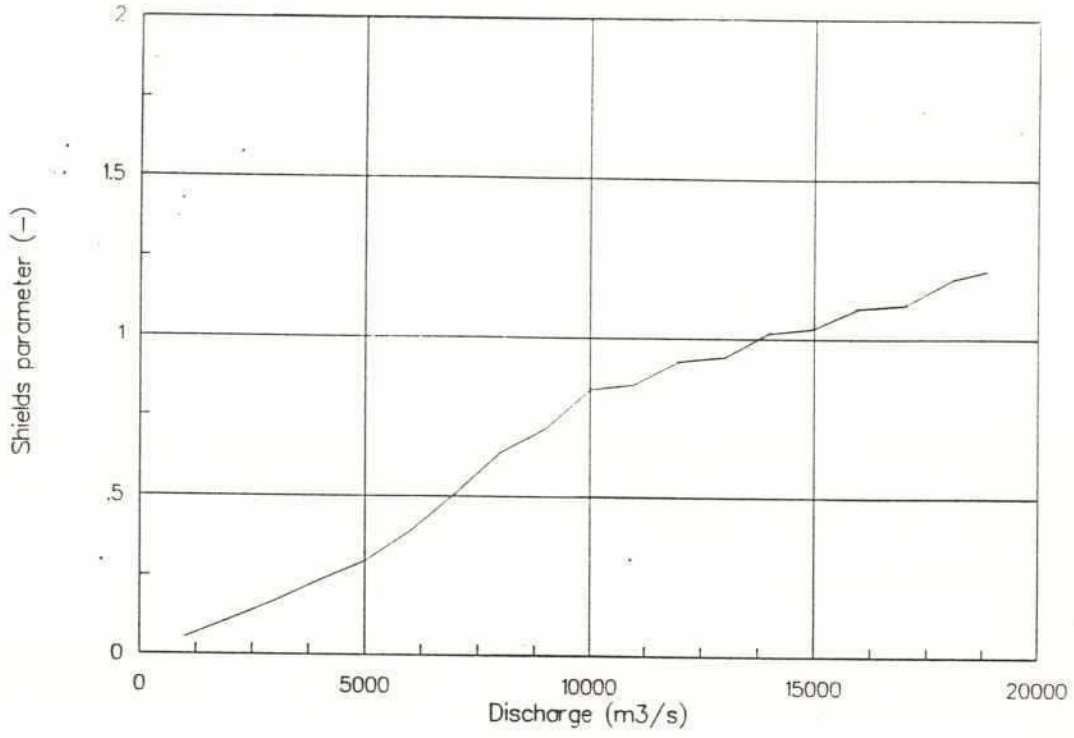
Re (2) **Predicted and measured sediment transport rates**

Using the hydraulic characteristics of the Upper Meghna River (see Section B.4.3.5) in combination with the bed material characteristics (see Section B.3.6) it is possible to predict the sediment transport in this river. For this a sediment transport formula has to be selected. For the Jamuna River it was found that the sediment transport predictor proposed by Engelund and Hansen (see Engelund & Hansen, 1967) provides a fair estimate (Klaassen et al, 1988), hence this formula will be used here too. This formula reads as:

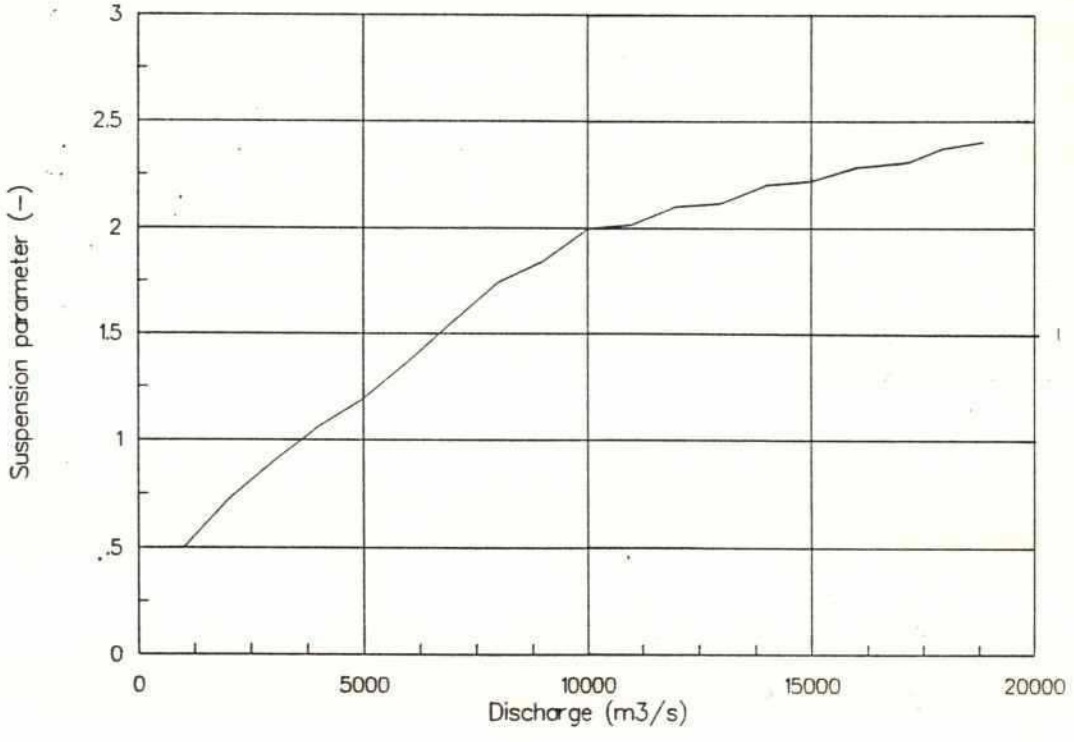
$$\frac{s}{\sqrt{g\Delta D^3}} = \frac{0.05}{(1-\varepsilon)}\left(\frac{h\,i}{\Delta\,D}\right)^{2.5}\frac{C^2}{g} \qquad \text{(B.4.10)}$$

where s = sediment transport per unit width (m^2/s), g = acceleration of gravity, Δ = relative specific density (-), defined as $\Delta = (\rho_s - \rho)/\rho$, where ρ_s = density of sediment (kg/m^3) and ρ = density of water (kg/m^3), ϵ = porosity, h = water depth (m), i = slope (-), and C = Chezy coefficient (m$^{1/2}$/s). The results of the application of the Engelund & Hansen formula on the Upper Meghna River are shown in Figure B.4.15. The results are plotted both as sediment transport in m^3/s (after multiplying the result of application of Equation (B.4.11) with the width of the river) and in ppm. The predicted concentrations are very low.

Results of sediment concentration studies of bulk sediment samples collected from the river Upper Meghna River at Bhairab Bazar show that the sediment concentration in ppm is indeed very low (in most samples less than 100 ppm) and also that the sediment concentration does not really increase with increasing velocity or discharge (see Figures B.4.16).



(a) Shields parameter



(b) Suspension parameter u./w

Sediment transport parameters of the Upper Meghna River as function of the discharge	Figure B.4.15

(3) **Yearly sediment transport**

The predicted sediment concentrations can be used to determine the yearly sediment transport rates of the Upper Meghna River. For this purpose the duration curves of the discharges of the Upper Meghna River at Bhairab Bazar (Figure B.4.5) can be used. The total spectrum of discharges can be divided in a number of classes and for each class i the probability of occurrence p_i can be determined. The volume of sediment transported for each class can be determined by computing: concentration x discharge x probability of occurrence. Summing up the contribution of all discharges and dividing it by the estimated density yields the average yearly transported volume of sediment. In formula:

$$V = \frac{1}{\rho_s} \sum p_i Q_i C_i \qquad \text{(B.4.13)}$$

where C is concentration in ppm, and i is the index of the class.

For the assumption of ρ_s = 2650 kg/m^3 an a porosity of 40% a yearly sediment transport of some $1.3*10^6$ ton is found. This is only about two promillage of the yearly sediment transport of the Jamuna River (see Klaassen et al, 1988 or China - Bangladesh Joint Expert team (1991).

(4) **Dominant discharge**

If the dominant discharge in a river is defined as the discharge that carries most of the sediment, then the above computation can be used to determine this dominant discharge. It is found that the thus defined dominant discharge of the Upper Meghna River is about 11,000 m^3/s.

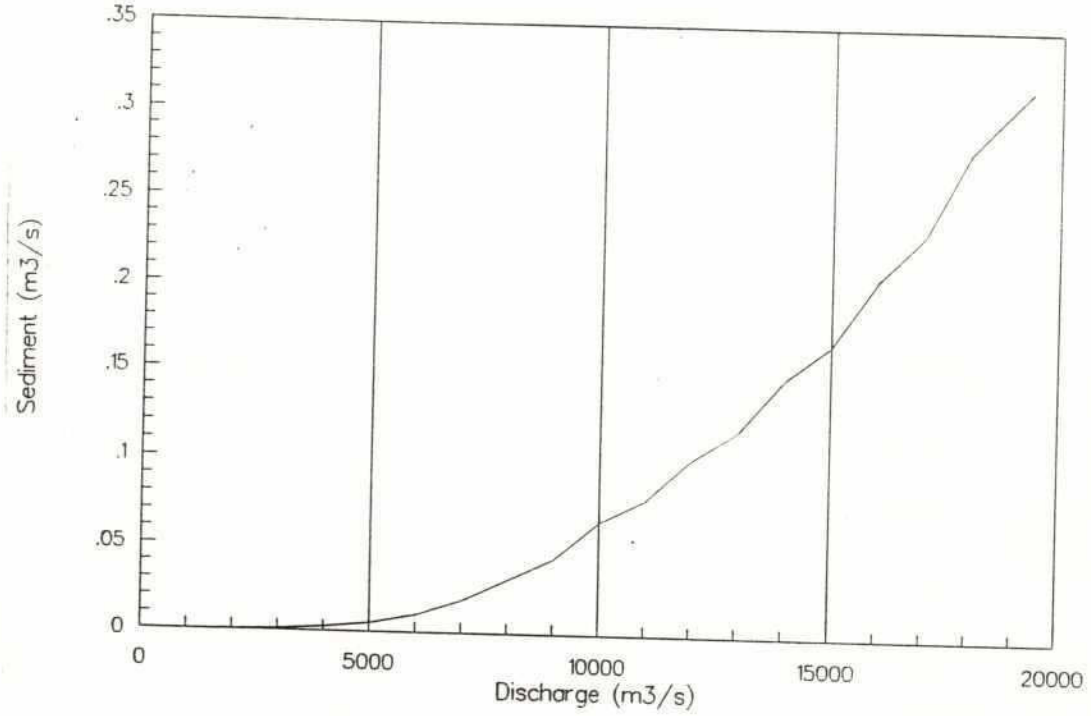
B.4.3.8 **Synthesis**

In the preceding sections some characteristics of the Upper Meghna River are described. The image emerges of a river with a very gentle slope that carries hardly any sediment. A possible explanation for this is that the Upper Meghna River carries very little sediment this is due to the silting up of the upper catchment area where all the sediments settle down. Hence no sediment is left in the Upper Meghna River.

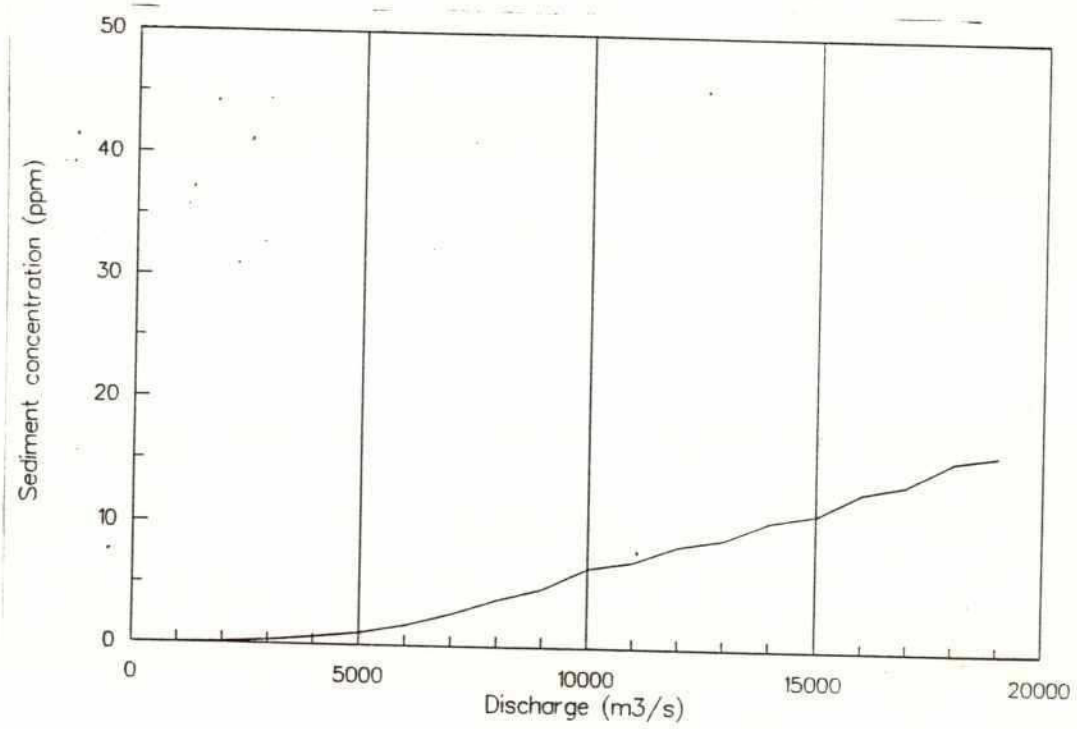
An interesting fact is that branches of the Upper Meghna River which are relatively unimportant in the sense that they carry little water in comparison with the main channel, do not seem to change over the years. For example if we consider M#8, many channels can be observed. Only one channel is responsible of the conveyance. The other, relative unimportant, channels do not seem to be filled in with sediment over a period of 8 years, although one would expect that the velocity in these minor channels is not high. The depth of these channels is about 2 m and it seems to remain at about this value. This is possibly also due to the very small amounts of sediment being transported by the Upper Meghna River; hence hardly any sediment is available for deposition.

Also the fact that the bankfull discharge is exceeded so often may be explained by recent geological changes. If indeed the ground level is subsiding as quickly as indicated in Section 4.2, in combination with the low sediment transport rates, the Upper Meghna River will probably not be able to raise its floodplain level with the same celerity as the ground levels are subsiding. This probably causes the frequent flooding of the floodplain.

This phenomenon may also explain the large difference between the dominant discharge as defined in Section B.4.7, and the bankfull discharge. In many handbooks it is stated that the bankfull discharge does most of the "work", but in the case of the Upper Meghna River this is definitely not the case.



(a) Expressed in kg/m³



(b) Expressed in ppm

Predicted sediment transport in the Upper Meghna River	Figure B.4.16

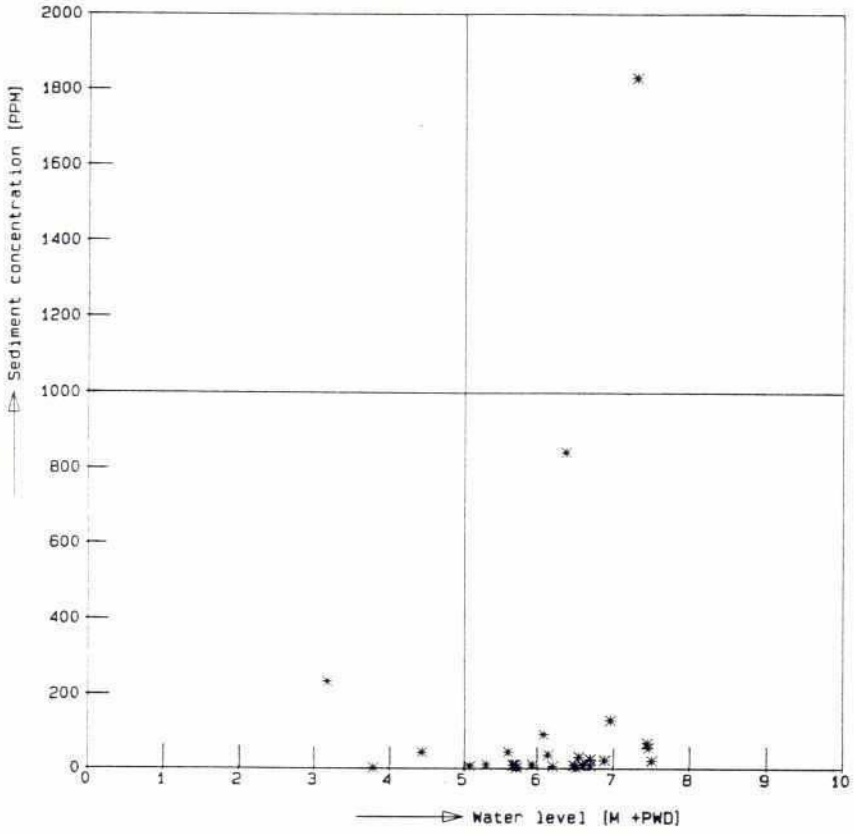


Figure B.4.17 Measured sediment concentrations at Bhairab Bazar

The present planform of the Upper Meghna River can be studied using recent developments in the field of river morphology. Struiksma et al (1985) have shown the importance of the interaction between the two parameters λ_w and λ_s, which are defined as:

$$\lambda_w = \frac{C^2 h}{2g} \qquad \text{(B.4.14)}$$

and

$$\lambda_s = \frac{1}{m \pi^2} h \left(\frac{B}{h}\right)^2 f(\theta) \qquad \text{(B.4.15)}$$

where m = mode of bed level deformation (-), see Figure B.4.19, B = width of the river (m), and $f(\theta)$ is defined via:

$$f(\theta) = 0.85 \sqrt{\theta} \qquad \text{(B.4.16)}$$

The values of λ_w, λ_s and the interaction parameter λ_s/λ_w are indicated in Figure B.4.17. Inspection of the values of the various parameters, especially for the dominant discharge conditions (Q of about 11,000 m^3/s) yields the conclusion that indeed the Upper Meghna River classifies as a meandering river with possibly the tendency of the formation of islands during low flow conditions.

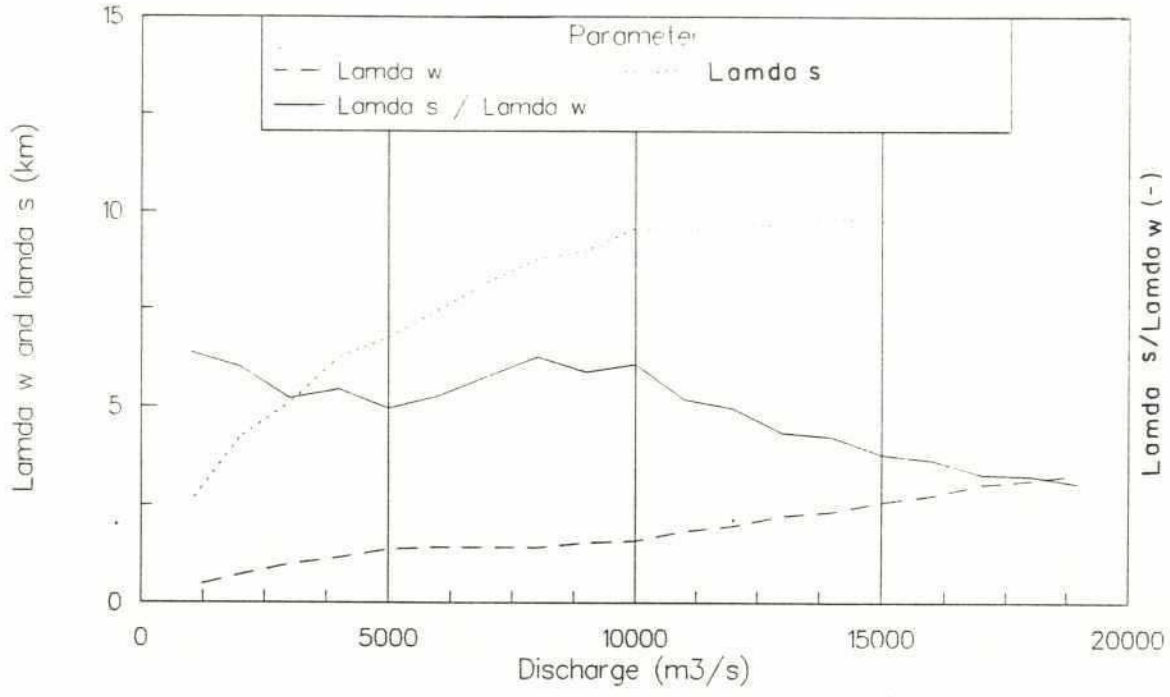
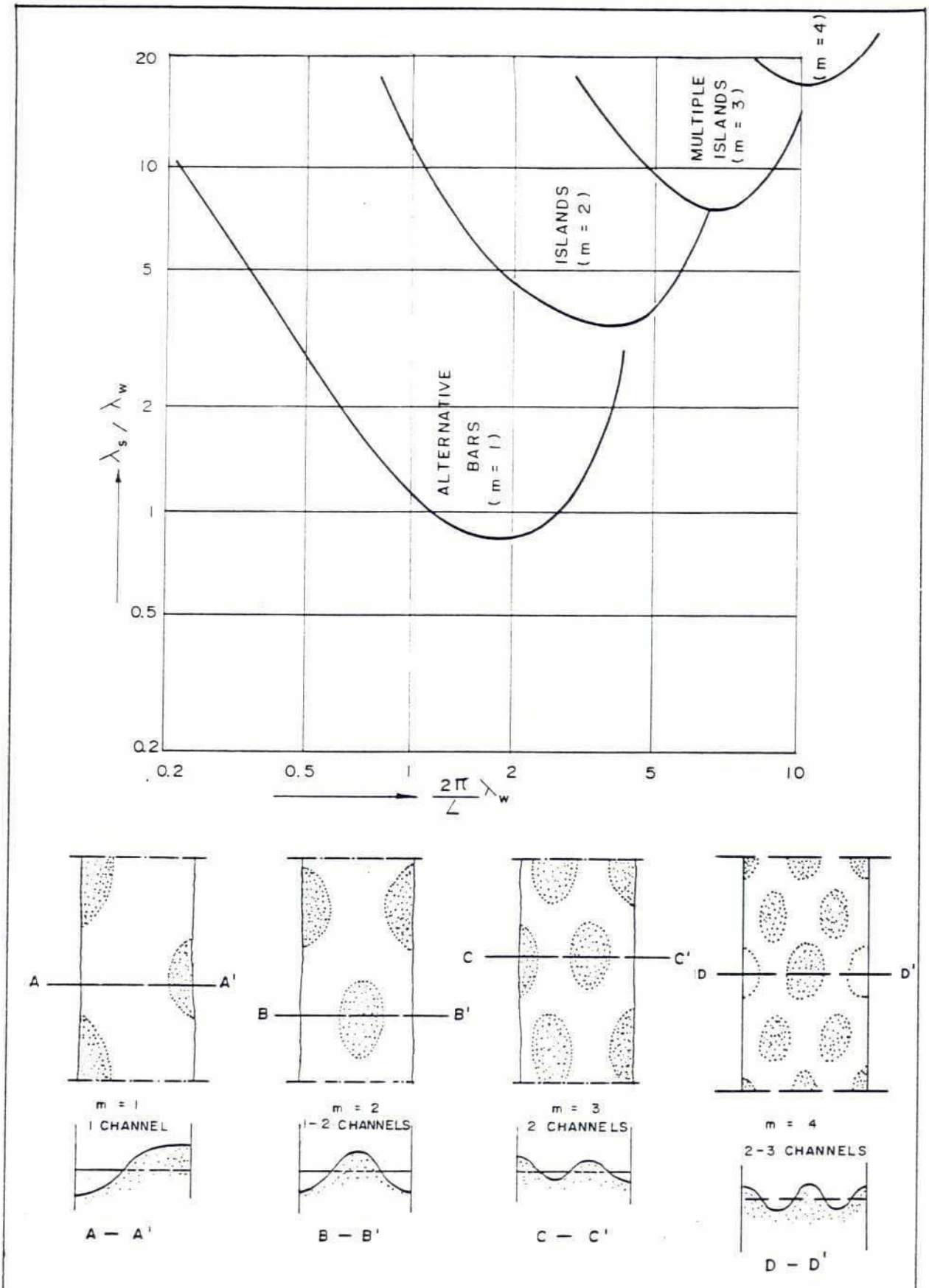


Figure B.4.18 Variation of λ_w, λ_s and λ_s/λ_w of the Upper Meghna River with the discharge



Occurrence of alternate bars and islands (theory)

Figure B.4.19

B.4.4 Padma/Lower Meghna River system

B.4.4.1 Short description of the river

The Lower Meghna carries the combined flow of the Padma and the Upper Meghna Rivers. The Padma River in turn carries the discharge of the Brahmaputra and the Ganges River. Hence the Lower Meghna River is one of the largest rivers in the world. The river flows from the confluence of the Upper Meghna River and the Padma River via Chandpur into the Bay of Bengal (see Figure B.1.1). The discharge of the Lower Meghna varies between 10,000 and some 160,000 m3/s. The average slope of the river is around $0.5*10^{-4}$ (5 cm per km).

The Padma/Lower Meghna River system is characterized by a wide river bed of several kilometres in which various channels develop in combination with large propagating sand bars (locally called chars). Going downstream, the Padma increases its width towards the confluence with the upper Meghna. Together with this increase in width, the dimensions of the bars increase. A very peculiar aspect is the sudden turn to the south of the Lower Meghna River just downstream of the confluence with the Upper Meghna River. As was explained in Section 4.2, this sharp turn has been present for a very long time and may be the cause of the gradual shift of the Ganges River, and later the combined Ganges and Jamuna system, in easterly direction. The overall tendency of the Lower Meghna River is erosion on the eastern bank and accretion on the western bank.

The Padma/Lower Meghna River system does not have major tributaries, apart from the Upper Meghna River. Smaller tributaries join the river on the left side downstream of the confluence with the Upper Meghna River, notably the Gumti River and the Dhakatia River. Major distributaries from the Padma River are the Dubaldia and the Arial Khan.

Along the left bank of the Lower Meghna at some sites erosion causes severe problems. Going in downstream direction, problem sites are or have been in the recent past: Eklashpur, Chandpur and Haimchar.

B.4.4.2 Hydrology

The hydrological conditions (stages and discharges) in the Lower Meghna River are extensively discussed in Annex A. Here only those elements that are relevant for the morphological study are highlighted. The salient hydrological features are:

(1) **Stages**
The average daily water levels at Chandpur vary between 0.56 m and 4.99 m (see Appendix IV of Annex A). A duration curve of the daily average water levels at Bhairab Bazar is provided in Appendix IV of Annex A. Stages in Mawa were derived from BWDB hydrology data that were included in the HYMOS data base.

(2) **Tidal influence**
The stages along the Lower Meghna are subject to tidal influence. During low flows in the Lower Meghna River the tidal range near the confluence with the Upper Meghna River is about 0.4 m; under those conditions still a vertical tide of some 1.6 m is noticeable in Chandpur.

(3) **Discharges**
The maximum discharges in the Lower Meghna system at Chandpur are estimated to be about 155,000 m^3/s (return period 100 years, see also Section 7.6 of Annex A). A duration curve for the daily discharges could be prepared in an approximate way. This tentative duration curve is shown in Figure B.4.20.

(4) **Water balance**
No insight is available on the quantities of water conveyed by the Arial Khan and the Dubaldia,

taking off from the right bank of the Padma River. It may well be that these distributaries carry substantial discharges.

These hydrological data are used in Section B.4.4.5 for the determination of the hydraulic conditions in the Upper Meghna River.

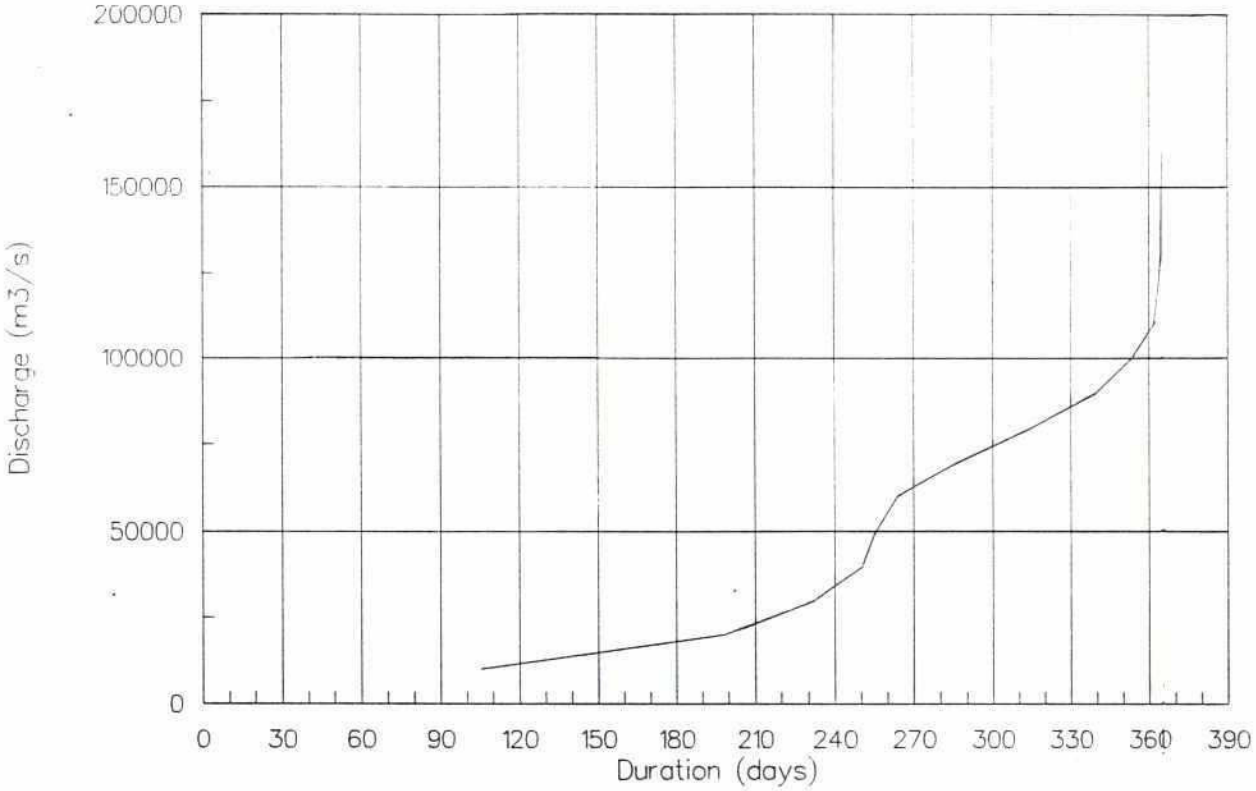


Figure B.4. 20 Tentative duration curves of the daily discharges at Chandpur

B.4.4.3 **Planform characteristics**

The Padma River is characterized by a fairly straight channel with a width of several kilometres. Downstream of Mawa the river widens from some 3.5 km to almost 15 km over a distance of some 20 km. In this widening reach channels develop in combination with large propagating sand bars (locally called chars). Just downstream of the confluence with the Upper Meghna the river bends in southern direction. Here the name of the river changes from Padma River to Lower Meghna River, a reminder of the past when the Brahmaputra River still joined the Meghna River downstream of Bhairab Bazar.

The large bend downstream of the confluence has a radius of curvature of some 15 km. At the inner side of this bend a large point bar appears to be present. Here the river narrows again to a few kilometres only. The geometry of the confluence has changed substantially over the last three decades, mostly due to the continuing bank erosion along the outer bend. As can be observed from maps and satellite images the islands that are generated downstream of Mawa vanish when entering the bend. This phenomenon is discussed at much more length in Section B.5.3.1. During some years a "southern" channel is present in the bend, that acts as a short cut. Also for this phenomena and its effect on the conditions near Chandpur reference is made to Section B.5.3.1.

Chandpur is located at the lower end of this bend. About 15 km downstream of Chandpur Haimchar is located. Near Haimchar a large bend used to be present but over the last two decades a natural cutoff has occurred, and now the river reach near Haimchar is essentially straight. More detailed information on this

cutoff is provided in Section B.5.3.4.

Within the present frame-work it is of interest to have a closer look at the planform characteristics by inspecting the results of an analysis of the soundings of BIWTA. These soundings do not cover the full width of the river but they do allow for an interpretation of the planform characteristics of the Padma/Lower Meghna system. The results of this analysis of the BIWTA soundings is presented in the Figures B.4.21 through B.4.22. Figure B.4.21 presents the total width of the river as a function of the chainage of the Padma/Lower Meghna River. Here the confluence is located at km 115, while the upstream chainage is related to the Padma River. Mawa is located at about km 80. Clearly the initial increase and the later decrease of the total width of the river can be observed. The Padma River is the continuation of the Jamuna and the Ganges River. Considering its discharge, slope and bed material size it seems logic to assume that without any constraints the Padma River would be a braided river system like the Jamuna River (see also Struiksma & Klaassen, 1988) with a width of 15 km or even more. Near Mawa the river is constricted, possibly by more resistant banks and hence the river is substantially narrower over there. Downstream of the influence of these more resistant banks appears to vanish and hence the river tends to widen again. In fact this happens quite rapidly: over a distance of some 15 km the river widens from 3.5 km to some 12 km, or an increase on both sides of about 1:4. This figure is of interest for the mutual distance of the proposed groynes along the Lower Meghna River (see Chapter 6).

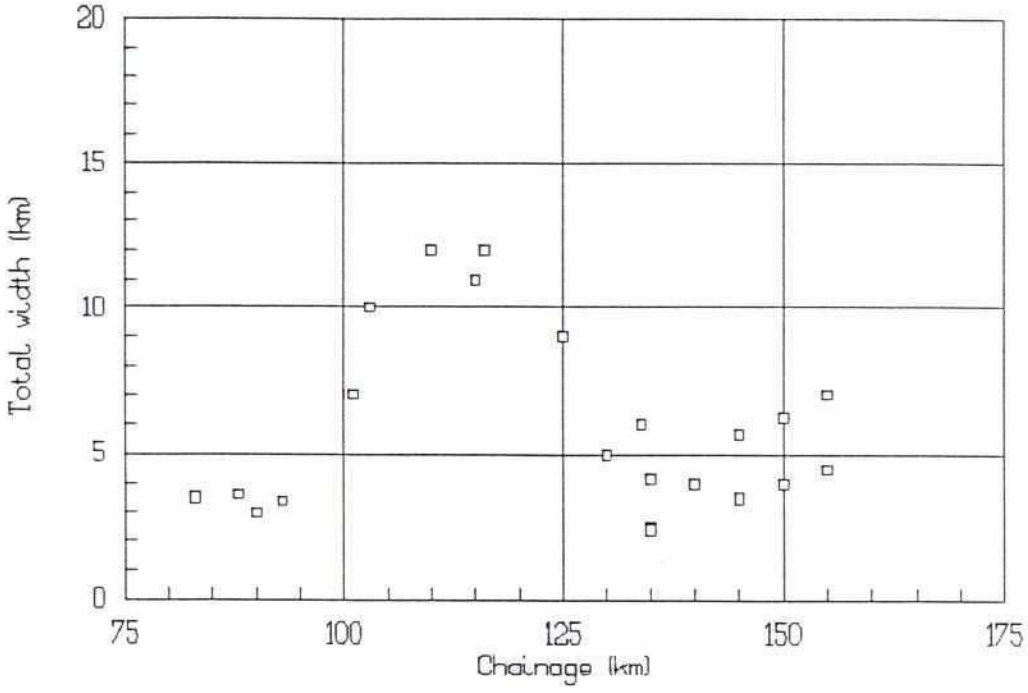


Figure B.4.21 Total width of channel and bar pattern in the Padma/Lower Meghna system versus the chainage

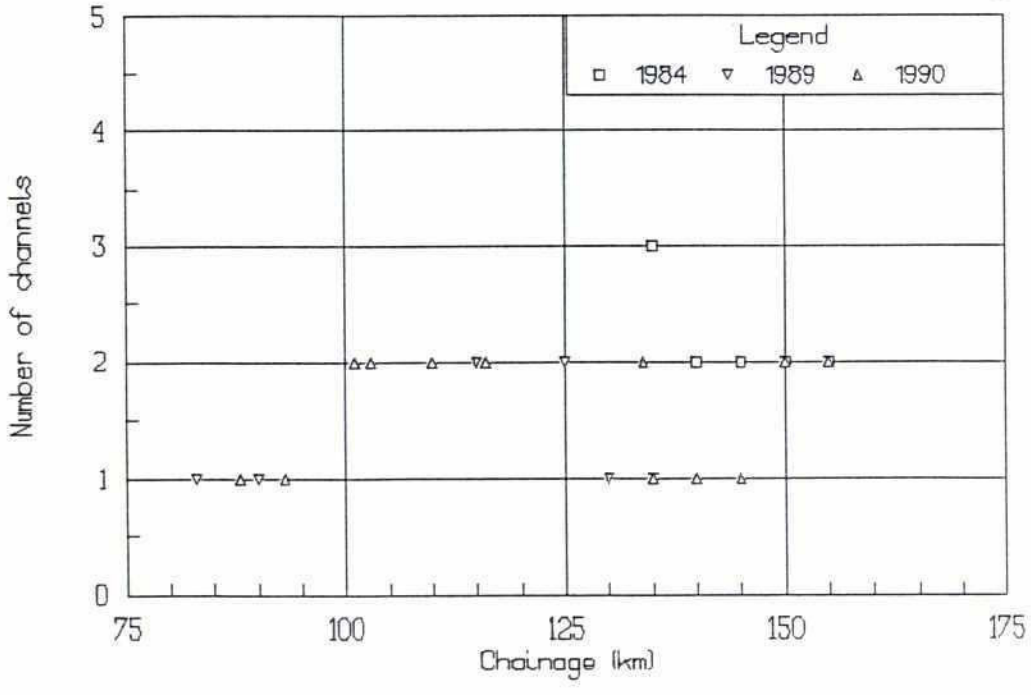


Figure B.4.22 Number of channels in the Padma/Lower Meghna system versus the chainage

In the bend the total width of the river decreases substantially. The bend covers the chainage between km 115 and km 135 (Chandpur). Downstream of Chandpur the Lower Meghna River widens from 2.5 - 4 km to some 4.5 - 6 km near Haimchar.

Furthermore it is of interest to consider the number of channels that are present in the Padma/Lower Meghna River system. For three years this number is plotted in Figure B.4.22. As can be observed this number increases from 1 near Mawa to 2 some 20 km more downstream. In the beginning of the bend mostly two channels are present in the later years. In 1984 only one channel was present in the lower end of the bend upstream of Chandpur. Downstream of Chandpur, where the river widens again, the number of channels increases again to 2 in the latter years. It seems as if the number of channels is correlated with the total width of the river (see also Section B.4.8). The length of the islands between Mawa and the downstream end of the bends is approximately 15 km. These islands are moving through the system. Depending on the conditions one, one-and-a-half or two islands are present.

Information on the movement of the channel and bar pattern in the Padma/ Lower Meghna system, on rates of bank erosion and on the natural cutoff near Haimchar is provided in Section 5.3.

B.4.4.4 **Channel dimensions**

The BIWTA soundings were also used to get some insight into the dimensions of the individual channels in the Padma/Lower Meghna system. This was done for bankfull conditions. The approximate height of the banks was inferred from the BWDB soundings (to be presented in Chapter B.5 as the Figures B.5.17 through B.5.19) as about 6 m+PWD near Mawa and 3.5 m+PWD at Chandpur. Through these levels a straight line was drawn and the bankfull height was estimated via interpolation (between Mawa and Chandpur) or extrapolation (between Chandpur and Haimchar). Next for a number of cross-sections the bankfull depth and the bankfull width, and per cross-section also the combined width of the channels, the bankfull area and the total conveyance. The conveyance is defined as:

$$C = \sum_{i=1}^{n} B_{bi}\, h_{bi}^{3/2} \qquad \text{(B.4.17)}$$

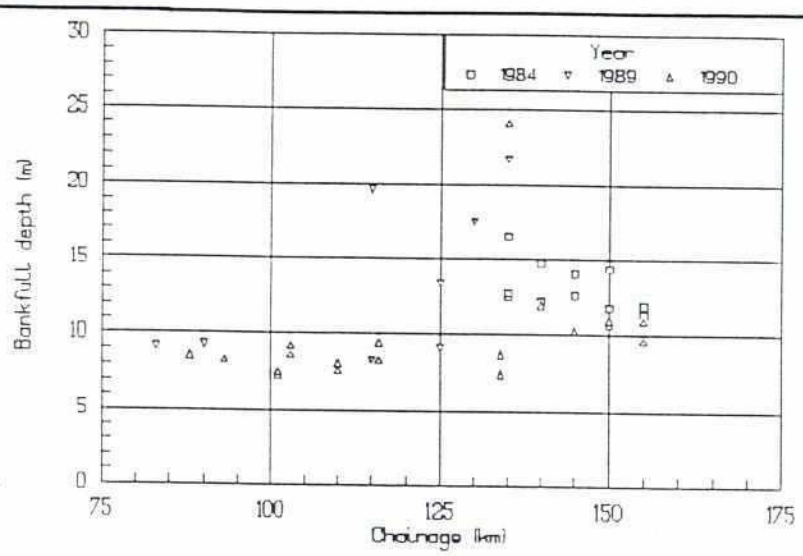
where C = conveyance ($m^{5/2}$), B_b = bankfull width (m), h_b = bankfull depth (m), i = index varying between 1 and n, and n = number of channels. The results of this analysis are presented in the Figures B.4.23 and B.4.24.

