People's Republic of Bangladesh
Ministry of Irrigation, Water Development
and Flood Control

Flood Plan Coordination Organisation

Southwest Area Water Resources Management Project

United Nations Development Programme
(BGD/88/038)

Asian Development Bank
(TA No 1498-BAN)

FAP 4

FINAL REPORT

Volume 3

Morphological Studies

August 1993

Sir William Halcrow & Partners Ltd.

in association with
Danish Hydraulic Institute
Engineering & Planning Consultants Ltd.
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SOUTHWEST AREA WATER RESOURCES MANAGEMENT PROJECT

MORPHOLOGICAL STUDIES

CONTENTS

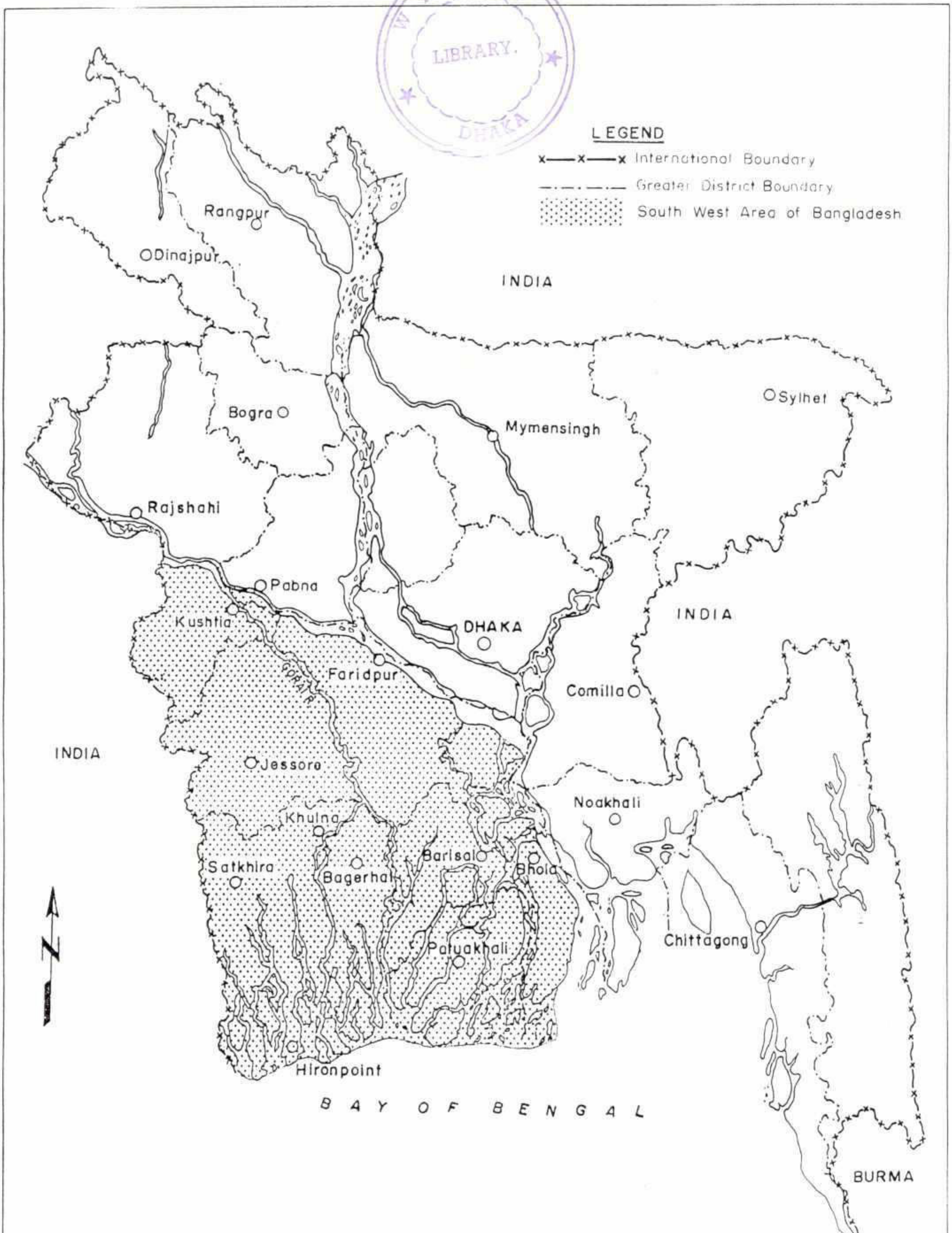
LIST OF TABLES

LIST OF FIGURES

ACRONYMS AND ABBREVIATIONS

BIWTA	Bangladesh Inland Water Transport Authority
BRTS	Bangladesh River Training Study
BWDB	Bangladesh Water Development Board
CEP	Coastal Embankment Project
DHI	Danish Hydraulic Institute
FAP	Flood Action Plan
FPCO	Flood Plan Coordination Organisation
GIS	Geographical Information System
G-K	Ganges - Kobadak
GPS	Global Positioning Stations
IECO	International Engineering Company Inc.
MBR	Madaripur Beel Route
MG Canal	Mongla Ghashiakhali Canal
MPO	Master Plan Organisation
NE	Northeast
NW	Northwest
PWD	Public Works Department (Datum)
SE	Southeast
SPARRSO	Bangladesh Space Resource and Remote Sensing Organisation
SW	Southwest
SWA	Southwest Area
SWMC	Surface Water Modelling Centre

Figure 1.1



South West Area Location Map

1 INTRODUCTION

1.1 General Description

The Southwest Area of Bangladesh forms a part of the Ganges Delta which has a mosaic of numerous channels that are interdependant and in a constant state of change. The main rivers have multiple roles such as for irrigation, water supply, drainage, navigation and fisheries. For planning purposes it is necessary to understand the various linkages and dependencies when considering interventions. The Boundary rivers have a major impact on the Area and therefore attention is focussed on the Ganges and Padma in particular, as well as important regional carriers of water such as the Gorai. With more than half the Area under the influence of tidal action and the second largest sea port of Bangladesh, Mongla on the Pussur river, tidal effects including salinity changes are also studied.

The location of the SWA is shown in Figure 1.1.

1.2 Scope of this Report

The purpose of this report is to describe the comprehensive morphological studies of the region carried out as part of the development of the regional water resources plan described in the Main Report. The morphological studies have been carried out in accordance with section 2(iii) of the terms of reference for the project and particular emphasis is placed on the priority areas identified under the Flood Action Plan for further examination. These include:

Flood Control along the Right Bank of the Ganges-Padma river,

Drainage Improvement in the Coastal Embankment Area,

Augmentation of the dry season flows in the Gorai river.

The morphological aspects of these areas are discussed in this report and the overall analysis within the regional planning framework is given in Volume 1 Main Report. Coastal studies are given in Volume 4 and a summary of the conclusions are included in this report for completeness.

1.3 Approach to the Morphological Studies

The complexity of the river network in the Southwest Area has been fully appreciated in the study through field visits and surveys by the Consultants. The studies described in this report include analysis of historic mapping and satellite imagery using GIS, morphological analysis of cross sections and long profiles, analysis of the flow and sediment regime and morphological modelling of the river network.

The study covers the major boundary rivers of the Ganges, Padma and Lower Meghna, the regional distibutary rivers such as the Matabhanga, Gorai and Arial Khan as well as the major inland rivers such as the Nabaganga, Chandana and Kumar. Morphological analyses of the main tidal rivers and estuaries are also given. The historical development of the rivers in the area has particular prominence in the studies as this gives a valuable insight into the future changes that can be expected.

The studies initially follow a modular approach with different techniques employed for fluvial and tidal rivers as appropriate, the latter part of the report however brings out the important linkages between the studies, though it must be recognised that the present state of knowledge about the interactions between the fluvial river and the tidal river is limited and the data available is sparse. Finally recommendations are given for the future implemetation stage of the FAP and for continuing studies.

1.4 Other FAP studies

Related Studies

The Flood Action Plan contains a number of supporting studies to the main regional studies and additionally there is a limited overlap and some interaction between studies. In carrying out the study, use has been made of these related studies and findings of other studies relevant to the morphology studies were taken into account where possible, this includes:

FAP 1	Brahmaputra River Training Studies: The Jamuna supplies vast quantities of water and sediment into the Padma and Lower Meghna. The studies carried out by FAP 1 are therefore of particular relevance to studies of the Padma. Morphological modelling results using the SWMC GPJ model were also found relevant.
FAP 2	North West Regional Study: Though the region studied borders the Ganges, FAP 2 did not cover the river Ganges and it is assumed that the Ganges left bank embankment is complete and operating satisfactorily.
FAP 3	North Central Regional Study: The Regional Plan for FAP3 includes no embankments along the Padma.
FAP 5	South East Regional Study: Limited study of the changes in the Lower Meghna is described.
FAP 9A	Secondary Towns Flood Protection: Under this project detailed designs for bank protection works at Khulna were derived.
FAP 9B	Meghna River Bank Protection Short Term Studies: The study included significant morphological analysis of the area local to the works being proposed at Chandpur, Eklashpur and Haimchar on the Lower Meghna though no analysis is given of the likely impacts of the works on the right bank.
FAP 16	Environmental Study: Some analysis of the changing patterns of Charlands in the Ganges, Padma and Meghna has been proposed for the future. Studies at Bhola including an area of erosion should be available in future.
FAP 18	Topographic Mapping: Maps of the SPOT imagery for 1989 were provided through FPCO at a scale of 1:50000. Maps of the boundary rivers for 1990 were also made available.
FAP 19	Geographic Information System: FAP 4 has worked closely with FAP 19 who processed two Landsat Images for FAP4 and provided other imagery around the Gorai Mouth and for the Padma in 1993.
FAP 21/22	Bank Protection and Active Flood Plain Management: The data compiled were of interest and may have application in the Ganges however the emphasis of the study is solely on the Jamuna.

FAP 24 — River Survey Programme : This project started too late to provide any data to FAP 4 though the surveys proposed will provide data for future studies.

FAP 25 — Flood Modelling/Management Project: Specific Gauge Analysis by FAP 25 was used and data on the impact of embankments on flow and level in the Padma were also used.

Other Studies

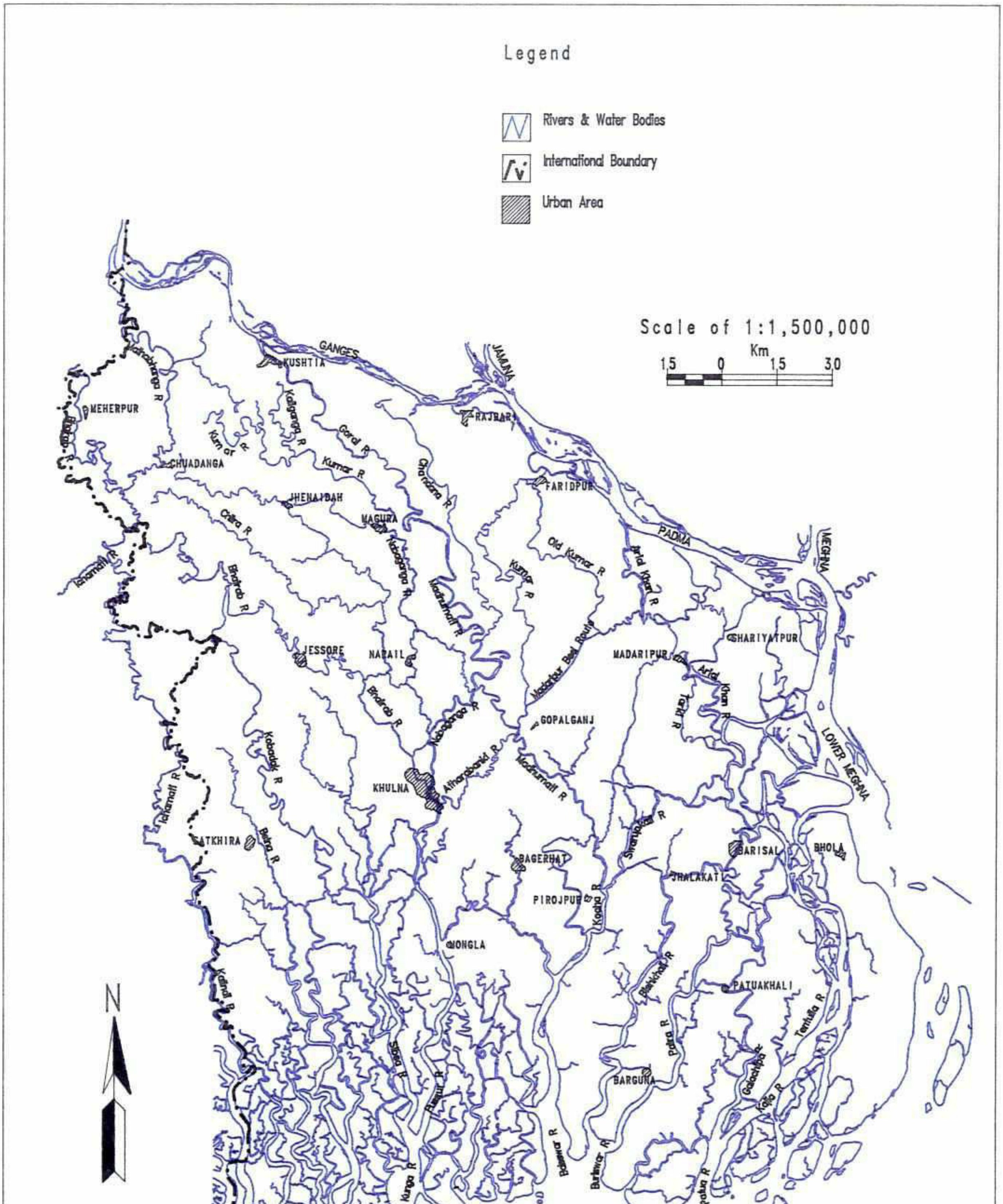
SWMC — The Surface Water Modelling Centre provided equipment for field surveys and carried out sediment size analysis for the project. SWMC worked closely on the analysis of the Gorai historical data and carried out the development and running of morphological models of the Tidal zone as well as development of a mobile bed sub model of the Ganges and Gorai which has been of great use in the prediction of channel changes.

Pussur Sibsa Studies for Mongla Port — Extensive modelling of Pussur and suggested future actions.

CERP II — The concept of sustainable rivers was used in this report but no detailed analysis of the morphology of the system is given as it is argued that the data was not yet available for the development of a comprehensive morphological model of the study area.

SPARRSO — SPARRSO have an on-going study of bankline movement in the major rivers. No reports were available although initial results were seen.

Figure 2.1



Major River Network

2 MORPHOLOGY, GEOLOGY AND PHYSIOGRAPHY OF THE SOUTHWEST AREA

2.1 General Description of the Rivers

The Southwest Area is demarcated by the courses of the major rivers bounding the area, the Ganges, Padma and Lower Meghna together with the Bay of Bengal to the south. The boundary rivers spill into several major distributaries which cross the Area giving access to fresh water and maintaining internal drainage channels. The regional distributory rivers receive runoff during the monsoon season from inland rivers though this makes up only a small part of the total flow through the Area. The inland rivers mostly follow the course of former regional rivers. More than half of the area is tidally influenced and the major regional rivers of the south central area are dependant on tidal effects which generate large net flows. Much of the drainage of the southern coastal region can only take place at low water.

The major rivers of the Area are shown in Figure 2.1 and characteristics of selected rivers are given in Table 2.1. The border with India leaves the Ganges downstream of Rajshahi around the offtake of the Matabhanga river. The Ganges follows a meandering pattern in the approach to the Hardinge Railway Bridge at which the river is constrained and contracted by extensive training works. The bridge marks a point of particular interest as it is the main gauging site for the Ganges and is also the only point at which a major river has been trained in Bangladesh. The site is a natural constriction at a harder clay outcrop on the left bank. The Intake to the G-K irrigation project is just downstream of the bridge and the Gorai offtake at Talbaria point is some 15 km downstream.

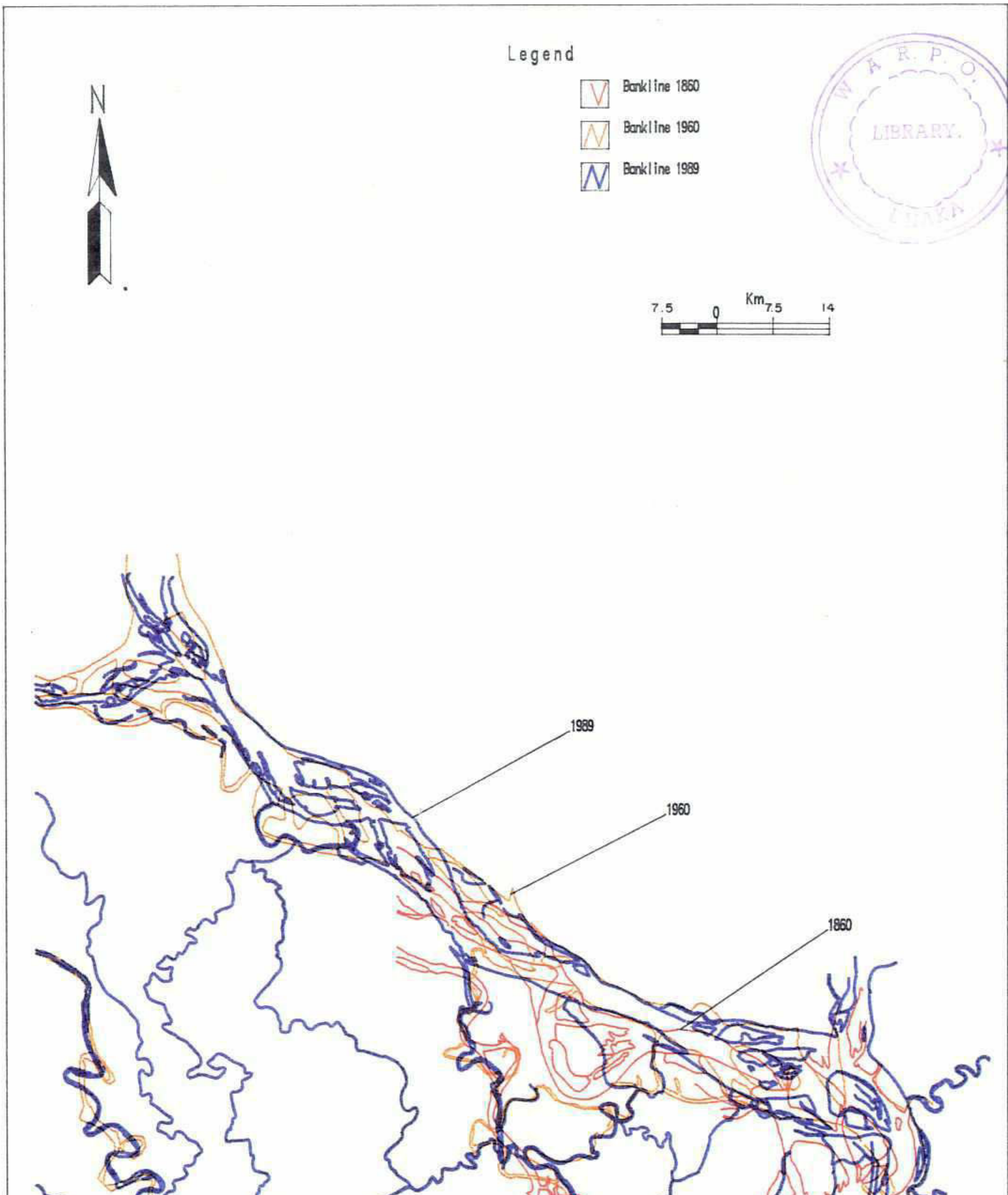
TABLE 2.1

Characteristics of Main Regional Rivers

River Name	Tidal/Non-Tidal	Dominant Discharge (m^3/s)	Peak Tidal Flow		Nett Flow m^3/s		Width (m)
			August	April	August	April	
Gorai	N	4250	-	-	-	-	500
Madhumati	N/T	-	4490	1300	5010	93	600
Lower Madhumati	N/T	-	400	31	320	2	250
Arial Khan	N/T	2000	2900	300	2120	150	400
Swarupkati	T	-	16880	7120	3500	770	400
Buriswar	T	-	19340	9150	3070	620	1250
Biskhali	T	-	10990	8920	2400	360	1600
Tentulia	T	-	9020	4820	4380	1108	4000

Notes: (1) Tidal Flow given for spring tide 1991 from model simulation.
(2) Nett Flow derived from mean monthly flow of 25 year tidal simulation using current cross sections.
(3) Width at section for which flows given.
(4) Flows for Madhumati given just above Halifax cut, Lower Madhumati values given just below. Flow split indicated is subject to further studies.

Figure 2.2



Bank Movement of Padma 1860 – 1989

Downstream of the Gorai the Ganges adopts more braided characteristics and major chars and anabranches are apparent. The river is characterised by a wandering pattern of movement within former courses with a periodicity of 40-50 years. In the 100Km reach to the confluence with the Jamuna near Rajbari, two formerly major channels, the Chandana River and Kumar rivers receive spill only during high levels in the Ganges. Both these rivers are now controlled by intake gates. The confluence of the Ganges with the Jamuna marks the transition to the Padma which has significantly greater dry season flows than the Ganges and is geologically much younger and more active than the Ganges.

The Padma has a single channel and carries a dominant bankfull flow of about 70,000 m3/s and conveys an annual suspended sediment load of about 1 billion tonnes. The movement of the banks of the Padma can be extremely fast as illustrated in Figure 2.2. This results in the favouring or cutting off of the various spill channels. The upper part of the Padma has tended to move in a North easterly direction on average over the last century allowing embankments to be constructed on the right bank in the Faridpur area. Further south towards the Meghna the channel becomes tide affected and is also constrained by geological features upstream of which the greatest channel movements take place. Towards the confluence with the Meghna shifting chars are present possibly due to the constricting effect of the large bend into the Lower Meghna. The spill channels from the Padma are the Kumar at Faridpur and the three channels feeding the Arial Khan, the dominant one at present is the upstream channel though for navigation purposes the middle channel at Dubaldia is the favoured route. The upper Meghna joins the Padma providing only a relatively small additional freshwater flow.

The Lower Meghna is tidal throughout with a mean tidal range of less than 1m at the Chandpur to over 2.5m at the Bay of Bengal. The influence of the tide varies between the monsoon period and the dry season. During high monsoon flows tidal influence is decreased as well as saline intrusion into the estuary and into the regional rivers as shown in Figure 2.3. The Meghna is the main active delta building river and significant changes to the patterns of erosion and accretion can be seen over relatively short time spans including a general trend for accretion on the right bank.

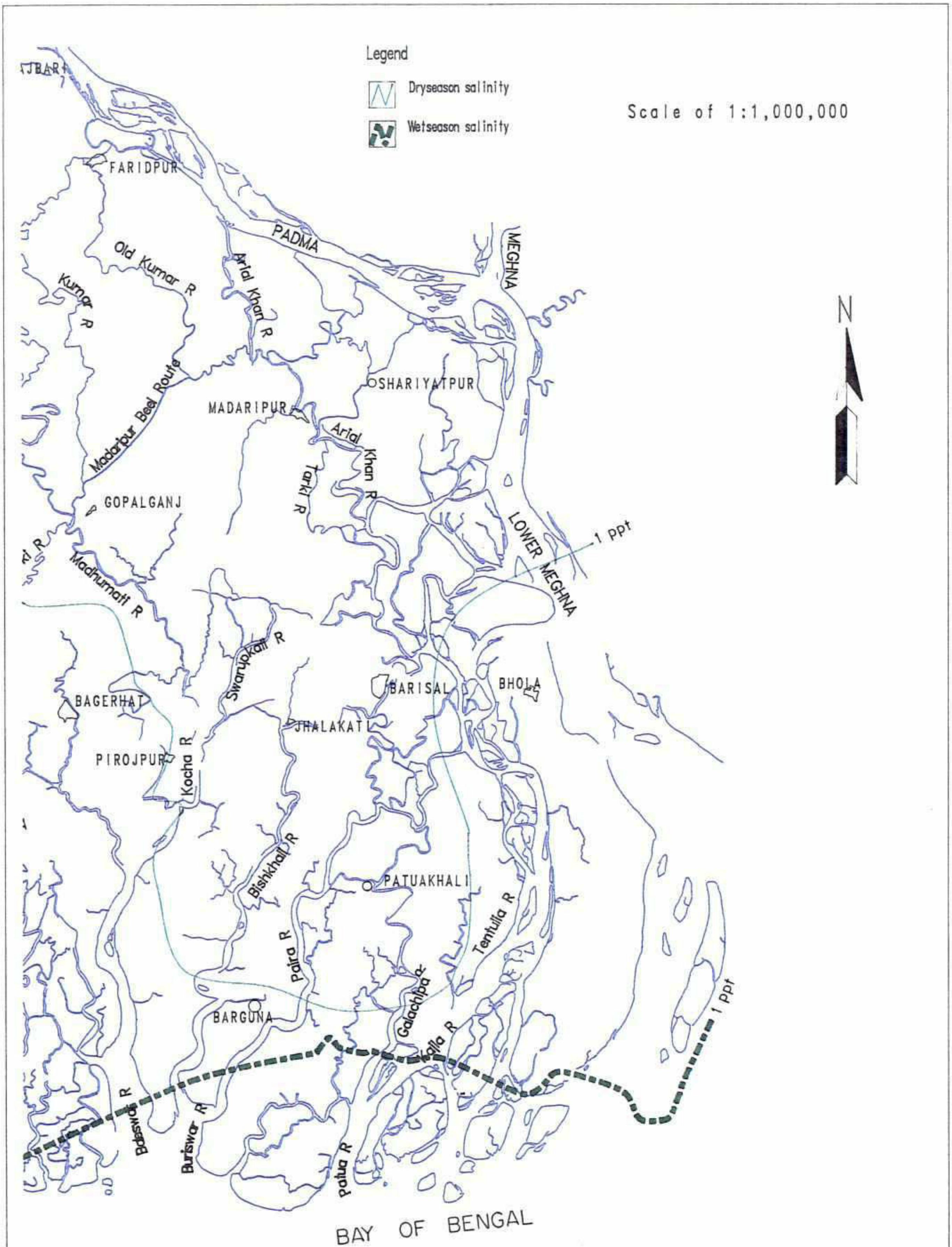
The main regional rivers are the Gorai-Madhumati, the Arial Khan and the tidal rivers of the South Central region which feed into the Baleswar, Bishkhali, Buriswar, Lohalia and Tetulia channels. These regional rivers play a key role in maintaining the health and vitality of the Area and detrimental changes must be guarded against.

The Gorai river is the only remaining major spill channel from the Ganges. The Gorai is important as it fulfills a number of functions such as salinity control, maintenance of a large tidal volume at the head of the Pussur-Sibsa system, and influencing the siltation rates in the tidal zone. The gradual decline of the Gorai that may be expected is thus of concern and is discussed further in Section 5.

The tidal areas of the Southwest are characterised by large estuaries such as the Pussur, Sibsa, Malancha and Raimangal/Hariabhanga (marking the border with India) which are interlinked by numerous smaller channels and are sustained by tidal spill, fresh water flows and differences in the time of tidal propagation which causes net flow from one estuary to another. The western part of the area is saline even during the monsoon season, whereas the central Pussur-Sibsa is fresh during the monsoon and increasinly saline at other times. The eastern rivers are fresh due to high net flow from the Meghna though there is limited saline intrusion at the coast. The Tetulia channel to the west of Bhola Island is dependant on the position of the saline front in the Meghna and can become more saline than desirable if the front moves above the top of the Island.

Major inland rivers such as the Nabaganga, Chandana, Chitra, Kumar, Kobadak and Bhairab serve as essential drainage channels that are generally at a lower level than the regional

Figure 2.3



Source: Mike11 Simulations by FAP 4 for April 1991

MEGHNA ESTUARY SALINITY LEVEL(WET & DRY SEASON) rivers. With the completion of the Ganges right embankment the spill flow from the main rivers has been controlled at inlet structures.

2.2 Morphological Changes

The region is in constant state of change and with the huge inputs of sediment to the area changes in the hydraulic equilibrium can result in large changes. The Bhubaneswar at Faridpur for example was a channel larger than the Gorai at the turn of the century but has now almost completely disappeared. The coast line of the South west however shows little change from the earliest mapping but it is apparent that the rivers that sustain the estuaries are declining. The size of the estuarial channels is determined by the tidal volumes and this has led other studies to conclude that the fresh water flows are not important (Farleigh 1984). This is certainly the case in the short term, as the part of the channel that is fluvial forms only a small part of the tidal volume. However in the longer term the interface where the size of channel changes from being determined by fluvial flows to tidal flows will inevitably move seaward causing the whole channel to decrease in size. This effect will be dependant on changes in the dominant flows of the fluvial river, but the timescale in which changes take place will depend on the sediment input and the environment for deposition such as whether the river is saline and the depositional characteristics of the sediment. The construction of Farakka to improve the western part of the delta in India and halt the decline of the Hooghly is therefore questionable in terms of geomorphic processes as the high channel forming discharges of the Bhagirathi have been reduced by a control dam. The knowledge base on such aspects of morphological changes is limited and recommendations for further applied study are made at the end of this report.

2.3 Regional Geology

The Bengal Basin or Himalayan Foredeep covers virtually the whole of Bangladesh. It is boundered to the west by Pre-Cambrian rocks of the Indian Shield and to the north by the Shillong block, comprising Pre-Cambrian basement with Cetaceous and Tertiary shelf sediments. In the north of the country, the E-W Dauki Zone (see Figure 2.4) separates the Shillong block from the subsiding Surma Basin to the south. To the east lies the N-S trending fold zones of the Neogene phase of the Indo-Burman orogeny.

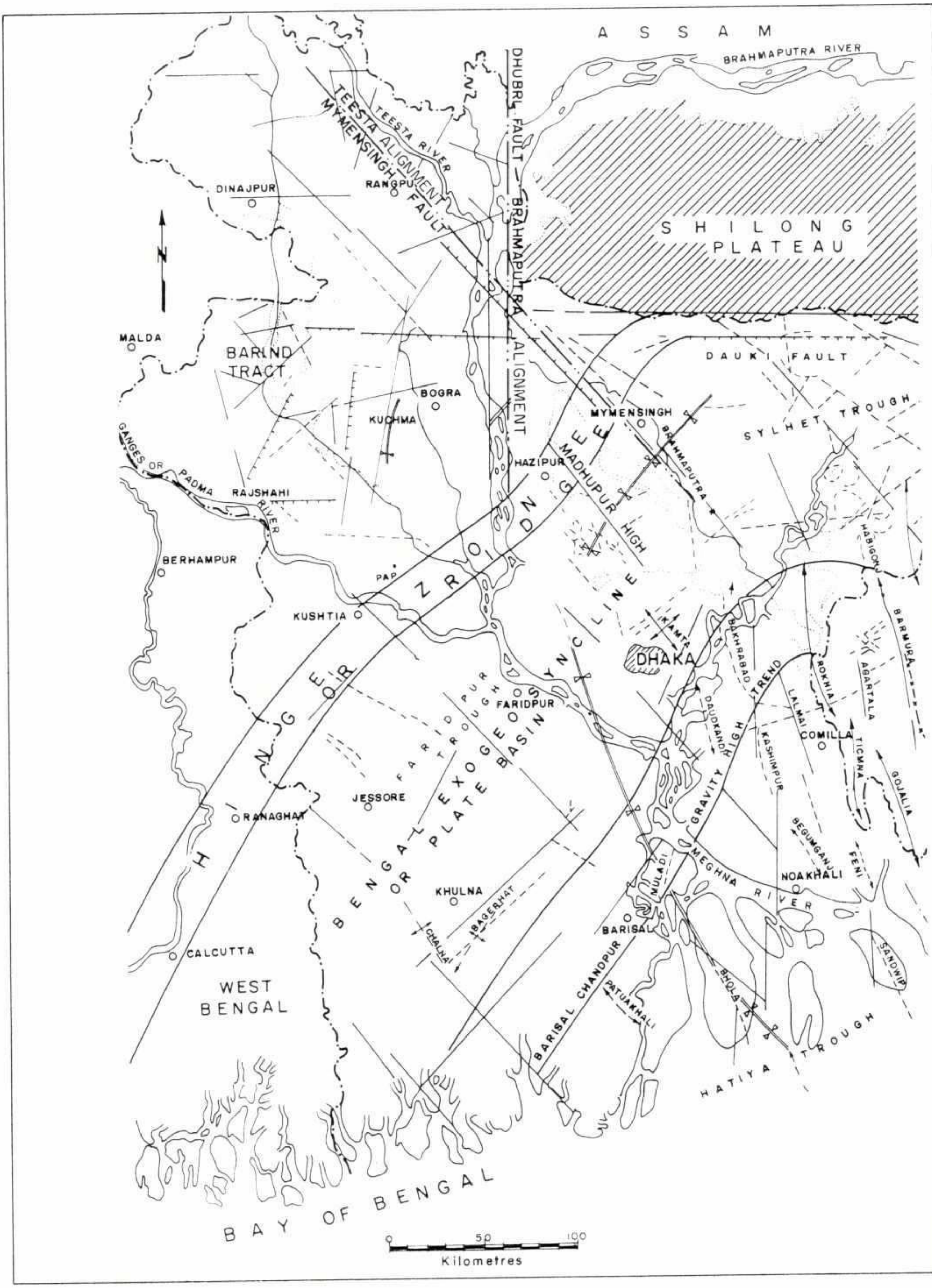
The Bengal Basin is sub-divided tectonically into two zones by the Eocene hinge line. To the NW is the shelf area and to the SE, the geosynclinal area (see Figure 2.4), with both areas having different stratigraphic histories. This sub-division has only been possible to make since the 1960s, after a considerable amount of data were collected during the exploration for hydrocarbons. While to the NW of the hinge line the area is relatively stable, to the SE the basin is deep and marked by a gravity high and magnetic anomalies some 25 km wide. The deeper area, or Bengal Foredeep, is divided into folded and non-folded areas with the division between them being marked by a NE-SW trending gravity high, known as the Barisal - Chandpur gravity high (see Figure 2.4).

The Bengal Basin is essentially a flat (1 in 15,000) Cetaceous - Eocene depositional centre, having been formed by the deltas of the Ganges, Brahmaputra and Meghna rivers and covers an area of some 60,000 km^2. Offshore, the Bengal Fan complex extends over 3000 km to the south and is the largest fan in the world (Curray and Moore, 1974).

The surface topography of the Quaternary deposits is very gentle, the highest elevation being 90 m at Tentulia. Some 75% of Bangladesh is below 29 m and 50% below 12.5m. The whole of the SW Area is below elevation 17m and 75% of the Region is below 5m (Figure 2.5). In the SW Area slopes vary from 1 in 6,000 in the north to 1 in 10,000 overall, reflecting the recent depositional history.

22

Figure 2.4



Structural Geological Map

The surface geology consists almost entirely of Quaternary sediments although there are some Tertiary deposits in the eastern fold belt. These latter deposits consist of sedimentary rocks ranging from Oligocene to Plio-Pleistocene in age and are found in the north and east of the Basin.

2.4 Structural History

The Bengal Basin forms part of the Indo-Australian Plate, which is moving NE beneath the Eurasian Plate, with the margins between the plates being identified by two subduction zones. The average rate of northerly drift of the Indo-Australian Plate is given as 80 mm/year since the Cretaceous period (Jhingran et al, 1982). The Bengal Basin evolved some 35 million years ago due to crustal extension and later, crustal collision, with the first phase being transgressive and the second broadly regressive.

The movement of the Plate has been considerable as has the movement of the main boundary thrusts which have been estimated to move at 10mm/year, based on geomorphic evidence. While such movements do not occur in the SW Region, they are important as the erosion and transport of sediment from these upland areas has resulted in the development of the deltas that form the Region.

Evidence of major crustal movement can also be seen in the Shillong block or plateau, which is an uplift block or horst and resulted from a horizontal movement of some 300 km along the Dauki fault (Evans, 1964). Some of the movement has been quite rapid with 2m to 3m being recorded after the Great Assam Earthquake in 1897 (Kailasam, 1975).

The eastern and north-eastern parts of the Bengal Basin have been subjected to more structural modifications than the western and southern parts. Indeed, nearly all the Quaternary faults and folds mapped lie north of the Ganges and Padma rivers.

2.5 Geology of the South West Area

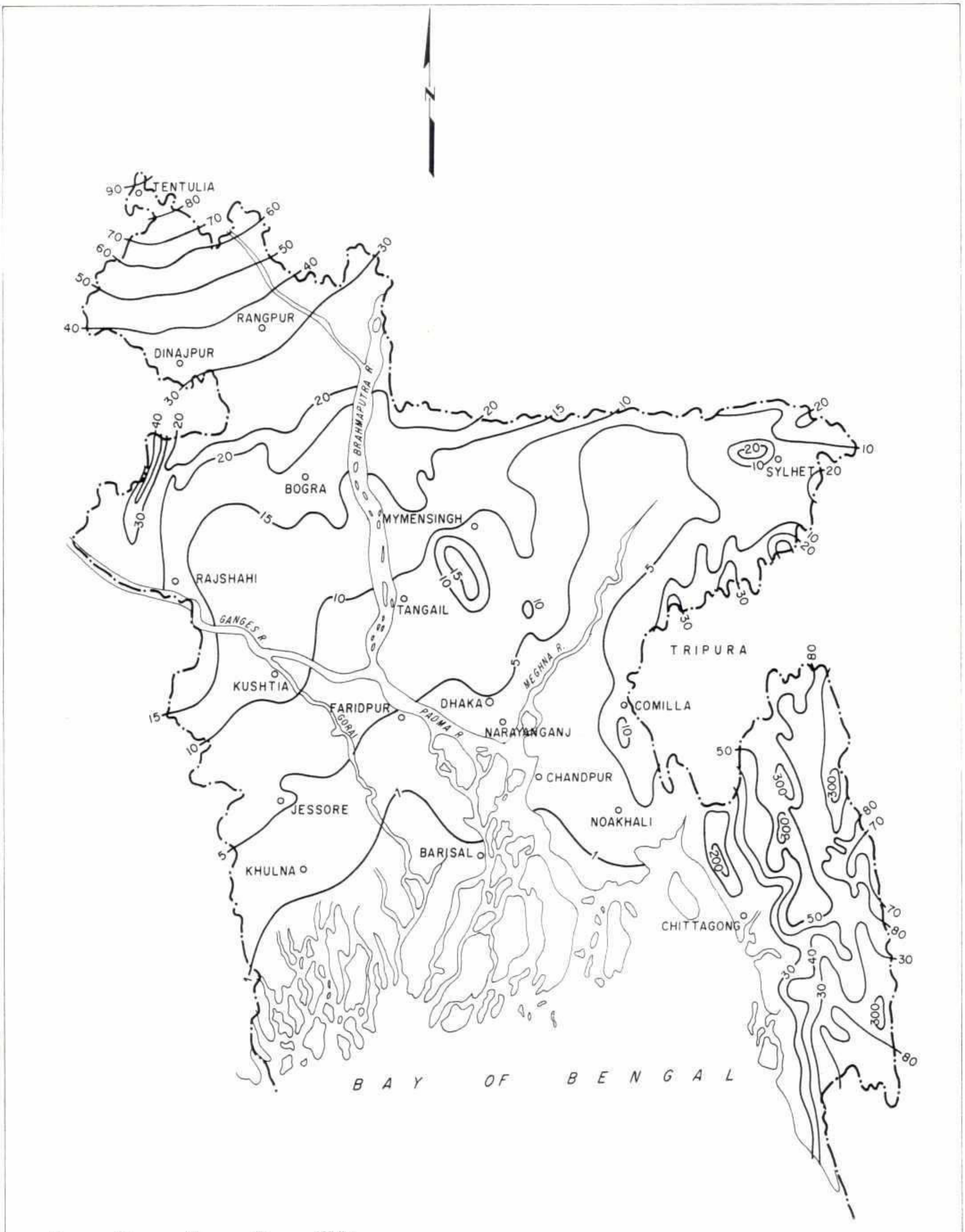
The Bengal Basin is a long established area of subsidence and deposition and contains an almost complete sequence from the Cretaceous to Recent alluvium. Investigations by deep boreholes and the results of Bouger anomaly and aeromagnetic anomaly mapping indicate that throughout the Basin the depth of sediment above the Pre-Cambrian basement is variable. For example in the east in the Meghna estuary it is over 12,000 m thick while in the west, in the Sundarbans it is 5,000 m, and at Khulna and Kushtia thicknesses are 8,500m and 6,500m, respectively. The general sequence in the Basin is as follows:

Recent	Alluvium
Pleistocene	Madhupur clay
Pliocene	Dupi Tila formation
Miocene	Surma formation
Oligocene	Bogra formation
Eocene	Sylhet limestone and Tura sandstone
Cretaceous	Rajmahal
Jurassic	Trap Basalt
Pre-Cambrian	Basement Gneiss

The Quaternary sediments in the SW Area consist of fresh water sands and silts and are intercolated with marine silts and clays. The intercolation is a reflection of crustal movement (transgression and regression) as well as recent Pleistocene changes in sea level. During such times, with sea level falls of up to 200 m, the rivers would have cut deeply into the Basin's relatively unconsolidated sediments and areas such as the "Swatch of No Ground" would have been developed.

24

Figure 2.5



Surface Contour Map

Since the beginning of this century there has been a general worldwide rise in mean sea level, equivalent to about 150mm/century. In many areas of the world the actual rise has been greater due to crustal downwarping and subsidence. As described earlier, subsidence in Bangladesh had been considerable although sedimentation of the deltas appears to have kept pace with the general relative rise in sea level. However, in recent years the rise in sea level appears to have been accelerating, firstly, due to generally warmer worldwide climate, which has increased the melting of the ice caps, and secondly, due to the warming of the ocean waters which has caused them to expand (IGC 1990). The predicted rise in sea level (ignoring subsidence) is thought to be of the order of 0.18m in the next forty years, with the rate accelerating in the next forty years. If this occurs, it will have a significant impact on the sediment distribution and deltaic deposition in the SW Area and affect drainage of the coastal areas.

The present distribution of surface sediments in the SW Area can be seen in Figure 2.6, which is based on the "Geological Map of Bangladesh" published in 1990. The map, compiled from LANDSAT Imagery and field data, indicates the presence of, in the main, fine grained deltaic deposits, which can be described as follows:

Alluvial Silt - This light to medium grey fine sandy to clayey silt is chiefly deposited in the flood basin and interstream areas, but it also includes backswamp deposits. As these areas are normally flooded annually, it contains lenses of sand and artefact between 500 and 6000 years old in the upper 4m. These deposits are only found on the left bank of the Ganges and Padma rivers.

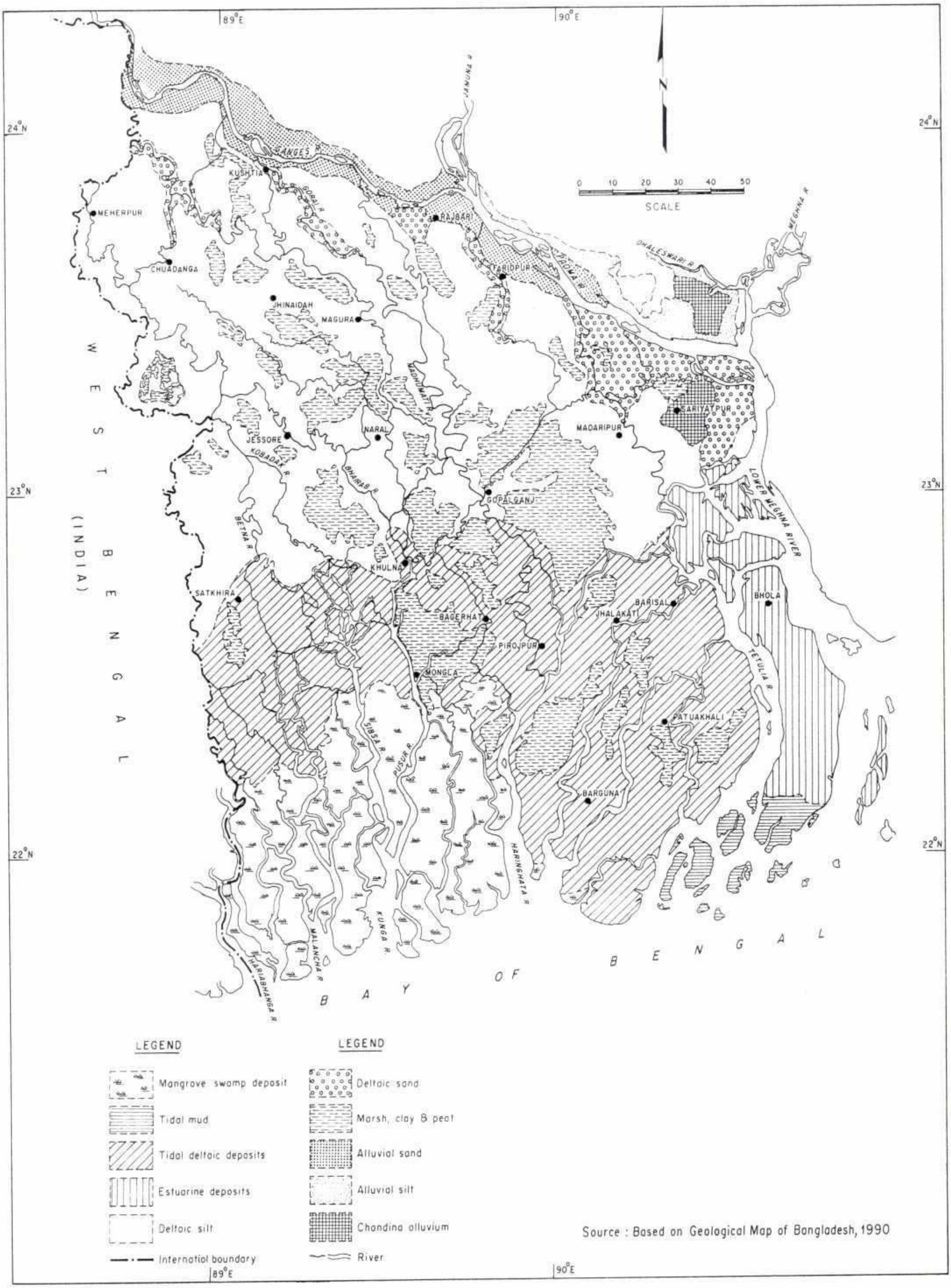
Alluvial Silt and Clay - This medium to dark grey silt to clay is a combination of alluvium and paludal deposits, including flood basin silts, sag ponds and large depression deposits. Again, these deposits are only found on the left bank of the Ganges and Padma rivers.

Alluvial Sand - This medium to fine light to brownish grey sand constitutes channel, bar and levee deposits in active rivers. The mineralogical sand contents are different in the Ganges and Brahmaputra, reflecting the rocks in their different source areas and historic pottery and artifacts are found in the upper 4m to 6m. These sands clearly identify the flood plains of the Ganges and Padma rivers and can be related to historic positions of the rivers. It is interesting to note that while the whole of the Ganges flood plain is represented by these deposits, in the Padma they are only found in the west and are not present at all in the Meghna.

Deltaic Sand - These light to yellowish grey fine to silty sands are deposited in channels and flood plains, including channel bars and point bars. They are found on the right bank of the Ganges and clearly identify existing and old offtakes from the river e.g. in the Mathabhanga, Gorai, Chandana and Old Kumar at Faridpur. It is not clear whether or not such deposits indicate the demise of the offtake, or are simply symptomatic of the sediment supply from the Ganges. Significant areas of these deposits are present on the right bank of the Padma and Meghna, commencing just upstream of the Arial Khan and extending southwards almost as far as Madaripur. While on the Ganges these sands represented channel deposits, on the Padma they are clearly flood plain deposits and start almost at the point where the alluvial sands (ad) of the narrower flood plain die away. Thus, the bank of the Padma in this area might be considered a very wide flood plain.

Deltaic Silt - These fine sandy to clayey silts, grey in colour, represent overbank and flood deposits. They cover almost the whole of the northern part of the region representing both moribund delta deposits in the west and more active deltaic deposits in the east. Morphologically they contain the remnants of many river

Figure 2.6



Surface Geology

courses, oxbows etc. In the extreme northwest of the Area, as far south as Kushtia, the deposits are mottled and may represent an older flood plain deposit.

Marsh Clay and Peat - These paludal deposits consist of grey to bluish grey clay, black peat and yellowish grey silts. Alternating beds of peat and peaty clay are common in the beels and large structurally controlled depression with the peat being thickest in the deeper parts. North of the Ganges/Padma, in the Sylhet basin, these areas are subsiding. In the north of the SW Area these deposits are scattered and though quite large appear to represent abandoned depressions in the now relic Ganges delta. Large areas, such as the Madaripur/Gopalganj beel and the beels near Khulna may also be relic depressions but may also, because of their size, be subsiding like those in the Sylhet basin.

Tidal Deltaic Deposits - These silts to clayey silts with lenses of fine sand are light to greenish grey in colour, but when weathered are yellowish grey. They contain some brackish water deposits and large areas are submerged during spring tides.

They constitute a band, some 50 km wide in the Khulna area, between the Deltaic Silts of the moribund Ganges delta and the Mangrove Swamp Deposits. As such their landward limit is coincident with the winter saline tidal limit and, if the area continues to subside or the sea level rises, their limit with move landward. The band is much wider in the south east of the Region, extending to the sea. In this latter area the deposits are similar to those of the Mangrove Swamp Deposits as, within recent history, this south eastern corner formed part of the Sundarbans.

Mangrove Swamp Deposits - These dark grey to black silts and clays are deposited in the active tidal zone and are dominated by the mangrove swamps. They are covered by as much as 1 m of brackish or saline water during normal tides.

Their presence is significant in that they can act as sediment traps (mainly of marine sediments) building up land levels, while at the same time protecting the hinterland from extreme storm (marine) events.

Estuarine Deposits - These silty clays to clayey silts are light grey to brownish to yellowish in colour, containing bedding and thin lenticular horizons of fine sand along channel edges, representing ephemeral levee deposits.

These deposits are only found in the Meghna estuary in areas which can undergo considerable changes in morphology. In general the estuarine islands, which are made up of these deposits, erode on their upstream end and accrete at their downstream end. These deposits are flanked in the north by Deltaic Sand Deposits and in the south by Tidal Muds.

Tidal Mud - These dark to bluish grey saturated silty clays contain shell fragments and scattered lenses of beach sand. This zone is defined by high and low water marks and represent areas of active accretion, at the downstream ends of the Meghna estuary islands.

Chandina Alluvium - This yellowish brown to redish grey silt to clay represents a more consolidated deposit than that in the active flood plain (asl and abc) with the upper 0.5m generally oxidised. These deposits are at an elevation of +4m and thus in general about 1m above the present normal flood level, but below the Tippera surface (Morgan and McIntire, 1959). The amount of uplift of the Tippera surface is not precisely known, but is thought to be of the order of 1m to 2m.

One outcrop of the Chandina Alluvium (ac) is present in the Area, in the north east corner around Shariatpur (see Figure 2.6). However, it is interesting to note that it is also present on the opposite left bank area of the Padma as well as further to the north in the vicinity of the old Brahmaputra river. Its presence in this latter area lends some weight to the theory regarding the connection between the diversion of the Brahmaputra into its present Jamuna course and seismic activity. Possibly, a local uplift of these relatively consolidated silts and clays, which are more resistant to erosion than the adjoining deposits (apart from Madhupur Clay), would have forced the Brahmaputra to take a more southerly route.

What is particularly interesting as far as the SW Area is concerned is that Chandina Alluvium occurs on the Padma right and left banks near its confluence with the Meghna. The presence of this material here could indicate that, prior to the Brahmaputra's re-direction and its capture of the Tsangpo river in Tibet, these deposits were joined and formed a bar to the flow of the Ganges, that consequently the Ganges tended to flow southwards, building its delta. Once the Brahmaputra diversion took place, the combined flow possibly assisted by subsidence, was sufficient to erode the Chandina Alluvium and this allowed the Ganges to abandon its old deltas and join the Meghna river. If this theory is correct, the area must have been relatively stable in recent years, but undoubtedly subsidence was and is taking place in the Meghna estuary to seaward ie in the Bengal Fan and Hattia Trough.

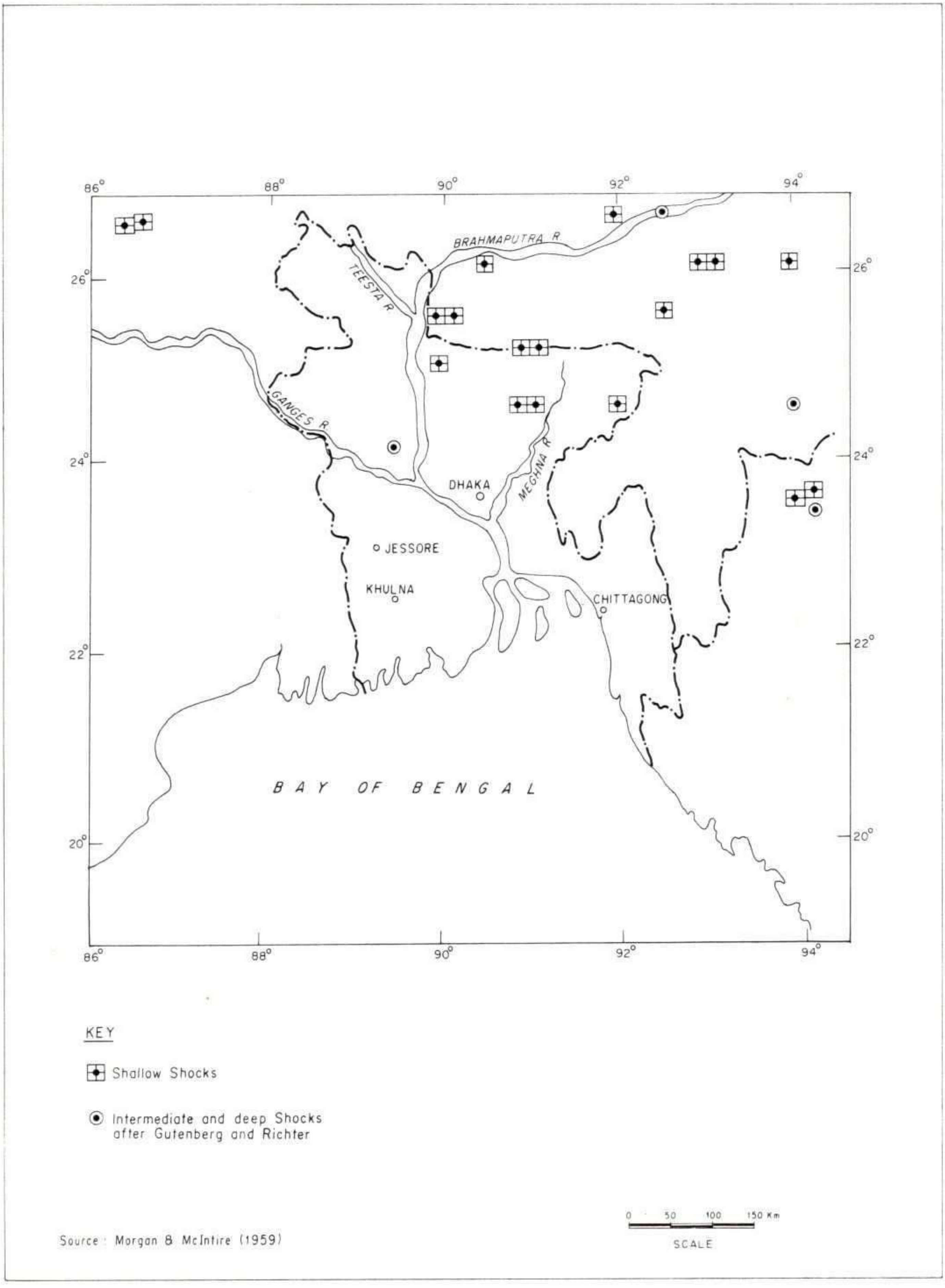
Examination of the satellite images, old maps and aerial photographs indicates the Chandina Alluvial deposit to be stable and relatively resistant to erosion from both the Padma and Meghna rivers. The elevation of these deposits at Shariatpur is about the same as those on the left bank of the Padma and the left bank of the Meghna (see Figure 2.6).

2.6 Seismic Events

There appear to be two distinct populations of seismic event, very large, disasterous earthquakes such as those in 1897, 1934 and 1950 and the smaller, more frequent events. The latter appear to be much more frequent north of the Himalayan mountain front, while the former are usually travel south of the front (Seeber, 1981). Catastrophic earthquakes in 1762 and 1782 are believed in part to have been responsible for the diversion of the Old Brahmaputra river to its present, Jamuna course and the Ganges river from the Arial Khan line to the present Padma Channel (Morgan and McIntire, 1959). Earthquakes and their associated crustal movement might also have assisted in the changes seen in the Teesta River's course. It is also claimed by Fergusson (1863) that, at the time up to the Brahmaputra diversion, the Ganges was fordable in several places upstream of the junction. This may have been because a significant proportion of the flow was diverted into the Gorai or other upstream distributories. It could also mean there was some structural movement in the SW Area, but this seems unlikely.

Figure 2.7 shows a map of epicenters in the vicinity of the Bengal Basin since 1900. These data indicate that the recent seismic activity in the area is almost coincident with that of the Quaternary faults and folds and thus lie to the north of the Ganges and Padma rivers. It is interesting to note that since 1900, while the size of the seismic events have been variable, most of them have been relatively shallow, which is to be expected. Since 1860 there have been over 20 shallow and intermediate earthquake events, the most significant of which occurred in January 1869, July 1885, July 1897, July 1918, July 1930, January 1934 and August 1950. It is notable that most of these earthquakes occurred during the Monsoon season at time of a relatively high water table.

The most obvious effect of seismic events is the impact of the energy being released. However, the July 1897 earthquake in the Rangpur area had a significant impact in addition to the loss of property and life. Ground movements caused major fissuring, up to 3m wide



Source: Morgan & McIntire (1959)

Map of Eathquake Epicentres Since 1900

and 1 km in length, the beds of many streams were changed and the Teesta and Ghoghat rivers became fordable. Relatively high areas, difficult to irrigate, were created as well as low marshy zones. Thus, the morphology, hydrology and agriculture were affected over large areas.

In the Chittagong earthquake in April 1762 large areas of land were submerged while other areas were raised. What was particularly significant as far as the SW Area is concerned, is that the earthquake also generated a tidal wave (tsunami) which caused deaths in Dhaka and must have swept through the rivers in the Area.

As such the SW Area can be considered a zone with a relatively low risk of seismic activity and rapid crustal movement (Figure 2.8). According to the MPO Report (1986) risk zoning puts the entire SW Area into the Zone III - Low Risk Class.

It is unlikely that seismic events would have a direct impact within the area, but could significantly influence the Boundary Rivers i.e. Ganges, Padma and Meghna. Tsunamis could also affect the area, but their impact would be temporary.

2.7 Recent Crustal Movement

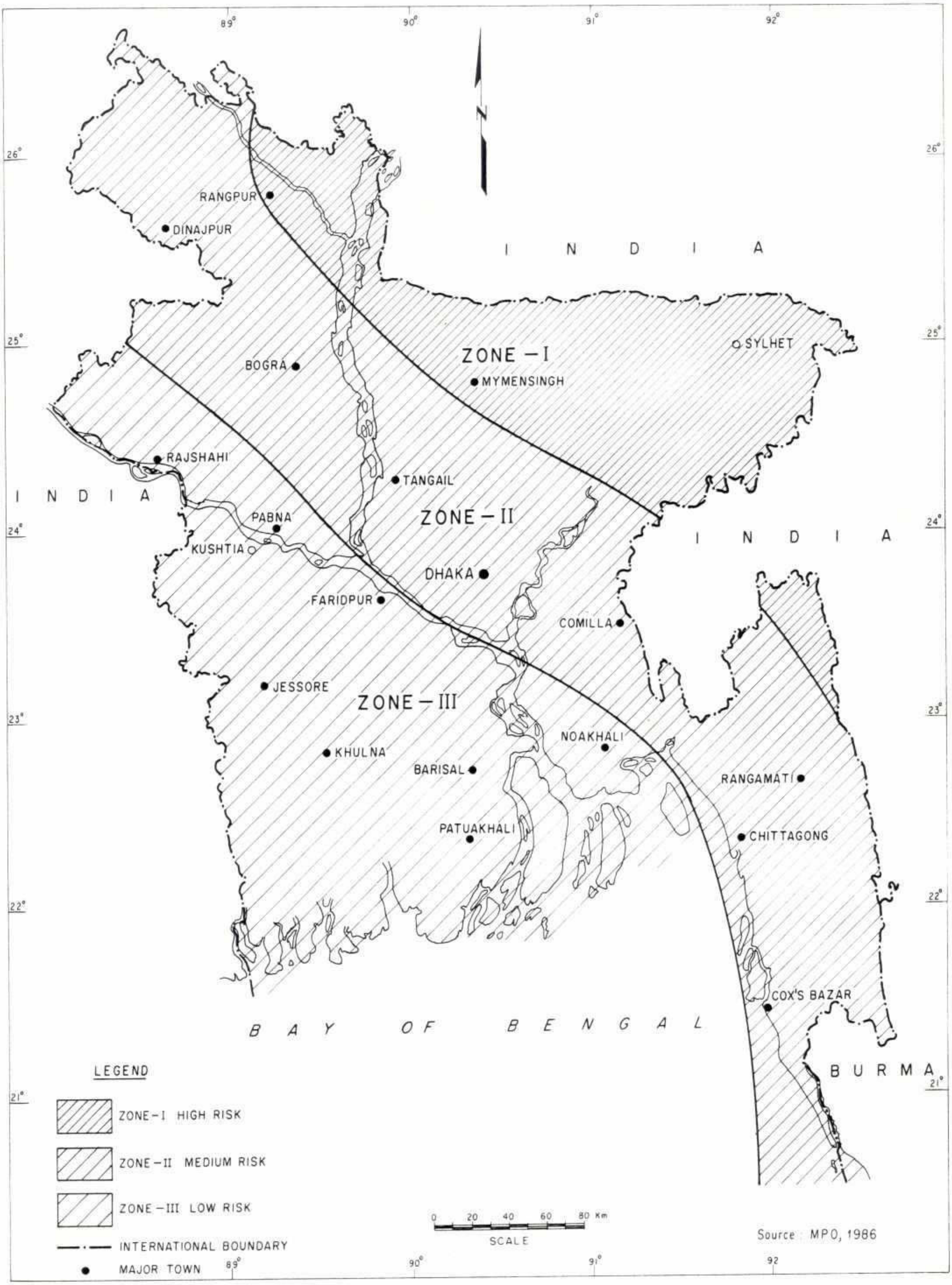
Geological and geomorphic studies together with seismic, geophysical, gravity and magnetic data indicate that the late Pliocene - Pleistocene orogenic movement is continuing. There are clear indications that parts of the Bengal Basin have been uplifted while other areas have been subsiding since the Pliocene, some 7 millions years ago (Figure 2.9).

Examples of areas of uplift are the Barind Tract and the older Madhupur Jungle, which has also tilted and, as has been described earlier, exhibit areas of surface faulting and, in general, shows seismic activity. These areas lie on either side of the so-called Hinge zone which actually appears to be more of a ridge (see Figure 2.5) but, in general south of this zone there has been subsidence, certainly in the Hatiya Trough in the mouth of the Meghna and possibly in the Faridpur Trough.

The deltaic region of the Basin is thought to be constantly subsiding due to crustal downwarping and the compaction of recent sediments e.g. the Faridpur Beel. Within the SW Area the presence of peat and wood at depth, according to Morgan and Mc Intire, 1959, indicate subsidence at Khulna of between 1mm and 5mm annually, with rates of between 0.75mm and 1.4mm annually in the Sundarbans. However, it is not known whether or not at least some of these organic deposits were associated with the lower Pleistocene sea levels and the 3m tidal range in the area.

Recent work on the detailed geology of Pleistocene and post-pleistocene soils, including radio-carbon dating, has been carried out by Umitsu (1991). Based on variations in soil strength, grain size characteristics etc in subdivides the sediments in the Region into five members namely, uppermost, upper, middle, lower and lowest. As can be seen on Figure 2.7, the boundaries are marked by changes in lithology and that between the lower and middle members is marked by a weathered surface and a sharp change in lithology, representing a period of marine regression. He correlates the boreholes at Khulna (Daulatpur) with ones in Faridpur and Barisal and, while between Khulna and Faridpur, the slope is consistent with present day ground elevations, it is steeper between Khulna and Barisal. Also, while ground levels are higher at Barisal, the uppermost member is twice as thick as that at Khulna (12m compared with 6m). Thus, Barisal appears to be an actively accreting area which is subsiding, while Khulna and Faridpur appear moribund.

Figure 2.8



Earthquake Risk Zones

Figure 2.9

NOTES:

- Contours based upon Bouger isostatic anomolies, integrated with sedimentation/erosion rates of last 1000 years.
- Contours in mm/yr.

Source : Bangladesh Geological Survey

Neotectonic Map of Bangladesh

The shells identified in the Khulna borehole at depths of 20m and 35m lived in the tidal zone and clearly at the time of this deposition, say 7000 and 9000 year before present (BP), the sea penetrated a considerable distance north of its present position. Figure 2.10 also shows the sea level rise against time using radio-carbon dating, the results from which are variable. Apart from a regression around 12,000 BP the rise in sea level has been regular and, as seen elsewhere in the world (Maddrell, 1990), the rate of rise reduced in the last few thousand years. Care should be taken when interpreting these results as the tidal range in this area is between 3m and 4m (maximum), elevations would have been low and slopes flat. Thus, radio-carbon dates could come from a range of depths, commensurate with the tidal range.

The results from these boreholes tend to confirm the impression that while the western side of the region is relatively stable, the south eastern corner is an actively accreting sedimentary area that is subsiding.

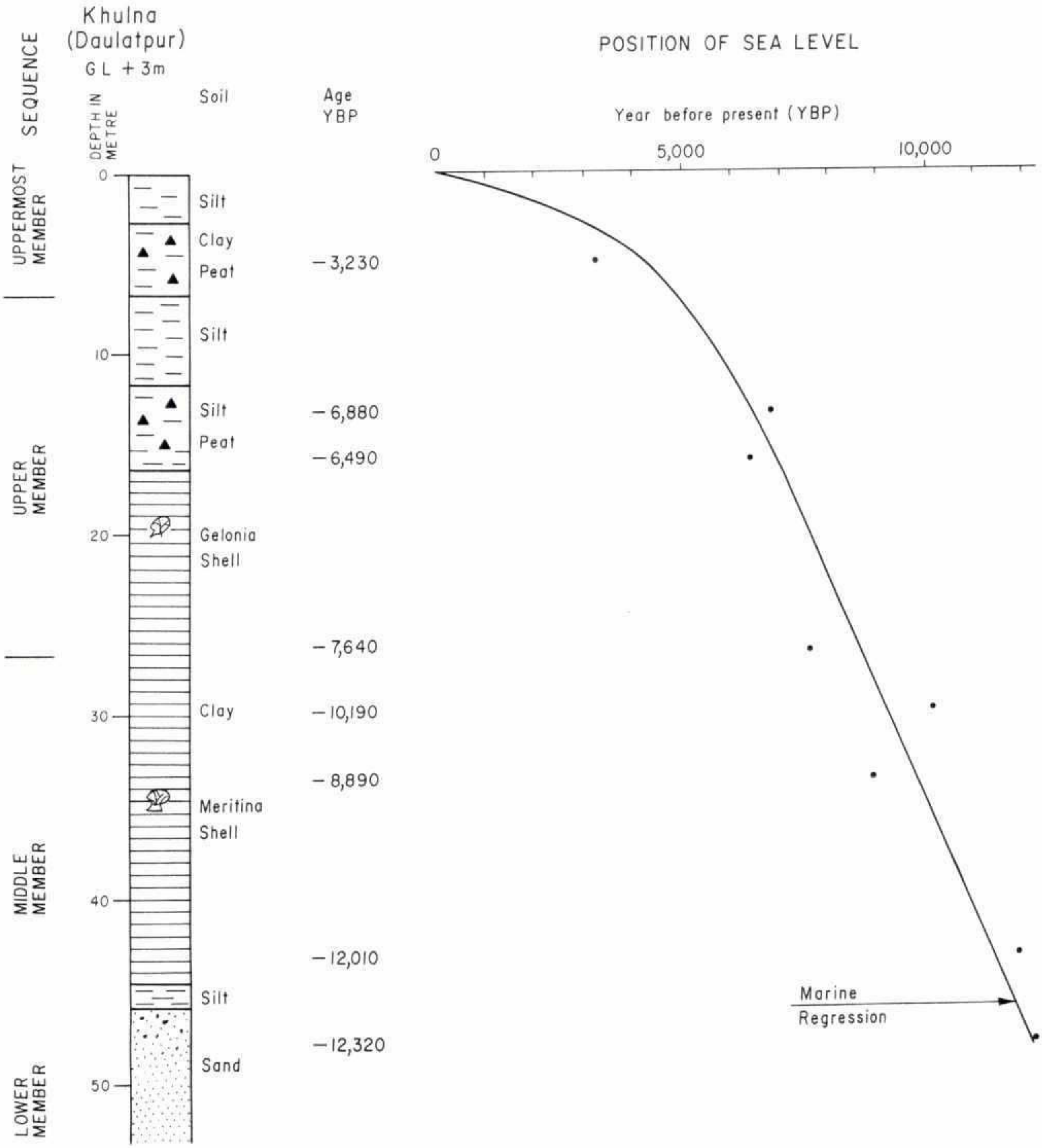
2.8 History of the Ganges Delta

The Ganges was probably the first river to break through the Indian Shield (Khan, 1990), possibly during the Pleistocene upheaval as a result of faulting. Thus, during and towards the end of Pleistocene, the Ganges and its tributaries were building deltas to the west of Calcutta. As these deltas grew, the delta front and thus the course of the Ganges gradually migrated eastward. The Ganges appears then to have built a delta in the Jessore area, while extending it later into the Sundarbans (Master Plan Organisation, 1985). At this time, the early Meghna and Brahmaputra rivers would have built their delta to the east, in the Barisal region and now, in combination with the Ganges, they are maintaining the present active delta (Figure 2.11) in the Barisal-Hatiya region.

Sometime in the 15th or 16th century the river swung eastwards to follow a line of multiple faults along the Rajmahal Hills and Dinajpur Shield. At this time the Ganges probably followed a course close to the present Gorai River, and its former main course along the Bagirathi - Hoogly system was reduced to the status of a right bank distributary. At this time a number of formerly left bank spill channels became right bank distributaries. Indeed, it is suggested by Addams Williams (1919) that during the time when the Ganges channel was in the area of the Hoogly, it had a major left bank tributary which flowed through the SW Region. He suggest that this was the Bhairab and that present day rivers such as the Kobadak, Chitra and Nabaganga were tributaries of it. He also suggests that the development of the Bhairab was in part controlled by older, more consolidated delta silts in the Kushtia area (the presence of older estuarine silts is described in Section 2.5 and their distribution may explain the narrowness of the river section in the area of Hardinge Bridge). The movement of the Ganges eastwards in the 15th or 16th centuries was to the north of the Bhairab converting it from a left to, a right bank distributary. The Bhairab appears from the early maps and Satellite imagery to have rapidly become moribund as did its tributaries. These old tributaries are now simply internal rivers, which have been dissected by newer Ganges offtakes such as the Mathabanga, Chandana and now the Gorai.

The Ganges continued to migrate eastwards and by the mid-eighteenth century it entered the sea close to the present Arial Khan. Up until this time it had no confluence with either the Brahmaputra or Meghna Rivers, both of which flowed into the north-eastern part of the Bay of Bengal. However in 1762 and 1782 major earthquakes occured and, following a particularly large flood in 1787, the Teesta, a major left bank tributary, was diverted to the east and confluenced with the Brahmaputra rather than the Ganges. A few years later the Brahmaputra itself avulsed westwards to meet the Ganges near Goalanda and form a very large combined river, the Padma. This change seems to have taken place over decades rather than years, but was essentially complete by about 1830. The last major change

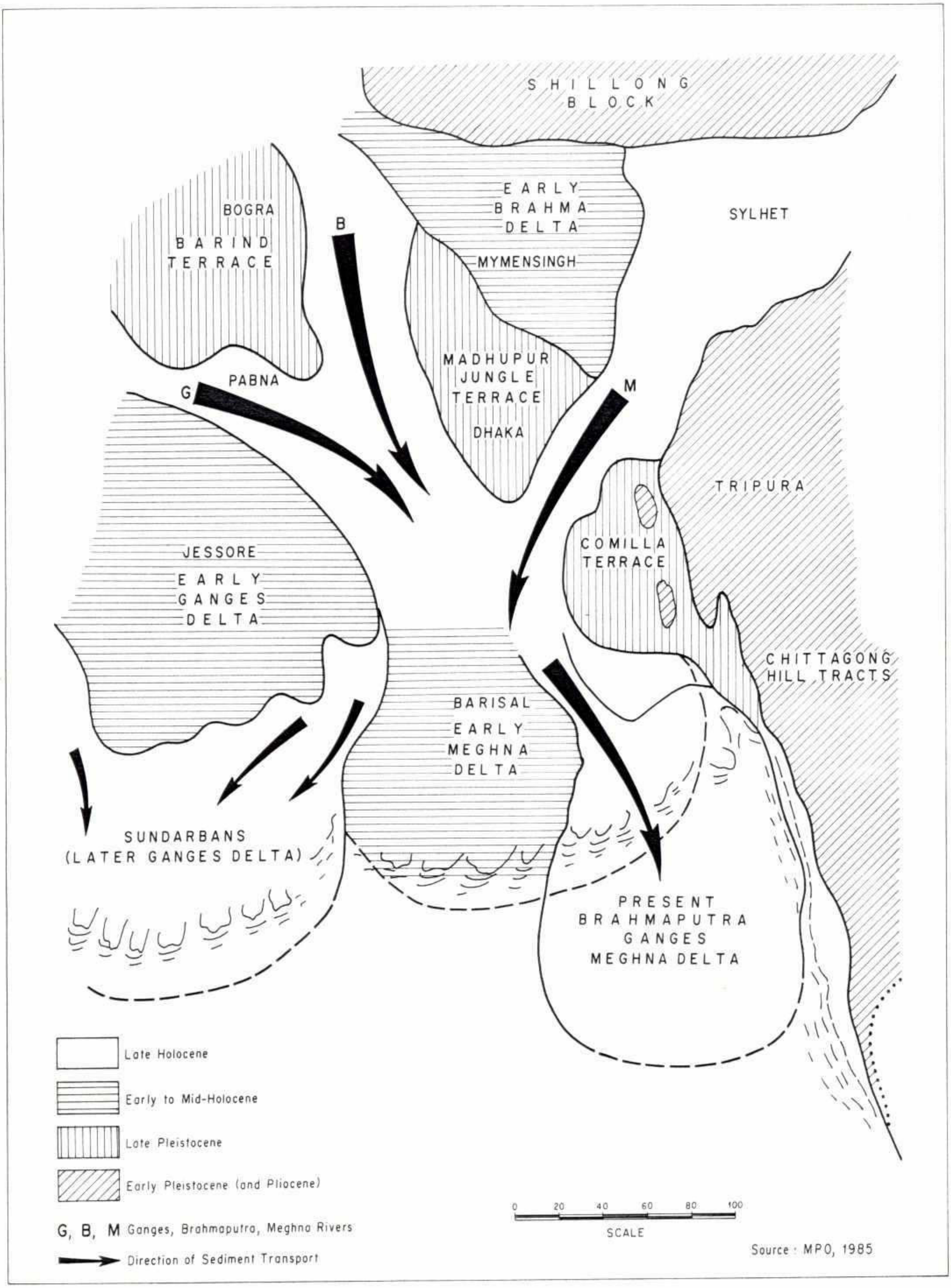
Figure 2.10



Source : Umitsu (1991)

Sedimentary Sequence and Position of Sea Level

Figure 2.11



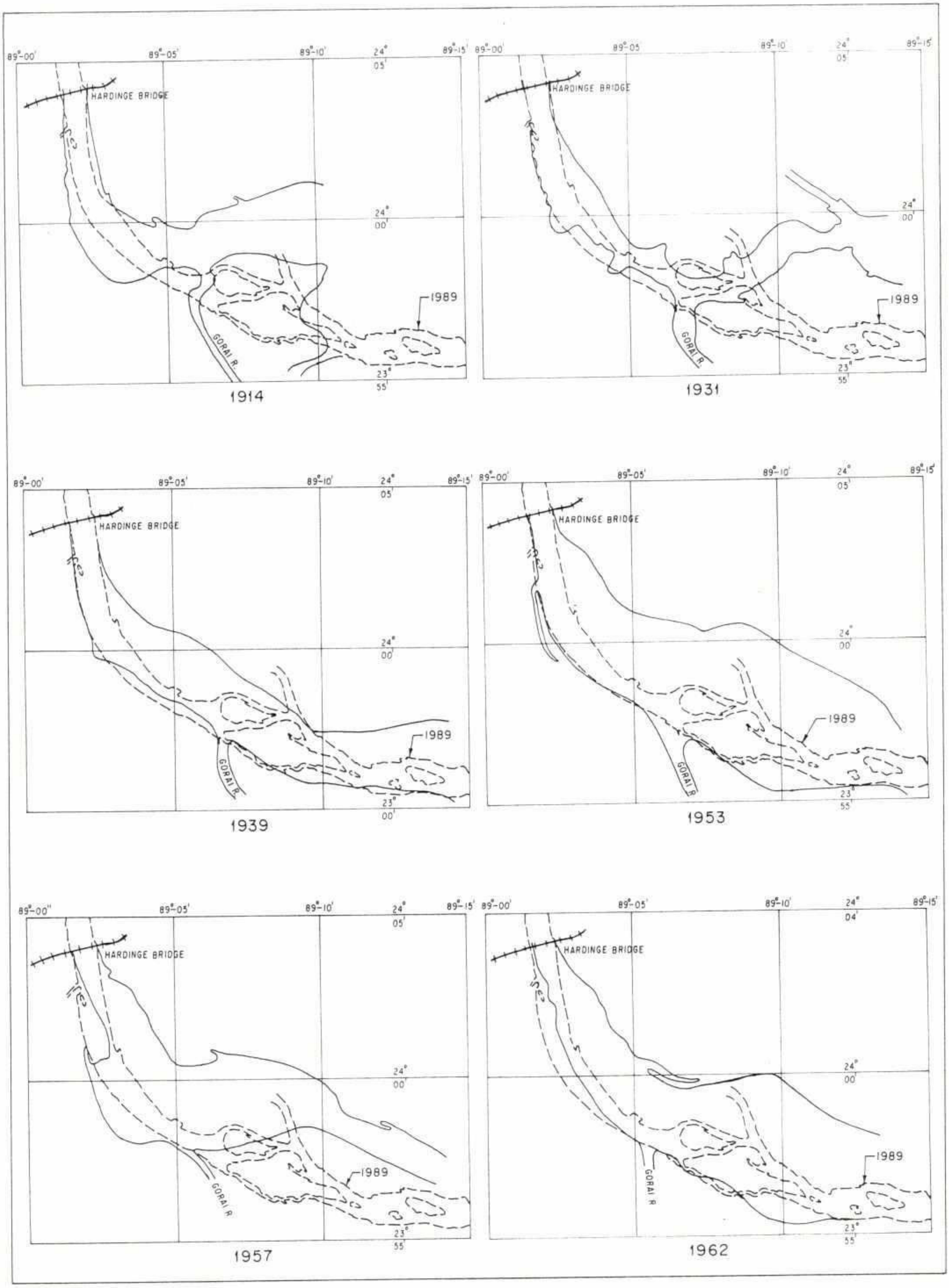
Development of the Ganges Delta

followed shortly when the combined flows of the Ganges and Brahmaputra broke through a strip of resistant Chandina Alluvium to form a confluence with the Meghna. For the first time the three great rivers entered the Bay of Bengal together - the situation which still prevails today. It is this sequence of events in the building of the Ganges delta which sets the context for the present studies of regional and inland rivers in the Southwest Area. Any considerations of water resources management and proposals for river and coastal engineering must bear in mind the dynamic nature of the great rivers which have built and now bound the Southwest Area.

After the diversion of the Brahmaputra in the early 1800s, Fergusson (1863) postulated that the Ganges was forced to develop a branch on a more southerly route. He claims that it was not possible for the Ganges' flows to develop the Chandana or Kumar (Coomar) rivers as they were small, old, their banks were well consolidated and they contained numerous meanders. Consequently, the Gorai, which was then apparently a small local river draining some beels was developed as a major distributary. He also suggests that, as a consequence of the diversion of the Brahmaputra, there would have been a significant backwater effect in the Ganges, raising levels by 0.7m to 1m at the mouth of the Gorai; the bed gradient of the Ganges at that time being 1 in 5.2×10^{-5}. This explanation does not seem correct as Rennell's 1760 map shows the Gorai as already being a significant river, though draining into beels to the NE of Khulna. The Gorai did, however, develop and in 1828 its mouth was 183m wide. By 1863 it had widened to 580m. A survey carried out in May 1992 as part of this study indicates that the mouth is now over 1 km wide though its channel width is about 0.5 km. The Gorai remained the major right bank distributary throughout the 1800s and into the twentieth century. When engineers came to bridge the Ganges at Sara, just upstream of the Gorai offtake in 1910, they noted that the Gorai was 'an important offshoot' but that the distributaries to the west, the Nadia rivers including the 'Bhagirathi, Jalangi and Matabhanga' were diminishing. At that time a Government inquiry into silting of the Nadia rivers (which fed the Hoogly) was undertaken, while in contrast the Gorai was "increasing its size owing to a change in the main river and the establishment of a fresh offtake" (Gales, 1917).

The strength of the Gorai in the early 1900s was attributed both to its development of a new mouth and also to the location of that mouth on the outside of a main bend of the Ganges. However, this situation was not permanent as not only does the Ganges sweep back and forth across its meander belt, but also there appears to be a finite life to the mouth of any offtake. Writing in 1919, Addams Williams noted the stages in the development and eventual demise of right bank offtakes of the Ganges. He observed that after sometime in one location, "the offtake becomes of a funnel shape, being abnormally wide at the mouth and rapidly decreasing width inside : in addition, the direction of flow of the water is rapidly changed, leading to a loss in the velocity and therefore in almost every case a bar of considerable dimensions is thrown down in the mouth and cuts off the supply in the dry season". Addams Williams' account of the demise of some offtakes to the west also predicted the fate of the Gorai in the second half of the twentieth century. The survey of the mouth in 1992 shows it has become very funnel shaped, a bar has grown and the dry season flow has diminished to zero. This suggests that the current state of the Gorai can be linked to natural processes that have been operating for centuries. Figure 2.12 shows that in 1953 the Gorai's mouth had a similar shape to that seen in the 1992 survey. The shape of the entrance appears to be controlled by the bank position of the Ganges and its position, in relation to that bend in 1953 and 1992, suggests that it could attract significant quantities of bed load from the Ganges. If this were the case then the entrance could become blocked by bars. This explanation is supported by the fact that there were no recorded winter flows in the Gorai in 1952/53.

Figure 2.12



Bankline Movement of Ganges Near Kushtia 1914-1962

(ii) Marine Delta

The influence of the tidal zones of the SW area are extremely important in the creation of the delta's morphology and in predicting future changes. Tidal waters are important in that they generate relatively high velocities which transport sediment as well as introducing sediment along the seaward boundary.

During and after the period when the Ganges broke through the Indian Shield i.e. during the Pleistocene, deltas were being created in an easterly direction in response to fluctuating Pleistocene sea levels. As described in the previous Section the present fluvial deltaic area of the Ganges was being created by a series of left bank and later right bank tributaries, which would have discharged into the sea. Consequently there would have been tidal channels similar to those seen today with over bank flow of sediment laden water and thus the gradual accretion of fluvial and marine sediments on the delta. This would have occurred even without the Sundarbans which act a efficient sediment traps. The amount of bank overflow controls the quantity of water in the channel and thus its size.

The gradual rise in delta land levels caused by tidal action would not be even, as more sediment (mainly silt) would tend to be deposited closer to the channels, so producing natural levees. Eventually, the channels would break through to the lower areas leaving the old channel to accrete. According to Addams Williams (1919) moribund ridges associated with old tidal channels were apparent in the delta. While the amount of movement seen in the tidal rivers would be partly dependent on the vegetation on the delta flats (which could stabilise the channel banks) tidal spillage would gradually diminish as land levels were raised. The net effect of this reduction would be to increase the bed level of the channel and thus of the tidal levels, ensuring continuous though decreasing rates of accretion in the landward tidal areas. As the delta built out, channel width decreased and the flow resistance in the channels increased, tidal penetration would reach its limit and, if there was significant fluvial accretion to landward, the tidal area would be pushed back. It is claimed that some 500 years ago Jessore was on the sea face (see Addams Wlilliams, 1919) and, while this sounds improbable, it may indicate that the whole area was tidal, much as Khulna is today. If this is the case, the tidal front has moved seawards since that time.

2.9 Conclusions

The Bengal Plate has been an active geological area for many millions of years and is still active. The SW Area lies to the south of the so called Hinge Zone and thus in an area of general subsidence.

To the north of the rivers that form the north eastern boundary of the SW Area, ie Ganges and Padma, older surface deposits illustrate active faults, which appear to be associated with recent seismic activity. The very active crustal movements, while not affecting the SW Area directly, can and do influence the Boundary Rivers and thus have a significant though indirect effect on its development.

While the SW Area appears to lie in a general area of subsidence, subsidence appears to be greatest in the east and southeast of the Area. This may in part explain why the Ganges has gradually moved northwards and eastwards, joining the Brahmaputra to become the Padma and then breaking into through the Chandina Alluvium and into the Meghna south of Dhaka.

The depth of sediment above the Pre-Cambrian basement appears to be greatest in the east rather than the west of the Area. This may help to explain the differences in subsidence rates, the presence of moribund and active deltas and the movement of the Ganges.

Sediments in the Area consist of freshwater sands, silts and clays intercolated at depth with marine silts and clays. Surface deposits are variable with the alluvial sands of the Ganges flood plain being replaced by deltaic sands in the eastern area of the Padma but west of its junction with the Meghna. Most of the moribund delta deposits consist of deltaic silts, which pass into tidal deltaic deposits and then mangrove swamp deposits adjacent to the coast south of Khulna. Where the Sundarbans have been removed by humankind, mangrove deposits have become tidal deltaic deposits.

Marsh clay deposits are present in pockets throughout the Area, but in the north are smaller, representing lower areas in the moribund delta. Deposits in the Meghna estuary consist in the main of estuarine deposits with accreting tidal muds at the seaward ends of the Islands.

The presence of Chandina Alluvium at the mouth of the Padma where it joins the Meghna is thought to have influenced the development of the Ganges. Its presence in the north, assisted by seismic activity and structural movement, may have influenced the re-routing of the Brahmaputra some 200 years ago. These deposits are also thought to have controlled the distribution of the deltaic sands on the right bank of the Padma and the present course of the Padma.

The present fluvial portion of the SW area delta is thought to have formed over 500 years ago, but contains older delta deposits. The area has been reworked and partially dissected by right bank offtakes of the Ganges such as the Gorai.

The Gorai's development from a stream into a river might possibly have been the direct result of the diversion of the Brahmaputra and its joining with the Ganges. The Gorai has been a major offshoot of the Ganges for nearly 150 years, but recent morphological changes such as its increasing sinuosity indicate that its importance is diminishing.

The influence of tidal action on the creation and maintenance of the land in the SW Area has been and will continue to be critical. The delta appears to have kept pace with sea level rise and subsidence and actually advanced in recent times in the active delta areas.

3 DATA COLLECTION AND FIELD SURVEYS

3.1 Hydrological Data

The flow and rating curve data available covered 140 stations as shown in Table 3.1. The available data on sediment flux was more limited covering only the Ganges, Gorai and Padma. The more recent sediment flux data was not consistent with earlier data and in line with SWMC the earlier data of 1966-1971 was taken to be more reliable for deriving sediment rating curves. Because of its critical importance to the study, the flowrates in the Ganges at Hardinge Bridge was extended to from 1934 to 1992 as the study progressed and the Gorai flows from 1946 to 1991.

3.2 Historical Mapping and Aerial Photography

Historical maps of the area at various scales were obtained from the British Library in London covering various parts from 1779 to 1942. These were supplied on high quality humidity stable sheets in a form suitable for quantitative analysis. A summary of the maps obtained is given in Table 3.2. Other more recent mapping of the area was obtained in Bangladesh. A set of aerial photographs of the area was obtained for 1983. The Gorai mouth area was unavailable as it is classified. The photographs give better detail than the satellite imagery but because they are not geographically registered they are time consuming to use for quantitative comparisons. Selected parts of the mapping was digitised onto the project GIS system enabling accurate comparison of changes in the course of the major rivers.

Special studies of the Ganges between Farakka and the Gorai were also completed by BWDB and the comparisons presented were used in early studies.

Table 3.1

List of Hydrometric Stations

Sl.No.	Stn.No.	Station Name
1	1	Alipur Khal, Daratana-Ghasiakhali at Bagerhat
2	2	Alipur Khal, Daratana-Ghasiakhali at Kumarkhali
3	3	Anderson Khal at Brahmanbaria Railway Bridge
4	3 A	Anderson Khal at Brahmanbaria Railway Bridge
5	4	Arial Khan River at Kalikapur
6	4 A	Arial Khan River at Arial Khan
7	5	Arial Khan River at Madaripur
8	6	Bahia River at Surma Offtake
9	18	Barisal-Buriswar River at Barisal
10	18.1	Barisal-Buriswar River at Bakerganj
11	19	Barisal-Buriswar River at Mirzaganj
12	20	Barisal-Buriswar River at Astali
13	21	Begabati River at Arpara
14	22	Betna - Kholpetua River at Navaran
15	23	Betna - Kholpetua River at Kalaroa
16	24	Betna - Kholpetua River at Benerpota
17	25	Betna - Kholpetua River at Chapra
18	26	Betna - Kholpetua River at Pratabnagar
19	28	Bhadra River at Dumuria
20	29	Bhadra River at Suterkhali
21	30	Bhairab River (Lower) at Afraghat
22	31	Bhairab River (Lower) at Gilatala
23	37	Biskhali River at Jhalakati
24	38	Biskhali River at Basna
25	39	Biskhali River at Patharghata
26	50.6	Brahmaputra-Jamuna River at Teota
27	51	Chandana River/Arkandi Khal at Ramdia
28	51 A	Chandana River at Chandana Rwy. Bridge
29	52	Chandana River/Arkandi Khal at Ghoshpur
30	54	Chitra River at Kaliganj
31	55	Chitra River at Khatursagura
32	55 A	Chitra River at Ratnerdanga
33	56	Chitra River at Gobrahat
34	56.1	Chitra River at Narail (road crossing)
35	89.5	Ganges River at Golapnagar
36	89.9 L	Ganges River at Paksey Transit
37	90	Ganges River at Hardinge Bridge
38	91	Ganges River at Talbaria
39	91.1	Ganges River at Sengram
40	91.2	Ganges River at Mahandrapur
41	91.7 L	Ganges River at Teota
42	91.7 R	Ganges River at Urakanda
43	91.9 L	Ganges River at Baroria Transit
44	91.9 R	Ganges River at Goalundo Transit
45	92	Ganges River at Goalundo
46	92.3 L	Ganges River at Kadamtali

Contd....

Table 3.1

List of Hydrometric Stations

Sl.No.	Stn.No.	Station Name
47	92.3 R	Ganges River at Charshalda
48	93	Padma River at Kusum Hati
49	93.4 L	Padma River at Jashida
50	93.4 R	Padma River at Chrjanajat
51	93.5 L	Padma River at Bhagyakul
52	93.5 R	Padma River at Bateswar
53	93.6 L	Padma River at Wari
54	94	Padma River at Tarapsha
55	95	Ganges River at Sureswar
56	99	Gorai River at Gorai Rwy. Bridge
57	100	Gorai River at Janipur
58	101	Gorai River at Kamarkhali
59	101.5	Gorai River at Kamarkhali (Transit)
60	102	Gorai Madhumati River at Bhatiapara
61	103	Gorai Madhumati River at Bardia
62	104	Gorai Madhumati River at Manikdaha
63	105	Gorai Madhumati River at Atharabanki River
64	106	Gorai Madhumati River at Patghati
65	107	Gorai Madhumati River at Pirojpur
66	108	Gorai-Madhumati-Baleswar River at Charduani
67	160	Kobadak River at Andulbaria
68	161	Kobadak River at Tahirpur
69	162	Kobadak River at Jhikargacha
70	163	Kobadak River at Tala Magura
71	164	Kobadak River at Chandkhali
72	165	Kobadak River at Kobadak Forest Office
73	167	Kumar River at Ibrahimdi
74	168	Kumar River at Faridpur
75	169	Kumar River at Muzurdia
76	170	Kumar River at Bhanga
77	171	Kumar River at Geraganj
78	183	Lohalia River at Kaitpara
79	184	Lohalia River at Patuakhali
80	185	Lohalia River at Golachipa
81	187	Lower Kumar River at Takerhat
82	188	Lower Kumar River at Rajoir
83	189	Lower Kumar at Asgram
84	190	Lower Kumar at Mustafapur
85	191	Lower Kumar at Charmuguria
86	193	Madaripur Beel Route River at Kabirajpur
87	194	Madaripur Beel Route River at Fatehpur
88	195	Madaripur Beel Route at Jalipar
89	196	Madaripur Beel Route at Satpar
90	197	Madaripur Beel Route at Tentulia
91	198	Madaripur Beel Route at Haridaspur
92	205	Mathabhanga River at Kazipur

Contd....

Table 3.1

List of Hydrometric Stations

Sl.No.	Stn.No.	Station Name
93	205 A	Mathabhanga River at Insafnagar
94	206	Mathabhanga River at Hatboalia
95	207	Mathabhanga River at Chuadanga
96	208	Mathabhanga River at Darsana
97	215	Nabaganga River at Jhenaidah
98	216	Nabaganga River at Magura
99	216 A	Nabaganga River at Magura
100	217	Nabaganga River at Kalachandpur
101	217 A	Nabaganga River at Lohagora
102	218	Nabaganga River at Bardia
103	219	Nabaganga River at Gazirhat
104	219.2	Nangoora River at Bridge No. 27
105	220	Hilakhi River at Khepupara
106	241	Rupsa-Pussur River at Khulna
107	242	Rupsa-Pussur River at Jalma
108	243	Rupsa-Pussur River at Chalna
109	244	Rupsa-Pussur River at Mongla
110	253	Swarupkati River at Swarupkati
111	254	Satkhira Khal at Satkhira
112	255	Satkhira Khal at Shovonali
113	256	Satkhira Khal at Habraganj
114	258	Sibsa River at Paikgacha
115	259	Sibsa River at Nalianala
116	277	Meghna River at Chandpur
117	277.3	Meghna River at Nilkamal
118	277.5	Meghna River at Charkurulia
119	278	Meghna River at Daulatkhan
120	279	Meghna River at Jajauddin
121	288	Meghna River Offtake in Meghna
122	289	Tentulai River at Dhulia
123	290	Tentulia River at Dasina
124		Pussur River at Hiron Point
125		Pussur River at Sundari Kota
126		Pussur River at Mongla
127		Nilganj River at Khepupara
128		Meghna River at Char Ramdaspur
129		Barisal River at Barisal
130		Dakatia River at Chandpur
131		Lohalia River at Galachipa
132		Laukati River at Patuakhali
133		Jeffort Point (vs. Hiron Point)
134		Tiger Point (vs. Hiron Point)
135		Patua @ Rabnabad Channel (vs. Hiron Point)
136		Jaymon Reach (vs. Hiron Point)
137		Ghasiakhal (vs. Hiron Point)
138		Betibunia (vs. Hiron Point)
139		Chalna Reach (vs. Hiron Point)
140		Dasmonia (vs. Char Ramdaspur)

TABLE 3.2

List of Historical Maps being used in the Morphological Studies

Lower Ganges	1767
Ganges Delta (Francis Russel, after Rennells)	1778
Ganges from Sundah to the Calligonga (Rennells)	1789
River Navigation Map (Entire Region)	1840
Bay of Bengal	1840
District of Jessore (Padma, Ganges, Gorai etc)	1855/59
Dhaka and Faridpur Districts [4 miles to 1"]	1857/60
Lower Provinces Revenue Survey	1867/69
Sundarbans	1873
Sundarbans [4 miles to 1"]	1879
Sundarbans + Arial Khan	Undated
Bengal 4 miles to 1" series Maps	1911/12, 1919, 1931, 1937, 1940s
Major River Network	1989
Surface Contour Map	Undated
Surface Geology	1990
Structural Geological Map	1964
Sedimentary Sequence and Position of Sea Level	1991
Neotectonic Map of Bangladesh	Undated
Maps of Earthquake Epicentres Since 1900	Undated
Earthquake Risk Zones	1986
Development of the Ganges Delta	1985

3.3 Satellite Imagery

The earliest satellite data available of the area is for 1973. Two Landsat images for 1973 were obtained by FAP-4 and these were processed for the project by FAP-19. The images cover approximately from Hardinge Bridge southwards to Mongla and to the Lower Meghna to the east. A complete coverage of the area for 1989 from SPOT imagery was obtained from FPCO, and additionally February and November 1990 SPOT images covering the Ganges and Padma were obtained. Details of the bankline changes at the Gorai mouth for 1973, 1976, 1978, 1980, 1984, 1987, 1990, 1992 were supplied by FAP 19 from corrected Landsat images. Banklines of the Padma and Meghna for 1993 were also digitised at the FAP 19 office from Landsat image and transfered to the FAP 4 system.

3.4 Cross Section and Bed Topography data

The BWDB has been measuring cross sections on the main rivers since the 1960s. All the available sections were collected as shown in Table 3.3. BIWTA have a number of charts of selected parts of the river system available and although these are normally referenced to a chart datum, for the Ganges and Gorai it was possible to convert these to PWD datum including a 1963 survey of the Gorai mouth.

TABLE 3.3

Summary of Maps

BWDB CROSS SECTIONS

River : Gorai-Madhumati

Drawing No.	Year	Cross Section No.
D-01	1978-79, 81-82, 83-84, 88-89	GM-1, GM-2
02	DO	GM-3, GM-4
03	DO	GM-5, GM-6
04	DO	GM-7
05	DO	GM-8, GM-9
06	DO	GM-10, GM-11
07	DO	GM-12
08	DO	GM-13
09	DO	GM-14
10	DO	GM-15
11	DO	GM-16, GM-17
12	DO	GM-18, GM-19
13	DO	GM-20, GM-21
14	DO	GM-22
15	DO	GM-23
16	DO	GM-27
17	DO	GM-25
18	DO	GM-26
19	DO	GM-24, GM-28
20	DO	GM-29, GM-30
21	DO	GM-31
22	DO	GM-32
23	1968-69, 76-77, 77-78	GM-13
24	DO	GM-14
25	DO	GM-15
26	1968-69, 69-70, 72-73	GM-1, GM-2
27	1968-69, 1973-74	GM-3, GM-4
28	1968-69, 1973-74	GM-5, GM-6
29	1968-69	GM-5.1, GM-7
30	1968-69, 1973-74	GM-8, GM-9
31	1967-68, 68-69, 75-76, 76-77	GM-1, GM-2
32	DO	GM-3, GM-4
33	DO	GM-5, GM-6
34	1968-69, 75-76, 76-77	GM-7
35	1968-69, 76-77, 78-79	GM-8, GM-9
36*	1980-81	GR-1
37*	DO	GR-2
38*	DO	GR-3
39*	1966-67, 1967-68	GR-1, GR-2
40*	DO	GR-3, GR-4
41*	DO	GR-5, GR-6

Note : Sections marked with * is for Gorai only

BWDB CROSS SECTIONS

River : Arial Khan

Drawing No.	Year	Cross Section No.
42	77-78, 78-79, 79-80, 80-81	AKU-1, AKU-2
43	70-71, 72-73, 77-78, 78-79	AKU-3, AKU-4
44	DO	AKU-5, AKU-6(UP)
45	DO	AKU-7, AKU-8
46	DO	AKU-9
47	68-69, 69-70, 70-71, 72-73, 77-78, 78-79	AKU-10, AKU-12(UP)
48	69-70, 70-71, 72-73, 78-79	AKU-11(UP)
49	1968-69, 69-70, 70-71, 72-73, 77-78	AK-1, AK-2
50	DO	AK-3, AK-4
51	DO	AK-5, AK-6
52	DO	AK-0, AK-7
53	DO	AK-8
54	DO	AK-9
55	DO	AK-10, AK-11
56	DO	AK-12
56	DO	AK-13
58	DO	AK-14, AK-15
59	DO	AK-16, AK-17
60	DO	AK-18
61	DO	AK-19

River : Nabaganga River

Drawing No.	Year	Cross Section No.
62	1977-78, 78-79	NGA-1, NGA-2
		NGA-3, NGA-4
63	DO	NGA-5, NGA-6
64	DO	NGA-7, NGA-8

River : Atai

Drawing No.	Year	Cross Section No.
65	1978-79, 78-79	AT-1, AT-2, AT-3, AT-4
66	DO	AT-5, AT-6
67	DO	AT-7

BWDB CROSS SECTIONS

River : Ganges River

Drawing No.	Year	Cross Section No.
68	1976-77, 77-78, 78-79	G-0-1
69	DO	G-1
70	DO	G.1-1
71	DO	G-2
72	DO	G-3, G-4
73	DO	G-5
74	DO	G-6
75	DO	G-7
76	1976-77, 77-78, 78-79, 79-80	G-8
77	DO	G-9
78	DO	G-10
79	DO	G-11
80	DO	G-12
81	DO	G-12-0-2
82	DO	G-13
83	DO	G-13-0-3
84	DO	G-13-14
85	DO	G-15
86	DO	G-16
87	DO	G-17
88	DO	G-18
89	1966-67, 67-68	G#0-1
90	DO	G#1
91	DO	G#-1-1
92	DO	G#-2
93	DO	G#-3, G#-4
94	DO	G#-5, G#-6
95	DO	G#-7
96	DO	G#8
97	DO	G#9
98	DO	G#10
99	DO	G#11
100	DO	G#12-1
101	DO	G#13-1
102	DO	G#12, G#13
103	DO	G#14
104	DO	G#15
105	DO	G#16
106	DO	G#17
107	DO	G#18

BWDB CROSS SECTIONS

River : Padma River

Drawing No.	Year	Cross Section No.
108	1964-65, 65-66, 65-67,68	P#01
109	1964-65, 65-66, 66-67, 67-68	P#0-1
110	DO	P#1
111	DO	P#1-1
112	DO	P#2
113	DO	P#2-1
114	DO	P#3
115	DO	P#3-1
116	DO	P#4
117	DO	P#4-1
118	DO	P#5
119	DO	P#5-1
120	DO	P#6
121	DO	P#6-1
122	DO	P#7
123	1967-68, 68-69, 69-70	P#4
124	DO	P#4-1
125	1969-70, 71-72, 72-73, 73-74	P#3-1
126	DO	P#4
127	DO	P#4-1
128	1973-74, 74-75, 75-76, 76-77	P#0
129	DO	P#0-1
130	DO	P#1
131	DO	P#1-1
132	DO	P#2
133	DO	P#2-1
134	DO	P#3
135	DO	P#3-1
136	DO	P#4
137	DO	P#4-1
138	DO	P#5
139	DO	P#5-1
140	DO	P#6
141	DO	P#6-1
142	DO	P#7
143	1976-77, 77-78, 78-79, 79-80	P#3-1
144	DO	P#4
145	DO	P#4-1
146	1979-80, 80-81, 81-82, 83-84	P#0
147	DO	P#1
148	DO	P#2
149	DO	P#2-1
150	DO	P#3
151	DO	P#3-1
152	DO	P#4
153	DO	P#4-1
154	DO	P#5
155	DO	P#5-1
156	DO	P#6
157	DO	P#6-1
158	DO	P#7

3.5 Field Surveys

A number of surveys were completed by FAP 4 staff and also by survey contractors. The surveys completed on the fluvial rivers are summarised on Figure 3.1 and those in tidal areas are shown in Figure 3.2. The surveys included detailed topographic/bathymetric survey of the Ganges and Gorai at the Gorai mouth (Figure 3.3) and at the Arial Khan mouth (Figure 3.4). Sections in the Gorai to Kamarkhali were measured in the dry and in the monsoon season. Long profiles with continuous depth measurement and position fixing by GPS were run from the Ganges to Khulna via the Nabaganga at the Halifax cut on the Madhumati and from the Padma to Khulna via the Arial Khan, Kumar, Madaripur Beel Route (MBR) and Atharabanki. Bed sediment sampling was completed for the Gorai/ Madhumati and for limited positions in the MBR.

A sample of the cross-sections surveyed is given in Appendix 1.

3.6 Stream Reconnaisance Sheets

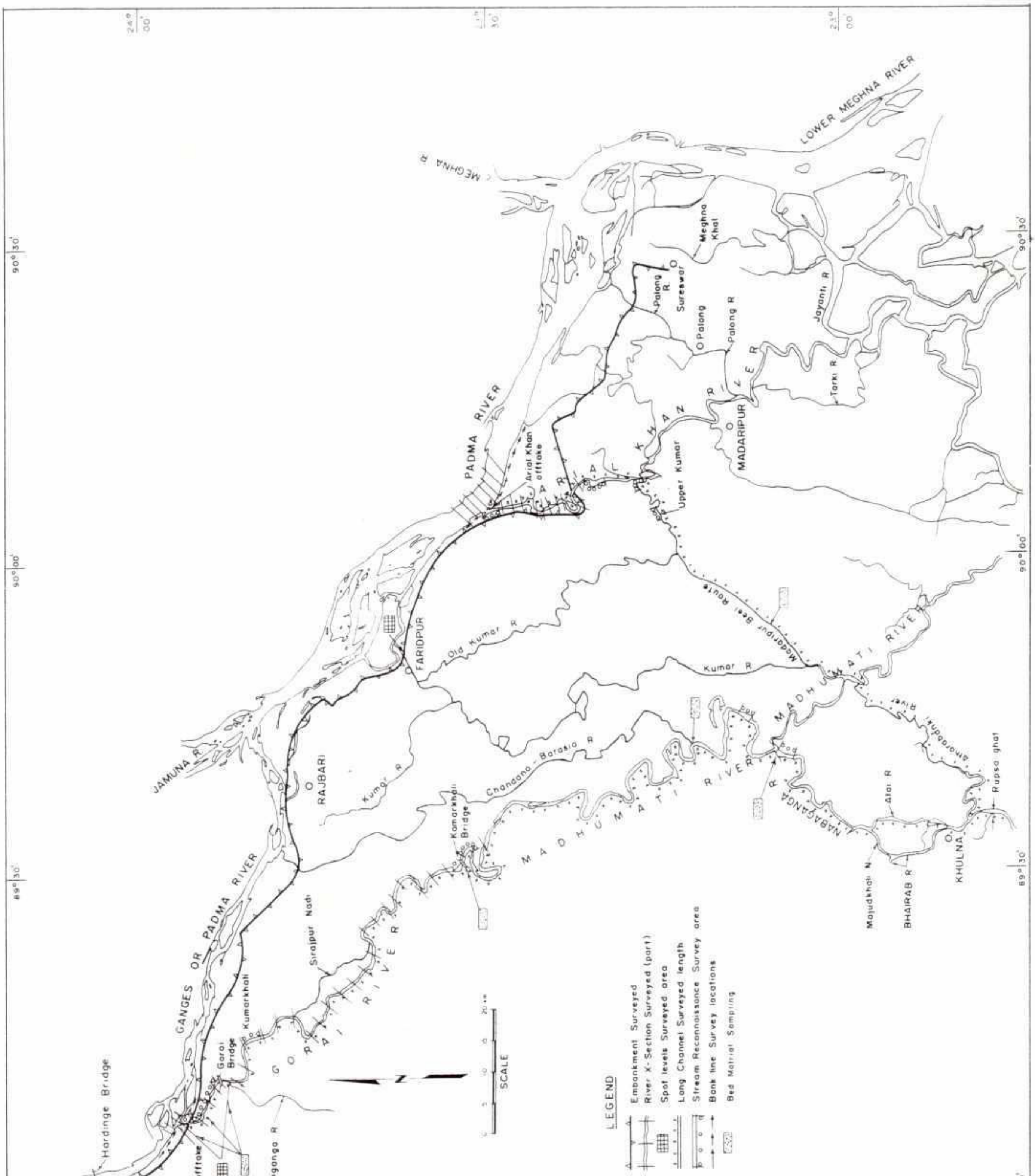
Stream Reconnaisance sheets developed to use in morphological observations for the US Corps of Engineers (Thorne 1992) were used to record river features and were completed during surveys and field visits. These aid in assessing the geomorphic features of the river, identifying the current issues and problems and provide a standard reference for future studies. These sheets were used to produce maps of notable geomorphic features along the Gorai and Arial Khan (Figures 3.3 and 3.4).

A sample of the stream Reconnaisance sheets is given in Appendix 2.

3.7 Supporting FAPs and Other Studies

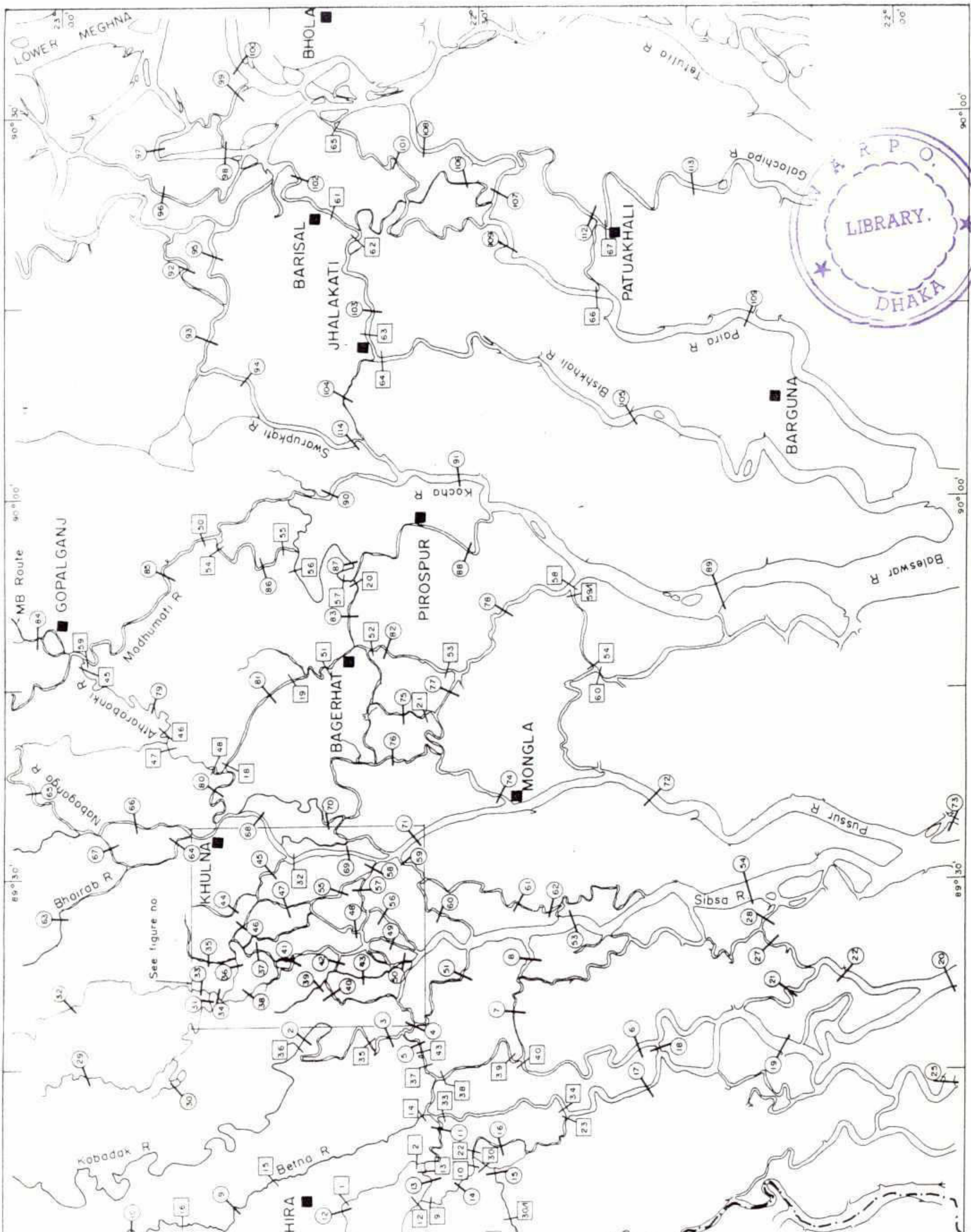
Relevant survey work reported by other FAPs included FAP 1 work on sediment movement in the Jamuna and FAP 9B work on the Padma and Lower Meghna. Partial sections of the Rupsa are presented by FAP 9A.

Figure 3.1



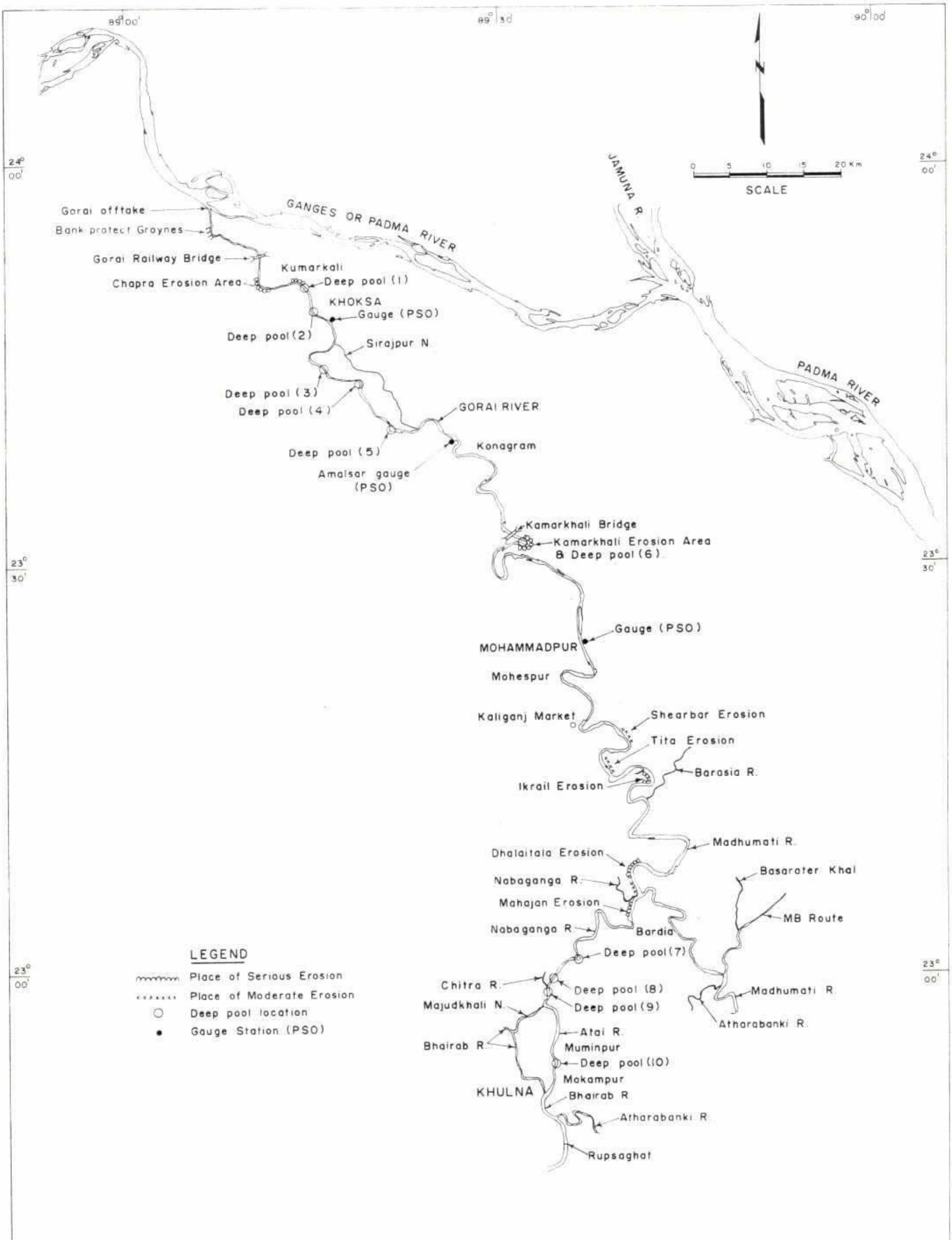
Map Showing Survey Features
April, 1992—February, 1993

Figure 3.2



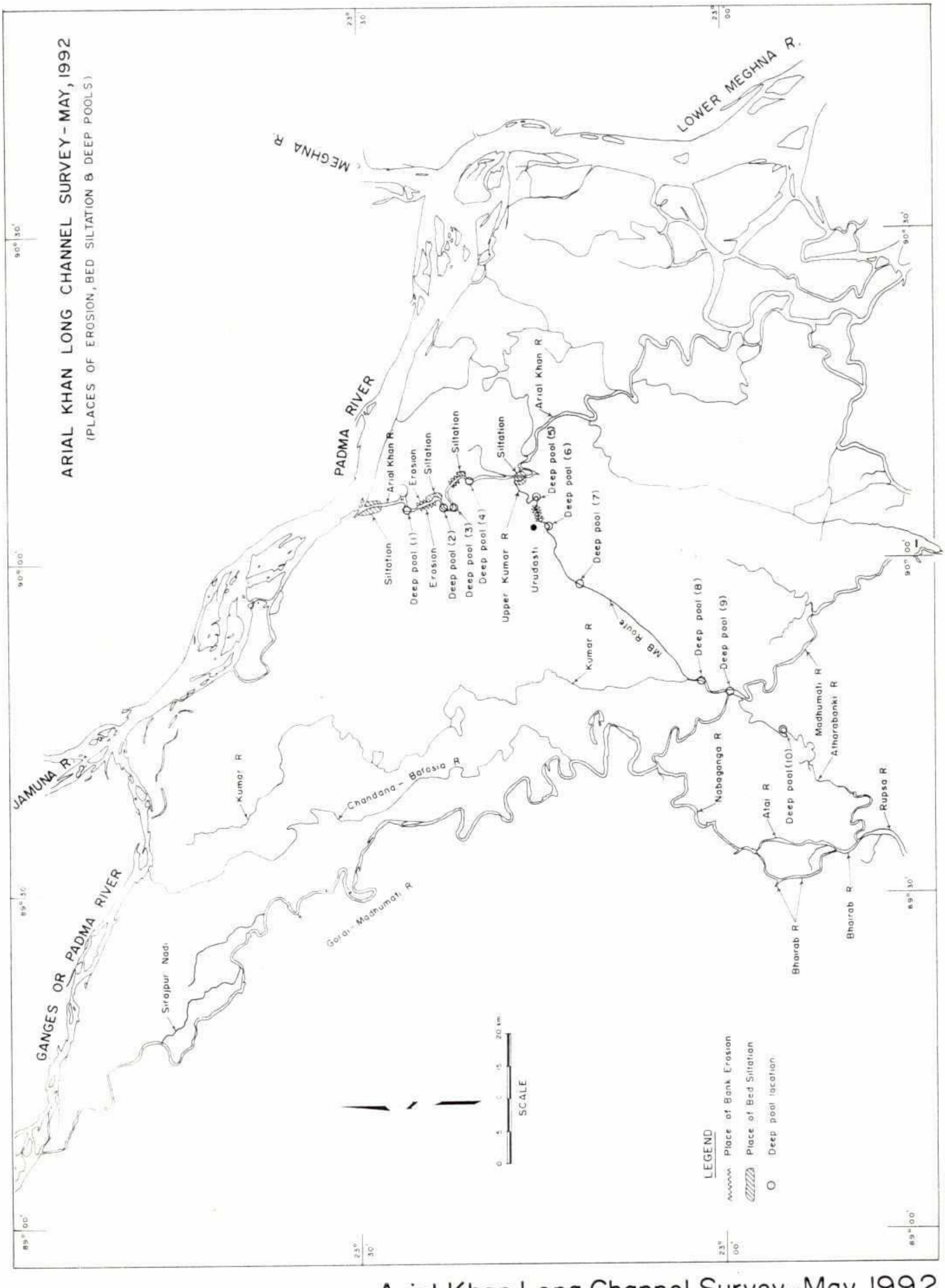
Survey Competed in Tidal Areas

Figure 3.3



Gorai Long Channel Survey July 1992
(Places of Erosion Deep Pools & Gauge Stations)

Figure 3·4



Arial Khan Long Channel Survey - May 1992

(Places of Erosion, Bed Siltation & Deep Pools)

4 BOUNDARY RIVERS

4.1 River Ganges

4.1.1 Flow and Sediment Regime

The mean annual flow of the Ganges is of the order of 11,000 m^3/s but there is an extremely high variation of the mean monthly flows throughout the year from 600m^3/s in April (at present) to 39,000 m^3/s in August, a factor of 65. The natural low flows of the Ganges are closer to 2000 m^3/s making the natural variation only a factor of around 20, the discrepancy being made up by upstream abstractions notably at Farakka in India. This variation is still much higher than in the Brahmaputra or the Padma (11 and 11.5 respectively) and helps to explain the dry season form of the Ganges which essentially becomes a series of interconnected pools and though still a major river course much of the river bed is exposed.