The following observations can be made from an inspection of these Figures:

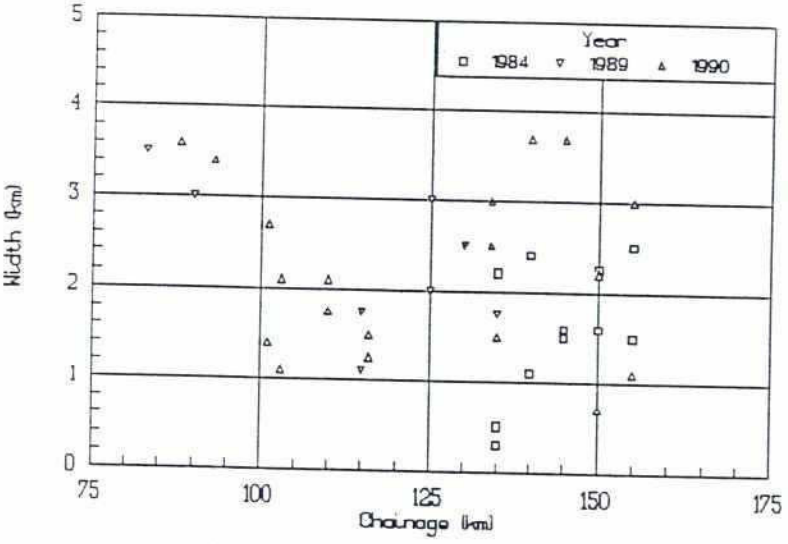
(1) The bankfull depth of the channels in the Padma River is about 7 to 9 m; in the Lower Meghna River these depths are substantially larger, varying from 7 to 24 (sic!) m near Chandpur to 10 to 15 m near Haimchar. The average depth near Chandpur is about 12 m.

(2) The width of the single channels, as far as can be inferred from the BIWTA soundings, is mostly around 2 km, but essentially varying between less than 0.5 km to almost 4 km. The combined width of the channels in one cross-section is always about 4 km. Near Chandpur the width is varying between 2.5 and 4 km, with an average of some 3.5 km.

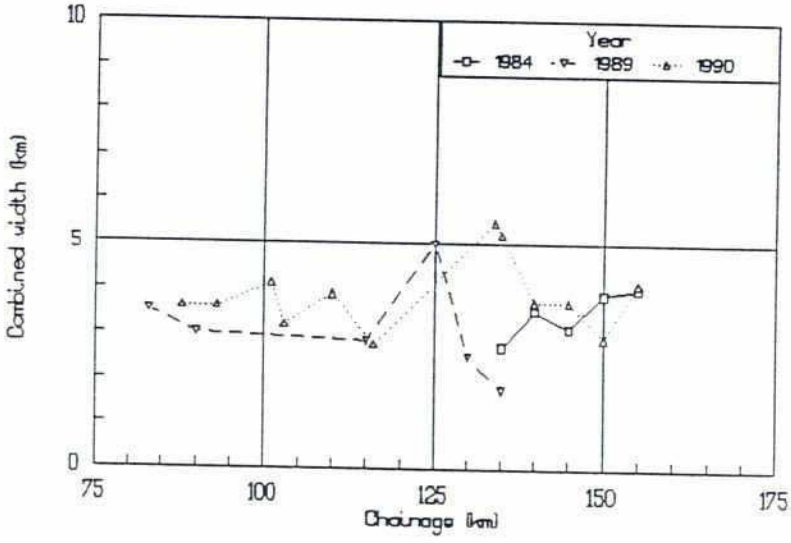
(3) Both the total area and the conveyance increase substantially when the Upper Meghna joins the Padma/Lower Meghna system. This is probably not only due to the increased discharge, but also due to the tidal variation that is increasing in downstream direction (see Annex A).



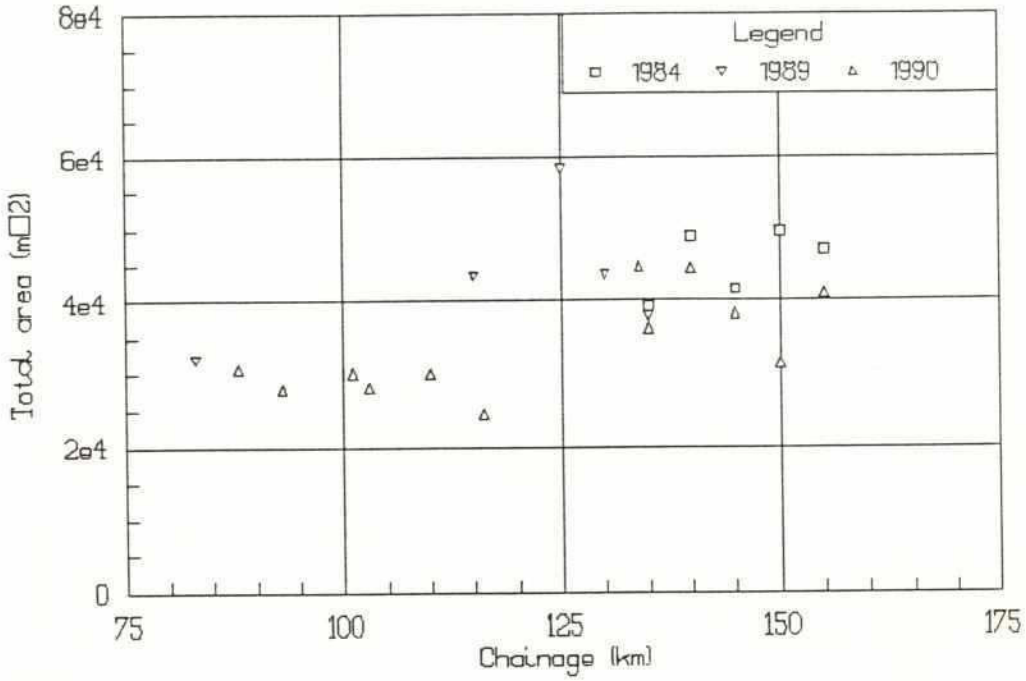
(a) Bankfull depth versus chainage



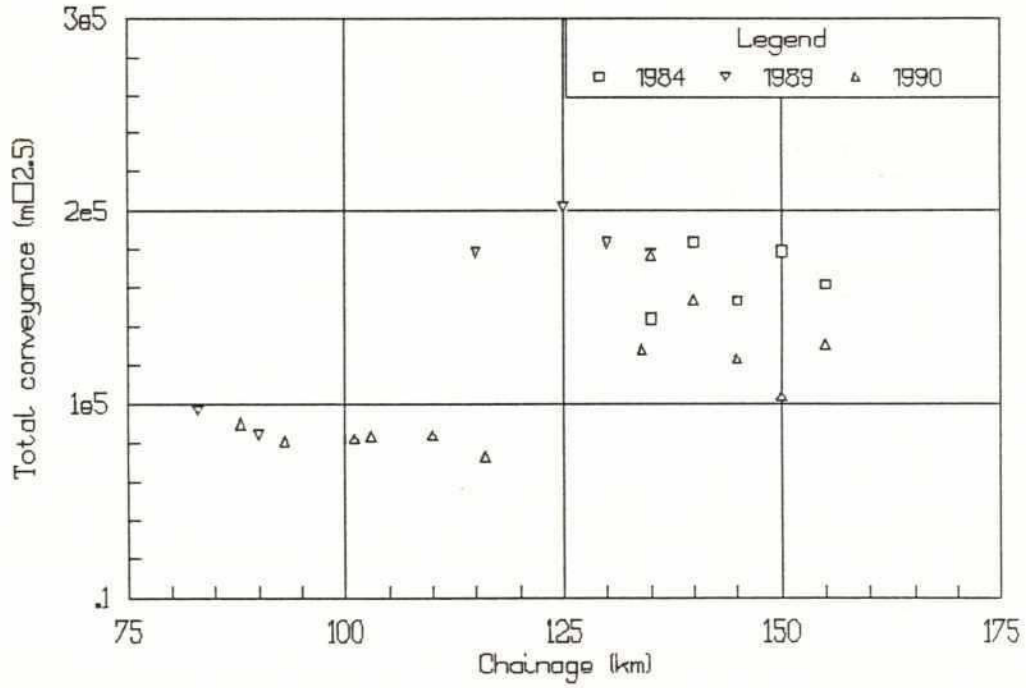
(b) Bankfull width of single channels



Channel dimensions of the Padma/Lower Meghna system	Figure B.4.23

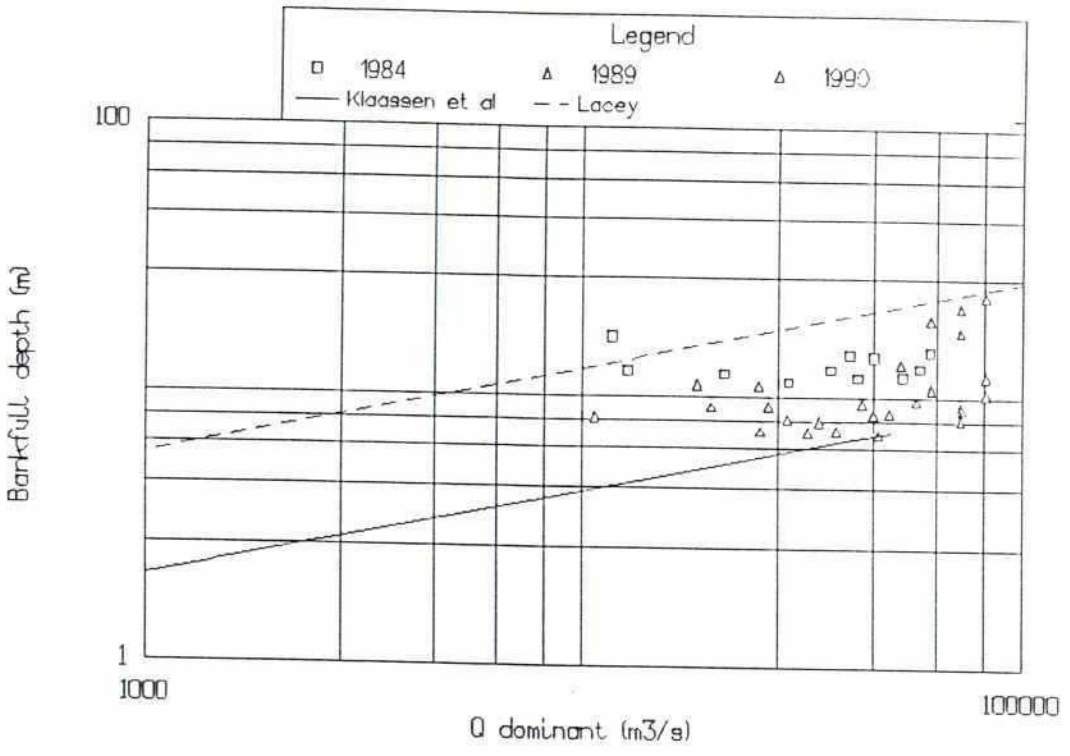


(a) Bankfull area versus chainage

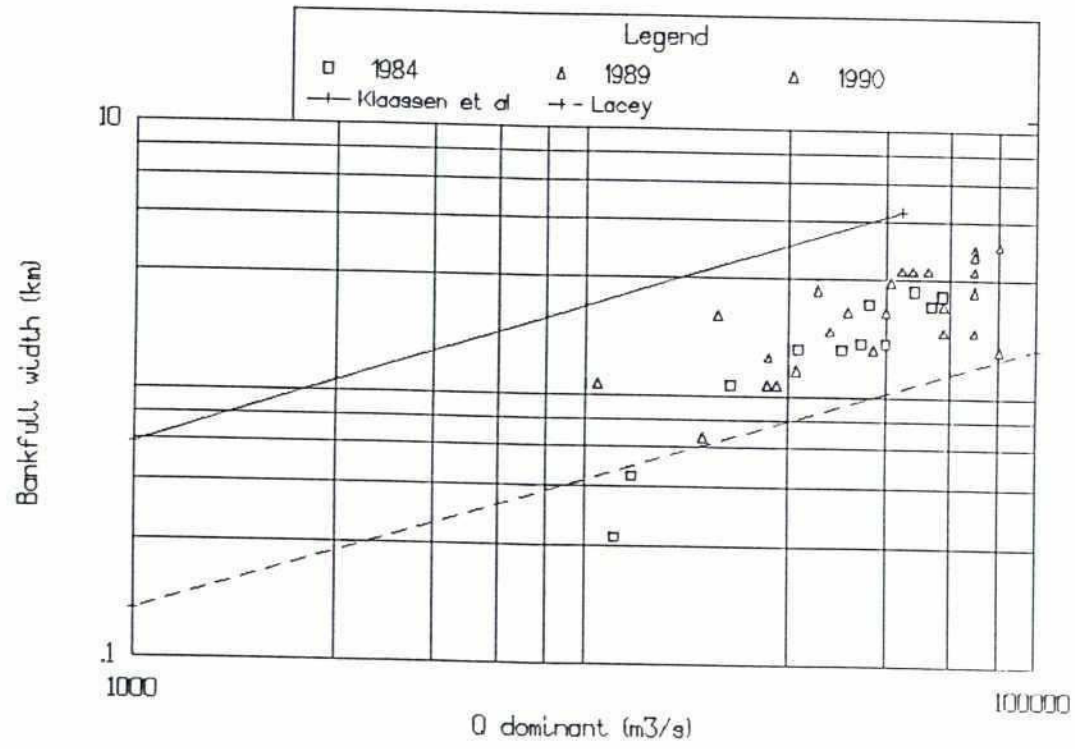


(b) Bankfull conveyance versus chainage

Bankfull area and conveyance of the Padma/Lower Meghna system	Figure B.4.24



(a) Bankfull depth



(b) Bankfull width

Bankfull dimensions of the Padma/Lower Meghna River compared with regime equations	Figure B.4.25

Finally it is of interest to compare the channel dimensions of the Padma/Lower Meghna system with the regime equations presented for the Jamuna River. In first instance it would be expected that the channels would be comparable to the channels of the Jamuna River, as the Padma/Lower Meghna system can be regarded as the continuation of in particular the Jamuna River. For this it is required to define the bankfull discharge of the Padma and the Lower Meghna River. Tentatively these were assumed to be 72,500 and 82,500 m^3/s, respectively, based on the rating curve at Mawa (see RPT et al, 1987) and Chandpur (deduced from Annex A). Also here the total bankfull discharge is divided over the channels in one cross-section according to their conveyance, similar as was done for the derivation of the Jamuna regime equations (see Klaassen and Vermeer, 1988b). The comparison is made in the Figure B.4.25, where the observations are plotted versus the regime relations given in Section B.4.3.4, notably:

(a) Jamuna regime equations: Equations (B.4.5) and (B.4.6),
(b) Lacey regime equations, for a wide river given as the Equations (B.4.7) and (B.4.8).

It is observed that the channels of the Padma/Lower Meghna system are on the average narrower and deeper than the Jamuna channels. For a possible explanation see Section B.4.4.8.

B.4.4.5 **Hydraulic parameters**

In Annex A, Appendix IV, water levels for different discharges for different recurrence intervals have been produced for a number of stations along the Lower Meghna River. These water levels have been drawn versus the chainage, in Figure B.4.26 together with the data for the Mawa Station along the Padma River. The confluence is approximately located at km 115; hence the reach km 80 - 115 relates to the Padma River. The data relate especially to the flood levels with recurrence intervals of 5, 10, 25, 50 and 100 years.

The following observations can be made upon inspection of the more downstream part of Figure B.4.20:

(1) The water level slopes in the Lower Meghna River are in the order of 2 m per 50 km (corresponding to $0.4*10^{-4}$).

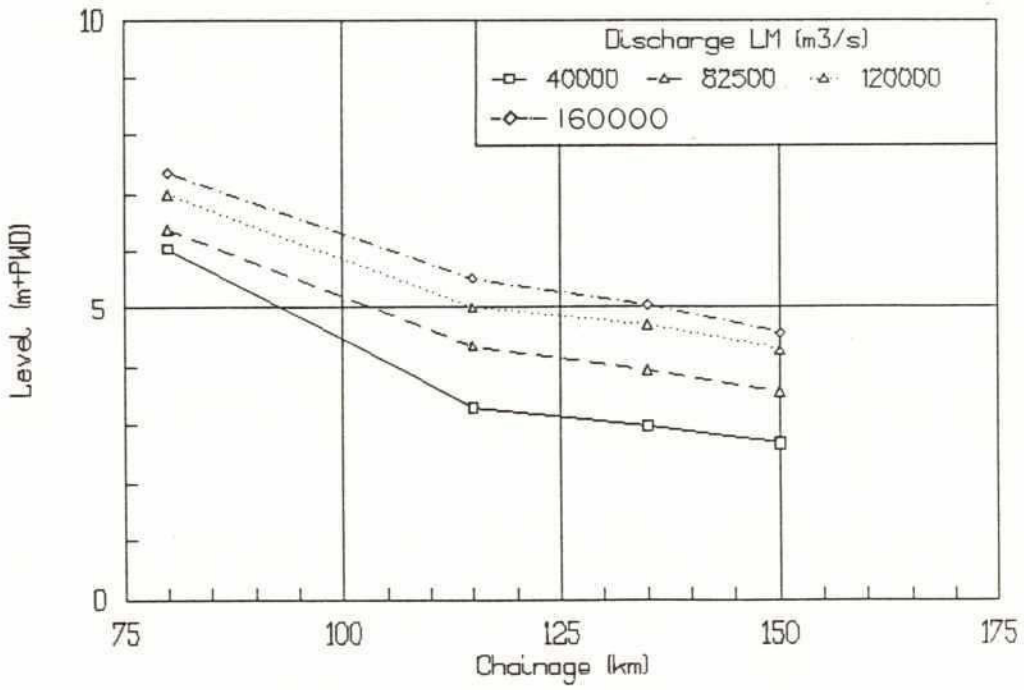
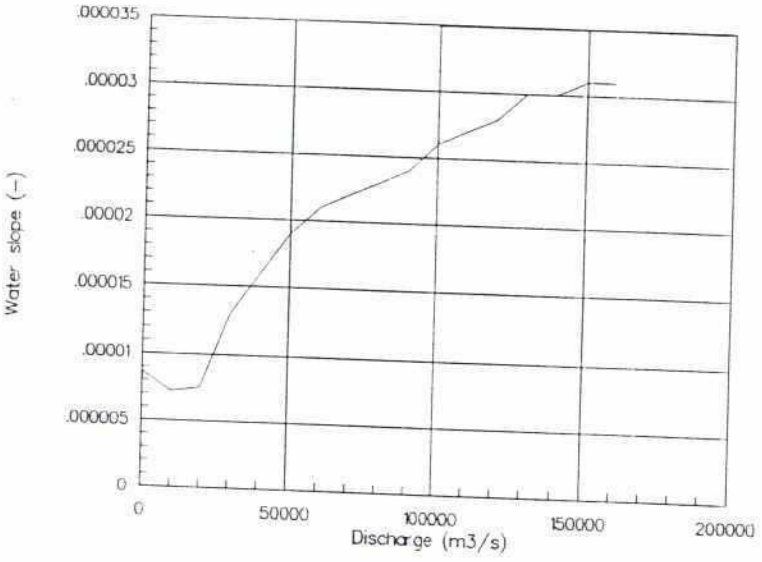
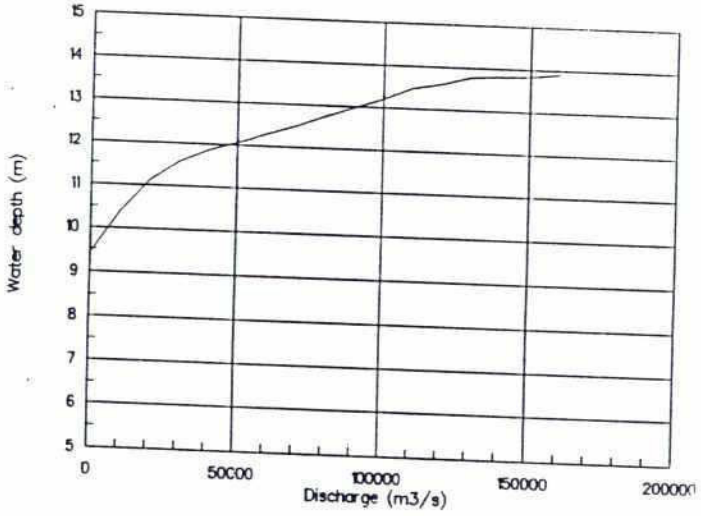


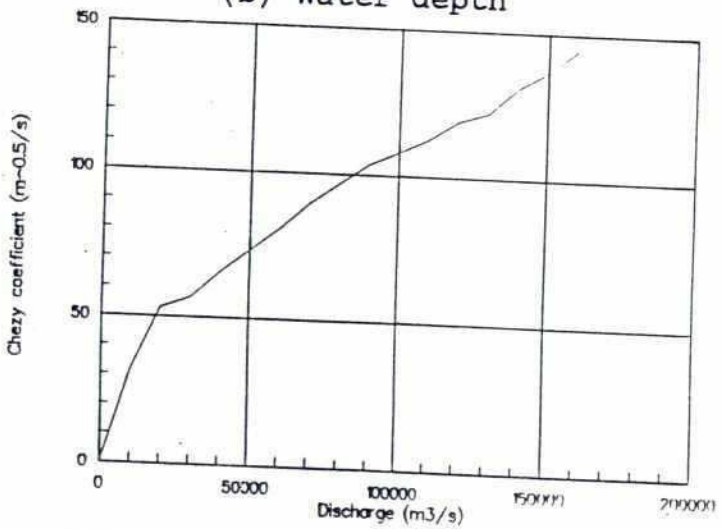
Figure B.4.26 Water levels in the (Upper and) Lower Meghna River



(a) Water level slope



(b) Water depth



(c) Computed Chezy coefficient

Water level slope, water depth and computed Chezy coefficient near Chandpur as a function of the discharge	Figure B.4.27

This is slightly smaller than the present slope of the Jamuna River (in the order of $0.7*10^{-4}$), and about two times larger than the slope of the Upper Meghna River. Also it is observed that the slope increases with the magnitude of the flood.

(2) The increase over the last 20 km in the Lower Meghna River is doubtful, and is probably due to some inaccuracy in the basic data.

Similar as was done for Bhairab Bazar here a more detailed analysis of the conditions near Chandpur is presented. The average bed levels have been combined with the water levels and slopes as a function of the discharges. The channel dimensions for bankfull discharge of 82,500 m^3/s were assumed to be a depth 13 m and a width of 3,5 km (see Section B.4.4.4). The results are presented in Figure B.4.27. It is found that during low discharges the slope is even much smaller, while the Chezy coefficient increases from about 30 to 140 $m^{1/2}/s$. The latter value is probably too large as the conveyance of the Dubaldia and the Arial Khan was not taken into account. It has to be stated however, that very low Manning coefficients (and hence very large Chezy coefficients) were observed for the Padma River too (Stevens and Simons, 1973).

B.4.4.6 **Bed material**

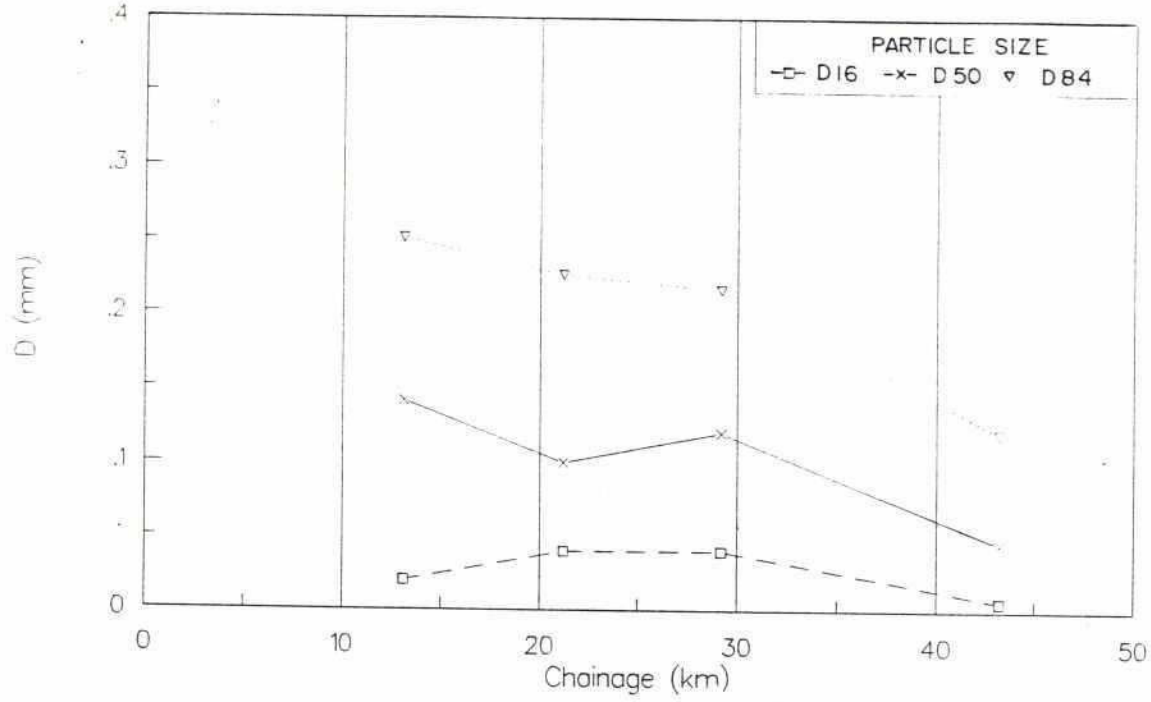
During the additional data collection phase, data on the bed material characteristics were obtained both for the Padma and Lower Meghna River. The Figures B.4.28 and B.4.29 present the results after processing all available data, whereby in the Figures B.4.28(a) and B.4.29(a) the results of the average of the right, middle and left sample is indicated. The Figures B.4.28(b) and B.4.29(b) present the average particle size distribution over the whole reach of the Padma and Lower Meghna River, respectively.

The following observations are made:

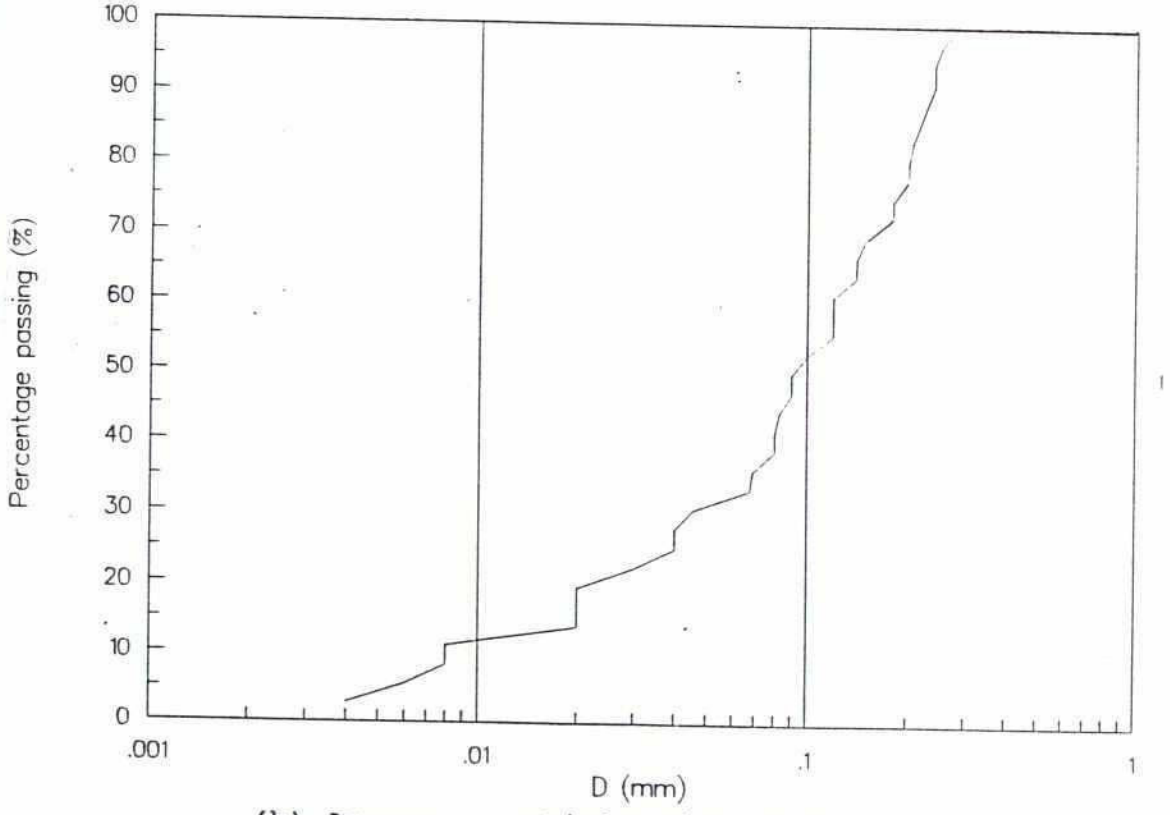
(1) The characteristic particle sizes D_{16}, D_{50} and D_{84} do hardly vary with the chainage, implying that abrasion and longitudinal sorting are not noticeable over such short reaches.

(2) The average values of these characteristic particle sizes for the Padma River are:

D_{16} = 0.02 mm,
D_{50} = 0.09 mm, and
D_{84} = 0.20 mm.

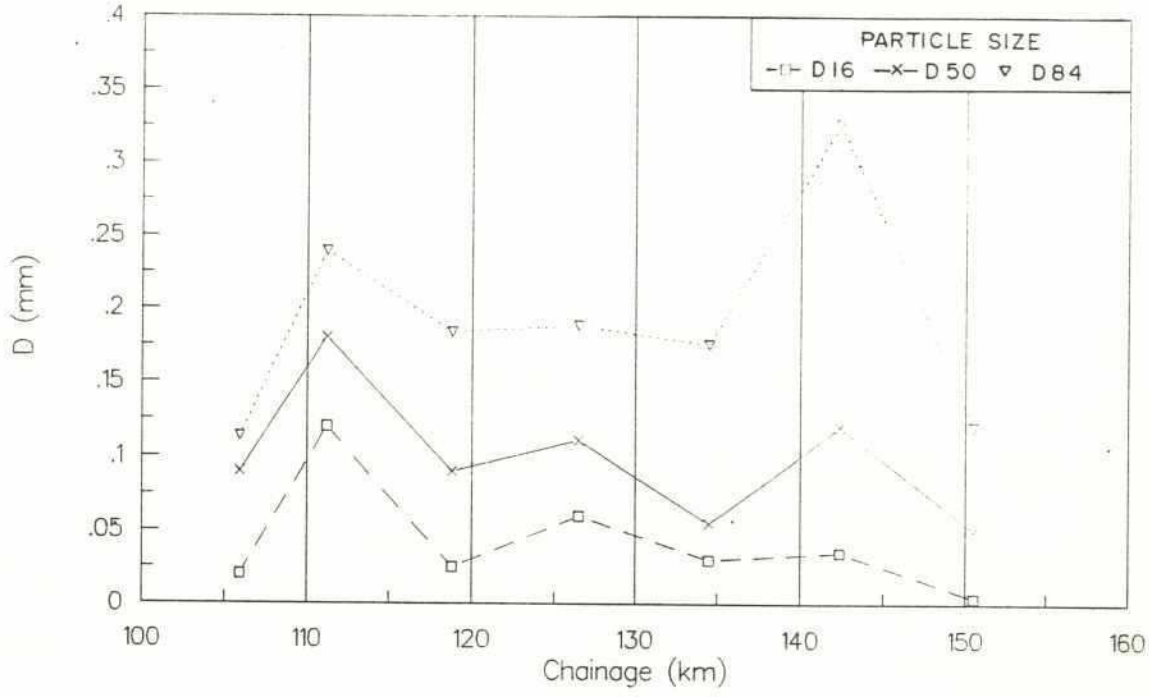


(a) Variation of the D_{16}, D_{50} and D_{84} with chainage

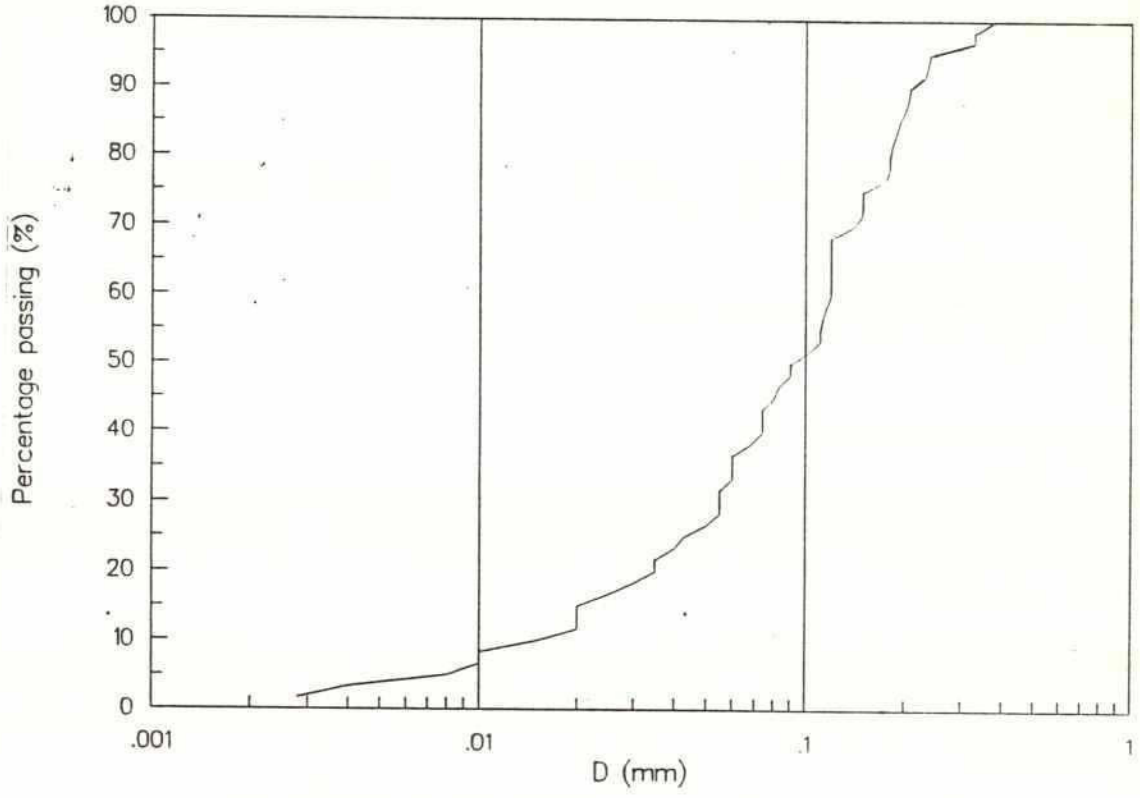


(b) Average particle size distribution

Bed material characteristics of the Padma River	Figure B.4.28



(a) Variation of the D_{16}, D_{50} and D_{84} with chainage



(b) Average particle size distribution

Bed material characteristics of the Lower Meghna River	Figure B.4.29

For the Lower Meghna River these average values are:

D_{16} = 0.02 mm,
D_{50} = 0.14 mm, and
D_{84} = 0.19 mm.

Hence the bed material of the Padma / Lower Meghna system can be characterized as rather uniform and fine sand, with a small fraction (some 20 %) of finer silt.

(3) It is of interest to compare the particle size distribution of the Padma and Upper Meghna River with the distribution of the Lower Meghna River. That is done in Table B.4.2.

TABLE B.4:2 COMPARISON OF CHARACTERISTIC PARTICLE SIZES OF THE UPPER MEGHNA RIVER, PADMA RIVER AND LOWER MEGHNA RIVER

River reach	Characteristic particle size		
	D_{16} (mm)	D_{50} (mm)	D_{84} (mm)
Upper Meghna River	0.04	0.14	0.25
Padma River	0.02	0.09	0.20
Lower Meghna River	0.02	0.09	0.19

It can be concluded that the bed material of the Upper Meghna River is slightly coarser than the Padma River. This causes however, no increase of the bed material size of the bed material in the Lower Meghna River. This is explained by the fact that the sediment transport in the Upper Meghna is negligible compared to the sediment transport in the Padma/Lower Meghna system (see hereafter).

B.4.4.7 **Sediment transport**

Similar to the discussion presented in Section B.4.7, here the following aspects of the sediment transport of the Upper Meghna River are dealt with:

(1) Mode of transport
(2) Predicted sediment transport rates
(3) Yearly sediment transport
(4) Dominant discharge

Re (1) **Mode of transport**

As was discussed in Section B.3.7, whether or not the bed material is in movement can be evaluated with the Shields parameter θ. The value of θ in the Lower Meghna River near Chandpur as function of the discharge Q is presented as Figure B.4.30. From inspection of this figure it follows that the bed material is always in movement.

Whether bed material is moving in the suspended or bed load mode is indicated by the suspension parameter u_*/w. The value of u_*/w near Chandpur as a function of Q is shown in Figure B.4.30. It may be concluded that u_*/w is well above 1 for all discharges, hence the dominant mode of transport is apparently suspended load.

Re (2) **Predicted sediment transport rates**

Using the hydraulic characteristics of the Lower Meghna River (see Section B.4.4.5) in combination with the bed material characteristics (see Section B.4.6), it is possible to predict the bed material load in this river. Also for the Lower Meghna River the Engelund & Hansen formula is used. The results of the application of this formula on the Lower Meghna River is shown in Figure B.4.31. The results are plotted both as sediment transport in m^3/s (after multiplying the result of application of Equation (B.4.11) with the width of the river) and in ppm. The predicted concentrations are very low. No measurements at Chandpur are available to verify these predictions.

(3) **Yearly sediment transport**

Also here the predicted sediment concentrations is used to determine the yearly bed material transport of the Lower Meghna River. For this purpose the duration curves of the discharges of the Upper Meghna River at Bhairab Bazar (Figure B.4.20) were used, conform the method described in Section B.4.3.7. For the assumption of ρ_s = 2650 kg/m^3 and a porosity of 40% a yearly bed material transport of some $70*10^6$ ton is found. This is only about 12 % (see China - Bangladesh Report Joint Expert Team (1991)) of the yearly sediment transport of the Padma River at Mawa. Because the Lower Meghna River has to transport the sediment from the Ganges, the Brahmaputra River and the Upper Meghna River this result obtained seems very doubtful.

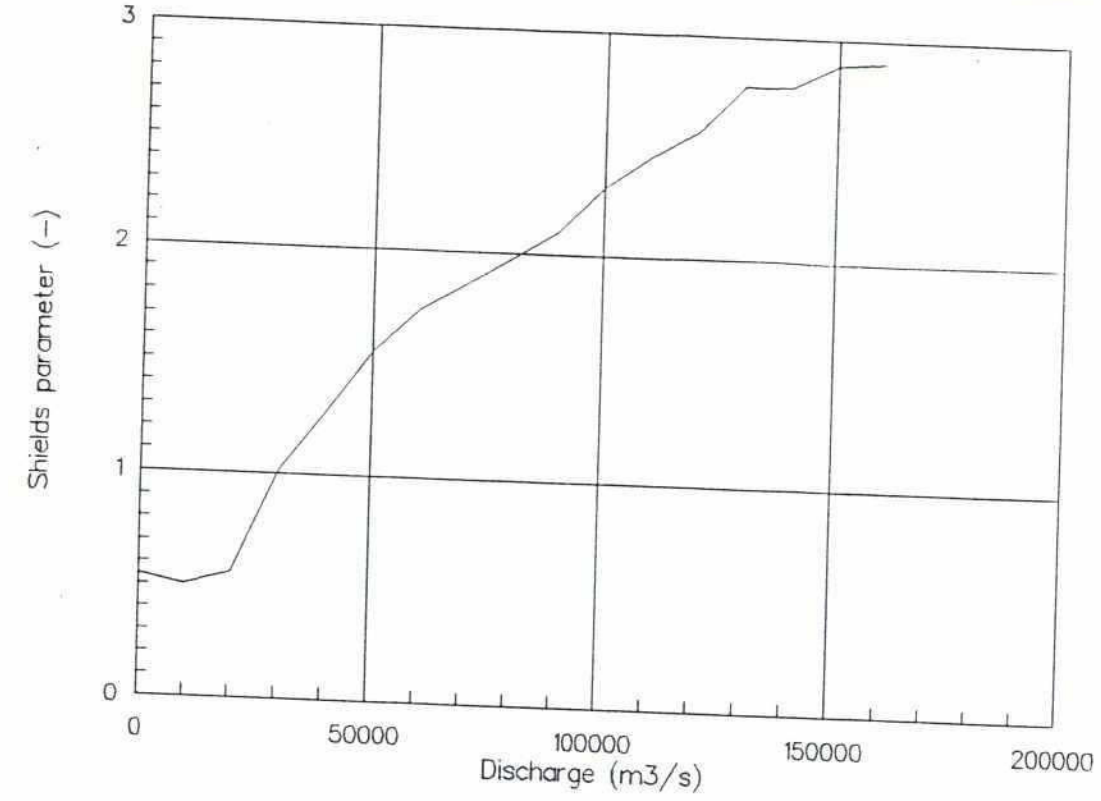
Possible explanation for this discrepancy are:

(i) the use of the average depth at Chandpur rather than using the actual depths (keeping in mind the strong non-linearity of S as function of $hi/\Delta D_i$;

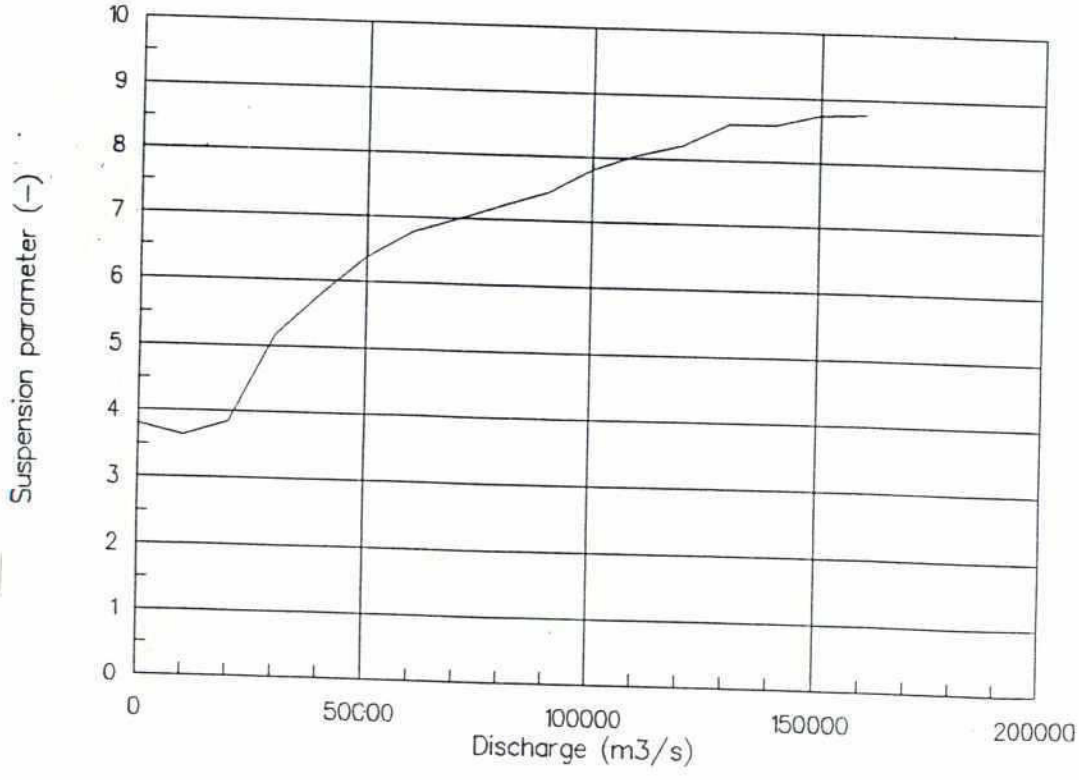
(ii) the tidal variation increases the sediment transport;

(iii) the possible transport of sediment into the Dubaldia and arial Khan.

This causes have not been explored any further, but a long-term study should definitively address this major differences. Note that the computed yearly sediment load of the Lower Meghna River is about 50 times larger than the load of the Upper Meghna River (see Section B.4.3.7). This explains also the negligible influence of the coarser sediment of the Upper Meghna River (see Section B.4.4.6)

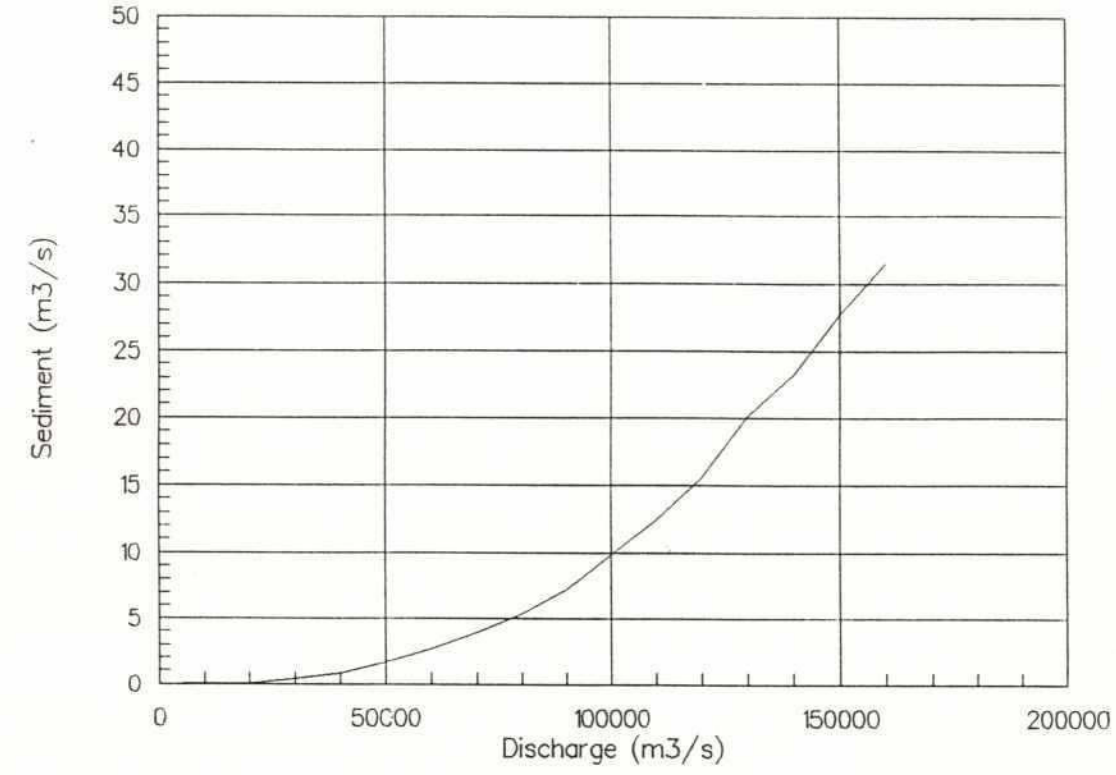


(a) Shields parameter

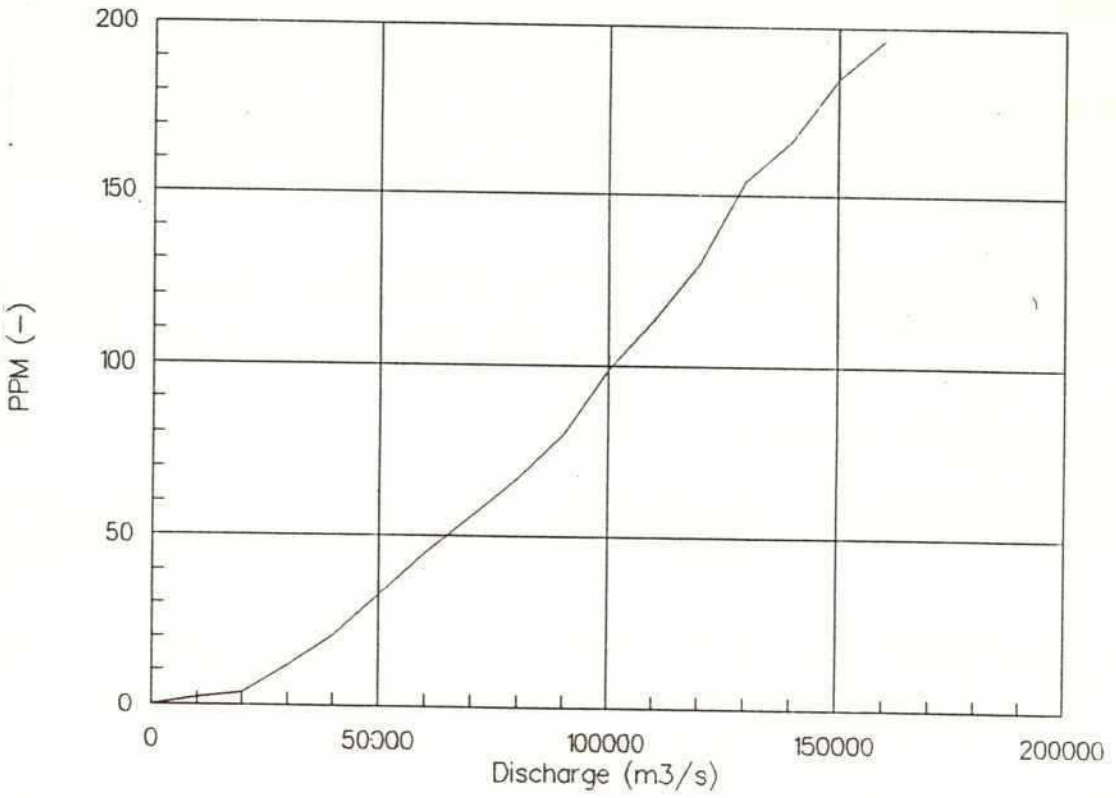


(b) Suspension parameter u./w

Sediment transport parameters of the Lower Meghna River as function of the discharge	Figure B.4.30



(a) Expressed in kg/m^3



(b) Expressed in ppm

Predicted sediment transport in the Lower Meghna River	Figure B.4.31

(4) **Dominant discharge**

Using the same definition for the dominant discharge as applied in Section B.4.3.7 ("the dominant discharge in a river is defined as the discharge that carries most of the sediment") the dominant discharge in the Lower Meghna River can be determined. It is found that the thus defined dominant discharge of the lower Meghna River is about 80.000 m^3/s. This slightly lower than the bank full discharge of 82.500 m^3/s assumed in Section B.4.4.4.

B.4.4.8 Synthesis

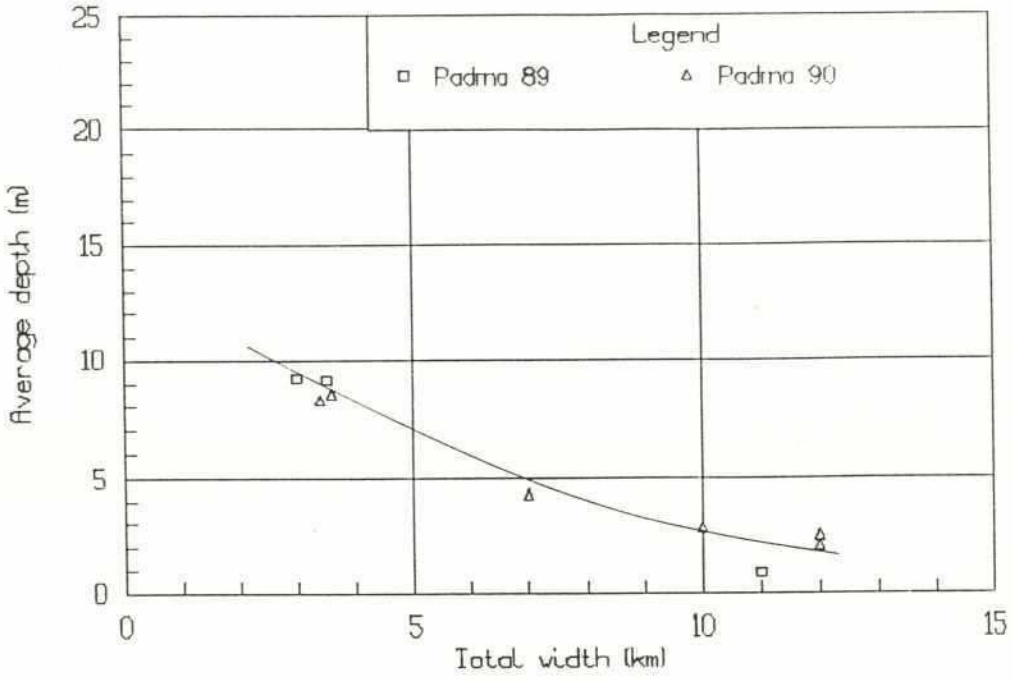
In the preceding sections some characteristics of the Padma/Lower Meghna River system are described. The image that emerges from the information provided is a river that is quite variable over a relatively short distance. Near Mawa the river is narrow and deep. Some distance downstream of Mawa the river widens substantially and a system of channels and islands is formed that moves towards and into the large bend. This bend coincides at present with the confluence with the Upper Meghna River. There the total width of the river reduces considerable due to the formation of a very large point bar. It seems that the system of channels and islands is almost fully suppressed and only downstream of Chandpur the river widens again and more channels develop again. It should be noted that downstream of Chandpur, where the river still seems quite constricted compared to the conditions upstream of the confluence, usually two channels are present but these are separated by a char that does not normally emerge even not during low water conditions. Nevertheless the tendency seems to be towards two channels.

Similar to what is done in Section B.3.8 for the Upper Meghna River, here an attempt is made to explain the observed phenomena in terms of the two parameters λ_w and λ_s and the interaction parameter λ_s/λ_w. To compute these parameters the average width and water depth of the river should be known. In the case of a meandering river these parameters are not difficult to define. This is different for a braided river. Here the width is defined as the total width of the river including both chars and channels. The average depth is defined as the average depth taking into account both the channels and the chars. This corresponds to the zero order solution of the system (see Struiksma et al, 1985). It may be expected that the average depth and width are a function of the total width of the river. This is explored in Figure B.4.32 where the average depth is plotted as a function of the total width of the river. In this figure different relations are presented for the Padma and the Lower Meghna River, as it can be inferred that the area of these rivers and hence this relationship is different. This is supported by the results of the analysis presented in Figure B.4.32, as derived from an analysis of the BIWTA soundings.

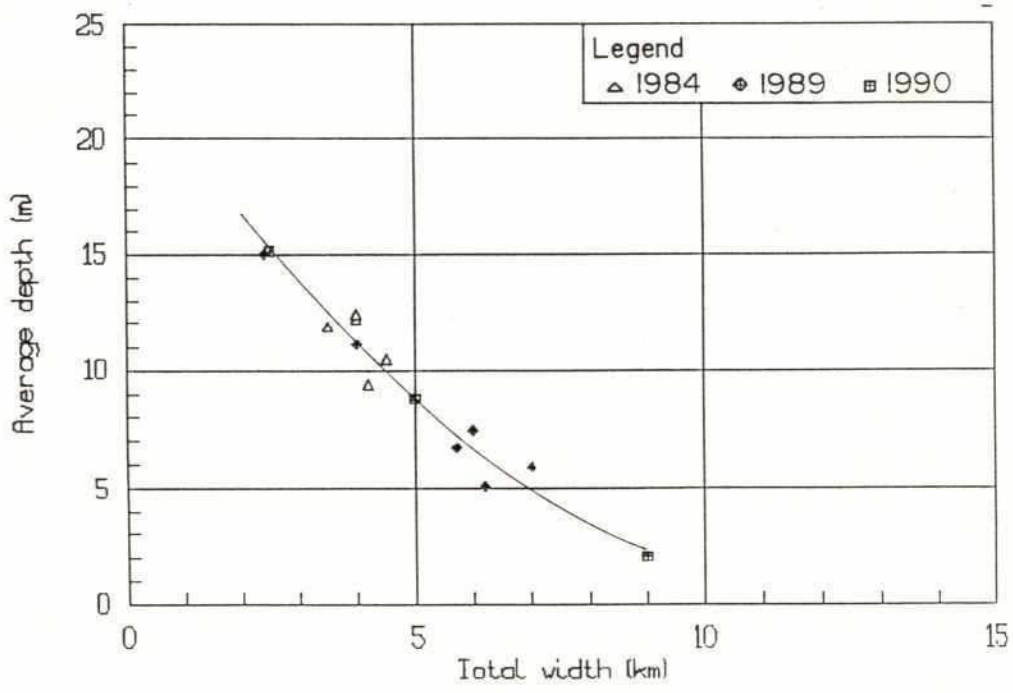
In a further elaboration the values of relaxation length of the water motion λ_w, of the relaxation length of the water λ_s and the interaction parameter λ_s/λ_w were computed. It is reminded here that the values of λ_s were computed assuming the mode m to be 1 (corresponding to alternate bars). In the case of the widening river system also values of m higher than 1 may be expected as a system of channels and chars develops. The higher the mode, the more channels are present. The bed configuration for higher modes of m are schematically indicated in Figure B.4.19. The relationship between modes and number of channels is indicated hereafter:

Mode m	Average number of channels
1	1
2	1-2
3	2
4	2-3

This corresponds to finding solutions for a combination of m, λ_w and λ_s that fit into Figure B.4.19 for a given value of the total width B (and hence the average depth according to Figure B.4.26).



(a) Padma River



(b) Lower Meghna River

Relation Between the average depth and the total width as inferred from BIWTA Soundings (chars included)

Figure B.4.32

Using the above relationships and assuming the following data to be representative for the Padma River: dominant discharge 72,500 m^3/s, slope is 5 cm/km and a Chezy coefficient of 125 $m^{1/2}/s$, the modes (and hence the number of channels) were thus determined on a theoretical basis for values of the width of the river B between 3,000 and 12,000 m. It was found that B = 10,000 corresponds to m = 4 and hence results in the formation of 2 to 3 channels, while a width B of 6,000 m would result via m = 3 into approximately 2 channels. This corresponds nicely to the information provided in Section B.4.4.3 about the number of channels in relation to the depth. For values of B of some 3,000 m in reality one channel is found. This was not predicted with the theoretical model used here. The theoretical model allows to predict also the length of the islands in the Padma River as these should be about half of the dominant wave length L (see Figure B.4.19). The values predicted are, however, much smaller than observed in reality.

Nevertheless it can be stated that the cause for the occurrence of the channels and islands in the river reach concerned is caused by the substantial increase of the total river width (chars and channels both included). It will be shown in Chapter 5 that these channel and bar system has a major influence of the bank erosion problems in the Lower Meghna River, and therefore an increased understanding of these phenomena is of large importance for the planning and design of bank protection works along the Lower Meghna River.

B.5 HISTORICAL PLANFORM CHANGES

B.5.1 General

Changes in the planform of both the Upper and Lower Meghna River are discussed in this Chapter. The main purpose of this analysis is to identify any trends that may still be ongoing. The insight obtained is used in the subsequent Chapter B.6 ("Future planform development at different sites") to predict future changes.

The data used in the present analysis have already been described in Chapter B.3 of this Annex. In short they are (old) maps, satellite images, cross-sectional soundings, BIWTA sounding charts, and some specific measurements of e.g. the bank line positions over the years.

Many of these data are not very accurate or there is some doubt as to e.g. the positioning. This is one of the reasons that trends can not always be identified univocally. Another, and possibly even more important reason, is that the processes that cause bank erosion are not uniform in time and space, and that similar to the morphological processes in the Jamuna River (see Klaassen and Masselink (1992) for an extensive discussion of this aspect), the processes involved are possibly only deterministic to a certain extent. The implication is that some type of chaotic behaviour is probably inherent to bank erosion processes along straight and braiding rivers alike. This poses also a limit to the possibilities of "understanding" all bank erosion and channel migration events, but more importantly, it restricts the predictability of the system as far as the future behaviour is concerned.

The structure of this Chapter is as follows: The Upper Meghna and the Lower Meghna Rivers are discussed separately (as their behaviour is quite different and independent of each other, see also Chapter B.1). For each river first the overall trend is discussed (in the Sections B.5.2.1 and B.5.3.1, respectively). In a second step the conditions at the different problem sites are considered in more detail. These problem sites are:
Upper Meghna River:

- Bhairab Bazar (Section B.5.2.2)
- Maniknagar (Section B.5.2.3)
- Meghna Road & Highway Bridge (Section B.5.2.4)
- Munshiganj (Section B.5.2.5)

Lower Meghna River:

- Eklashpur (Section B.5.3.2)
- Chandpur (Section B.5.3.3)
- Haimchar (Section B.5.3.4)

B.5.2 Upper Meghna

B.5.2.1 Overall trend

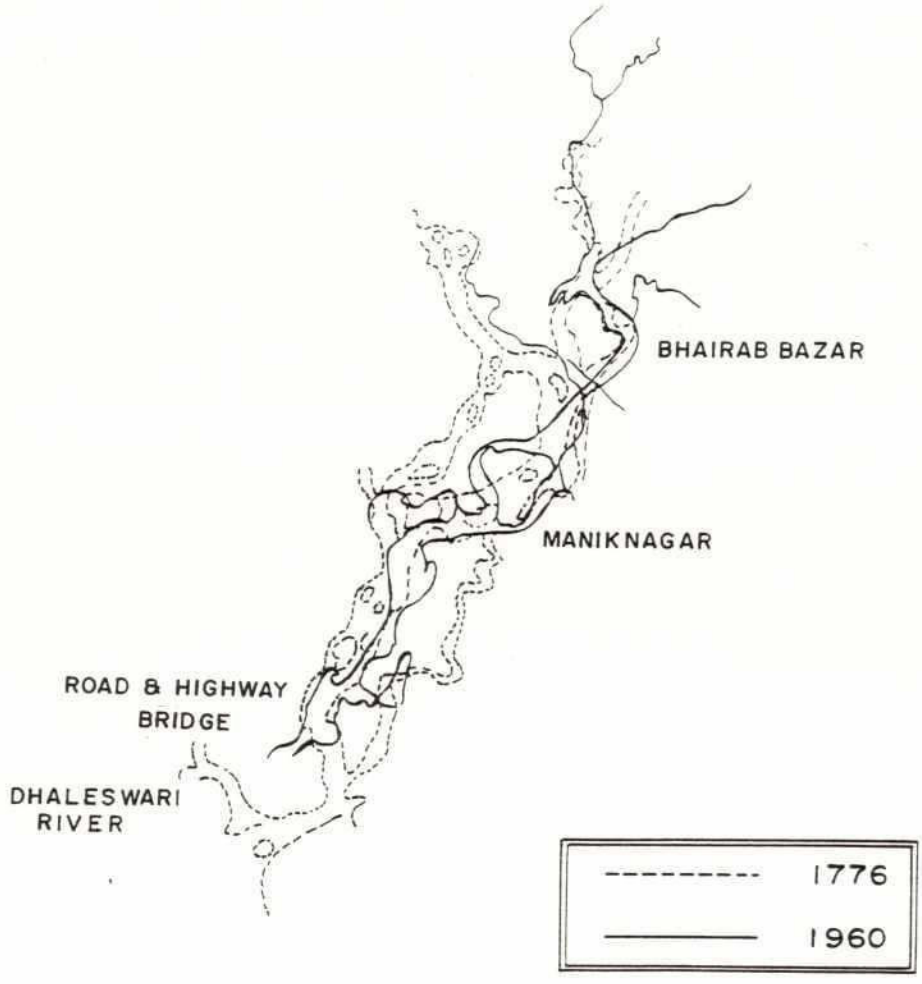
Possible overall trends of the planform changes of the Upper Meghna River were studied on the basis of maps, satellite images and BDWB cross-sections. Satellite images are available since 1973, whereas the available BWDB cross-sections cover only the last 10 years. Only the maps cover a much longer period, but the large time intervals between the maps and their inaccuracy make the interpretation more difficult.

Comparison of the available **maps** reveals definite changes. When the course of the Upper Meghna in 1960 is compared with the course in 1776, the decrease in size of the river channel is clearly visible (see also figure B.5.1). Furthermore it can be noticed that the number of parallel channels has decreased significantly. Nevertheless the present Upper Meghna course is approximately corresponding with previous Brahmaputra channels. This is slightly amazing as it was noted that in a braided river like the Jamuna River the channel pattern changes quickly while it is not certain that the major avulsion of the Brahmaputra River occurred

in a very short time and immediately after the preparation of Rennell's map. Therefore some doubt is present as to the foregoing conclusion. Furthermore it should be realized that the comparison between these two maps is not reliable as a result of the limited accuracy of the Rennell's map (not being based on aerial photography).

Comparison of the other available maps (1860, 1953 and 1960) does reveal changes in the Upper Meghna course (see figure B.5.2). Near the confluence Dhaleswari - Upper Meghna the some major changes can be identified clearly:

(1) In the Dhaleswari River upstream of the confluence with the Lakhya River the evolution of a cutoff can be followed: between 1860 and 1953 the bend radius of the bend just upstream of the Lakhya junction decreases, resulting in a cut off; in 1960 the old channel has been abandoned.



Comparison of Rennell's map and the 1960 map	Figure B.5.1

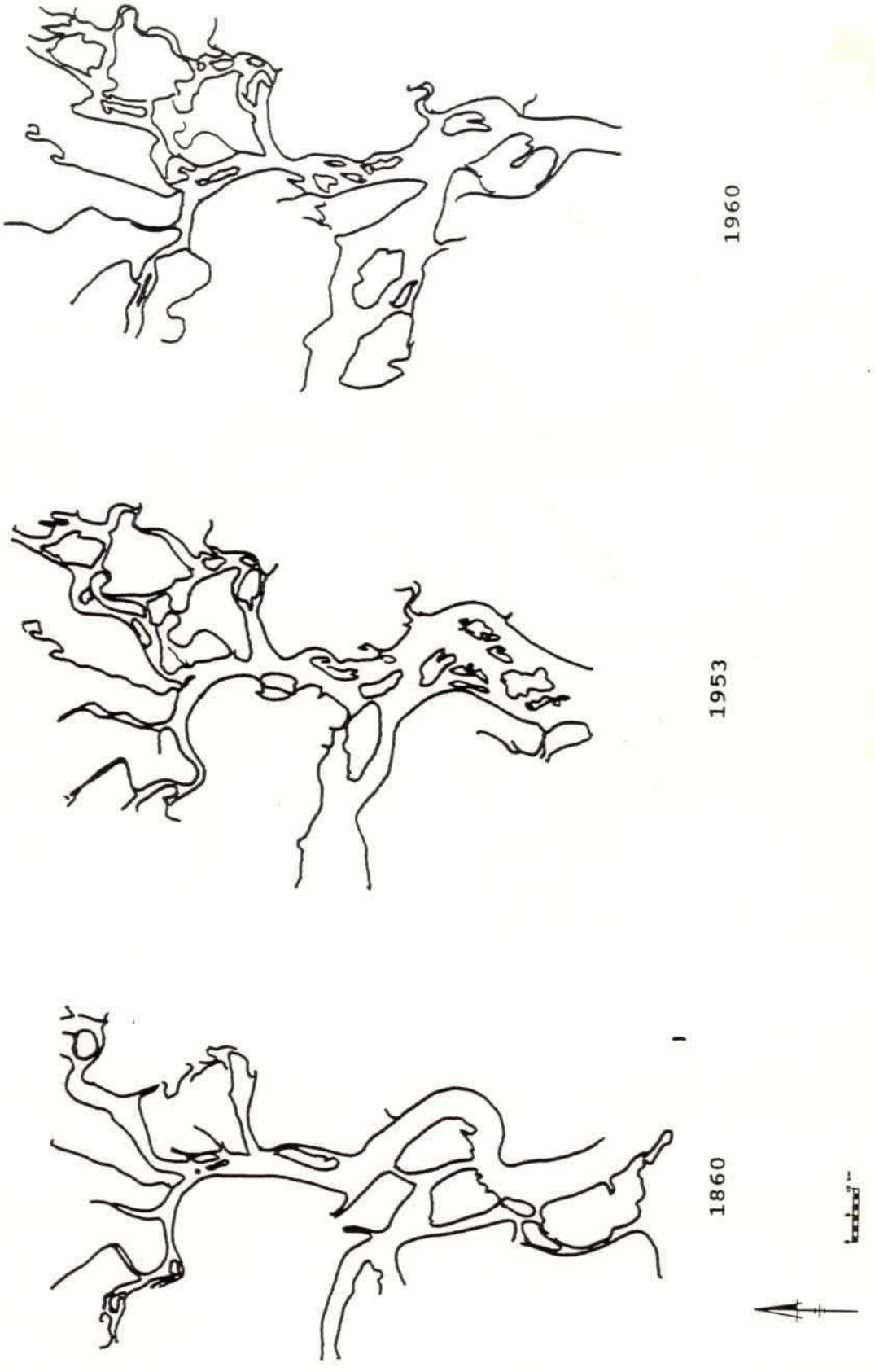
(2) The bends of the channel just upstream of the Dhaleswari - Upper Meghna confluence become more pronounced, as the bend radii become smaller.

Other changes have also occurred but the accuracy of the maps does not allow to draw definitive conclusions.

In the NEDECO (1967) maps are drawn of the Upper Meghna which have been surveyed between 1964 and 1966. The scale of these maps is 1:100,000. Because the other available maps are at a scale of approximately 1:250,000, comparison with the NEDECO maps is difficult due to differences in details of schematisation. Hence they were not used in the present study.

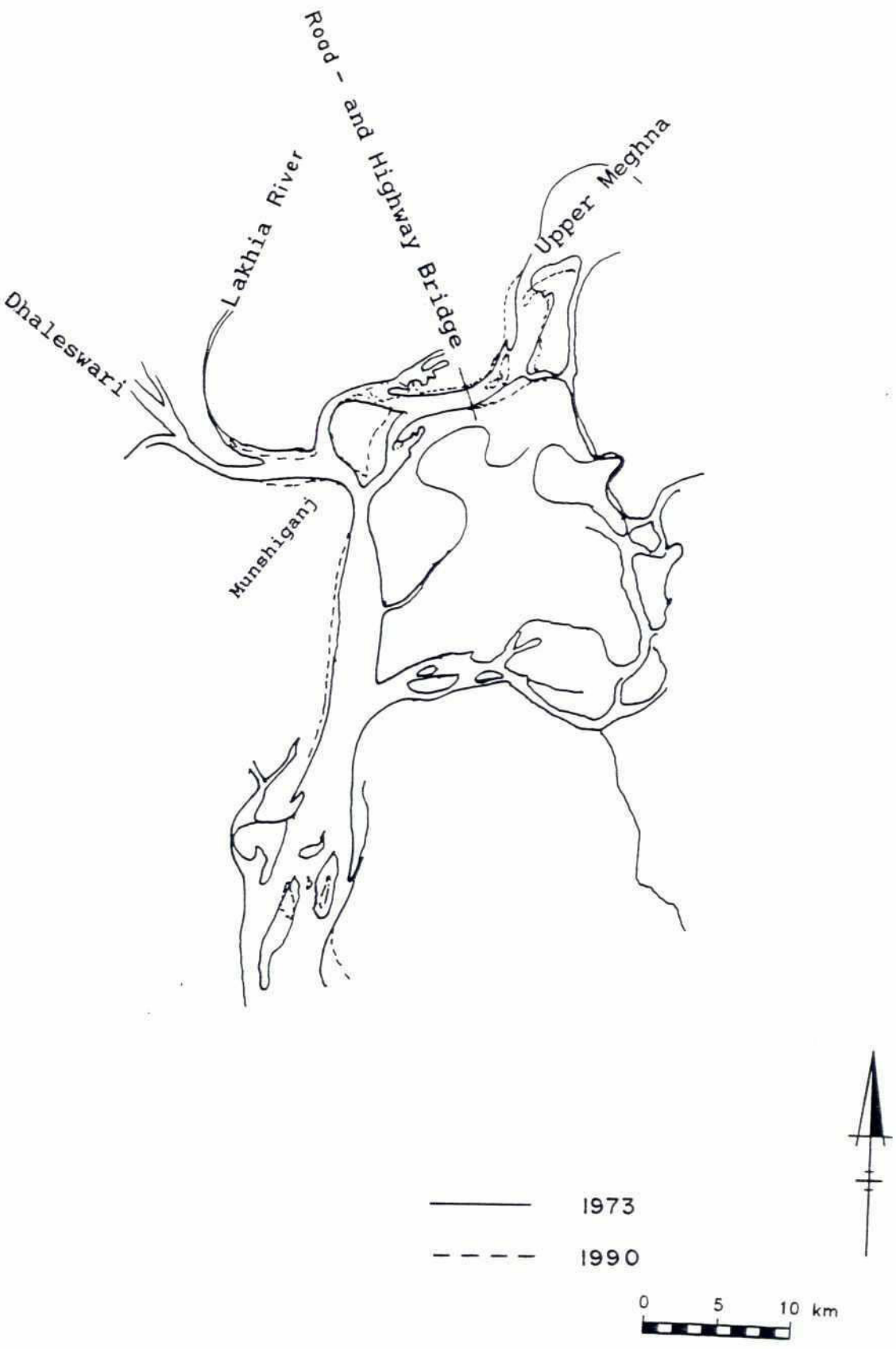
Also for this study available **satellite images** were used. In figure B.5.3 the image of 1973 is compared with an image of 1990. The dashed line represents the contour line of the 1990 image. Some changes can be identified: the char upstream of the confluence Dhaleswari - Upper Meghna has become smaller, some sedimentation at the left bank at the confluence Lakhya River - Dhaleswari River is visible, while erosion has occurred of the right bank. Furthermore, some bank erosion at the right bank downstream of the Dhaleswari - Meghna confluence can be observed. Some other minor changes have also taken place, e.g. at the confluence of the Dhaleswari and the Upper Meghna. The overall picture however is that no large differences have occurred over the 17 years the comparison covers. Considering also the accuracy of the technique applied (comparison of prints made in Bangladesh of negatives of satellite images) it can be stated that the differences are probably too small to be ascribed to erosion or sedimentation processes rather than to differences in scale of the different satellite images. In this respect it should be noted that the correction applied to the satellite images within the Jamuna Bridge Appraisal Study (see RPT et al, 1990b) on the digital data was not only straightforward adapting the scale but involved complicated geometrical corrections.

Analysis of the available **cross-sections** showed that planform properties and location of the river banks have not changed much. Four cross sections are analyzed in a more extensive way. In one of the cross sections, (M#14), a shifting of the 50 % conveyance point was significant. This shifting, however, was not of a systematic nature: the 50 % conveyance point moved in either of the two possible directions (to the right or to the left bank). Other available cross-sections were also analyzed and it appeared that location, width and depth remained the same.

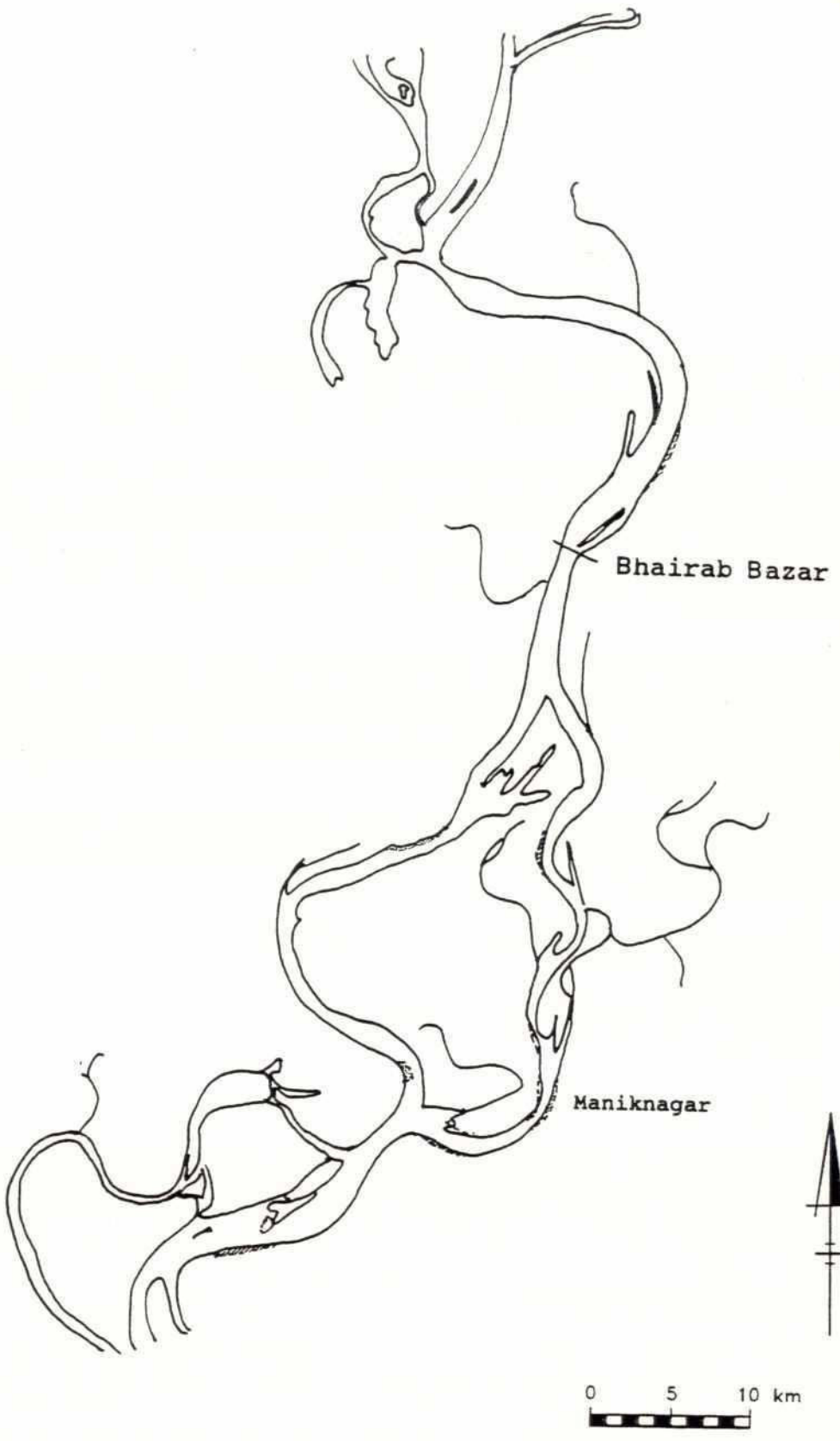


Comparison of planform from maps of 1860, 1953 and 1960

Figure B.5.2



Comparison of planform from satellite images of 1973 and 1990	Figure B.5.3(a)



Comparison of planform from satellite images of 1973 and 1990	Figure B.5.3(b)

In summary it can be stated that, although definitely changes have occurred since Rennell's map was prepared, apparently the overall changes in the planform of the Upper Meghna River over the last decades are so small that they cannot be quantified using the technique of comparing (prints of) satellite images. Erosion of the river banks does occur along the Upper Meghna River, but the erosion rates are so small that studies on the basis of the available data used here do not reveal a reliable picture of the rate of erosion and sedimentation in most places.

B.5.2.2 Bhairab Bazar

In this section the conditions at Bhairab Bazar are considered in more detail. For this use is made of old maps, satellite images and BWDB cross-sections. The latter have been processed as described in Section B.3.4.

Comparison of the **maps** of 1953 and 1960 reveals no difference in the Upper Meghna River near Bhairab Bazar. From an inspection of the map of 1860 it may be concluded that the radius of curvature of the upstream bend radius of the Upper Meghna is in 1860 somewhat larger than about one century later, but the reliability of the 1860 map is not that large that this conclusion can be drawn beyond any doubt.

A comparison of the available **satellite images** shows that near Bhairab Bazar no significant change of the river course can be observed. Even the char just upstream of the railway bridge did not change its position over the period 1973 - 1990 (see figure B.5.3 (b)). The width of the river at Bhairab Bazar has decreased probably due to the protection of the river banks. The right bank at the bridge site is situated at the outer bend. At this site erosion problems do occur, but on the satellite images no difference can be identified between 1973 and 1990.

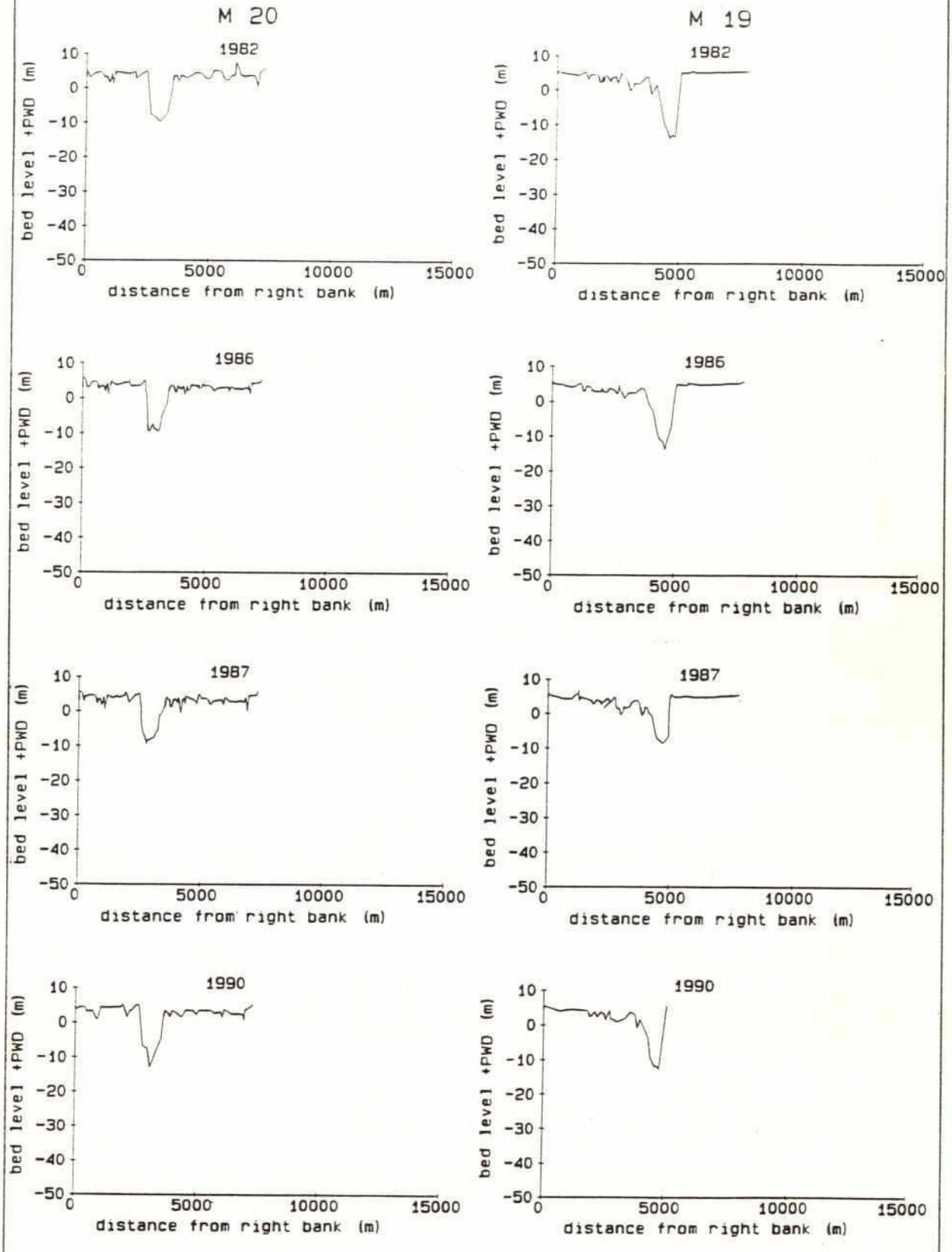
The most detailed information available are the **BWDB cross-sections** measured near Bhairab Bazar. An analysis was carried out of three cross-sections namely M#18, M#19 and M#20, upstream of and at the location of the railway bridge at Bhairab Bazar (see Figure B.3.2 for the location of these cross-sections). The results of the measurements of these different cross-sections for the years 1982,1986, 1987 and 1990 are drawn in the Figures B.5.4 and B.5.5.