The hydrograph of the Ganges is driven by summer monsoon rains and usually peaks in August while that of the Brahmaputra responds primarily to snowmelt in the Himalayas and peaks a little earlier, in July. Both rivers experience comparatively low flows during a dry season that extends from January to May.

However, there is clear evidence that recently dry season flows in the Ganges have been seriously depleted due to upstream abstractions. Table 4.1 shows mean monthly flows in the Ganges for the years 1934 to 1993. This demonstrates that even during the period of the Indo-Bangladesh agreement on water sharing (1976-1988) dry season flows in the Ganges were nearly halved. Since the expiry of the agreement minimum flows have practically halved again dropping below 450 m^3/s in 1989 which is well below the minimum flow in the agreement (approximately 725 m^3/s), again in 1992, and reportedly again in 1993.

The continuing decline in dry season flows clearly has major implications for planning, morphology and the use of water resources in the Southwest Area. This issue is at the forefront of recent discussions between the Indian and Bangladesh governments and a renewal of the previous agreement is being sought.

Recession curves

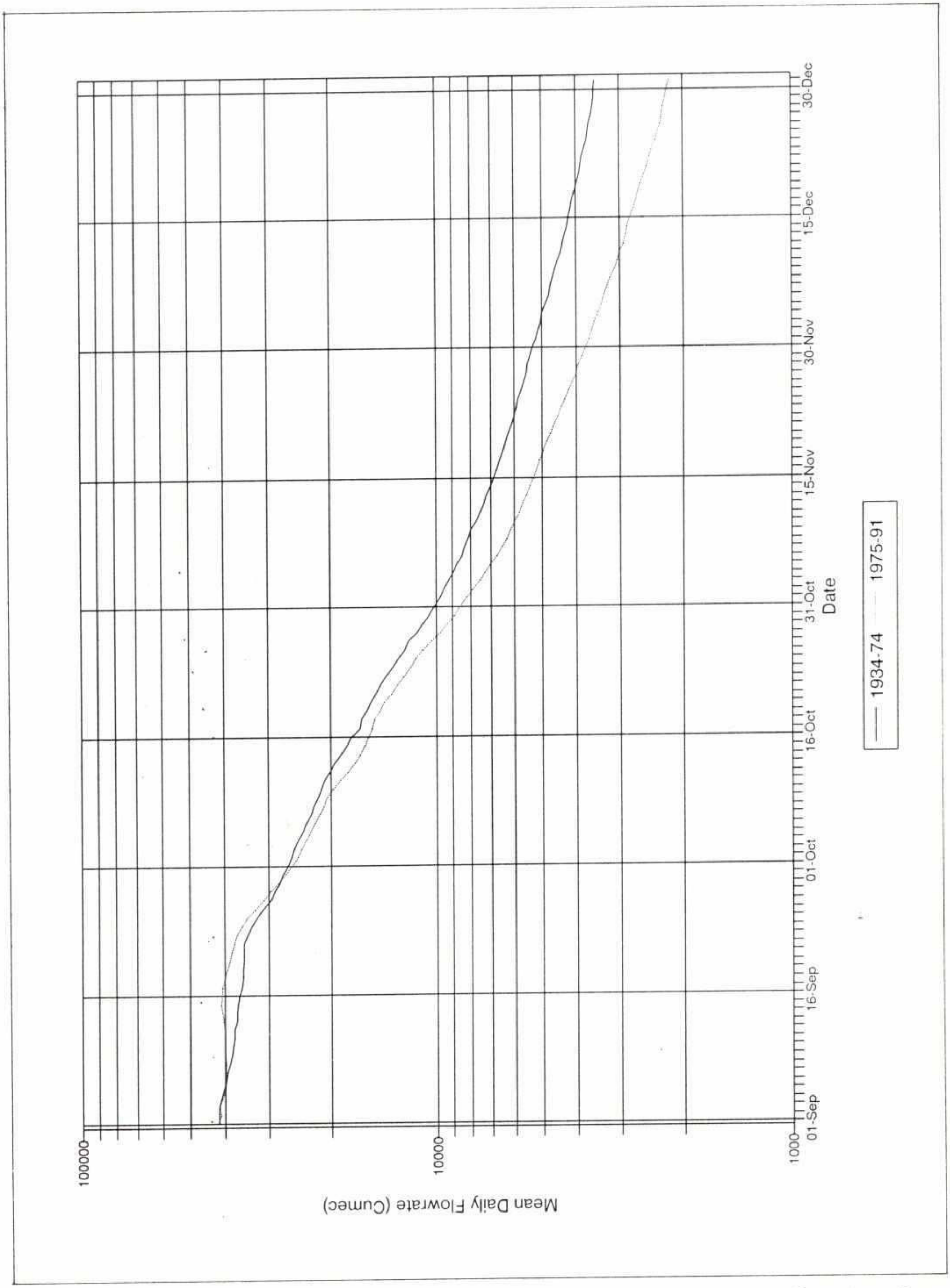
The rate of change in flow in the Ganges after the monsoon has increased markedly since the operation of Farakka as illustrated in Figure 4.1. This is due to the need to fill the pool upstream of the barrage as well as due to the diversion of water.

Sediment Gauging Data

The flow and sedimentary regimes of the large rivers forming the northern and eastern boundaries of the Southwest Area are characterised by wide variations and few measuring sites with variable periods and quality of sediment gauging. The relevant gauging stations are, from upstream to downstream, Hardinge Bridge on the Ganges and Baruria and Mawa on the Padma. Under FAP 24 (River Survey Programme) high quality flow and sediment flux data will be collected, however the data will not be available in time for this study and the existing data base must be used.

The data considered to give the most reliable indication of sediment fluxes was collected as part of the FAO Second Hydrological study in 1966 and 1967. Further data of good quality was collected in the following two years. Data is available for both suspended bed material load (sand sized sediment - the important sediment size for the analysis of fluvial channel form) and for wash load (silt size sediment which is more important for the tidal region).

Figure 4.1



Mean Daily Discharge Ganges Sept. – Dec.
at Hardinge Bridge 1934–1991

TABLE 4.1

Mean Monthly Flow in River Ganges at Hardinge Bridge (cumecs)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1934				2138	1987	3646	19776	36277	40160	18625	6202	3432	
1935	2778	2461	2228	1889	1654	2911	13086	38239	27707	13908	4535	3356	9563
1936	2389	2062	1625	1433	1778	5172	22873	39497	37980	16688	6672	3830	11833
1937	2858	2317	2442	1806	1877	3443	11893	33913	30137	18748	6391	3495	9943
1938	2630	2495	2392	2215	2053	8630	28319	43681	33527	10132	4884	3254	12018
1939	2550	2176	2013	1749	1790	3104	13052	28607	26507	12759	5281	3132	8560
1940	2291	2163	2097	1911	1838	2920	12997	30807	25113	8468	4374	3203	8182
1941	2749	2298	1930	1565	1947	4247	10760	23584	26750	10306	4671	2997	7817
1942	2389	2248	2271	1822	1889	2600	17709	39713	36447	14615	7006	3379	11007
1943	2641	2534	2062	1812	2022	4768	14023	33952	35000	15699	6572	3496	10382
1944	2585	2354	2396	2470	2423	3435	13056	31000	29173	14299	5945	3456	9383
1945	2744	2517	1998	1943	2008	2899	17212	26284	36067	20571	9510	4886	10720
1946	3206	2515	2183	2039	2629	7197	26590	45484	39203	16071	7927	3643	13224
1947	3197	2503	1987	1738	1653	3333	13665	34990	40827	18252	6630	3917	11058
1948	2827	2447	2069	1939	2151	3954	19882	45581	56000	24387	7524	6094	14571
1949	3834	3440	2669	2306	3080	5352	15599	41797	35260	16868	10119	5255	12132
1950	3770	3243	2721	2200	2069	6227	20284	45745	33823	11779	5102	3459	11702
1951	2714	2616	2121	1994	1969	3713	16116	25836	28297	9945	4929	3407	8638
1952	2444	2104	1891	1834	2090	4201	21813	41671	37473	13612	4811	2869	11401
1953	2055	1897	1615	1260	1400	2344	21741	43174	35257	15678	5529	3158	11259
1954	2353	1922	1893	1492	1516	4484	16401	48026	38190	20508	7462	4436	12390
1955	3296	2931	2694	2168	2079	4097	29482	53019	48367	30807	11741	6319	16417
1956	4182	3523	2789	2334	3136	9677	25297	47984	46373	31390	16537	6726	16662
1957	5099	4743	3592	2714	2493	3475	16722	35036	34163	12178	6716	4859	10982
1958	3643	3016	2405	2314	2430	2979	14158	49216	35260	26055	9135	5507	13010
1959	4388	4419	3592	2973	2886	5382	16017	43232	33017	22365	8742	5438	12704
1960	3898	2934	2462	2234	2014	3764	19166	39423	38990	24455	6518	3266	12427
1961	2439	2325	2170	1898	1934	5106	17233	46032	55570	42300	12362	6116	16291
1962	4271	3744	3338	2685	2886	6794	19887	46119	43077	23309	7227	4546	13990
1963	3670	3045	2503	2391	2727	5976	22016	40623	47677	21077	9145	4984	13819
1964	3621	2840	2409	2228	2417	3309	21411	40274	40927	21506	7235	4285	12705
1965				2219	2161	3209	9704	24442	25510	9160	5272	3565	
1966	2853	2316	1958	1408	1460	2637	12374	31315	25508	7714	4145	3275	8080
1967	2493	2138	1764	1647	1744	3093	16337	30971	43439	12010	5294	3686	10385
1968	2909	2550	2039	2084	2045	4684	22720	36485	20907	17644	5556	3605	10269
1969	2604	2003	1576	1868	2066	5062	17516	44407	35309	18685	6934	4527	11880
1970	3015	2504	2294	1870	2435	4903	19784	32663	32941	15656	6061	4143	10689
1971	2981	2434											
1972				2472	2813	4714	13382	23877	28969	12700	6070	4156	
1973	3007	2615	2059	1962	2776	7596	18692	42251	41906	29219	9848	5764	13974
1974	4049	2989	2391	2224	2807	4518	18047	48678	35733	14665	7046	4262	12284
1975	2855	2273	1722	1585	1827	3797	30092	44132	40326	20908	6931	3654	13342
1976	2032	1525	843	263	706	3732	14198	34425	44329	13352	4682	2601	10224
1977	1456	1060	834	1501	1813	4056	21814	41942	33789	17251	6099	3339	11246
1978	2242	1741	1535	1502	2179	6025	26032	51086	43889	20149	6862	3561	13900
1979	2050	1907	1520	1293	1517	1512	14390	29896	15360	7813	2864	1951	6839
1980	1249	884	742	725	1221	3235	25071	48032	44484	14008	5064	2770	12290
1981	1844	1567	1256	1320	1695	2394	22799	40970	33577	15795	3846	2186	10771
1982	1302	1162	1011	1206	1520	4786	11725	38336	47952	10556	4934	2888	10615
1983	1484	1223	806	664	1485	2409	12481	26574	44454	23903	7021	3334	10486
1984	2245	1666	1304	982	1435	7958	24959	33919	44922	11068	4214	2377	11421
1985	1599	1187	854	832	945	2422	17752	37898	37528	35058	11949	4598	12718
1986	2610	1724	1538	1191	1541	2365	25324	39269	30533	17868	6066	3395	11119
1987	2433	1515	1060	889	1070	2102	13553	45215	51760	15042	5941	2621	11933
1988	1653	1310	1147	929	1349	3169	21361	50861	36363	10820	3752	1930	11220
1989	1453	862	523	741	1187	5377	18914	26650	27035	15329	4090	2064	8685
1990	1204	551	638	733	1508	4547	30256	42931	31344	20466	4790	2266	11769
1991	1472	852	625	663	1232	5125	11636	28209	38348	8599	3519	2125	8534
1992	1616	889	517										
1993			319	399									
Avg 34-74	3090	2668	2287	2031	2178	4489	17920	38348	36063	17870	7091	4180	11685
Avg 75-88	1932	1482	1155	1063	1450	3569	20111	40183	39233	16685	5730	2943	11295
Avg 89-93	1436	788	524	634	1309	5016	20269	32596	32243	14798	4133	2151	9663
Min 34-74	2055	1897	1576	1260	1400	2344	9704	23584	20907	7714	4145	2869	7817
Min 75-88	1249	884	742	263	706	1512	11725	26574	15360	7813	2864	1930	6839
Min 89-93	1204	551	319	399	1187	4547	11636	26650	27035	8599	3519	2064	8534
Max 34-74	5099	4743	3592	2973	3136	9677	29482	53019	56000	42300	16537	6726	16662
Max 75-88	2855	2273	1722	1585	2179	7958	30092	51086	51760	35058	11949	4598	13900
Max 89-93	1616	889	638	741	1508	5377	30256	42931	38348	20466	4790	2266	11769

There is no data on bed load movement of sediment although this is generally found to be small compared with suspended load transport. Bed load is difficult to measure or calculate with confidence and FAP 1 found that some suspended sediment settled behind dunes contributing greatly to their movement. The distinction between suspended load and bed load is therefore not as clear as theory would suggest. It was therefore neglected in the calculation of dominant flow.

The total measured suspended loads for May to November for the Ganges at Hardinge Bridge is shown below:

Year	Suspended Bed Material Tonnes x 10^6	Wash Load Tonnes x 10^6
1966	214	-
1967	164	326
1968	146	292
1969	154	286

However the suitability for sediment monitoring of the only gauging site for the Ganges in Bangladesh at Hardinge Bridge near Kushtia is now being questioned (see below). This makes it difficult to confidently determine a precise reference flow for analysis of the channel geometry and condition. It is fortunate however the calculation of dominant discharge is relatively insensitive to the sediment rating.

4.1.2 Dominant Discharge Analysis - River Ganges, Hardinge Bridge Gauging Site

At Hardinge Bridge the available records have been used to perform a dominant discharge analysis as described by Wolman and Miller (1957). Three decades of practical work in fluvial geomorphology has demonstrated that in alluvial rivers the gross features of the channel are adjusted to the dominant flow. This means that if the flows or sediment regime in a channel are altered, for example by constructing a regulator on the river then changes to the channel size can be expected until it is again adjusted to the controlled discharges.

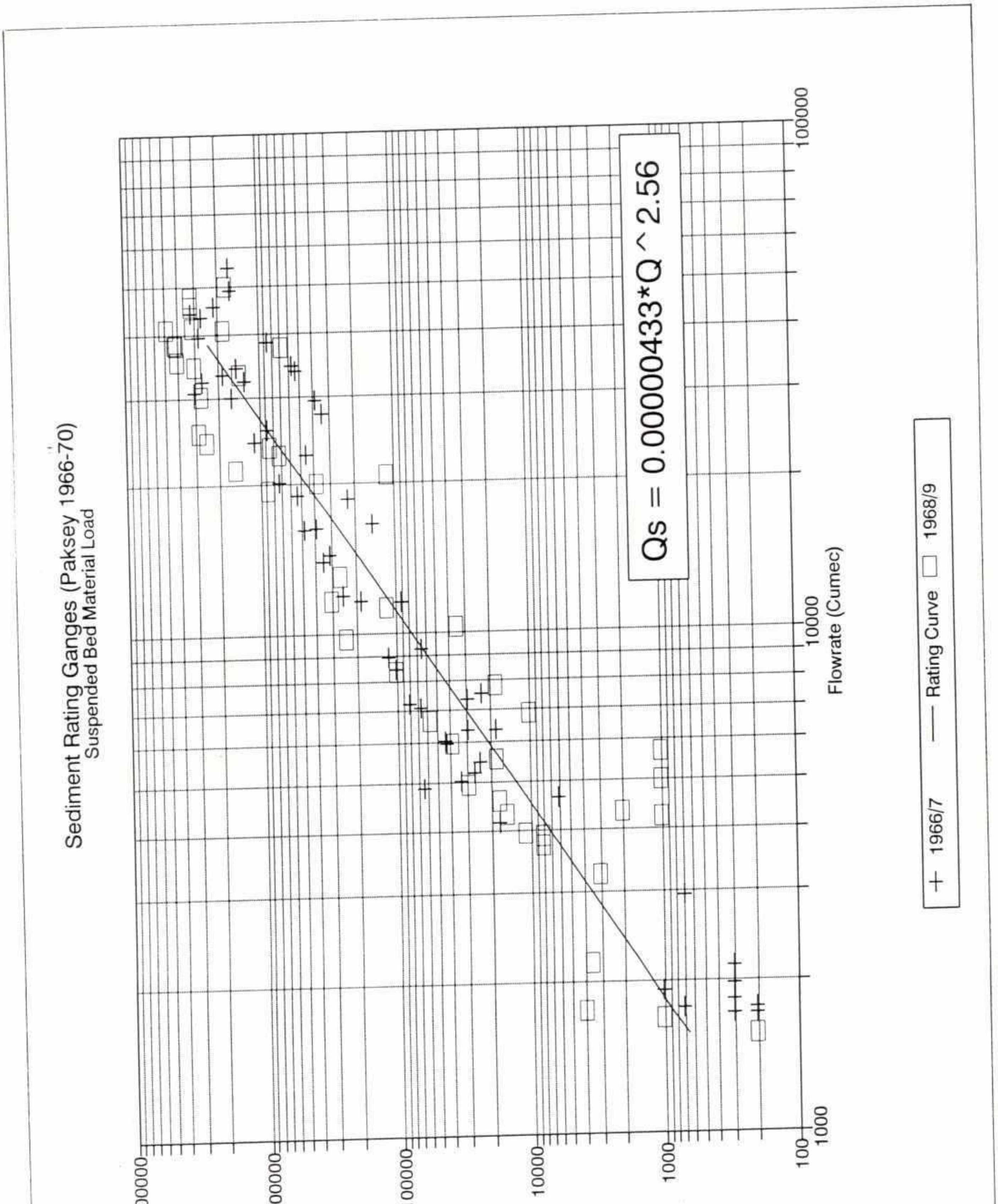
A sediment rating curve for suspended bed material was derived by regression as shown in Figure 4.2. It is appreciated that a single rating curve will not accurately represent sediment transport rates under all conditions, for example when the Ganges is backed up by high flows in the Brahmaputra, sediment deposition may take place. However the correlation obtained was good and the following expression was found to fit the data within typical error bands for sediment transport :

$$Qs = 4.33 \times 10^{-6} Q^{2.66}$$

where,

Qs = Sediment flux (tonnes/day)
Q = Flowrate (Cumec)

Figure 4.2



Sediment Rating Curve River Ganges (1966-1969)

This was in close agreement with a rating derived independently for the same site by SWMC. The exponent found is relatively high and indicates a greater than expected increase in sediment transport with an increase in flow.

In discussions with SWMC who were calibrating a morphological model of the Ganges it became clear that the rating curve for the site is strongly influenced by the constriction of the river near the bridge site. The Ganges is restricted here to less than 1Km width and there is a sharp bend immediately upstream. The rating at Hardinge Bridge was found by SWMC to be consistent with the morphological model which showed strong seasonal changes in bed level. At high flows the bed is deeply scoured (the central bridge piers extend 46m below low water and are heavily protected with additional boulders to allow for such scouring) but recovers again in the flood recession. Monitoring of sediment in the restricted reach is therefore affected by silting of the channel at low flows decreasing the sediment flux measured relative to a more typical section of the Ganges and at high flows the sediment flux is increased by bed scour. The sediment rating is correct for the constricted reach and should give correct sediment volumes over a typical year, but is not representative of the majority of the length of the Ganges which is unrestricted. SWMC derived the following equation for a more typical upstream reach and verified that using this rating the model gives a sediment rating at Hardinge Bridge in agreement with that measured.

$$Qs = 0.536 \times Q^{1.429}$$

The above equation was used for the dominant discharge analysis. The flow record for 1934 to 1992 was sorted into frequency bands as shown in Figure 4.3 and the mean sediment transported for each band calculated. The product of the frequency of occurrence of each flow interval and mean sediment flux for the discharge class was then used to derive Figure 4.4.

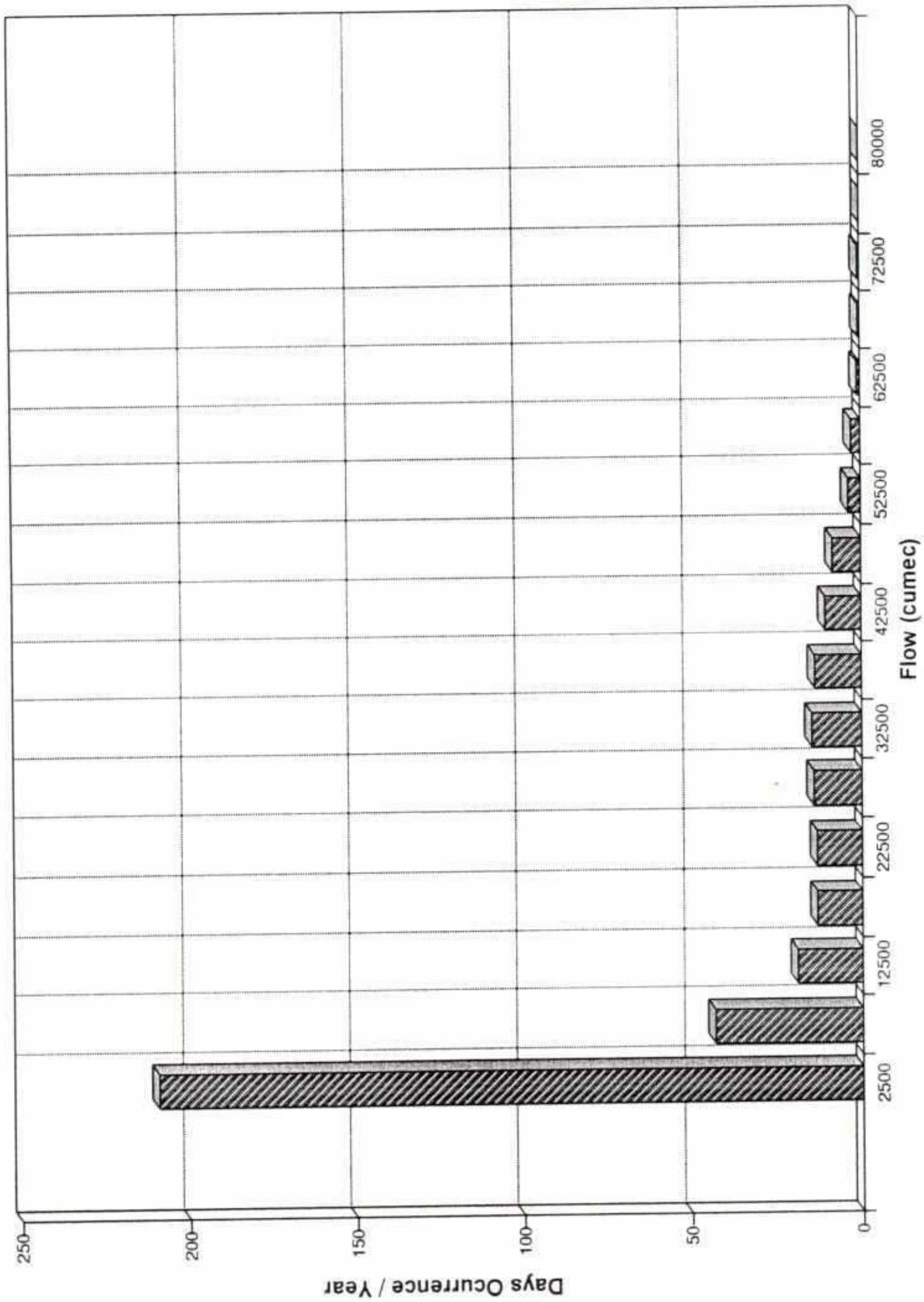
From Figure 4.4 it can be seen that the flow class doing the most sediment transport on average is 35000-40000 m^3/s. The dominant discharge is therefore approximately 38000m^3/s. The selected figure is close to the figure identified in 1988 by the Bangladesh Ministry of Irrigation, Water Development and Flood Control. When the sediment load is plotted cumulatively it shows the charcteristic reverse 'S' curve (Figure 4.5), dominant discharge corresponds to the 58th percentile of sediment transport. This is similar to results on the Jamuna - Brahmaputra River under FAP-1.

Based on the break points the dominant range of flows is 23,000 to 50,000 cumecs. Flows in this range are responsible for transporting 63% of the total mass of sediment load over the period of record. Flows less than 23,000 cumecs contribute 22% of the load and flows greater than 50,000 cumecs together transport 15%.

These results indicate the range of flows which should be responsible for forming the major morphological features of the channel.

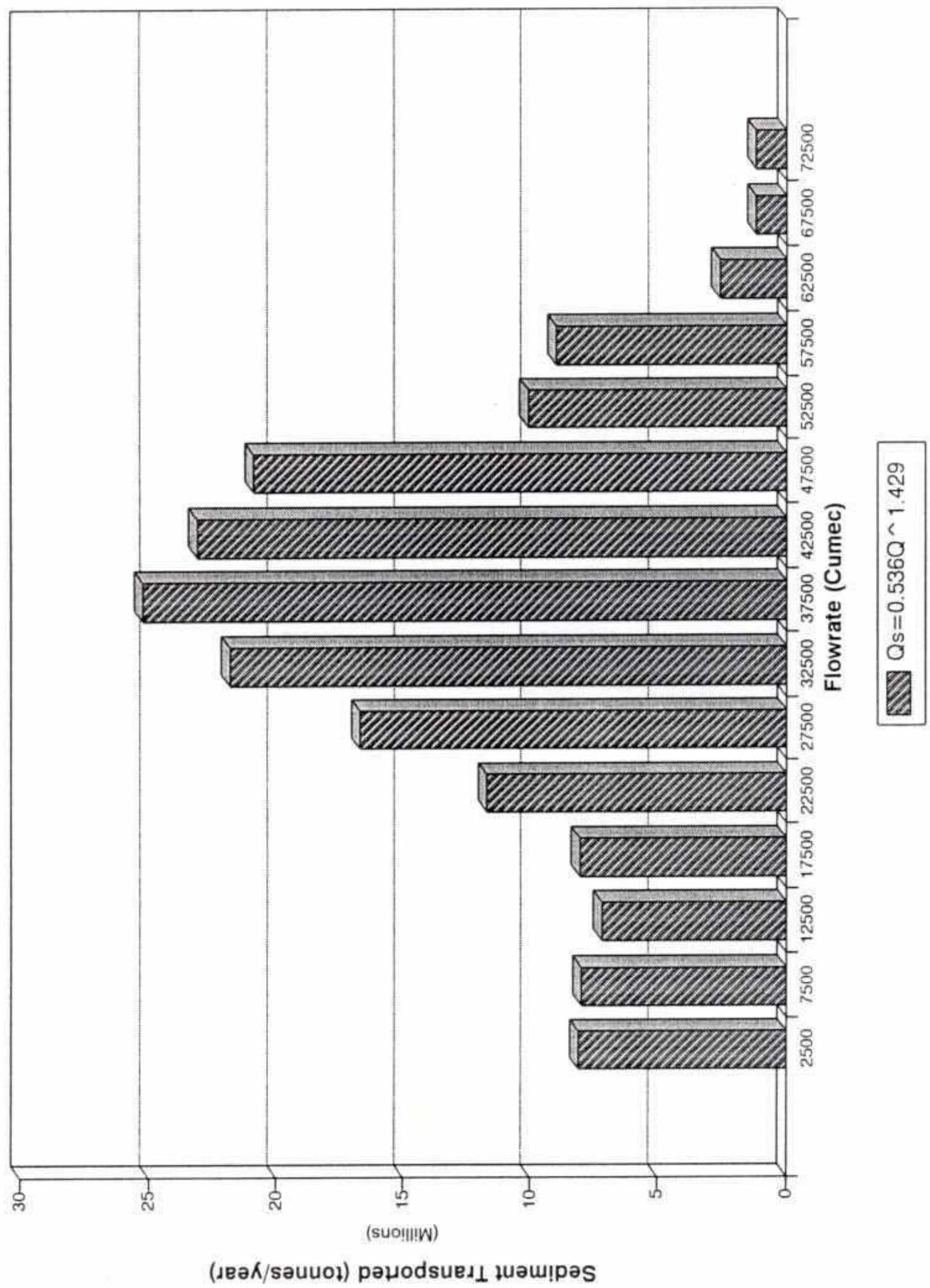
Further examination of Figure 4.5 indicate that all flows greater than 57,000 cumecs together only transport 5% of the sediment load. Flows greater than 61,000 cumecs transport 3% and those greater than 70,000 cumecs only a mere 1%. The relative sediment transporting capacity of the highest flood discharges over periods of 30 years or more is demonstrated to be relatively small in relation to the total sediment transported. At the low flow end of the range, flows less than 10,000 cumecs together transport only about 10% of the load. Their impact on medium to longterm sediment movement and channel form is likely to be small, but can be locally significant. The 1 in 2 year peak daily flowrate at Hardinge bridge is 49,000 m^3/s indicating that the dominant flows should occur most years.

Figure 4.3



Flow Frequency River Ganges
at Hardinge Bridge 1934-1992

Figure 4.4



Dominant Discharge in Ganges at Hardinge Bridge 1934-1992

The next phase of the study was to extract from the period of record the post Farakka record and to examine carefully the impact of the barrage on the sedimentary regime of the river. Figure 4.6 shows the dominant discharge computation for post-Farakka years compared to that for the earlier period. Visual inspection suggests that there are no significant differences. The dominant discharge or model value is unchanged and the secondary peak associated with low flows is present in both records. The higher sediment loads at large discharges are associated with the 1987 and 1988 floods which both occurred in the post-Farakka period. The gross channel features should therefore be unchanged by the construction of the Farakka barrage and only the secondary low flow features should be affected.

The record for Hardinge Bridge has been sub-divided into pre and post-Farakka periods. In the 1st Interim report it was concluded that there was no significant difference but this conclusion may be re-evaluated in the light of subsequent findings. Close examination of the relevant plot (Figure 4.6) indicates that:

1. high flows above 50,000 cumecs appear to be more important post-Farakka, reflecting the limited period of record since 1975 and illustrating the short-term impact of the high runoff years of 1987 and 1988;

2. low flows below 5,000 cumecs are more important post-Farakka (if a smaller class interval were used it would be found that flows less than say 2,500 cumecs are much more important), reflecting the impact of reduced dry season flows in transporting sediment;

3. intermediate flows of 5,000 to 15,000 cumecs are less important post-Farakka, indicating a reduction in the effectiveness of these flows in transporting sediment and forming the sedimentary features of the channel.

It cannot be assumed that these differences in the dominant discharge distributions for the two periods are either (1) significant morphologically, or (2) solely due to the operation of the barrage. In fact, the evidence supplied by the dominant discharge analysis must be considered along with that from all the other components of the morphological studies in a balanced and objective assessment. However, there can never be "proof positive" of cause and effect and so some doubt will always remain about linking hydrologic and hydraulic regime changes to channel evolution and alteration.

4.1.3 Morphology and Hydraulic Geometry of Ganges

Having identified the dominant flow or range of flows, the next step is to examine whether the salient features of the channel morphology show some clear relation to this discharge. If it is actually the channel forming flow and if the channel is close to adjustment then there should be some expression of dominant flow in the fluvial landform.

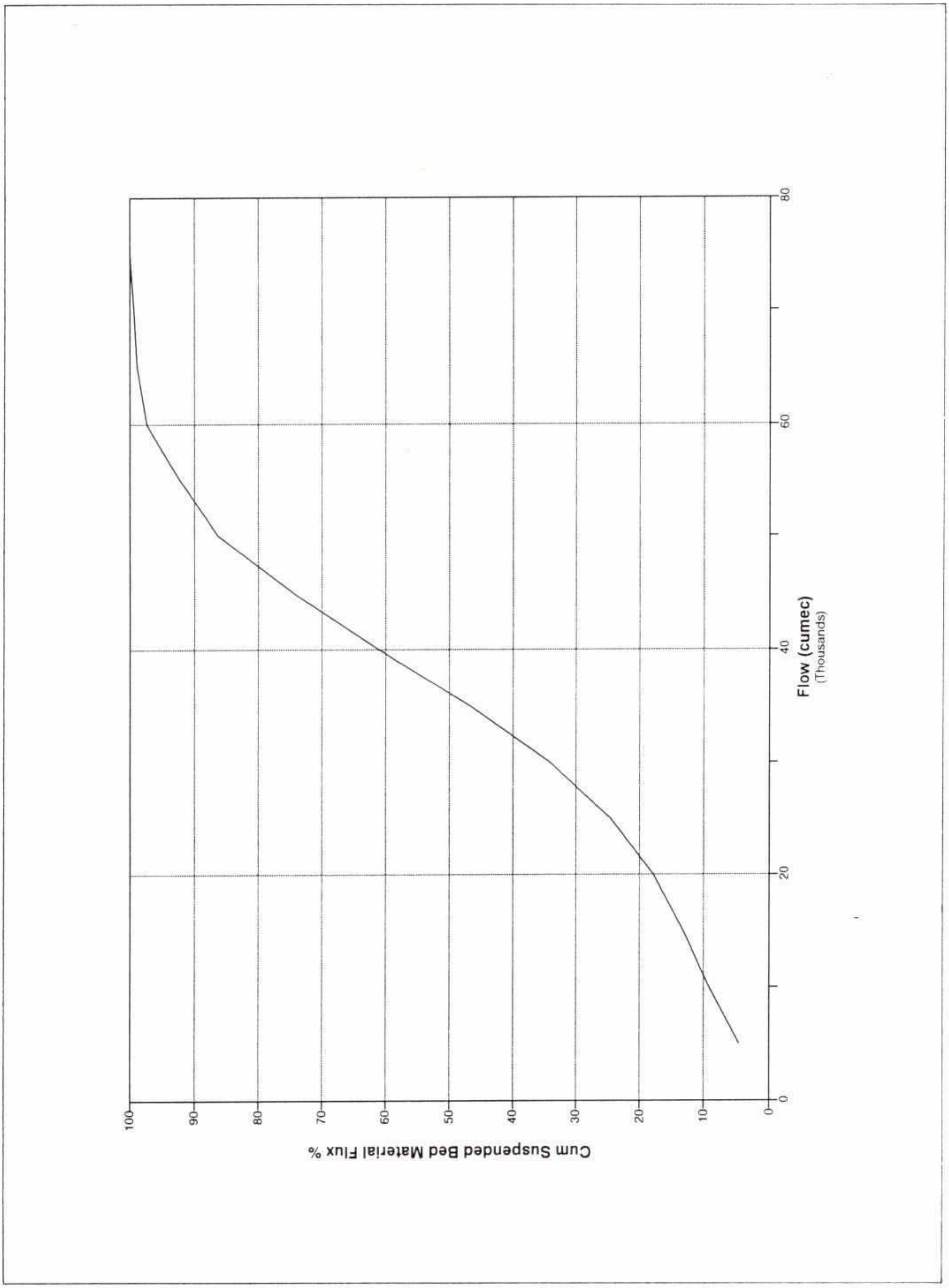
Hydraulic geometry relationships were developed for the Jamuna Bridge study and found to give reasonable predictions of the width and depth of large anabranches at dominant flow.

$$B = 16\,Q^{0.53}$$

$$d = 0.23\,Q^{0.32}$$

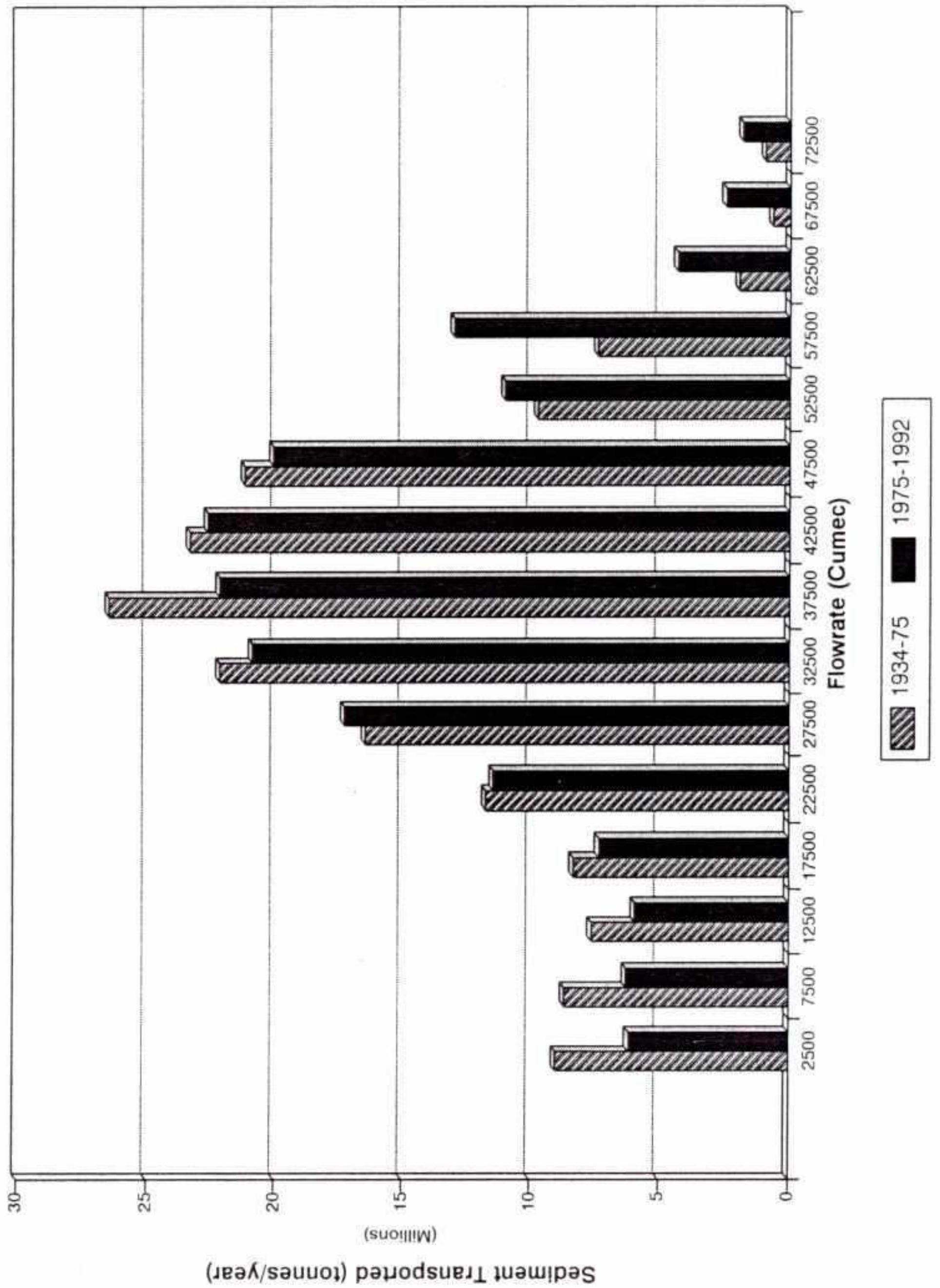
For the Ganges at 38,000 cumecs the predicted mean width and depth are 4.3 km and 6.7m, respectively.

Figure 4.5



Cumulative Sediment Flux Distribution
River Ganges at Hardinge Bridge

Figure 4.6



Dominant Discharge in Ganges at Hardinge Bridge (Pre and Post Farakka)

To determine the relationship between the dominant flow and channel form the results of the one-dimensional flow model MIKE 11 were used to generate a water surface profile for 38,000 cumecs. The water level corresponding to this dominant flow has been plotted onto existing BWDB cross-sections to check the validity of the hydraulic geometry relationships. Initial qualitative inspection indicates that the observed widths and depths are commensurate with predicted values. Further, the elevation of dominant stage can be compared to bank and bar heights to establish whether dominant flow is a bar topping or a bankfull flow (Figure 4.7). These sections represent surveyed cross-sections of the Ganges just downstream of Hardinge Bridge, midway to the Jamuna, and just upstream of the Jamuna. Inspection of the cross-sections indicates that dominant discharge is one which just tops the major bars, but without overtopping the banks and inundating the flood plain. This would strongly support the conclusion that the cross-sectional morphology of the Ganges is alluvially adjusted to the dominant flow.

There is some evidence from the sections between the Hardinge Bridge and the mouth of the Gorai that the channel may be slightly degraded. Dominant discharge here is a little below bankfull height.

The planform of the Ganges is characterised by sweeping meanders and divided flow reaches within a broad meander belt. The meander wavelength for the largest meanders is of the order of 35 km. This is consistent with discharge-slope relationships, which place the Ganges close to the threshold between meandering and braiding. For alluvial rivers, the meander wavelength is often found to be between 7 and 10 times the flow width. In the case of the Ganges this would suggest a wavelength of 30 to 43 km, which brackets that observed on maps. This relationship will needs to be fully and quantitatively investigated as hard data become available, but this early indication is that the planform of the Ganges is alluvially adjusted to the dominant flow.

On the basis of the hydraulic geometry so far examined the Ganges appears to be in dynamic equilibrium in terms of its cross-sectional and planform geometrics. However, this does not preclude aggradation/degradation, or progressive channel shifting.

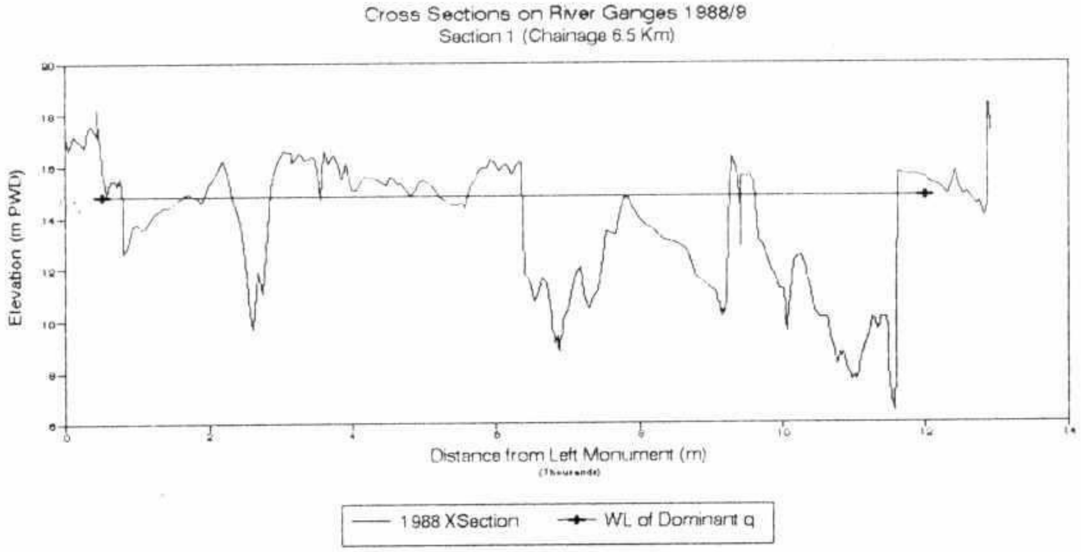
4.1.4 Specific Gauge Analysis of Ganges at Hardinge Bridge

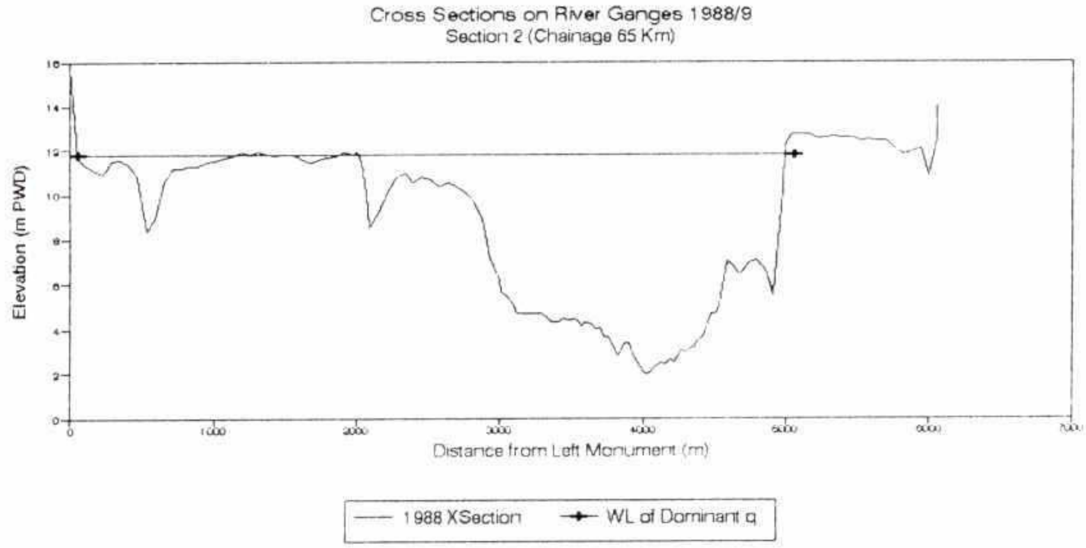
The records presented in the 1st Interim Report (1966-1989) have now been superseded by a much fuller record that includes both the more recent and earlier periods of observation. The record now covers 1934-1990, but with a break between 1960 and 1966. The results are plotted in a composite figure for 6 discharge levels from 10,000 to 40,000 cumecs in Figure 4.8.

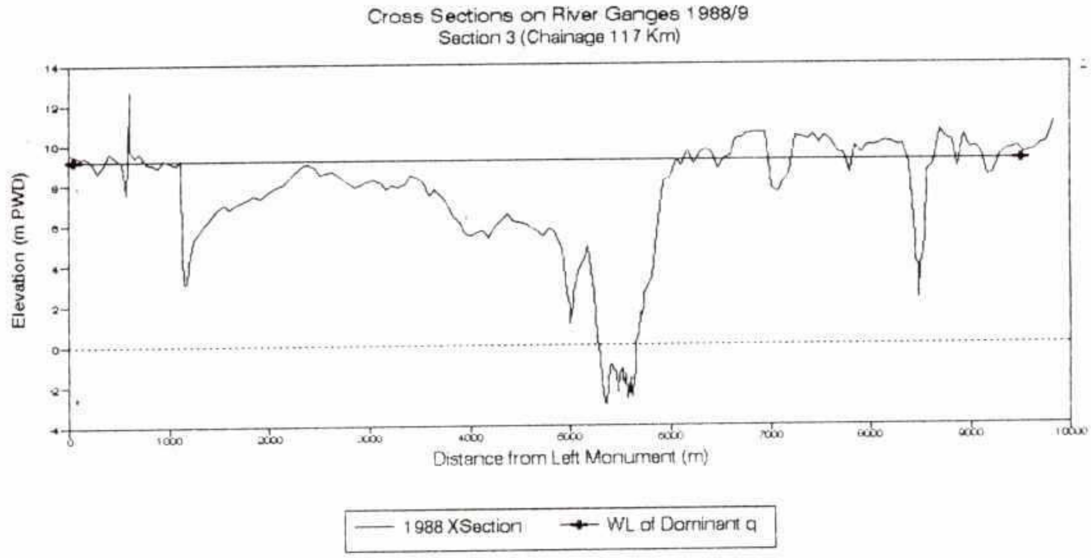
The specific gauge analysis for the 50 year+ period shows some inconsistencies in the record. For example, the large and abrupt stage changes in the late 1950s are unlikely to be real and the blip in low water stages in 1976 may be due to an error in the rating curve for that year. These indications of variability in the data mean that the record must be treated with caution when drawing conclusions regarding morphological interpretation of the apparent channel changes. However, there are year by year changes which are probably real and may be associated with the movement of large dune bedforms and sand bars through the gauging reach.

The record also shows longer cycles of stage changes for a given discharge over periods of perhaps 5-10 years or so which may be caused by changes in channel alignment and with the swinging of the deep channel across the bed as the flow first hugs the outer bank of the upstream bend at Sara, and then migrates to the inner bank through a periodically re-activated chute channel. In this respect the specific gauge record is consistent with other morphological cycles which are known to take place. However, the main purpose of

Figure 4.7

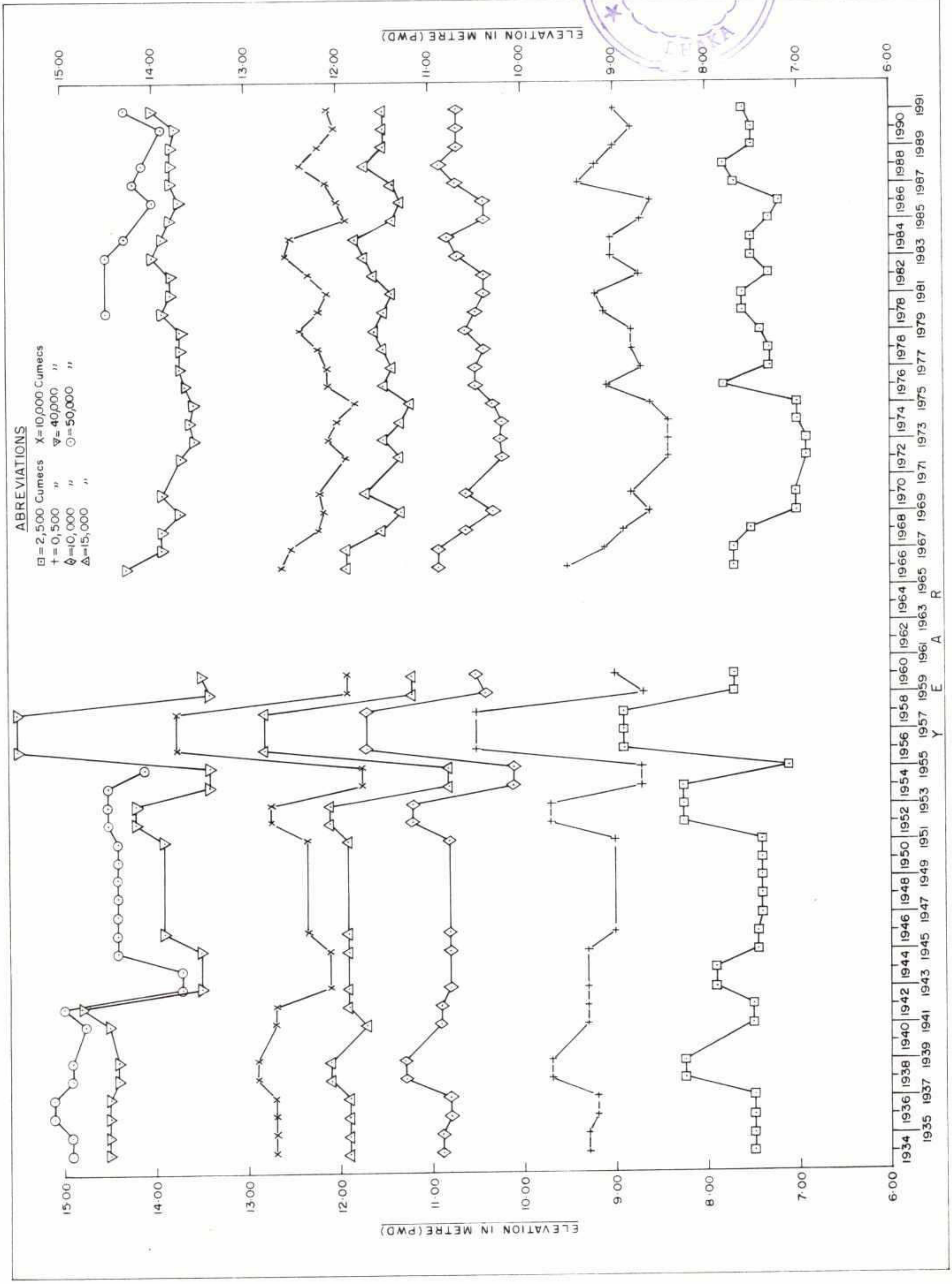






Cross Sections of River Ganges

Figure 4.8



Water level Variation for seven discharges in the Ganges at Hardinge Bridge 1934 – 1991 the specific gauge analysis is to detect longer-term and sustained trends in water levels which are indicative of aggradation or degradation.

Examining the complete record for an overall trend it appears that between 1934 and the late 1950s there was a gentle net lowering of stages which accelerated after 1960. The low point for stages occurred in the early 1970s, when stages for a given discharge were of the order of 1.5 metres below those for equivalent discharges in the 1930s. This could indicate a degradational trend in river morphology. However, the trend was reversed in the 1970s, and with only two short term dips in 1984/5 and 1988, an aggradational trend has been sustained since that time. The overall result is that flow levels in 1990 are no different to the 1930's values, so that there has been no net change over 50+ year period of record.

There are at least three conflicting theories that could explain this record:

1) The observed degradation-aggradation that has occurred is part of a long-term, 50 year <u>cycle</u> of stage level change and does not represent any significant trend in river elevation.

2) In response to some change in river regime in the 1970s a sustained degradational phase was ended and an aggradational trend began. It should be noted that the aggradational trend (if it exists) clearly begins before 1975 and so pre-dates the start of river regulation at Farakka.

3) Apparent changes are associated with changes in gauge location and difficulties in measuring the water level consistently.

Looking at the record as a whole the salient feature is the fact that stages in 1990 are demonstrated to be no different to those of fifty years ago, so that there is no evidence of a trend over this period. Fifteen years is much too short a period for any degradational or aggradational trend to be identified. The difficulties of producing a reliable record over decades should also be recognised. Periodic changes of methodology and datum shifts must be expected to produce noise in the record.

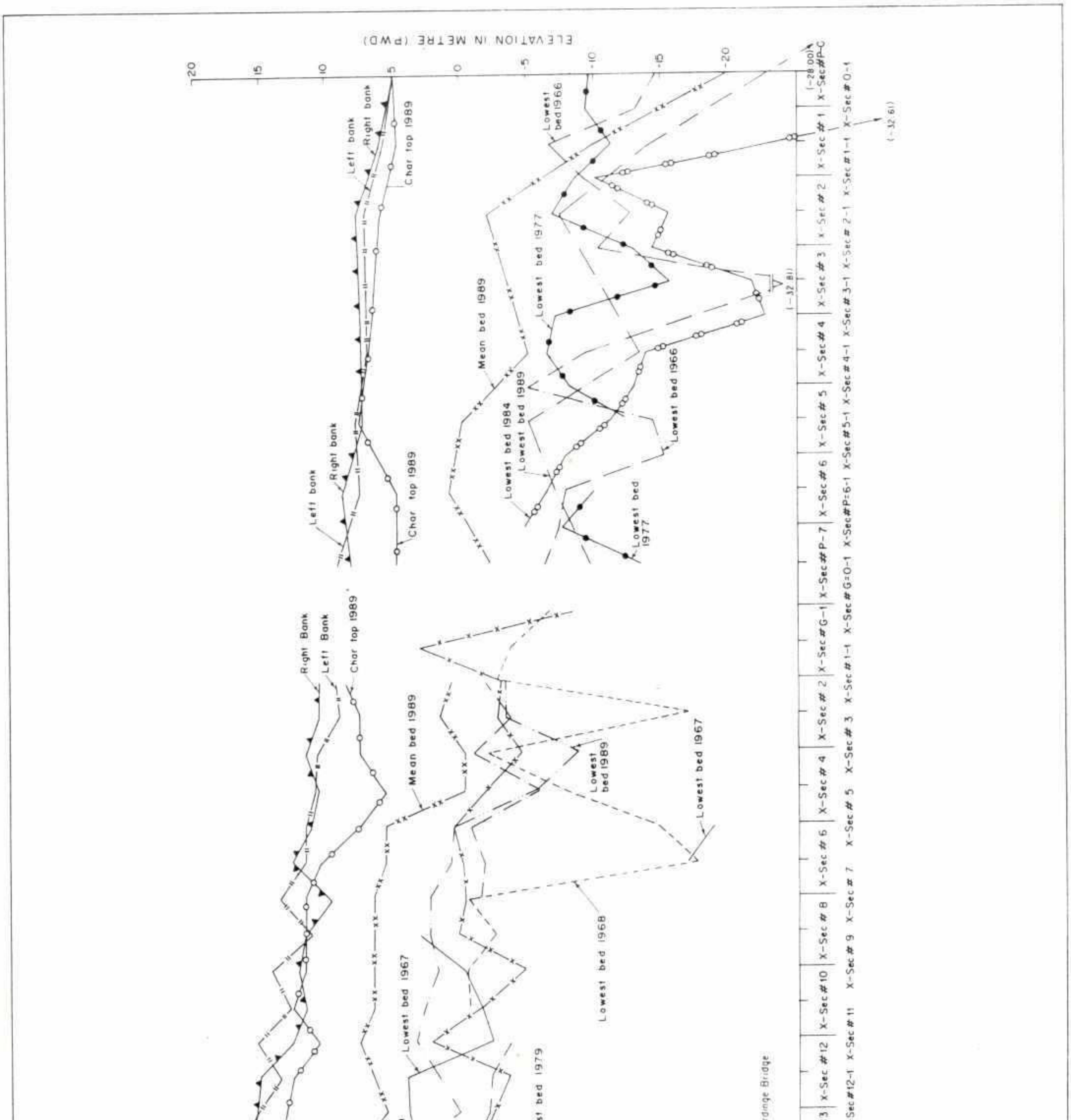
While monitoring of the specific gauge record should be continued in the future so that the current trend can be kept under scrutiny, at present it can be concluded that the specific gauge analysis of the Ganges at Hardinge Bridge shows no evidence of bed aggradation or degradation over the last fifty years.

4.1.5 Long Profile Analysis of Channel and Floodplain

The thalweg long-profiles of the Ganges for 1967, 1968, 1979 and 1989 are given in Figure 4.9. The changes in bed levels are broadly consistent with the specific gauge analyses. The bed elevation of the Ganges was degrading between 1967/8 and 1978/9, but rose markedly between 1979 and 1989 in the reach from the Indian Border to x-section No. 5. In places the 10 year rise is of the order of 5m, which seems unrealistic. From x-section 5 to the confluence with the Brahmaputra there was aggradation in 1967/8 to 1978/9, followed by some degradation. Large fluctuations of thalweg level are associated with shifting of anabranches, bar migration and over channel dynamics, but no clear rising or falling trend of bed levels can be discerned.

Examination of the slope of the channel of the Ganges reveals an increase downstream of the Gorai. This has been proposed as a cause of the observed change in planform from meandering to braided that occurs in the reach. It must be noted, however, that channel slope is a *dependent* variable of planform not a controlling variable. As a river straightens,

Figure 4.9



Long Profile of Ganges-Padma

the channel slope increases, rather than the other way around. It is the *valley slope* which is independent of channel pattern at least over engineering timescales. If this increased downstream of the Gorai, then that could explain a change of planform. Consideration of the structural geology of the area (see Chapter 2, Section 2.3) shows that the Eocene Hinge line runs through the Kushtia area from southwest to northeast. This separates a stable shelf zone to the northwest from subsiding geosyncline to the southeast. The hinge crosses the Ganges roughly at right angles, with subsidence on the downstream side and stability on the upstream side. Hence, geological movements could be producing an increase in valley slope downstream of Kushtia. Indeed such neo-tectonic control is often believed to explain the shift of the Ganges to its present course during the last few hundred years (Basu, 1992). While the topographic map of the region does not show such an increase in slope, and if anything indicates a decrease in slope in the lower course of the Ganges, this is not surprising given the subtlety of neo-tectonic slope adjustment. It is very doubtful that such a slope change could be detected in a regional topography map. Also, with regard to the slope of the water surface of the Ganges, it should be remembered that the base level for the river is water level in the Padma, where the Ganges joins the Brahmaputra. Hence, the effective elevation of the base level of the Ganges varies by several metres annually depending on flow stage in the Brahmaptra. For example, in July and August the Brahmaputra commonly rises more rapidly than the Ganges, so that a backwater curve in the Ganges reduces the water surface slope measurably for tens of kilometers upstream of the confluence. Conversely, usually in September the Ganges reaches peak flow and flow in the Brahmaputra is receding, so that the gradient is steepened significantly. Since large slope changes directly impacting channel form occur annually in the Ganges due to fluvial hydraulics, it is unlikely that the far smaller changes driven by neo-tectonics could have a discernible impact. This does not preclude the fact that major earth movements associated with earthquake activity have triggered channel changes in the past and could do so again in the future.

On the basis of the long-profile study, it may be concluded that the long profile of the Ganges in the study reach responds annually to channel shifting and bar movement, but that no trend of aggradation or degradation can be detected over the period of record.