Each cross section was analyzed for the four years (1982, 1986, 1987 and 1990). In order to try and identify any systematic changes in the cross-sections over the years, for each cross-section the following parameters were determined:

- distance of the 50% conveyance point to the right bank.
- average channel level
- maximum depth
- distance of maximum depth to the right bank
- average level
- width of the main channel
- average depth of main channel

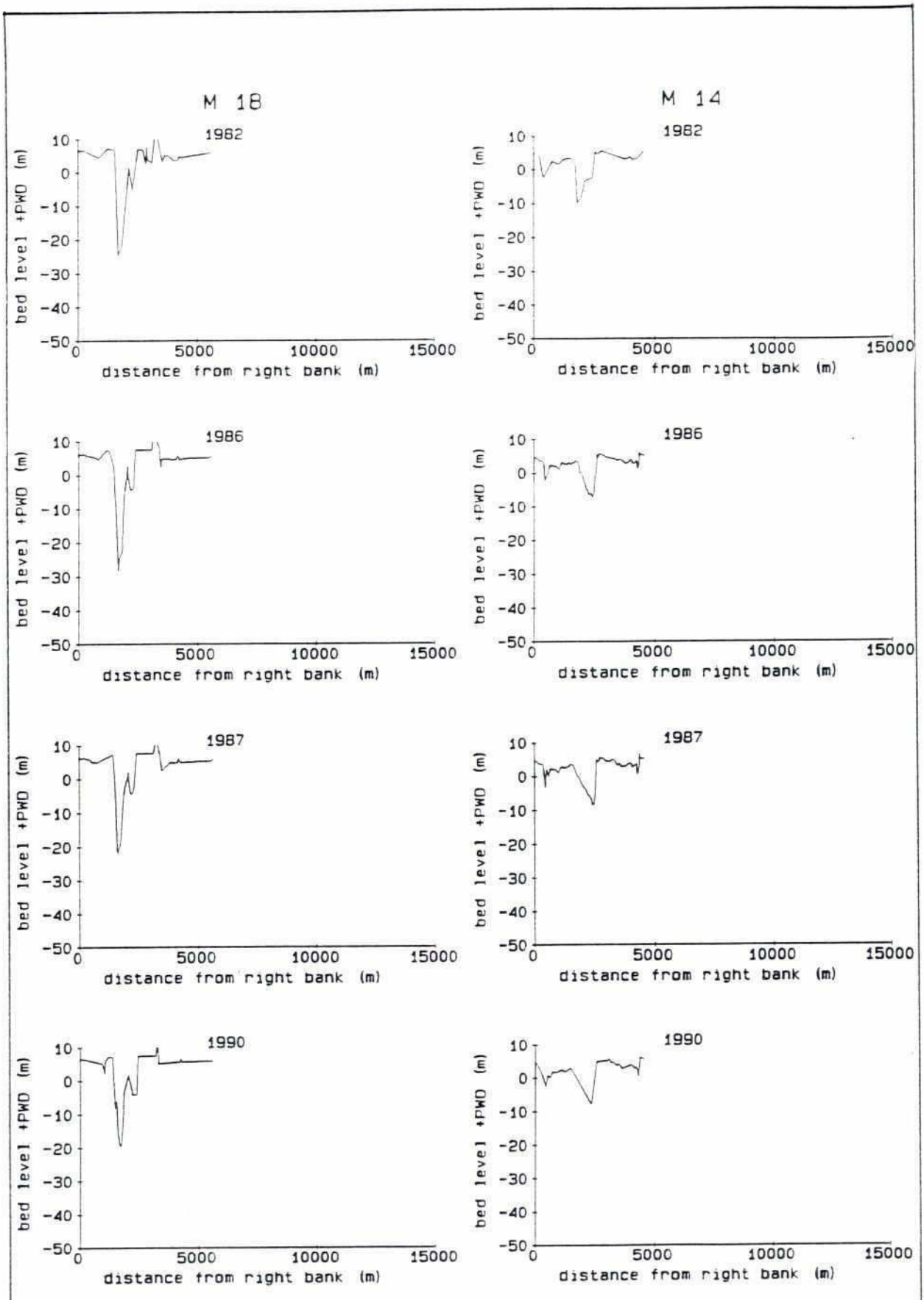
The analysis was carried out with respect to the bankfull level of the different cross-sections (see Section B.4.3.5) This level corresponds to about 5.5 m+PWD for M#18, and 5.7 m+PWD for M#19 and M#20. Some results of the analysis are presented in Table B.5.1. The 50% conveyance point represents the "centre" of the bankfull discharge; at either side of this point 50% of the total conveyance is available. A systematic change in the location of the 50% conveyance would imply a systematic shift of the cross-section (and hence the river channel) to either side.

From Table B.5.1 it appears that there are no systematic changes in location and depth of the main channel since the location of the 50% conveyance point does not change systematically. The changes are in fact very small (less than 100 m). The table thus shows no trends in horizontal or vertical shifting. What can be observed in this table, is that the depth at the location of the railway bridge is, due to the fixation of the banks, greater than the depth at the other cross-sections (This is discussed in greater depth in the Chapters B.7 and B.8).



Measured cross-sections M#20 and M#19 for the years 1982, 1986, 1987 and 1990

Figure B.5.4



Measured cross-sections M#18 and M#14 for the years 1982, 1986, 1987 and 1990	Figure B.5.5

TABLE B.5.1 ANALYSIS OF CROSS SECTIONS M#20, M#19, M#18 AND M#14 THE LOWER MEGHNA RIVER

	location 50 % con veyance point	max depth	distance of max. depth	average level
M20-82	3060	- 9.4	2990	2.44
M20-86	3080	- 9.7	2810	2.32
M20-87	3017	- 0.8	2850	2.42
M20-90	3217	-13.5	3093	2.08
M19-82	4630	-14.2	3160	2.77
M19-86	4585	-12.3	3160	2.58
M19-87	4663	- 9.3	3160	3.15
M19-90	4635	-13.0	3080	1.45
M18-82	1860	-24.9	1630	3.30
M18-86	1790	-31.1	1700	3.60
M18-87	1750	-22.5	1633	3.81
M18-90	1760	-23.2	1701	3.96
M14-82	1900	-10.4	1792	1.88
M14-86	2180	- 7.2	2130	2.27
M14-87	2180	- 8.5	2140	2.03
M14-90	1830	- 7.9	2190	1.85

In summary it can be concluded that there is no evidence from the available information used here that any bank erosion has occurred near Bhairab Bazar since 1973.

B.5.2.3 Maniknagar

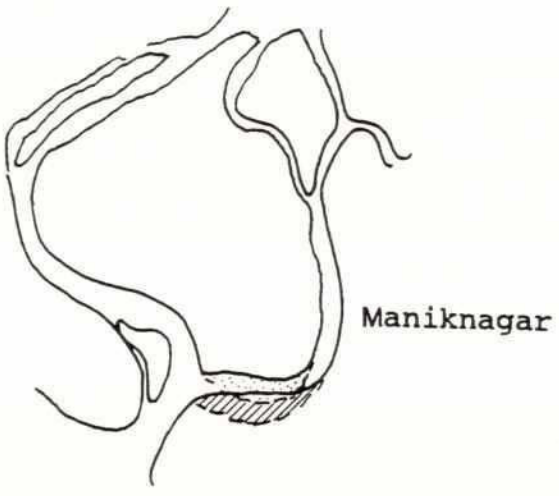
In this section the conditions at Maniknagar are considered in more detail. For this use is made of old maps, satellite images and BWDB cross-sections.

Comparison of the **maps** of the years 1953 and 1960 show no changes at Maniknagar. Downstream of Maniknagar there is erosion at the outer bend noticeable between 1953 and 1960 (see Figure B.5.6). The map of 1860 is not very clear at the location of Maniknagar, hence this map could not be used for making a comparison.

mparison of the **satellite images** betwe[illegible] 1973 and 1990 does reveal some changes in planform of
ver at Maniknagar. Between 1973 and [illegible]90 an erosion of about 250 m on the left bank is observed.
e right bank of this site there is some se[illegible]mentation. Maniknagar is situated along an outer bend of the
er Meghna, and apparently this curved [illegible]annel is gradually shifting in eastern direction.

e BWDB cross-section is available for th[illegible] analysis of any systematic changes. For this cross-section
14), located slightly downstream of Ma[illegible]nagar, a significant horizontal shift is noticeable (see Table
.1). A similar analysis as was made for [illegible]ss-sections M#18, M#19 and M#20, was also carried out for
ss-section M#14. The results are also p[illegible]ented in Table B.5.1. The location of the 50 % conveyance
int has shifted significantly over the ana[illegible]d period. In 1982 this point was located at 1.9 km from the
ht bank, in 1986 and 1987 at 2.2 km. and [illegible]1990 at 1.8 km. from the right bank. Inspection of the profiles
r the different years in Figure B.5.5, re[illegible]s that the main channel erodes at the left bank, this bank
ecoming steeper while the opposite ban[illegible]comes more gentle. It seems that the left bank shifts from a
onvex to a concave bank. Between 198[illegible]d 1990 there is sedimentation at the left bank of the main
hannel although the steepness of the b[illegible]emains the same.

n summary it may be concluded that th[illegible]ved channel near Maniknagar has caused erosion along the
outer bend of some 250 m over the last [illegible]decades. The location of the bank erosion appears to have
shifted through the years.



Comparison of river planform near Maniknagar from maps	Figure B.5.6

B.5.2.4 Meghna Roads & Highways bridge

In this section the conditions near the Roads & Highways bridge are considered in more detail. For this use is made of old maps and satellite images.

Significant changes can be identified when comparing the **maps** of 1860 and 1953. In 1860 the river was wider than in 1953. Also the bends were less curved than in 1953. It may well be that in 1869 the Upper Meghna was still in transition from a major braided river with discharges up to 100.000 m^3/s to the present meandering river with maximum discharges "only" up to 20,000 m^3/s. In 1953 the bridge was not yet present. In Figure B.5.7 a comparison is made between the planform of the Upper Meghna River at the location of the bridge in 1953 and in 1960. In the upper figure also the 1860 planform is drawn. Between 1953 and 1960 erosion of the left bank at the location of the bridge had occurred and at the right bank there is sedimentation at the char, which in the mean time has become part of the right bank.

Recent information can be obtained from **satellite images** (see Figure B.5.3 (a)). The Meghna Roads & Highway bridge is presently situated along a bend in the Upper Meghna River. Upstream of the bridge the radius of curvature of the bend is decreasing causing the thalweg únds to shift to the left bank. At the site of the bridge erosion is noticeable at the right bank. Also upstream and downstream of the bridge changes have occurred (see Figure B.5.3(a)). The left bank upstream of the bridge has eroded about 250 m between 1973 and 1990. A char has developed in the Upper Meghna upstream of the bridge. Downstream of the bridge the right bank has eroded about 100 m since 1973.

B.5.2.5 **Munshiganj**

Munshiganj is situated at the right bank of the Dhaleswari River, a tributary of the Upper Meghna, joining the Upper Meghna river sligtly upstream of the confluence with the Upper Meghna River. Information on the changes in river planform near Munshiganj is available from maps and from satellite images.

A comparison of the **maps** of 1860, 1953 and 1960 (see Figure B.5.8) shows that the width of the Dhaleswari River has decreased over that period. The strip of land between the Dhaleswari River and the Upper Meghna River has been eroded between 1860 and 1960. In the same period the Dhaleswari River shifted in northeastern direction. Apparently a bend was present that migrated slowly towards the confluence with the Upper Meghna River.

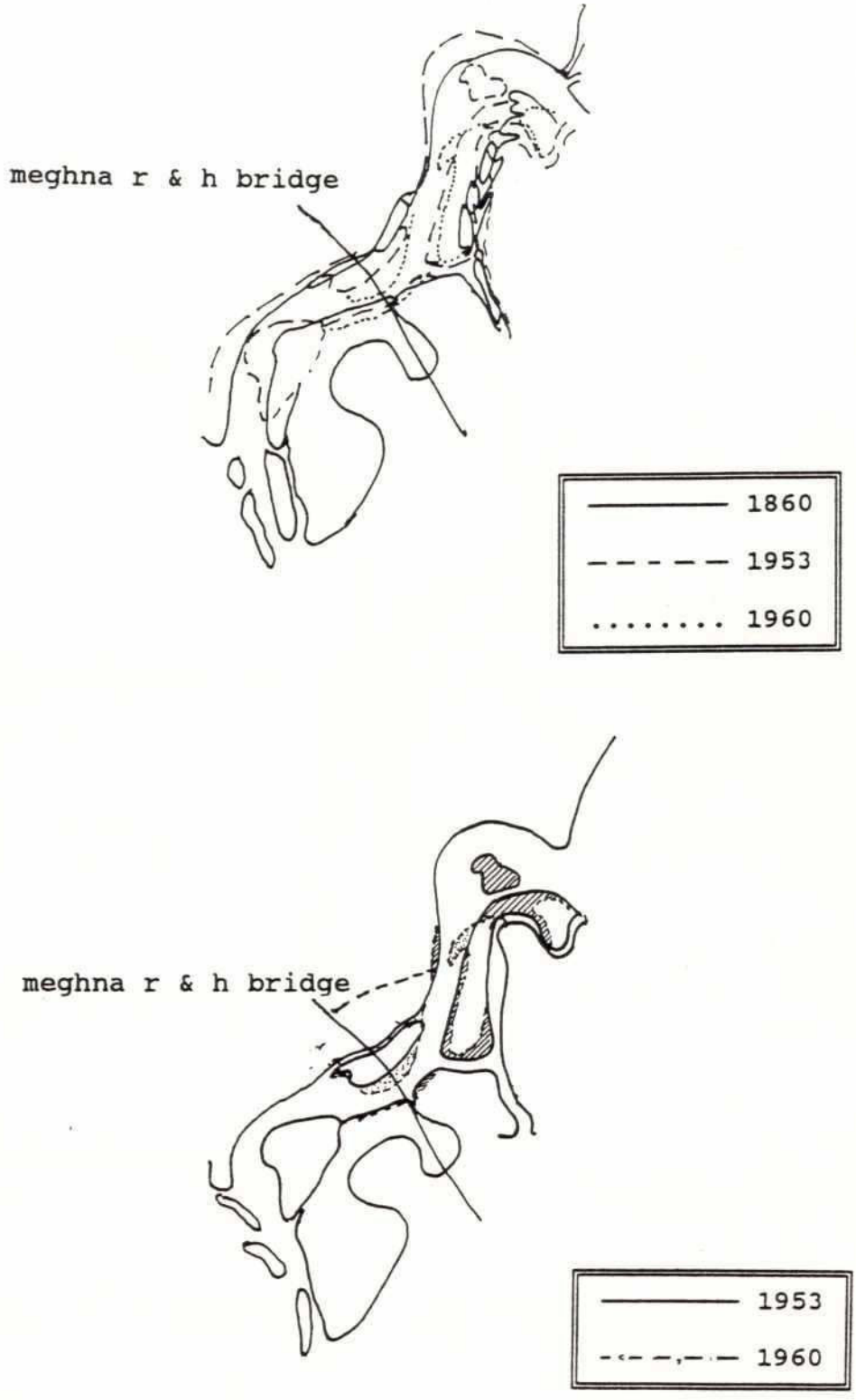
Comparison of the satellite images of 1973 and of 1970 shows a widening of the river channel with erosion on both the right and the left bank. At the right bank, the river has eroded some 250 m and at the left bank the river has eroded even more. According to oral information erosion has concentrated on the right bank in the recent years.

B.5.3 **Padma/Lower Meghna River system**

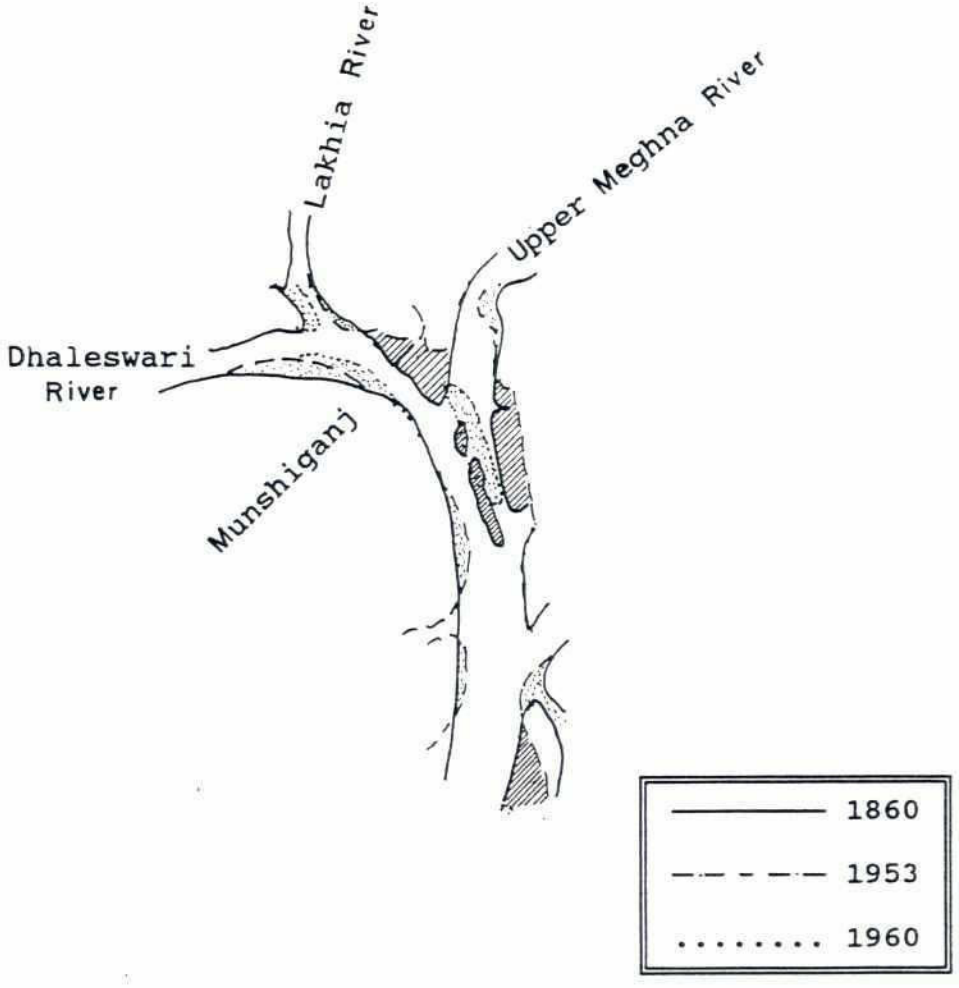
5.3.1 Overall trend

In this Section the overall trend of the planform movement of the Lower Meghna River is discussed. Different from the Upper Meghna River, where changes of the planform are minor only, in the Lower Meghna River major changes are taking place. Because it was found that these bank line changes are closely related to the movement of the system of channels and bars in the combined Padma / Lower Meghna system, the whole system from Mawa along the Padma River down to Haimchar in the South is considered.

Use was made of all the available information, notably old maps, satellite images, BWDB soundings, BIWTA sounding charts and other information. Also quite extensively use was made of the results of a study carried out fairly recently by Galay (1980), which attempted to analyze the changes in the Lower Meghna River too.



Comparison of river planform near the Meghna Road & Highway Bridge from maps	Figure B.5.7



Comparison of river planform near Munsjiganj from maps of 1860, 1953 and 1960

Figure B.5.8

Different from the discussion of the overall trend of the Upper Meghna River (where the different problem sites are quite far apart) here the problem areas (Eklashpur, Chandpur and Haimchar are fairly close, with the implication that the different sites cannot be considered in an isolated way. The consequence for the present discussion is that the Section dealing with the overall trend is quite long. Here in fact most of the analyses carried out are described.

Hence the considerations on the different problem sites are relatively short.

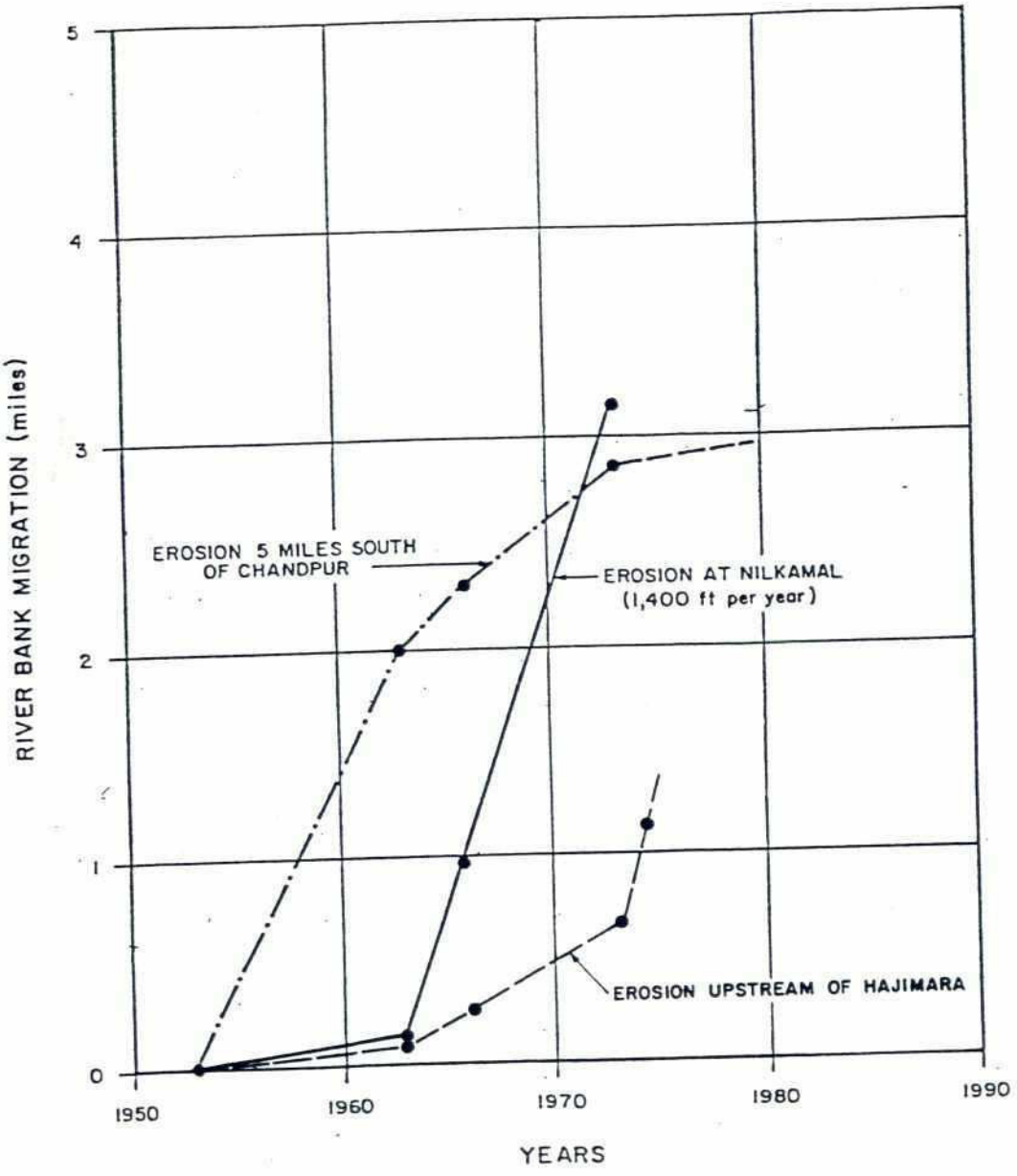
In a previous study (Galay 1980) it is stated that in the Meghna River two types of channel shifting processes occur, notably:

(1) gradual migration of the major flow channel, and
(2) rapid shifting of the major channel during the development of a cutoff.

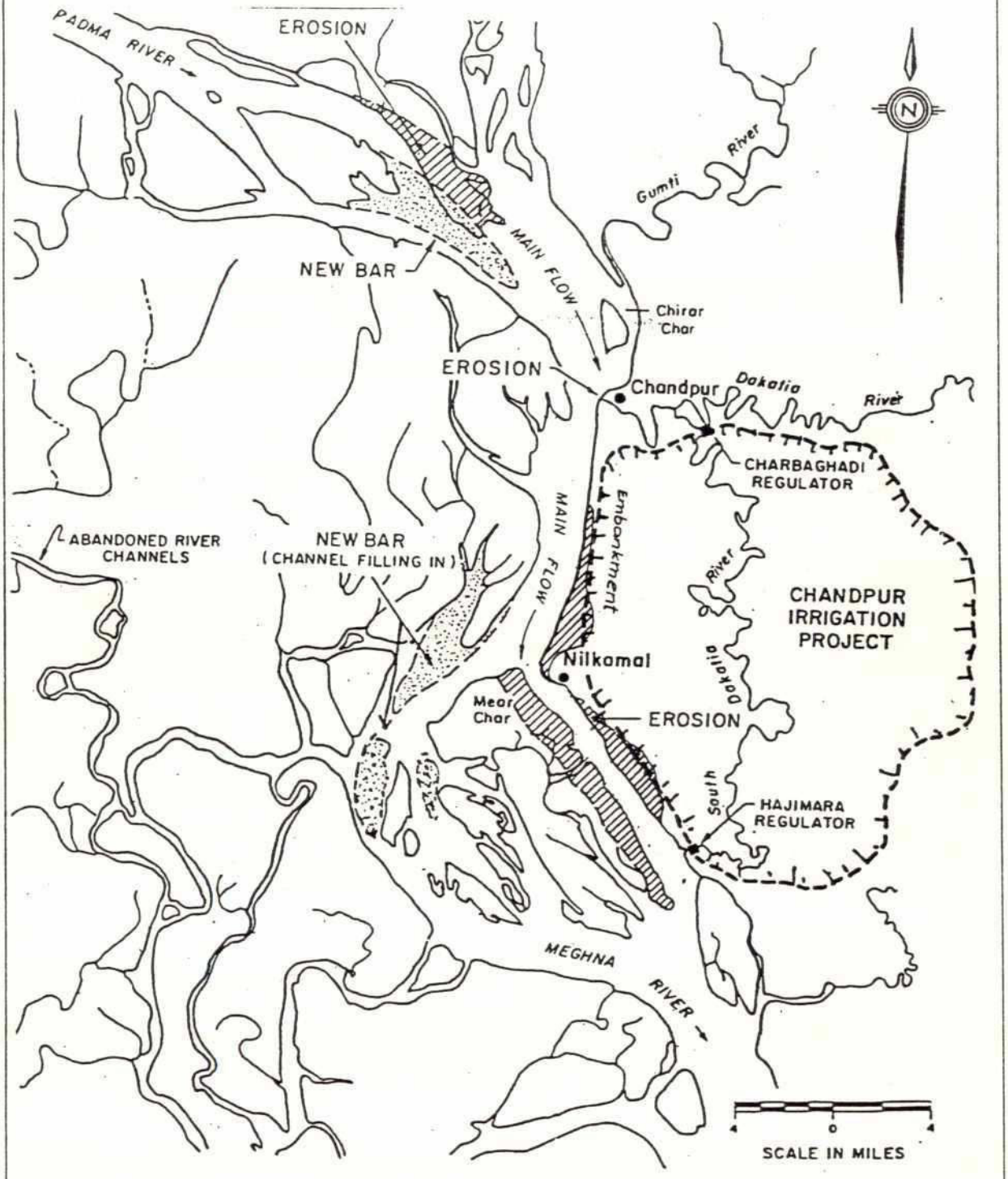
As an example of gradual migration, Galay (1980) presents a figure (included in this report as Figure B.5.9), which shows the erosion rate 5 miles south of Chandpur. The gradual migration of the Meghna eastward has been carrying on for years. This migration has endangering the town of Chandpur for decades. Maximum migration rate south of Chandpur has been 425 m/year (Galay 1980).

As an example of rapid shifting of a major flow channel is the development of a cut off of the Meghna River, to the east of Mear-char and opposite of Haimchar (here included as Figure B.5.10). As the main channel slowly migrated eastward near Chandpur, more and more flow entered the secondary channel at the east side of Mear-Char. From 1963 to 1973, the left bank of Hajimara (some 30 km downstream of Haimchar which is located near Nilkamal) was migrating at a rate of 100 m/year. However, during the 1974 flood, this secondary channel became the main channel; the left bank eroded approximately 600 m and the original main channel slowly silted up. More details on this cutoff are presented in Section B.5.3.4. According to Galay, the possible development of a cut off makes it difficult to predict rates of bank erosion in the Lower Meghna; a bank that has not moved for years can suddenly undergo rapid erosion when the main flow channels shift rapidly.

Another study of the changes in the location of the river banks of the Lower Meghna River was done by Md Abul Kalam (1983), who created two change detection maps utilizing remote sensing techniques: first, the river course change during the period of 1973 - 1980, and second, the river course change during the period 1968 - 1980, utilizing a river course map published in 1968 (NEDECO,1968?). He found far more erosion and accretion in the 1973 - 1980 map than erosion and accretion during 1968 - 1980. The explanation for this difference between the two maps is, according to Kalam, that his study indicated that the rates of erosion and accretion are episodic. If a short-term time period is analyzed, in which a catastrophic flood occurred or a drought, the erosion and accretion figures will appear considerably higher or lower than a more average long term time period. In this case, the 1968 - 1980 figure were considered a better representative of the normally shifting of the Meghna (Kalam 1983) as they were less affected by the extreme flood in 1974.



Erosion rates of the Lower Meghna River south of Chandpur (Galay, 1980)	Figure B.5.9



Major changes in the Lower Meghna River due to the 1974 flood (Galay, 1980)	Figure B.5.10

To get a clear view of the morphological changes of the Lower Meghna the satellite "thick" images of the available years were compared with each other. To do this the different images have to be on the same scale and water levels have to be approximately equal. Applying the procedure described in Section B.3.4, ensured that these conditions were approximately fulfilled.

An inspection of the different **satellite "thick" images** available revealed the following observations regarding the channel and bar system in the Padma/Lower Meghna river system:

(1) chars in the Padma River which are generated downstream of Mawa, are moving in easterly (hence downstream) direction towards the confluence with the Upper Meghna River, and while doing so change their size and their number in lateral direction;

(3) it seems that these chars have a certain periodicity, which is tentatively estimated at some 15 years;

(2) when the front of a char enters the confluence where the Lower Meghna River makes a turn to the South, the char is being eroded instead of moving on around the corner;

(4) when an eroding char is located just upstream of the sharp bend, extreme bank erosion takes place at the opposite bank (near Eklashpur).

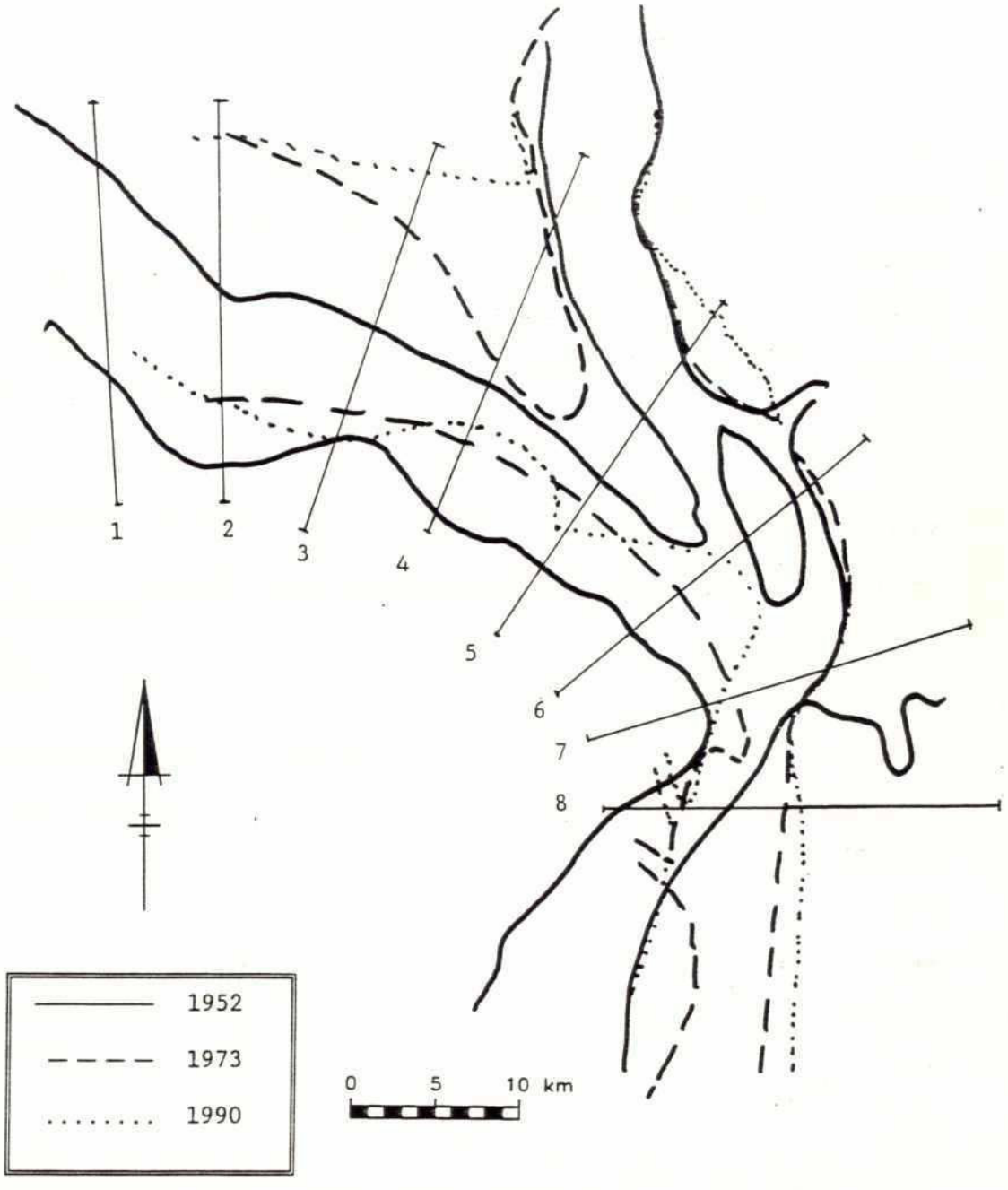
These observations are in line with predictions made in Section B.4.4.8. They are furthermore in accordance with the predictions made by Seminara (1988). It was found that alternate bars in a straight river are arrested by the point bar in a subsequent bend if that bend exceeds about 30 degrees. Downstream of this point bar the alternate bars are emerging again.

The above observations are substantiated hereafter by an extensive description of the phenomena in the considered river system. For this use is made of a reference system that consists of 8 ("imaginary") cross-sections over the Padma and Lower Meghna system. The location of these cross-sections is indicated in Figure B.5.11. All these cross sections are 15 km long and the reason for introducing these cross sections is to visualize the changes in bankline position, and the movement of the channels and chars system, in time.

Figure B.5.12 presents the location of some chars with respect to cross-section 4. From the figure it can be observed that the progress of the downstream end of the different chars stops at some 7.5 km downstream of cross section 4. At the same time the char is being eroded at the upstream side by the channel. The location of the char in 1974 is taken over by the next char in 1990, indicating a periodicity of some 16 years. In this respect it is of interest to mention that Baset Sarker et al (1984) found a periodicity in the char movement in the Ganges River in Bangladesh of some 20 years.

To illustrate the changes near the confluence over the period from 1952 to 1990 Figure B.5.11 can also be used, because the banklines of 1952 - 1973 - 1990 were drawn in this figure too. The erosion of the left bank of the Padma River and the Lower Meghna River can clearly be identified. What happens depends on the movement of the channels and chars in the Padma and Lower Meghna river. The position of the bankline of the left bank near Eklashpur is presented as the coordinate system along cross-section no. 5. The distance (in km) of the bankline with respect to the right zero "level" of the cross-section is plotted against time in figure B.5.13. From this figure it appears that the left bank has eroded continuously from 1952 to 1988, although with varying celerities.

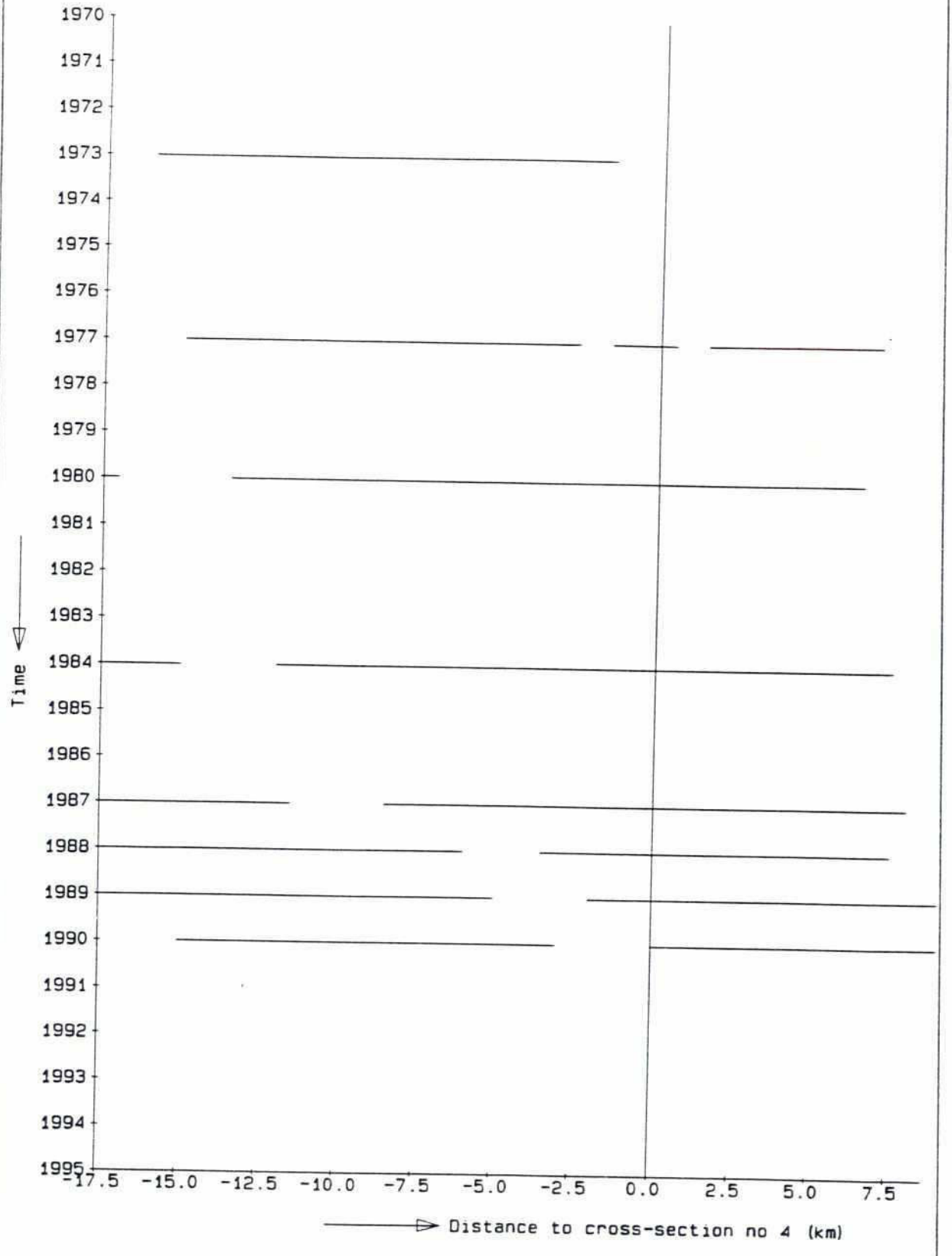
The erosion of the left bank just downstream Chandpur is represented by Figure B.5.14, in which the position of the left and the right bank on cross-section 5 is plotted versus time. The position of the left bank is moving to the east until 1980 and stays at that location, probably as a result of stabilization of the bank with bank protection works. The position of the right bank is moving to the east in some years and in other years to the west. In other words, the width of the Lower Meghna River just downstream Chandpur varies considerably over the years.



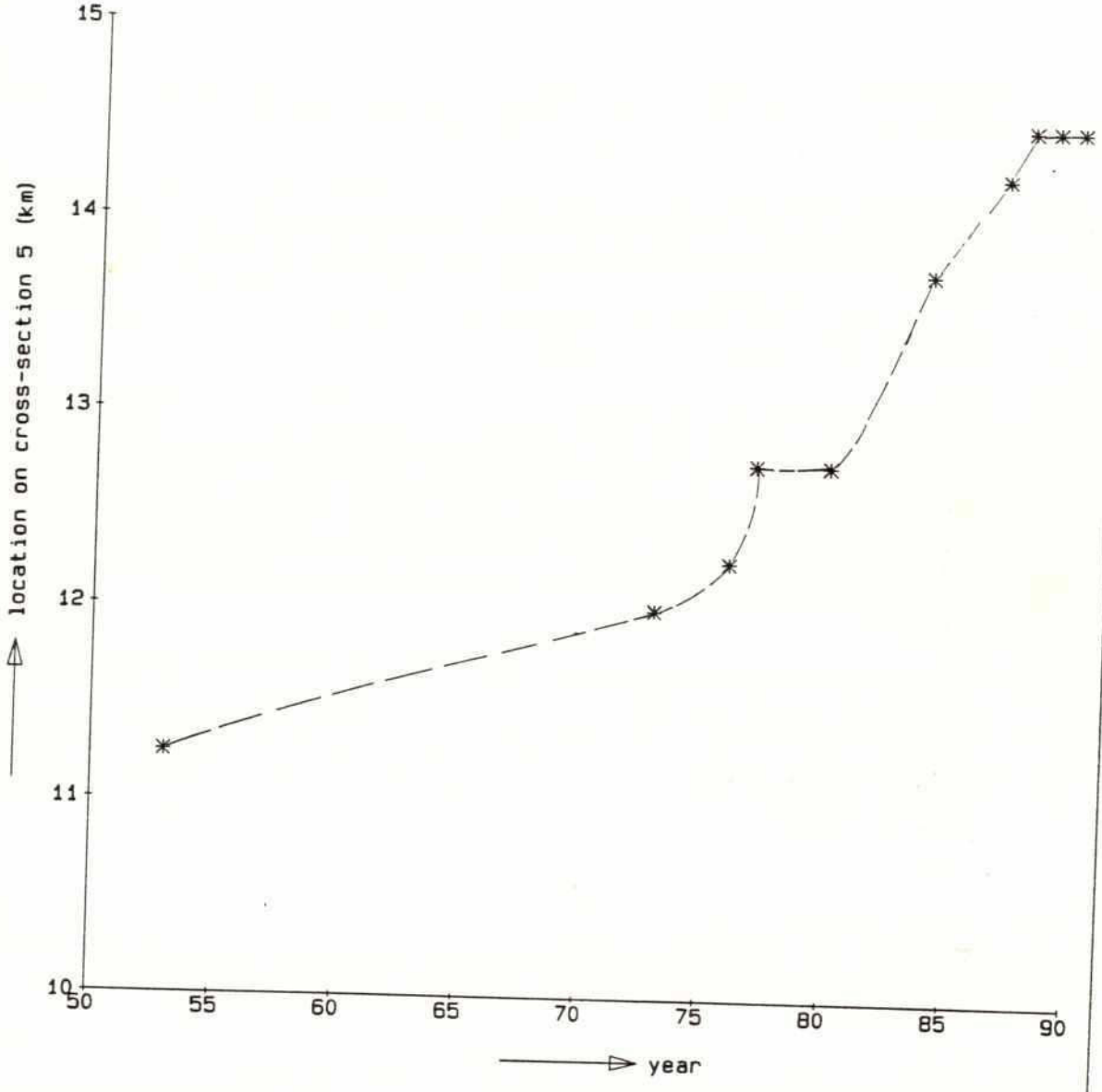
Reference system with respect to banklines of the Padma River and Lower Meghna River

Figure B.5.11

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Location of chars in Padma River in time	Figure B.5.12



Location of the left bank of the Lower Meghna River near Eklashpur (cross-section 5)

Figure B.5.13

The reason for this variation in width (and consequently the depth) is the fact that upstream of Chandpur changes occur in the number of channels and the angle of approach of the upstream channel. This is explained hereafter in some detail. The changes of the upstream channel of Chandpur are presented in simplified form in Figure B.5.15. This figure gives a summary of the location of banklines and thalweg for various years. Each different image presents the contour lines of the river and the chars in the river together with the location of the thalweg. The banklines of the satellite image of the next available year is also drawn in the figure to show the changes of the channels and chars. Hereafter the planforms of the different years are described.

1952: In 1952 the thalweg of the Padma and the Lower Meghna was situated at the southern side of the main river bed, the angle of approach at Chandpur being small which should account for considerable erosion at Chandpur. The left bank at Chandpur is heavily eroding as is clearly visible in the difference of the location of the left bank in 1952 and 1960. The right bank of the Padma is also eroding and there is considerable accretion of the bank between the Padma and the Upper Meghna. The location of the confluence is near Chandpur.

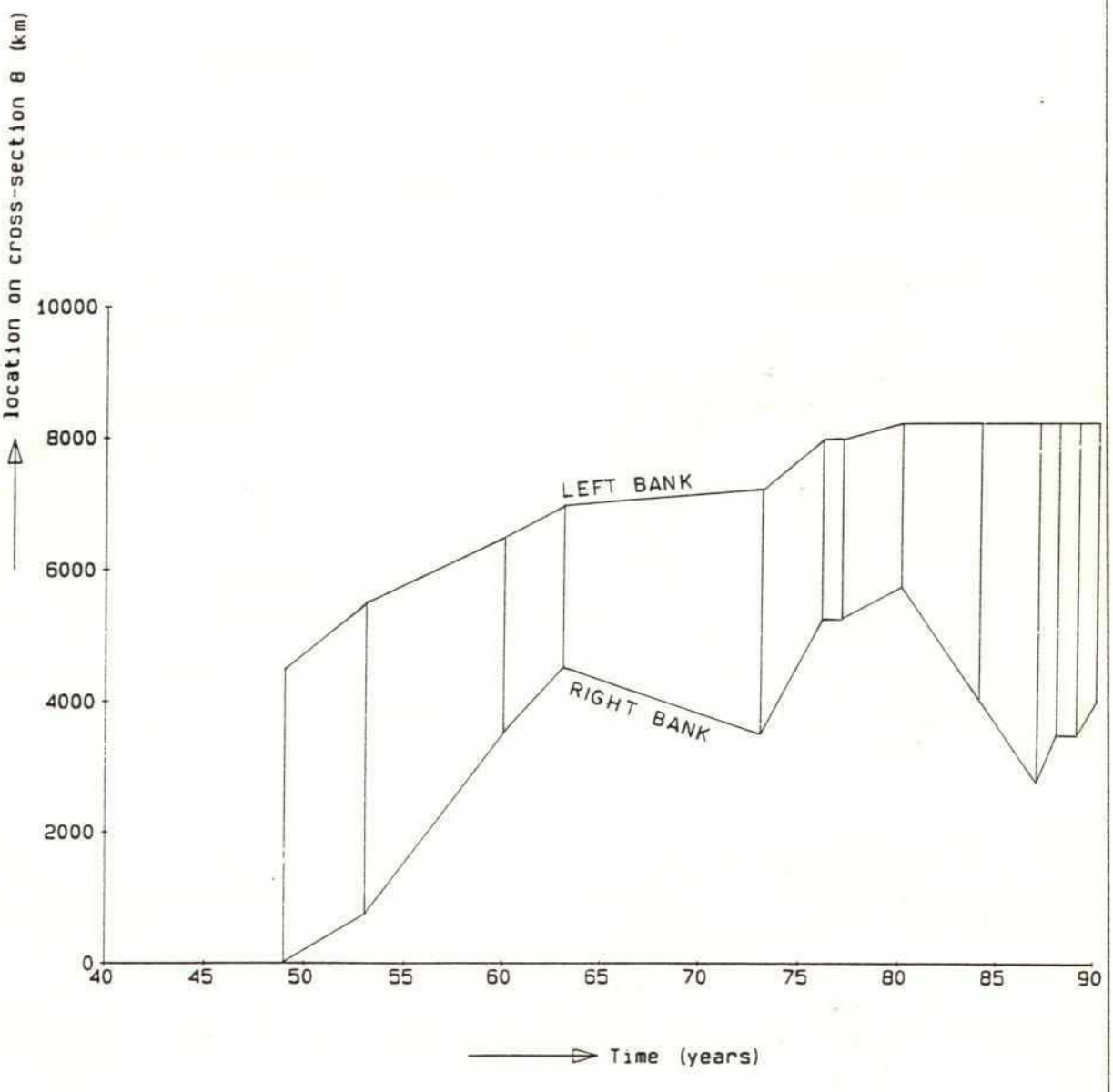
1973: In the Padma River, upstream of the confluence, two channels have approximately the same size, with a char in between. The angle of approach at Chandpur is about the same as in the 1952 situation. The left bank at Chandpur is eroding and there is considerable erosion of the left bank of the Padma as was also reported by Galay (1980). The right bank of the Padma is also eroding. The char in the Padma River which is situated between the two channels is eroding at the downstream side and there is accretion at the upstream side.

1977: The thalweg consists of two channels in this situation. One channel flows at the northern side and the other at the southern side of the channel of the Padma River. The char, which is present between the two channels is liable to sedimentation at the upstream end causing the southern channel to become less important in relation to the northern channel. There is some erosion at the right bank of the Padma and some accretion at the left bank. The thalweg of the two channels meet each other at Chandpur, but no erosion of the left bank is visible. Due to the erosion at the northern side of the plain, the Padma River meets the Lower Meghna near Eklashpur now, instead of near Chandpur.

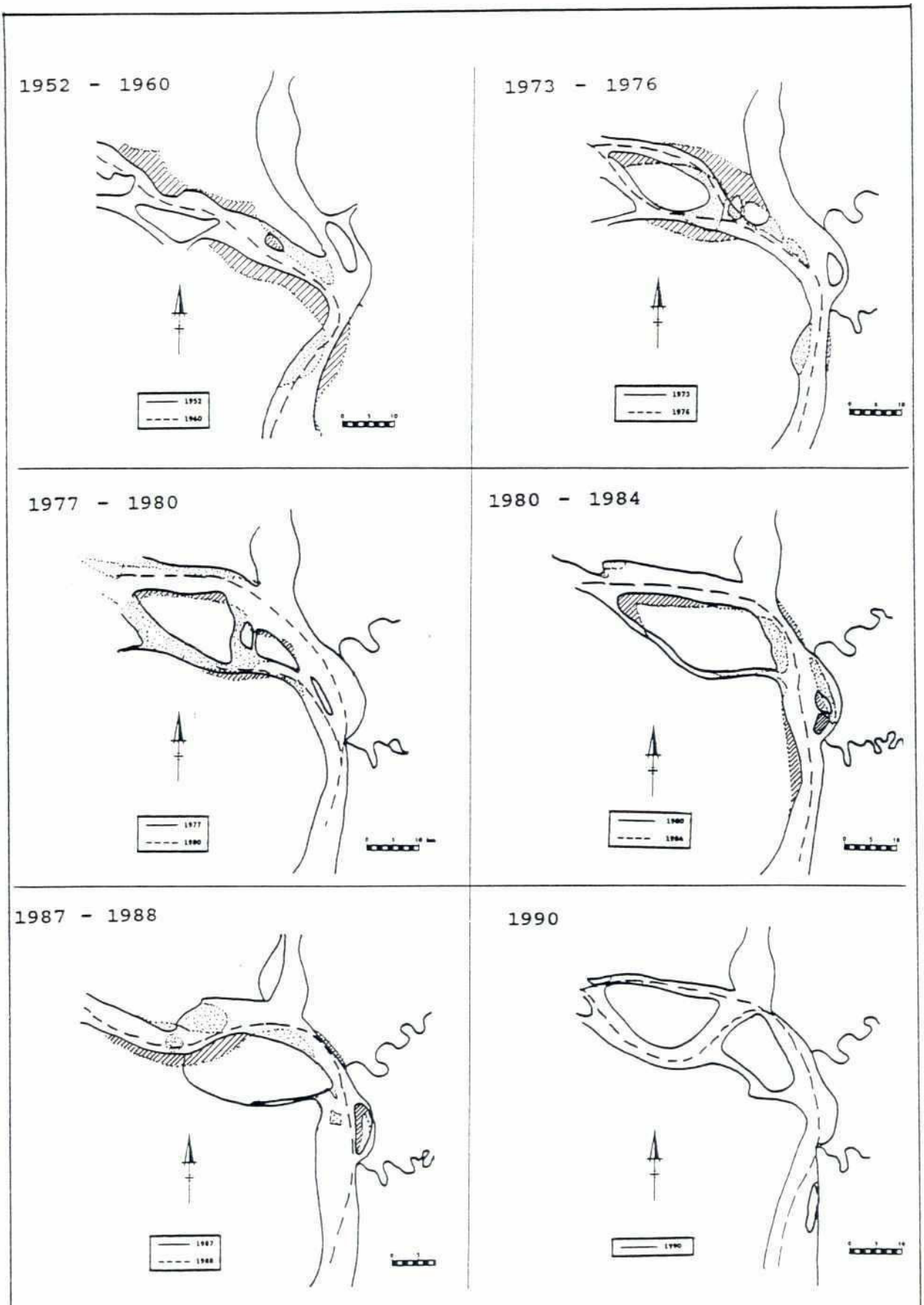
1980: The thalweg in 1980 consists of only one channel which is situated at the nortern side of the river. The southern channel has disappeared as a result of the char who has become part of the right bank due to sedimentation. The angle of approach at Chandpur has increased. As a result of this change in number of channels, less erosion at the left bank at Chandpur is expected. At the left bank near Eklashpur the thalweg is situated more to the east which accounts for erosion of the left bank near Eklashpur. Sedimentation of the right bank at Chandpur is visible. Upstream of the char in the Padma River another char is developing.

1987: In 1987 the thalweg moved further to the east as the left bank near Eklashpur is further eroded. The char which was developing in 1984 has further developed and is situated in the inner bend of a meander in the Padma. The radius of curvature of this bend decreases and erosion of the downstream char is visible. Erosion of the left bank near Eklashpur continues.

1990: In 1990 the thalweg upstream of the confluence consists two channels with a char in between. The char downstream of this char is being eroded by the channel which is located between these two chars. The radius of curvature of this bend decreases until it has reached a critical value; the length of this bend increases until the slope becomes too small, forcing the channel to follow another route where the slope is much steeper.



Location of the channel just downstream of Chandpur on cross-section no 8 in time	Figure B.5.14



Changes in the planform near the confluence of the Padma and the Upper Meghna River

Figure B.5.15

If the erosion that is estimated by comparing the satellite images is plotted in a figure similar to Figure B.5.9, it appears that the erosion rates found in the present analysis are somewhat less than the erosion rates found by Galay.

The above analysis is based solely on a comparison, and an analysis and interpretation of satellite images. Hereafter the **BWDB soundings** are used to check whether they provide a similar picture. Cross sectional data are available for 4 cross sections (notably the cross-sections M#2-1, M#2, M#1-1 and M#1, see Figure B.3.2) for the years 1982, 1986, 1987 and 1990. In addition cross-section M#3 was considered. The cross-sectional data were provided by the Bangladesh Water Development Board (BWDB). The exact location of the cross-sections is not known, which makes it difficult to compare the cross-sections with the satellite images. Drawings of the cross-sections are presented in Figures B.5.16, B.5.17 and B.5.18. The measurements of the cross-sections have been carried out at low stage and in the analysis it was assumed that the flood stage morphology did not differ significantly from the low stage morphology.

The cross-sections were analyzed in a similar way as done for the cross-sections along the Upper Meghna River (see Section 5.2.2 for Bhairab Bazar and also Section B.3.4) and some of the results are presented in table B.5.2. To get an idea of the variation of channel location in time the location of the 50 % conveyance point was computed. The 50 % conveyance point represents the "centre" of the cross-section: on either side of this point 50 % of the total discharge is being conveyed. The computation of the 50 % conveyance point is made for bankfull stage which for these cross-sections is about 4.6 m+PWD. The results of the analysis is discussed hereafter.

Cross-section M#3

Cross-section M#3 is located in the downstream end of the Upper Meghna River. The location of the 50 % conveyance point does not change much. Considering the drawings of cross sections M#3 in Figure B.5.16 one has to conclude that little change is noticeable. Only the char which is located in the centre in 1982 is being eroded in time. The left and right bank of the Upper Meghna River did not erode in the time between 1982 and 1990.

Cross section M#2-1

Cross section M#2-1 is located just at the confluence of the Padma River and the Upper Meghna River. The cross section does not cover the entire width of the river before the confluence, as can be observed in Figure B.3.2. There is no erosion of the left bank noticeable between 1982 and 1990 because the location of this cross section is so far upstream that the left bank is only influenced by the Upper Meghna. Considerable erosion takes place between 1982 and 1986.

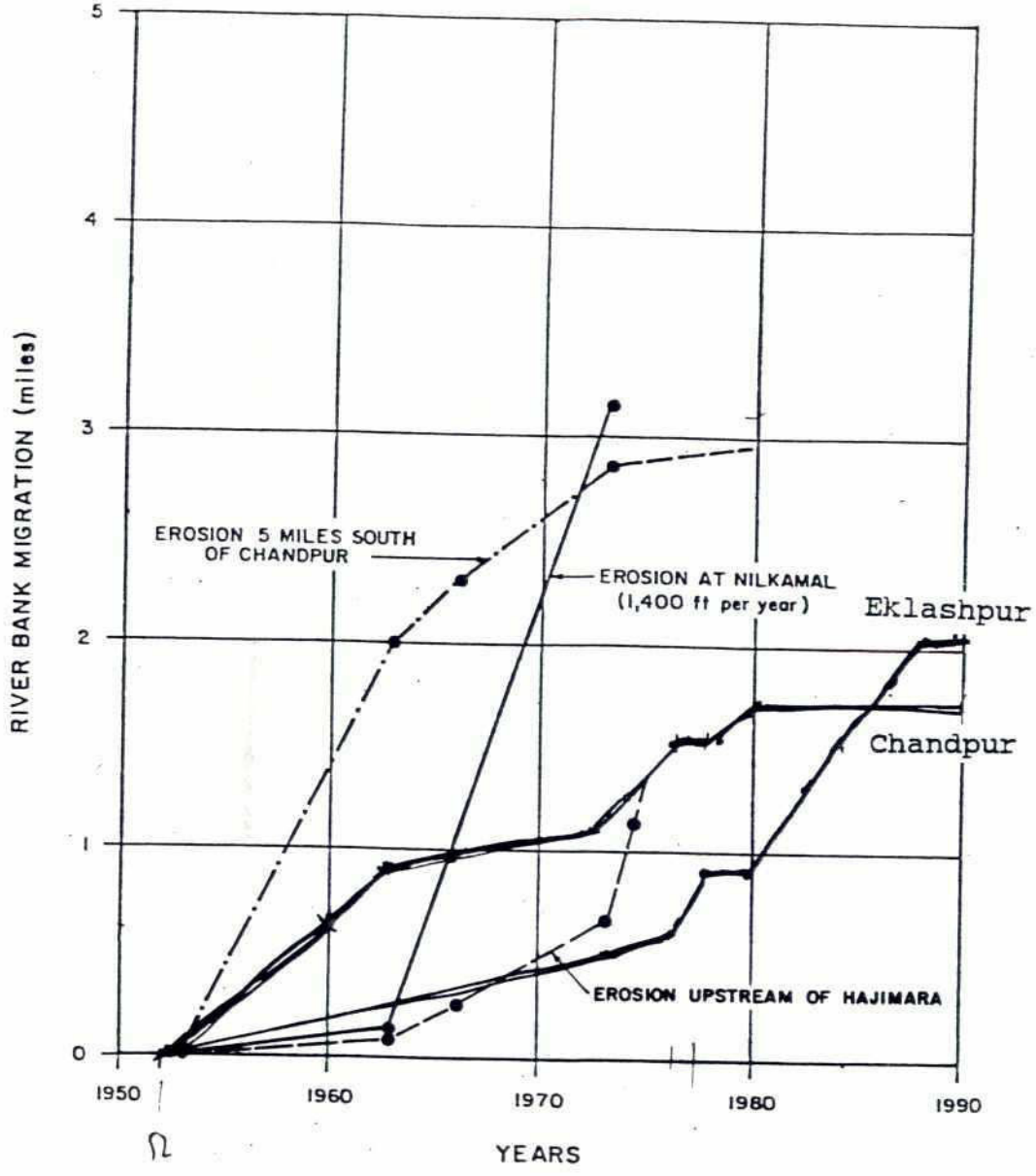
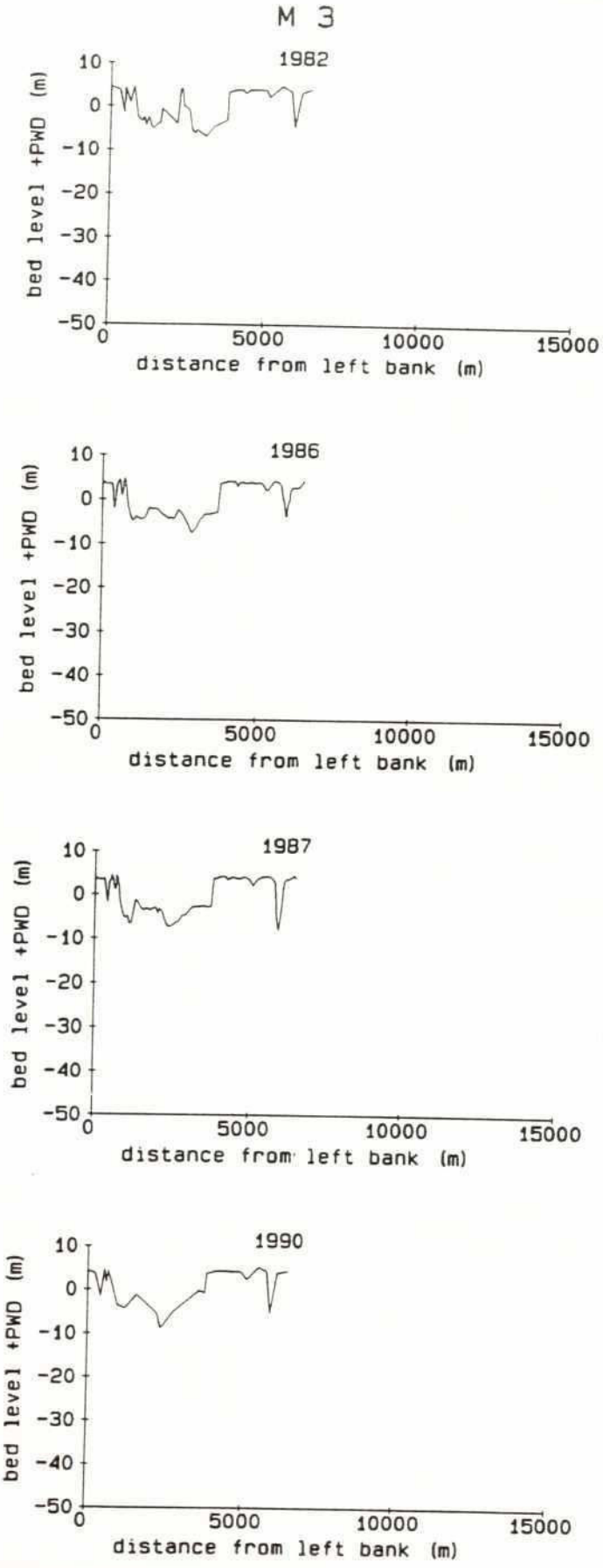


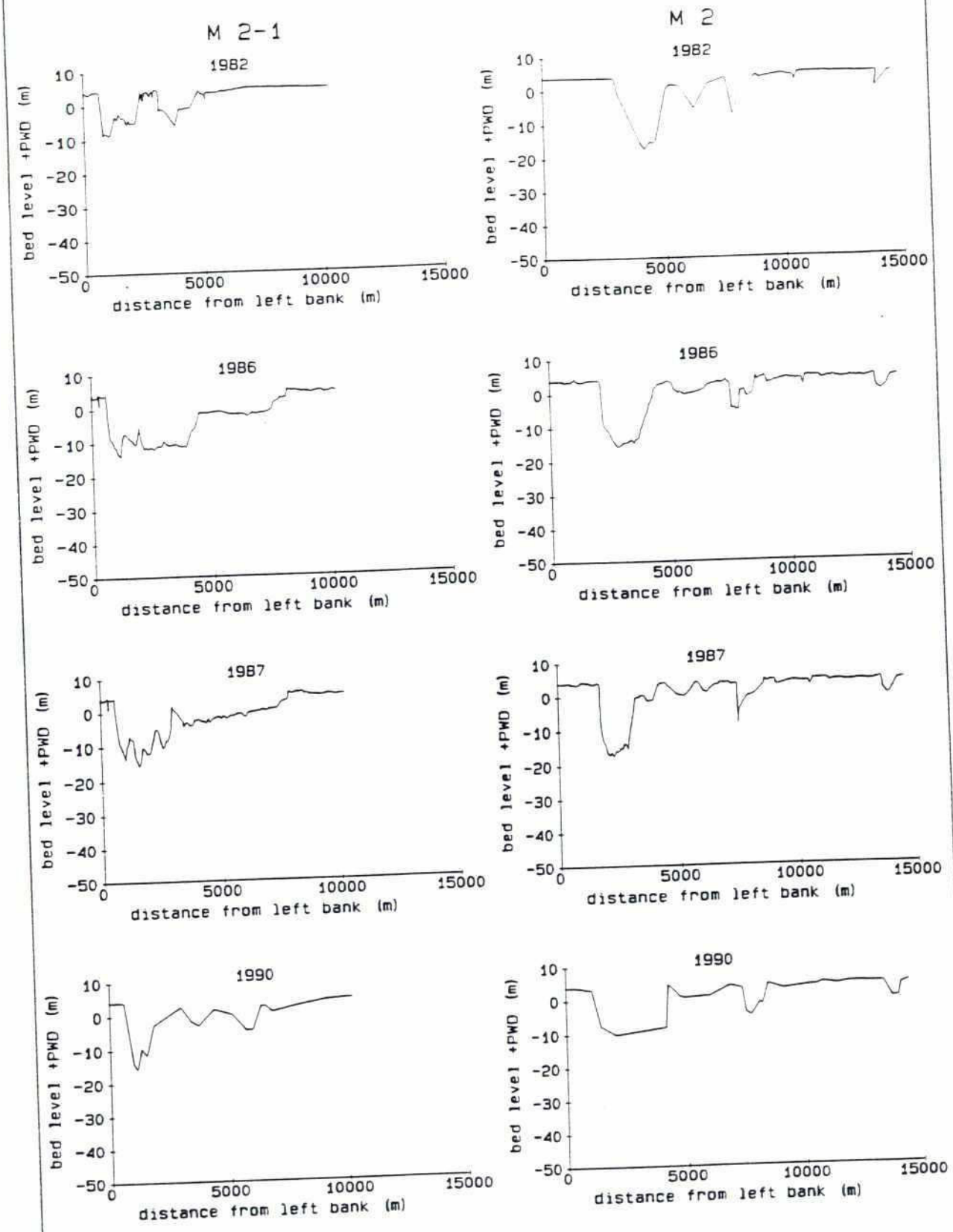
FIGURE 9
RATE OF EROSION OF THE LEFT BANK
MEGHNA RIVER NEAR CHANDPUR

Erosion rates south of Chandpur according to present study, Galay (1980)	B.5.16



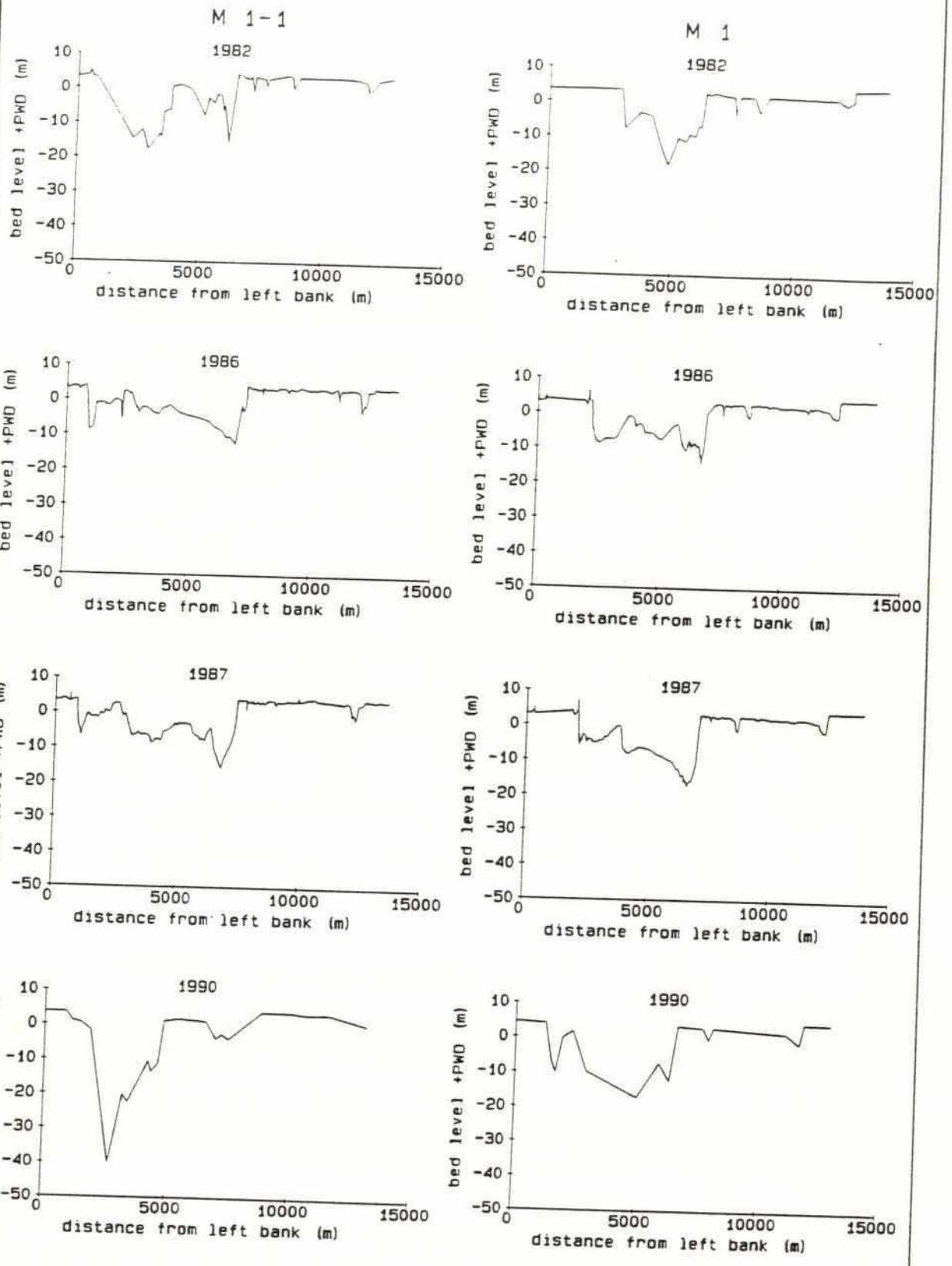
Cross-section M#3 across the Upper Meghna River for the years 1982, 1986, 1987 1990

Figure B.5.17



Cross-section M#2-1 and M#2 across the Lower Meghna River for the years 1982, 1986, 1987 and 1990

Figure B.5.18



Cross-section M#1-1 and M#1 across the Lower Meghna River for the years 1982, 1986, 1987 and 1990

Figure B.5.19

TABLE B.5.2 ANALYSIS OF CROSS SECTIONS M#3, M#2-1, M#2, M#1-1 AND M1 ACROSS THE LOWER MEGHNA RIVER

	location 50 % conveyance point	max depth	distance of max. depth	average level
M#3-82	2730	- 7.0	3140	0.02
M#3-86	2460	- 7.5	2860	0.13
M#3-87	2430	- 8.1	2800	-0.27
M#3-90	2390	- 8.8	2340	0.13
M#2-1-82	1910	- 8.0	1030	1.77
M#2-1-86	2930	-14.0	1100	-2.94
M#2-1-87	2320	-15.5	1540	-1.49
M#2-1-90	2140	-15.5	1100	-0.12
M#2-82	4340	-17.5	4100	0.83
M#2-86	3290	-16.0	2750	0.71
M#2-87	2630	-17.0	1880	1.12
M#2-90	3140	-10.0	2050	0.28
M#1-1-82	3060	-17.5	2850	-0.93
M#1-1-86	5440	-13.6	6900	-0.18
M#1-1-87	5280	-16.0	6850	-0.43
M#1-1-90	3110	-40.0	2650	-2.89
M#1-82	5008	-18.5	4700	-0.08
M#1-86	5070	-14.0	6610	-0.16
M#1-87	5640	-18.0	6520	-0.66
M#1-90	4410	-18.0	5560	-2.04

The total conveyance increases with a factor 3. The channel becomes wider and deeper. After 1986 the total conveyance decreases again although the depth remains the same. The position of the 50 % conveyance point moves closer to the left bank. Since the total conveyance over the total width of the river has to be more or less stable, the conveyance of the channel at the other side of the big char, which is in this cross-section considered as the right bank, has to change also. The conveyance of this channel is relatively large in 1982, relatively small in 1986 and increases gradually after 1986.

Cross-section M#2

Cross-section M#2 is located more downstream than cross section M#2-1 and covers the entire width of the river. The total conveyance does not change much. The left bank is situated near Eklashpur. The erosion along the left bank erosion amounts from 1982 up to 1990 about 1.8 km. The location of the 50 % conveyance point moves to the left bank as a result of this erosion. In 1990 the location of the 50 %

conveyance point has moved some further from the left bank because the channel at the left bank is wider and shallower. The channels which are situated at the western side seem to be stable in these cross sections, so the assumption is made that the location of this cross section is just downstream the large char which divides the Padma in two channels, at the confluence of the Padma and the Meghna rivers. The most important feature that is observed when comparing the cross-section M#2 for the available years is the erosion of the left bank.

Cross-section M#1-1

Cross-section M#1-1 is located just upstream Chandpur. The location of the 50 % conveyance point moves considerable in time in this cross section. In 1982 it is situated some 3 km from the left bank. In 1986 at 5.4 km, in 1987 at 5.3 km and in 1990 again at 3.1 km from the left bank. The reason for this shifting of the 50 % conveyance point are the changes upstream where sometimes one, and sometimes two main channels are responsible for the greater part of the total conveyance. Where two channels are active, one northern and one southern, the angle of approach at Chandpur is much smaller, so the deepest point of the channel at Chandpur is situated more to the left bank, see 1982 and 1990. As a result the location of the 50 % conveyance point is more to the left bank. In 1986 and 1987, where the total conveyance upstream is carried by one channel (which flows into the Meghna with a great angle and more upstream than the southern channel), the deepest point of the channel is situated more to the right bank. The deepest point of the channel in 1986 is situated some 4 km further to the right bank in comparison with the 1982 situation. In 1987 the location of this deepest point remains the same and in 1990 this point has moved again about 4 km to the left bank.

Another striking fact is that depth of the channel in 1990 being 40 m - PWD, which is more than 20 m deeper than in the other considered years. A possible explanation for this increase in depth is that as a result of erosion of the large char upstream, sedimentation on the right bank of the Lower Meghna causes a decrease in width of the Lower Meghna and consequently a deepening of the channel. The scour near Chandpur is discussed at greater length in Chapter 8.

Cross section M#1

Cross section M#1 is located downstream of Chandpur. The location of the 50 % conveyance point is situated at 5 km from the left bank in 1982 and 1986. In 1987 this point has shifted about 600 m to the right bank, because the channel at the left bank has become shallower in 1987. The left bank has eroded between 1982 and 1986. In 1986 the left bank about 700 m more to the east. The channel has become wider and consequently shallower. The right bank has also eroded between 1982 and 1987. In 1990 the left bank eroded further and the channel has become deeper. The 50 % conveyance point shifted to the left bank about 1.2 km. Near the left bank a char is grown, which is also good clearly visible on the satellite image of 1990.

The total conveyance of the cross sections M#1 and M#1-1 has increased significantly in 1990 in comparison with the other years. The reason for this is not known at the moment.

Finally the **BIWTA Soundings** are considered here. These soundings are extremely useful for comparing the location of the channels with the depth of the channels in time. In Table B.5.3 the width of the Lower Meghna River at Chandpur is compared with the maximum depth of the channel and the width of the channel(s) upstream.

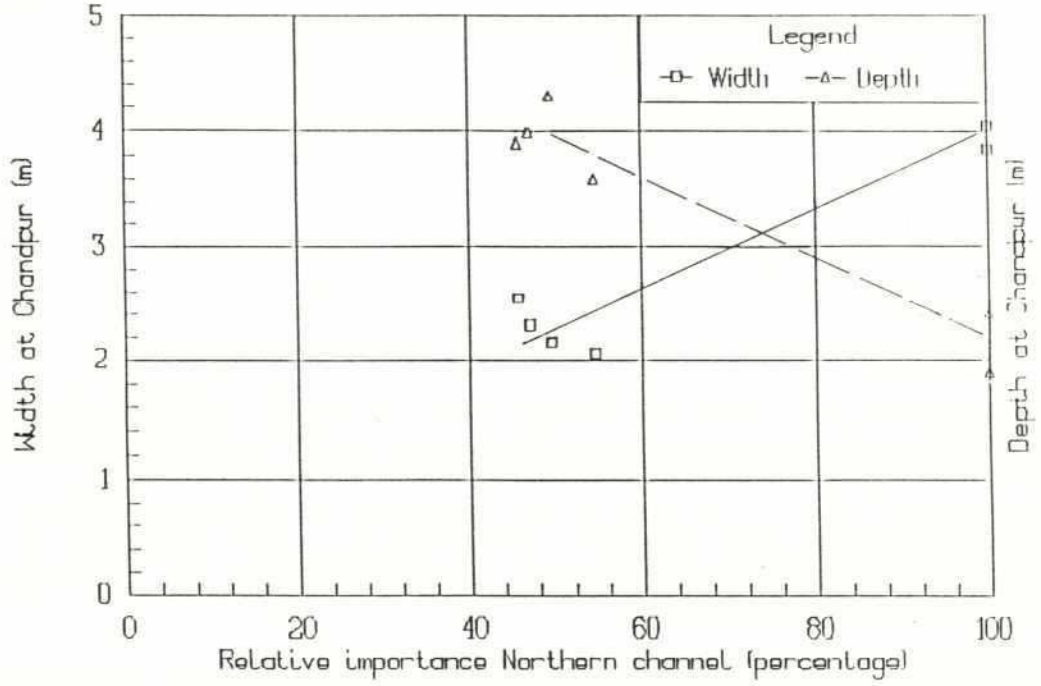
TABLE B.5.3 WIDTH AND DEPTH OF THE CHANNEL AT CHANDPUR TOGETHER WITH THE WIDTH OF THE CHANNELS UPSTREAM

year	width at Chandpur (m)	max. depth at Chandpur	width southern channel (m)	width northern channel (m)
1968	2500	18	2575	?
1975	2550	39	2500	2100
1976	2150	43	2150	2100
1977	2300	40	2600	2300
1983	3850	24	0	3750
1984	4050	19	0	2500
1988	5050	16	?	2650
1990	2050	36	2500	3000

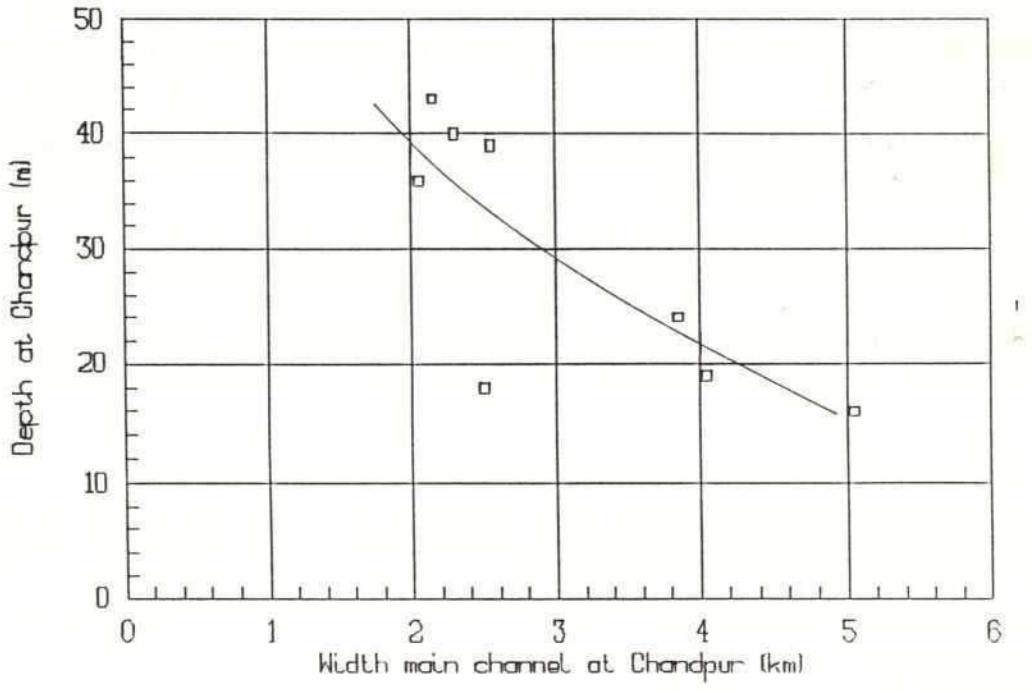
? = Width of the southern channel(if any) not visible on the map

From this table it appears that there is a definite correlation between the width and depth at Chandpur and the number of channels upstream and the angle of approach. This correlation is also demonstrated in Figure B.5.20(a). If there are two channels present upstream, the channel at Chandpur is small and deep. In Figure B.5.20(b) the width of the channel at Chandpur is plotted versus the depth, and it can be observed that they are very well correlated.

In the analysis of the morphological changes it appeared that there are two processes going on in the Padma River and Lower Meghna; on the one hand there is a tendency of the channels to move in the direction of the left bank and on the other hand the chars in the Padma are moving in downstream direction forcing the channel to bifurcate at some points which leads to a shifting of places where erosion occurs.



(a) Channel dimensions at Chandpur versus relative conveyance of Northern channel



(b) Correlation between width and depth of channel near Chandpur

Figure B.5.20 Correlation between channel system upstream and the conditions near Chandpur

The present morphology at the confluence of the Padma and Lower Meghna Rivers is such that the width of the cross-sections increases considerably before the confluence, leading to a decrease of stream velocity and consequently the generation of large chars (see also Section B.4.4.8). These chars influence the course of the channels. Erosion on the upstream end and sedimentation on the downstream end of the chars result in the downstream movement of the chars through the Padma River, into the direction of the confluence.

At the confluence the three rivers (the Padma, Upper Meghna and Lower Meghna Rivers) are determining the conditions. The discharge of the Upper Meghna River is relatively small in comparison to the other rivers, but its influence is not negligible. Chars entering the mouth of the Upper Meghna River are being eroded by this river. In other words, a char in the Padma River can not block the Upper Meghna, hence there will always be a northern channel. This in contrast to what happens at the southern side, where a char can block the southern channel This forces the river to convey the total discharge through one channel, which is located at the northern side and causes erosion near Eklashpur. Upstream of this char another char usually develops at the northern side, forcing the channel to flow more to the south and thus eroding the char which is present at the southern side of the floodplain. This process is going on until a cutoff takes place. In 1990, the southern channel is becoming more and more important, which is visible at the difference between the satellite image of 1990, which dates from January 7, and the BIWTA sounding of 1990, which dates from December. This situation of December 1990 is represented as situation A in figure B.6.1. Because this southern course is becoming more important, erosion at Chandpur is becoming more severe. The width of the channel at Chandpur is decreasing as a result of sedimentation on the right bank of the river, and the Lower Meghna River is becoming deeper.

From the above combined analysis of satellite images, old maps, soundings and cross sections the following conclusions may be drawn:

(1) chars migrate in the Padma River until they reach the bend downstream the confluence, then the migration stops, and the char is being eroded;

(2) the position of a char, upstream of the confluence, is being taken in by the next char within a period of some 15 years;

(3) there has been a considerable amount of erosion at the left bank of the Padma and the Lower Meghna between 1952 and 1990:

- the erosion at the left bank near Eklashpur amounts about 3.25 km,
- the erosion at the left bank near Chandpur amounts about 2.75 km.