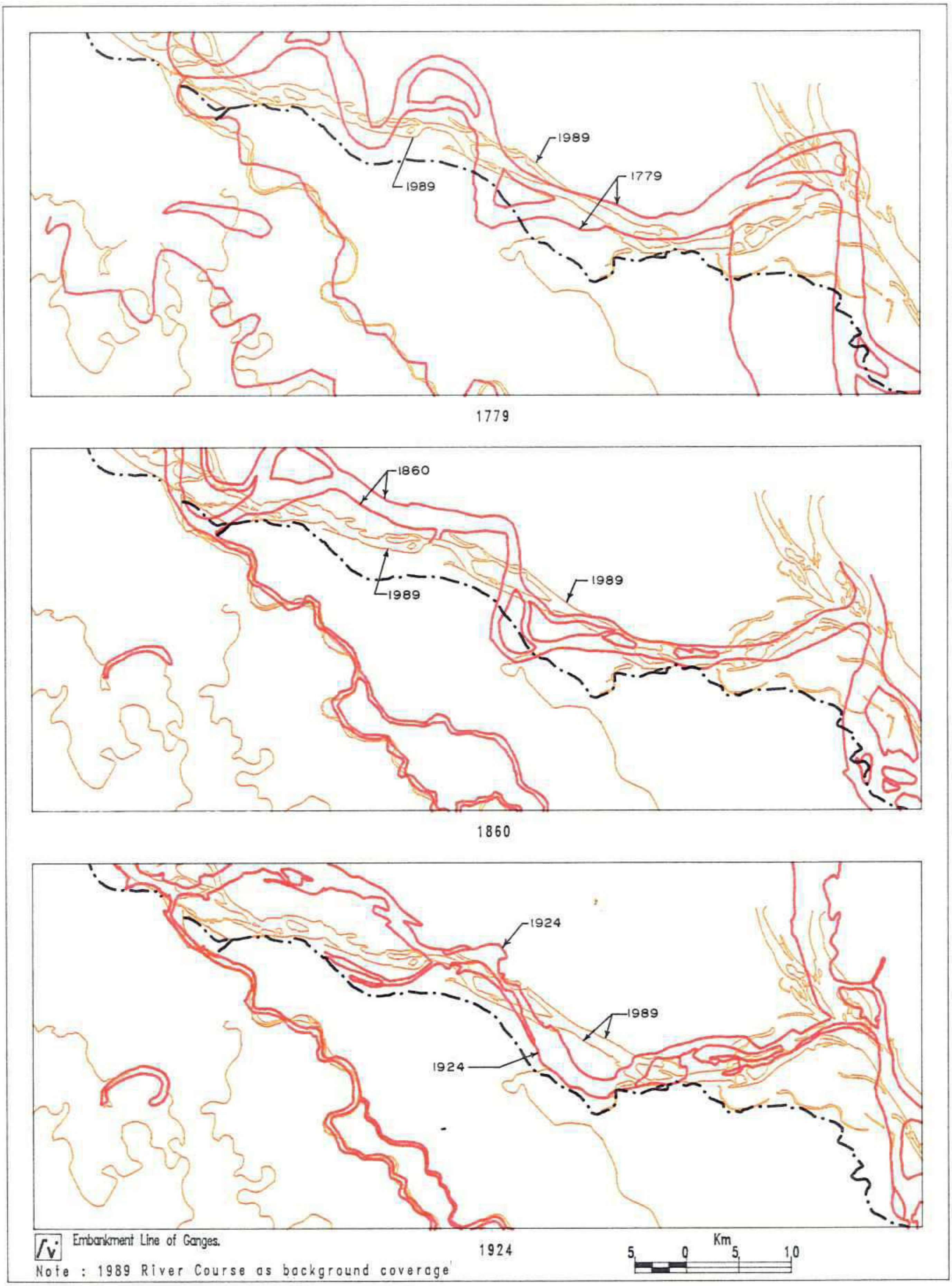
4.1.6 Planform Developments of the River Ganges

a) General Description

Satellite images showing the river in 1973, 1989 and 1990 have been examined to assess the current channel planform. GIS based maps of present and historical channel courses have been prepared. The changes in the Ganges from Hardinge Bridge to the confluence with the Jamuna from 1779-1993 is shown in Figures 4.10 and 4.11. Features of particular note are:

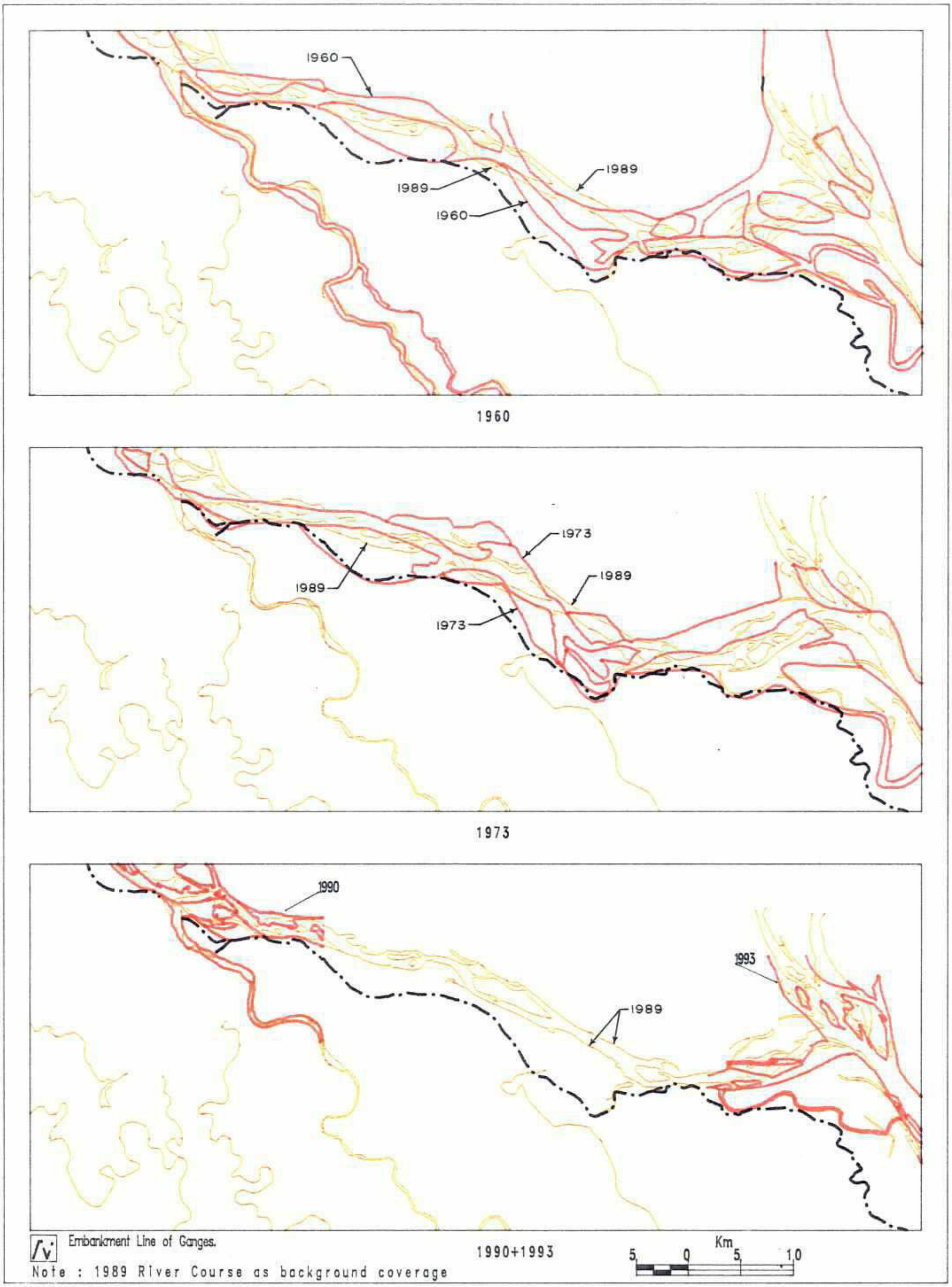
- Stability of the Talbaria Point
- The embayment at the Chandana which is not currently occupied but developed to an extreme extent in 1973. The railway line was eroded at this point earlier this century and set back. The Ganges embankment also follows a similarly cautious line.
- Some lengths of the embankment are at risk
- The left bank at Aricha is a very stable point
- There are a number of stable nodal points at which any barrage should be located though none of these gives a channel that is always in the same position.

Figure 4.10



BANKLINE MOVEMENT OF GANGES 1779 – 1924

Figure 4.11



BANKLINE MOVEMENT OF GANGES 1960–1993

R3

b) Sinuosity

The sinuosity (straight channel length divided by reach length) and wavelengths of the Ganges have been studied using a series of maps from 1778 onwards, the dates of which are given in Table 4.2. The maps cover different reaches of the river.

TABLE 4.2

Ganges Meander Geometry

YEAR	SINUOSITY	AVERAGE WAVELENGTH (km)
From maps, Mathabhanga to Jamuna		
1778	1.5	16
1870	1.3	32
1952-58	1.15	39
1989	1.24	29
From "BWDB" maps used for calculating bank line movements, Mathabhanga to Gorai		
1780	1.6	
1855	1.4	
1875	1.4	
1910	1.2	
1955	1.1	
1961	1.05	
1973	1.2	

An examination of the maps, together with satellite images for the post 1973 period, indicates that at the time of the first maps (18th century) the Ganges had a very clearly apparent meander pattern with an average wavelength of about 16 km and a sinuosity of about 1.5 from the Mathabhanga to Faridpur (see Table 4.2). One hundred years later (in 1870) its sinuosity had decreased to 1.3 ie it was becoming straighter, while its average wavelength had increased to about 32 km ie the river gives the appearance of being "stretched". The increase in wavelength would usually be taken to indicate an increase in discharge but, during this period the dominant discharge should have decreased as the Teesta, which had fed into the Ganges, avulsed eastward to join the Jamuna. It is probable, however, that flows to the Bay of Bengal via the Hoogly were reducing at this time, thus increasing the discharge of the Ganges overall. Also at this time the Jamuna flow had become diverted, joining the Ganges to form the Padma.

The Ganges' maps for the area between the Mathabhanga and the Jamuna,show that after 1870, and up to 1950s the sinuosity continued to decrease while the average wavelength remained between 30 and 40 km. Between the 1950s and 1989 the sinuosity increased slightly to 1.24 and the wavelength reduced to 29 km. Consequently there has been almost doubling in wavelength and marked decrease in sinuosity compared to the first map in 1778 ie from about 16 to 29 km and 1.5 to 1.24 respectively. The overall decrease in the average sinuosity is confirmed by the "BWDB" maps for the Mathabhanga to the Gorai, decreasing from 1.6 in 1780 to 1.2 in 1973, reaching a minimum value in of 1.05 in 1961.

The planform of the Ganges can be sub-divided further as, at the present time, the offtake of the Gorai on the Ganges appears to mark the dividing line between two contrasting planform sections of the Ganges after 1778 when it had a strongly developed meandering pattern throughout. Above this point the Ganges still meanders though with a longer wavelength and below it, while meandering is apparent, sinuosity is much lower and there is a tendency for the channel to wander with a number of nodal points spaced at between 24 km and 28 km apart ie at about the meandering wavelength.

Further commentary and analysis of the movement of the Ganges near to Hardinge Bridge are given in Section 5.

4.1.7 Morphological Modelling

A morphological model of the Ganges was developed by SWMC and is described in their report (1992). The model was set up with idealised cross sections of standard properties but a special constricted reach around the Hardinge bridge was included. The observed rating curve was matched and the model showed the dynamic movement of the bed around the Hardinge Bridge and the creation of a large bar downstream that took several years to re-erode after a large storm.

4.1.8 Morphological Assessment

The Ganges is broadly in a state of dynamic equilibrium and will not experience marked overall changes of bankfull channel form and position in the immediate future.

Continued acceleration of the post-monsoon recession and reduction of dry season flows due to upstream abstractions will lead to the morphological adjustments within the active river corridor, through changes of the bed topography and the nature of the low flow channel.

Detrimental impacts of the accelerated post-monsoon recession and reduction of dry season flows on in-stream and riparian habitats and on distributary channels will continue.

4.1.9 Effects of Embankments on the Ganges Right Bank

In the case of the Ganges, the present course of the river in Bangladesh is several hundred and, possibly, several thousand years old so that the planform has had time to fully mature. An equilibrium planform for this river should have been established by now, but the historical fact is that even though during different periods both meandering and braiding have dominated the planform neither has become permanently established and elements of both patterns can always be detected in the appropriate map or satellite image. This is typical of the behaviour of a wandering river that is hunting for a non-existent 'equilibrium planform' through constant transition between braiding and meandering.

The width of the active corridor produced over the centuries is larger than both the meander amplitude and braided width of the channel. Consequently, erosive encounters between the present channel(s) and the flood plain margin have become less common. At present only about 15% of the flood plain margin is under attack by the flow, including a substantial portion which occurs where the active corridor meets the edge of the erosion resistant clays in the northern valley side at Rajshahi and Sara. Embayments and nodes in the line of the flood plain along the margins of the active corridor are readily discernible in false colour satellite images.

The practical implications are that provided the edge of the river corridor is used as a guideline, embankments can be built quite close to the existing channels without unreasonable risk that they will be breached due to bank erosion. This is especially so on the southern flank because historically the net movement of the active corridor has been northwards. The risk is not zero however, as both embayments and nodes in the flood plain edge are still susceptible to erosion should the river happen to attack them and this is always a finite possibility.

There seems little reason to suppose that the embankment should have any marked morphological impacts on these two very large rivers in the short to intermediate term unless they are actually aggrading significantly. On the present evidence it cannot be concluded that the apparent aggradational trend in the recent stage-discharge analysis and long-profile changes is anything more than a periodic oscillation.

Impacts of Rivers on Embankments

A much more immediate problem to engineers is the impact of the rivers on the embankments. Without instigating major bank protection works like those along the Brahmaputra right bank, the only sensible policy is to keep back from the active morphological corridor of the river. This is a term describing the zone of valley floor that is being actively re-worked by the channel due to its dynamic meander and/or braiding tendencies. Alluvial channels need room to work in, and the river's morphological corridor defines a strip of land that is very liable to be occupied by the channel within any short span of time. The probability of any particular hectare of ground being converted into a hectare of open water over about a ten or fifteen year period is approximately constant everywhere within the active corridor. Since channel movements may result from incremental erosion, char deposition, re-occupation of old sloughs and cut-offs and major avulsions with about equal probability, predictions of future changes of alignment within the active corridor for more than a year or two are essentially and practically meaningless.

Unless it is decided to train the river and through controlling both the morphological pattern and, to some extent, the flow and sedimentary regimes, then building any permanent structure in the geomorphologically active corridor is unwise, including unprotected flood embankments.

A sensible course of action is to stay back from the active corridor. This is relatively safe because although the corridor itself is widened from time to time and although it moves across the flood plain, the rates and patterns of corridor movement are slower, more orderly and easier to predict than those of the river channel or anabranches.

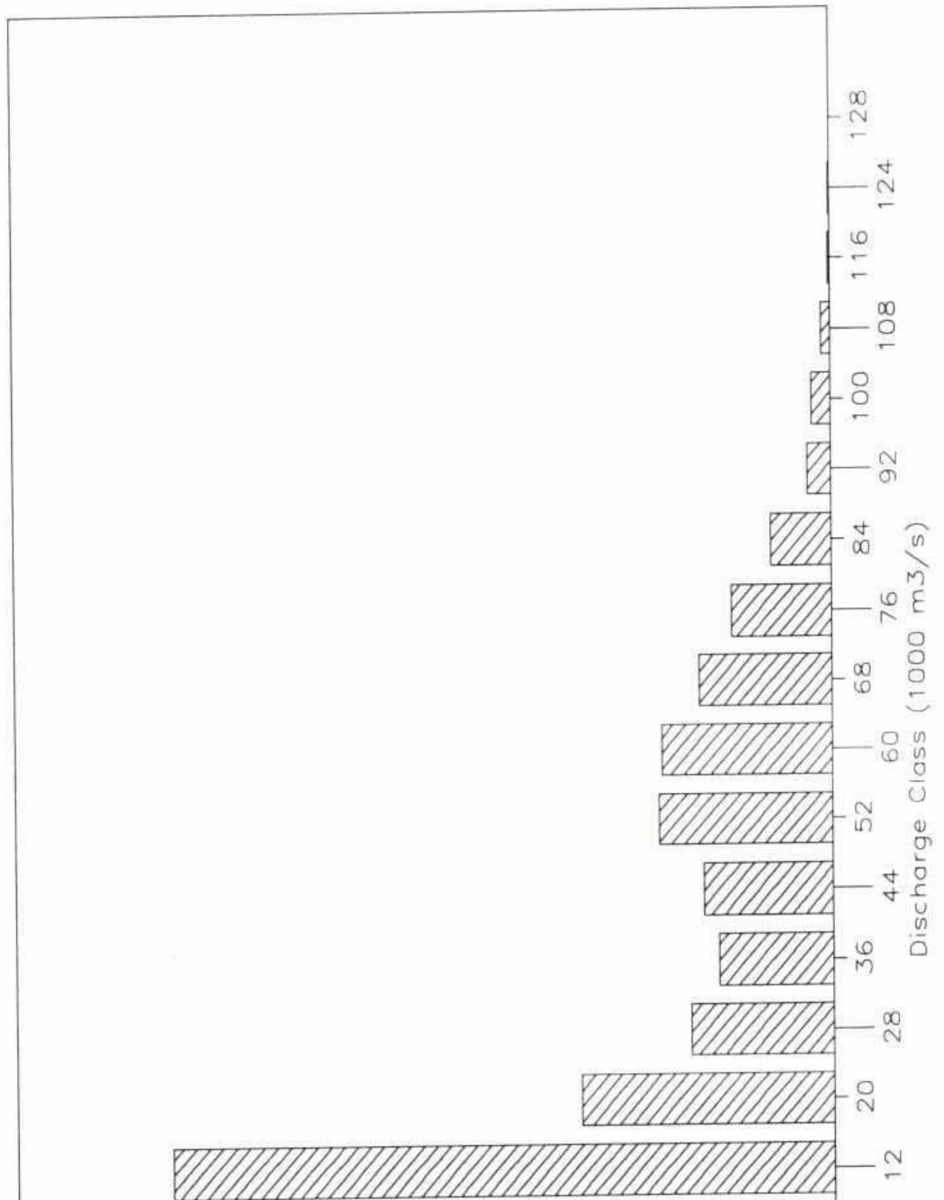
Given that structures should be kept out of the morphologically active corridor, the remaining practical problems which remain are those of correctly identifying the edge of the active corridor and of predicting if retreat of that edge due to channel erosion is liable to threaten the embankment during the design lifetime of the project. Solution of this problem is greatly aided by satellite imagery and GIS comparisons of historic changes.

4.2 River Padma

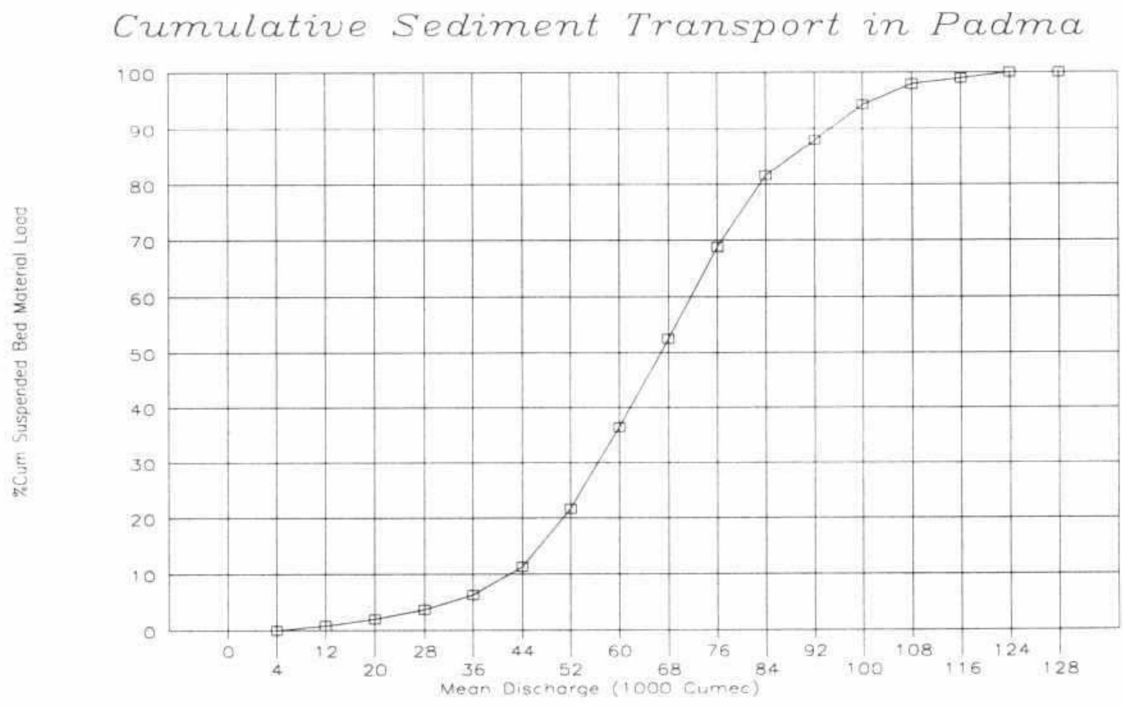
4.2.1 River Padma Flow and Sediment Regime

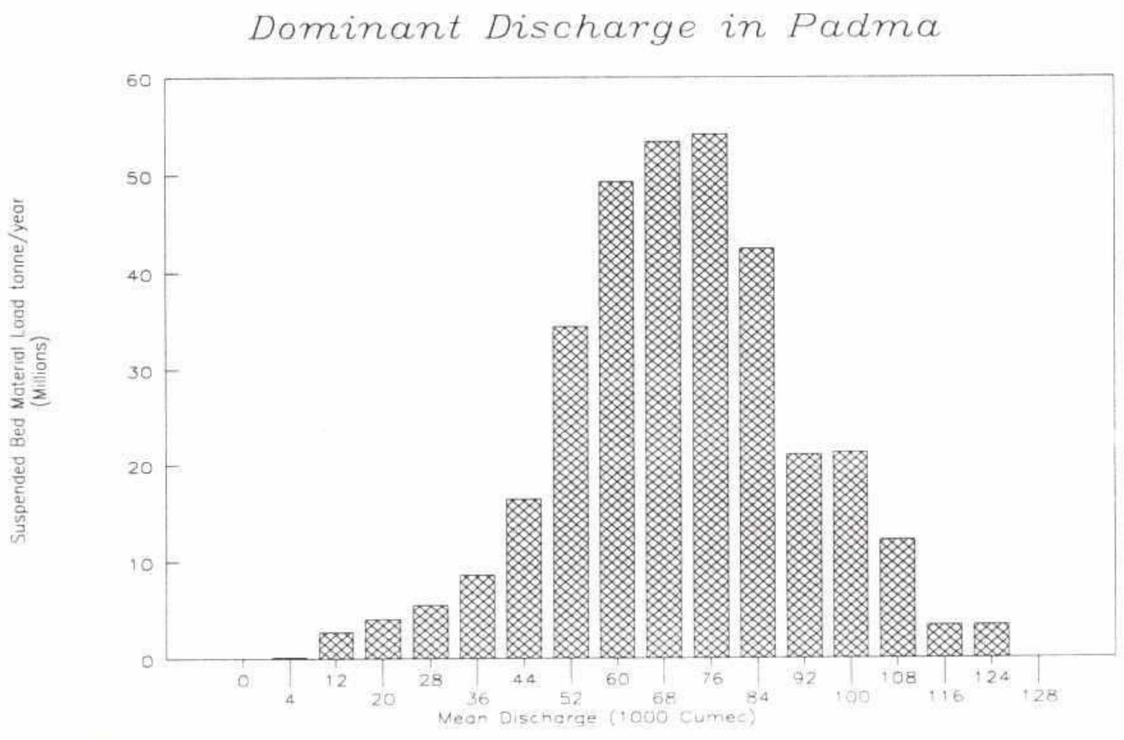
The dominant discharge was calculated for the two gauging sites on the Padma at Baruria and Mawa. The Baruria site has the more complete record and Mawa is affected by tidal influence at low flows. The sediment rating curves for both have exponents similar to those found for Hardinge Bridge on the Ganges possibly indicating that similar constriction effects (or in the case of Baruria, confluence scour effects) may be taking place. The flow frequency, dominant flow and cumulative sediment transport for both sites are shown in Figures 4.12 to 4.15 and the results are given below. The dominant flow for the Padma

Figure 4.12



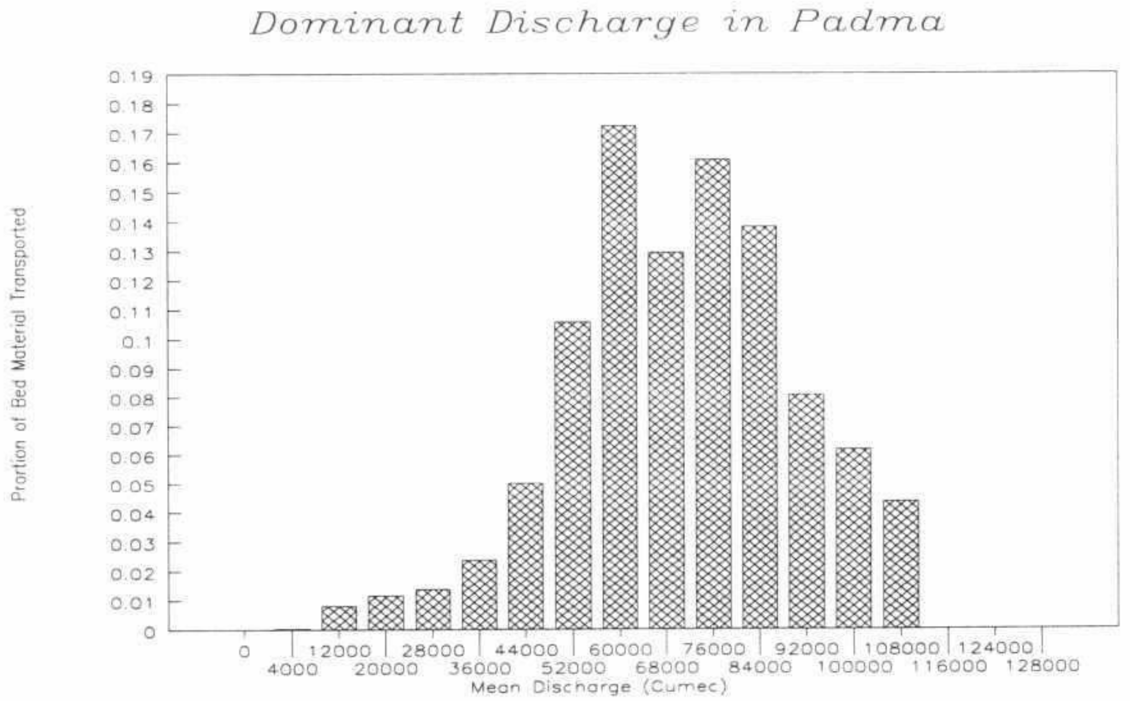
Flow Frequency in Padma
Baruria / Goalundo 1965-1989

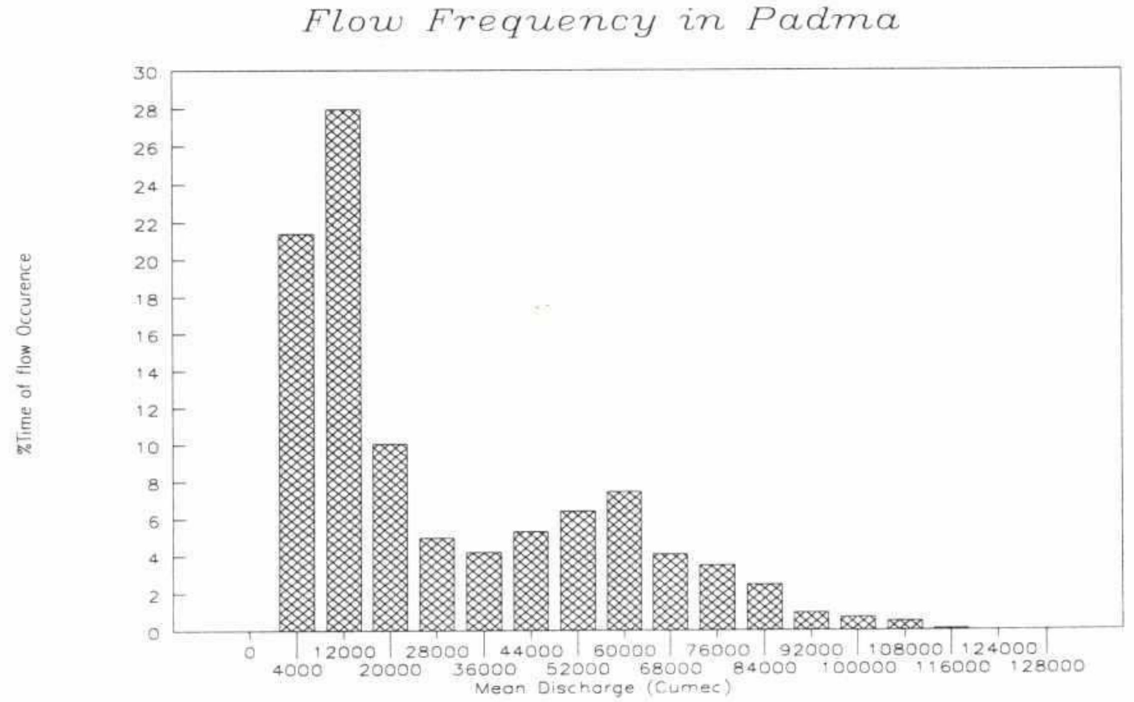




Cumulative Sediment Transport & Dominant Discharge in Padma Baruria / Goalundo 1965-1989

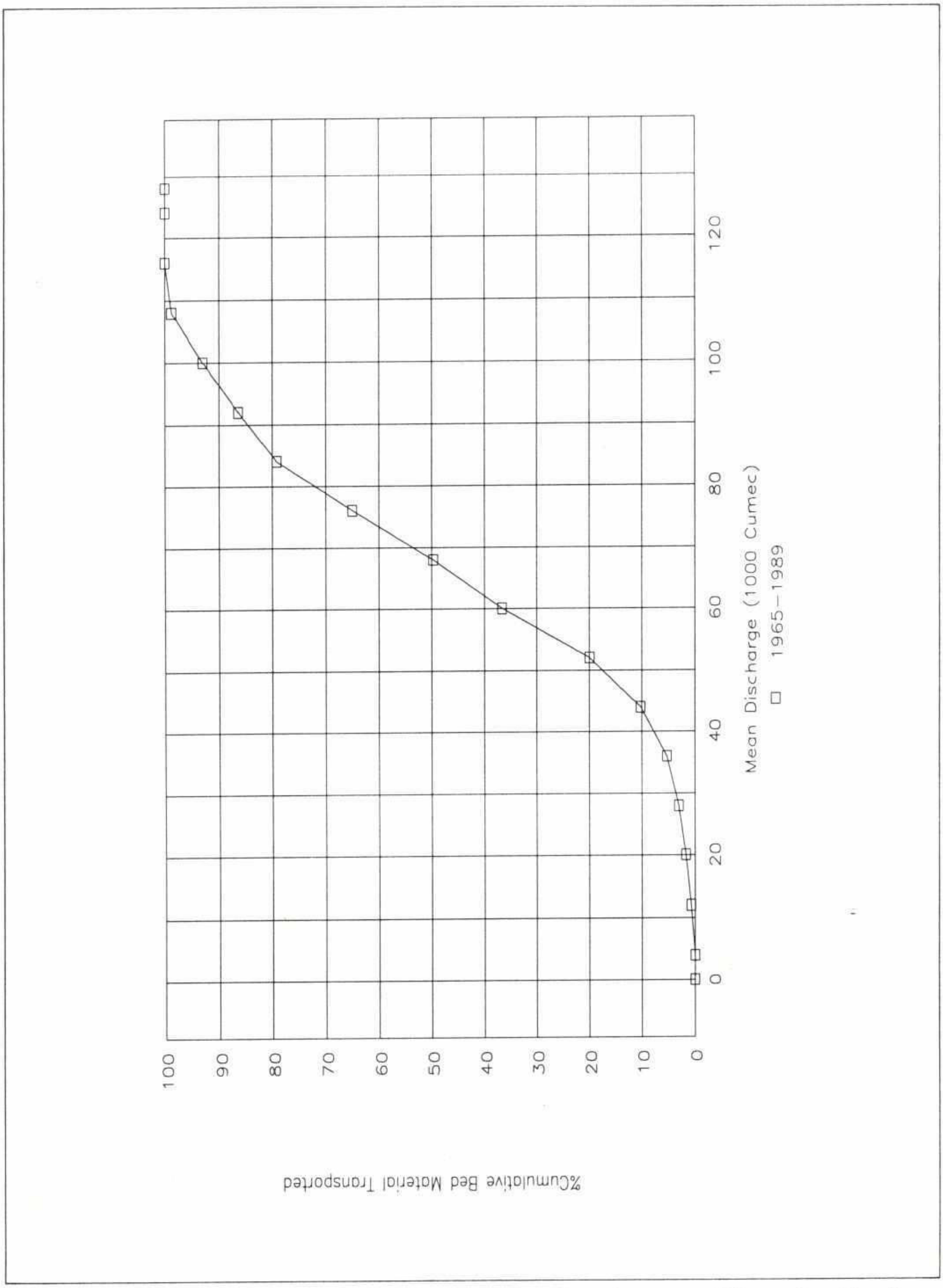
Figure 4.14





Dominant Discharge & Flow Frequency in Padma
Mawa 1966-1986

Figure 4.15



Cumulative Sediment Flux in Padma Mawa 1965–1989 is not as clearly defined as that for the Ganges probably because of the effects of two very large rivers converging. The 1 in 2 year return period peak daily flowrate is 88000 m^3/s.

River	Location	Dominant Discharge Range m^3/s (prop.cum.load)
Padma	Baruria	50,000 to 83,000 (0.2-0.8)
Padma	Mawa	42,000 to 85,000 (0.2-0.8)

4.2.2 Cross Section and Regime Analysis

Cross Sections of the Padma are shown in Figure 4.16. The sections are broadly adjusted to the dominant flows.

4.2.3 Specific Gauge Analysis of the Padma at Baruria

In Figure 4.16 it can be seen that the period 1960s to early 1980s shows a degradational trend which reverses in the mid-1980s. The net result is a small lowering of flowlines in the last twenty five years, but the aggradational trend in the 5 to 7 years up to 1989 is strong. This is consistent with the trend in the record for Hardinge Bridge and could indicate system wide aggradation. If this were to be verified it would have serious implications for the Southwest and Southcentral Regions. However, the absolute magnitude of the stage changes is relatively small in a river of this size and could easily be explained in terms of bed adjustments and changes in flow configuration associated with channel shifting in the Ganges and Brahmaputra Rivers upstream of the gauging station. In any case the period of record is really too short for a specific gauge analysis to definitely identify an aggradational or degradational trend in a river of this great size.

The specific gauge analysis for Mawa is less clear due to gaps in the record as shown in Figure 4.17. Overall the same trends as for Baruria are present.

While monitoring of the specific gauge record should be continued in the future so that the current trend can be kept under scrutiny, at present it can be concluded that the specific gauge analysis of the Padma at Baruria and Mawa show no clear evidence of bed aggradation or degradation over the last twenty five years.

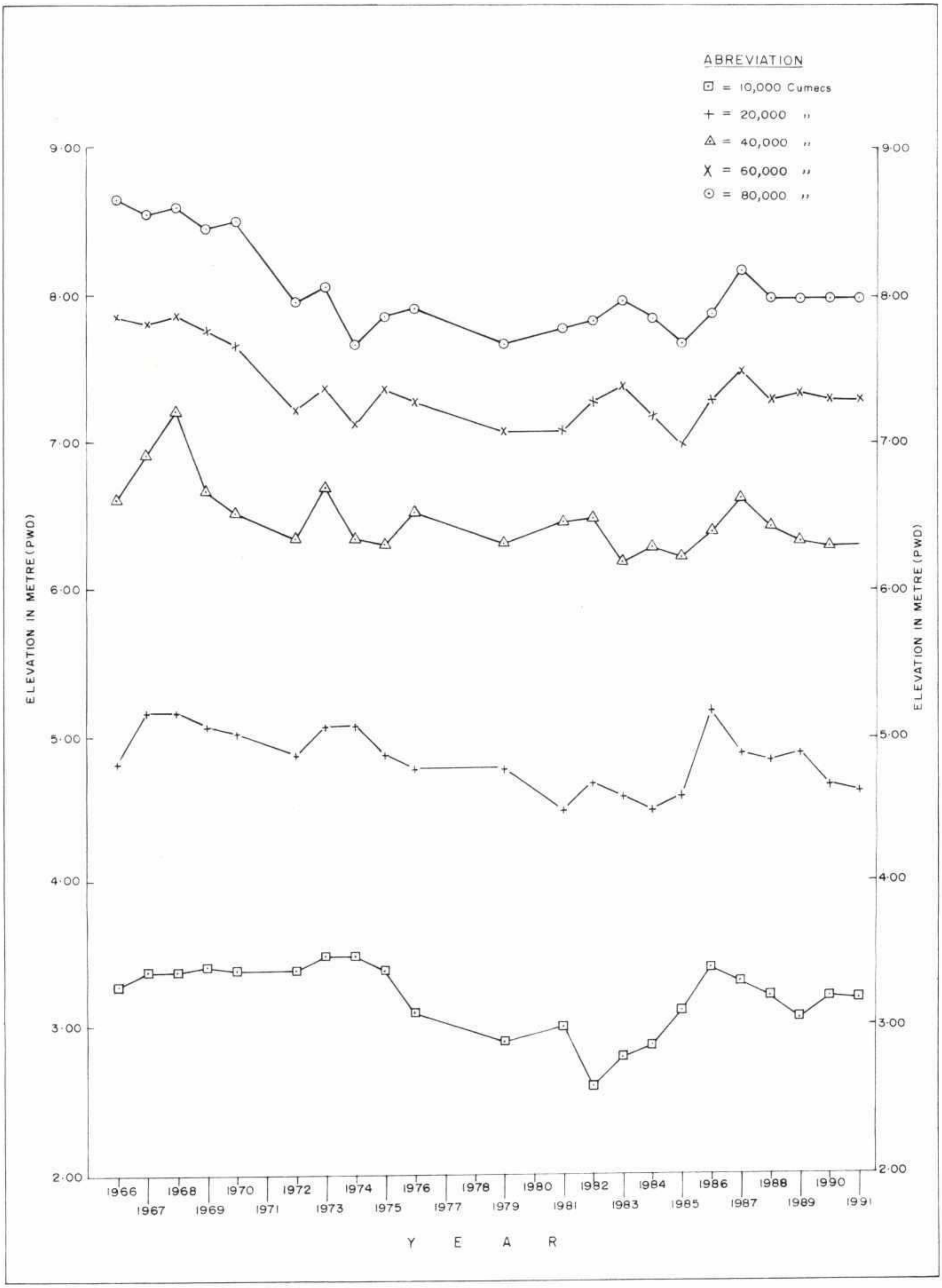
4.2.4 Long Profile Analysis

In the Padma, the amplitude of the pool and crossing variations in bed level, and the movement of bars along the channel induces large variations in thalweg level that make it very difficult to discern any net change. However referring to Figure 4.16 there is no clear evidence of any aggradational or degradational trend during the period of record.

The slope of Padma channel is about 0.5×10^{-4} (5cm per km) which is relatively steep for such a large water course and this to some extent explains the morphology of the channel. Padma Bed material D16 = 0.02mm, D50 = 0.09mm, D84 = 0.2mm (FAP 9B, 1990).

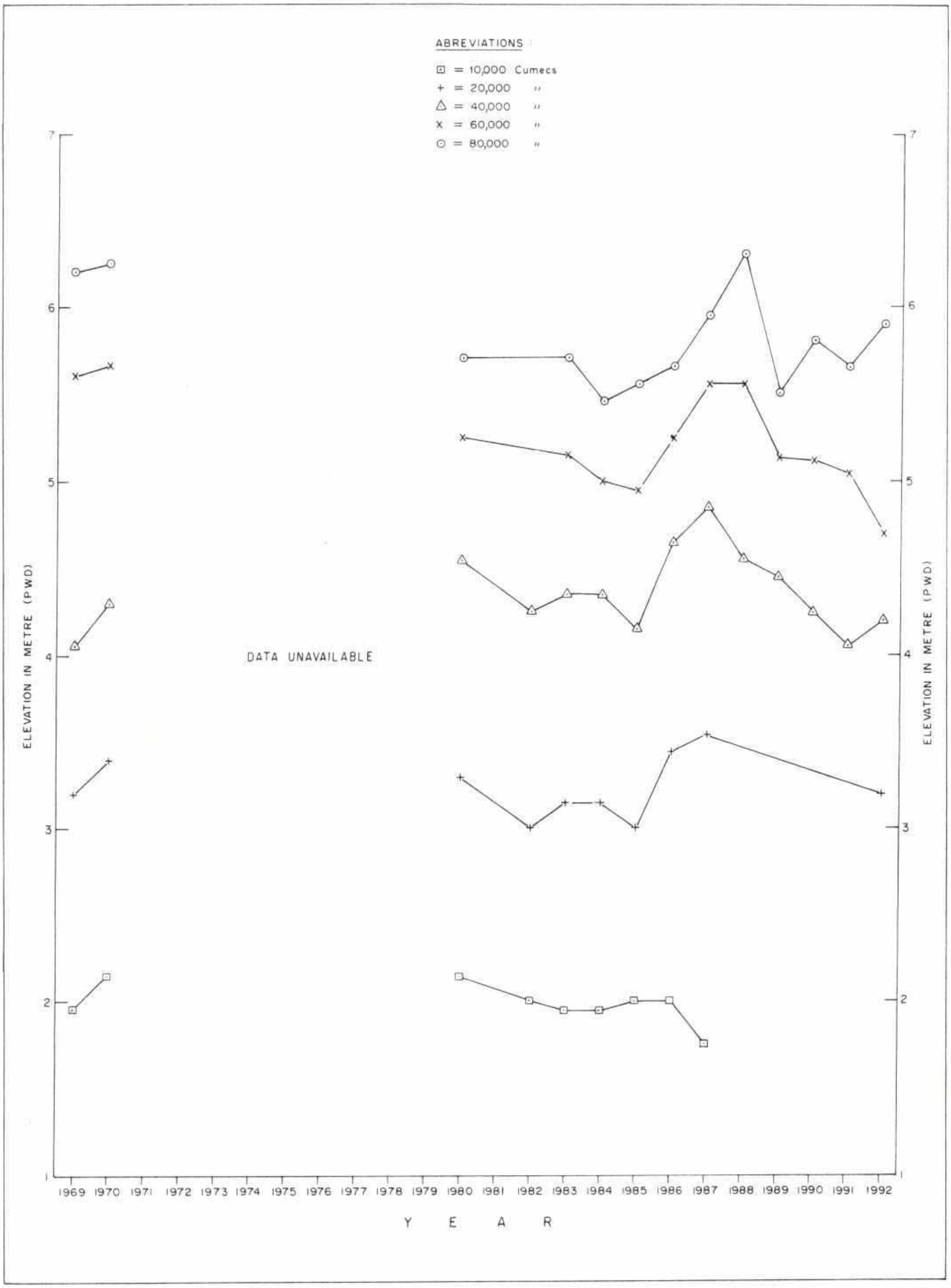
The combination of a large and seasonally highly variable discharge together with a relatively steep slope produces enormous stream power. Such high power rivers characteristically adopt a braided pattern, especially when the sedimentary has a heavy supply of sediment in the form of bed material load and when the banks are formed in

Figure 4.16



Water level Variation for five discharges in the Padma at Baruria 1966–1991

Figure 4.17



Water level Variation for five discharges in the Padma at Mawa 1969–1992 easily eroded silts and sands. On this basis, the long profile of the Padma is consistent with a braided planform. However, resistant bank materials are known to occur in the banks, particularly on the north side of the river and on both sides around Shariatpur. This may be limiting the braiding intensity below that expected from long profile analysis. This finding was first put forward by Klaassen (FAP 9B, 1990) and is supported in principle here.

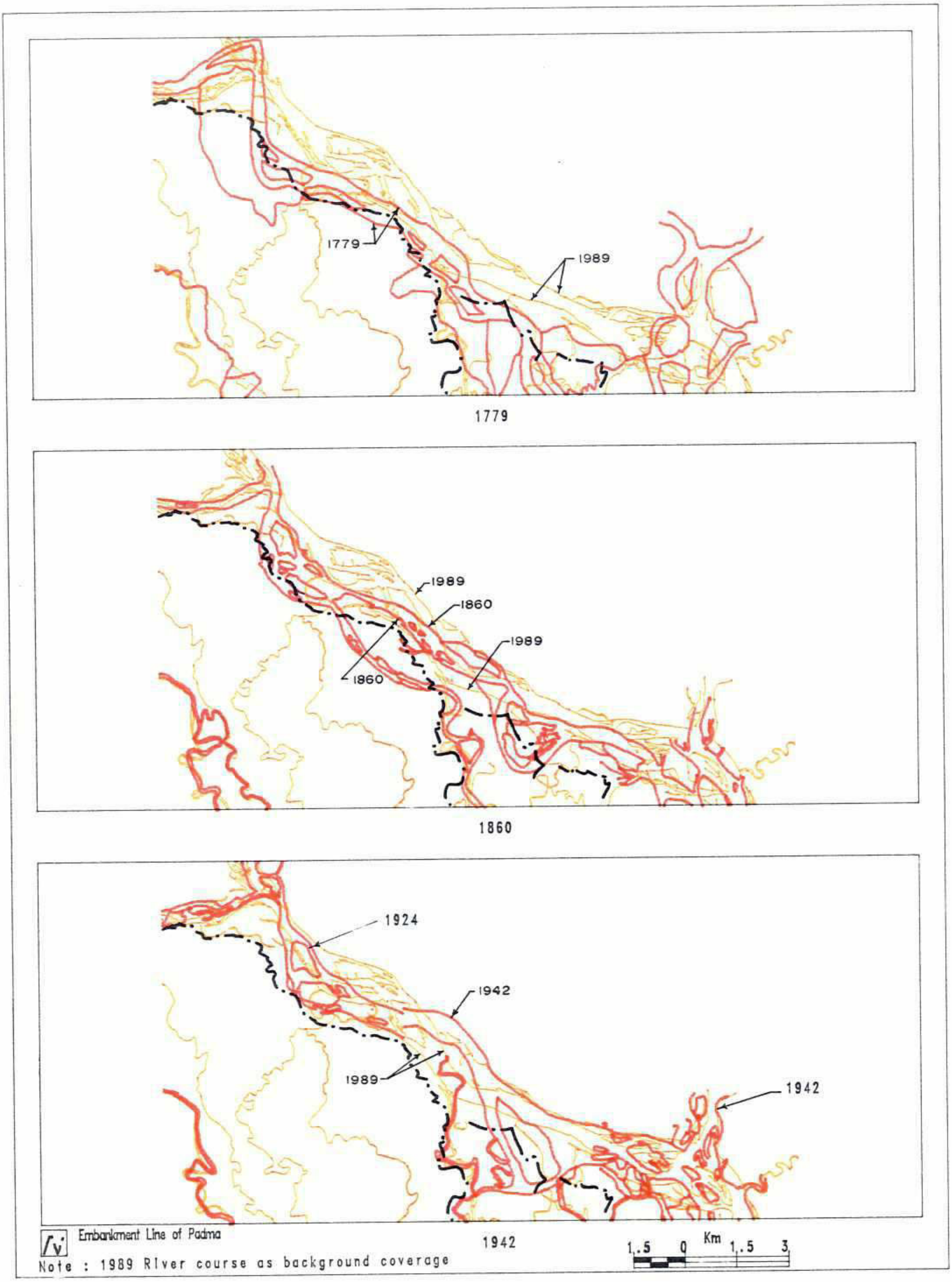
4.2.5 Planform Developments of the River Padma

The planform of the Padma displays elements of meandering and braiding, but its present planform is unusually straight for an alluvial river, with the channel orientated almost directly southeast from the confluence of the Ganges and Brahmaputra Rivers at Goalanda to a very large bend in the Padma where it is joined by the much smaller Upper Meghna River. This straight alignment has not always been present. As recently as 1973 there were still major loops cut into the south bank, in the areas of Faridpur and the off-take of the Arial Khan. The north bank also has scars left by large embayments in it. The general spacing of the scars and past embayments is consistent with their being formed by bank erosion in meander loops and around medial braid bars during past phases of planform evolution from a straight to either a sinuous or braided pattern. Historically, island chars in the braided channel are found to be about 15km long and based on satellite images. FAP 9B (1990) suggest that chars move downstream in the Padma with a periodicity of 15 years however the movement of the upper part of the Padma seems to follow a longer cycle. The movement of the bank from historical mapping and satellite imagery is shown in Figures 4.18 and 4.19.

The width of the river varies markedly along its length. For example, at Mawa the width is only about 3.5km, but this widens to 12-15km in only 20km channel length due to char formation. FAP 9B (1990) concluded that the width at Mawa must be constricted due more resistant bank materials. In fact the Geological map of Bangladesh does show resistant materials in the banks of the Padma, but they actually occur opposite the wider reach downstream of Mawa, where the river is attacking the banks at present. It is found that bank elevations at the narrow point are a little higher than elsewhere, being +6m PWD at Mawa compared to say Chandpur at + 3.5m PWD. This could be the reason for the narrows, but a more plausible alternative explanation based on river planform dynamics is that the narrow point at Mawa is a node in the braided pattern which is relatively narrower and more stable than the island (char) reaches to either side. The number of sub-channels in the Padma is related to the width of the primary channel. At Mawa there is just one channel, two anabranches usually occur in the wider reaches. This is a surprisingly low braiding intensity for a river of such high stream power and heavy sediment load and Struiksma and Klaassen's analyses suggests a width of 15km and a more braided pattern than that observed. Hence, morphologically, the Padma is less braided and much narrower than would be expected given the flow regime (Ha, 1990). It may be concluded that the Padma potentially has the stream power to braid more intensively and, therefore to widen its channel markedly. The historical trends fortunately show no such tendency.

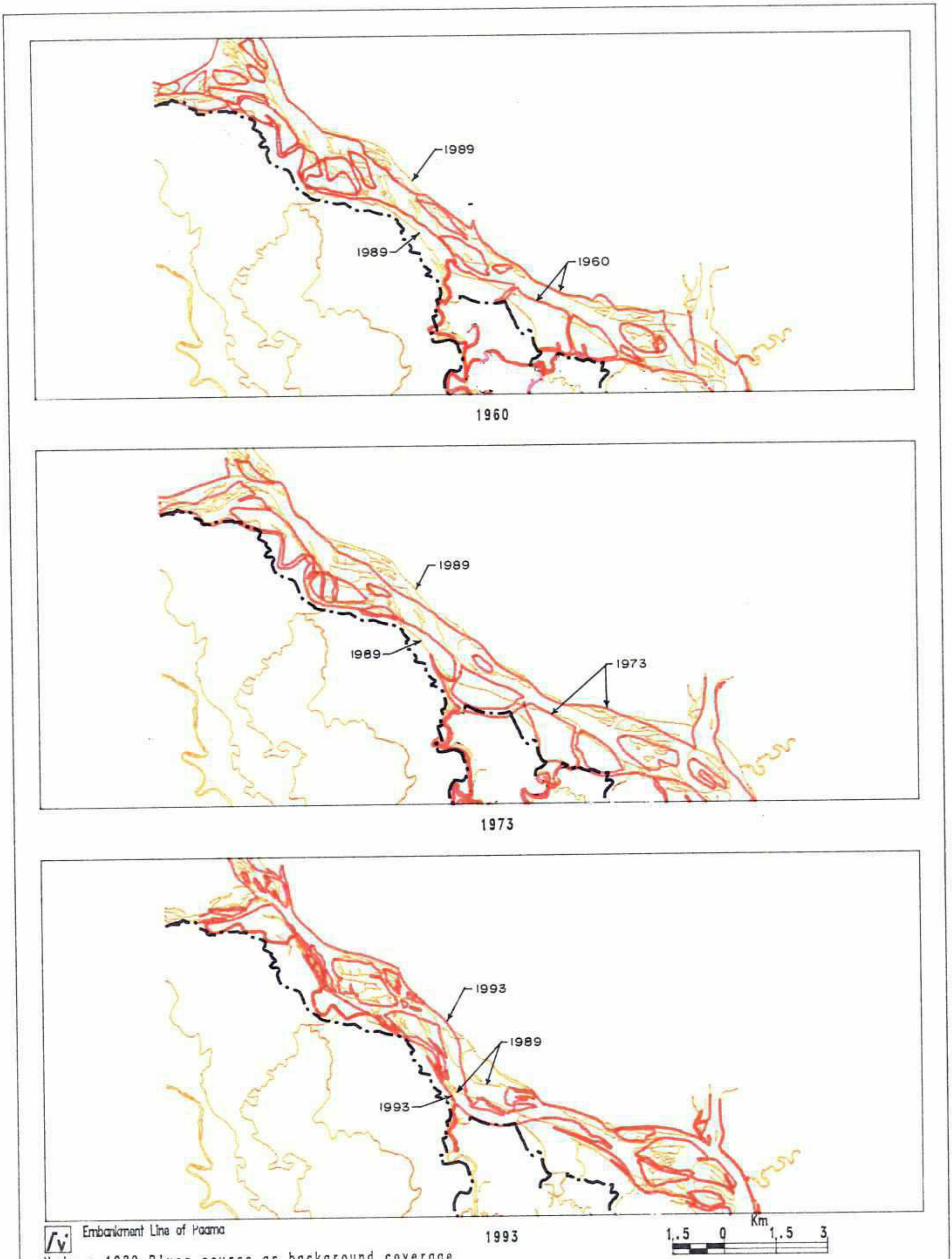
The large bend at the confluence with Upper Meghna is a prominent feature of the river's planform. It has a radius of about 15km and an arc angle of around ninety degrees. The width is also reduced at the big bend being about 2.5 to 4km. The main channel switches alternately between a northern, outer bank and a southern chute channel around a large medial char that periodically forms just upstream of the bend. Some years both channels are open. However, in this divided reach while the southern channel can sometimes be completely blocked, the northern channel is always kept open by the Upper Meghna flow. Basat Sarker et al., (1984) found periodicity of 20 years in char movement and switching of the main channel from north to south. When flow is predominantly in the southern channel extreme bank erosion takes place at the opposite bank (near Eklashpur). When the northern channel predominates, erosion is concentrated further around the bend around

Figure 4.18



BANKLINE MOVEMENTS OF PADMA 1779–1942

Figure 4.19



Note : 1989 River course as background coverage

BANKLINE MOVEMENT OF PADMA 1960 -1993

Chandpur. Hence, the configuration of the approach flow has a direct impact on the pattern of flow and distribution of erosive attack of the outer bank in the bend.

When migrating bars reaches the confluence with Meghna they are eroded rather than rounding the bend, and the sediment load merges into the mobile, macro-point bar at the inner bank. This behaviour is consistent with bend flow theory as demonstrated by Seminara's (1988) theory of bed wave propagation which explains why chars are absorbed by the point bar in a big bend.

These attributes of the big bend are consistent with the behaviour of curved channels in general, and on this basis it can confidently be predicted that without heavy and continuous efforts to stabilise the right bank in the reach around Eklashpur and Chandpur the bend will migrate downstream and through sustained erosion of the outer bank downstream of the bend apex extending to the bend exit. Conversely, success in stabilising the outer bank by the creation of one or more hard points will result in distortion of the outer bank line as the Padma attempts to out flank the protection. This could lead to large-scale changes in channel configuration both at the bend and further downsteam with serious implications for the South Central Region.

Haskoning (1990) produced sketch maps of channel positions for the years:1952, 1960, 1973, 1976, 1977, 1980, 1984, 1987, 1988, 1990 and these are reproduced in Figure 4.20. Movement is continuously eastwards. They also present predictions for the future evolution of the Padma at the Meghna confluence. By definition such predictions must be somewhat subjective and speculative. However, the fairly orderly behaviour and natural constraints on planform changes - particularly the limits imposed by the outcrops of Chandina Alluvium both north and south of the Padma just upstream of its confluence with the Meghna, make predictions possible.

Further analysis of the movement of the Padma is given in sections on the Padma spill channels the Arial Khan (Section 5.4) and the Old Kumar (Section 6.8).

4.2.6 Morphological Modelling

Studies of the impact of upstream works such as embanking the Jamuna and building the Jamuna bridge were completed as part of FAP 1. The modelling carried out showed that the Padma had sufficient capacity to absorb changes in sediment load or flow regime with very little change in bed levels.

4.2.7 Morphological Assessment

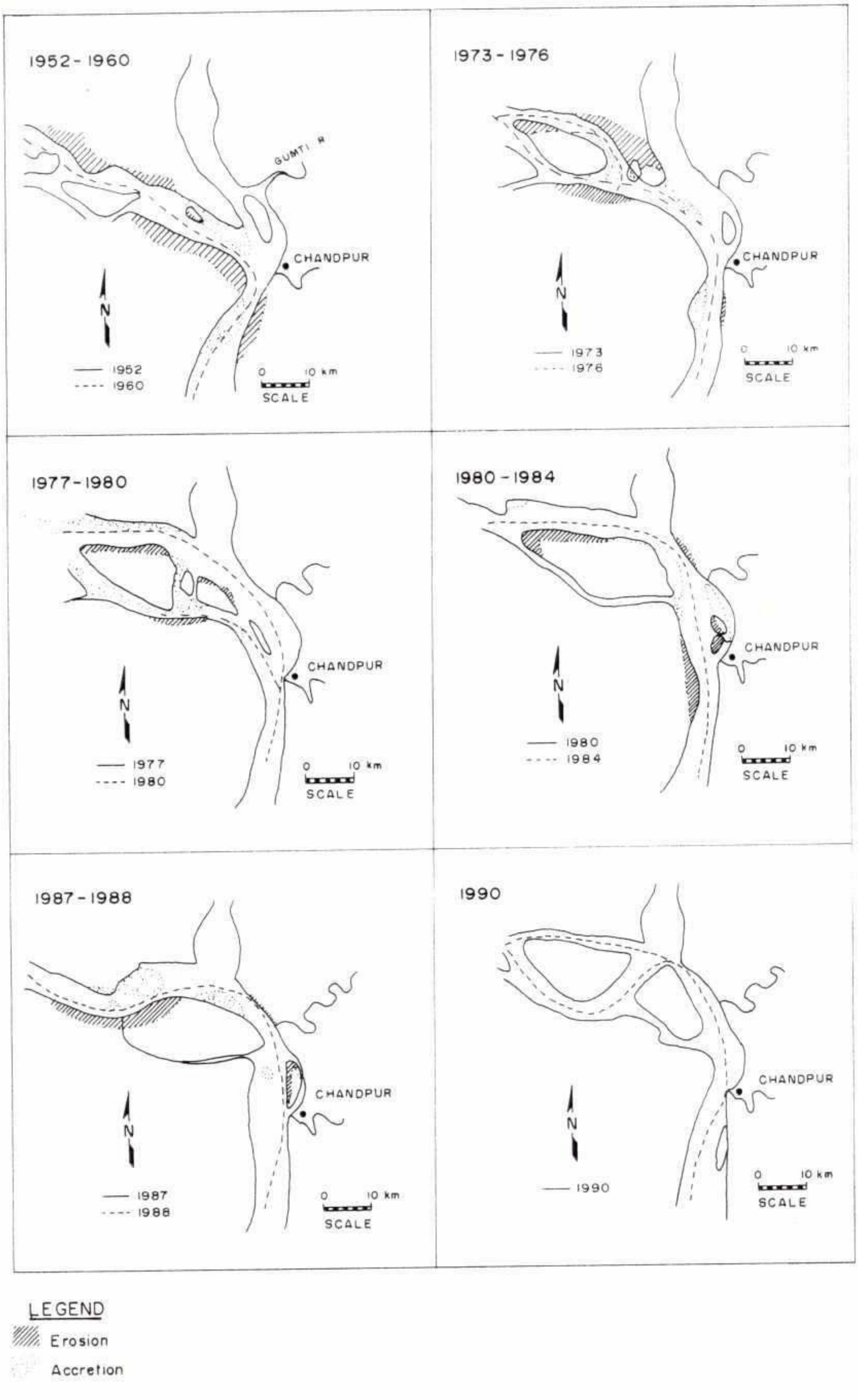
The Padma is still adjusting to the avulsion of the Brahmaputra and has not yet attained a state of dynamic equilibrium. It will therefore continue to adjust its morphology and widen its active corridor for some years.