(4) in the period 1952-1990 the erosion of the left bank near Eklashpur has not been constant: in certain years erosion is not noticeable, while in other years the erosion rate is very large;

(5) the width and depth of the channel at Chandpur are correlated to and depend on the number of channels upstream and their angle of approach;

(6) the banks of the lowest reach of the Upper Meghna remain at the same location, no horizontal erosion is noticeable between 1982 and 1990;

(7) due to stabilization of the left bank at Chandpur after 1980 no erosion is noticeable on the available satellite images;

(8) erosion in vertical direction has continued after 1980, as was deduced from the comparison of the cross-sections at the Chandpur site.

The above analysis has concentrated on the river reach between Mawa and Chandpur. The conditions more downstream are analyzed in some detail in Section B.5.3.4. It appears that over the last decades a major cutoff has occurred in that reach.

Concluding it can be stated that the overall trend of the planform of the Lower Meghna near the confluence of the Padma River with the Upper Meghna River is a continuous movement in eastern direction. This is accomplished by continuous bank erosion along the long bend of the Lower Meghna river in southern direction. The location of the bank erosion varies depending on the channel pattern in the Padma River and seems to vary with a periodicity of some 15 years. It may well be that the cutoff of the channel south of Chandpur is the way the Lower Meghna River is trying to cope with the continuous movement of the upper reach in eastern direction.

B.5.3.2 **Eklashpur**

In Section B.5.3.1 the overall trend in the movement of the Lower Meghna River is dealt with. Already there much information on the conditions at Eklashpur is presented. In this Section the conditions at Eklashpur are considered in some more detail.

Erosion rates between 1952 and 1990 for the left bank near Eklashpur are presented in Figure B.5.13. It appears that they are not constant but that they vary in time. Between 1952 and 1973 the mean erosion rate was some 40 m/year. In this period a considerable part of the discharge of the Padma River was flowing mainly through the southern channel. Between 1973 and 1980 the discharge of the Padma was flowing mainly through the northern and through the southern channel. The mean annual erosion rate for these conditions was 70 m/year. Between 1980 and 1990 the discharge of the Padma was flowing through the northern channel only, because the southern channel was blocked. The mean annual erosion rate under those conditions was some 200 m/year.

It is felt that this cycles in the bank erosion at Eklashpur of some 15 years has occurred in the past also, and may be present in the future as well.

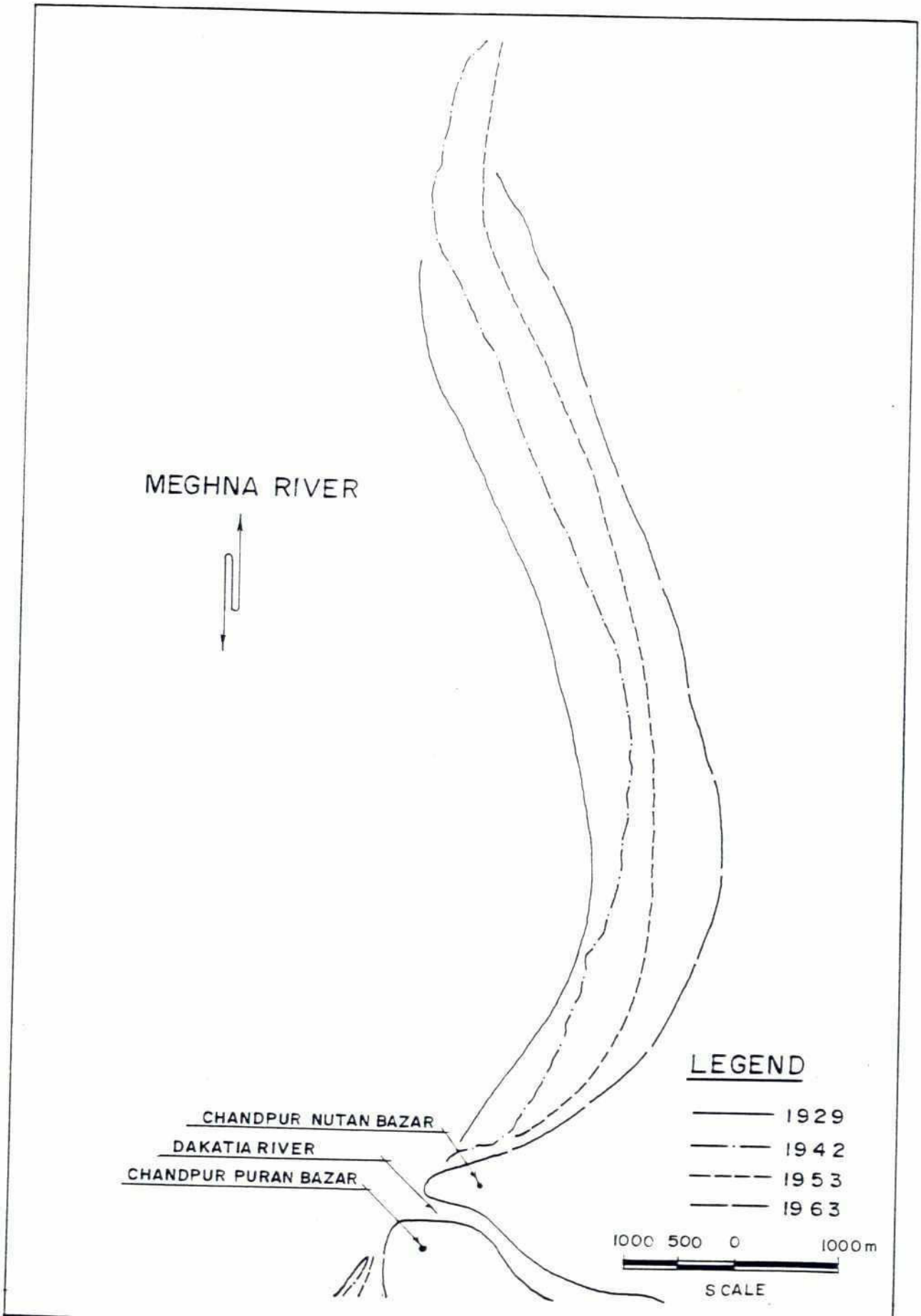
B.5.3.3 Chandpur

At Chandpur the Lower Meghna carries the combined flow of the Padma and Upper Meghna Rivers. The location of the confluence has shifted in northward direction, but when the southern channel is active the direction of the flow is more towards Chandpur.

Detailed information on the bank erosion rates both upstream and downstream of Chandpur is provided in the report of the Task Force of the BWDB. The Figures B.5.21 and B.5.22 provide a copy of this information. It is observed that both upstream and downstream the bank erosion has occurred over a number of decades already.

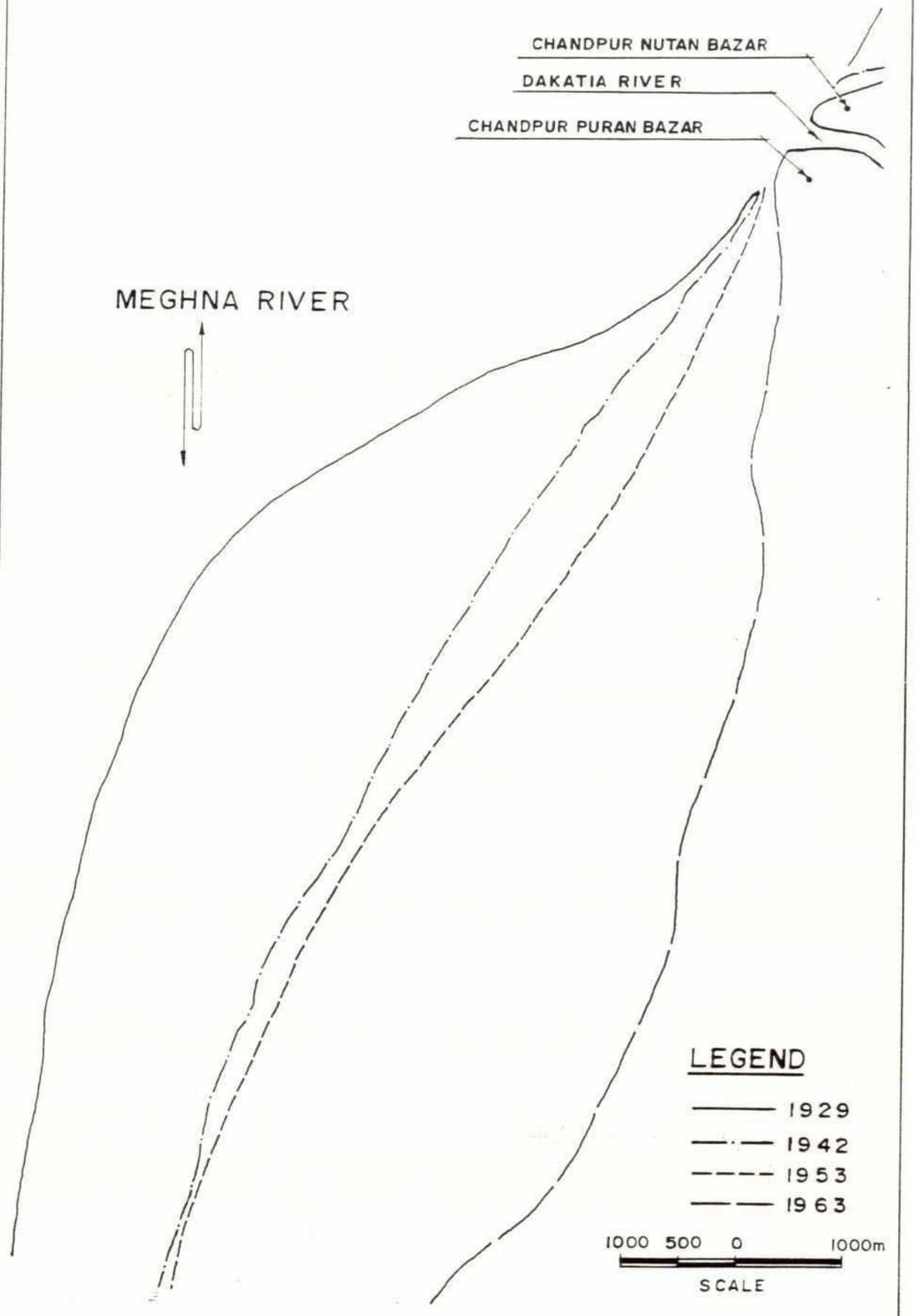
It has been suggested that dredging to improve navigability may have attracted the flow towards Eklashpur and hence have accelerated the bank erosion. Considering the small quantities dredged compared to the transport capacity of the river it may be stated that the influence of dredging must have been negligible.

Erosion rates for the left bank south of Chandpur between 1952 and 1990 are presented in Figure B.5.14. The erosion of the left bank virtually ceased in 1980, probably as a result of bank protection works at Chandpur. Since 1988 the channel at Chandpur has decreased its width resulting in erosion in vertical direction. This decrease in width is due to the increase in relative importance of the southern channel.



Bank erosion upstream of Chandpur (BWDB,1984)

Figure B.5.21



Bank erosion downstream of Chandpur (BWDB, 1984)

Figure B.5.22

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B.5.3.4 Haimchar

Haimchar is situated about 20 km south of Chandpur at the left bank of the Lower Meghna. Since 1929 bank erosion of this left bank has been reported. Erosion of the left bank was also reported by Galay (1980). Recent developments were studied by analyzing LANDSAT images over the period 1973 through 1990.

It appears that in 1973 a cutoff was occurring, that continued to take place over the next decades. This cutoff is of major dimensions, the length of the cutoff channel being some 20 km. The length of the channel that is being cut off is about some 35 km. To get some insight in the phenomena that are taking place at Haimchar, the changes of the width of the cutting off channel in time was studied. A clear picture of what has happened over the last decades is obtained from Figure B.5.23. In this picture the width of the cutting off channel was plotted in a dimensionless way by dividing it by the total width of the (western) curved channel and the (eastern) cutting off channel. From the figure it can be observed that the cutting off phenomenon develops only gradually. In a total period of 17 years the relative importance of the cutting off channel increases from some 30 % to some 100 %. The figure shows clearly that the cutting off process is being accelerated during years with exceptional floods (1974 and 1988). These floods cause a substantial increase of the importance of the cutting off channel.

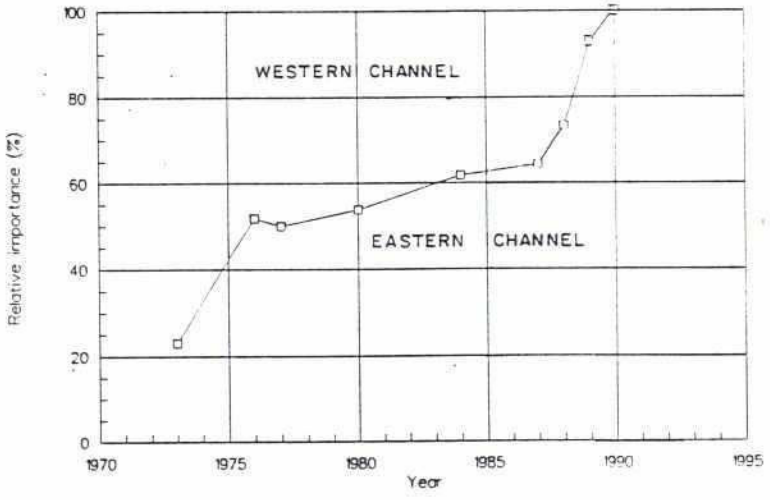


Figure B.5.23 Progress of cutting-off process near Haimchar in time

This is in line with the predictions of Klaassen and van Zanten (1989) who indicated that the larger the depth (hence the discharge), the quicker the cutting off process takes place. By 1990 it seems that the cutoff has been completed, although it should be realized that the satellite images relate to low flow conditions only. It may well be that during floods still a substantial discharge was flowing through the Western channel.

To study the conditions at Haimchar in more detail, three cross-sections were reviewed more extensively. These cross-sections are indicated in Figure B.5.24. The changes in bank line location in these three cross-sections over the years 1973 through 1990 are indicated in Figure B.5.25. It appears that only at Haimchar the eastern bank is receding.

In the two more downstream reaches the eastern bank is silting up, resulting in a western movement of the Meghna channel. At the same time the western bank is eroding substantially at all three locations. This movement in western direction is caused by the increased importance of the channel along Haimchar. Because it seems that the cutting off process is almost finalized, it may be expected that the erosion process along the western bank comes to a standstill in the near future.

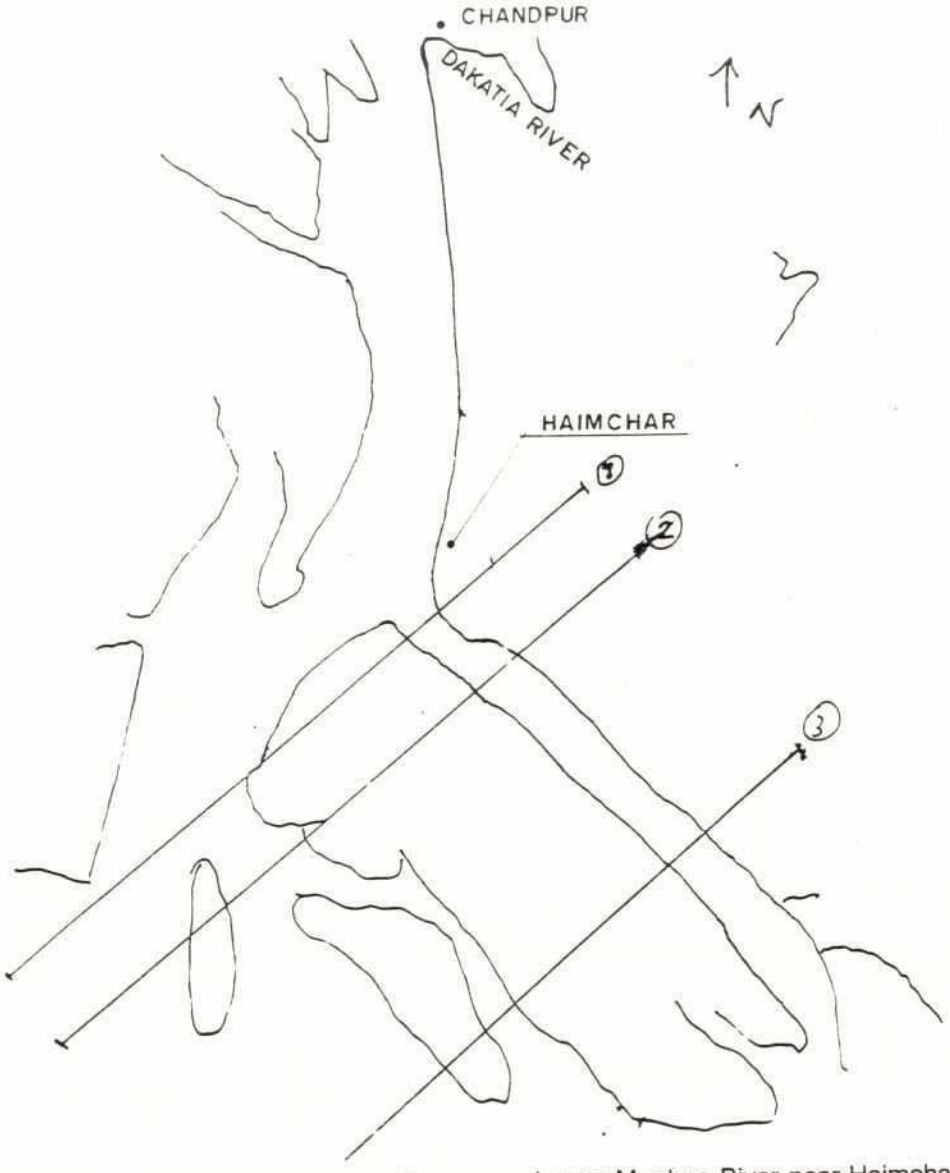
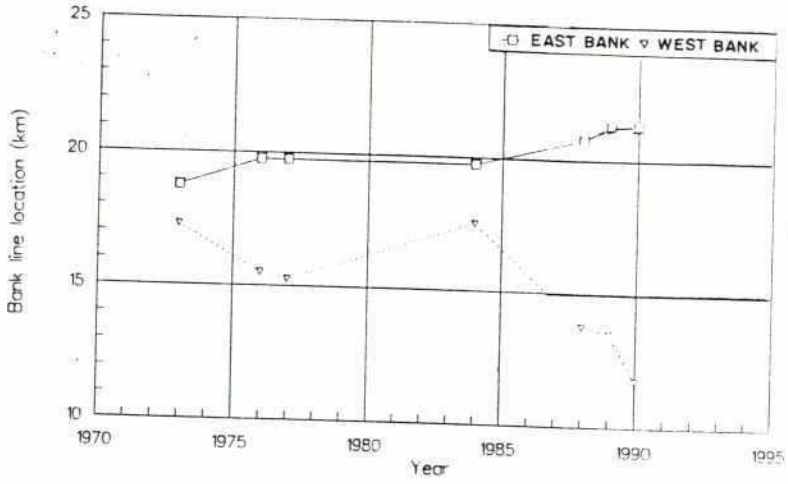
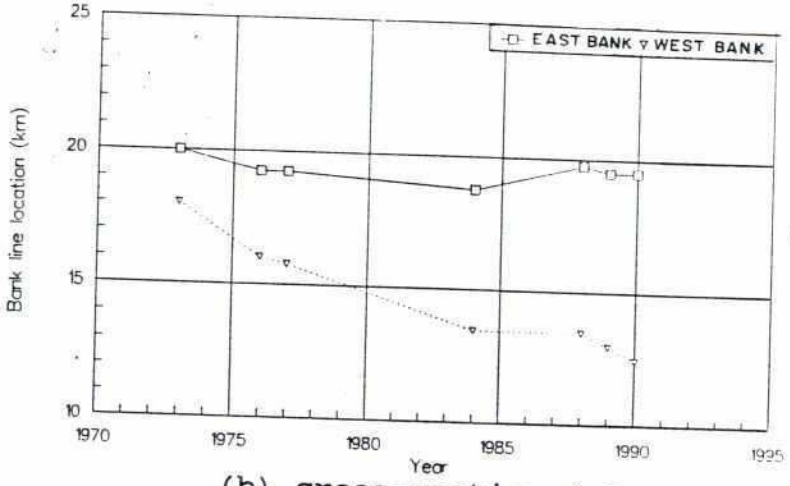


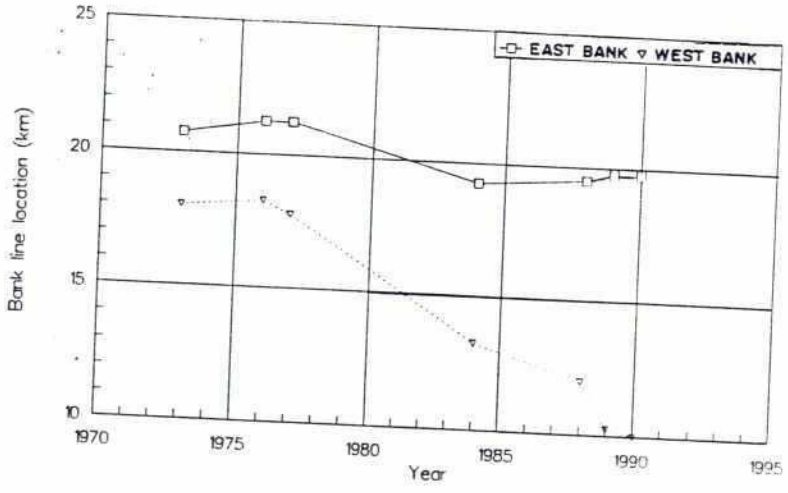
Figure B.5.24 Considered cross-section across Lower Meghna River near Haimchar



(a) cross-section # 1



(b) croos-section # 2



(c) cross-section # 3

Bank line changes near Haimchar	Figure B.5.25

B.6 FUTURE PLANFORM DEVELOPMENTS AT DIFFERENT SITES

B.6.1 Introduction

In Chapter B.5 the historical development of the planform of the Upper and Lower Meghna Rivers was reconstructed as good as possible with the help of old maps, satellite images, cross-sections and soundings. In the present Chapter an attempt is made to predict the changes in planform in future. This is done for two reasons:

(1) to identify areas that will be threatened in the future and which should be protected against bank erosion if this bank erosion is not acceptable;

(2) to estimate the extent of the bank erosion at sites that have been selected for potential bank protection to identify the benefits if the bank erosion would be stopped.

Although not part of this short-term study, of course also the possible long-term development of the Upper and Lower Meghna River should be taken into account when considering bank protection works at some sites. Preferably these should fit into a long-term strategy regarding bank protection works along both rivers, and hence they should be based on a prediction of the long-term development of the planform of both rivers. The possible effect of the bank protection works planned on this long term development should also be taken into account.

Hence the present Chapter is divided in three parts:

(1) a part dealing with the future planform development of the Upper Meghna River (Section 6.2),

(2) a part dealing with the future planform development of the Lower Meghna River (Section 6.3), and

(3) a part dealing with the effect of any bank protection works on the development of the planform of both the Upper and the Lower Meghna River (Section 6.4).

B.6.2 Upper Meghna

B.6.2.1 Overall trend

From the analysis described in Section 5.2 it emerged that the (relatively speaking) the planform of the Upper Meghna River is fairly stable. Only along outer bends like Maniknagar substantial changes are noticeable. Hence the overall trend of the Upper Meghna River will be: minor changes of a local nature only.

B.6.2.2 Bhairab Bazar

According to Section 5.2.2 bank erosion is reported at the right bank, both upstream and downstream of the railway bridge. The upstream bank erosion is considered more as a land slide due to geo-mechanical instability (See Annex - C). The erosion downstream is possibly caused by the flow of the water downstream being not fully parallel to the river bank, in combination with the effect of the local constriction causing deeper scour depths (see also Section 7.4) and possibly some local effects of the railway bridge.

Upstream of the railway bridge there is a major outer bend with potentially the deepest reaches along the left bank. At present this bend is not eroding (the measured thalweg is even along the other bank), but it is expected that in the future the outer bend scour along the left bank may become active again. This would result in a outflanking of this upstream bend. It is felt that this will cause the most serious conditions for the conditions downstream of the bridge. Estimates were made on the basis of the bend characteristics of the Upper Meghna River, and the best estimate of the bend that may develop downstream of this outer bend is a bend with opposite curvature and a radius of curvature between 2,000 and 8,000 m. For the design of

the bank protection it is advised to use a radius of curvature of some 4,500 m.

B.6.2.3 Maniknagar

Upstream of Maniknagar a total erosion of the left bank of some 250 m was observed over the past 17 years. This means an annual rate of 15m. The best estimate at present is that in the future this erosion will continue, because of the fact that the thalweg is presently located near the left bank. The real annual rate of erosion is difficult to estimate because of the limited reliability of the satellite images due to small scale differences and differences in water level. Using the results of the analysis of Hickin and Nanson (1983) it may be assumed that the bank erosion will accelerate as the ratio R/B is still much smaller than 2. Hence, the annual erosion rate may increase over the coming decades to some 20 m/year.

B.6.2.4 Meghna Road and Highway Bridge

The abutment of the bridge is located at an eroding outer bend. The annual erosion reported in the last four to five years amounts to between 40 m and 50 m per year.

Analysis of the satellite images reveals an erosion upstream of the bridge of 250 m in the last 17 year and an erosion of 100 m between 1973 and 1990 downstream of the bridge. The left bank is eroding upstream and the right bank is eroding downstream of the bridge.

The best estimate of the future development of the planform at this site is that the upstream erosion continues at a rate of about 15 m per year, while the downstream erosion may continue at the slightly smaller rate at a rate of about 10 m per year. This estimations are based on an extrapolation of the Nanson & Hickin (1983) approach calibrated to the Maniknagar data and next applied to the Meghna Roads & Highways Bridge conditions. The estimated bank erosion until the year 2000 is indicated in Figure B.6.1.

B.6.2.5 Munshiganj

Munshiganj town is located near the confluence of the Dhaleswari and the Upper Meghna. Erosion problems have occurred both along the left and the right bank (see Section 5.2.3), but presently the erosion is concentrated along the right bank of the Dhaleswari River.

Because of the limited accuracy of the satellite images and their processing, here no definite figures can be provided regarding the future erosion at Munshiganj. It is preferable to base any considerations on more detailed local measurements and, if appropriate, other local information.

B.6.3 Lower Meghna

B.6.3.1 Overall trend

On the basis of the information discussed in Section B.5.3 it is possible to make a prediction of the future developments of the planform of the Lower Meghna River. In doing this a distinction is made between the conditions upstream of Chandpur and the conditions in the downstream reach.

For the reach upstream of Chandpur the generation and movements of the channel and bar system in the Padma River is of paramount importance. It was shown in Section B.5.3.1 that the bank erosion near Eklashpur is very much linked to the occurrence of islands and to the development of the southern channel as a release for the constricted conditions at Eklashpur, when a char is moving into the bend of the Lower Meghna River. Based on this understanding an estimate of the future development of the planform upstream of Chandpur can be made. The estimated development is presented in Figure B.6.2. The tendency in the present period will be to create a situation similar to 1952, where two channels, one at the south side and

one at the north side, convey all the discharge. The char at the northern side of the river upstream of the confluence can become part of the left bank forcing the Padma to convey most of its discharge via the southern channel (see Figure B.6.2).

The most probable future development of the Padma and the Lower Meghna Rivers is indicated in figure B.6.2. Situation A corresponds approximately to the year 1991. Situation B, where most of the discharge of the Padma flows through the southern channel is expected to occur in 1993. In situation C erosion of the bar between the Padma and the Upper Meghna has taken place, so the discharge of the Padma flows through the northern and the southern channel. As figure B.5.6 shows, the bar can be eroded during one single flood. The char upstream of the bar between the Padma River and the Upper Meghna River has to be nearby to force the thalweg to be near the left bank. The time needed to go from situation B to situation C is about 5 years, but this estimate is approximate only. The reason the time needed is only 5 years is that the upstream char is still present, so erosion of the bar will not last long. In situation D most of the discharge of the Padma flows through the northern channel. Situation C is the same situation as in 1974 and situation D is the same as 1980. Hence time needed to go from situation C to situation D is 6 years.

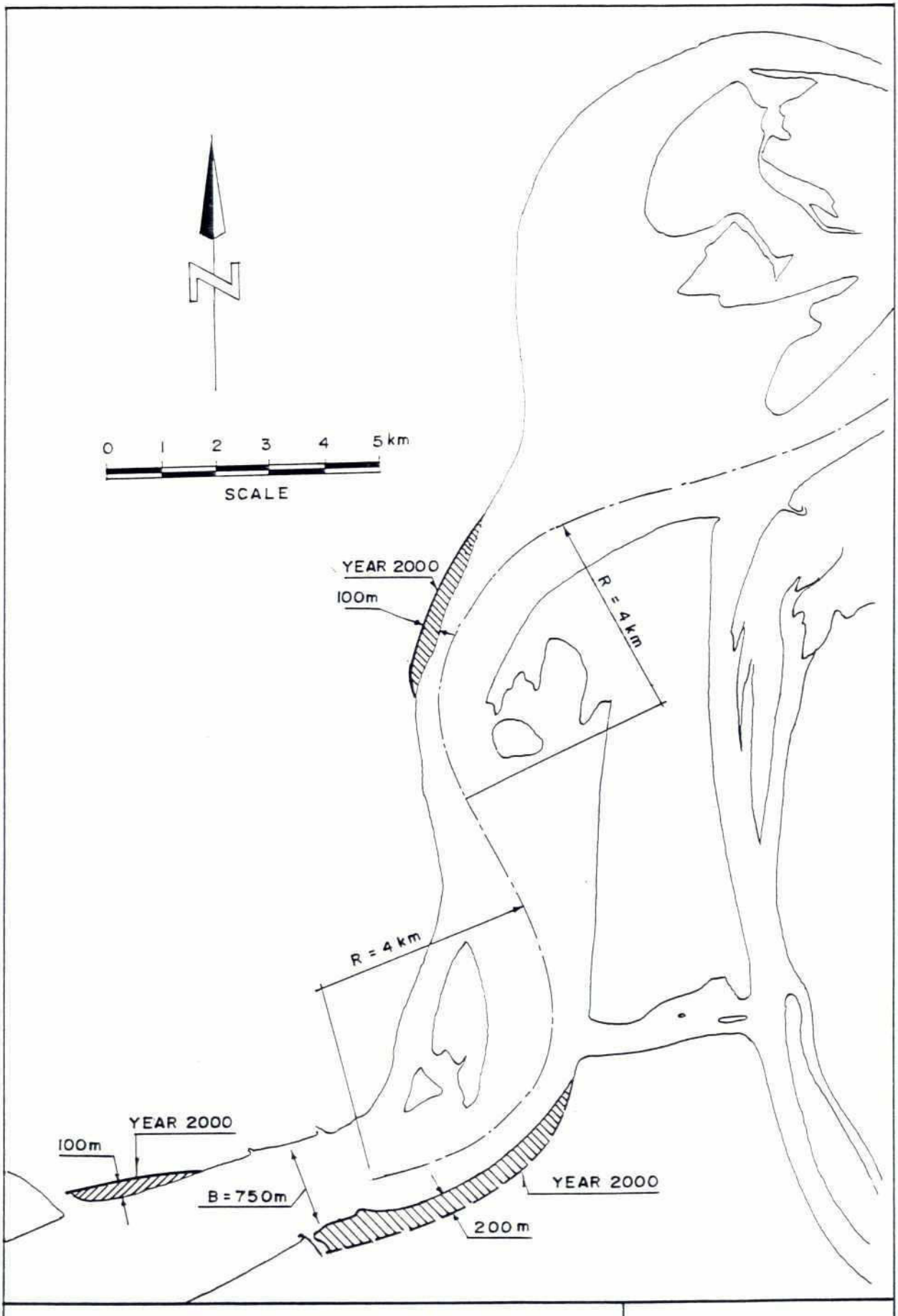
The above estimate can also be used to estimate the bank erosion along the Lower Meghna at Eklashpur. This is done in Section B.6.3.2 in a detailed way. Here it suffices to conclude that this bank erosion will proceed as a kind of cyclic process with a periodicity of some 15 years. Around the year 2006 erosion of another 700 m (approximately!) will have taken place, and around 2021 another 700 m (or more if the curvature of the channel along Eklashpur decreases).

This erosion will not be limited to Eklashpur but a reach of some 10 to 20 km especially south of Eklashpur will be eroded gradually. It should be stressed here that this will not be a continuous process, that will proceed at a constant speed. Due to the periodic nature, but also due to the additional effect of second-order bars in the system, the bank erosion will be intermittently and may even be interrupted by short periods of accretion. The overall trend however will be erosion.

As estimated above without bank protection works parts of Chandpur town will gradually be eroded. At present the estimated rate of bank erosion of the area which has been protected heavily the past is estimated to be 20 m/year. The adjacent areas will also erode although at a lesser rate than along the outer bend near Eklashpur. A rate of some 30 m/year (on the average) is assumed to be a fair estimate.

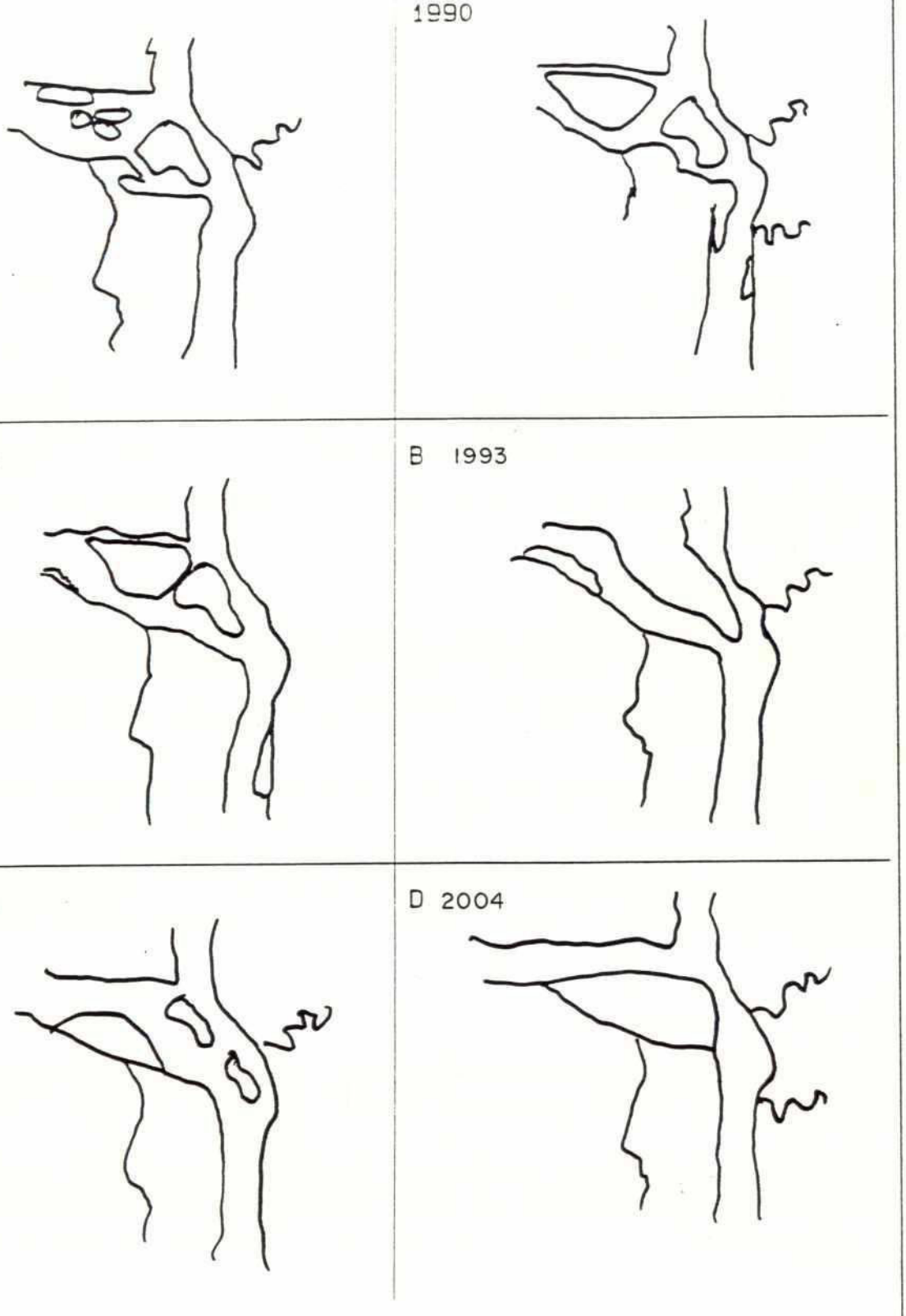
In the river reach near Haimchar still some erosion is estimated to occur. This erosion process however, will gradually proceed at a slower rate, as this erosion is due to the further widening of the cutoff channel. This process is almost completed. Still erosion in the order of (on the average!) some 20 m/year is expected over the coming decade.

Hence the overall trend of the Lower Meghna River over the coming decades will be a continued movement towards the east, with intermittent periods of reduced erosion or possibly even some accretion from time to time.



RECORDED BANK EROSION NEAR MEGHNA ROADS AND HIGHWAYS BRIDGE

FIGURE B.6.1



Future development of the planform of the confluence of the Padma River and the Meghna River

Figure B.6.2

B.6.3.2 Eklashpur

Further on the considerations above regarding the movement of the channel and bar movement in the Padma and Lower Meghna River and the resulting bank erosion, the following table can be prepared as an estimate of the bank erosion near Eklashpur over the coming 15 years:

TABLE B.6.1 ESTIMATED BANK EROSION NEAR EKLASHPUR OVER THE COMING SAY 15 YEARS

situation	year	erosion rate (m/year)	total erosion(m)
A	1991	40	0
B	1993	40	80
C	1998	70	280
D	2004	200	700

In the decades after 2004 it is estimated that this erosion cycle will be repeated approximately.

B.6.3.3 Chandpur

Also near Chandpur erosion will continue if no further bank protection measures are taken. It may be estimated, however, that near Chandpur the rate of erosion will be less than at Eklashpur for two reasons:

(1) Anyhow the natural erosion of the Meghna River near Chandpur is less than 700 m per 15 years (see B.5.3.3);

(2) Even if no bank protection works would be carried out anymore, the presence of many blocks etc. from previous protection works will retard the bank erosion rate Chandpur.

It is estimated that the erosion of Chandpur town will proceed at a rate of 20 m/year on an average, and of the adjacent unprotected banks 30 m/year. Also this erosion will have an intermittent character, as it will be affected by the upstream changes in channel pattern, and, to a lesser extent (because the channel is much deeper near Chandpur), by the second-order bars.

B.6.3.4 Haimchar

Haimchar has experienced bank erosion probably mostly due to the cutting off process of the large bend that was present in the Lower Meghna River downstream of Chandpur. As is shown in Section B.5.3.4 it seems that this cutting off process is now approaching its final stage. This implies that the erosion rate at Haimchar is expected to decelerate. For the time being the erosion rate at Haimchar is assumed to be some 20 m/year over the coming decades. For the further future it is extremely difficult to make an estimate without having studied the lower reach of the Lower Meghna River in much more detail. For the time being it is assumed that this slow rate of erosion will continue. More studies are needed to arrive at better estimates.

B.6.4 Influence of protection works

B.6.4.1 Introduction

In this Section the effect of any protection works along the Upper and along the Lower Meghna River is evaluated. Use is made of the river characteristics that were derived in Chapter B.4, especially as far the Lower Meghna River is concerned.

B.6.4.2 Upper Meghna

It is estimated that the influence of protective works on the Upper Meghna River will be very small. Of course the local effect of these works will be that the banks will not retreat anymore. However, the changes in the planform of the Upper Meghna River are anyhow very minor and they proceed at a low rate. Hence also the effect of bank protection works will become noticeable at other locations after a very long time only. For the time being the effect of bank protection works on other reaches of the river does not have to be taken into account.

B.6.4.3 Lower Meghna

Along the Lower Meghna River the bank erosion proceeds at a much larger rate than along the Upper Meghna River. Bank protection works are being considered out at Chandpur and at Eklashpur. If they would be sufficient, two "hard points" would have been created. The question now is how the Lower Meghna River will react upon these two hard points. It may be expected that the bank erosion between Eklashpur and Chandpur will continue, but the effect will be that a curved alignment of the bank will develop. The distance between Eklashpur and Chandpur is about 20 km and this is in the same order of magnitude as the length of the islands estimated in Section B.4.4.3 for the Lower Meghna River. The implication is that these river training works may impose a meandering pattern upon the Lower Meghna River. This may in due time result in accretion of the left bank of the Lower Meghna River downstream of Chandpur. Considering the celerity of the bank erosion at Eklashpur it may take several decades for this development to start taking place.

In addition it may be questioned whether a distance of some 20 Km is not too long. Considering the length of the islands, it is preferable to create an intermediate point between Eklashpur and Chandpur, This is in line with the proposals for the Brahmaputra River (see Brahmaputra River Training Studies, 1991), where a distance of the hard points of some 8 km is proposed with additional guidance in between. This is in line with the present distance of 20 and 10 km respectively, considering the almost double discharge of the Padma/Lower Meghna system.

A similar development may take place when Eklashpur is not developed as a hard point.

It was suggested that the conditions may improve by improving the Sureswari channel by dredging. The following remarks are made in this respect:

- for the particular conditions such an improved channel will reduce the attack on Eklashpur, but definitively worsen the conditions at Chandpur (see above);
- different from the conditions in meandering channels here it is not sufficient to dredge only a pilot channel, as it may be anticipated that this pilot channel will quickly silt up unless the whole development of the river is towards the development of a Southern channel; it is estimated that at best such a channel may alleviate the conditions at Eklashpur one flood season in advance;
- to develop and maintain a channel that does have a substantial effect on the bank erosion at Eklashpur, dredging capacity has to be used far in excess of what is presently available in Bangladesh.

More detailed studies and a substantial improvement of our understanding of these large river systems is needed before definitive conclusions can be drawn as to the effect of the protection works on the Lower Meghna River. This improvement of understanding should be part of the contemplated long-term strategic plan. For the design of the short-term studies, such a study would have taken far too much time.

B.7 SCOUR

B.7.1 Introduction

Local phenomena (like bends, confluences, constrictions, etc.) may cause large scour depths in alluvial rivers. These scour holes may threaten the bank protection works already present or to be constructed in the future. This Chapter analyses the various types of scour that occur in the Upper Meghna and the Lower Meghna Rivers. The main purpose of this analysis is to provide tools to estimate the maximum scour depth for the different proposed bank protection works. The tools can be used to generate design conditions. The results of the present analysis, in combination with predictions of the future planform of the river near the sites to be protected, will be used to generate these design boundary conditions in Annex G.

A distinction can be made between general scour and scour that occurs more locally. **General scour** is the reaction of the river on changes in its boundary conditions, like aggradation or degradation owing to accelerated soil erosion, sea level rise, cutoffs of bends etc. More localized scour can be distinguished in a number of different types, notably:

(1) **constriction scour,** caused by a local constriction of the width of a river;

(2) **bend scour**, occurring along the outer bank of rivers, and being characterized by deep scour holes together with a point bar in the inner bend;

(3) **confluence scour**, occurring in the reach downstream of the junction of two river reaches, like in the case of the branches of a braiding river or of the confluence of a tributary with a main river;

(4) **protrusion scour**, occurring when the bank of the river protrudes into the channel, like in the case of a local strong point (a non-erodible reach);

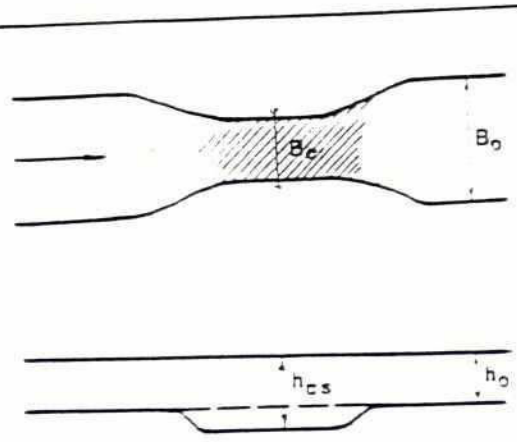
(5) **bedform scour**, related to the possibility of occurrence of deep troughs, downstream of dune crests;

(6) **local scour**, occurring near bank protection works like groynes and revetments.

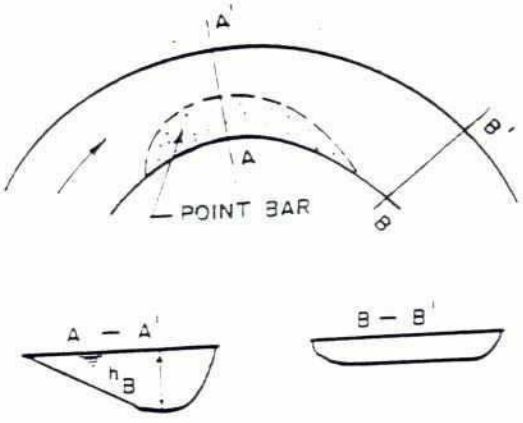
See also Figure B.7.1, where the different types of scour are schematically indicated.

In principle there are two different ways for estimating the scour depth near structures. The first method is based on the regime approach. For the river under consideration the regime depth is estimated with an appropriate formula. Next this regime depth is multiplied with a coefficient, that essentially is based on experience. Hence, the different types of scour listed above are not explicitly accounted for (and computed), but the local conditions are reflected in the estimated values of the multiplication coefficient which indeed depend on local conditions. This first method has been used extensively in the Indian subcontinent. It is described in Section 7.2. To the thus obtained estimate the general scour still has to be added.

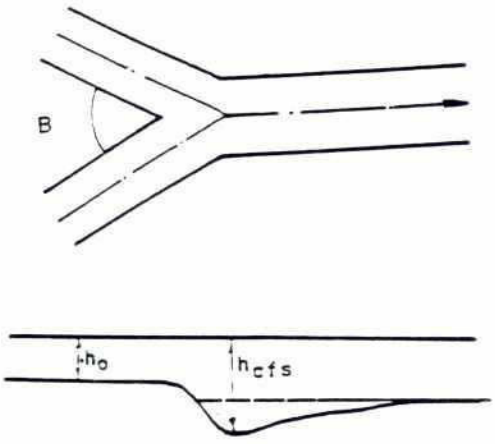
The second method is a more recent development, based on the increased understanding of river processes and local scour phenomena. This method attempts to distinguish between the different types of scour, and for each type a quantitative estimate is made. In a second step the different values are combined to arrive at the combined scour depth that will actually occur. The latter method has the additional advantage that it can be combined with a probabilistic design approach. In the present study mainly the second method is used. For this purpose, the occurrence of the different types of scour is analyzed in the subsequent Sections, whereby the main purpose is to derive design formula applicable to the conditions in the Upper and the Lower Meghna. Also how to combine the different types of scour is discussed. Scour estimates according to the first method are also made, to compare them with the ultimately obtained scour estimates.



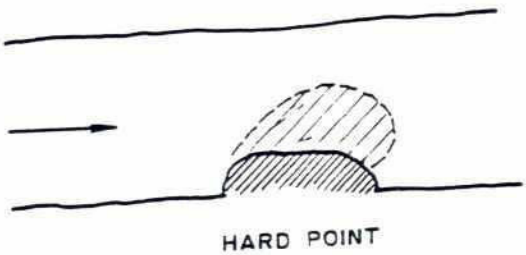
(a) CONSTRICTION SCOUR



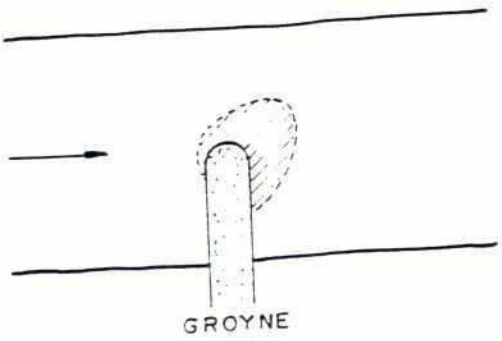
(b) BEND SCOUR



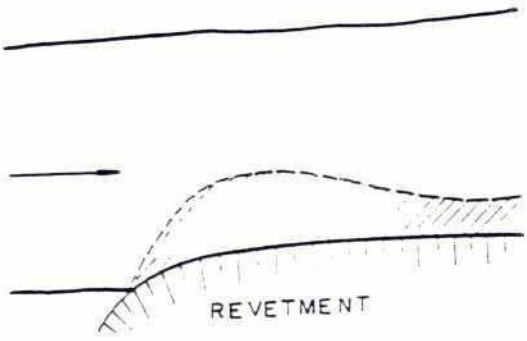
(C) CONFLUENCE SCOUR



(d) PROTRUSION SCOUR



(C1) LOCAL SCOUR AROUND GROYNE



(C2) LOCAL SCOUR ALONG REVETMENTS

Different types of scour	Figure B.7.1

B.7.2 **Regime approach**

The estimate of the maximum scour depth around groynes according to the regime approach is summarized in Breusers and Raudkivi (1991). Here the relevant part of their manual is quoted, whereby the notation is explained in Figure B.7.2.

"Inglis (1949) analyzed field data on the maximum scour depth observed near spur dikes and guide banks in India and Pakistan. He compared the total scoured depth, $h_c + h_s$, with the three-dimensional Lacey regime depth, h_{3r}, which can be obtained from the equation:

$$h_{3r} = 0.47 \left(\frac{Q}{f}\right)^{1/3} \qquad \text{(B.7.1)}$$

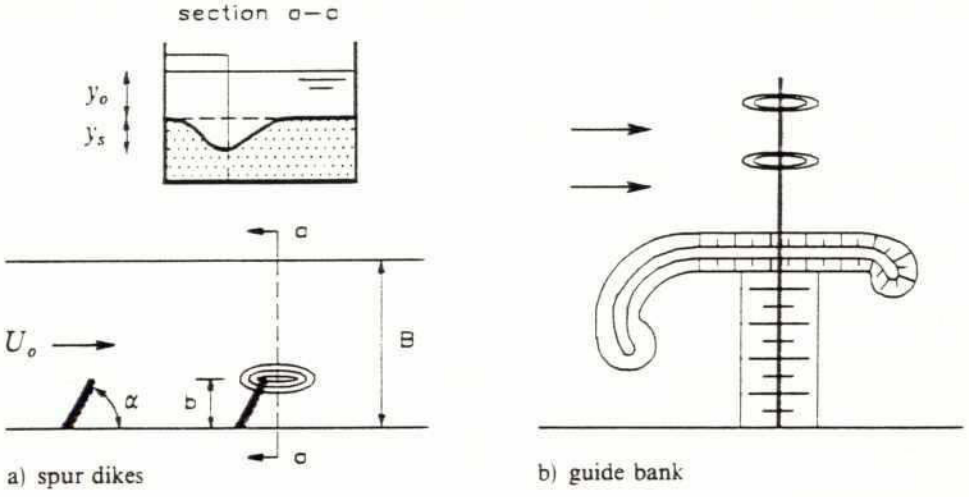


Figure B.7.2 Definition sketch

In Equation B.7.1, the silt factor, f, is equal to 1.76 $\sqrt{D}$, where D is expressed is mm. The ratio $(h_c + h_s)/h_3$ ranged from 1.6 to 3.9, and Inglis (1947) recommends the use of the following values:

Scour at straight spur dikes angled upstream ($\alpha > 90°$) with steeply sloping noses (1.5V:1H)	3.8
Scour at similar dikes but with long sloping noses	2.25
Scour at guide bank noses of large-radius	2.75

Ratios over the observed range should be used with judgement as to the severity of the river's attack on the structure.

Laboratory studies of these structure were performed in flumes with fixed vertical side walls and erodible beds, and they could therefore be compared with Lacey's two-dimensional regime depth, h_{2r}, defined via:

$$h_{2r} = 1.34 \left(\frac{q_1^2}{f}\right)^{1/3} \qquad \text{(B.7.2)}$$

in which q_1 is the discharge per unit width in the contracted section, as noted.

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The most readily useful of the available studies are those of Ahmad (1953) which provided, particularly, information on the effect of the angle α on the depth of scour, and of Liu et al. (1961) whose results cover the widest range of the pertinent variables. Most of the available results are for spur dikes in the form of a vertical wall. Various other studies have added marginally to the limited information on this subject. (...)

Ahmad presented his results on the basis of an equation with the form

$$h_0 + h_s = K\, q_1^{2/3} \qquad \text{(B.7.3)}$$

which is compatible with the Lacey regime equation (K taking the place of $1.34/f^{1/3}$). His results for the effect of angle are summarized, with other relevant factors, hereafter.

Satisfactory results can be obtained from empirically determined values of K (...) with a value of 2.0 ± 15% for a nearly vertical spur dike. Correction factors modify this result for various other conditions as follows:

Spur dike angle α

α	30°	45°	60°	90°	120°	150°
K_1	0.8	0.9	0.95	1.0	1.05	1.1

Shape of dike	K_2
Vertical board	1.0
Narrow vertical wall	1.0
Wall with 4.5° side slopes	0.85

Position of dike	K_3
Straight channel	1.0
Concave side of bend	1.1
Convex side of bend	0.8
Downstream part of bend, concave side	
Sharp bend	1.4
Moderate bend	1.1

To an acceptable approximation, the combined use of the various factors (K, K_1, K_2, K_3) is recommended".

For revetments no special recommendations are provided in the manual of Breusers and Raudkivi (1991).

B.7.3 **General scour**

General scour (or aggradation) is the response of the river to changes in the river itself and in its boundary conditions ("outward controls"). A typical change in the river itself is the effect of a straightening of the river via the cutoff of a number of bends. This straightening will cause lowering of the water level and of the bed levels in the upstream river. This effect should be taken into account when designing bank protection works in this upstream reach. Also boundary conditions like the sediment yield in the basin or the downstream control water level will affect the bed levels in the river and should be taken into account.

Until now the Upper and Lower Meghna River have not been subjected to major changes in the river itself. In the outward controls, however, there have been changes over the past decades and centuries, notably:

(1) the shifting of the Brahmaputra River to its present (Jamuna) course, leaving the Upper Meghna River as an over-sized channel system;

(2) the sinking away of the Hoar area that is probably continuing also now (see Section B.4.2.);

(3) accelerated soil erosion in the catchment.

Future developments that can be foreseen at present are:

(4) flood embankments;

(5) sea level rise;

(6) increased diversion of water for irrigation from the Upper Meghna River.

The influence of these factors is discussed briefly hereafter, especially as far as the effect on bed levels is concerned:

Re (1) **Shifting of the Brahmaputra River**
The "scars" of the Brahmaputra River had to be filled up, and that will have caused aggradation. Whether this process is still continuing cannot be ascertained, but the deviation of the present planform of the Upper Meghna River from a meandering course suggest that this aggradation might still go on. No effect on the Lower Meghna River.

Re (2) **Sinking away of the Hoar area**
This may have a substantial influence on the Upper Meghna River, also in the more downstream reaches. Data are missing to evaluate this effect. Negligible effect on the Lower Meghna River.

Re (3) **Accelerated soil erosion in the catchment**
Most of the possibly increased sediment yield from the Tripura will deposit in the Hoar region, and hence will have a negligible effect on the downstream reaches. Some effect from the Kushiara River. No effect on the Lower Meghna River.

Re (4) **Flood embankments**
Will cause an increase of the bankfull discharge and increased depth of the main channels. The effect will be scour. Also some scour may become noticeable in the Lower Meghna River, if the discharges in the main channels of the Ganges and the Jamuna may increase in future.

Re (5) **Sea level rise**
The possible sea level rise has been estimated to be some 0.5 m in the year 2050. The effect of this sea level rise will be a tendency for aggradation in both the Lower and Upper Meghna Rivers.

Re (6) **Increased diversion of water for irrigation**
May cause a slight increase in slope and hence aggradation in both rivers. As this diversion is only substantial during the low flow season, the effect will be negligible for the Lower Meghna River, and may load some aggradation in the Upper Meghna River.

Recently, Consultants have studied the effect of "outward controls" for the Jamuna Bridge using a 1-dimensional mathematical model of the river morphology. It was found that the sea level rise is dominant over the other possible causes, also because of the short distance between the sea and the bridge. Based on the experience obtained, Consultants estimate for the Upper and Lower Meghna Rivers a negligible effect and some aggradation, respectively (see Table B.7.1).

TABLE B.7.1 POSSIBLE GENERAL SCOUR (AGGRADATION) AS CAUSED BY OUTWARD CONTROLS

Possible cause	Effect on	
	Upper Meghna	Lower Meghna
Shifting of Brahmaputra R.	possible aggradation	no effect
Sinking away of Hoar area	scour	negligible effect
Accelerated soil erosion	no effect	no effect
Flood embankments	possibly scour	possibly scour
Sea level rise	aggradation	aggradation
Diversion of water	slight aggradation	negligible effect

Because this occurs only in the coming decades, general scour need not be taken into account for the design of the bank protection works.

B.7.4 **Constriction scour**

Constriction scour occurs if the width of an alluvial river is constricted over a substantial length. This may be caused by e.g.:

- bank protection works,
- bridge approaches in the floodplains,
- houses and even towns in the floodplains of the rivers.

The effect of the constriction will be that the depth increases and usually the slope in the constricted river reach decreases.

For constant discharge and steady conditions simple expressions for the increased depth and the related reduced slope can be derived (Jansen, 1979):

$$\frac{h_{cs}}{h_0} = \left(\frac{B_0}{B_s}\right)^{\frac{b-1}{b}} \qquad \text{(B.7.1)}$$

$$\frac{i_c}{i_0} = \left(\frac{B_c}{B_0}\right)^{1-\frac{3}{b}} \qquad \text{(B.7.2)}$$

where h_{sc} = water depth in constriction (m), h_0 = original water depth (m), B_0 = original width (m), B_c = constricted width (m), b = power of a simple transport formula (-), i_c = water level slope in constriction (-), and i_0 = original water level slope
(-). The simple sediment transport equation referred to reads as:

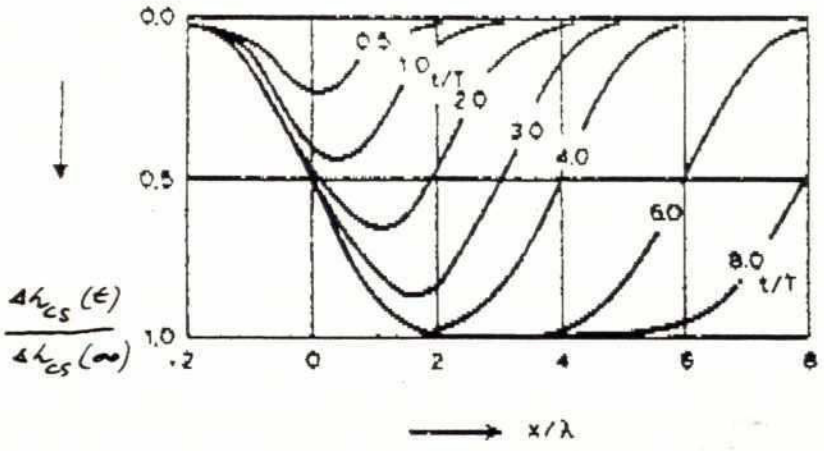
$$s = a * U^b \qquad \text{(B.7.3)}$$

where s = sediment transport per unit width (m^2/s), and a = coefficient.

The additional increase in depth is given by:

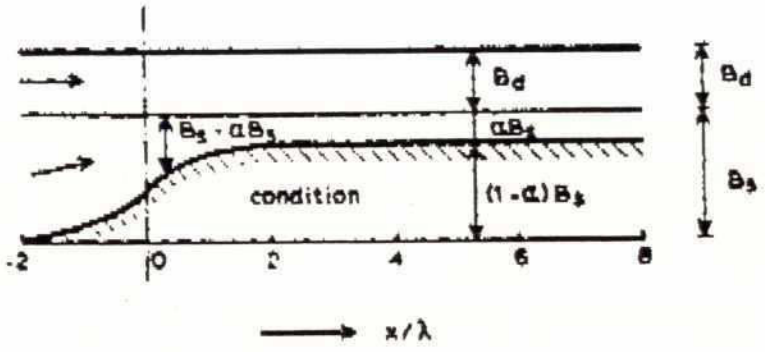
$$\Delta h_{cs} = [(\frac{B_0}{B_s})^{\frac{b-1}{b}} - 1] * h_0 \qquad \text{(B.7.4)}$$

Hence, the constriction scour depth is a function of the original water depth. As the original water depth varies with the discharge and the discharge is a function of time also, the constriction scour is a function of time too. Even for constant discharge, however, it takes some time for the constriction scour to fully develop. This time-dependent behaviour has been studied by Klaassen and Struiksma (1988) and the following graph represents a summary of their results:



(a) Design graph

Figure B.7.3 Time-dependent constriction scour (continued)



(b) Schematization

Figure B.7.3 Time-dependent constriction scour (continuation)

On the left axis the ratio between that part of the constriction scour that has developed after a certain time at a certain place and the ultimate constriction scour has been plotted. The other parameters are:

$$\textit{dimensional space parameter} \quad \frac{x}{\lambda}$$

$$\textit{dimensionless time parameter} \quad \frac{t}{T} = \frac{t}{h_0 * \lambda/(b * s_0)} \qquad (8)$$

where x = length coordinate, λ = typical length scale (see Figure B.7.3(b), t = time (s), T = typical time scale of constriction scour (s), s = sediment transport per unit width (m^2/s). This graph allows to estimate whether equilibrium constriction scour can be assumed to have established after a certain time t at a certain location x.

Formula (B.7.1) was tested versus observed water depths in Bhairab Bazar, where owing to the presence of bank protection works the width is constricted already now. In a number of cross-sections inside and outside the constricted area, the average depth and the corresponding width were determined. The depth was measured from the bankfull discharge level. Typical values for h_c and B_c obtained were h_c = 10 m and B_c = 1,000 m. Next, the values of h_{cs}/h_c and of B_c/B_0 were determined for the constricted reaches. These values are plotted in the Figure B.7.4.

From this graph the following conclusions can be drawn:

(1) Equation (B.7.3) yields a good estimate of the scour caused by the constriction of the Upper Meghna River at Bhairab Bazar.

(2) The power of the velocity in the simple transport relation (B.7.3) is approximately equal to 5. This is a fair value: the sediment transport formula of Engelund/Hansen (1967), which was shown to be valid for the Jamuna River by Klaassen and Vermeer (1988b), yields a power of 5.

It may therefore be concluded that the above equations can be applied with confidence to the Upper Meghna River also.

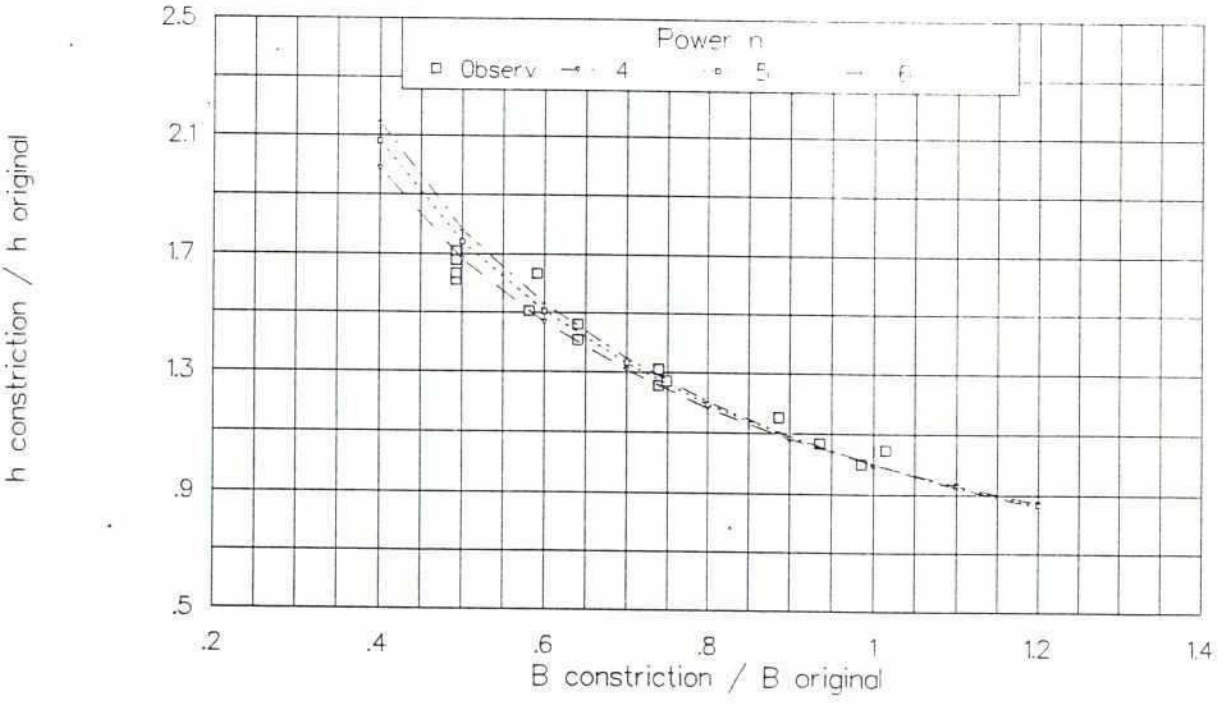


Figure B.7.4 Testing of prediction method for constriction scour versus Bhairab Bazar data

B.7.5 Outer bend scour

Outer bend scour is the type of scour that develops in the outer part of river bends. River bends are characterized by the so-called helical flow, causing sediment particles to move to the inner bend. This causes scour in the outer bend and deposition in the inner bend. The variation of the bed level in transverse direction is given by the equation (see Jansen, 1979):

$$\left(\frac{1}{h(y)} - \frac{1}{h_c}\right) = \left(\frac{1}{R(y)} - \frac{1}{R_c}\right) \frac{1.5\ \alpha\ i_c\ R_c}{\Delta\ D} \qquad \text{(B.7.5)}$$

where

h(y) = is the water depth at the transverse location y (m), h_c = water depth in the middle of the river (m), R(y) = radius of curvature at the transverse location y (m), R_c = radius of curvature in the middle of the river (m), α = coefficient (for definition see Jansen (1979), p.142), i_c = water level slope in the middle of the river (-), $\Delta = (\rho_s - \rho_w)/\rho_w$, and D = size of bed material.

It can be shown that in a first approximation the relative outer bend depth (the depth in the outer bend h_B normalized by dividing it by the average water depth $h_{average}$) can also be written as a function of the following to parameters

$$\textit{relative width}\ \frac{B}{R_c}$$

$$\textit{bend parameter}\ A\sqrt{\theta}$$

where

B = width of river (m), R_c = radius of curvature of the bend related to the centre of the river, A = coefficient (-), defined by:

$$A = 2\ K^{-2}\ \left(1 - \frac{\sqrt{g}}{K.C}\right) * 0.85 \qquad \text{(B.7.6)}$$

(usually A is about 10), and θ = Shields parameter, defined via:

$$\theta = \frac{h.i}{\Delta.D} \qquad \text{(B.7.7)}$$

The theoretical relationship between these parameters is given in Figure B.7.5.

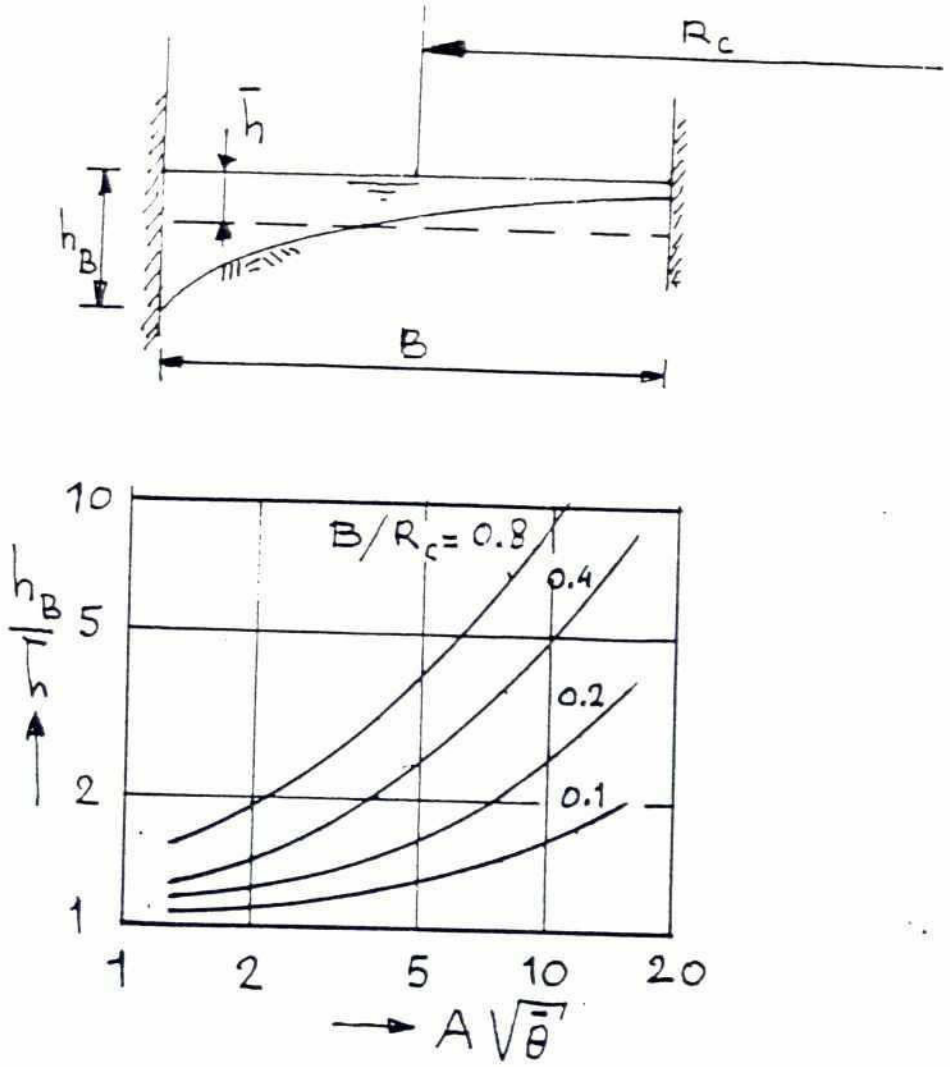


Figure B.7.5 Theoretical relationship for estimating outer bend scour

This graph is approximate only for a number of reasons: it was derived for bedload only, the outer bank was assumed to be vertical, sorting was no taken into account, etc. It may therefore be assumed that deviations are present when comparisons are made with real rivers.

In addition the following remarks have to be made:

(1) The transverse bed level is apparently dependent on the value of Shields parameter θ which in turn is determined by the discharge via the water depth. Apparently the transverse bed level slope in bends varies through the year.

(2) Not only does the transverse bed level depend on the discharge, but also this transverse bed level is adapting itself with some delay. For this delayed adaptation a typical time scale has been developed which reads as:

$$T = \frac{B^2 * 0.85\sqrt{\theta}}{\pi^2 * s} \qquad \text{(B.7.8)}$$

where B = width of the river (m), and the other parameters have already been specified. If a time span of T has passed the adaptation has taken place for 67%. For more information see Klaassen (1988).

(3) The derived formulae hold for the lower part of a bend where the initial effects are not noticeable. In the beginning of a bend an over-deepening of the bend takes place due to an "overshoot" effect (see e.g. Struiksma et al, 1985 and Olesen, 1987). This causes a still deeper outer bend in the beginning of a bend and the typical point bar formation.

To test the above formula, for some bends in the Upper Meghna River the different bend parameters were determined from the available BWDB soundings (at the time of the analysis the BIWTA soundings were not available). The selected bends are in the cross-sections M#19 and M#14. Both cross-sections are located in the lower part of a bend allowing to estimate the transverse bed level slope for fully developed bend flow (i.c. the case for which the above formulae should hold). In the Figure B.7.6 the value of $h_B/h_{average}$ is plotted as a function of the two parameters mentioned.

It can be concluded that the data for the Upper Meghna River cover a limited range only. Comparison with Figure B.7.5 shows that the outer bend scour in the Upper Meghna River is approximately 3 times smaller than would follow from the theory. A similar conclusion was found for the Jamuna River, but there the deviation could be explained by the influence of bank erosion products. In the case of the Upper Meghna River the bank erosion rates are so small (see Section B.4.3.3. of this Annex), that this influence is probably negligible. Figure B.7.6 is used for design purposes.

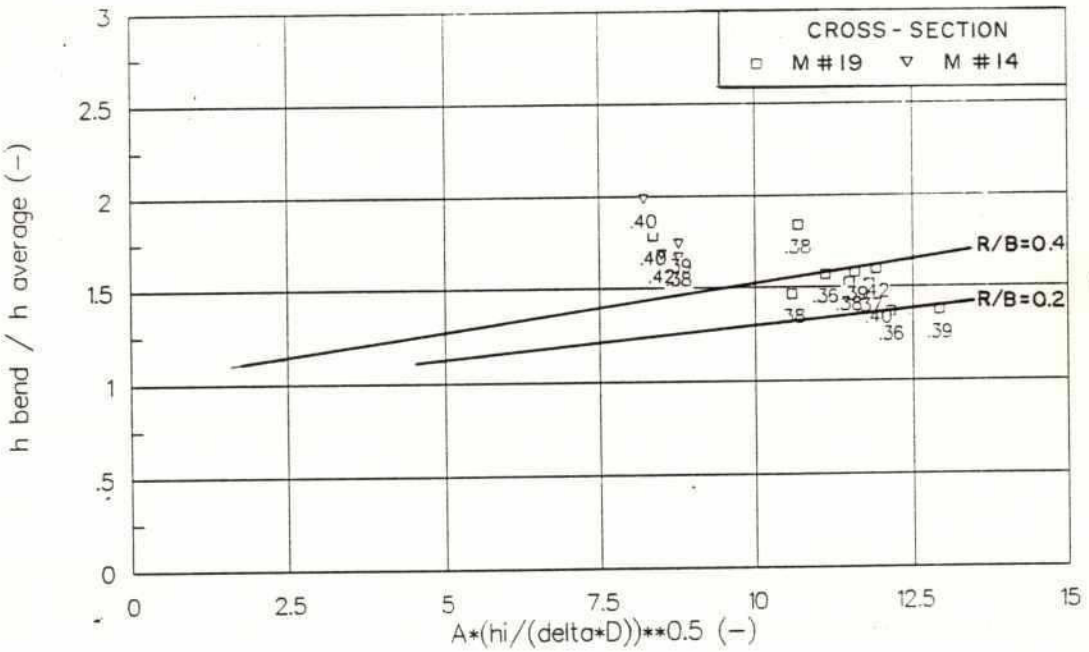


Figure B.7.6 Testing of predictor for bend scour versus data from the Upper Meghna River

B.7.6 **Confluence scour**

Confluence sour in rivers with fine sand as bed material has been studied within the frame-work of the Jamuna Bridge Appraisal Study. Results have been published in the feasibility report (RPT et al, 1990a) and by Klaassen and Vermeer (1988). A predictor for the confluence scour was developed along the same lines as done by Ashmore and Parker (1983) for gravel-bed rivers. The predictor for river with fine material reads:

$$\frac{h_{cfs}}{h_0} = 1.29 + 0.037\beta \qquad \text{(B.7.9)}$$

where h_{cfs} = maximum depth in confluence scour hole (m), h_0 = average depth of the two confluencing channels, and β = the angle between the two confluencing channels (see also Figure B.7.1). As this equation was developed using data from the Upper Meghna/Padma confluence as well, it may be assumed

that this formula can be applied in the present study too.

The following remarks are made:

(1) Equation (B.7.9) was derived assuming that the discharges in both rivers are approximately the same. For the Padma/Meghna confluence this is approximately fulfilled, also because usually the discharge in the Padma River is divided over different channels.

(2) In general confluence scour is less important for bank protection projects, because usually confluence scour in alluvial rivers by its nature occurs away from the river banks.

B.7.7 Protrusion scour

In the Phase I report of the Jamuna Bridge Appraisal Study, protrusion scour is introduced as a separate type of scour, different from bend scour and confluence scour. It was observed that along the Jamuna river and the Lower Meghna river some protrusions are present that cause major scour holes. In the Lower Meghna River Chandpur is the most extreme (and presently only) example of such a protrusion. The protrusion forces the flow to occupy locally a smaller width. This results in an increase of the unit discharge near the protrusion and hence, in alluvial rivers, in scour of the river bed. Near Chandpur the deepest scour holes are found upstream of the protrusion. This distinguishes protrusion scour from local scour. The deepest local scour hole are usually found downstream of the structures.

Protrusion scour has not been studied extensively. No established prediction methods are available for estimating the scour depth due to this type of scour, apart from the method proposed by Simons and Senturk (1977). Consultants have tried to identify the most appropriate prediction method. Essentially three different approaches were used. They are summarized below, and they will be referred to as (1) the method of Ahmad (the former name was chosen as the method uses the approach by Ahmad, discussed in section B.7.2), (2) the method of Simons and Senturk, and (3) the outflanking method.

(1) Method of Ahmad

In this method use is made of the approach of Ahmad in relating the scour to the regime depth. The method of Ahmad is described in Section B.7.2 and the following equation is given there:

$$h_0 + h_s = K\, q_1^{2/3} \qquad \text{(B.7.10)}$$

Values of K could be determined from the BIWTA sounding maps. The distribution of the discharge per unit width in the river at the location of the protrusion was determined. This was done on the basis of the BIWTA sounding maps. It was assumed that during "dominant" discharge the slope in the river is 0.000023 (See Section B.4.4) and the Chezy coefficient about 125 $m^{1/2}/s$ (same section). Also the water level during "dominant" conditions was estimated. The discharge per unit width is given by:

$$q = C\, h^{3/2}\, i^{1/2} = 125\, \sqrt{0.000023}\, h^{3/2}$$

This unit discharge is integrated over the width at the location of the protrusion, thus providing the specific discharge in the contracted river section. From the observed maximum (comprising the original water depth h_0 plus the scour depth h_s), the value of K could be determined. For the different years the thus obtained values of K are plotted in figure B.7.8. It was found that K varies between 2.6 and 6.0.

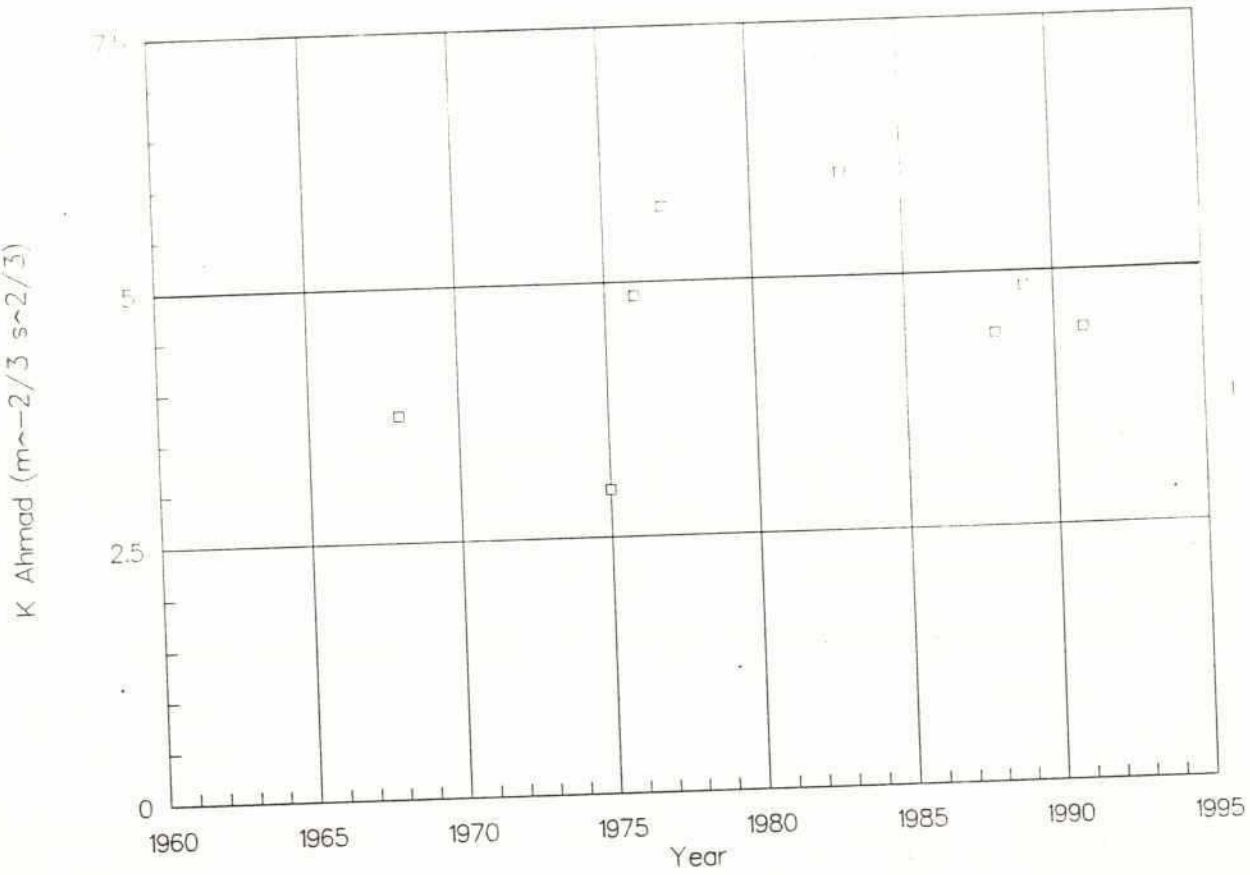


Figure B.7.7 Values of K according to Ahmad for different years

These values of K are quite high compared to the values given in Section B.7.2. The following remark should be made in this respect. For the specific discharge the average value was taken over the full contracted section. It appears logic, however, that the contraction is mostly noticeable near the protrusion. If it is assumed that the local specific discharge is 2 times higher than the average value, the above range of K would be reduced to 1.4-3.0, which is more in line with the values to be expected.

(2) Method of Simons and Senturk

Simons and Senturk (1977) propose a relationship to estimate the scour near abutments, but from the drawing of structure and the scour hole in their book it is clear that this compares to what is here called protrusion scour. They state that, based on experience from the Mississippi River the scour can be estimated with the following equation:

$$\frac{h_{protusion\ scour}}{h_{average}} = 4\ Fr^{0.33} \qquad \text{(B.7.11)}$$

For the conditions in the Lower Meghna River, where the Froude number corresponds to about 0.15, this relation yields the following predictor:

$$\frac{h_{protusion\ scour}}{h_{average}} = 2.1 \qquad \text{(B.7.12)}$$

The equations holds for $L/h_0 > 25$, where L = length of protrusion. For lower values of L/h_0 also an equation is proposed, but these lower values are not really relevant for the case of e.g. Chandpur.

(3) **Outflanking method**

The outflanking method assumes that the scour depth is mainly determined by the relative importance of the discharge being "blocked" by the protrusion. The larger the protrusion, the larger the protrusion scour. To investigate a possible relationship, the distribution of the discharge per unit width in the river upstream of the protrusion was determined. This was also done on the basis of the BIWTA sounding maps and using the same method as described under (1). The thus obtained distribution of the unit discharge was integrated over the width being blocked by the protrusion and, separately, over the remaining width of the river. This yields two estimators for the partial discharges hereafter referred to as Q_o for the protrusion and Q_r for the remaining discharge. The outflanking factor K_o is defined via:

$$K_o = \frac{Q_o}{Q_o + Q_r} \qquad \text{(B.7.13)}$$

Reasoning that all other factors like total discharge, regime depth, particle size of the bed material, Chezy coefficient, slope, etc., remain the same for one location, the maximum observed depth in the river near the protrusion can be plotted as function of K_o. The result is plotted as figure B.7.8.

The following remarks are made with respect to figure B.7.8:

(1) No clear increase of the maximum depth with the outflanking parameter is observed.