The present planform is unusually straight and active corridor widening might be achieved through development of meander loops and braid bar embayments.

As the course of the Padma is partially constrained by resistant materials and terraces (Chandina Alluvium), no major avulsions or shifts are expected.

The rate of corridor widening should decrease through time, reducing the frequency of erosive attack of the flood plain.

Figure 4.20



Haskoning Map of Padma, 1952 - 1990

4.2.8 Effect of Embankments on the Right Bank of the Padma

In terms of its geomorphic age and adjustment, the Padma River is perhaps more similar to the Brahmaputra than to the Ganges, as it does not seem yet to have completely adjusted to the joining of the Ganges by the Brahmaputra (Jamuna) less than 200 years ago and the vast increase in water and sediment inputs that resulted. In a dynamic fluvial environment like Bangladesh the form and dimensions of the actual river channels adjust annually so that channel morphology quickly responds to changing water and sediment inputs, but adjustments of the active corridor take much longer. To develop dynamic equilibrium in the width, slope and sedimentary features of the corridor requires the movement of enormous quantities of sediment even measured on the scale of transport possible in the Padma. On average around one billion tonnes of silt and sand a year move through this reach and although that is a great deal of sediment, it only equals the storage in a single large island char (say 15km by 2.5km by 15m thick). The active corridor between Goalanda and the Meghna confluence is 100km long, about 15km wide and contains both chars of with bar top elevations near flood plain level and scour holes up to 35m deep. Given the sheer amount of sediment to be rearranged (over $5 \times 10^{10} m^3$), establishing a mature river corridor must be a long-term process. The Padma apparently has yet to complete this task and in all probability erosion will occur along both flanks of the corridor in the foreseeable future as the width of the active corridor increases to accommodate the oscillations of the larger river. The chances of flood plain erosion, either due to meander loop formation or to deflection of anabranches around island chars, are therefore much greater than they are along the Ganges.

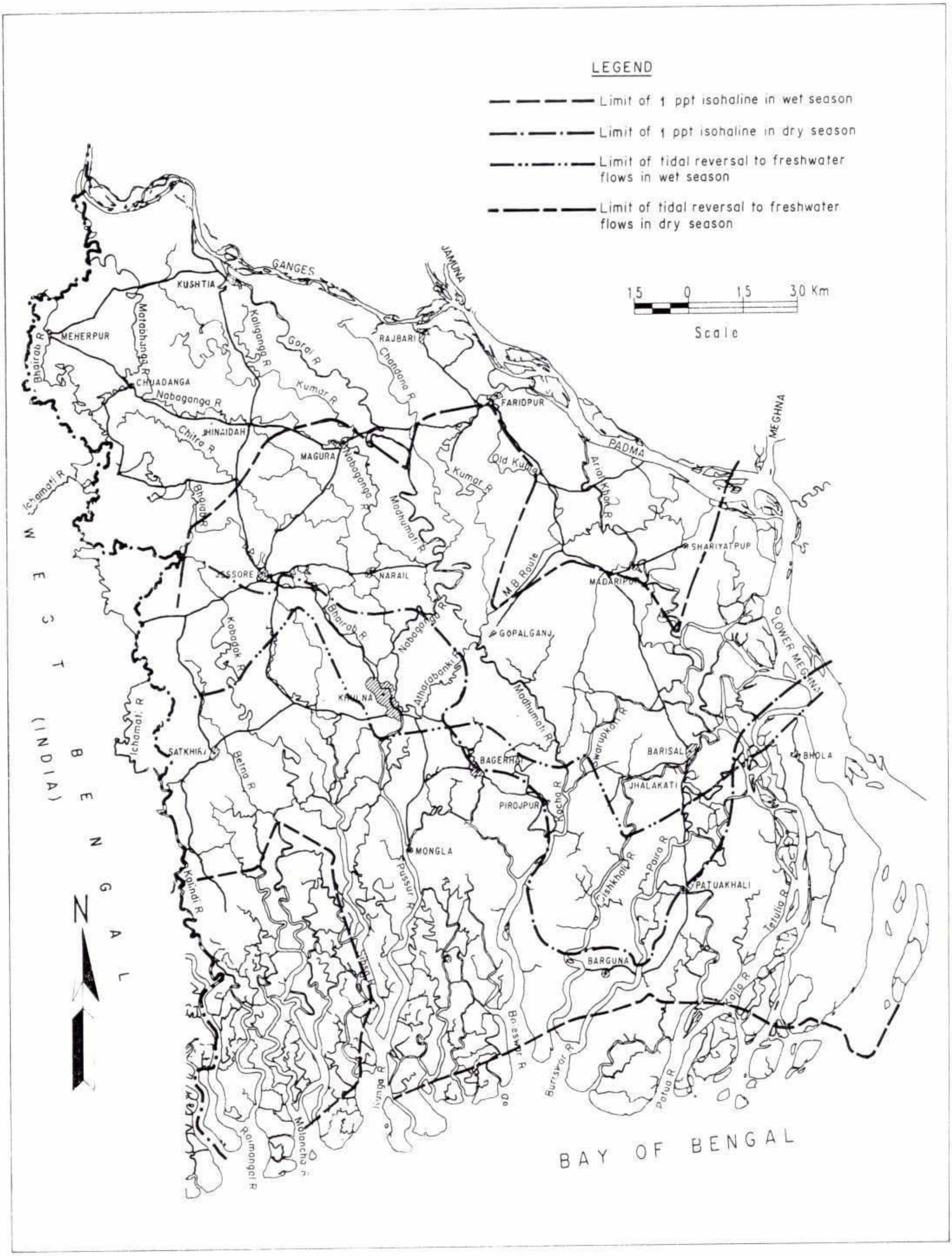
In the case of the Arial Khan the high level of channel shifting and active erosion along the right bank of the Padma, at rates approaching 1 km/yr since 1989, effectively precludes the construction of a regulating structure in the foreseeable future. While building a flood embankment close to the eroding margin of the active corridor may be just about acceptable, the greater investment in a regulator of the size required on the Arial Khan (which has a dominant discharge of 2,000 cumecs) could not be justified owing to the morphological risks involved.

If control structures cannot be built on the Arial Khan offtakes then further embankments must also be constructed along the open spill channels to prevent flooding behind the Ganges-Padma right embankment. With regard to embankments along the spill channels, these rivers too have active corridors which should not be encroached into. However, because the spill channels are predominantly meandering in planform it should be easier to define the likely width of the active corridor and to predict the likely points of erosive attack at the corridor margins by flow in the meandering channel. In the case of a single-thread meandering channel it is the meander belt width which defines the active corridor and this is a function of the meander amplitude. Examination of existing bends and ox-bows during a fieldtrip in September 1992, discussion with the district engineers and inspection of past and present satellite images demonstrates that there are in fact finite limits to the amplitude of meander bends that develop along spill channels like those of the Arial Khan. Limiting values of meander amplitude are a function of the meander radius of curvature, channel width and bend arc length. It may be possible to use the "cut-off ratio" defined by Klaassen in his work for FAP-21/22 (FAP-21 Interim Report, 1992) to predict limiting meander amplitude and, hence, river corridor width to be maintained when spacing embankments.

Padma Embankments - Summary

The practical implications of this analysis of the planform of the Padma are that great care must be taken over the placement of embankments because the flood plain margin at the edge of the active corridor is rather more liable to fluvial attack and retreat than is that of the Ganges. However, recognition of the planform control provided by the Chandina

Figure 4.21



Limits of 1 ppt Line and Tidal Flows in the Wet and Dry Season

Alluvium on both banks, together with a historical analysis of scars left by meander loops and braid embayments together with consideration of the location of crossing and node in the planform suggests that for much of its length the southern margin of the active corridor does present a reasonable alignment for an embankment. The most difficult reach is that around the mouth of the Arial Khan, where the river is already close to the southern margin and shows no sign of ceasing its southern shifting. The situation further is complicated by the existence of the offtake which has three separate spill channels. However, examination of the topography and vegetation patterns south of the river between the Arial Khan and the Chandina Alluvium reveals scroll bars and channel scars with alignments and geometries that indicate that they were formed when the Ganges flowed to the west of the Chandina Alluvium nearly 200 years ago. The area has not been reworked by the spill channels since then, because their easily discernible flood plain features can easily be identified and are only found further to the west. Also, it is apparent that the area has not been reworked by the Padma, because the flood plain features would then be orientated east-west rather than north-south.

The likelihood of the embankment being eroded would seem to increase downstream as shown in Figures 4.18 and 4.19. While it is acceptable to put the line of the embankment through this area at the edge of the present active corridor, the margin of safety is rather less than it is along the rest of the right bank of the Ganges-Padma.

4.3 Lower Meghna

4.3.1 Flow and Discharge Regime (Tidal)

The study of the lower Meghna focusses less on the river per se than the influence of the river on the land and spill channels.

The Lower Meghna is formed by the confluence of the Padma with a much smaller river, the Upper Meghna. For comparison, the dominant discharge of the Upper Meghna at the Bhairab Bazaar gauging station is 9,500 cumecs, compared to 70,000 cumecs for the Padma at Mawa. The dominant range of flows for the Upper Meghna at Bhairab Bazaar is 6,500 to 11,000 cumecs. This range of flow transports 65% of the total load of sediment. Discharge of the Lower Meghna varies from 10,000 to around160,000 cumecs (100 year flood).

In their study of the Lower Meghna , FAP 9B (1990) find bankfull discharge to be 82,500 cumecs (based on the rating curves). They further report that 80,000 cumecs is the dominant flow based on "the flow that carries most sediment". This is consistent with the results of this study for the two tributaries making up the Lower Meghna which have dominant discharges of 70,000 and 9,500 cumecs respectively. In a strongly tidal channel defining the dominant flows in terms of the freshwater discharge only must be limited in its usefulness.

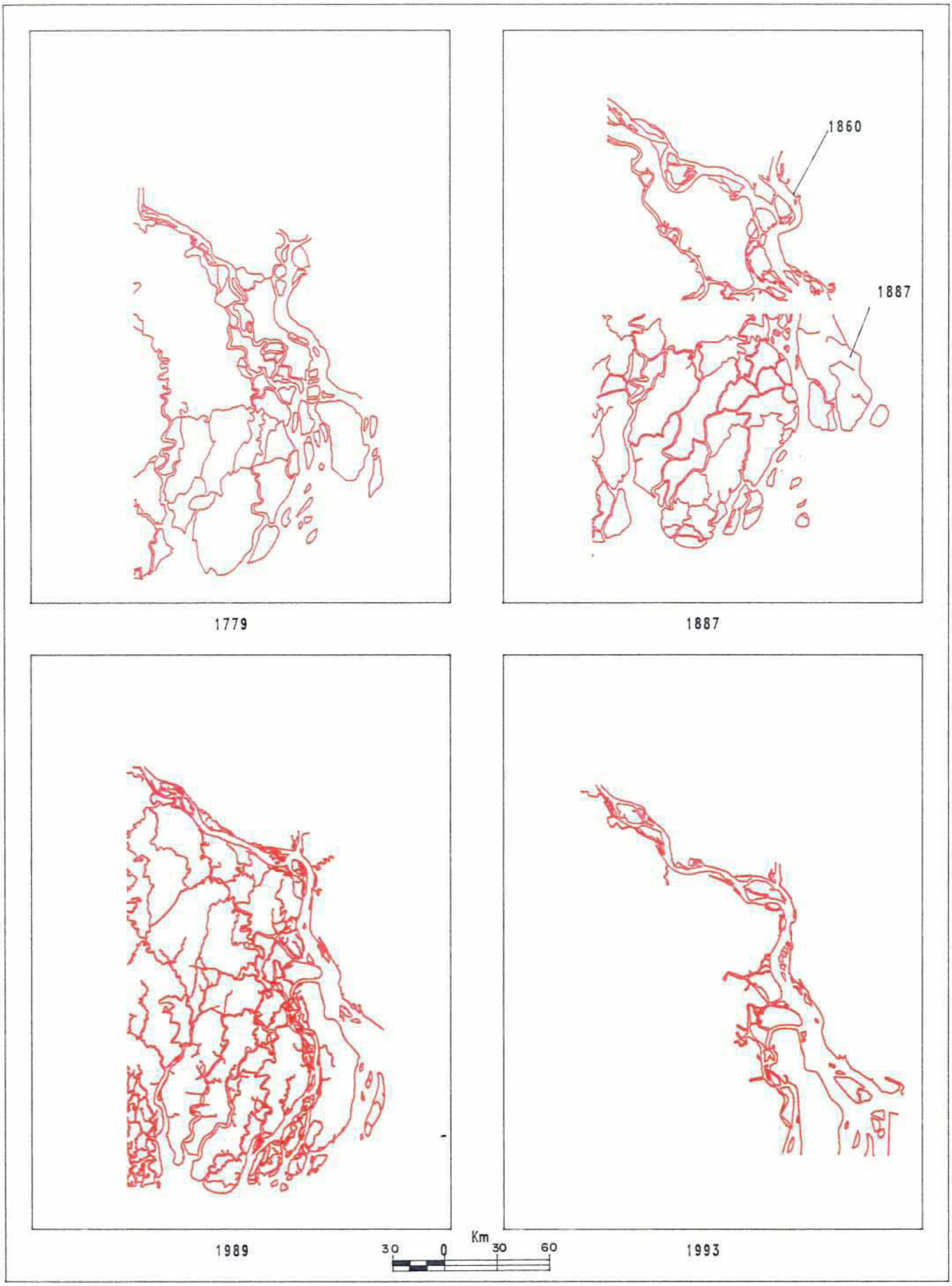
The slope of the Lower Meghna is 0.4×10^{-4} but the river is strongly tidal, with a tidal range at Lower/Upper Meghna confluence of 0.4m.

The sediment regime has not been established but bed material sample indicate D16 = 0.02mm, D50 = 0.14mm, D84 = 0.19mm (FAP 9B, 1990) which is similar to the Padma and Ganges.

4.3.2 Salinity Regime and Tidal Flows

Saline water is completely flushed out of the estuary each monsoon season but later with the decreasing freshwater saline intrusion increases with the 1ppt line reaching above the

Figure 4.22



Historical Changes of Lower Meghna

Hilsa channel as shown in Figure 4.21. The increase in tidal flows from the confluence is shown in Figure 4.21 illustrating the overwhelming tidal movement of water in the estuary which helps to drive freshwater down the spill channels as the tide travels faster up the deeper channel.

4.3.3 Planform Developments of the Lower Meghna

The planform of the Lower Meghna is complex. Unlike the Padma and the Ganges, the Lower Meghna is an estuary that is influenced by both freshwater runoff and tidal action. It carries great amounts of water and sediment to the Bay of Bengal and is by far the most geomorphically active part of the delta. This is clear both from the rapidly changing configuration of the main channel and its shifting left bank spill rivers such as the Tetulia, and from the constant creation and destruction of land along the channel margins and in islands along the river course. The historic changes of the river are illustrated in Figure 4.22.

Activity is most pronounced around Haimchar on the left bank approximately 15 km downstream of Chandpur. Until tweny years ago this was the site of a large bend but since that time this bend has cut-off and the river is almost straight. While the average depth of the Lower Meghna depth is about 7m, deep scour holes are associated with the outer banks at bends. Maximum scour of 24m has been observed off Chandpur (mean 12m), and 10-15m scour has occurred historically near Haimchar.

Galay (1980) reported the sequence of planform developments up to that time. The Lower Meghna had been displaying gradual migration eastward for years and as a result the area south of Chandpur has been endangered for decades. Maximum migration rate south of Chandpur has historically been 425m/y. At the Haimchar bend to the east side of Mear char gained water as the bend at Chandpur migrated eastwards. Between 1963 and 1973, the left bank at Hajimara (30km d/s Haimchar) retreated at 100m/y.

Haimchar bend in 1973 was a pronounced curve that was developing a cut-off. The channel length of the bend was 35km, but the cut-off was only 20km, presenting the opportunity for channel shortening. While the cut-off process took many years, most of the cut-off occurred during big floods in 1974 and 1988. In 1974 the high runoff had a particularly heavy impact on the bend at Haimchar: the eastern cross-char chute channel enlarged to become the main channel. As a result the left bank eroded 600m very quickly and west channel silted up. Thus a major change of channel alignment and position was completed in months or years, demonstrating the propensity of the Lower Meghna for large channel shifts to through a combination of predictable incremental erosion and rapid channel avulsion.

In this connection, Abul Kalam (1983) noted that erosion and accretion rates are in fact episodic. Short periods can have very high or low rates depending on sequence of floods or droughts. The period 1968-1980 was found to represent normal shifting rates, while the period 1973-80 was strongly affected by 1974 flood.

FAP 9B (1990) presented sketch maps of channel positions for the years:1952, 1960, 1973, 1976, 1977, 1980, 1984, 1987, 1988, 1990. They also presented some predictions of planform changes in the future which are speculative, although the fact that the big bend at the junction of the Padma and Upper Meghna Rivers is anchored by the outcrops of Chandina Alluvium in the north and south banks gives some confidence that channel position can be predicted. Generally, it is predicted that stabilisation of the left bank at Chandpur will deflect the main flow across the channel of the Lower Meghna towards the Tetulia offtake. This could be expected to maintain a strong flow of fresh water into the South Central region for some years to come, although bank erosion along the Tetulia and the other distributaries might be expected. Also, bank erosion and westward channel shifting of the Lower Meghna may threaten the right bank opposite and downstream from Chandpur, with serious implication for land loss and the breaching of any embankments constructed close to the bankline in this reach.

In their predictions of channel evolution in the Lower Meghna, FAP9B (1990) envisage erosion at Haimchar reducing in rate as the new channel settles down, perhaps averaging 20 m/y. Overall the trend is for continued eastern movement.

4.3.4 Morphological Assessment

On the basis of the current study the following comments can be made on the morphology of the Lower Meghna:

- The Lower Meghna carries a vast amount of sediment to the Bay of Bengal and some active island building, channel siltation and re-erosion will continue.

- Overall sedimentation will exceed erosion so that the delta will pro-grade slowly, but subsidence and the efficiency with which silt is carried out to sea will continue to limit the rate at which new land is created.

- Impacts of left bank stabilisation and land reclamation that distort the natural planform pattern and evolution of the estuary will continue to produce channel instability and shifting as the river attempts to re-adjust channel form to fluvial and tidal processes.

- Right bank distributaries of the Lower Meghna will adjust to the changing inputs of water and sediment through erosion and/or deposition, which may have important resource implications for the South Central Region.

5 REGIONAL RIVERS

5.1 Flow and Sediment Regime of Offtake Channels

The wandering pattern of the major boundary rivers has particular implications for the hydrology, hydraulics and dynamic morphology of the regional rivers which are distributary channels. By definition, the distributary mouth of a spill channel is located at the edge of the active corridor. Statistically, it is more likely to be in an embayment than in a nodal reach, because nodal reaches are much shorter than embayments.

The amount of water and sediment spilled into the distributary depends primarily on the position of the mouth within the pattern of the wandering river. In turn, the channel characteristics and morphology of the distributary depend on the inputs of water and sediment that drive its fluvial system, together with the boundary conditions imposed by the valley slope and engineering properties of the boundary materials. It is important to recognise this when analysing process-form relationships in the regional rivers. It is tempting to see the inputs of water and sediment as dependent variables, controlled by the morphology of the distributary channel. This is a mistake because it confuses cause and effect. As a general rule the volumetric inputs of water and sediment and their annual variations are controlled firstly by channel dynamics in the parent river and secondly by conditions at the offtake mouth. Recognising the morphologically dynamic nature of a wandering parent river, it is to be expected that large variations in inputs to distributaries will occur, to which the size and morphology of the distributary river must constantly adjust.

For example, in a predominantly meandering phase, a loop in the single-thread, deep water channel may occupy the embayment next to an offtake mouth. At such times a supply of water is assured throughout the year. Given the strong secondary circulation found in such curved channels there will be a tendency to sweep bed material load away from the outer bank, reducing the input of sediment (especially of coarse bed load) to the distributary. In terms of the balance between water and sediment discharges, where a value of 1 indicates a fractionation of equal parts of water and associated sediment load from the main river, the input balance may be 0.8. Under these circumstances the distributary mouth will be swept clear as relatively lightly loaded water exits the main river and makes up any unfilled sediment transport capacity by scouring the distributary channel. At such times the channel of the distributary grows and is highly active morphologically.

In time the meander loop of the deep water channel in the parent river will abandon the embayment in the flood plain becasue of either migration downstream, or a chute cut-off that switches flow to the far side of the active corridor. In either case the input of water and sediment to the distributary changes and the form of the distributary mouth and channel must respond to these changes imposed by the parent river. In terms of the sediment balance, the water entering the spill channel will be more heavily sediment ladened and the input balance increases to 1.2. If the mouth is actually located behind a macro-bar in the parent river, bar sedimentation may engulf the distributary mouth isolating it from the deep water channel. Dry season flows may well cease entirely in these circumstances.

Whether the distributary survives, or is permanently disconnected from the parent river depends crucially on the hydrograph dynamics of the parent river and the ability of the distributary mouth and channel immediately downstream to transmit the heavy sediment input. To survive, the distributary must dissect the bar in the main channel that extends into the distributary mouth. The bar is built up during high flow, but emerges on the falling limb, to act as a bund that separates the distributary from the low flow channel of the parent river. This isolation is exacerbated by the fact that the low water channel in the parent stream is itself incised into the bar and is, therefore, at a low elevation relative to the crest of the bar and to the bed of the distributary.

Dissection of the high flow bar must take place on the falling limb of the monsoon hydrograph in late-September, October, November and December and must be sufficiently rapid that the bed of the connecting channel between the low water channel in the parent stream and the distributary channel downstream of the mouth is scoured faster than the water surface elevation falls. Unless this is achieved, the bar emerges through the falling water surface and this isolates the distributary channel from the receding flow in the parent stream. Continued recession, coupled with incision in the low flow channel, then ensures that the distributary is not re-connected until well into the rising limb of the next year's monsoon.

To be effective in dissecting the bar and keeping a connection open into the low water season, the falling limb flow must have certain attributes.

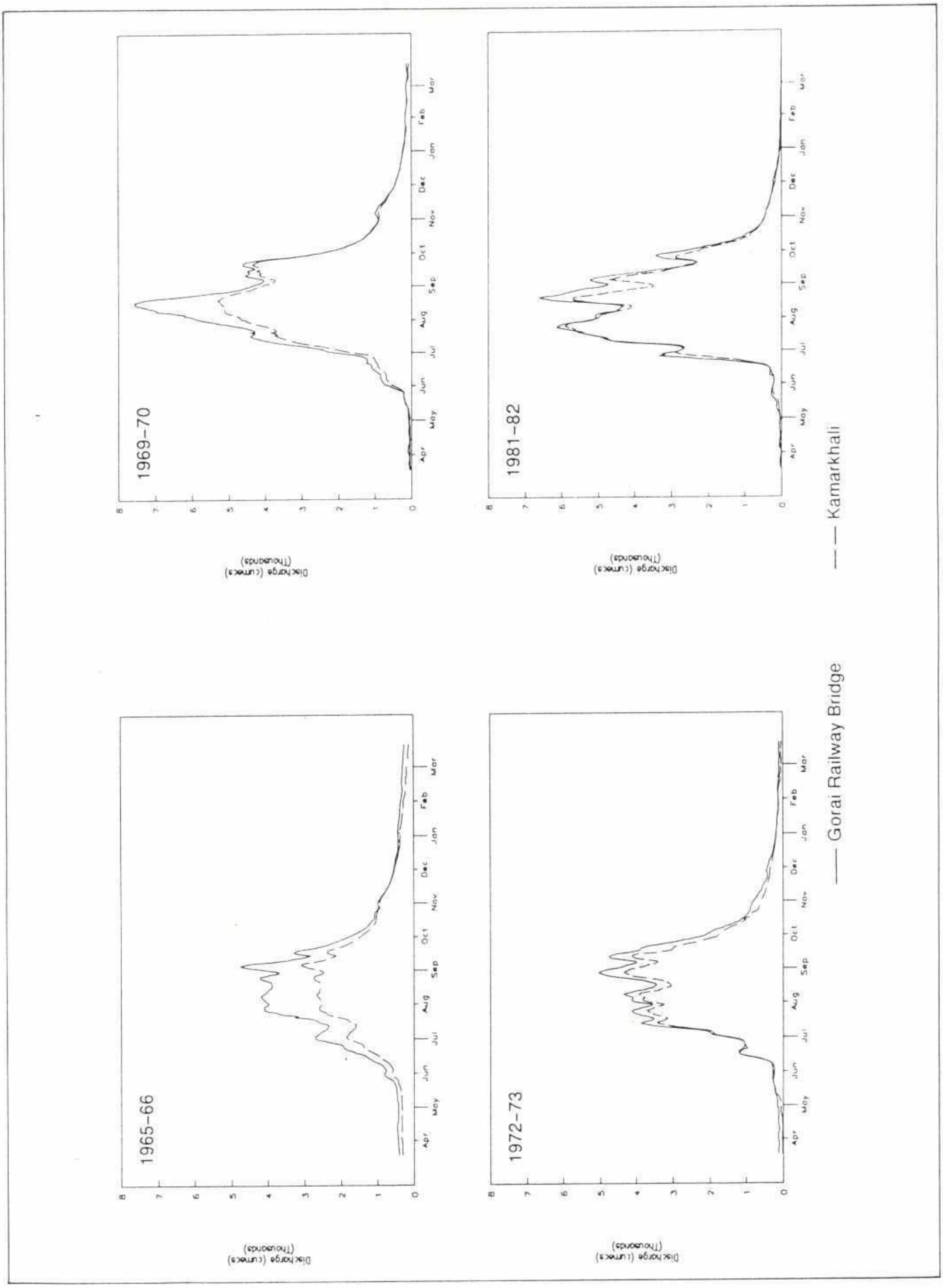
Firstly, it must be restricted to one low-flow channel. Multiple channels each have a sediment transport capacity which is a power function of their discharge. Hence, the total sediment transport capacity of two sub-channels must be less than that of their combined discharge in a single channel. Consequently, distributary mouths that are wide and shallow with multiple low-flow offtakes will always be more vulnerable to disconnection and isolation during the falling stage of the monsoon than mouths which are narrow and single-thread. In this respect, a wide funnel-shaped off-take mouth makes a distributary vulnerable to isolation from the parent river during the low flow season.

Secondly, the distributary channel must decrease its width rapidly as the stage falls, so that the water discharge per unit width remains high. If the flow width decreases only slightly and the depth and unit discharge decrease rapidly, then flow resistance is high, velocities low and sediment transport limited. As a result disconnection is almost certain to occur. In this respect, a wide funnel shaped off-take mouth, which will tend to have a flat or saucer-shaped cross-section, will make the distributary river very vulnerable to disconnection.

Thirdly, effective bed material scouring depends on maintenance of a high stream power per unit bed width during the falling limb. This, in turn, depends not only on the discharge per unit width (as addressed in the previous points), but also on the energy slope. For scouring on the falling limb to occur, it is absolutely vital that a steep energy slope exists from the water surface in the parent stream downstream into the distributary stream and that this steep slope is maintained during the flow recession. A high stream power and energy slope during flood stages is not in itself sufficient to keep a connection, because during high flows the sediment input from the parent stream is also high, and so the net result is the import and transmission of large amounts of sediment into the distributary. On this basis, an increase in flood peak discharges in the parent river and associated spills into the distributary would be expected to cause an increase in bar amplitude and minimum crossing elevations in the distributary, rather than a net scouring.

It is during the flood recession, when the input of sediment from the parent stream is decreasing, that a high stream power in the distributary becomes effective in scouring the high flow bars. Hence, to scour the bar at the mouth effectively, there must not be any backwater effects impeding flow at the mouth and the gradient in the distributary channel must be steep enough to 'draw' water out of the parent river across the bar. If the offtake flow is disrupted by poor entrance hydraulics and suffers large energy losses due to abrupt changes of flow direction that induce separation and large scale eddying (particularly at the banks), this will induce deposition and promote disconnection. Again, a funnel-shaped mouth is vulnerable to poor entrance conditions and alignments because the banklines do not constrain the orientation of the low flow channel, which is likely to lie at an oblique

Figure 5.1



Comparison of Flows on River Gorai

angle to the flow in the parent channel. Also, if the offtake flow at the mouth is impeded by backwater effects due high flow resistance (caused by a poor channel alignment and shoaling of the bed), or constricted flow caused by side bars, bends or structures causing afflux in the distributary channel downstream, then disconnection and isolation will be more likely to occur.

There is one further factor that does not depend on the distributary or its mouth, but which is crucial to bar dissection and maintenance of a low flow connection. This is the rate of stage fall in the parent river after the monsoon flood peak. The scouring of a channel across the high flow bar in the distributary mouth cannot be achieved instantaneously. In fact as the flow falls its bed scouring rate decreases and even more time is needed to lower the bed of the scour channel. Hence, a long recession with a slow rate of drawdown is required if the rate of bed lowering is to keep pace with the rate of stage reduction. If stage falls rapidly then the offtake channel is disconnected with minimal dissection of the intervening bar. This topographic high then delays re-connection on the next rising limb, reducing the number of days per year when spill flow occurs.

Summary

The channel dynamics of distributary channels are driven by the inputs of water and sediment from the parent river. These depend on:

(a) the planform morphology of the parent stream;

(b) the shape and geometry of the off-take mouth;

(c) the shape of the recession curve at the end of the monsoon flood and particularly, the rate of fall of the water surface elevation between mid-September and the end of December;

(d) the flow resistance of the distributary channel downstream of the mouth;

(e) any loss of energy slope due to backwater caused by afflux at a downstream structure or channel constriction.

The actual longterm case histories of individual past and present distributaries reflect the large number of possible outcomes that can result from continuous and stochastic inter-action of all natural controls. In addition, the recent history of distributaries may also have been affected by human impacts through catchment changes and river regulation of the parent river.

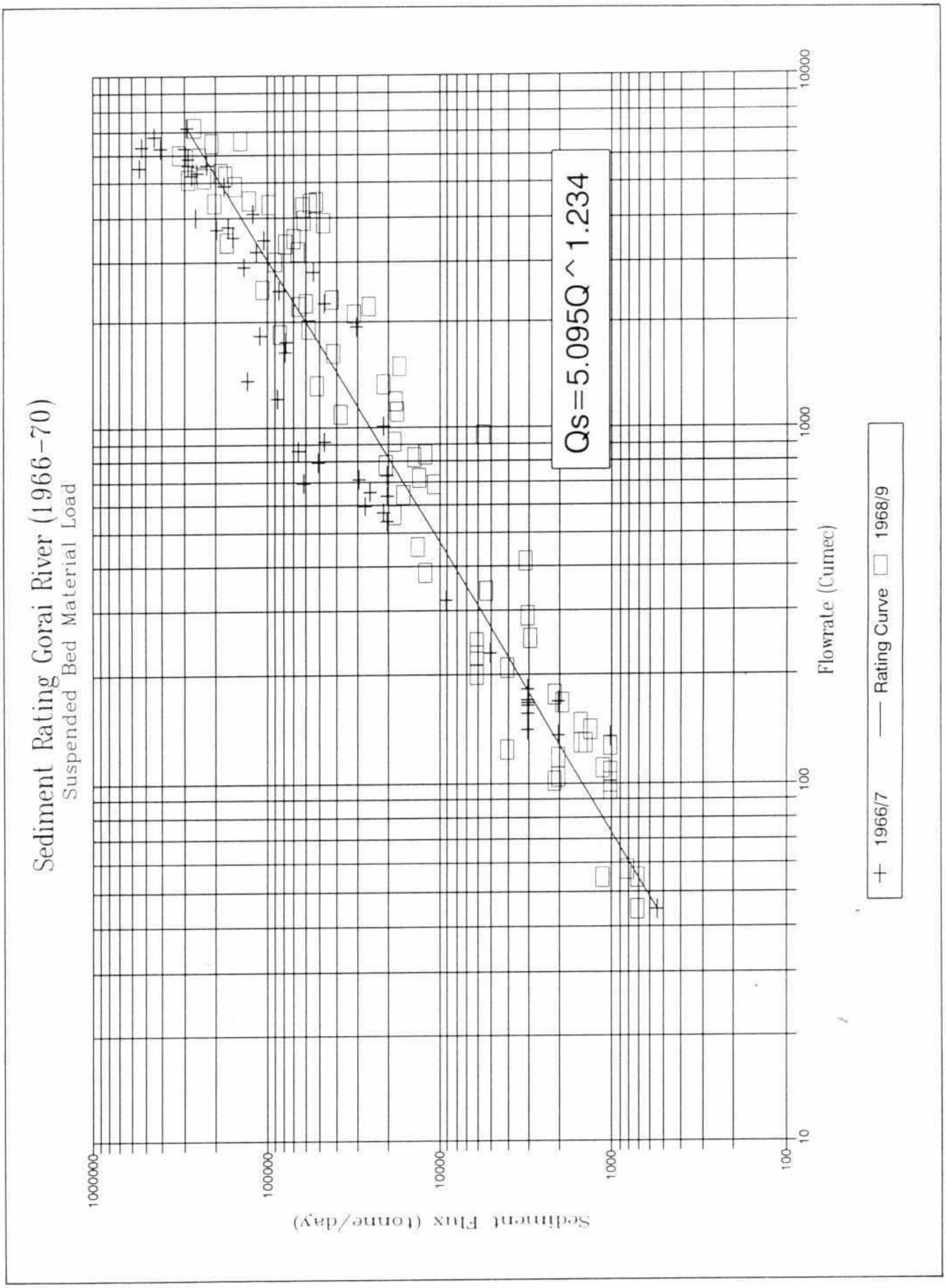
5.2 Gorai-Madhumati System

5.2.1 Flow and Sediment Regime

Dominant Flow

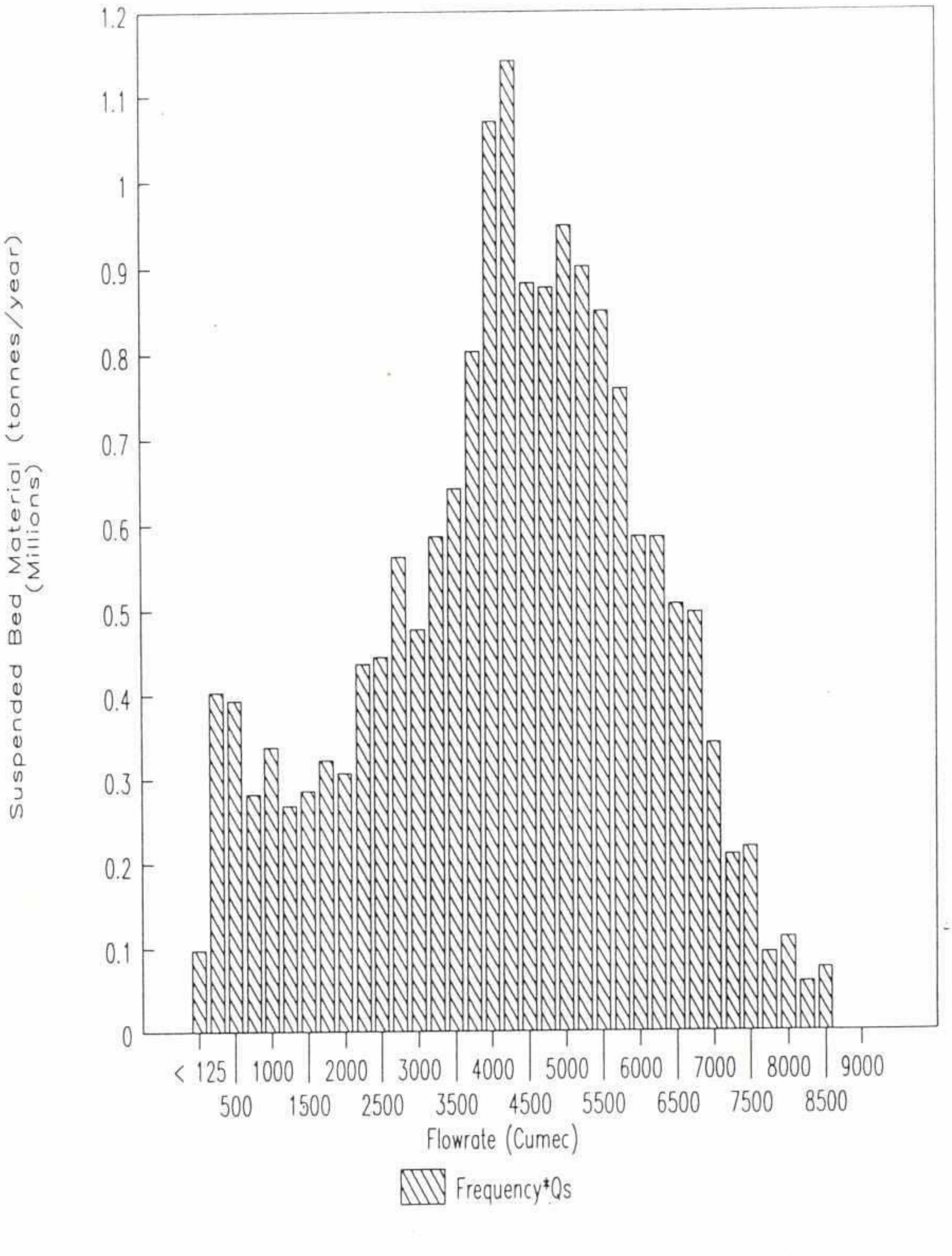
There are two gauging sites on the Gorai, the Gorai railway bridge (11.6Km from mouth) and Kamarkhali (about 90 Km from mouth). The rail bridge site has the longer period and records of all the flow entering the river whereas there may be some overbank flow during high floods over the left bank before Kamarkhali. The rail bridge record therefore normally shows higher flood peaks as shown in Figure 5.1. The calculation of dominant discharge for Gorai Railway bridge (Figures 5.2 and 5.3) shows a dominant peak at 4250 m^3/s. This is significantly lower than the 1 in 2 year maximum daily flow of 6100 m^3/s.

Figure 5.2



Sediment Rating Curve Gorai River, 1966-1970

Figure 5.3



Dominant Discharge in Gorai River
at Gorai Railway Bridge 1965–1989

Changes in Flow

Low flows in the river have declined to zero over the last ten years and as shown in Figure 5.4 this decline has coincided with particularly low flows in the Ganges due to extraction upstream at Farakka. Also apparent is a shorter period of decline in the early 1950's and examining the change in the proportion of Ganges flow (Figure 5.5), there is a cyclic trend of flow in the Gorai that is exagerated at present by the very low flows in the Ganges during the dry season.

Post Farakka Changes in Dominant Flow

The post-Farakka dominant discharge curve (Figure 5.6) shows large reductions in the sediment moved by low flows (less than 2,000 cumecs) and high flows (greater than 6,500 cumecs). The lack of low flow transport could be responsible for raised bed levels, especially at crossings between meander bends, since low flows scour bars and fill pools. Disconnection of the Gorai early on the falling limb and delayed re-connection in the spring, both due to the failure of flows entering the mouth to dissect the bar and maintain a low flow channel, could also be partially responsible.

It can be concluded that the change in the dominant discharge curve for flows in the 200 to 2,000 cumecs range is entirely consistent with the arguments put forward to explain the present hydrologic and sedimentary conditions.

There is some decrease in effectiveness of high flows which cannot be a product of the river regulation at Farakka, because large flows in the Ganges are transmitted downstream with little modification. Some other explanation must be found for the change, which would be expected to have some significant morphological impacts. It may be a function of the flood events since 1975. Events in the Ganges lead to an increase in the effectiveness of high flows (greater than 50,000 cumecs) post-Farakka. Presumably, less of this water (and sediment) is now entering the Gorai and so the importance of high flows in the Gorai is diminishing relative to intermediate flows.

5.2.2 Specific Gauge Analysis of the River Gorai at the Railway Bridge and Kamarkhali

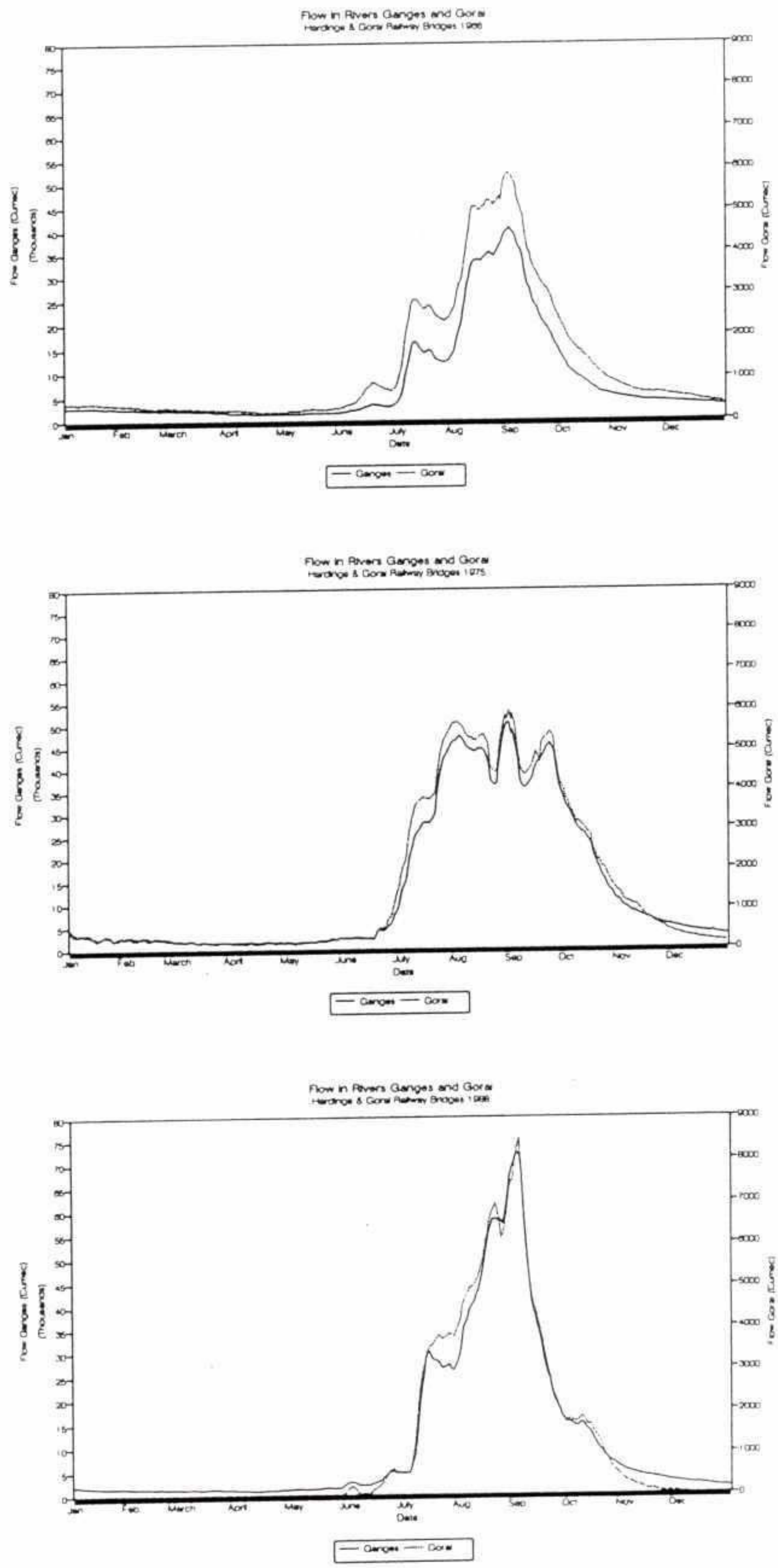
The record for the rail bridge gauging site goes back to 1947, data was available for Kamarkhali back to 1966. The specific gauge analyses for each site is given in Figures 5.7 and 5.8.

There is a strong upward trend in stages for low discharges that is not apparent in the high flow stages. At the rail bridge the lowest line, for 200 cumecs, rises by over 1.2 metres over the 45 year period. Increases diminish progressively as discharge increases, and the 2,000 cumec stage is barely affected. The stages associated with dominant discharge (about 4,000 cumecs) show no clear trend over the period. The Kamarkhali site shows a similar trend although there seems to be a stronger downward trend for high flows in the sixties that has reversed in the eighties.

The rising stages at low flows are consistent with the idea that falling stage flows in the Gorai are not dissecting the high flow bars sufficiently to maintain a low flow channel. The impact is to pond water behind bar crests and raise flow lines and stages for low discharges. Higher flows are able to remould the bed as required by their hydraulics, and so are relatively less unaffected by bar topography.

There are serious implications for dry season flows into the Gorai, because the raising of the water levels at the Railway bridge during low discharges reduces the head difference

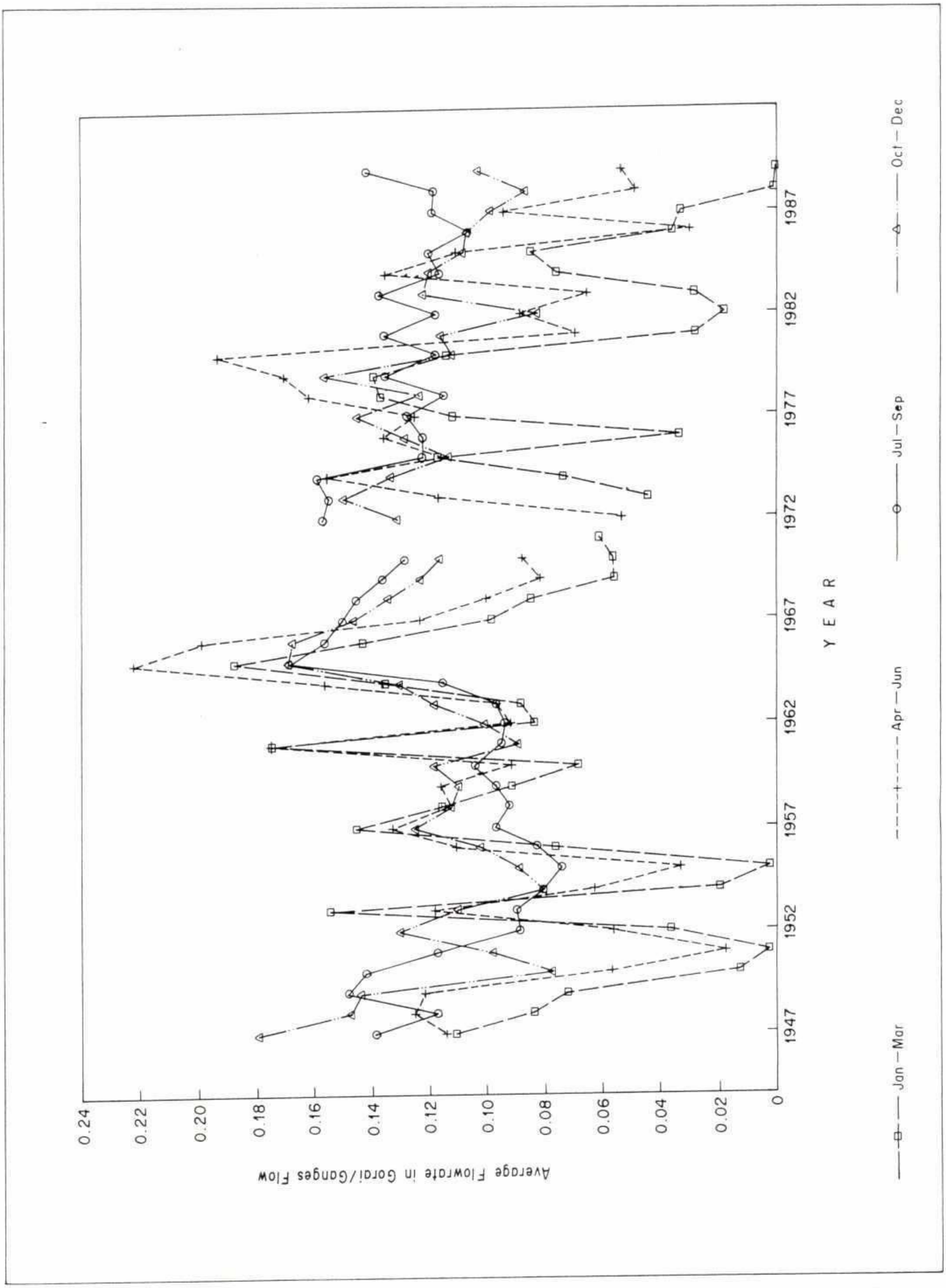
Figure 5.4



Flows in the Rivers Ganges and Gorai 1965, 1975 and 1988

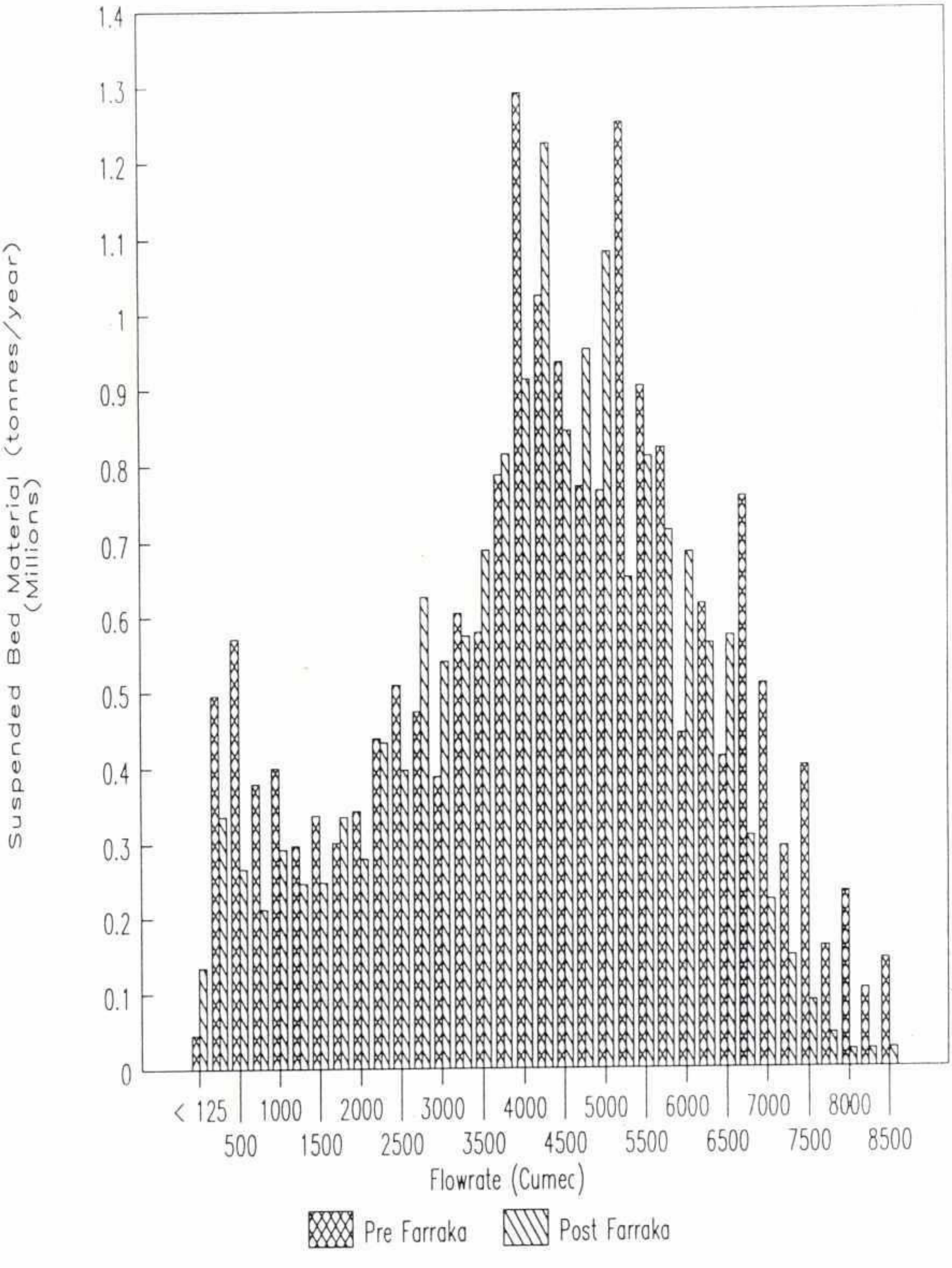
102

Figure 5.5



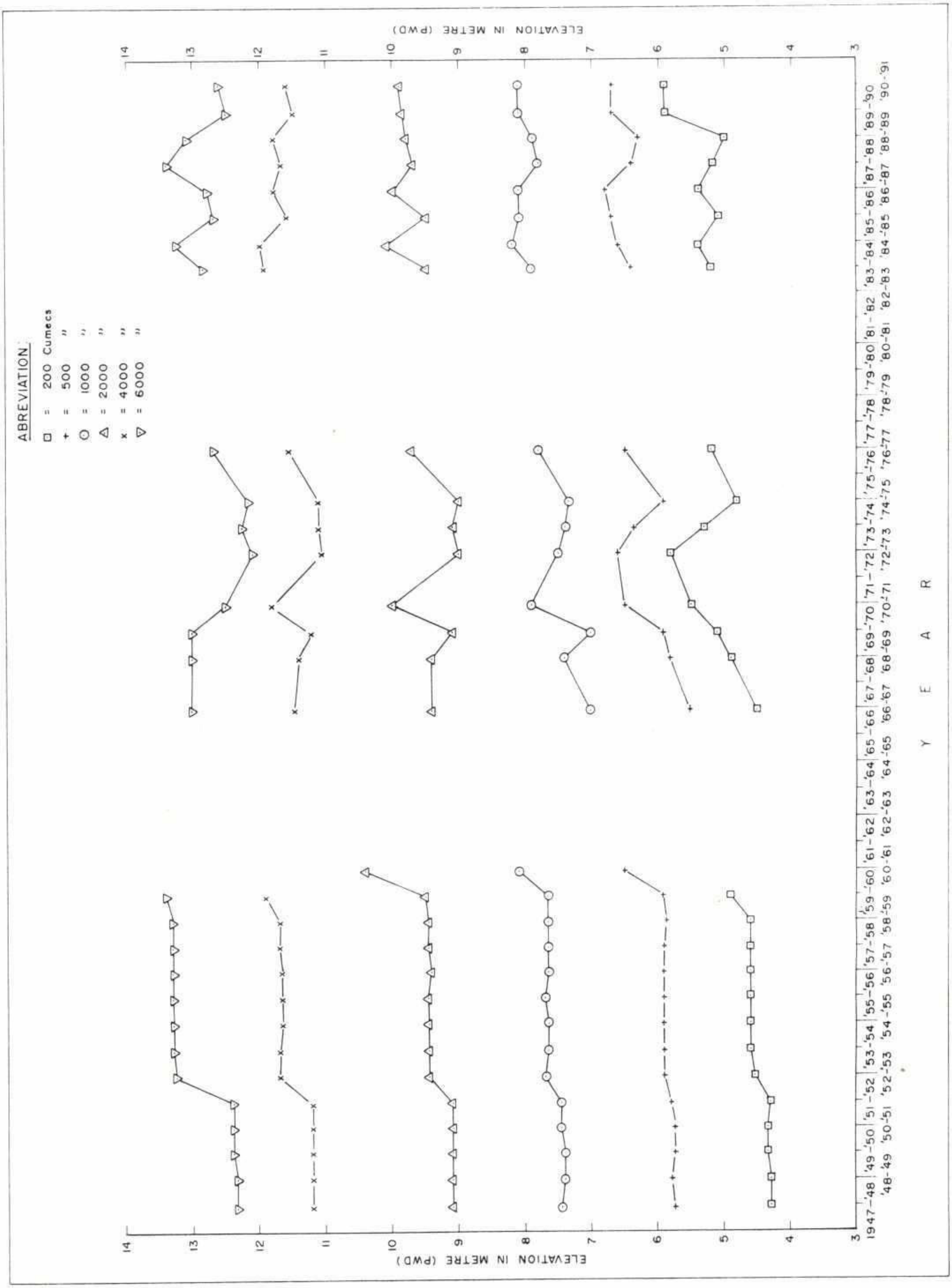
Proportion of Gorai to Ganges Flows
at Hardinge & Gorai Railway Bridges 1947–1990

Figure 5.6



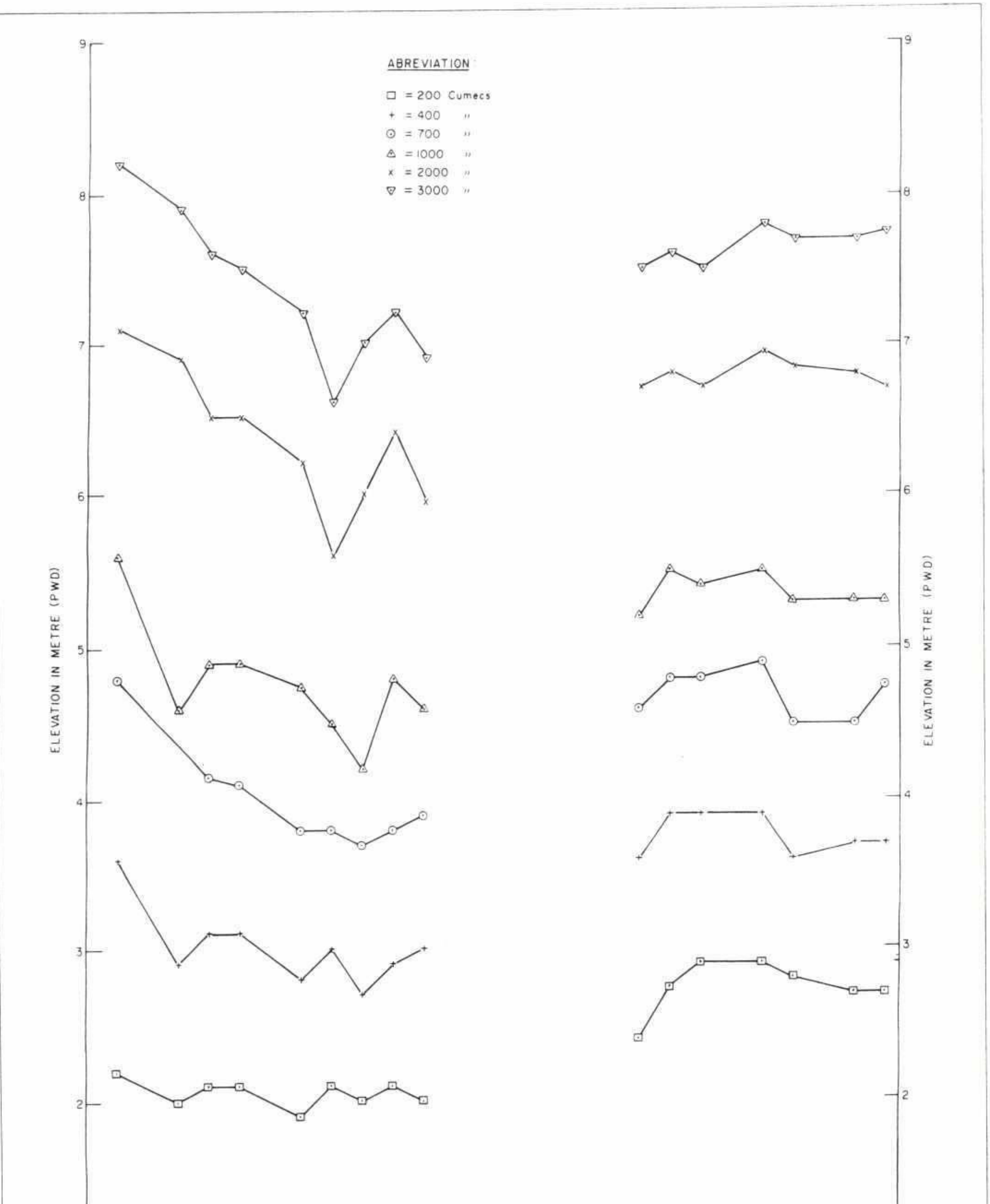
Dominant Discharge in Gorai River at Gorai Railway Bridge

Figure 5.7



Water level Variation for six discharges in the Gorai River at Gorai Railway Bridge 1947—1990

Figure 5.8



Water level Variation for six discharges in the Gorai River at Kamarkhali Transit 1966—1991 and, therefore, the energy slope between the mouth of the Gorai and the Railway Bridge. This could critically reduce the sediment transport capacity of the flow, leading to sedimentation and bar building in the mouth during high/intermediate stages.

Perhaps more critically, a reduction of energy slope (and sediment transport capacity) during falling stages (say at around 1,000 - 2,000 cumecs in the post-monsoon period, when the Ganges is at about 10,000 - 20,000 cumecs but is falling rapidly) would mean that flows entering the Gorai and flowing downstream via the Railway Bridge would be unable to scour a recession flow channel through the high flow bed and bars. The Gorai would be disconnected from the Ganges early in the autumn as a result. The effect of such scouring is illustrated by the change in rating curve at Talbaria on rising stage and the difference between the model results with a fixed bed and the measured flows and levels as shown in Figure 5.9. Talbaria is not a flow gauging station, so to construct a rating curve the flows measured at the railway bridge are assumed equal to the flow into the mouth.

The findings of the Specific Gauge Analysis of the Gorai Railway Bridge are disturbing from the point of view of water resources developments in the SW Region. They suggest that siltation problems are not confined only to the mouth of the Gorai but extend downstream at least as far as the Railway Bridge, a distance of about 12 kilometres.

5.2.3 Long Profile Analysis of the Gorai-Madhumati

Long profiles have been drawn from cross sections for all the available data from 1963 BIWTA survey to BWDB surveys 1966 - 1989 and surveys by FAP 4 in May and June 1992.

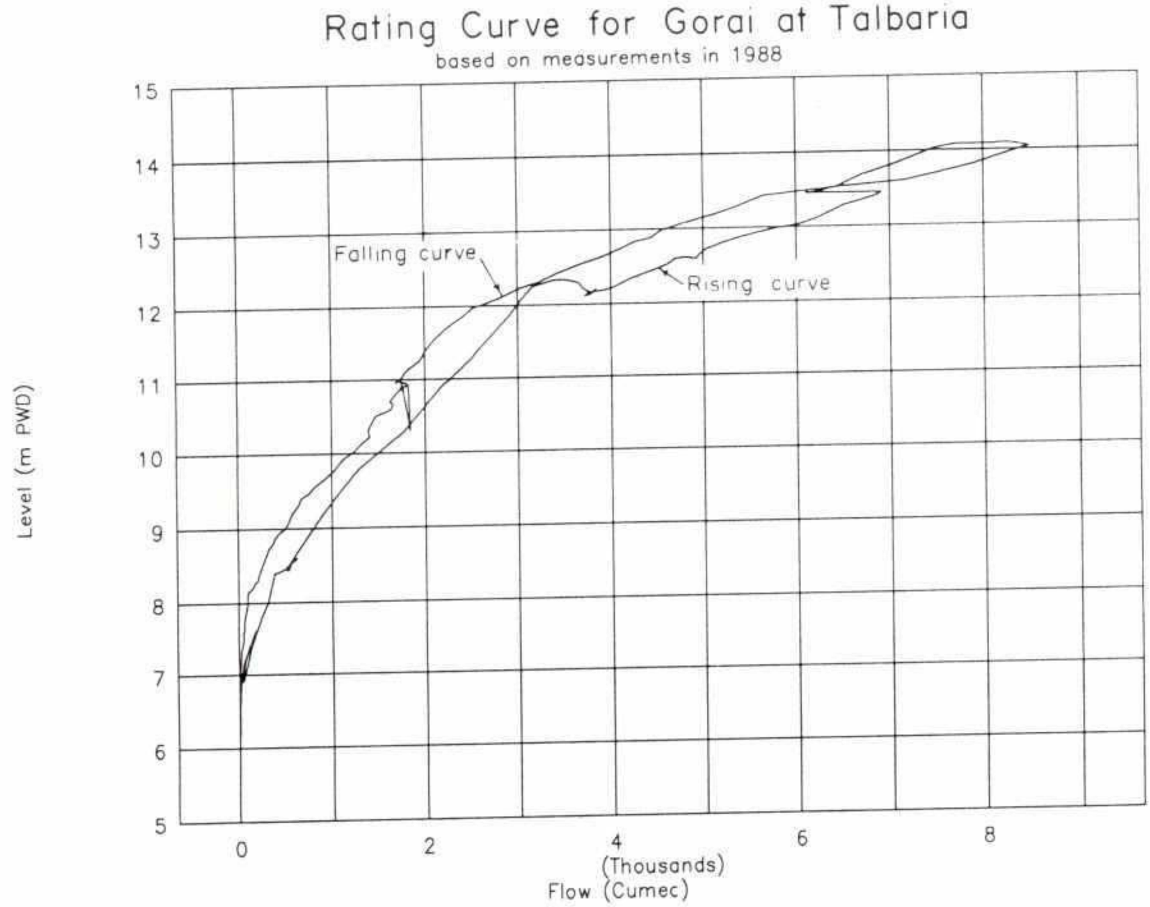
The long profile using the most up to-date sections for each reach is shown in Figure 5.10. This illustrates that for dominant flows the high banks in the upper reaches are above dominant flow levels but in the lower tidal reaches, the channel capacity is lower suggesting that significant spill would normally result. Four distinct reaches may be discerned : the mouth reach to about 20 Km which is relatively flat and at a high level, the reach to Kamarkhali which is at a lower level, the bend and following straight reach from Km 87 to Km 139, and finally the increasingly meandering tidal reach to Bardia.

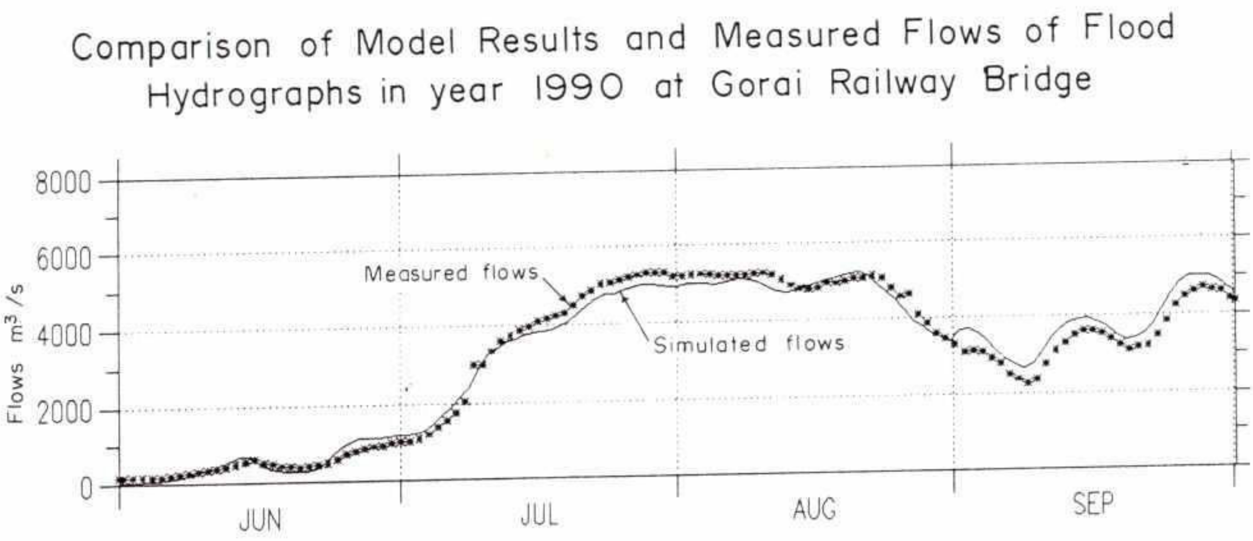
A long-profile was also made by echo-sounder in August 1992 during monsoon flow this is shown in Figure 5.11. The profile shows several salient features. Although this is a 'snapshot' in time representing conditions over one short period, the profile gives an excellent idea of recent conditions. It must be borne in mind that this profile does not follow the thalweg, which would be impossible in a moving boat, but represents a profile along the navigation route. Hence, some points may not be actual lowest points in the cross-section. This must be borne in mind when interpreting and analysing this data.

In geomorphology a long profile is classified as graded when the slope at each point along the river is adjusted so that the section is just able to transmit the sediment load supplied to it from upstream, plus any sediment supplied by local erosion. In a dynamically stable river, with discharge increasing in the downstream direction due to increasing catchment area and bed material size decreasing downstream due to sediment sorting, the long profile is described by a semi-log curve which is concave upwards. In a stable river with a constant discharge the slope should be uniform.

Overall the profile of the Gorai is in fact concave upwards between the mouth and Kamarkhali, which is indicative of a 'graded' alluvial river with, active sediment transport and no geological controls. However, since the river is a distributary, it is questionable whether discharge does increase significantly in the downstream direction. Also, sediment

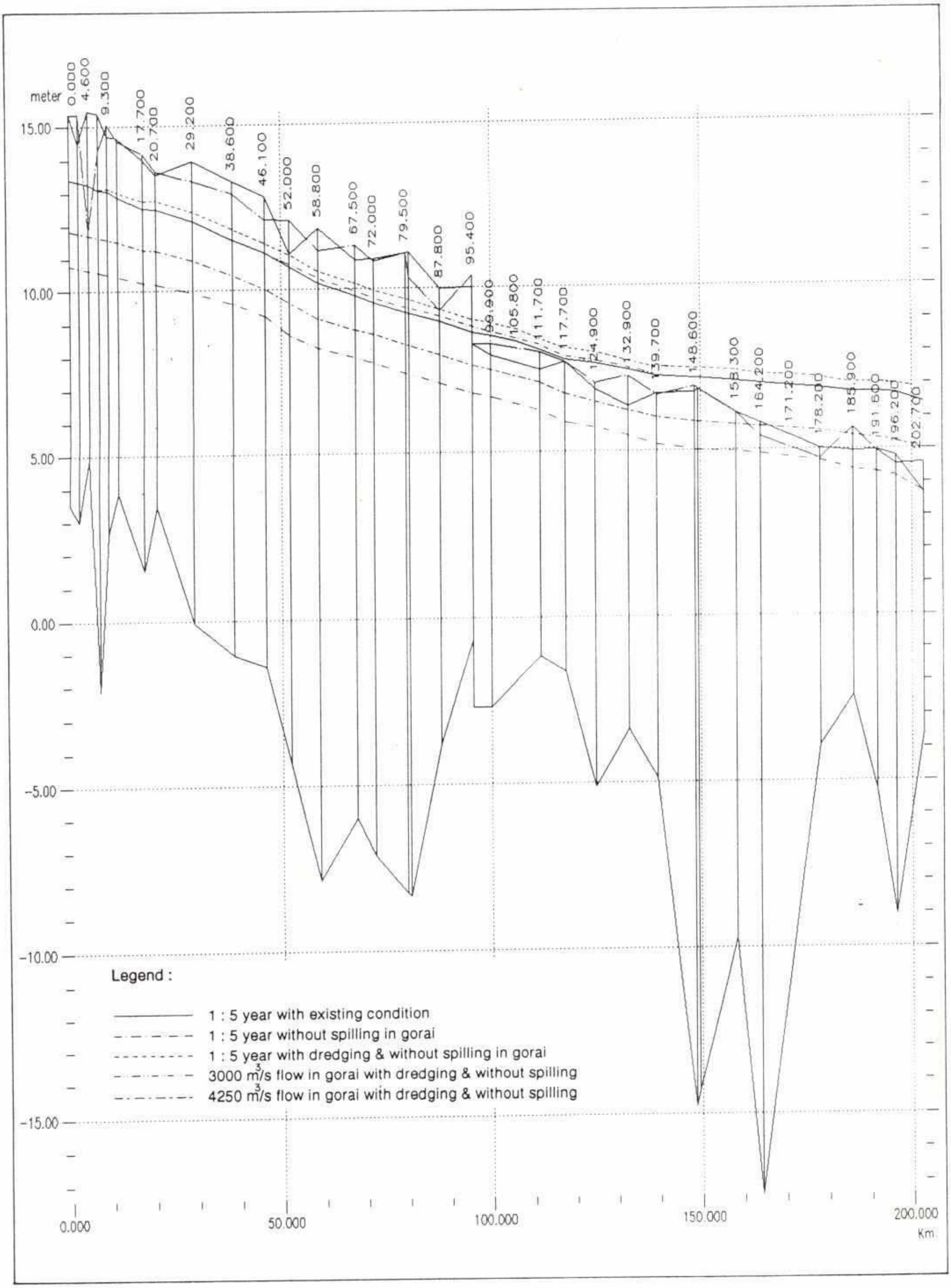
Figure 5.9





Gorai Rating Curve at Talbaria and Gorai Hydrographs at Railway Bridge

Figure 5.10



Long Profile of Gorai

size is almost constant with downstream distance (in the fluvially dominated reach). Hence, the profile may be indicative of overall dynamic disequilibrium because the slope in the lower part of the river is too low to transmit the bed material load from upstream. This could be associated with the development of overly tortuous meandering in the lower course of the river. In fact, downstream of Kamarkhali there is practically no drop in the profile, and if anything, an adverse bed slope. This is not commensurate with a dynamically stable channel and it is doubtful if such a reach could transport bed load effectively enough to be geomorphologically graded. It would be expected *a priori* that such a reach would by dynamically unstable.

There are also local problems relating to high points that break up the concave profile and these are discussed in detail in the next paragraph.

The following detailed observations can also be made:

(1) The bed between the mouth and 15km (just d/s of the Railway Bridge) is heavily silted. There is only one pool in the reach, at the Kushtia groynes. This is certainly related to the poor channel alignment and overly wide planform between the offtake and the Railway Bridge. Downstream of the Bridge, the bed falls away and a pool-bar system can be recognised as quite well developed.

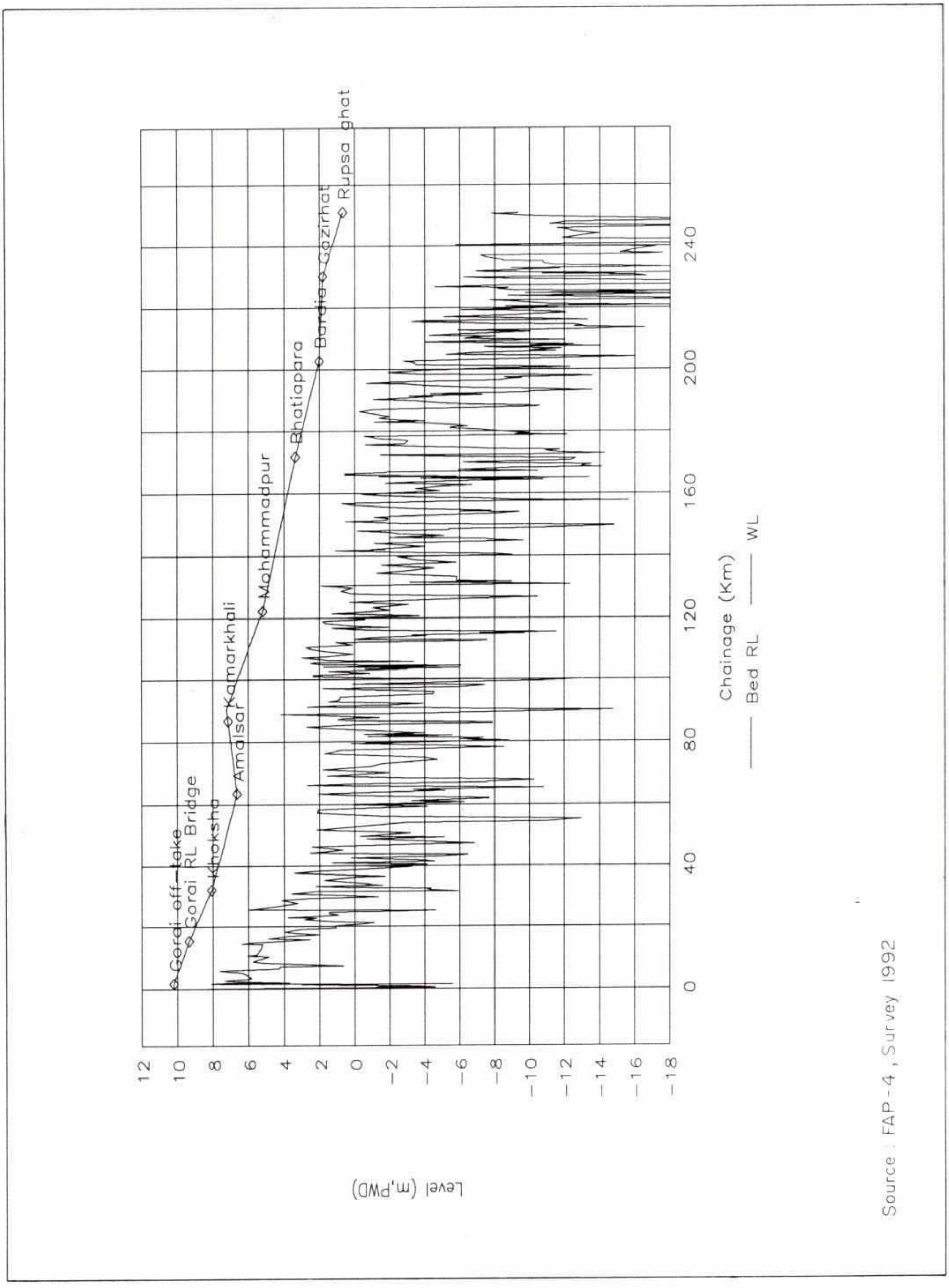
(2) There is a high point and heavy bed sedimentation in the reach at about 26 to 28km. This may be a flow impediment and should be investigated further.

(3) The reach from about 15km to the Kamarkhali bends has a series of pools and bars with occasional high points at crossings that deserve attention. For example, bar tops at 57, 66, and 84km look a shade high. Some local dredging and training work could be worthwhile to reduce these crossing heights and improve the local energy gradient, especially at low and intermediate flows.

(4) Conditions at the Kamarkhali bends appear to cause serious problems to the long profile. The crossing bar upstream of the first bend, at about 84km, is high and the crossing between the two major bends, at 88km is even higher. The first crossing crest is at about +2.5 m and the second has a crest height (about +3.5m) which is close to the bed elevation at the Railway Bridge 73 km upstream. There is only one higher point in between, a sedimented zone at 26-28km, mentioned previously in point (2). The scour pool in the downstream bend is also excessively deep and represents the lowest bed elevation in the entire reach. The bends at Kamarkhali appear on geomorphological grounds to be major features in the long profile and they can be interpreted as causing serious disruption to an otherwise graded long profile. This is without considering the head losses calculated to be over 1.3m in the bends at high flow. There could be great benefits to the morphology of the long-profile and channel form if training works produced a lowering of the crossing elevation by 1 to 2 metres through re-alignment of the river into a less convoluted and tortuous course that remains sinuous and has the correct crossing spacing.

(5) The bed profile downstream of Kamarkhali to 125km has practically no bed slope and possibly an adverse slope overall. This cannot be reconciled with geomorphological stability if there is any active bed material (especially coarse bed material) output from Kamarkhali, unless tidal ebb transport is sufficient to keep sediment output balanced with sediment input. The high bed elevations coincide with straight reaches which stand out in an otherwise meandering planform. It is well known in geomorphology that straight reaches lack the well developed pool-bar topography and properly spaced crossings of sinuous channels and are liable to silting. Straight reaches are specifically avoided in modern navigation schemes for precisely this reason. Naturally straight reaches are rare in alluvial

Figure 5.11



Long Profile of Gorai 1992

systems, and yet these reaches are easily discernible in 19th century maps of the river. They have persisted for many years. It would normally be expected in a freely meandering system that the bends upstream at Kamarkhali (which are likewise very old) would have migrated downstream through the 90 to 115km reach, introducing sinuosity as they did so. This has not happened. Instead, the bends at Kamarkhali have been almost static and have become extremely ingrown. None of this is consistent with a freely meandering river. Examination of the topographic map indicates that there is high ground around the straight sections that may be exerting a topographic influence. The area is also active with neo-tectonics and the reach is close to the limit of tidal influence, which could have some relevance.

5.2.4 Siltation in the Upper Reaches

The greatest changes in the thalweg level have occured in the upper reach of the Gorai and the long section for 1963 to 1992 to 30 Km is shown in Figure 5.12. This indicates that the thalweg has risen significantly over the past 30 years.

To assess how widespread the change in bed levels have been, contours for the mouth section were drawn and the changing plan area of the low flow channel is illustrated in Figure 5.13. Corresponding long profiles are shown in Figure 5.14.

It is concluded that there have been major changes in the low flow channel near the mouth such that even if the level in the Ganges were to increase, there would be little flow into the Gorai unless there is some intervention.

5.2.5 Morphological Analysis of Gorai-Madhumati

The Gorai cross-sections have been obtained from the BWDB. The water surface profile corresponding to dominant discharge (4,250 cumecs) has been generated using the 1-D model and the water levels marked onto the cross-sections as shown in Figure 5.15 and further sections are given in Appendix 1.

In its upper course the dominant flow is close to, but a little less than, bankfull stage which is consistent with the hydraulic geometry of a regime type river. This finding is also consistent with the long profile in this reach, which is concave upwards, and the planform of the river which shows a meandering course that has not altered greatly in the last 140 years (see Section 5.6).

The relationship of dominant flow to bankfull stage changes downstream of Kamarkhali. In the bend reaches the channel is incised, but the reaches downstream are under-sized, so that dominant flow involves overbank spillage. This is in agreement with the findings of the morphological modellers that there may be a great loss of conveyence in this reach.

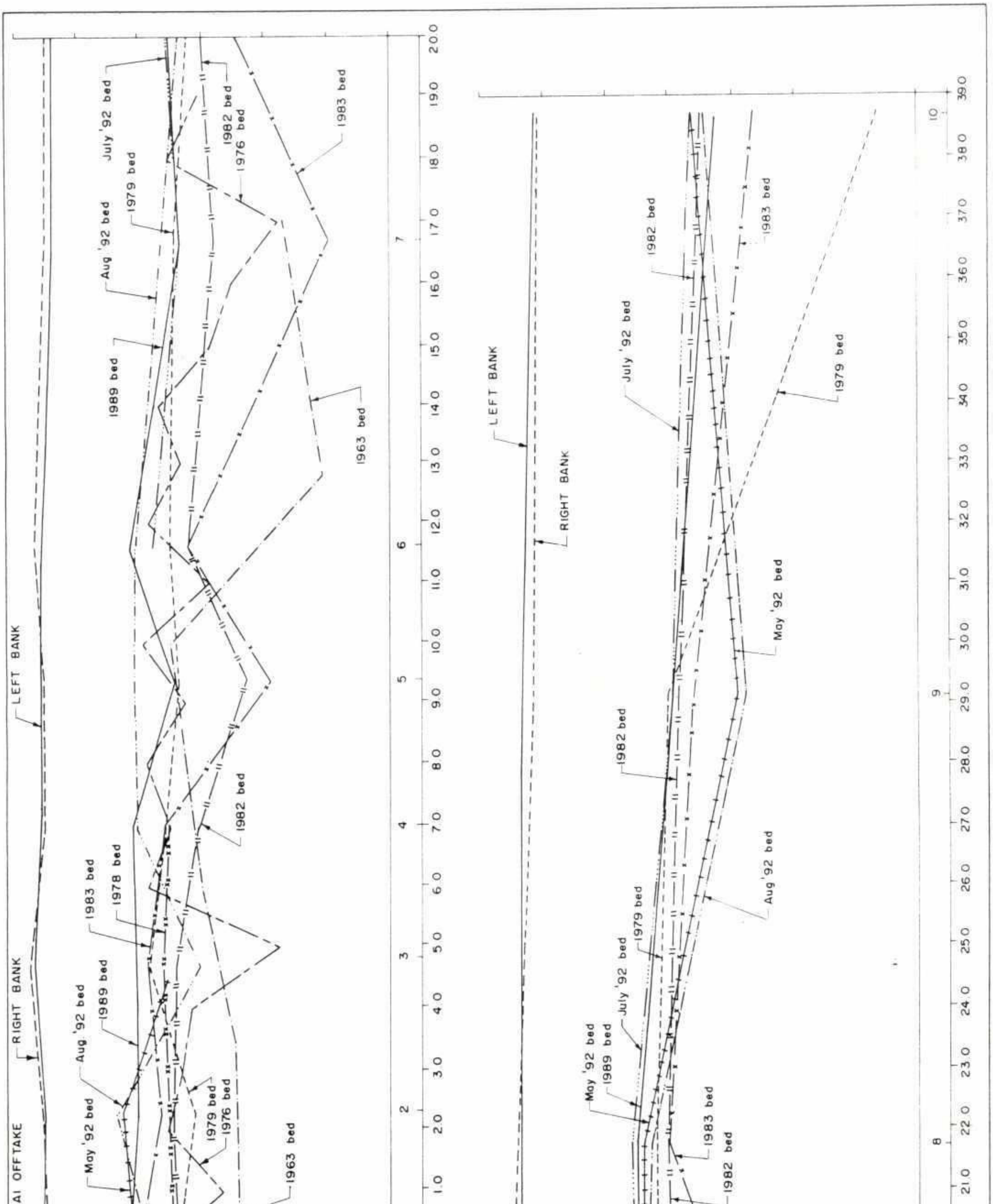
5.2.6 Planform Developments

Examination of recent satellite images and maps indicate that as shown in Figure 5.17.

(1) the upper course of the Gorai has been remarkably stable in the last twenty years.

(2) the bends at Kamarkhali are a prominent feature throughout this period. A neck cut-off of the downstream bend occurred in the 1970s, but after some years of using both the bend and cut-off channels, the river resumed flow in the bend

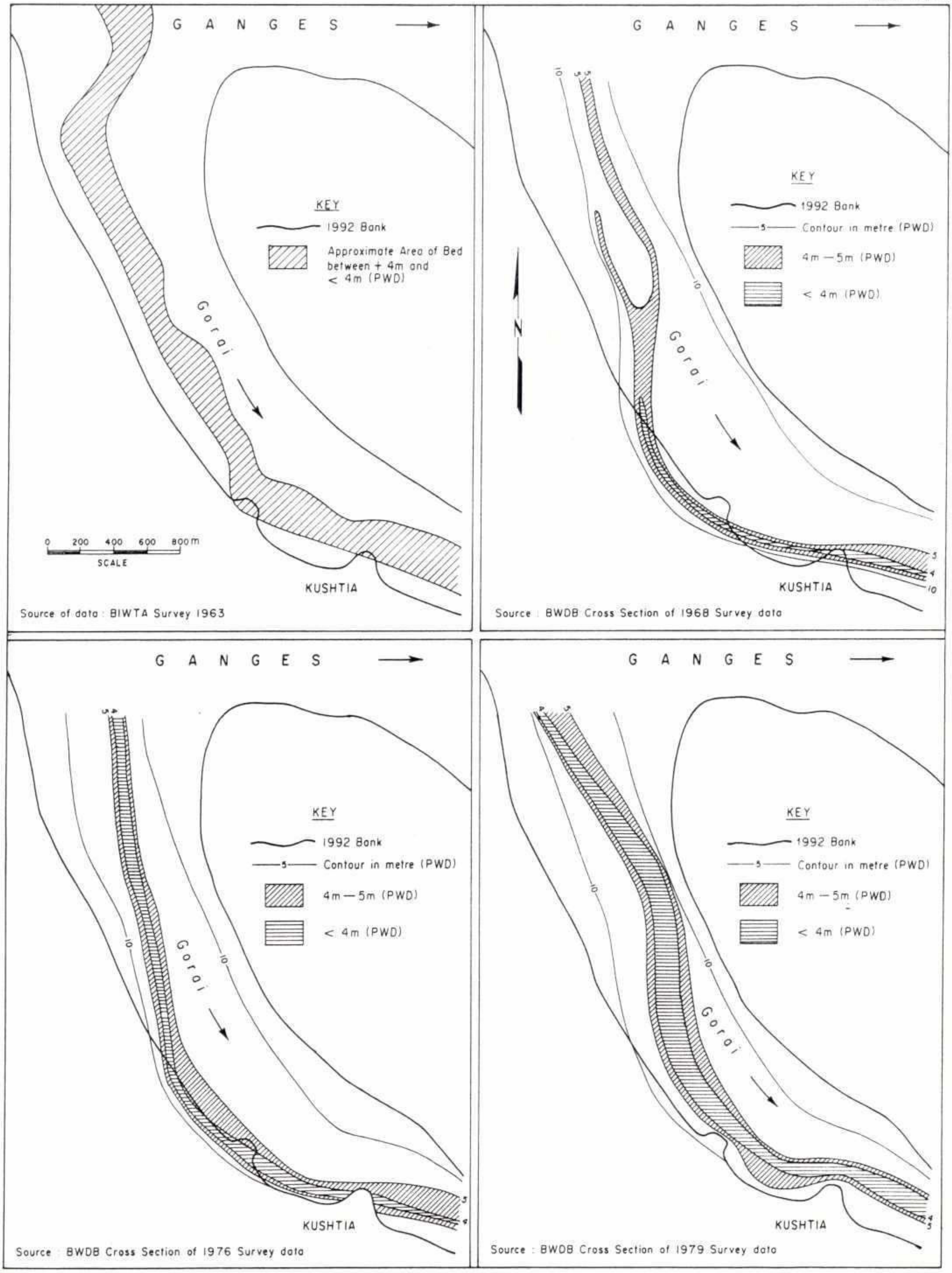
Figure 5.12



Gorai Long Sections Comparisons (30 Km)

Figure 5.13

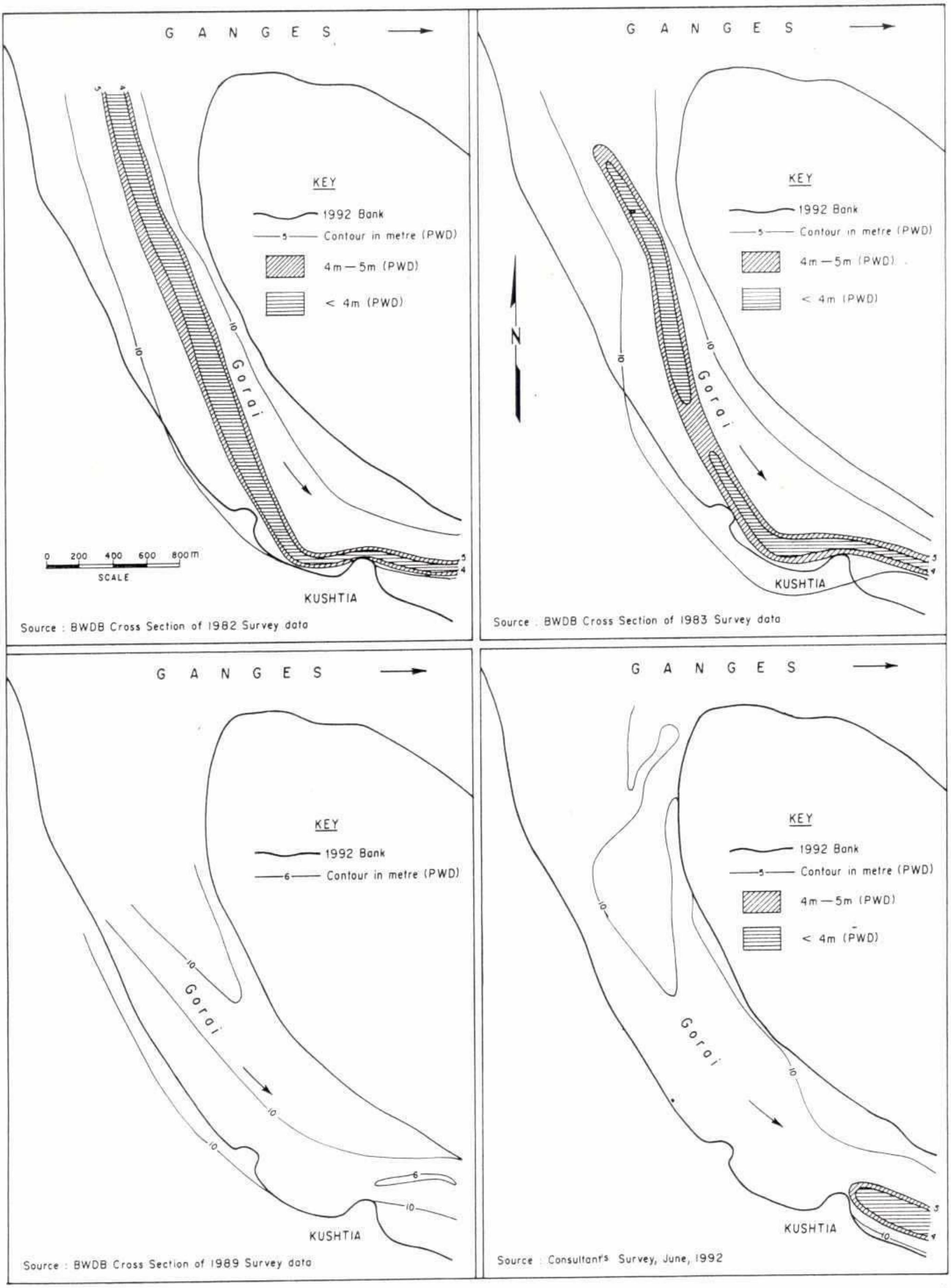
Sheet 1 of 2



Gorai River : Changes to Low Flow Channel (below 5.0m PWD) According to Surveys in 1963, 1968, 1976 & 1979

Figure 5.13

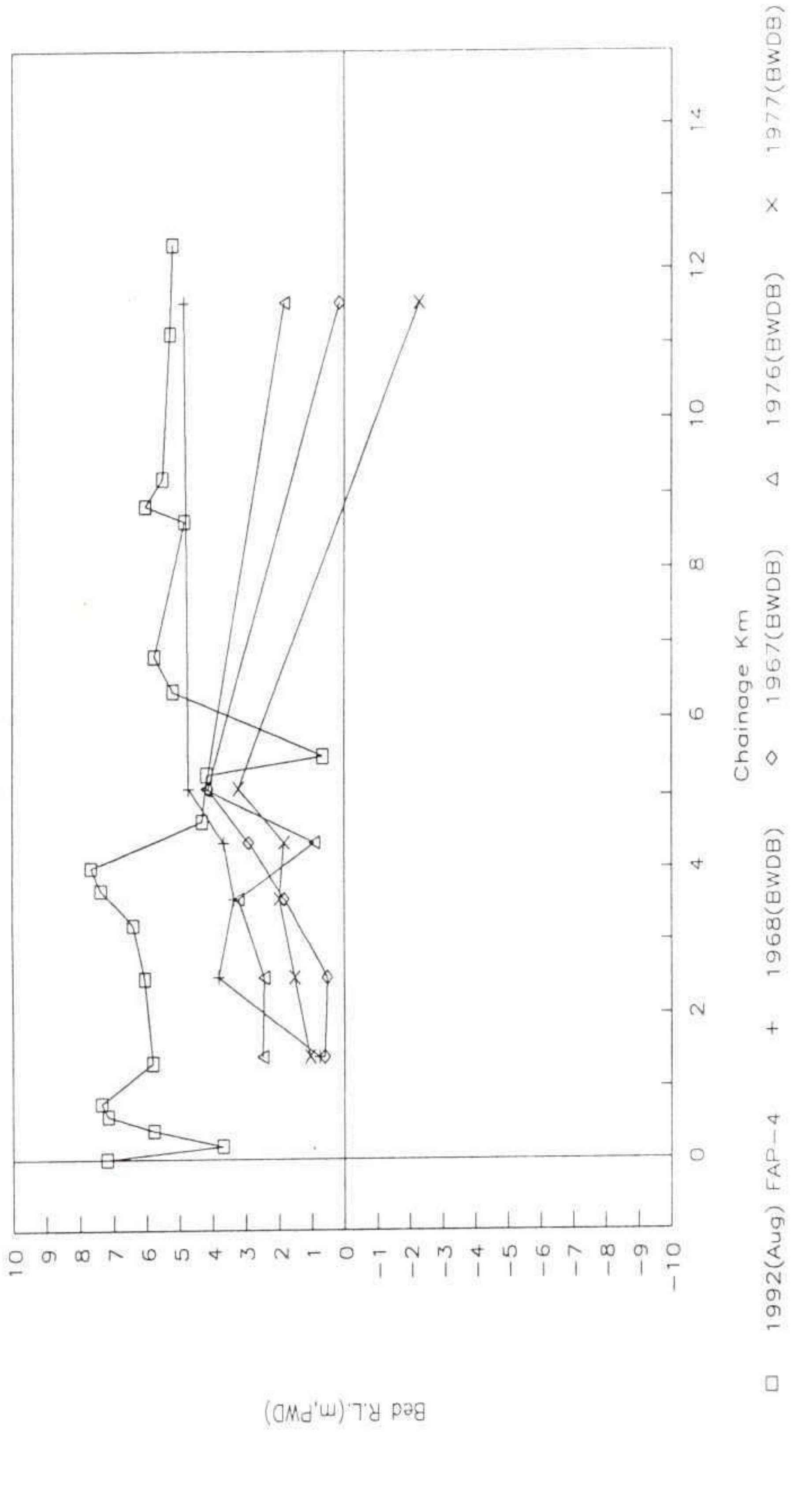
Sheet 2 of 2



Gorai River: Changes to Low Flow Channel (below 5.0m PWD) According to Surveys in 1982, 1983, 1989 & 1992

Figure 5.14

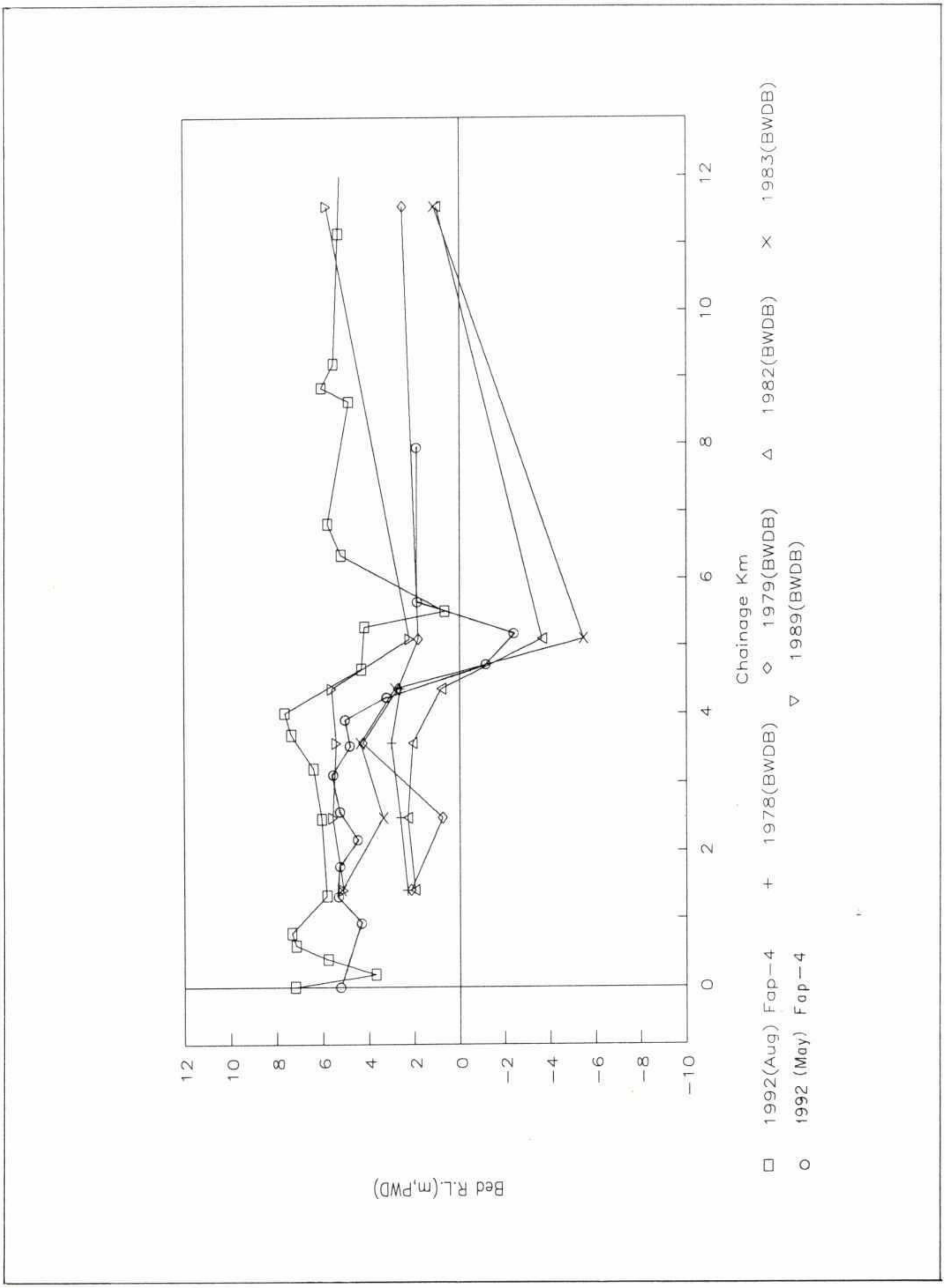
Sheet 1 of 2



Gorai Long Profile
From Gorai Mouth to 13 km

Figure 5. 14

Sheet 2 of 2



Gorai Long Profile
From Gorai Mouth to 13km

channel. This behaviour is not consistent with the usual sequence of events in alluvial bends and it strongly suggests that these bends are constrained in some way.

(3) the straight reaches downstream of Kamarkhali have been very persistent and there must be some reason for this. The planform appearance of the reaches is unusual for an alluvial stream and hints at exterior control by geology or topography.

(4) the lower Gorai-Madhumati has increased in sinuosity very markedly in recent years. Both Fergusson (1863) and Addams-Williams (1918) concluded that the deterioration in conveyance and velocity of an offtake channel due to the growth of tortuous meanders was a significant factor in its declining importance as a distributary. The comments of those two individuals were based on many years of first hand observation and monitoring of the real rivers and their conclusions cannot easily be dismissed.

The Gorai is a strongly meandering river. Measuring the meander wavelength at sinuosity for different years, the results in Table 5.1 show that the average sinuosity of the Gorai-Madhumati has increased from 1.5 in the 18th and 19th centuries to about 1.85 to-day, while since about 1904 the sinuosities of both areas above and below Kamarkhali have increased slightly.

TABLE 5.1

Meander Geometry of the Gorai-Madhumati

YEAR	AVERAGE SINUOSITY		AVERAGE WAVELENGTH (km)
1780	1.5		
1849-60	1.5		
1904-24	1.7	upper section 1.4 lower section 2.2	9.2
1952-58	1.74		9.6
1989	1.84	upper section 1.5 lower section 2.3	8.9

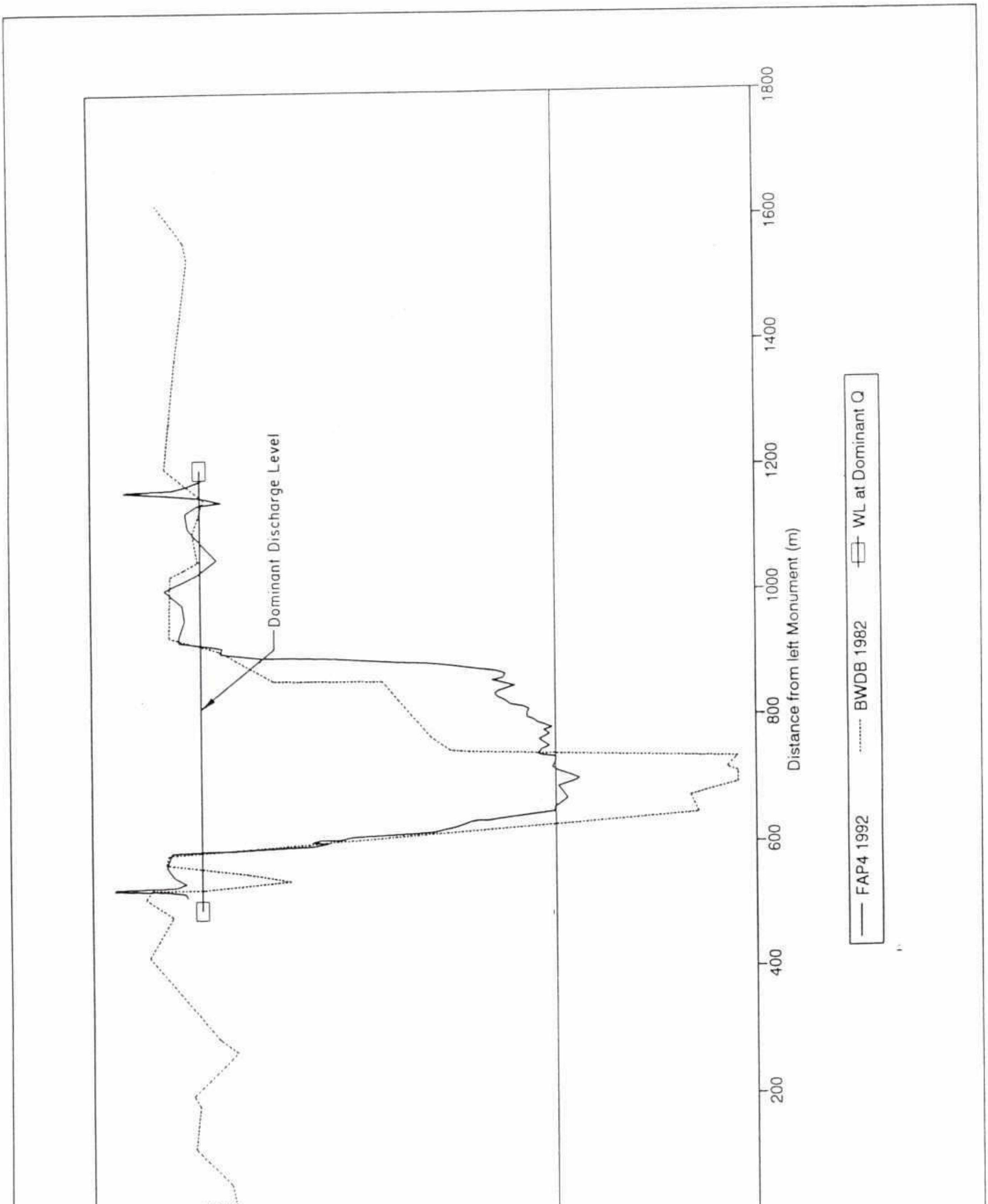
The average wavelength was about 9 km at the turn of the century and possibly decreased slightly. Changes in sinuosity and possibly wavelength would have meant the Gorai's ability to transport water and sediment in its lower reaches would be impaired as energy losses increased and the channel slope decreased, which could eventually affect the sections upstream.

5.3 Studies of the Gorai River Mouth

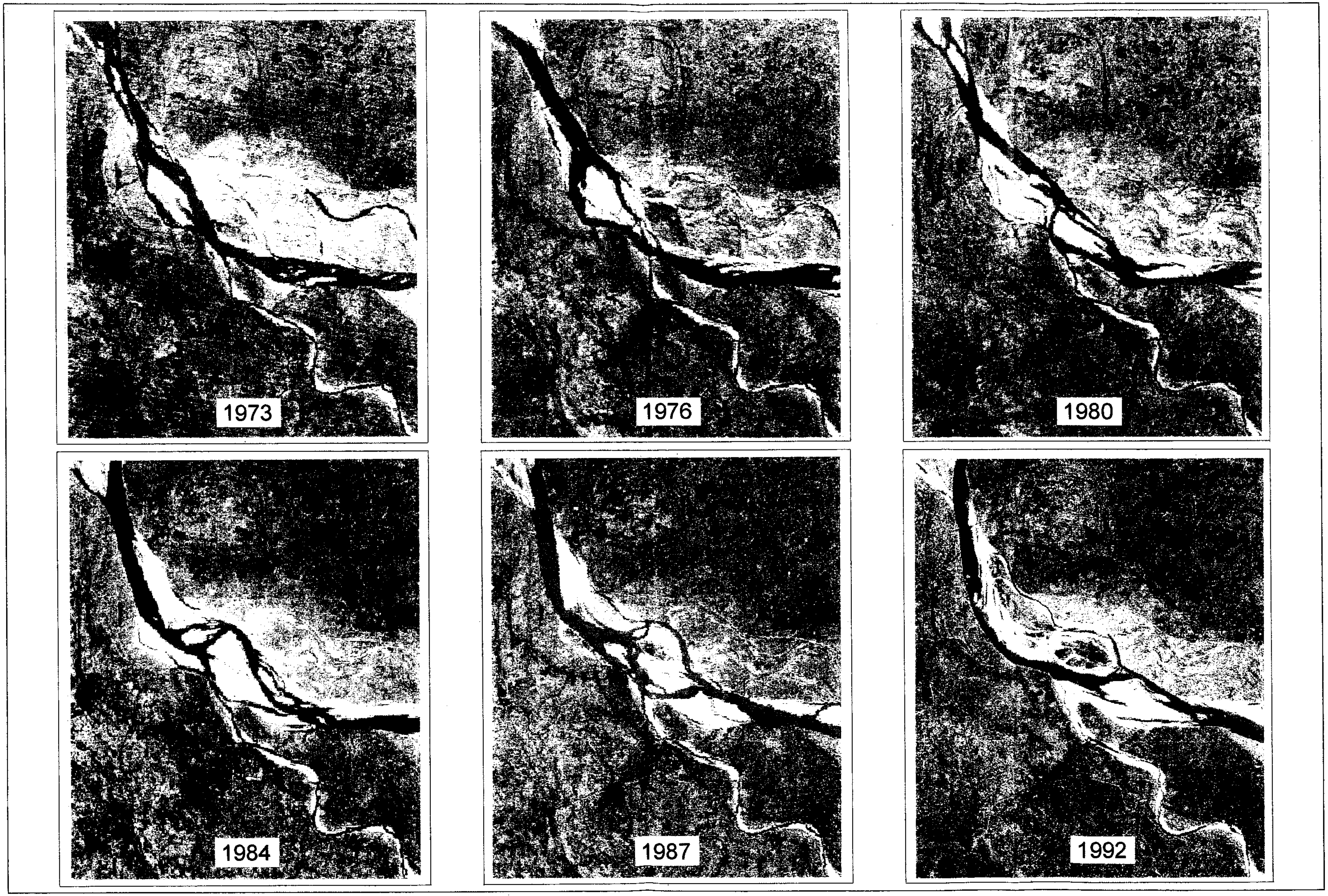
5.3.1 Bankline Changes in Ganges at Gorai Mouth

The medium and short-term evolution of the mouth of the Gorai River is one of the "Burning Issues" and has received great attention in the morphological studies. All available satellite

Figure 5.15



Gorai Cross Section at Ch. 28 Km
Dominant Discharge Level



(Source : Landsat Satellite Imagery, Supplied by FAP-19, Approx Scale : 1 : 300000)

Changes in Rivers Ganges and Gorai at Gorai Mouth, 1973 - 1992 images have been obtained and prints made of the mouth area by FAP-19. The changes in the Ganges at the Gorai mouth are shown in Figure 5.16. BWDB bankline surveys and maps have been obtained and banklines have been digitised from old maps dating back as far as Rennell's map of 1779 and earlier changes are shown in Figure 5.17.

The Ganges has a wandering planform that exhibits elements of both meandering and braided patterns. The macro-form of the river in recent years changes downstream of the Gorai off-take. Upstream of the off-take the planform consists of a braided channel that follows large, sweeping meanders with a wavelength of about 35km. Downstream of the Gorai the planform shows a meandering thalweg channel within a braid belt that displays nodes at about a 16km spacing.

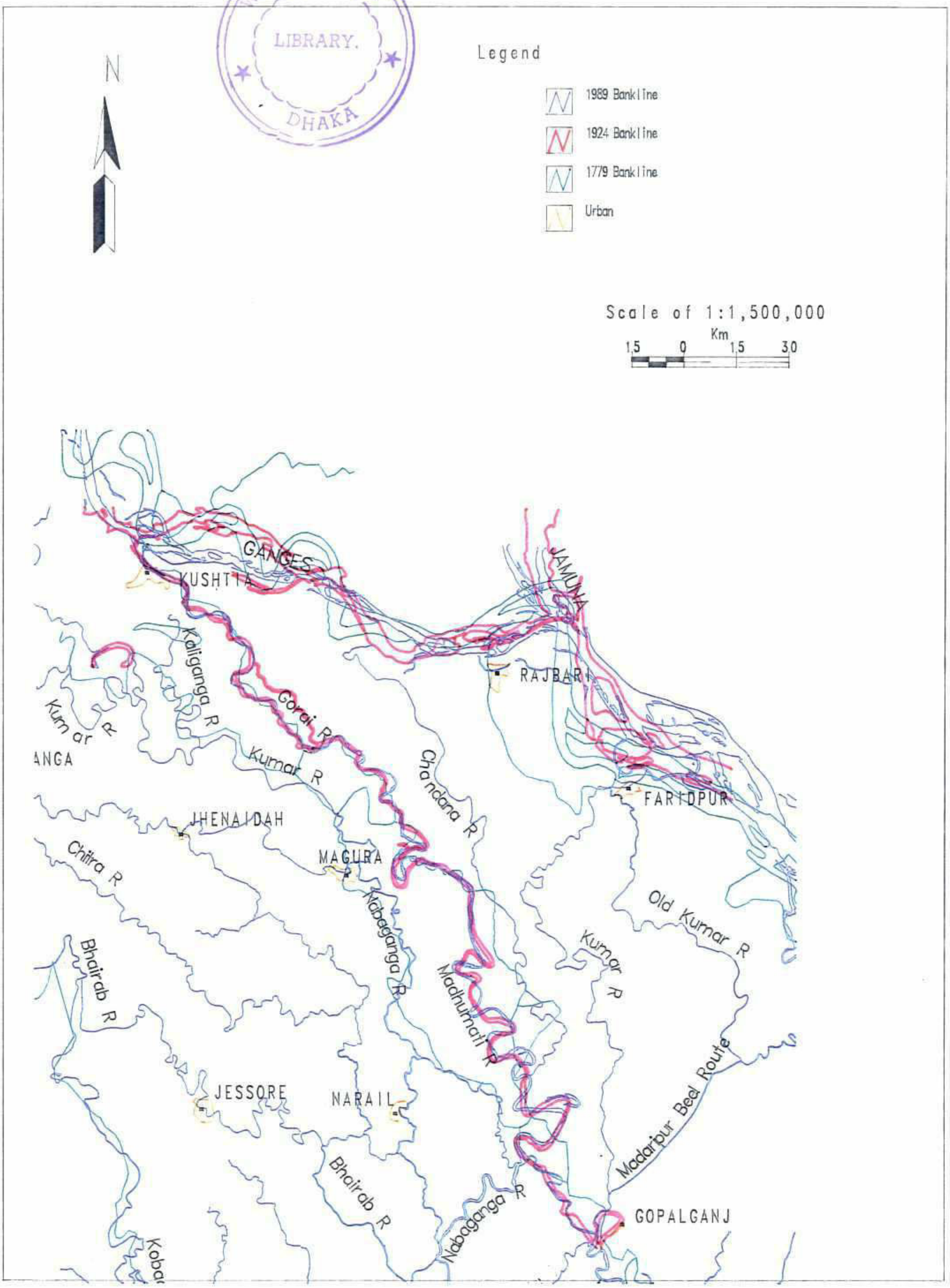
The Gorai off-take is situated just downstream of the first node in the right bank of the braided pattern, at Talbaria Point. This is significant, because it means that the mouth of the Gorai is actually in the right bank embayment of a sediment storage reach between two quite well defined nodes. The sequence of satellite images from 1973 to 1992 shows how the channel pattern in the Ganges changes in response to the passage of sand bars through the node-embayment-node geomorphic unit around the off-take. The channels and bars have been schematised in Figure 5.18.

In 1973 there is a major medial (braid) bar upstream of Talbaria, with divided flow around it. The flow converges to a crossing located in the Gorai mouth area. The main channel of the Ganges upstream of the node is orientated south-southeast and water flow approaches the off-take mouth almost directly along the line of the Gorai. At the mouth the flow turns onto an east-southeast direction. Deep water therefore occurs due to both flow convergence (confluence scour) and curvature (bend scour) very close to the mouth, supplying water to the Gorai throughout the year. The low flow Gorai channel shows a coherent meandering form with crossings between bends spaced at about 2.5km intervals and a series bends of alternate curvature originating at Talbaria point.

In 1976 the nose of the braid bar has grown wider and elongated downstream so that the bar tail is entering the Gorai mouth embayment. Flow still divides around the widening bar, and anabranches on both sides are deflected outwards. Curved flow in these anabranches is eroding into the channel banks on both sides of the bar. The left (north) anabranch is slowly eroding braid deposits in the active river corridor, while the larger southern anabranch is cutting more rapidly into an embayment in the flood plain margin. This embayment was formed by a previous anabranch loop sometime earlier. There is still confluence scour at the Gorai mouth, where the two anabranches converge and the left (north) channel of the Ganges upstream of the mouth is still orientated south-southeast so that its water flow approaches the off-take mouth almost directly along the line of the Gorai. The right (south) channel curves into the embayment upstream, flows around Talbaria Point and then curves again into the mouth of the Gorai. Dry season flow to the Gorai is maintained because the anabranches confluence and curve to scour the bed deeply at the mouth. The planform of the Gorai has the well organised bends and crossings still in place.

By 1978 the braid bar has widened further and the tail has migrated well into the embayment. The left anabranch channel on the north side of the bar has become dominant. The right anabranch in the embayment upstream has been abandoned at low flow. The main, (left) low flow anabranch divides just north of the Gorai mouth and the larger sub-channel crosses (dissects) the bar on a heading that lines up with the Gorai channel. The right sub-channel of the left anabranch is eroding the braid deposits north of the Ganges low flow channel. Confluence scour and bend scour still occurs at the mouth where the left sub-channel of the north anabranch meets the remnant of the right anabranch and the flow turns to the east. The confluence of the two sub-channels of the north anabranch is located well downstream of the Gorai. The reason that low season

Figure 5.17



Bankline Changes Ganges & Gorai

flow into the Gorai is maintained is that the left sub-channel of the north anabranch has dissected the bar and crossed to the Gorai mouth, allowing spill flow that is evident in the image.

The reason that the cross-bar sub-channel exists in the dry season is threefold. First, because the strong energy gradient across the bar and down the Gorai has drawn enough flow during the falling stage at the end of the monsoon to keep open cross-bar channel. Second, there was sufficient time during the flow recession for the falling flow to scour the high flow bar. Third, the positioning and topography of the bar were such that the cross-bar channel was located at a relatively low point across the bar tail.

Without this dissection the bar would in 1978 have separated the Ganges low flow channel from the Gorai and there would have been negligible spill flow. The energy slope into the Gorai is sufficiently steep to maintain a low flow channel in 1978 because the channel has an orderly arrangement of bends, pools and crossings (clearly visible in the image) and, therefore, a hydraulically and sedimentalogically efficient channel.

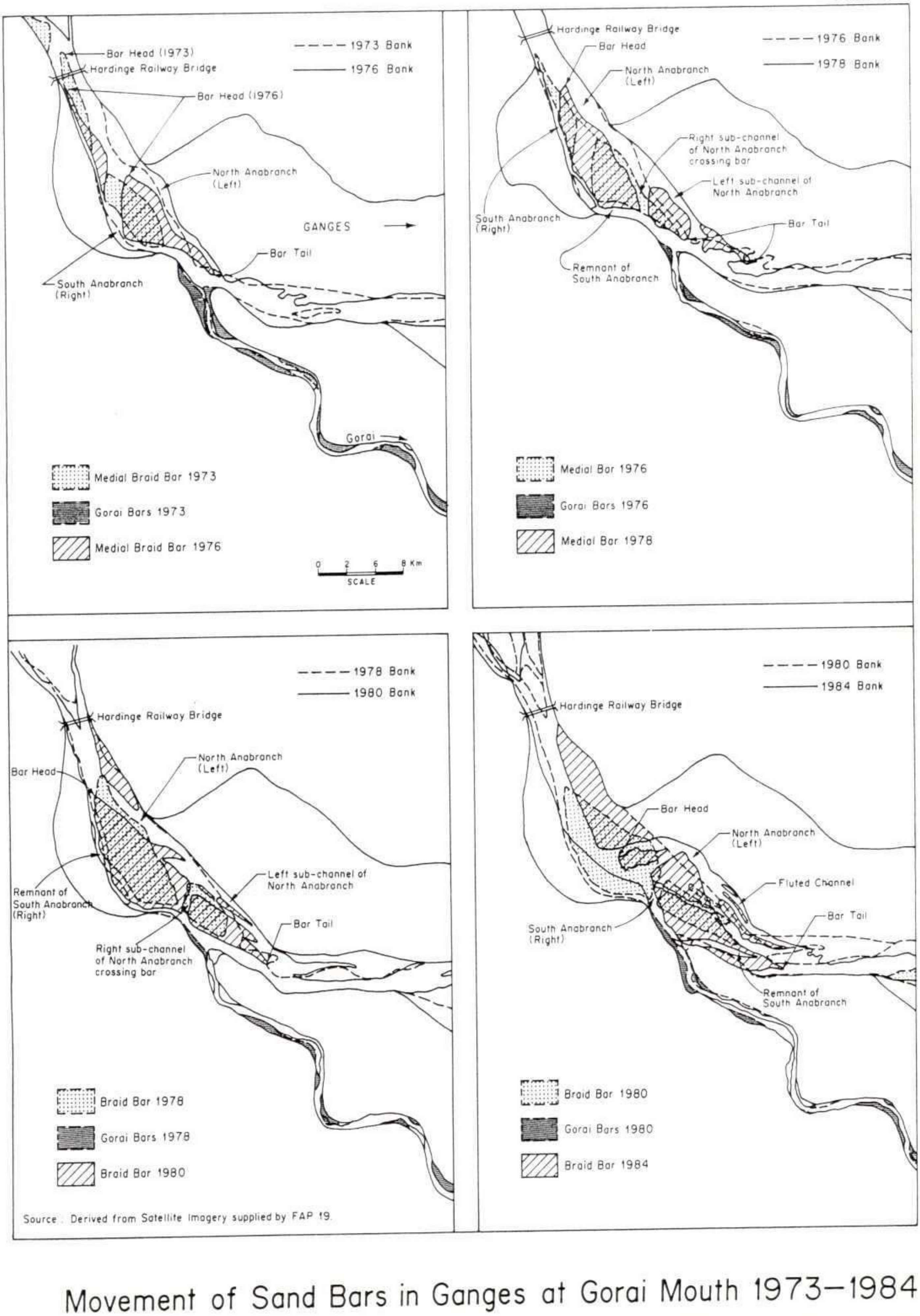
The situation in 1980 is broadly similar 1978. The medial braid bar has continued to grow in width (and probably in height also) and to migrate in the downstream direction and Ganges flow is still divided at all but high stages. The right anabranch in the embayment upstream of Talbaria Point has further diminished. A cross-bar sub-channel of the north anabranch still carries water to the Gorai mouth during the dry season, but its size relative to the left sub-channel has decreased. This channel was cut during the falling limb of the monsoon because of a large head difference between the left and right anabranches and across the bar generating sufficient erosive power. The head difference occurred in 1980 because water flow into the Gorai draws down the pool level in the right anabranch relative to that in the left anabranch. In this way, the Gorai pulls water across from the Ganges' main low flow channel, north of the bar all the way across the bar and into the offtake. For this to happen, the energy slope down the Gorai must be sufficient for water to drain freely and transport sediment so that it maintains a coherent low flow channel during the falling stage at the end of the monsoon.