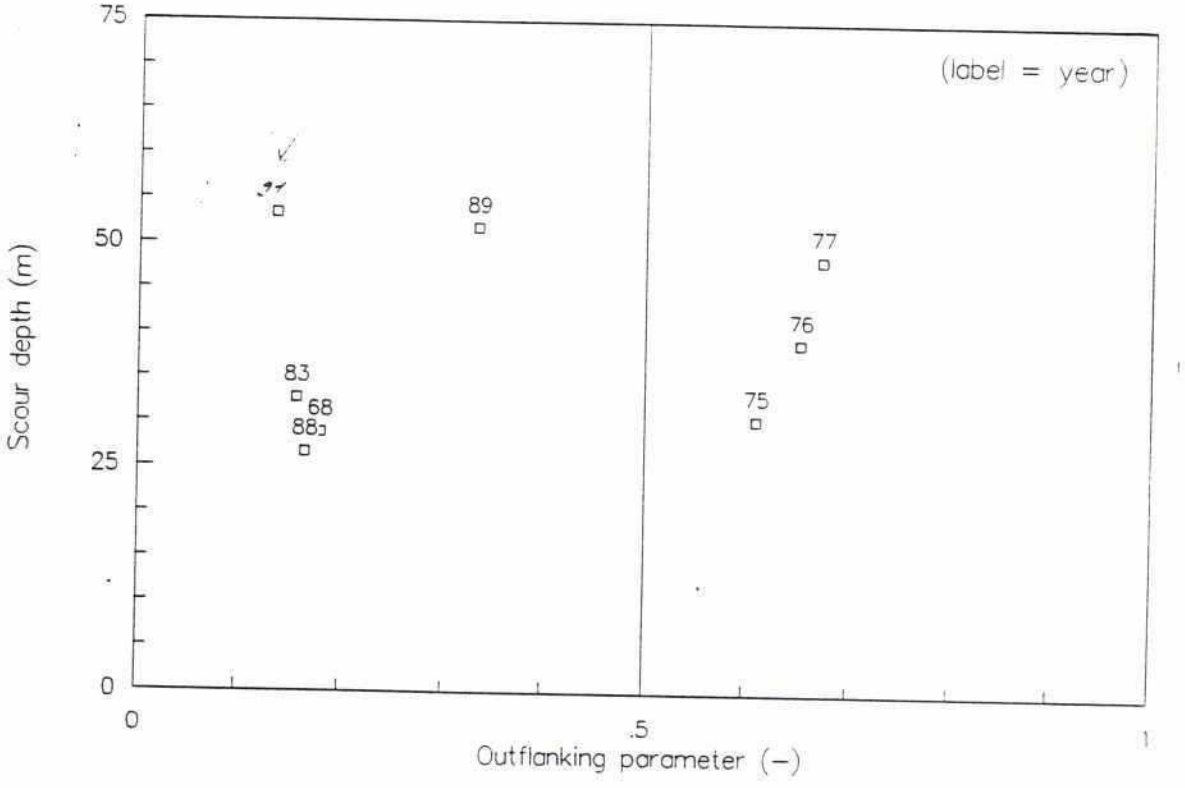


Figure B.7.8 Maximum depth near protrusion plotted as a function of the outflanking parameter K_o

(2) If the observations from the years 1989 and 1991 are left out of consideration, a much better relationship is obtained.

(3) It was investigated whether other parameters like the angle of the main river or the angle of the outflanking channel could explain the differences. It was found that the angle of the main channel was correlated with the outflanking parameter: the more the main channel deviates from the southern "valley" direction in the eastern direction, the larger the outflanking.

Because the years 1989 and 1991 were significantly and unexpectedly different from the other years, a comparison was made between the bed topography is these years compared to the bed levels in the other years. It was observed that from the year 1989 onwards the Eastern boundary of the main channel, bordering the char upstream of Chandpur had moved over some hundreds of meters. This has as effect that the thalweg is directed towards Chandpur and, although not showing up in the outflanking factor, this apparently causes deeper scour than before. The change in the boundary between main channel and char land can possibly be explained by the very extreme floods in 1988. There is anyhow a tendency of the bankline upstream of Chandpur to move in Eastern direction (conform section B.6.3) And apparently this causes increased scour. Due to the "abnormal" behaviour of the most recent years, the outflanking method cannot be used to predict the scour near Chandpur. Nevertheless it is obvious that over the recent years the conditions near Chandpur have worsened.

To get some more insight an additional analysis was done of the effect of a protrusion on the flow field, to explore whether it is possible to predict the increase in velocity near the end of the protrusion. The case studied is schematically indicated in Figure B.7.9.

It can be argued that the ratio $u_{max}/u_{average}$ will be a function of the relative protrusion. Data on the value of $u_{max}/u_{average}$ could be derived from three different sources, all of them results of computations with the 2-dimensional depth-averaged flow model WAQUA of DELFT HYDRAULICS. The sources are:

(1) Van Rijn (1987),
(2) Wijbenga (1985), and

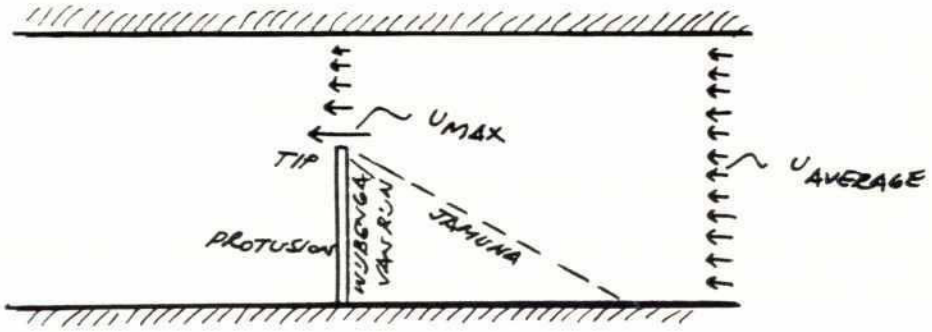


Figure B.7.9 Schematic indication of effect of protrusion on the flow field

(3) an investigation done within the frame-work of an additional study for the Jamuna Bridge Appraisal Study (RPT/NEDECO/BCL, 1990c).

The former two studies relate to a protrusion that extends perpendicular to the river bank into the river, while the latter concerns a triangle as indicated in Figure B.7.9.

In Figure B.7.10 the computed values of $u_{max}/u_{average}$ are plotted versus the percentage protrusion, in this case corresponding to the outflanking factor K_o. The following observations can be made in relation to this Figure:

(1) The ratios of $u_{max}/u_{average}$ for the fist two studies are in the order of 2, while for the additional study for Jamuna bridge this is substantially lower. It is assumed that this is due to the use of a triangle in stead of a sudden protrusion. This will cause a less drastic increase in the velocity at the tip of the protrusion.

(2) All observations are well above (1977) the threshold value of $L/h_0 = 25$, used by Simons and Senturk. For the Jamuna data it is observed that there is indeed hardly any increase in u_{max} if the percentage protrusion increases.

(3) Assuming potential flow the ratio of $u_{max}/u_{average}$ can be computed theoretically to correspond to 2.

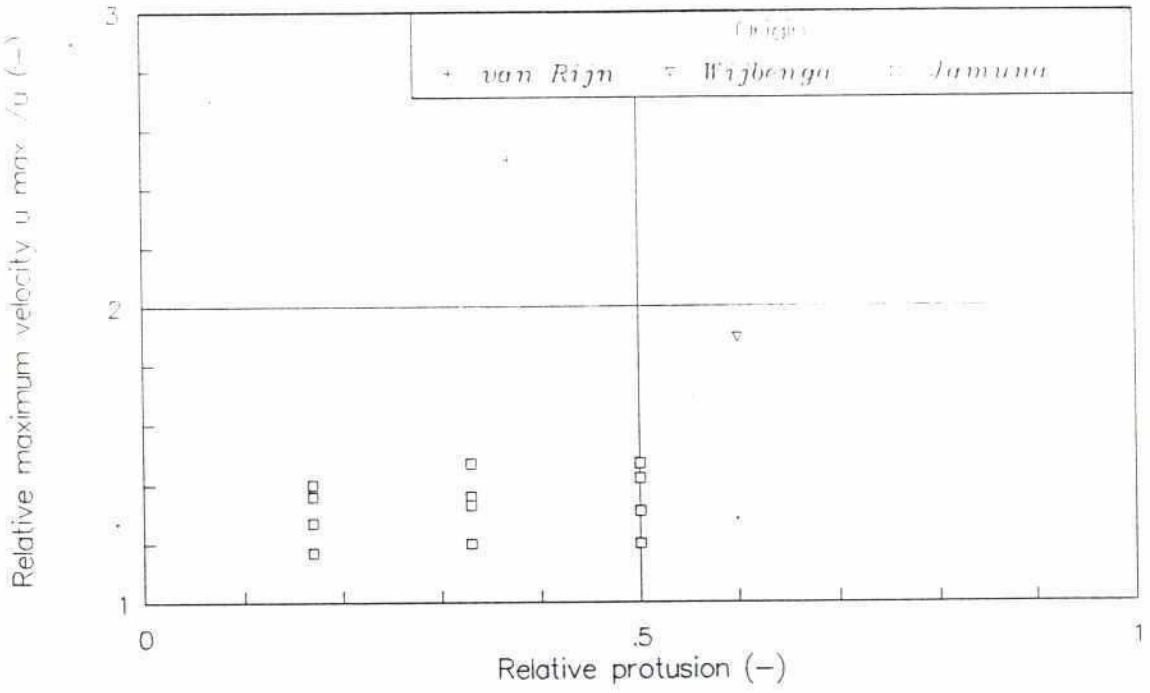


Figure B.7.10 Increase in velocity at tip of protrusion

In alluvial rivers an increase in velocity will lead to erosion. The extent of the erosion can be estimated assuming that q remains the same. This would yield the relation:

$$\frac{h_{pr} + h_0}{h_0} = \frac{u_{max}}{u_{average}} \qquad \text{(B.7.14)}$$

It may be assumed that due to the increase in depth also the distribution of the flow will change, resulting in more erosion. It may, therefore, be concluded that Equation (B.7.14) in combination with Figure B.7.10 yields an optimistic estimate of the scour depth.

The above analysis can be tested against data of the protrusion scour near Chandpur. For this the measured scour depths north of Nutan Bazar are used and they are compared with the average bed level upstream of the location of maximum scour. The results are presented in Figure B.7.11 as the computed values of $(h_{pr} + h_{average})/h_{average}$ (protrusion scour factor) for the different years for which data are available.

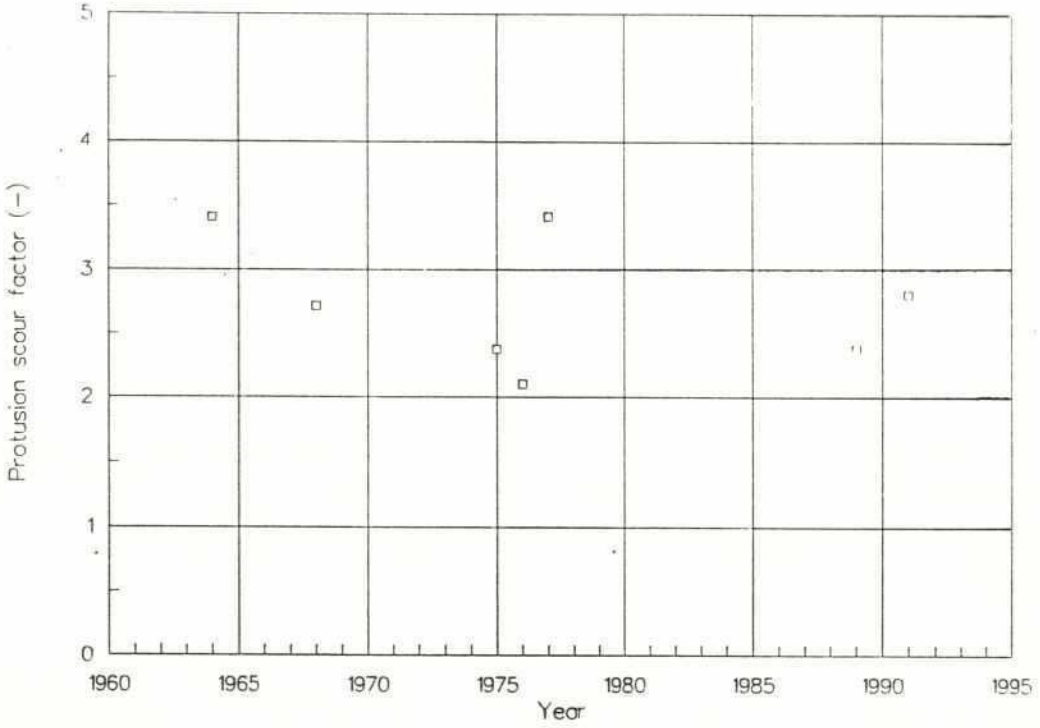


Figure B.7.11 Protrusion scour factor for different years

From an inspection of this Figure it can be seen that the protrusion factor varies between 2.1 and 3.4. As an average value a figure of 2.8 can be used with a standard deviation of 0.3. It is of interest to compare this value with the prediction of Simons and Senturk (1977), which in terms of Equation (B.7.14), proposed the following equation (Equation (B.7.12), adapted for the Meghna conditions):

$$\frac{h_{protusionscour} + h_{average}}{h_{average}} = 2.1 + 1.0 = 3.1 \qquad \text{(B.7.15)}$$

The value 3.1 is only slightly larger than the value of 2.8 found here. Especially when the magnitude of the standard deviation is considered it can be stated that the relation found here on the basis of the Meghna field data is in fair correspondence with the Simons & Senturk relation based on Mississippi data. Hence, Equation (B.7.15) will be used with a value of 2.8 ± 0.3 for the estimate of the contribution of the protrusion scour in the total scour near Chandpur.

The following observations are made:

(1) Different from the local scour, the protrusion scour is hardly affected by the dimensioning of the bank protection works as it is rather the stream contraction (determined mostly by the bed roughness) than the local conditions that is the cause of the protrusion scour.

(2) The predictor developed leans heavily on the BIWTA soundings. The BIWTA soundings, however, are done for identifying shallow area and may be biased slightly as far as the identification of the deepest scour holes is concerned.

B.7.8 **Bedform scour**

Bedform scour is related to the possibility of deep troughs occurring downstream of the crests of bedforms. During lower stages major dunes may be present in the Upper and Lower Meghna River, conform what has been observed in the Jamuna River (see e.g. Klaassen and Vermeer (1988b)). It was found, however, that during floods the dunes appeared to vanish, especially in local scour holes, in outer bends and in confluences. Within the frame-work of the present project, some longitudinal records from the Lower Meghna near Chandpur were obtained during the hydrographic survey in 1991. Also in these records bedforms are almost absent. Bedform scour is therefore not taken into account for both the Upper and the Lower Meghna River.

B.7.9 **Local scour**

Local scour is the scour produced by man-made structures like groynes, abutments, piers, etc. It is caused by local eddies and additional turbulence being generated by these structures. Within the present frame-work especially the local scour near groynes, near protrusions, and along revetments is of importance. These are discussed hereafter separately. Very often the scour depth h_s is expressed as a function of the initial water depth h_0.

(1) Groynes

For the local scour around groynes the expression suggested by Ahmad (1953), as cited in Breusers and Raudkivi (1991), can be taken. These are given in Section B.7.2. It seems logic to use for K_3 a value of 1.0, as the effect of the bend is taken into account according to the method described in Section B.7.5. The value of K_2 can be taken even less than 0.85 because the slopes of the groynes will be 1V:3.5H or less. For the time being a value of 0.7 is used here.

(2) Revetments

Along revetments local scour holes do occur, even if the velocities are parallel to the revetment. This is probably due to (i) the decrease in depth going towards the river bank, and (ii) the difference in roughness of the revetment and the adjacent river bed, both phenomena producing horizontal eddies. These eddies in turn cause local scour. No specific design formula are available for local scour along revetments. Within the frame work of the Jamuna Bridge Appraisal Study Phase 2, a scale model investigation of the existing revetment of Sirajganj was carried out. It was found that the scour depth was the same as the water depth, or:

$$h_s = \alpha\ h_0 \qquad \textit{with}\ \alpha = 0.3 \tag{B.7.10}$$

As the slopes of the bank protection works to be designed will have slopes of 1V:3.5H, while the slopes at Sirajganj were about 1V:2H, it seems fair to reduce this value (see also the reduction factor K_2 in Section B.7.2). For the time being a value of 0.3 has been used. This seems to be supported by the observations in the Bhairab Bazar model. Upon a water depth of some 0.4 m a scour depth of 0.04 m was observed. Because the model was distorted, the scour depth was approximately reproduced on the length scale, so about 4.5 times too small. This would give a value of (4.5*0.04)/0.4 = 0.45. Because the scour in the Bhairab Bazar model was also partly constriction scour, a value of 0.3 appears to be fair. It is expected that this value can be reduced slightly in downstream direction (conform the observations in the Jamuna model).

B.8 DESIGN SCOUR DEPTHS AT DIFFERENT SITES

B.8.1 Introduction

This chapter deals with the maximum scour to expect at the different sites that are considered for bank protection works. For the time being these predictions are limited to Bhairab Bazar and Chandpur.

In this chapter two predictions are made. The first one is related to the "natural development". This is important for an evaluation of the future risks and damages. The second prediction relates to the scour depth that may occur when appropriate bank protection works are carried out. Because these bank protection works will usually apply more gentle slopes than the existing (damaged) protection, it may be expected that the maximum scour depths will decrease.

B.8.2 Natural development

B.8.2.1 Introduction

In this section the "natural" development is discussed at two sites, notably at:

- Bhairab Bazar (Section 8.2.2);
- Chandpur (Section 8.2.3).

B.8.2.2 Bhairab Bazar

Presently the conditions at Bhairab Bazar are characterized by a fairly straight flow downstream of the bridge. The thalweg of the river is approximately in the middle of the river. There is constriction of the river, probably due to the presence of Bhairab Bazar. As stated in Section B.6.2.2 there is a tendency of the development of a bend in the upstream reach. This means that an unfavourable development may occur in time. This possible development is characterized by the formation of a bend upstream of Bhairab Bazar, with a radius of some 4,500 m. At the same time there is the constriction to 500 m in front of the proposed bank protection works. In this Section the scour occurring during the design flood of Q_{100} = 22,000 m^3/s, is estimated.

As far as the maximum scour during the passage of Q_{100} = 22,000 m^3/s is concerned, the total scour will consist of:

- constriction scour,
- bend scour,
- local scour.

The contributions of general scour, protrusion scour and bedform scour are assumed to be negligible for Bhairab Bazar (see also the Sections 7.3, 7.6 and 7.7 of this Annex). The different contributions are assessed hereafter separately.

As a basis the present dimensions of the Upper Meghna River are used. These were determined in Chapter B.4 and they are approximately:

- average bankfull width approximately 1 km,
- average depth during dominant discharge is approximately 13. m,

whereas the dominant discharge amounts to approximately 11,000 m^3/s. It should be remarked that compared to the Jamuna River regime equations (see Klaassen and Vermeer, 1988) the Meghna River is

rather narrow and much deeper. Its dimensions correspond fairly to the Lacey equations (see sections B.4.3.4). This deviation from the Jamuna dimensions may be due to the fact that the Meghna River still did not reach "regime".

(a) **Constriction scour**

Downstream of the Bhairab Bazar railway bridge the Upper Meghna River is constricted over a length of approximately 1 km. This constriction causes constriction scour. Data on constriction scour are available from the BIWTA maps and they confirm the applicability the equations cited in Section B.7.4 with the power of the transport equation b = 5. It was assumed that the bed levels observed on the BIWTA maps referred to dominant discharge. This may not have been true as the soundings relate to low water conditions. This would lead to an under-estimations of the constriction scour, but for the time being this possibility is neglected.

During Q_{100} the water levels will be higher. For the time being it is assumed that dominant discharge relates to a water level of 5.9 m + PWD (Q = 11,000 m^3/s), while Q_{100} corresponds to 7.8 m + PWD, implying an increase in water depth in the unconstricted reach of 1.8 m. As the constricted reach has a width of 500 m, the ratio $B_{constricted}/B_{normal}$ = 0.5. Hence the increase in depth is a factor of 1.7 (see Figure B.7.4.). In the constricted area the depth will become (13+1.8)*1.7 = 25 m.

There is, however, still another effect that causes increased scouring and that is the fact that in the constricted area all the flow has to pass through the river channel, as the flow through Bhairab Bazar town will of course be negligible. Bankfull discharge in the Meghna River near Bhairab Bazar corresponds to some 8,000 m^3/s. This bankfull discharge correspond to a water level of 5.0 m + PWD, an unconstricted depth of some 13 m, a water level slope of 0.000013 and a Chezy coefficient of about 50 $m^{1/2}/s$ (see section B.4.3.5.) For the conditions during Q_{100} the water depth has increased to 13+(7.8-5.0) = 15.8 m, the slope is approximately 0.000019 and the Chezy coefficient is about 67 $m^{1/2}/s$. The discharge in the main channel has increased with a factor which can be obtained via $Q_{main\ channel} :: C.\ h^{1.5}.i^{0.5}$.

Hence, the increase in discharge is computed by multiplying 8,000 m^3/s with a factor

$$\frac{67}{50}.(\frac{15.9}{13})^{1.5}.(\frac{0.000019}{0.000012})^{0.5} = 2.3$$

The discharge through the main channel during Q_{100} amounts to approximately 18,500 m^3/s. Apparently about 3,00 m^3/s is supposed to flow through the floodplains. Hence the discharge through the main channel at Bhairab Bazar increases with some 3,500 m^3/s. The apparent further constriction is 18,500/22,000 = 0.84, yielding an increase in depth to 1.15 * 25 = 29 m.(according to Figure B.7.2).

This estimated water depth during Q_{100} should be compared with the presently observed 17+7.8 = 24.8 m, so apparently an increase in water depth of 4.5 m can be expected due to constriction scour. Taking into account a water level rise of about 2.3 m, this induces a bed level lowering of another 2.3 m. Presently bed levels of about 17 m - PWD are present and this will lower to about 19.5 - PWD due to constriction scour over a length of approximately 1 km.

The typical time scale for this constriction scour was also computed. This was done by assuming that the Engelund-Hansen formula is applicable to the Upper Meghna River. For Q_{100} this results in an approximate sediment transport per unit width of $0.5*10^{-3}$ m^2/s, yielding a typical time scale of 25 days (for λ = 250 m). The typical length of a flood wave is some 10 days. Consultation of Figure B.7.3 yields the conclusion that over the period of the flood wave the maximum constriction scour is not reached. As slightly lower discharges (with approximately the same water depth) are exceeded over a much longer period, this aspect has not been taken into account here.

(b) **Bend scour**

As stated before, it is assumed that further bank erosion may occur upstream of Bhairab Bazar, resulting in a bend near the future bank protection works. The characteristics of this bend are estimated to be:

- radius of curvature R = 4500 m,
- width (in the constricted reach) B = 500 m.

Hence, B/R = 0.11. In Section 7.5 a method was developed for estimating the bend scour. Using this graph

$$\frac{h_{bend}}{h_{average}} = 1.2$$

it is found that:

A matter of consideration is still the average value of the water depth to be applied in this equation. For this an estimate was made of the typical time scale of the development of the bend profile, using the appropriate formula given in Section B.7.5. It was found that the typical time scale is more than 100 days. This implies that there is not sufficient time for the bend profile to adapt to the conditions during flood. Rather the dominant flow depth in the constriction should be used here, which corresponds to about 17 + 5.9 = 22.9 m.

Hence the water depth in the outer bend during dominant discharge is about 22.9 * 1.2 = 27.5 m, an increase of 4.6 m. Hence, the bed level in the outer bend during Q_{100} is estimated to be about 19.5 + 4.6 = 24 m - PWD, including constriction scour but excluding the effect of the local scour to be discussed hereafter.

(c) **Local scour**

In Section 7.9 the local scour near revetments is discussed and it was proposed to use the following equation:

$$h_{ls} = \alpha\, h_0 \quad \textit{with} \quad \alpha = 0.3$$

For the original water depth here the water depth in the constriction and in the outer bend is applied. This water depth is 24 + 7.8 = 32 m. The local scour amounts according to the above formula to 0.3 * 32 = 10 m. Hence during Q_{100} the total water level near the bank protection is estimated to be 24 + 10 = 34 m - PWD, corresponding to a water depth of about 42 m. This value has been used in Annex - G as upper limit for the design of the bank protection works at Bhairab Bazar.

It is of interest to compare the above value with the regime scour depth, using the equation of Ahmad. The following formula is presented in Section 7.2 for guide bunds:

$$h_0 + h_s = K\,(q_1)^{2/3}$$

Assuming for the time being that this equation is also applicable for revetments, an estimate of the total depth can be obtained, once the values of q_1 and K are known. Typical values for K are 1.7-2.3 (see Section 7.2). From the scale model investigations in Bhairab Bazar a value of K = 2.8 was derived, but this included some constriction scour. For the value of q_1 the effect of the bend has to be taken into account as this will cause more discharge to pass through the outer bend. As a first approximation the following equation can

be used:

$$\frac{u_b}{u_c} = \sqrt{\frac{h_b}{h_c}\frac{R_c}{R_b}}$$

Using:

$$q = u\,h$$

it is found:

$$\frac{q_b}{q_c} = \left(\frac{h_b}{h_c}\right)^{3/2}\sqrt{\frac{R_c}{R_b}}$$

Assuming:

$$q_c = q_{average} = \frac{22{,}000}{500} = 44\ m^2/s$$

and using R_c = 4,500 m and R_b = 4,500 + 500/2 = 4,750 m, and furthermore $h_b/h_c = h_b/h_{average}$ = 1.2 it is found that $q_1 = q_b$ is approximately 56 m^2/s. Introducing this in the above equation and using K = 2.0 yields a total scour depth of some 29 m. This is substantially lower than the value of 42 m found above. It should be realized, however, that the value of 42 m includes also constriction scour. This constriction scour is about 29-15.8 = 13.2 m. Adding this value to the above 29 m yields an estimated regime scour plus constriction scour of some 42 m. This compares favourably with the 42 m obtained before, and indicates that the value of 42 m is in good correspondence with previously derived estimators on the basis of the regime approach.

B.8.2.3 Chandpur

Before making an estimate of the future conditions at the Chandpur site, it seems appropriate to review the local conditions and to provide some data on measured scour depths in the past. Chandpur is located where the Dhakatia River enters into the Lower Meghna River. The part of Chandpur North of the confluence is called Nutan Bazar, while the Southern part near the river is called Puran Bazar.

Consultants made an extensive study of the scour pattern as presented on the BIWTA sounding maps over the period 1964 until 1991. The most important observations are listed below:

(1) Figure B.8.1. provides the time series of measured scour depths at both Nutan Bazar and Puran Bazar, whereby the scour depth is the depth below 5.00 m + MSL.

(2) It can be observed that initially the scour depths at Puran Bazar were larger than in Nutan Bazar, but especially in the last years the latter scour has substantially increased. It appears that especially the effect of the protrusion scour (see Section B.7.7) has increased recently.

(3) Furthermore it can be observed that presently the scour depth are in the same order of magnitude as in the mid seventies. This seems to support the period of 15 years which was identified for the bank erosion at Eklashpur (see Section B.5.3.2).

(4) The scour depths are plotted relative to a level of 5.00 m + PWD. It may well be that the scour reacts quickly upon changes in stages and/or velocities, and this may induce some additional scatter.

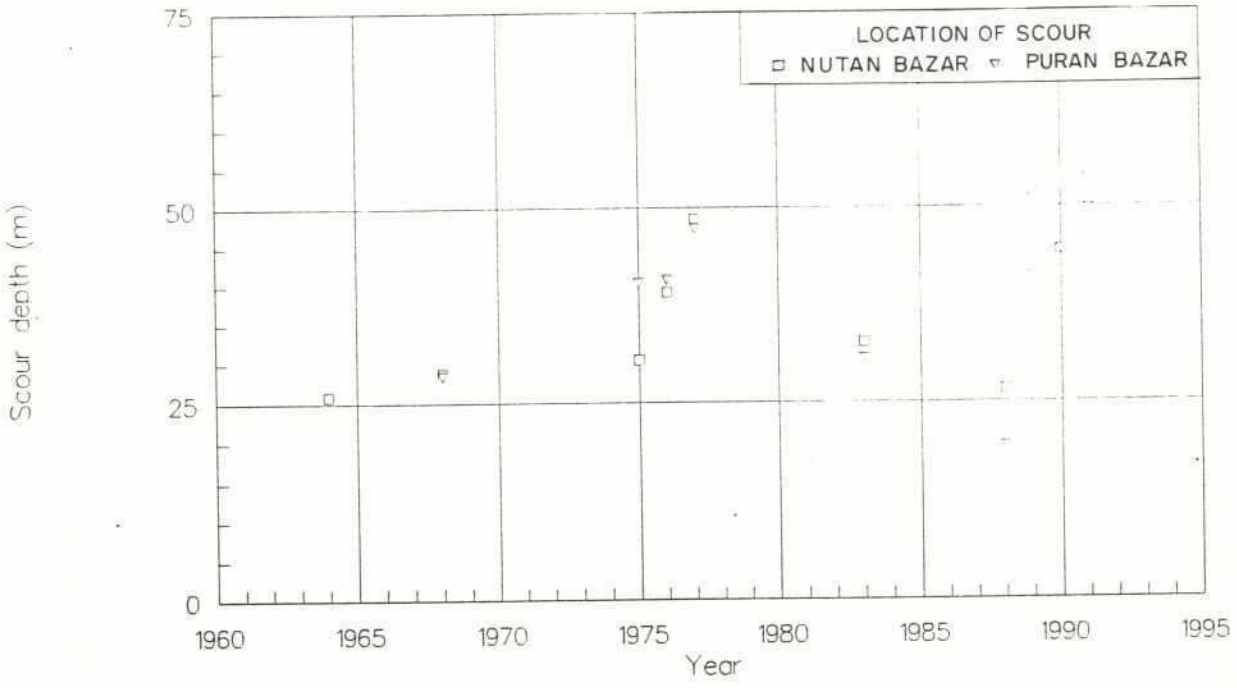


Figure B.8.1 Scour depth at Chandpur in the period 1964-1991

(5) The different components of the total scour observed at Chandpur were analyzed, and an overview is provided in Table B.8.1. From this Table it can be concluded that the mechanisms that cause scour are not constant in time, but that over the years the total scour depth is composed of the different types of scour in different proportions.

(6) The conditions at Nutan Bazar are mostly influenced by the protrusion scour, with a contribution of bend scour in about 50 % of the years listed in Table B.8.1., and some effect of confluence scour in about 25 % of the listed years. It is felt that the years with serious scour are over-represented in the Table, hence better estimates (based also on the satellite images) yield estimated probabilities of occurrence of some 20 and 10 %, respectively for a bend and a confluence respectively.

(7) The conditions in Puran Bazar are mostly determined, by total scour constriction scour becoming important over the last years, and confluence scour having been active in about 25 % of the time.

(8) From the Table it becomes also clear that critical periods have occurred in the mid seventies and over the recent years as in these periods different types of scour were simultaneously active, resulting in deep scour holes.

(9) The effect of general scour cannot be studied on the basis of the BIWTA soundings.

(10) Finally it can be stated that on the long run the conditions are gradually deteriorating: in the recent years there was no effect of bend scour, but nevertheless are the observed scour holes at Nutan Bazar deeper than ever before. It may well be that in the near future a unfavourable bend development may take place, causing a further increase in scour depth.

TABLE B.8.1 TYPES OF SCOUR ACTIVE AT CHANDPUR OVER THE YEARS

Year	Types of scour active [1]										
	Nutan Bazar					Puran Bazar					
	GS	BS	CFS	PS	LS	GS	CS	BS	CFS	PS	LS
1964	?	no	no	yes	no	?	no	no	no	no	yes
1968	?	yes	no	yes	no	?	no	no	no	no	yes
1970	?	yes	no	yes	no	?	no	no	no	no	yes
1971	?	no	no	no	no	?	no	no	no	no	?
1975	?	yes	yes	yes	no	?	no	no	no	no	yes
1976	?	yes	no	yes	no	?	no	no	no	no	yes
1977	?	yes	no	no	no	?	no	no	yes	no	yes
1983	?	yes	no	yes	yes	?	no	no	no	no	yes
1984	?	no	no	yes	no	?	no	no	no	no	yes
1986	?	yes	no	yes	no	?	no	no	no	no	yes
1989	?	no	no	yes	no	?	yes	no	no	no	yes
1990	?	no	yes	yes	no	?	yes	no	yes	no	yes
1991	?	no	yes	yes	no	?	yes	no	yes	no	yes

[1] Explanation of abbreviations:
GS = general scour
CS = constriction scour
BS = outer bend scour
CFS = confluence scour
PS = protrusion scour
LS = local scour

Based on the increased understanding that comes from the different analyses presented in Chapter B.7 and from inspection of Table B.8.1., it is now possible to make an estimate of the future scour depths at Nutan Bazar and at Puran Bazar. For this use is made of the predictions as to the bank line development upstream of Chandpur, as discussed in Chapter 6 of this Annex. In short this development can be characterized as a continued erosion with a rate of some hundreds of meters over the coming decades. Superimposed on this overall development there will be the influence of the changing channel and bar system of the Padma/Lower Meghna river system. That means that no exact prediction can be given for the development over the coming years. Also not because there seems to be some chaotic behaviour of such large river systems (see e.g. Klaassen and Masselink, 1992). Nevertheless it is possible to estimate the effects of the overall bank line development on the scour at the two different locations in more statistical terms.

(1) **Nutan Bazar**

At Nutan Bazar two possible extreme conditions can be identified, notably (a) an upstream bend, and (b) an upstream confluence. For each of these two cases an assessment of the total scour is made. The probability of occurrence of a upstream bend and of an upstream confluence is some 20 % and some 10 %, respectively (see before).

For the possible upstream bend and confluence the contribution of the different types of scour has to be assessed. General scour is considered not to be important (see Section B.7.3). Constriction scour does not occur at Nutan Bazar. The same holds for bedform scour and local scour. Hence the following combinations have to be considered:

- outer bend scour + protrusion scour,
- confluence scour + protrusion scour.

Outer bend scour + protrusion scour

This case considers the possibility of a large bend that may develop upstream of Chandpur. The estimated radius of this bend could be between 6 and 7.5 km, conform the bends presently observed in the Padma River and present upstream of Chandpur in the mid seventies. The width of the curved channel could be as much as 2 km, resulting in a ratio of B/R of about 0.3. The regime depth of the channels in the Lower Meghna River is about 13 m at bankfull discharge (see Section B.4.4) and about 1 m more during the 1:100 year flood. According to the predictor for bend scour the increase in depth along the outer bend is about 1.7 for B/R = 0.3 and θA = 15. This results in a depth in the outer bend of some 1.7*14 = 24 m. The effect of the protrusion has to be added to this. The extent of protrusion will increase due to the retreating bank line. This will, however, not lead to an explicit increase of the protrusion scour, because the factor L/h_o as used by Simons and Senturk (see Section B.7.7) is already much larger than 25. Hence, the local depth should be multiplied with a factor 2.8. So finally a scour depth of slightly more than 66 m is found. This scour is referenced to the water level during the 1:100 year flood (about 5.5 m + PWD), hence the scour depth will be about 60 m - PWD.

Confluence scour + protrusion scour

This case considers the possibility of a confluence to develop upstream of Chandpur. Such a confluence is caused by the cutoff of the point bar which is shown to occur periodically. The location of the confluence may shift over some kilometres. The most threatening situation for Chandpur is as has occurred in the years 1976 and 1990: the confluence about 2 km upstream and an angle of some 30 to 70 degrees. The average depths of two confluencing channels is (using the regime equation $h :: Q^{0.33}$) some 11 m. Using the formula derived for the Jamuna River (see Section 7.6 and taking for the angle a value of 50 degrees, results in a multiplication factor of 3.1. Hence the maximum depth will be some 35 m. During the 1:100 year flood this depth will be about 1 m more. This maximum occurs only very locally. The average depth in the confluence scour hole (more of importance for the protrusion scour) is some 20 + 1 = 21 m. Applying again the factor 2.8 results in a scour depth of some 59 m. This yields a scour depth of almost 55 m -PWD.

The conclusion of the above assessment is that in the coming decades the maximum scour depths in front of Nutan Bazar may become as large as 55 to 60 m - PWD during about 30 % of the time. In other years the scour depths may be (substantially) less, depending on the developments of the channel and bar system upstream of Chandpur.

(2) **Puran Bazar**

Also for Puran Bazar it may be assumed that general scour is not important (see Section B.7.3). The same holds for bedform scour. Protrusion scour is probably not noticeable anymore at Puran Bazar, as the main contraction takes place more upstream (this would of course become different if the protection at Nutan Bazar would fail and Nutan would be completely eroded). Confluence scour may be important, bend scour definitely not as it is expected that Puran Bazar will be in the lee of Nutan Bazar. Constriction scour is important (especially because of the declining bank line upstream of Chandpur), but considering the short distance between Nutan Bazar where the water is forced into Western direction and Puran Bazar, it may be assumed that the specific discharge near Puran Bazar is much higher than the average specific discharge in this reach. The most important contribution to the scour at Puran Bazar is by far the local scour. Hence the following combinations have to be considered:

- constriction scour + local scour
- confluence scour + constriction scour + local scour.

These two cases are considered hereafter. The local scour depends very much on the design of the river training works (a.o. its slope), and it was studied in the physical model investigations at RRI. The results of these studies, as far as available at the time the present assessment was made, are used here. For the time being it is assumed that the local scour can be determined with the formula of Ahmad, which reads as:

$$h_s = K\, q^{2/3} - h_0$$

where according to the physical model studies carried out so far K = 3.0 for the deepest scour holes. An estimate of the value of the specific discharge can be obtained from the computations with the 2-dimensional depth-averaged mathematical flow field model, which were also used for the generation of the boundary conditions for the physical models at RRI.

Constriction scour + local scour
Due to the continuing bank erosion the protrusion of Chandpur will increase. This could result in an increase of the unit discharge near Puran Bazar. There is some ground (see Section B.7.7) to state that continued bank erosion will at a certain moment not lead to a further increase of the specific discharge (conform the limit in the increase in velocity for "fixed" bed, see Figure B.7.10.). This would mean that the local scour will not increase any further, apart from the influence of the increased stage during the 1:100 year flood. During this flood the stage is about 1 m higher. As K is about 3 and $q :: h^{1.5}$ (hence $q^{2/3} :: h$), this will result in an increase of the scour of some 3 m. The present scour depth is about 45 m - PWD, so this may increase to about 48 m - PWD. It may be expected that after construction of the bank protection works the scour depth will be lower because the slopes of the designed bank protection works are only 1V:3.5H, which will give a reduction of the scour hole depth in front of the bank protection (see also Section B.7.9). For the time being it is assumed that this effect is small only , so for the combination constriction scour and local scour a scour depth of 48 m -PWD during the 1:100 year flood should be taken into account.

Confluence scour + constriction scour + local scour
Following the evaluation given above for Nutan Bazar, an average confluence depth of some 21 m during the 1:100 year flood is found. The constriction is due to the declining bank line is estimated to be about 10 % (150 m upon a width of 2000 m) and this will result in an extra lowering of the bed level of some 2 m. Accepting for the time being an average velocity of 3.5 m/s, the specific discharge is about 80 m^2/s. The local scour is estimated using the Ahmad formula and K = 3.0, yielding a water depth (including the scour) of some 56 m. The maximum scour depth reaches under these conditions down to 50 m - PWD.

The above implies that in some years (possibly occurring about 20 % of the time) the scour depth in front of Puran Bazar may be down to 48 to 50 m - PWD. The probability that during these years with extreme scour potential also the 1:100 year flood will pass is of course smaller than 1:100 (see also Jansen,1979).

B.8.3 Influence of protective works

B.8.3.1 Introduction

The scour depth at a certain site is affected by the natural conditions (see the preceding Section B.8.2), and by the influence of the works itself and by the protection (and other!) works in adjacent river reaches. For the design of bank protection works also the latter two aspects have to be considered. In Bhairab Bazar and for Chandpur it is difficult to isolate the natural phenomena from the "human-induced" scour, because in the past already bank protection works have been carried out at both sites. Nevertheless in the subsequent sections some attention will be given to the influence of the protection works themselves and of works in adjacent reaches.

B.8.3.2 Bhairab Bazar

Over the past bank protection works have already been made downstream of the railway bridge. The very reason that downstream of the bridge the river is constricted, is probably these protection works. The planned protection works will result in some more constriction, because the slopes of the designed bank protection works are gentler than the present ones. An estimate was made of this additional constriction and it appears to be some 25 m only, resulting in an additional scour of some 0.5 m. This is very small compared to the other effects. (see Section 8.2.3). Considering also the inaccuracy of the different estimates, the effect of this additional constriction need not to be taken into account.

Furthermore it is assumed that protection works elsewhere will not be noticeable at Bhairab Bazar over the coming decades, hence the effects of these possible works are also not taken into account.

B.8.3.4 Chandpur

The scour at Chandpur will be affected by the local bank protection works, but also (in due time) by the bank protection works at Eklashpur, if any.

The total scour depth will be affected by the following factors:

(1) **Outflanking**
If Chandpur is maintained as a strong point and at the same time the Lower Meghna will continue to move in eastern direction, then Chandpur will become more and more exposed. As discussed in Section B.8.2.3 this will probably not affect the protrusion scour as this is probably already at its maximum value. It may however be assumed that the channel passing Chandpur will become increasingly more narrow. Hence the average depth of this channel and hence the depth of the channel near the bank protection works will increase. This will definitely lead to increased scour depths. Assuming that the bank erosion rate continues to be some 30 m/year, this will result in 600 m in 20 years. The channel is about 3 km wide, hence the increase in depth will be about 20 %. Hence a substantial increase in total scour (in the order of 10 m) can be expected.

(2) **Slopes of protection works**
The local scour depths are very much affected by the slope of the future bank protection works. More gentle slopes will lead to less deep scour holes. Also this effect is quite pronounced. The influence of this effect is accounted for in Annex G using the results of the model tests and the information available in the literature.

If bank protection works would be constructed at Eklashpur this would in due time possibly reduce the bank erosion upstream of Chandpur. This then, in turn, would lead to less outflanking and a smaller increase in scour holes depths. Because this will probably be noticeable after a number of decades rather than years, this effect need not to be taken into account for design of works at works at Chandpur.

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W.A.R.P.O.
DHAKA