By 1984 the braid bar in the Ganges has migrated further downstream, so that its head is now north-northwest of Talbaria Point and its tail is due north of the Gorai Railway Bridge. The bar has widened considerably as it has entered the embayment containing the Gorai mouth and the elevation of the bar top has probably also increased. In the image it is possible to make out a small slough channel running right along the centre of the bar in the longstream direction. This slough turns out to be very important later.

Flow in the main, northern anabranch is very strongly curved around the bar and it both erodes the braid bar deposits in the river corridor and dissects the crest of the bar in a series of fluted sub-channels on the north side of the Ganges. The southern anabranch has re-opened but its curve no longer follows the embayment upstream of Talbaria. Instead it occupies the next embayment, which is the one containing the Gorai off-take. This brings it into the embayment along the line of the Gorai channel and most of the flow in the southern anabranch now goes down the Gorai. A little flow in the southern anabranch crosses the bar to confluence with the northern anabranch near the tail of the bar in the Ganges further downstream. Consequently, the bar is almost attached to the southern bank of the Ganges in the Gorai embayment. Probably, if the Gorai were not accepting spill flow from the southern anabranch, the southern channel would no longer exist at this time and the northern anabranch would carry all the Ganges low flow in a loop around the braid bar that would abandon the Gorai mouth entirely. The significance of this pattern is that the Gorai must itself draw enough water into the southern anabranch to keep a channel open at low flow. There will not always be a right bank Ganges anabranch to fulfil this role.

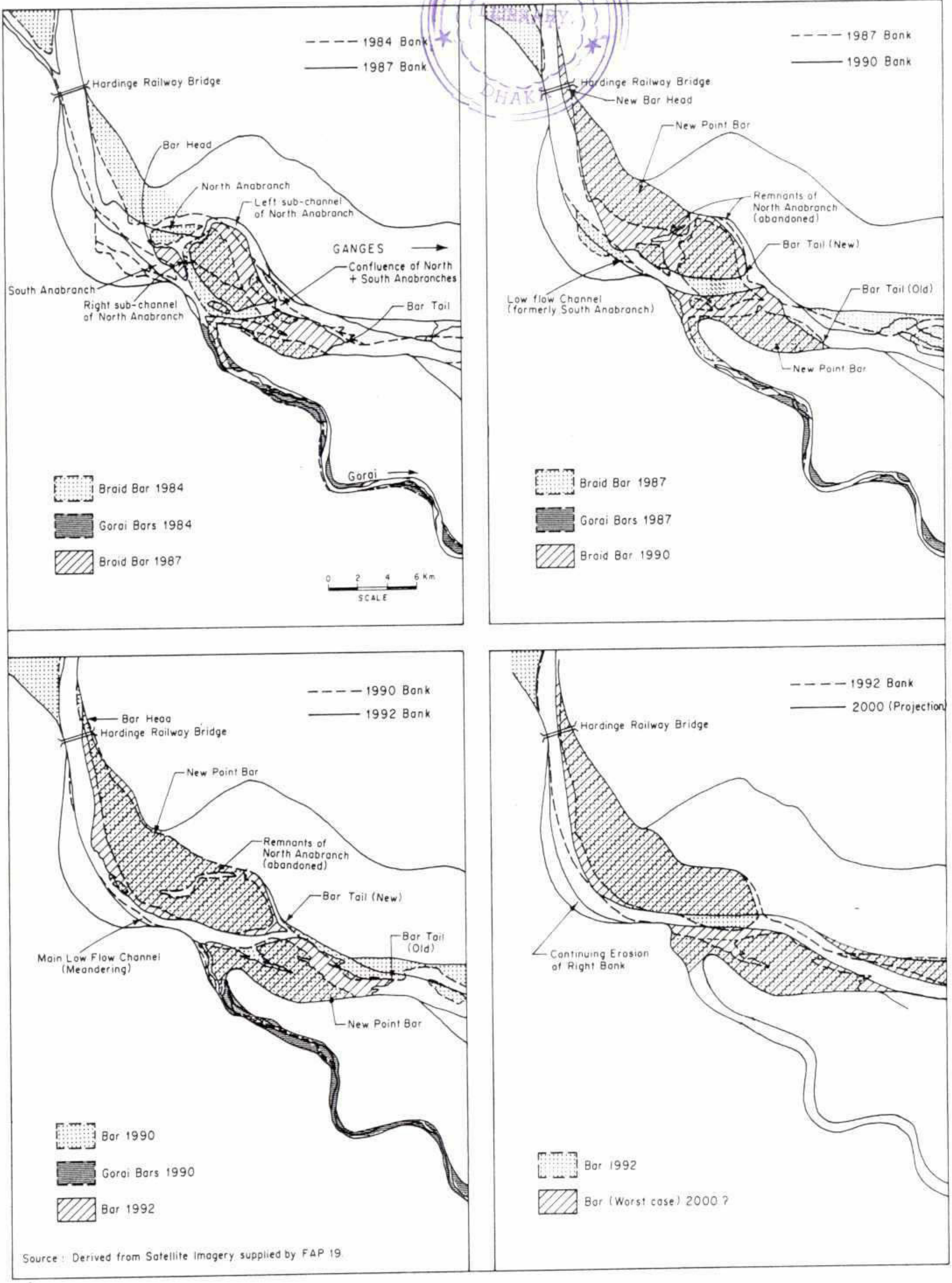
Figure 5.18

Sheet 1 of 2



Movement of Sand Bars in Ganges at Gorai Mouth 1973–1984

Figure 5.18
Sheet 2 of 2



Movement of Sand Bars in Ganges at Gorai Mouth 1984–1992

In 1987 the Ganges flow pattern is broadly similar to that in 1984. The braid bar has grown to full maturity. It is now very wide and its upper surface has started to become vegetated. The bar now occupies practically the whole width of the embayment at the Gorai offtake, ponding up the Ganges flow behind it and causing the flow to curve strongly around both sides of it. Upstream of the bar head the Ganges has a single-thread channel which is rapidly eroding its southern bank and moving into the right bank embayment upstream of Talbaria point.

In the Gorai embayment, the Ganges northern anabranch follows a very tight curve and the part of the flow dissects the bar crest near the head, to join the southern anabranch just north of the Gorai mouth. The remaining flow in the northern anabranch further erodes a loop into the braid bar deposits in the river corridor to the north of the channel. The southern anabranch is shallow and wide, dividing around smaller bars that split it into low-flow sub-channels, probably because it has not the capacity to transport all the incoming sediment from the rapid right bank erosion upstream. Its ability to maintain a single-thread low flow channel is being overwhelmed. The southern anabranch follows a similar course to that in 1980, but its increased curvature takes more obliquely across the bar, away from the Gorai mouth and to a confluence with the northern anabranch almost due north of Kushtia. The portion of the bar between the southern anabranch and the south bank downstream of the Gorai off-take has grown as a result, and this growth is starting to engulf the Gorai's mouth to the south of the attached bar.

Migration of the single-thread Ganges channel towards the embayment upstream of Talbaria means that the southern anabranch no longer approaches the Gorai mouth along the line of the Gorai channel, but tends to flow tangential to Talbaria Point. This seems to induce flow separation off the point, and a cuspate bar is evident downstream of the Talbaria between the bank and the low flow channel in the Gorai. As a result of sedimentation on both sides of the mouth, the low flow Gorai channel is now located in the centre of the mouth and almost at right angles to the approaching flow in the Ganges.

This change in entrance alignment may be the cause of disruption to the pattern of bends, pools and crossings in the Gorai channel between the mouth and the Railway Bridge. The low flow channel appears more ragged and sediment storage is not so orderly as it was in previous images. Because of the poor channel alignment and disorderly bed topography, the energy gradient into the Gorai is no longer sufficient to draw enough water into the off-take and to scour a coherent low flow channel. Also, due to the occurrence of severe bank erosion just upstream of Talbaria Point, the right anabranch may be supplying a heavy sediment load. This is suggested by the new cuspate bar downstream of the Point. There is still flow into the Gorai, but it is greatly diminished and not all the southern anabranch flow enters the river, some of it flowing back over the bar and to rejoining the main Ganges anabranch.

In 1990 the flow pattern in the Ganges has altered radically. The 1987-1990 period includes the high magnitude floods of 1987 and 1988, and so strong pattern changes is to be expected. The braid bar has been cut in two because the Ganges has abandoned the northern anabranch, which had become very tightly curved, and flow is concentrated in what was the southern anabranch. The combined flow has cut right through the centre of the braid bar, along the line of a slough channel visible on the 1984 image and on the falling limb of the last monsoon flow the entire Ganges low flow has occupied this channel, which has therefore dissected the bar heavily. The remnants of the bar to each side are left high and dry. The abandoned anabranch channels remain as sloughs with standing water in them. Upstream of the Gorai offtake embayment, the single-thread Ganges low flow channel is migrating southwest by eroding the right (south) bank in the embayment there. As a result, flow at Talbaria is heading almost due east, tangential to the point and at right angles to the mouth of the Gorai. The mouth of the Gorai is almost entirely dry and is located behind the right side remnant of the bar.

The channel of the Gorai has no flow and the standing water in pools shows that there is a poorly organised bed topography, with no strong coupling of bed features to planform until the first bend downstream of the Railway Bridge. There cannot have been sufficient energy gradient to draw any substantial discharge of water across the bar and down the Gorai during the flow recession after the last monsoon event.

In the last image, for 1992 the single-thread, curved Ganges channel has cut more deeply into the embayment upstream from Talbaria and the flow has hinged off the point at Talbaria, further away from the embayment at the Gorai mouth. The Ganges single-thread channel is developing a meandering planform which is half a wavelength out of phase with the Gorai embayment. As a result the southern remnant of the former braid bar has become a large point bar that now occupies the embayment at the Gorai mouth and entirely separates the off-take from the low flow Ganges channel. As in 1990, there is no low flow channel connecting the Gorai to the Ganges. The channel of the Gorai is dry except for standing water in pools and especially in the scour hole caused by the "T-head" groynes at Kushtia. The pattern of pools and the trace of the low flow channel are again out of phase with the planform until downstream of the Railway Bridge.

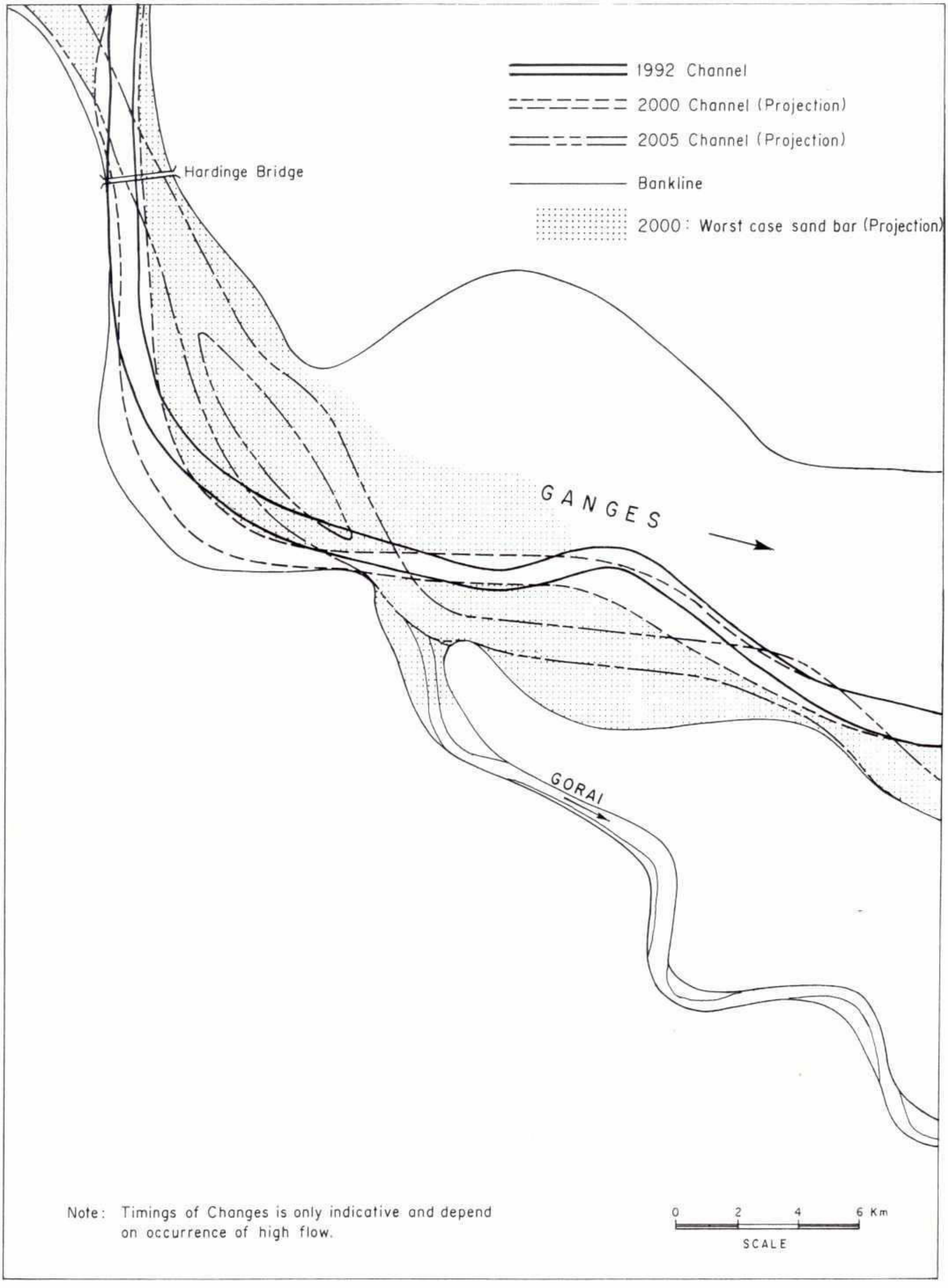
The sequence of morphogical change can be used to project channel positions into the near future. Initially, as the flow in the bend at Sara stays in the outer, thalweg channel, the flow in the right bank embayment upstream of Talbaria Point continues to erode the right bank and the big point bar on the left bank grows. Flow crosses directly north of the Gorai offtake and follows a sinuous path. The point bar in front of the offtake mouth grows and widens, further reducing spill flows into the Gorai and lengthening the period when the river is dry. This trend of development may be expected to continue until about the year 2000, at which time the Ganges has developed pronounced sinuosity and the embayments both upstream and downstream of the Gorai are occupied by deep water channels, but that at the mouth is filled by a point bar. In time, erosion of the right bank in the embayment upstream is likely to cause the flow at Talbaria to swing further and further east-northeast away from the line of the Gorai channel, making approach conditions worse, not better. This will lead to erosion on the left (north) bank of the channel in the embayment at the Gorai mouth, moving the low flow channel away from the off-take and widening the point bar at the right (south) bank. Conditions in the Gorai channel will deteriorate steadily up to this time.

For a low flow connection to be re-established either the main channel of the Ganges must re-occupy the embayment at the Gorai offtake, or the spill flow must develop a distributary channel across the intervening bar that has sufficient stream power to dissect that bar and scour a low flow channel on the falling stage of the monsoon.

Judging from the pattern and position of low flow Ganges channel the first possibility is unlikely to occur in the near future. But, eventually there will be a chute cut-off at the bend at Sara and a re-alignment of the approach flow to the big bend upstream of Talbaria. At this time, or shortly afterwards, the big bend will experience a chute cut-off abandoning the low flow channel at the right bank and the large point bar at the left bank will be dissected. The cut-off channel will enter the embayment containing the Gorai offtake on the line and heading of the Gorai channel and at that time a recovery in the distributary is expected. This might take place early in the next century, perhaps in around 2005 in a manner similar to that shown in Figure 5.19.

The second possibility for reconnection (by a low flow dissection of the point bar in the Gorai mouth) is also unlikely in the near future owing to the disorganised topography and high elevation of the Gorai channel bed. This is the result of the disorganised planform pattern and sediment deposition at the mouth and in channel extending down to the Railway Bridge, which has reduced the energy slope from the Ganges into the Gorai, promoting further high flow deposition and preventing low flow spillage entirely.

Figure 5.19



Potential Future Changes in Ganges at Gorai Mouth

It seems unlikely that either possibility for re-connection of the low flow channel is likely to occur in this century.

5.3.2 Gorai Mouth - Crossings

The recent satellite images show extensive bars and the lack of a distinct thalweg to provide a low flow channel upstream of the railway bridge. While the problem may not be at the bridge, and is probably not caused by the bridge itself, there is serious channel problem in the vicinity. This may tentatively ascribed to a poor channel alignment leading to the lack of properly spaced, short and well defined crossings between scour pools on opposite sides of the channel. This may at least in part be due to the effects of the groynes at Kushtia. Groyne tip scour produces a deep water thalweg in the centre of the channel at the bend exit. Not only does this tend to promote deposition of scoured sediment just downstream where the flow leaves the groynes, but also truncates the curvature of the flow opposite Kushtia. As a result, the flow crosses the channel from the right (south) bank too early and too abruptly. The deep water channel then follows an uncertain and shifting path along the centre-left of the channel downstream of Kushtia. This appears to disturb the entrance conditions for the tight right hand bend just upsteam of the Railway Bridge.

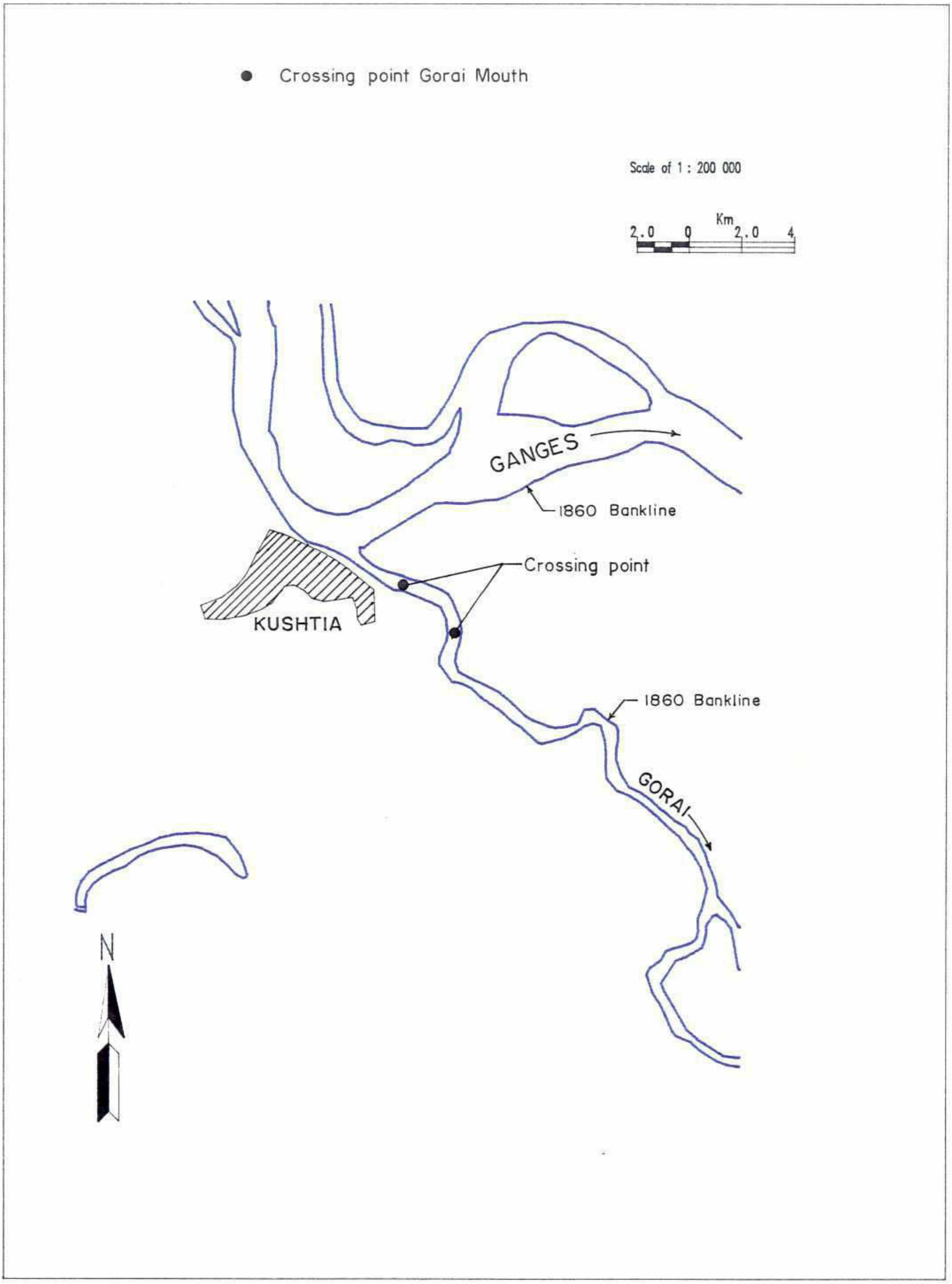
The Gorai originally developed into a large river when the alignment of the Ganges came past Kushtia as shown in Figure 5.20. This alignment gives a strong crossing point in the approach to the bend at the rail bridge. The retreat of the Ganges from the anabranch past Kushtia seems to have caused intermittant problems for the Gorai since but these may have been made worse by the three "T - head" groynes built to protect Kushtia.

As shown in Figure 5.21 prior to the groynes the reach between the offtake and the Railway Bridge had reasonably well spaced crossings and the bend upstream of the Bridge almost always had a well developed scour pool at the outer bank. The recent images (post-1987) show a wandering thalweg and the 1992 image shows the flow making a chute channel at the inner bank, with heavy sedimentation at the outer bank, and the introduction of short radius, tight bends, new crossings and extra sinuosity to the low flow channel. All of this will make the problems of siltation worse.

Bend Morphology and Crossing Spacing

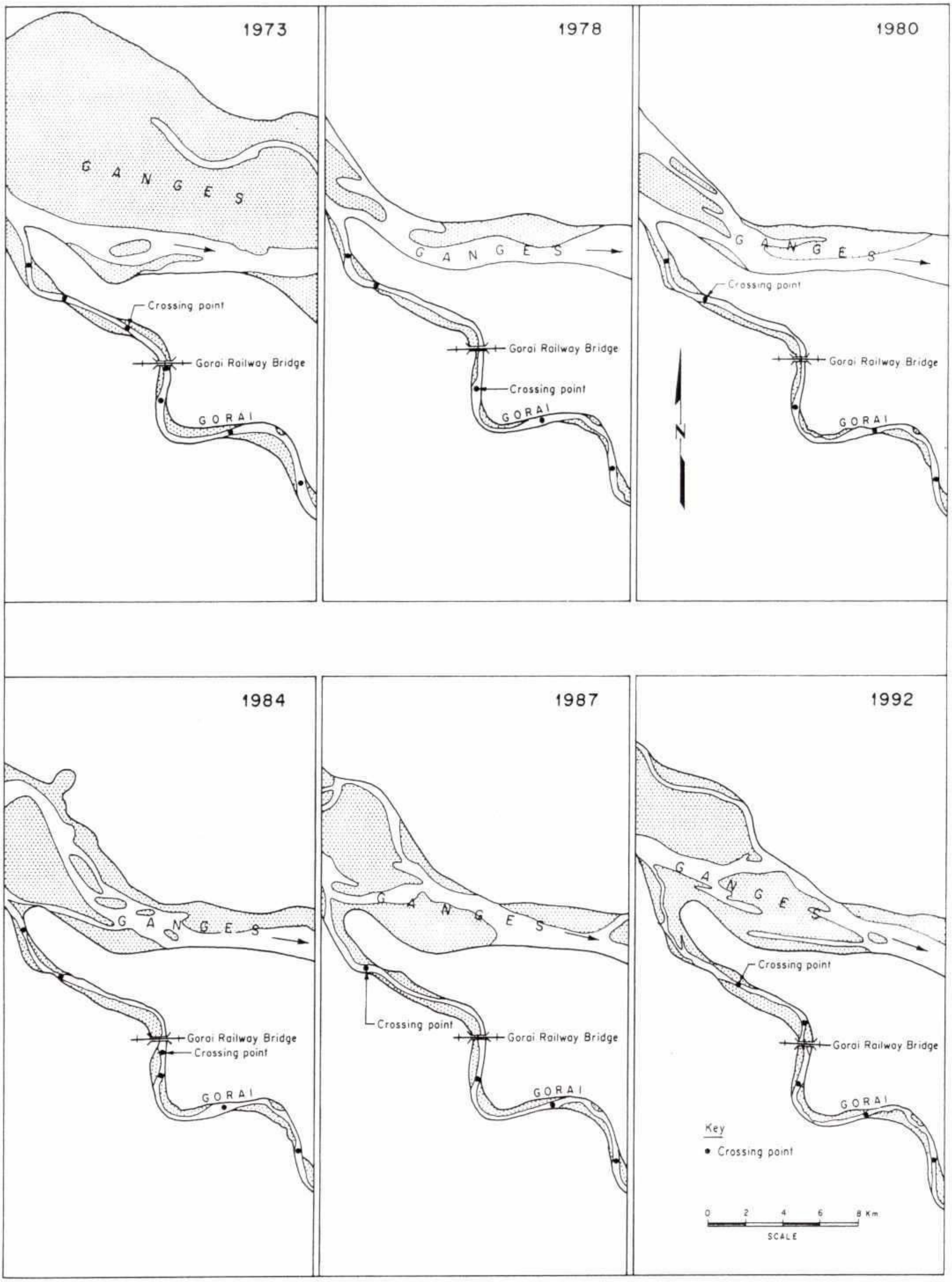
Data were taken from the planform of the Gorai to define the average spacing of crossings between bends and to test whether the bed topography at a bend could be predicted from its planform geometry and flow hydraulics using the BENDFLOW computer model.

Figure 5.20



Orientation of Ganges During Increase of Gorai 1860

Figure 5.21



Gorai River
Location of Crossing Points

For the first 20 bends downstream of the offtake the crossing spacings are listed in Table 5.2.

TABLE 5.2

Gorai - Bend crossing spacings

Bend Number	Spacing (km)	Comments
1	5	Rwy Bridge bend - well developed
2	4	big bend, very stable
3	4.6	Kumarkhali - long bend, stabilised
4	2.9	long bend - very stable
5	4.6	very long bend - flat apex
6	1.9	short bend, wide point bar
7	1.4	low sinuosity bend
8	4.0	very long bend
9	1.9	short bend, low sinuosity
10	1.6	low sinuosity, almost straight
11	2.1	low sinuosity, almost straight
12	1.8	low sinuosity, almost straight
13	1.7	low sinuosity, almost straight
14	4.4	long bend
15	2.6	sinuous bend
16	1.9	low sinuosity, short bend
17	1.5	short bend, local scour at crossing
18	1.9	low sinuosity bend
19	4.4	very long bend, some extra crossings
20	1.5	very tight bend
Spacing (km)	**Frequency**	
0.0-0.5	0	
0.5-1.5	1	
1.5-2.5	10	
2.5-3.5	2	
3.5-4.5	4	
4.5-5.0	3	
5 +	0	

These results show a bi-modal distribution of crossing spacings with characteristic spacings at about 2 km and 4.5 km. Examination of the crossing spacings with the bend geometries shows that as a general rule long bends correspond to the 4.5 km crossing spacing, while the low sinuosity, straighter alignments have crossings spaced at about 2 km.

The summary of the spacing and frequency is also given in Table above.

On this basis, it is suggested that morphologically, any schemes to train or stabilise the Gorai should be laid out with a sinuous alignment that maintains the characteristic crossing spacing for the chosen planform pattern. Where a low sinuosity channel is required the flow should cross the channel at 2 to 2.5km intervals. Spurs or longitudinal kicker dykes should be used to ensure that the flow crosses at the desired points. If big bends are to be used then these should mimic the geometry of natural bends on the Gorai, with crossings at 4 to 5km intervals.

These planform patterns allow the river to store sediments in an orderly arrangement of point and crossing bars. This helps the river to maintain a coherent low flow channel and to be self-cleansing with regard to sedimentation. This will minimise (but not eliminate) maintenance dredging, since dredging should only be necessary at crossings and spoil can be disposed of on and behind point bars.

The analysis shows serious problems with the planform and bed topography in the reach around and upstream of the Railway Bridge. Poorly positioned pools, bars and crossings in relation to the planform bends are apparent, and may well be partly responsible for medium and longterm aggradational trends in bed elevations. The present groyne structures in the channel, while effective in protecting the town of Kushtia from bank erosion, may be contributing to the problem. Serious consideration must be given to properly laid out training works for this reach that would produce a better flow alignment with a bed topography (pools, bars and crossings) that is matched to the planform of the river.

A suggested layout for groynes and crossings is given in Figure 5.22.

5.3.3 Study of the Gorai Mouth - Conclusions

The mouth of the Gorai in the last 20 years has changed radically. In the 1970s although the Ganges anabranch channels were not always in favourable positions for dry season spillage to the Gorai, there was always sufficient distributary flow to maintain a steep enough water surface slope to scour a cross-bar channel that linked the Gorai to a low flow Ganges channel.

The 1980s saw a braid bar move downstream into the embayment containing the Gorai off-take. First the Ganges flow divided to support anabranches on both sides of the bar, but then it abandoned its southern anabranch completely. Still a low flow channel to the Gorai survived due to the ability of spill flows to scour a sub-channel across the bar from the northern anabranch.

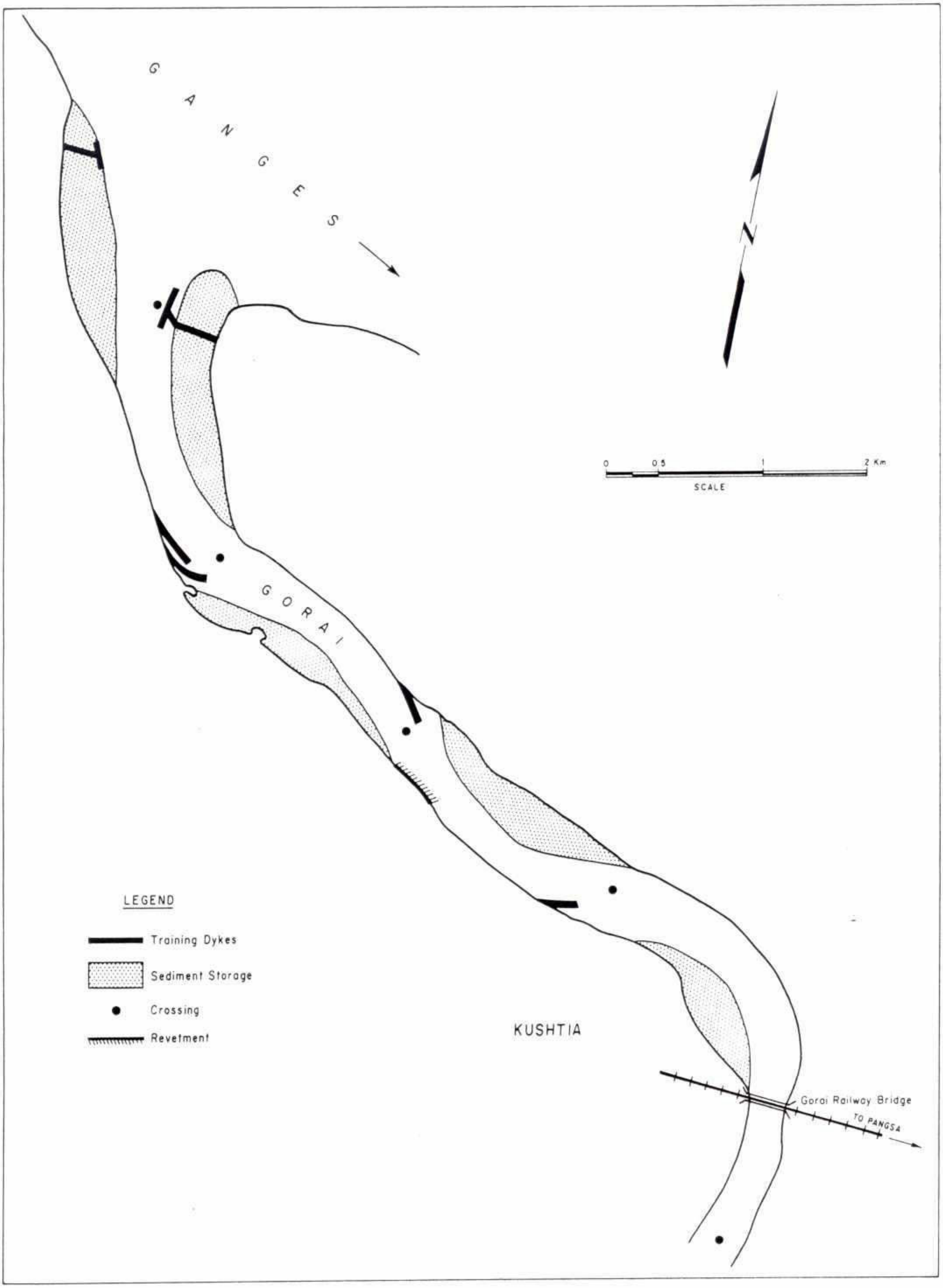
By the 1990s the Ganges had cut through the centre of the bar in the Gorai embayment, straightened its course and abandoned the divided anabranch channels of the 1980s. Flow into the Gorai was unable to scour and maintain a cross-bar channel and the mouth became entirely disconnected from the Ganges low flow channel. Subsequently, sinuosity developing in the single-thread channel has taken the low flow channel further away from the Gorai offtake and this trend looks set to continue. There is at present no prospect for an early re-connection of the Gorai at low flow without engineering intervention.

5.3.4 Development of the Kamarkhali Bends

A striking feature of the Gorai is the tortuous 20 Km loop in the river at Kamarkhali. The development of the bends is illustrated in Figure 5.23. It is remarkable that such a feature should have been apparent even in 1779 before the Gorai was formed and illustrates the erosion resistance of some of the clay/silt layers in the Southwest Area.

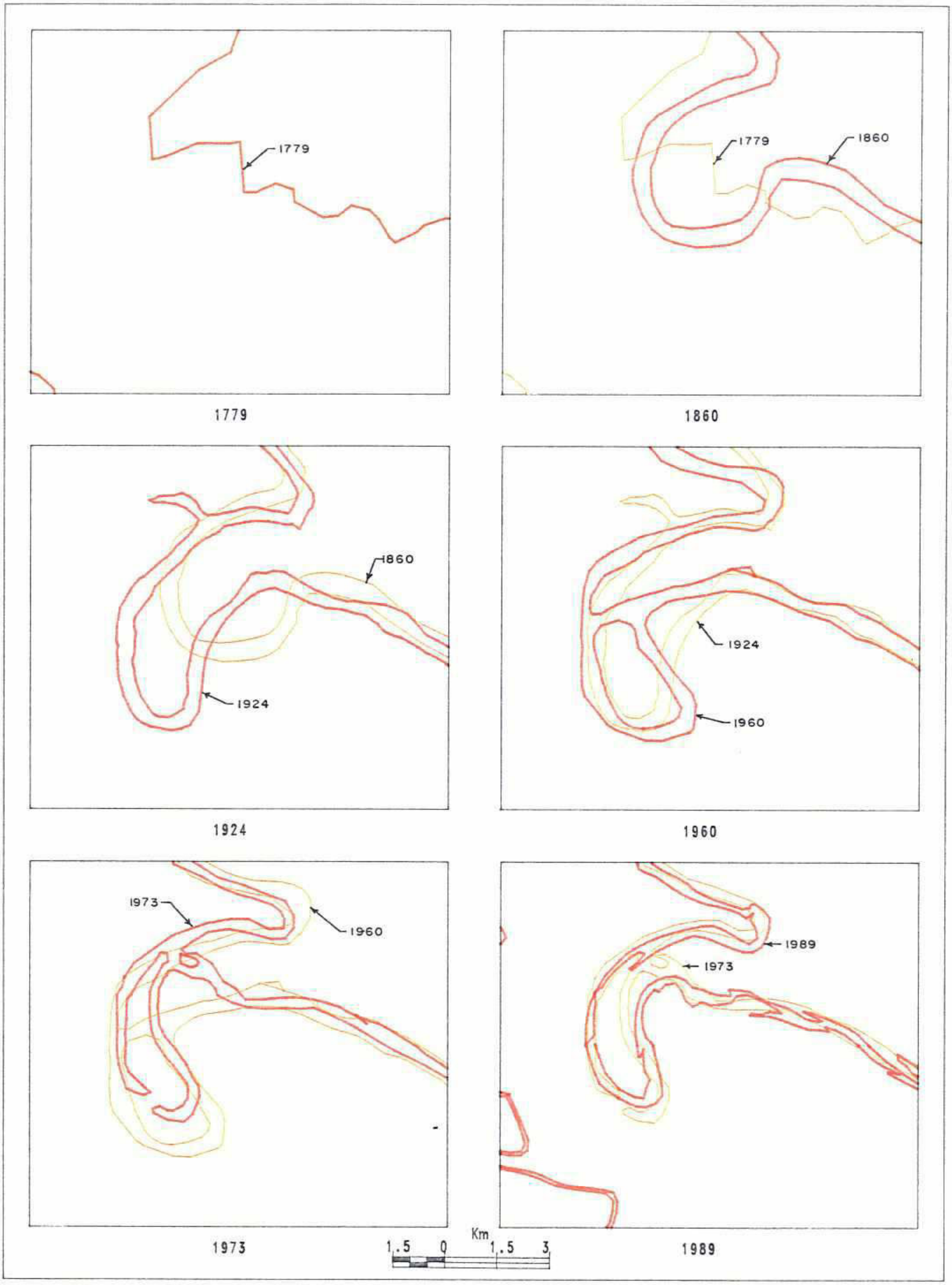
A cutoff channel in the bend seen in 1960 and 1973 has now been abandoned and the full loop is again developing similar to that seen in the 1924 mapping. The radius of curvature of such a cutoff was probably too small to be sustainable. Because the bend has been stationary for such a long period the upstream meander bends have also become very tight small radius bends at which a high headloss can be expected. The calculted headloss due to bend losses was over 1.0m at dominant flow and clearly a cutoff or some realignment would have a beneficial effect on upstream water levels and hence upstream bed levels.

Figure 5.22



Proposed Layout for Groynes & Crossings

Figure 5.23



Development of Kamarkhali Bends 1779–1989

5.3.5 Development of the Halifax Cut between the Madhumati and Nabaganga

The Halifax cut has developed significantly over recent years such that what was a small navigation channel cut with a width of 20m is now taking more than 90% of the flow down the Madhumati.

The flow geometry at the bifurcation is very peculiar and must result in a comparitively high headloss. The upstream bends are also very active possibly due to the changes at the cut. The change between 1924 and 1953 was relatively minor and it is only since that the Nabaganga has started to dominate (Figure 5.24).

5.4 Arial Khan

5.4.1 Dominant Discharge Calculation

Although there are no sediment monitoring data available for the Arial Khan applying typical factors to the flow frequencies (Figure 5.25) the dominant discharge at Chowdury Hat was found to be 2,000 m^3/s.

The analysis shows a peak which is not altered by the exponent on the sediment rating equation. 2,000 cumecs therefore seem a fairly secure result. This indicates that the capacity of the Arial Khan channel is second only to that of the Gorai in the regional rivers. These two rivers are much larger than any of the others and provide the best opportunities for low flow augmentation and any substantial regional water transfers.

5.4.2 Specific Gauge Analysis of the Arial Khan at Chowdury Hat

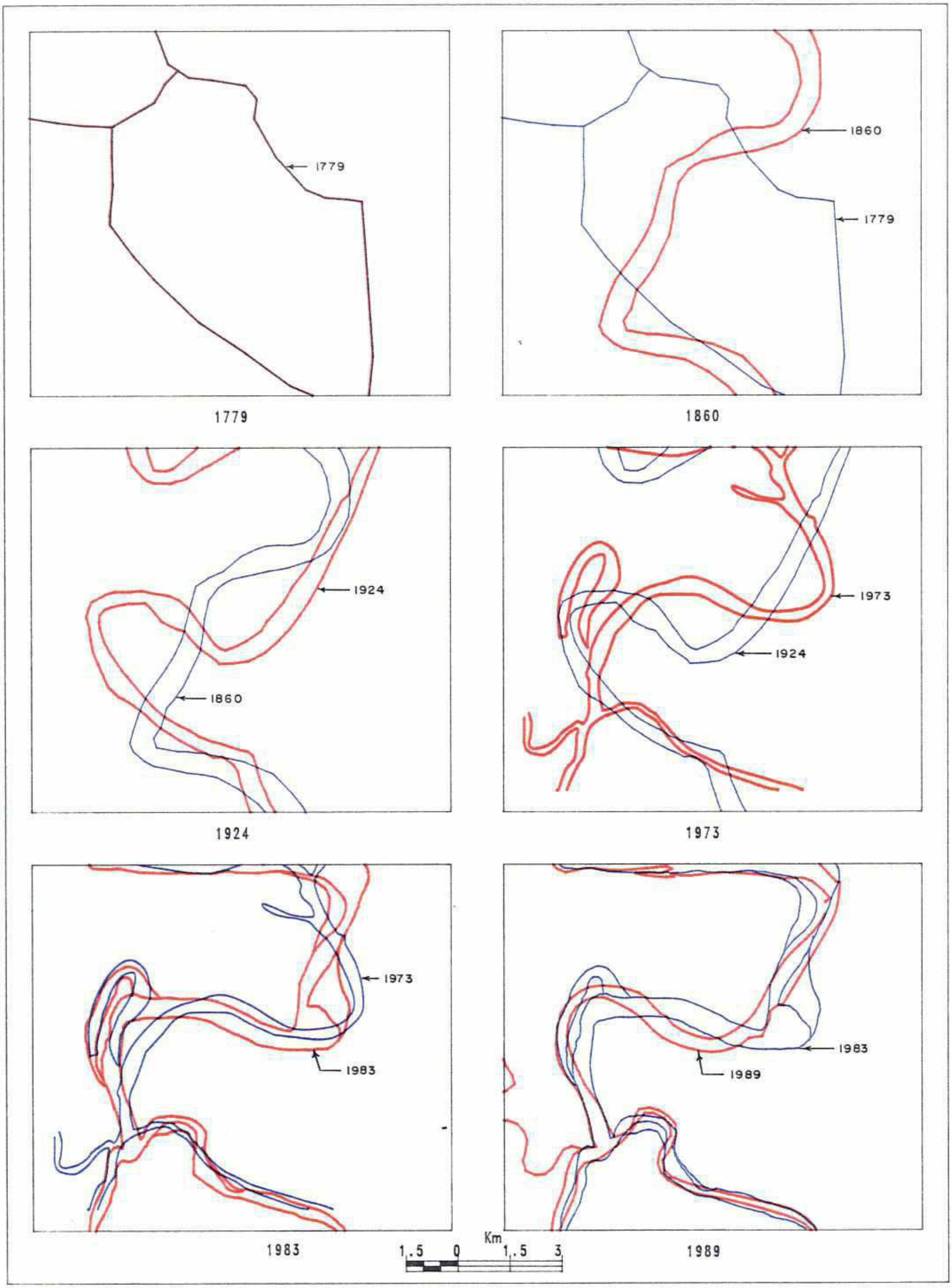
Specific Gauge records for the Arial Khan at Chowdury Hat go back to 1966. They show a strong degradational trend for all flow discharges, with water stages dropping by over 1.5 metres. There are short term fluctuations and reversals of the degradational trend during the period of record, but the overall trend is very clear and seems unequivocal.

These results indicate that the importance of the Arial Khan as a right bank Padma distributary is growing because as water surface elevation in the distributary is lowered, while that in the parent river remains about constant, the head difference increases. This increases the energy gradient, which draws more flow into the distributary.

The response of the alluvial channel will be to enlarge by bed scour and bank erosion, so adjusting its hydraulic geometry to the new imposed discharge of water and sediment. This then tends to lower the bed, attracting more water and leading to positive feed back. If there are no geologic controls, the limiting factor is the energy gradient of the distributary channel. As the channel degrades in its upper reaches this reduces the gradient in the middle reaches, because the upstream reach of the stream is lowered while the downstream reach remains the same or aggrades because of the heavy sediment load supplied by degradation upstream. Hence there is a hinging of the long profile, which tends to limit the amount of degradation that can occur. In this way the alluvial nature of the distributary allows it to adjust continuously to the inputs of water and sediment, hunting for but never attaining equilibrium.

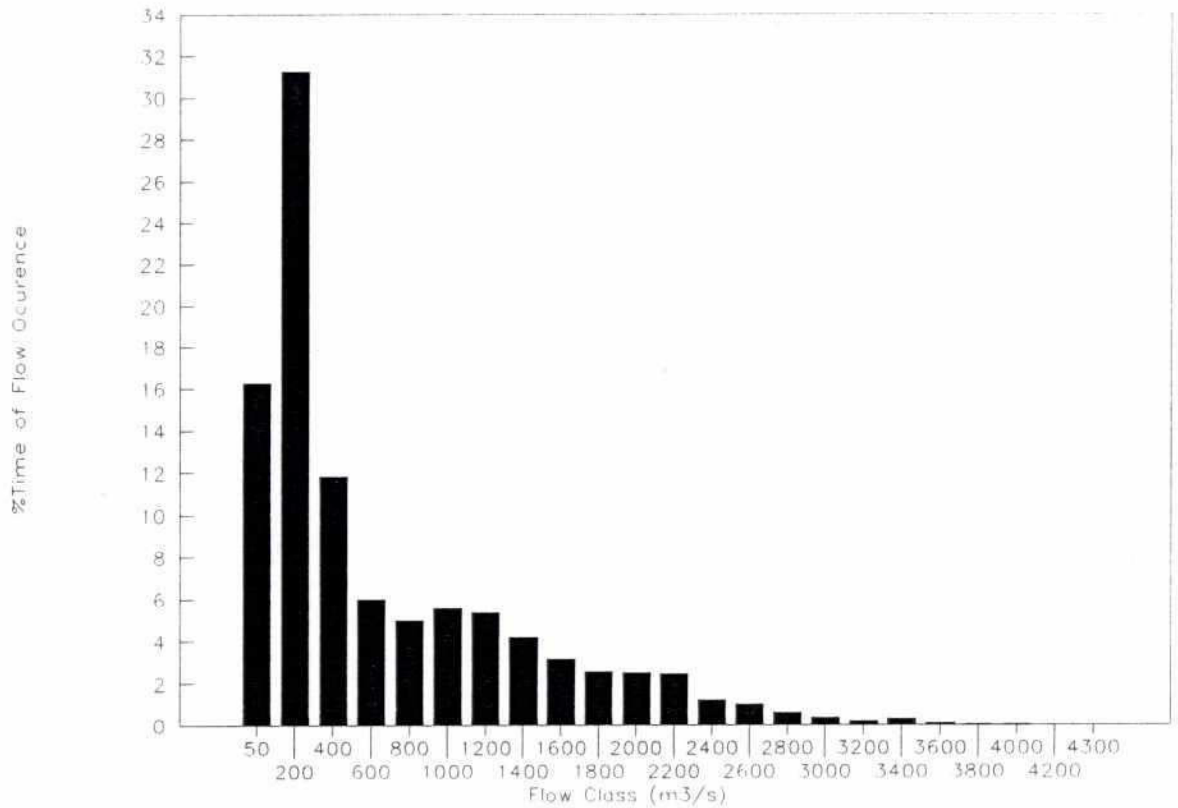
In the case of the Arial Khan it would appear that the last 10 years have been a period of expansion and the morphological evidence supports this. In water resource terms, the Arial Khan looks a strong contender for use in any water transfer scheme because its morphology shows no strong silting tendency and displays a large channel which is capable of transmitting extra water in the low flow season without noticeable impacts on the morphology. It is, however, also morphologically active under natural flows and care would have to be taken to allow for natural shifts, cut-offs and avulsions in the management strategy. In particular, the high mobility of the river might preclude the building of control structures at the mouth or along the course of the Arial Khan.

Figure 5.24



Bankline Movement of Madhumati near Halifax Cut 1779-1989

Figure 5.25



Flow Frequency Arial Khan River at Chowdhury Hat

The mobility and impact of the Padma at the mouth is illustrated in Figure 5.26 and 5.27. In 1983 the Chowdhury Hat channel was practically cut off from the main river with the result that flows were low (Figure 5.28). As the Padma swung back the channel increased significantly and rapid morphological changes occurred including erosion of part of the embankment built that year.

5.4.3 Long Profile of the Arial Khan

The thalweg levels in the Arial Khan were plotted as shown in Figure 5.29. This shows that although there are great changes in the upper reach of the channel, after the confluence with Dubaldia the changes are much less.

5.4.4 Contours of the Padma at the Arial Khan Mouth

The bathymetric survey of the Padma at the mouth of the Arial Khan (Figure 5.30) shows that upstream of the mouth there is a deep channel close to the bank indicating potential for continued erosion but downstream there is a much deeper channel (-19m PWD) further from the bank. This together with the observed slowdown in erosion rates indicates that the downstream bankline is stabilising after a period of rapid movement.

5.4.5 Long Profile Analysis of the Arial Khan - Kumar - MBR - Atherabhanki

A high flow echo-sounder profile has been produced along the Arial Khan River and across to the Khulna area (Figure 5.29). This is the line of a tentative route to augment dry season flows into the Khulna Basin from the fresh water in the Padma River.

The route follows a line between the 1 and 2 metre contours and, as expected, there is very little overall drop in the bed. Hence, the energy slope would be very small and it would probably be necessary to use "tidal pumping" to drive any appreciable volume of water through the system. However, the bed of the Madhumati (92 - 100km) is well below that of the route to the east and gravity flow at least that far looks potentially feasible.

The following details can be noted:

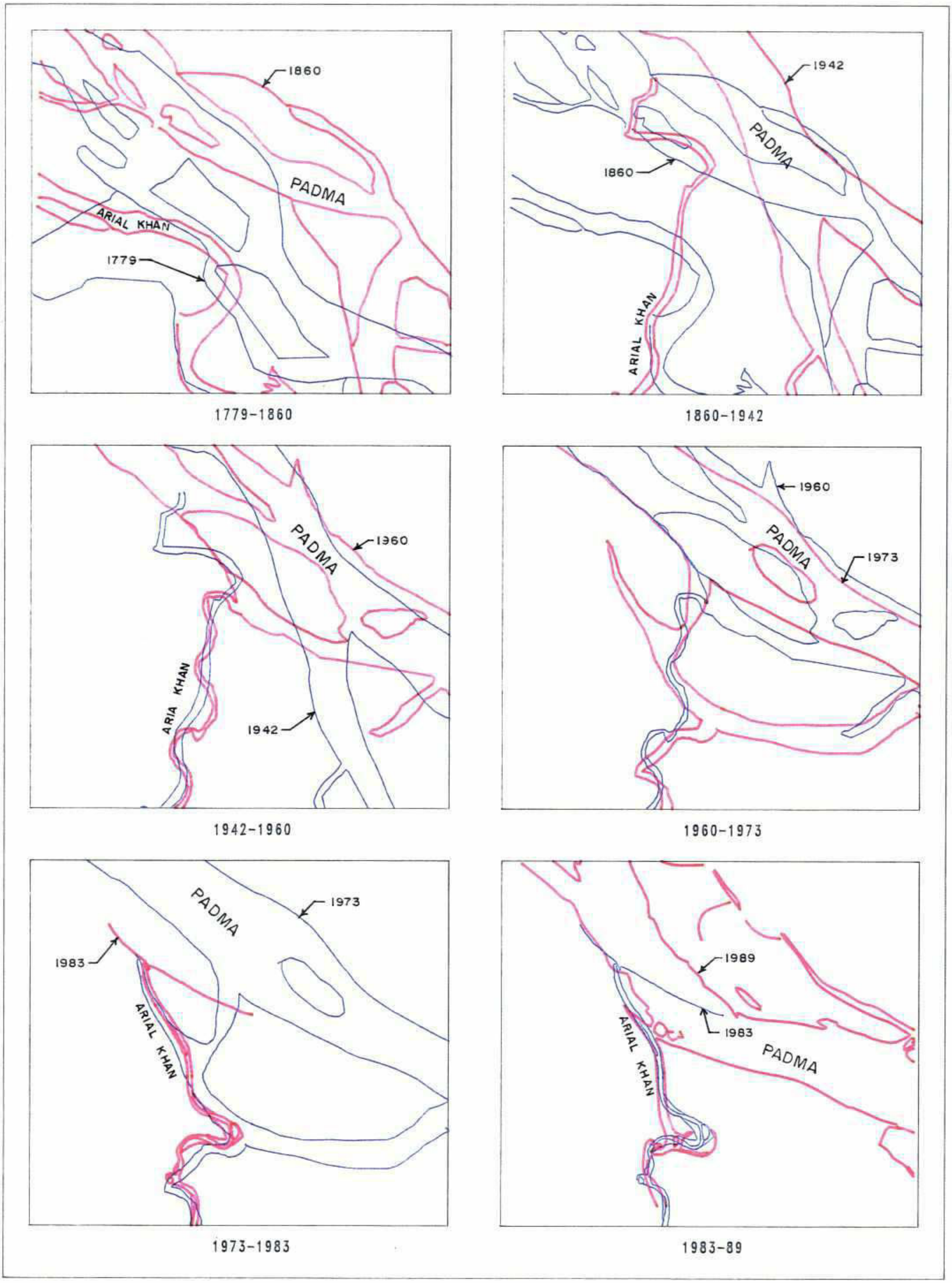
(1) The depth from the Arial Khan to the Kumar offtake (0 to 32km approximately) has a reasonable value of 3+m that is punctuated by high bar crests at crossings. Flow through this reach could be greatly improved by dredging and or training to lower the crossing bar height at about 20km and the bar just upstream of the Kumar offtake (28 - 30km). The amount of dredging would not be excessive as the bar crests are very sharp. Care would have to be exercised not to over-steepen the river given its tendency to degrade its bed in the last few years.

(2) The Old Kumar reach of the route (32 to 52km) has a very tortuous planform. There is a low depth at about 32km, associated with shoal bars in the mouth of the offtake that were noted in the field survey. Some dredging or re-positioning of the mouth would be absolutely essential. The rest of the Kumar shows the characteristic pools and bars of a regularly meandering river. Some training and or re-alignment might be needed to improve the profile from 46 to 52km, which has decreasing depths due to an adverse thalweg slope.

(3) There appears to be a problem at the mouth of the Madaripur Beel Route at about 52km. There is a high bar, that may prevent dry season flows entering the MB Route. Further bars in the MBR at 61km and near the exit, at 79km, would also need to be dredged.

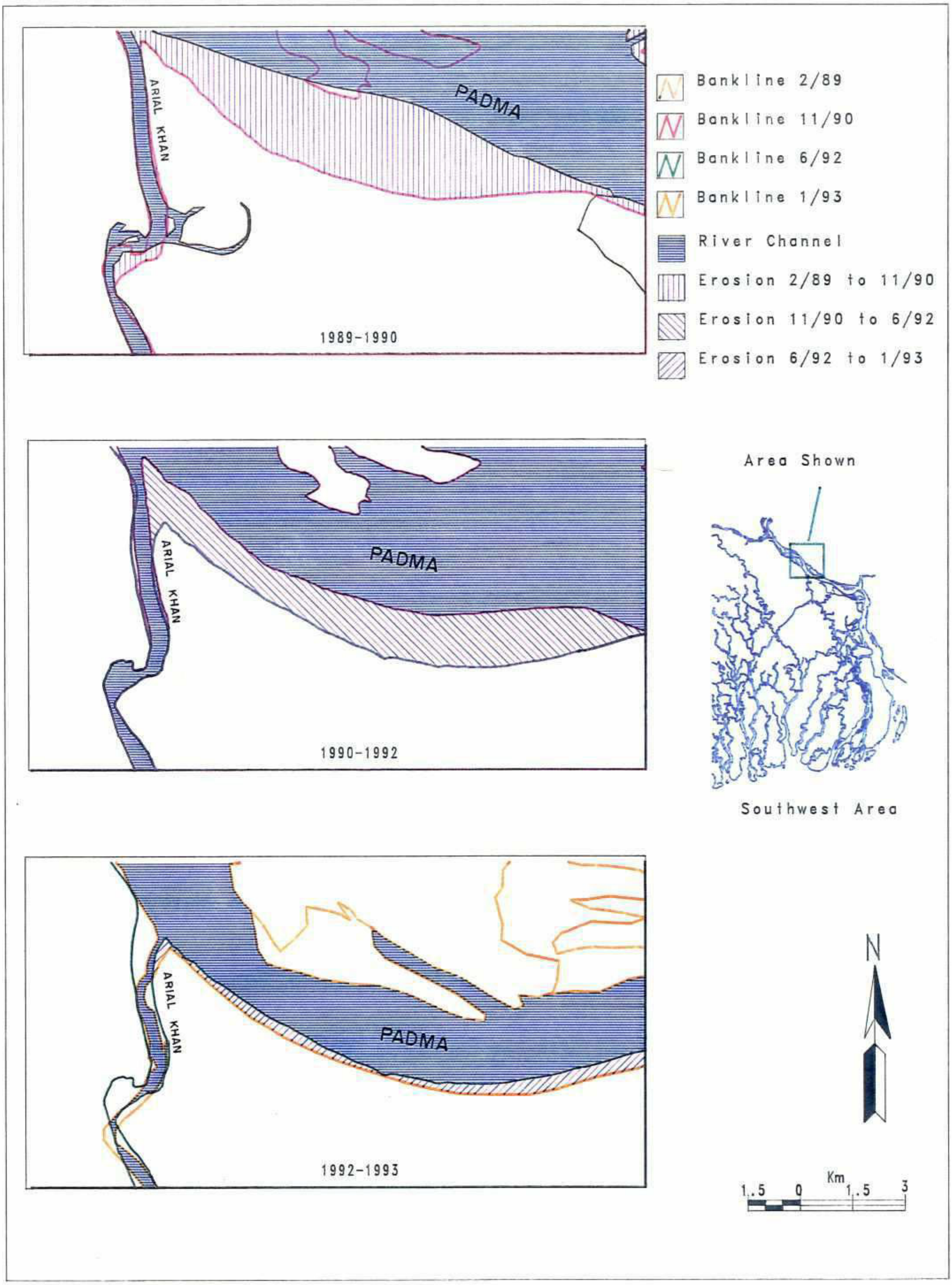
(4) The Lower Kumar and crossing into the Madhumati present no great problem. There is good depth. But the Atharabhanki River, from entrance at 93km to the

Figure 5.26



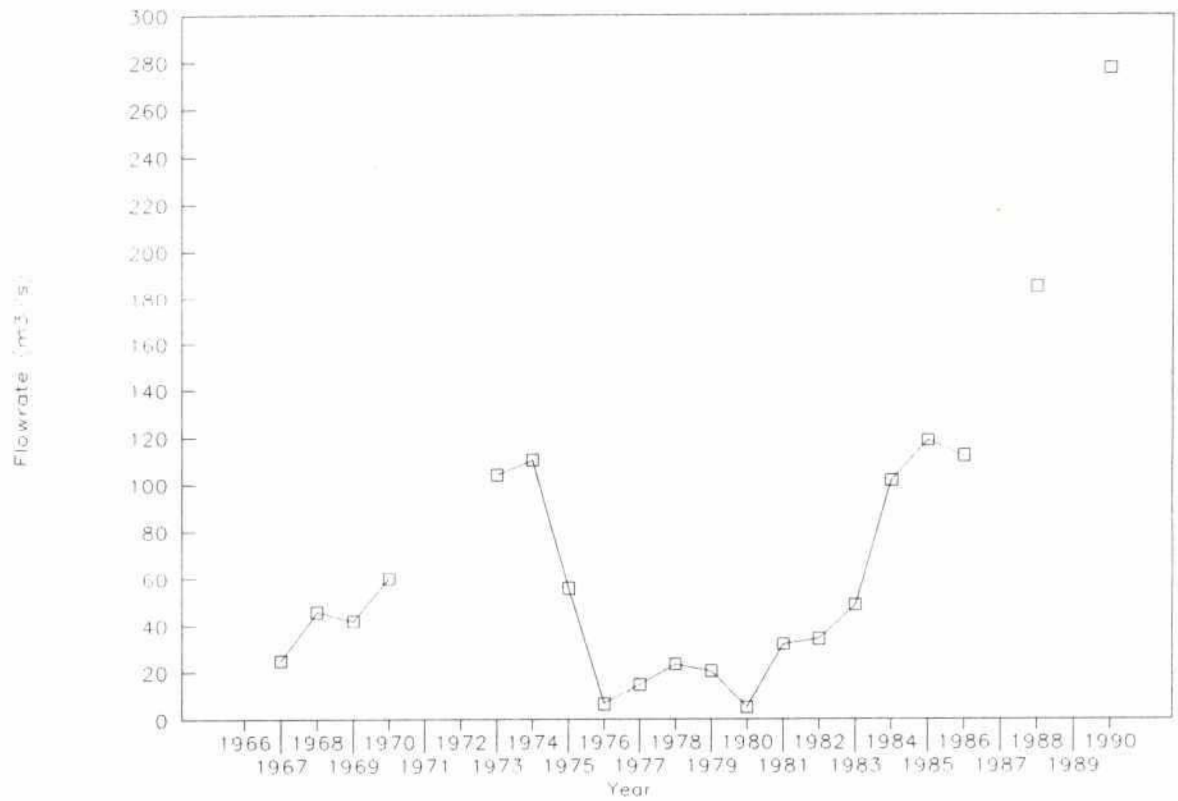
Movement of the Padma at Arial Khan Mouth 1779-1989

Figure 5.27



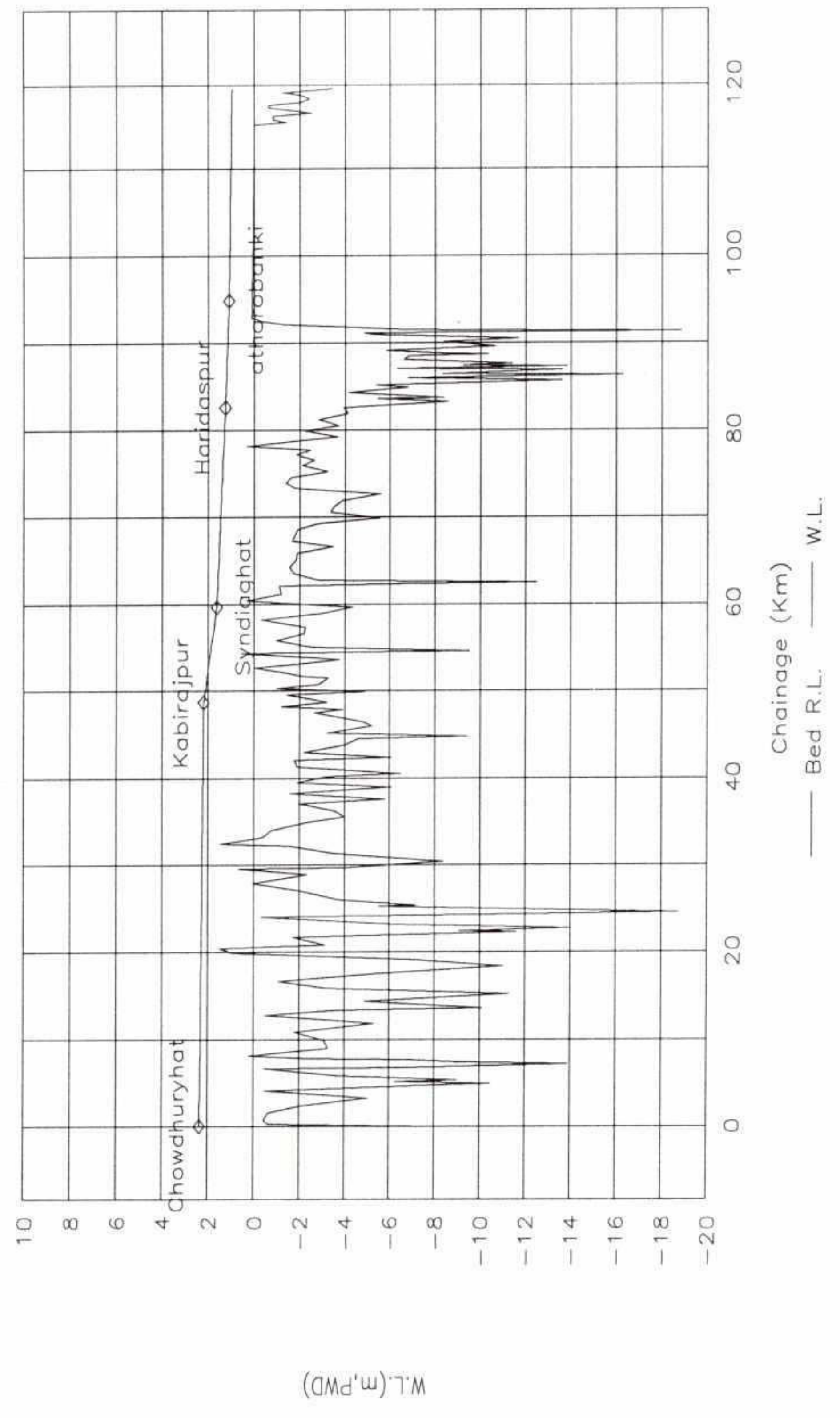
Movement of the Padma at the Arial Khan Mouth 1989-1993

Figure 5.28



Mean Flow in Arial Khan, Jan-March at Chowdhury Hat

Figure 5.29



Source : FAP - 4 (1992)

Long Profile of Arial Khan - MBR System

junction with the Bhairab at 126km has very low depths, less than 1m for much of its length. This reach would need heavy dredging intervention if it formed an essential component to the route.

5.4.6 Conclusions

The proposed route looks at this stage to be feasible at least as far as the Atharbhanki. The very low depths in the last 20km do not look at all promising and perhaps some other route for this section of the dry season flow augmentation scheme would have to be found. This might involve directing water upstream using a weir in the Madhumati, and into the Nabaganga via the Halifax Cut.

5.5 Mathabhanga/Ichamati

5.5.1 Flow and Sediment Regime

The flow in the Matabhanga is measured at three different sites Kazipur near the Ganges, Hatboalia and Darsona near the Indian border. Dominant discharges were calculated for Kazipur and Darsona with the results shown below.

Station	Dominant Flow (m^3/s)	Remarks
Kazipur	138 Range (40 - 280)	actual peak at 88, 138 preferred
Darsona	188 Range (110 - 310)	

The Matabhanga was a major Ganges right bank distributary 200 years ago. Since that time, in common with the other 'Nadia Rivers' feeding the Hoogly, it has declined in importance. The present channel only receives high flow spill flows from the Ganges, draining local rainfall at other times.

At Kazipur the dominant discharge is probably around 138 cumecs. The actual peak in the histogram occurs at 88 cumecs, but this is at the low end of the dominant range and only corresponds to the 30th percentile of the cumulative sediment transport curve. The histogram bar for 138 cumecs is only a little lower, and it is more reasonable because it falls in the middle of the dominant range and corresponds to the 50th percentile of sediment movement. The dominant discharge at Darsona is 188 cumecs, which is fairly consistent with the figure for upstream.

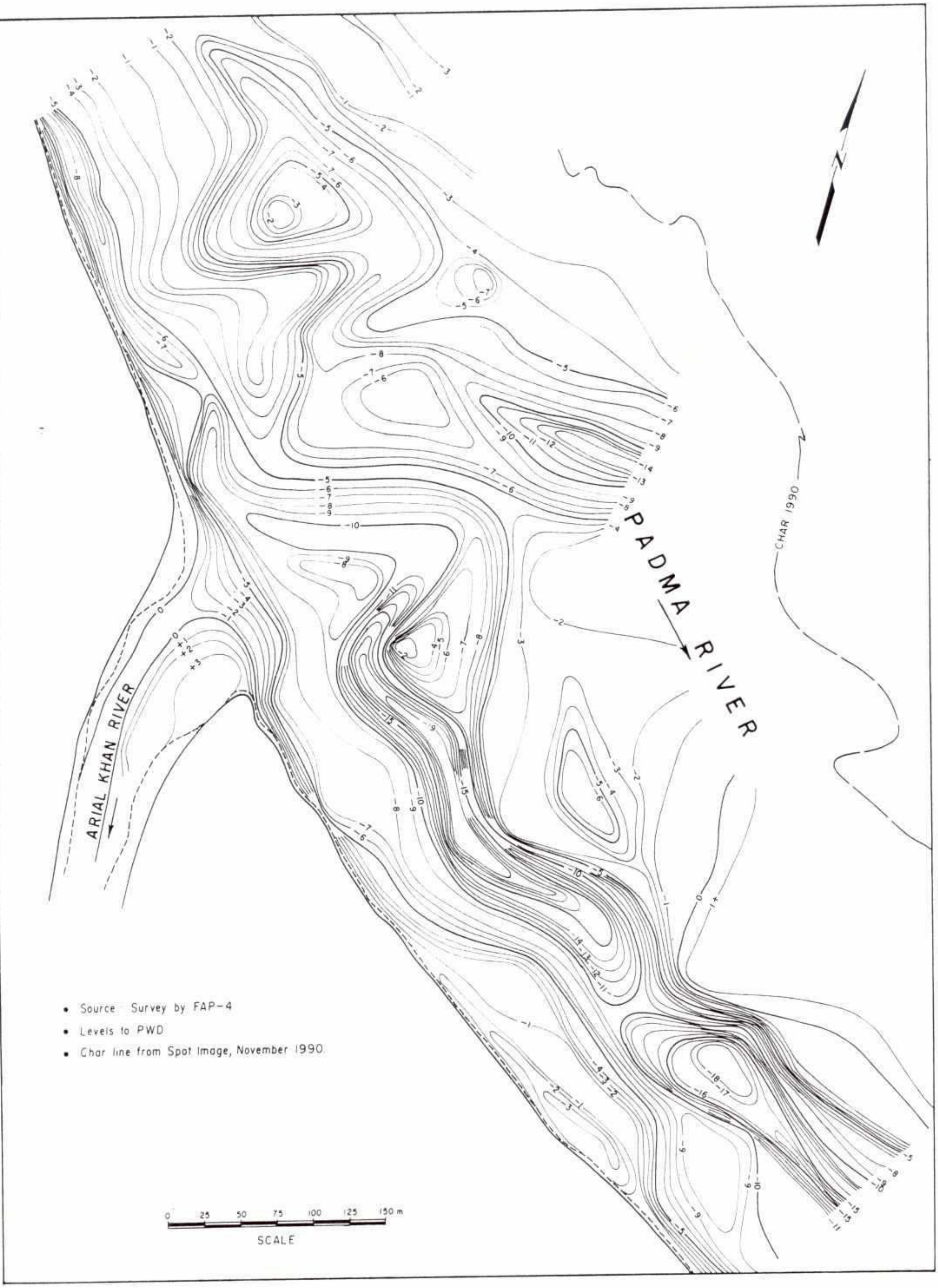
These two dominant discharges indicate a fairly substantial formative flow. Probably, the Mathabhanga could convey 50 to 75 cumecs of water to augment dry season flows without generating undesirable morphological instability.

5.5.2 Long Profile and Cross Sections

A long profile of the Mathabhanga using recent cross sections is given in Figure 5.31. The level of dominant flow is below the bank top. Cross sections are given in Figure 5.32 which shows that in the upper reach, the dominant flow is at bar top though the channel is deeper than is adjusted to the current flow regime and probably sized to a former large distributary.

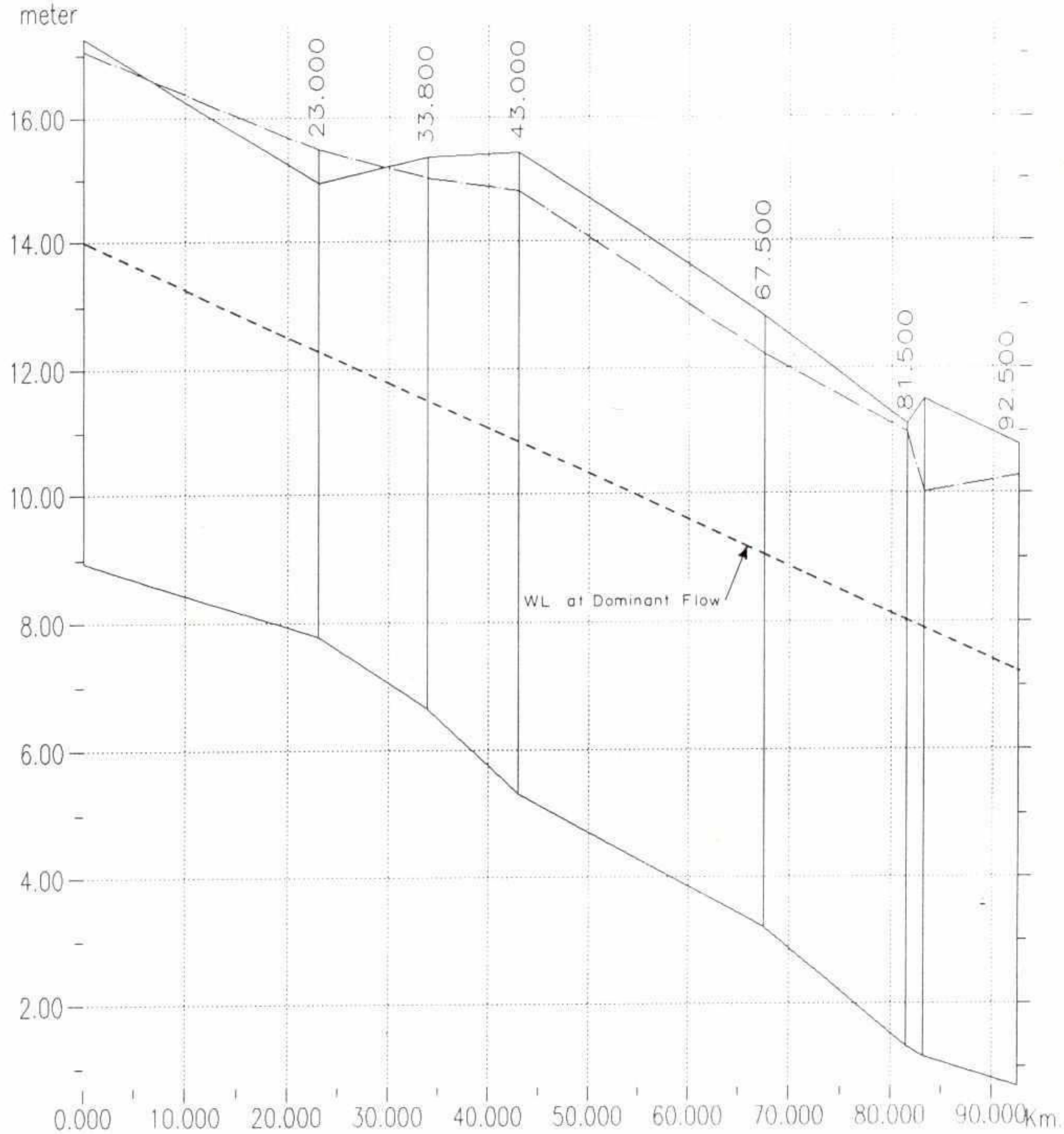
The thalweg at chainage 0m is +9m PWD which is lower than that assumed at the actual offtake for purposes of setting the pond level for the proposed Ganges Barrage, however the chainage is based on where the Mathabanga finally leaves the border which is at least 10 Km from the offtake.

Figure 5.30



Bed Contours of Padma at Arial Khan mouth
June 1992

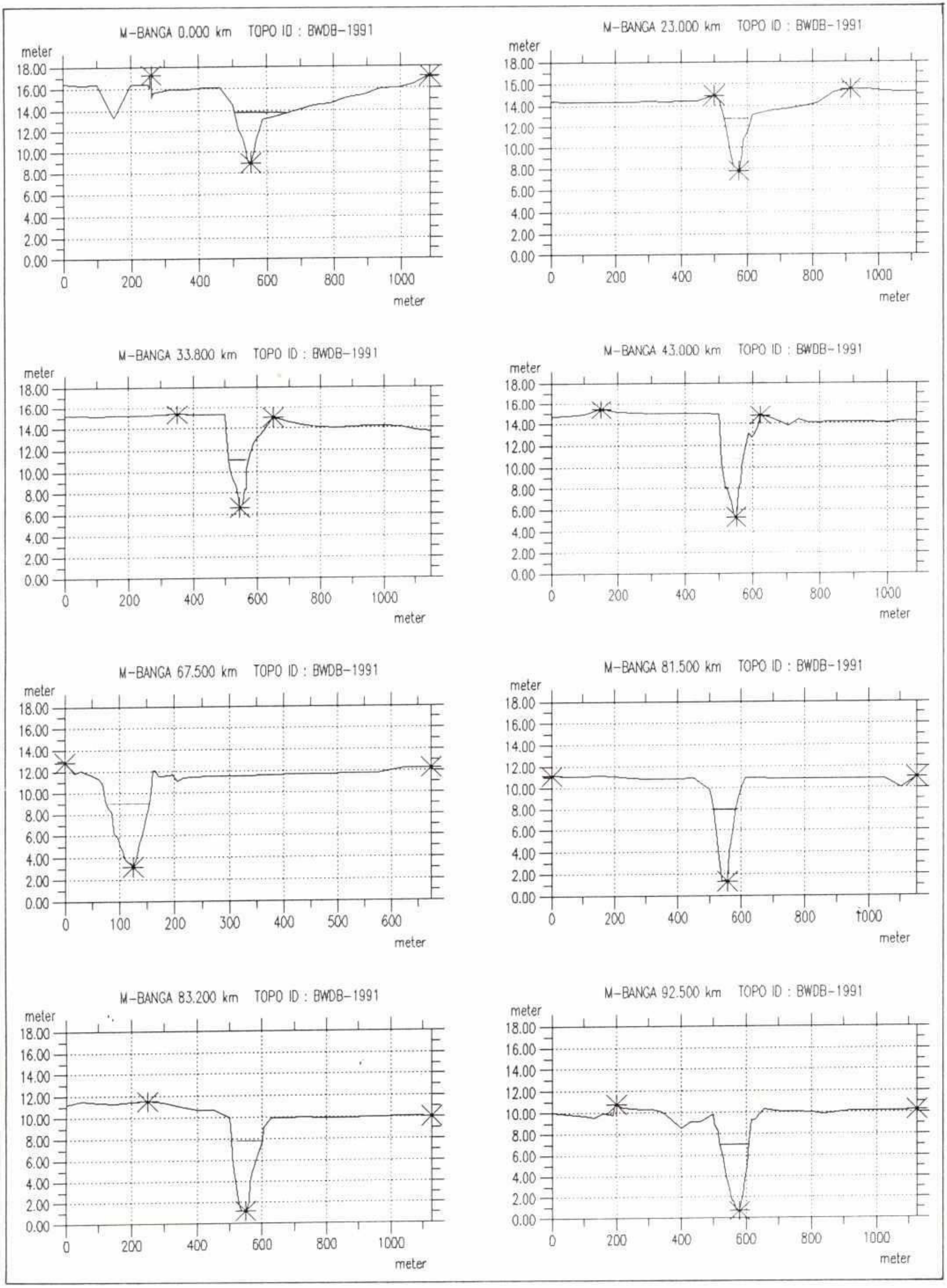
Figure 5.31



Long Section of Mathabhanga

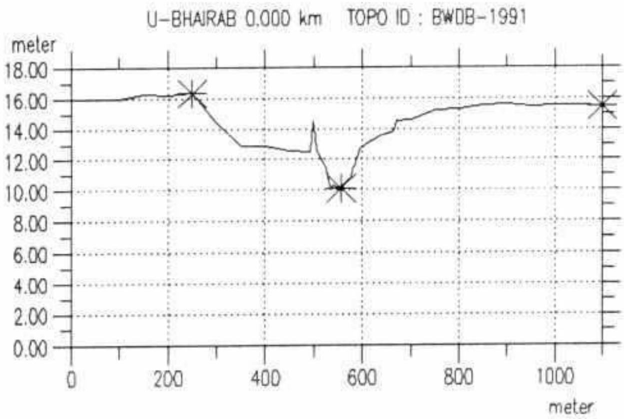
Figure 5.32

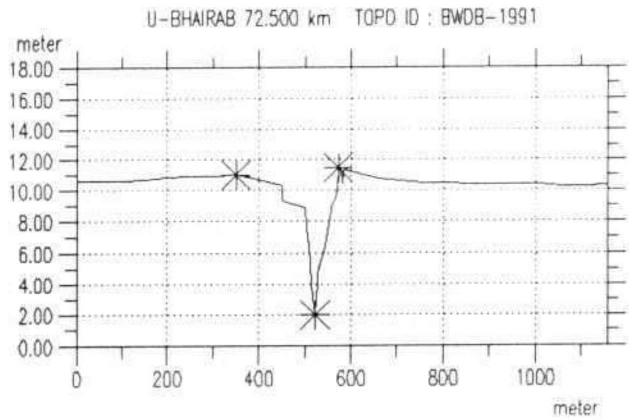
Sheet 1 of 2



Cross Sections of Mathabhanga

Figure 5.32
Sheet 2 of 2





Cross Sections of Mathabhanga

6 INLAND RIVERS

6.1 Drainage Basin Characteristics

The total flow generated by rainfall in the area is equivalent to a mean annual flow of about 800 m^3/s which is equivalent to 3% of the mean annual flow in the Padma. With flat topography the delineation of precise drainage basins is not possible, watersheds are altered by human interventions such as road and rail embankments, and they may change with depth of flooding. The general characteristics of the basins are clear however and are summarised in Figure 6.1. The NAM rainfall runoff model used in the modelling by FAP 4 gives an indication of the peak runoffs that can be expected in the area, the catchments are shown in Figure 6.2 and runoffs are given in Table 6.1 based on the 10 day 1 in 5 year storm.

The data available for analysis of discharges is understandably of a poorer quality than collected for major and regional rivers and thus the analysis of these rivers is more tentative than would otherwise be the case.

6.2 River Bhairab

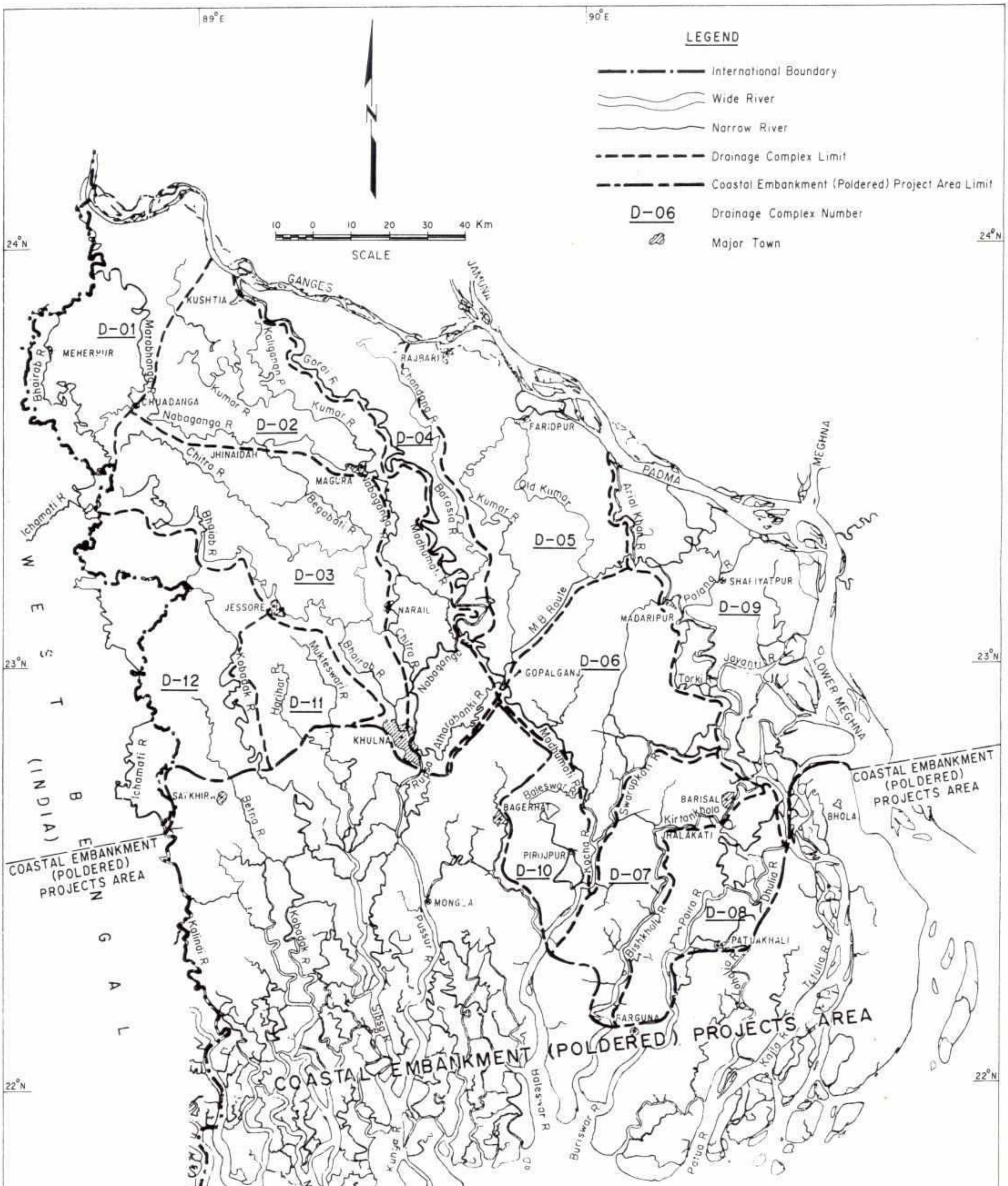
The Bhairab is an ancient river system which flows south east from the Ganges to Khulna as shown in Figure 6.3. Unfortunately there are no flow gauging stations on either the upper or lower parts of the river.

The historical changes in the river are documented by Addams Williams (1918) and may be summarised as follows. The original Bhairab flowed south east from the Ganges to the coast but was later cut through by rivers flowing southwest in particular the Matabhanga which cut off the direct connection to the Ganges. The Bhairab still maintained a connection with the Matabhanga near Darsona but the river bifurcated to the Kobadak which gained in size as the lower part of the Bhairab declined. In 1794 a dam was placed on the Kobadak to rejuvenate the Bhairab but this was unsuccesful and the Bhairab continued to decline. Addams Williams also reports that the connection of the Kobadak and Bhairab with the Matabhanga was cut off with the help of human intervention as the bend on which the offtake was situated was cut off and then abandoned by the river. The upper Bhairab has therefore been declining for two centuries and should therefore now be reaching equilibrium, the tortuous path of the river already had a sinuosity 2.4 in 1918. The lower reach of the river below Jessore becomes increasingly active as the river becomes more tidal and the stretch above Khulna in particular is strengthened by tidal pumping between the Bhairab and the Atai via the Madjudkhali as explained in Figure 6.4.

6.3 Chandana-Barasia River

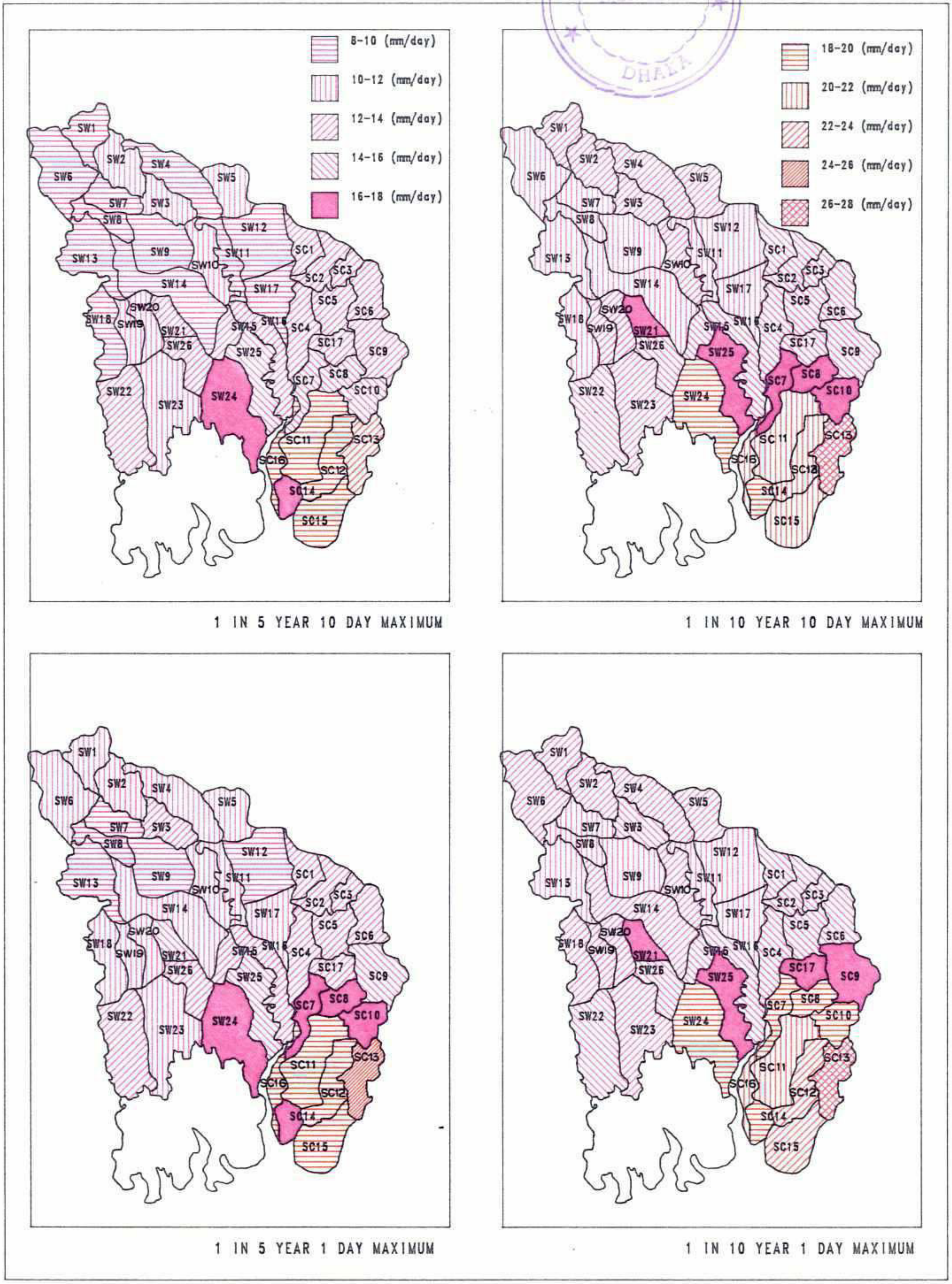
The Chandana is a former distibutary of the Ganges which has matured and declined over the past century. However the river remains an important part of the drainage system of the Gorai left bank. The river formerly drained partly into the Gorai channel near Kamarkhali and partly to the now dominant Barasia channel which flows to the Gorai near Bathiapara where the Madhumati is at a significantly lower level. The upper part of the Chandana is at a relatively high level compared with surrounding land possibly due to the natural levee building processes of a river liable to flood. Both Fergusson and Addams Williams speculate as to why the Chandana which was a larger river than the Gorai in 1779 did not develop further with the advent of the Brahmaputra avulsion. It seems likely that the well developed clay banks and sinuous form of the Chandana prevented this but the impact of the Jamuna may anyway be overestimated as the Padma seems to have developed sufficiently quickly to mitigate against any significant increase in level in the Ganges during floods.

Figure 6.1



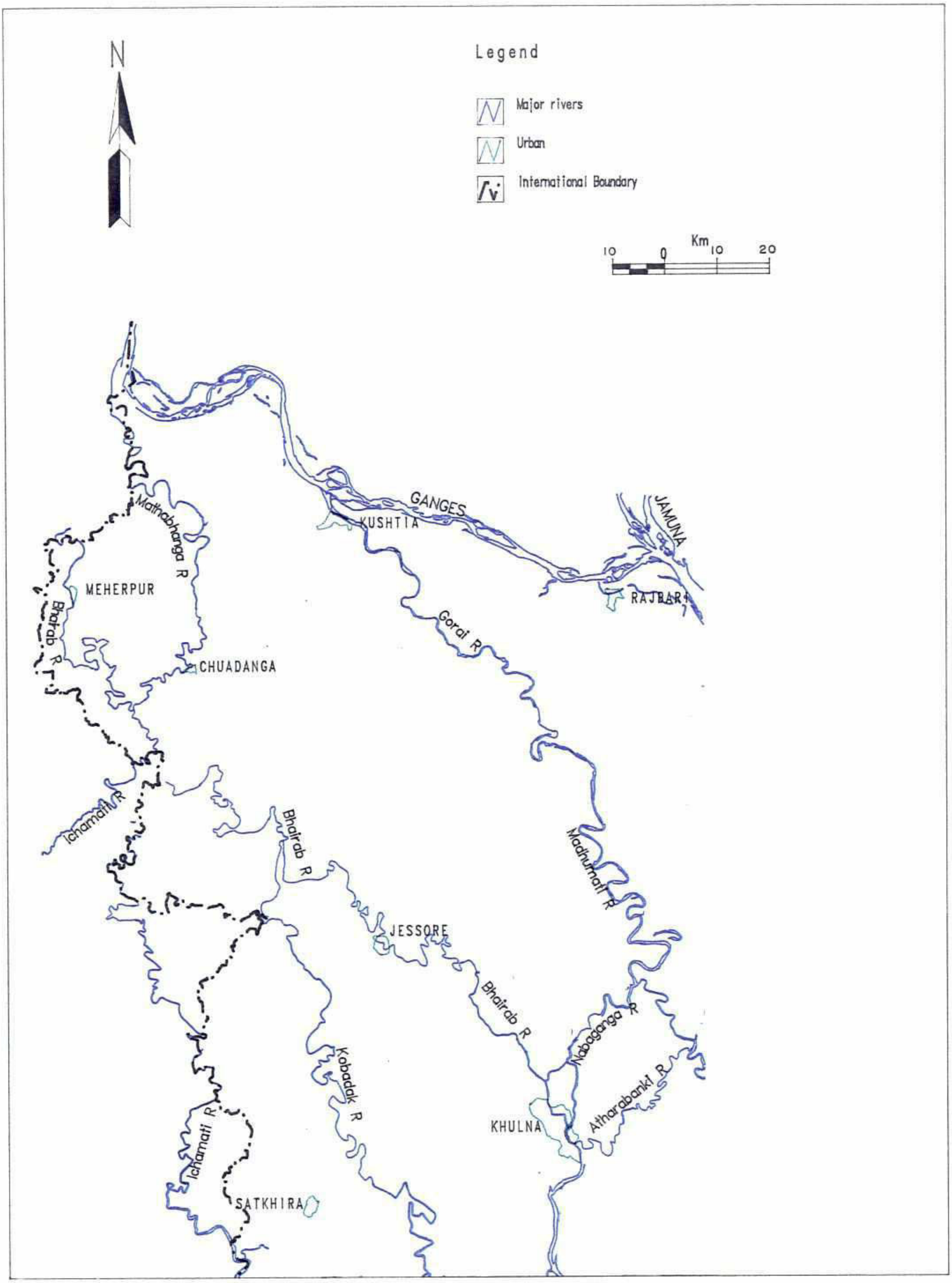
Drainage Complexes

Figure 6.2



NAM Catchment Runoff (Depth in mm)

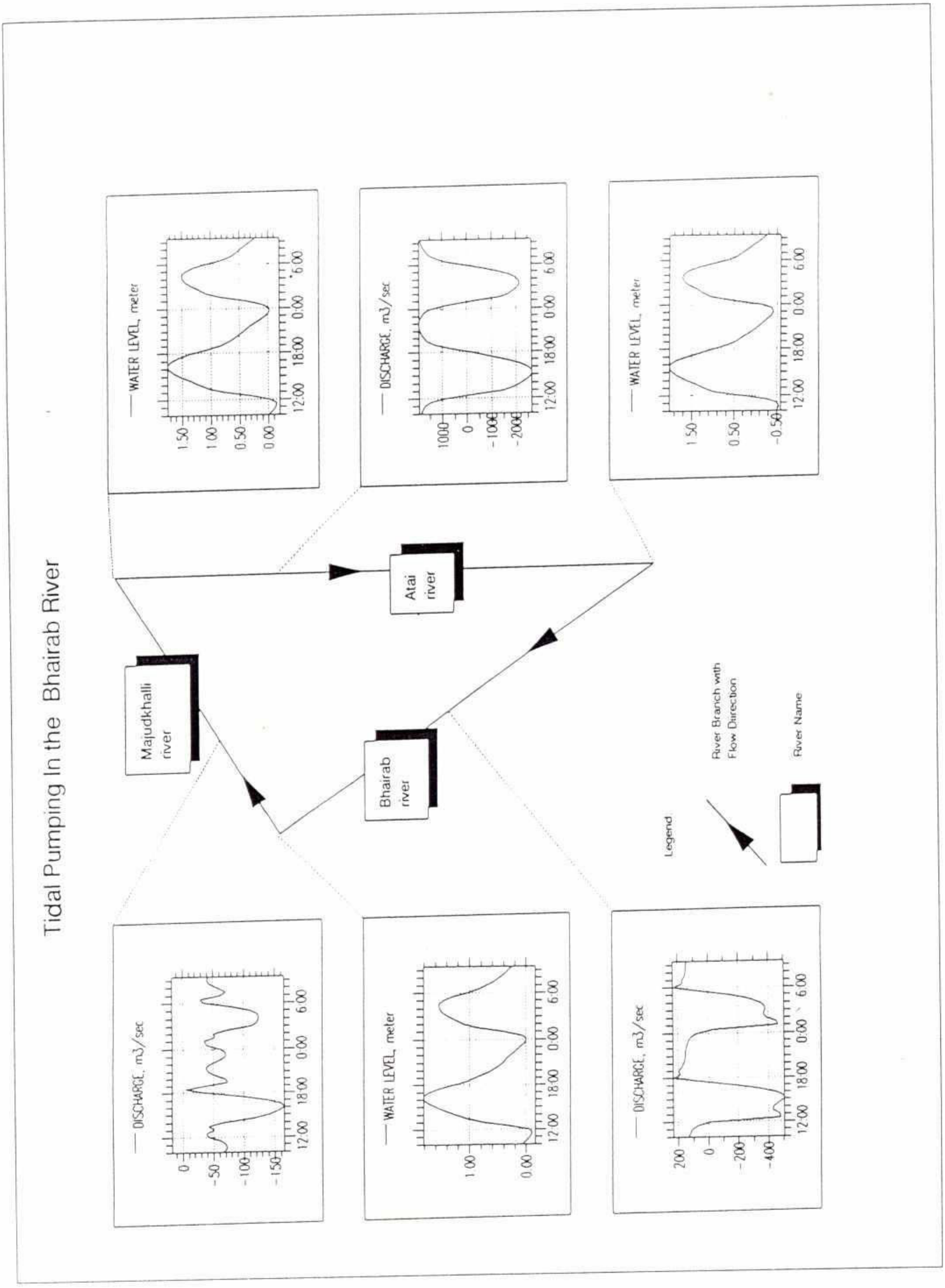
Figure 6.3



Bhairab River Layout

152

Figure 6.4



Tidal Pumping in the Bhairab River

TABLE 6.1

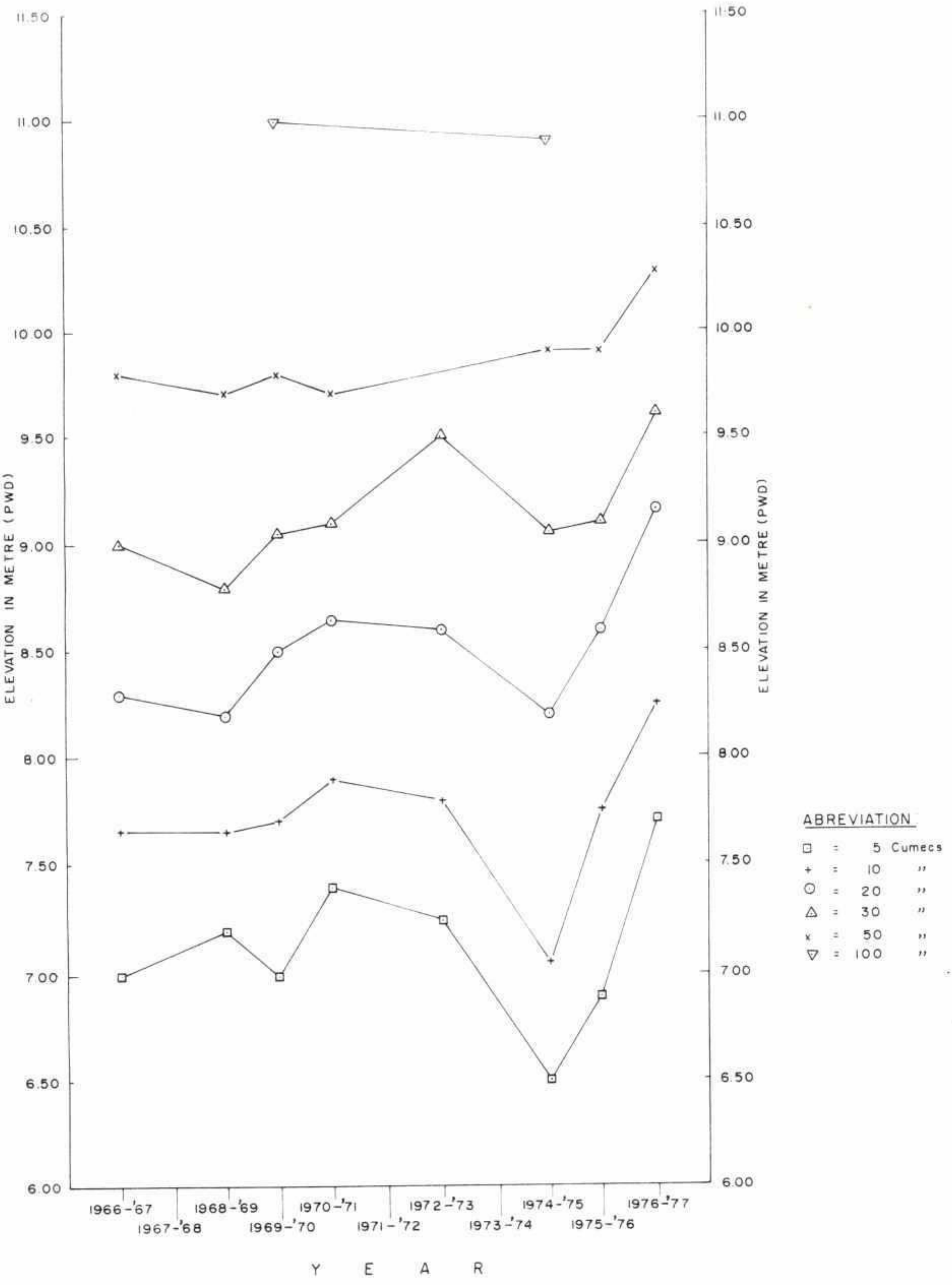
Rainfall-Runoff-Recharge Rates in the Drainage Complexes (Area North of the Coastal Embankment Polders)

Drainage Complex Name	NAM catchments partly/fully in the Drainage complex	Area Km²	Annual Mean (weighted)			
			Rainfall mm	Runoff mm	Ground water Recharge mm	Runoff co-efficient
D-01 Upper Bhairab-Mathabhanga Drainage Complex	SUW-1, 6	1510	1513	699	504	0.46
D-02 Kaliganga-Kumar-Nabaganga-Chitra-Atharbanki Drainage Complex	SUW-2, 3, 7, 10, 14B & 15	2813	1709	732	419	0.43
D-03 Begabati-Chitra-Bhairab Drainage Complex	SUW-8, 9, 13, 14A & 14B	2142	1692	642	503	0.38
D-04 Gorai-Madhumati-Chandana-Barasia Drainage Complex.	SUW-4, 11	2068	1699	792	428	0.46
D-05 Kumar-MBR canal Drainage Complex.	SUW-5, 12, 16, 17 & SUC-1	2455	1821	749	435	0.41
D-06 Madhumati-Swarupkati-Kocha-Drainage Complex.	SUW-16, 17 & SUC-2, 4, 5, 7, 17	1840	1936	975	442	0.50
D-07 Kirtonkhola-Bishkhali Drainage Complex.	SUC-7, 8, 11, 17	1116	2265	1471	623	0.65
D-08 Rangamatia-Paira-Buriswar Drainage Complex.	SUC-9, 10, 11, 12, 13	1450	2431	1625	698	0.67
D-09 Arial khan-Palang-Jayanti-Torki-Ilisha Drainage Complex.	SUC-1, 2, 3, 5, 6, 9, 10	2308	2135	922	583	0.43
D-10 Baleswar Drainage Complex.	SUW-16, 25	988	2167	1123	645	0.52
D-11 Mukteswari-Harihar-Bhadra Drainage Complex.	SUW-20, 21	698	1845	849	430	0.46
D-12 Betna-Kobadak Drainage Complex.	SUW-13, 14A, 18,19	1462	1656	658	561	0.40
For all the Drainage Complexes	37 Nos.	*20850	1875	890	508	0.47

* Excluding the areas of the major rivers such as the Ganges, Padma, L.Meghna etc.

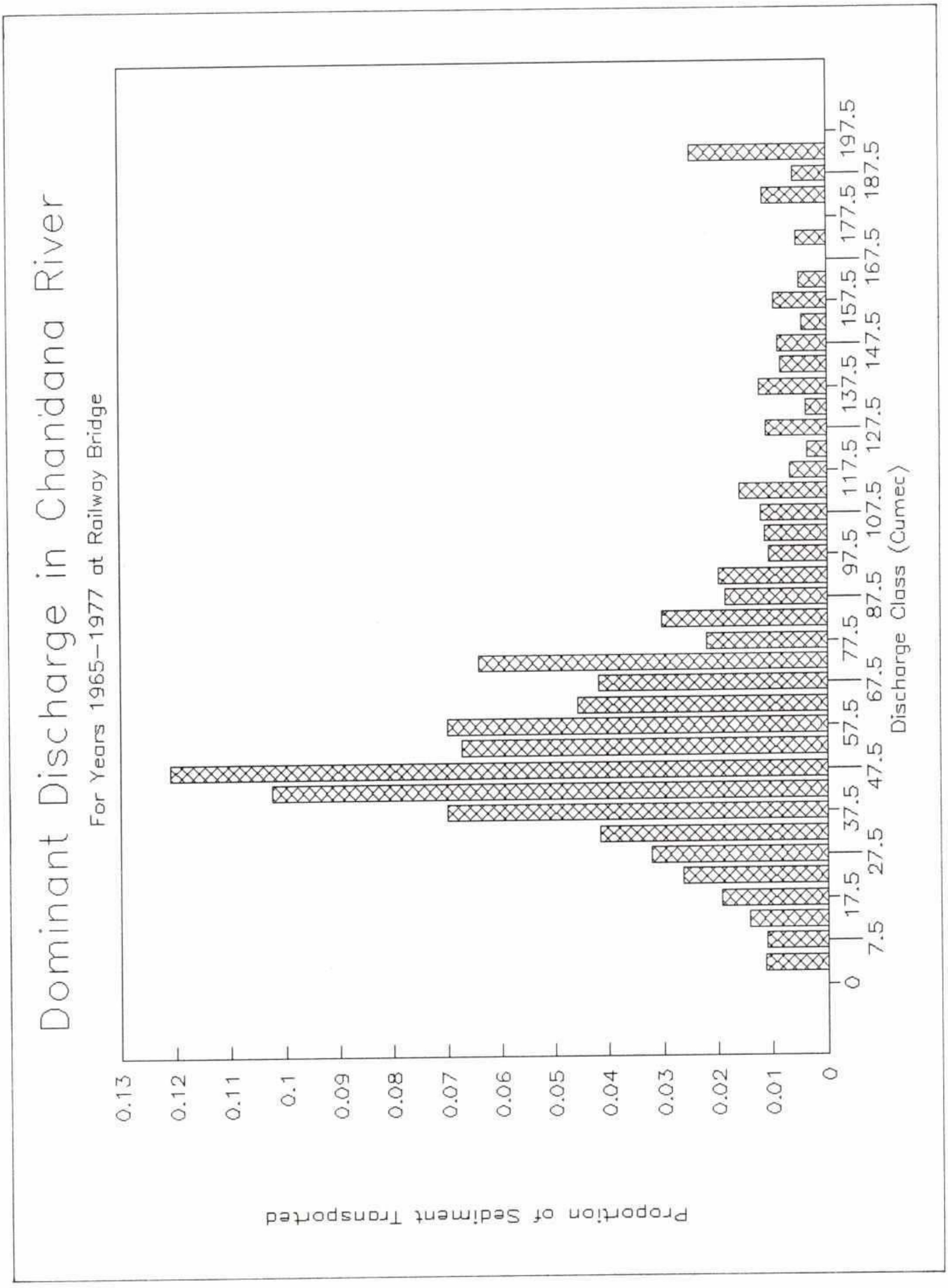
Source : Consultant's model analysis

Figure 6.5



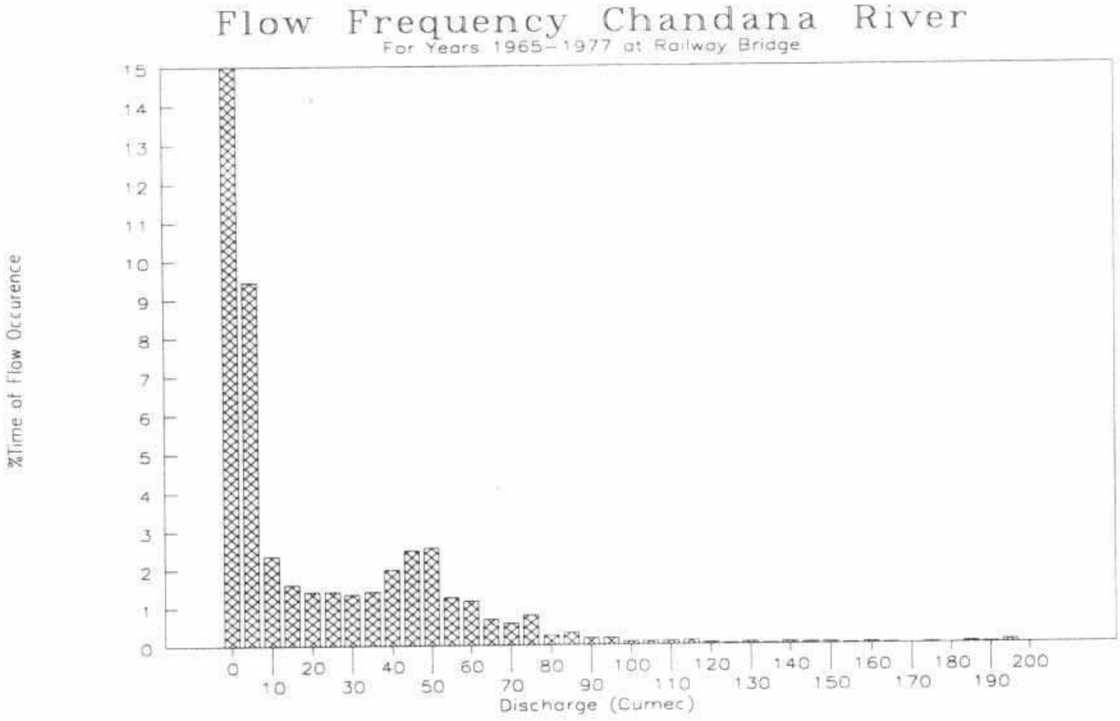
Water level Variation for six discharges in the Chandana River at Chandana Railway Bridge 1966—1976

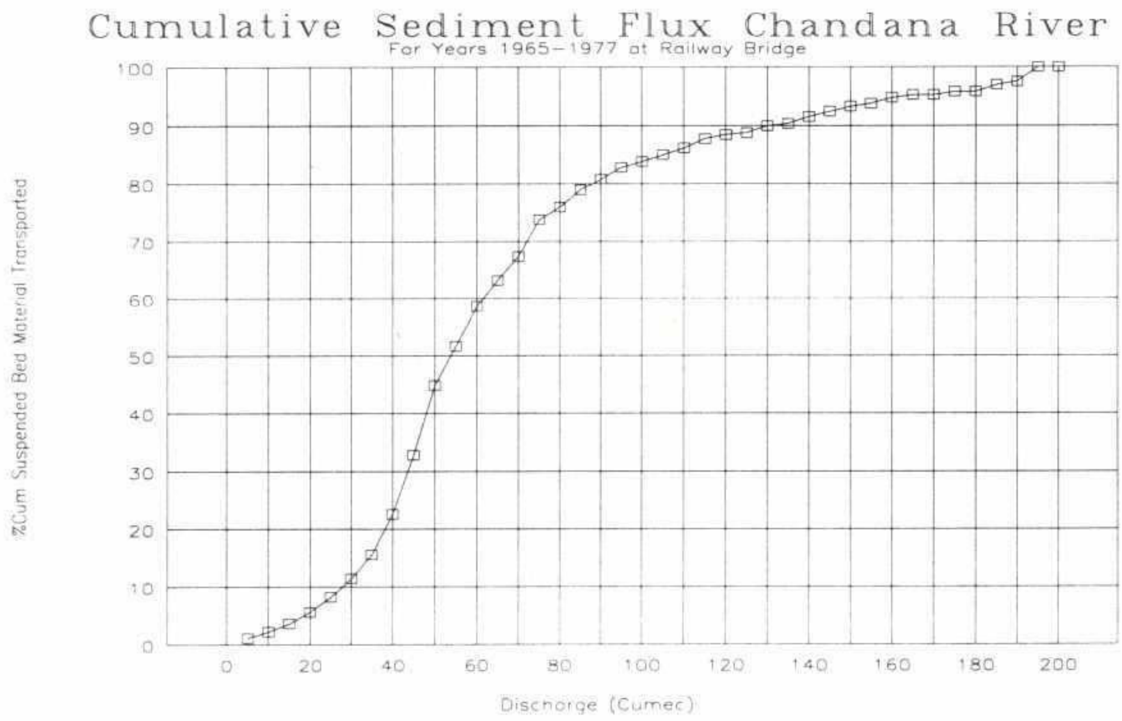
Figure 6.6



Dominant Discharge in Chandana River

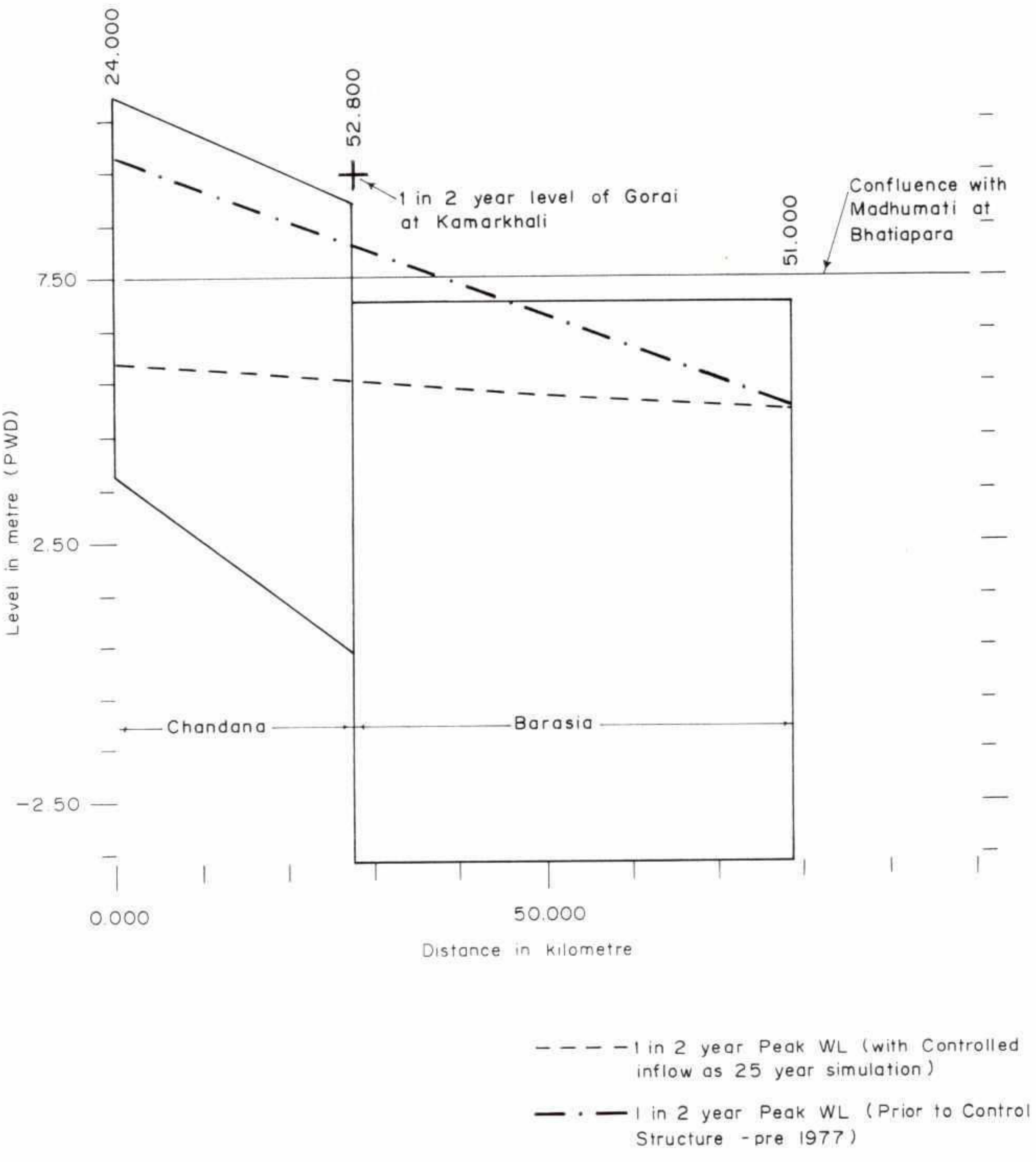
Figure 6.7





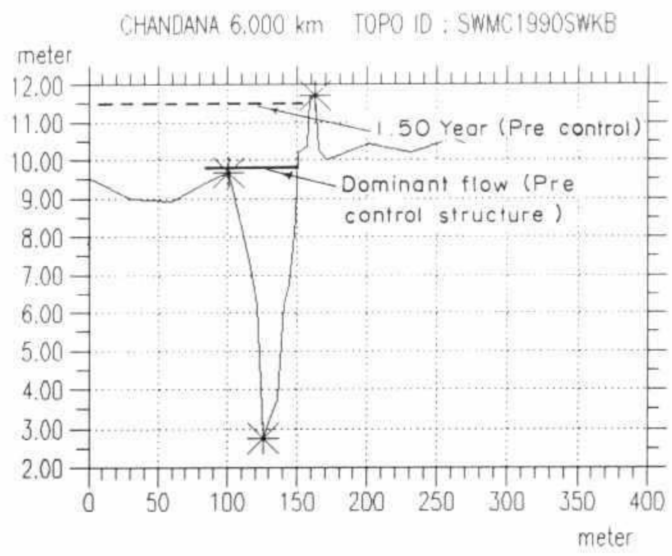
Chandana River : Flows and Sediment Flux

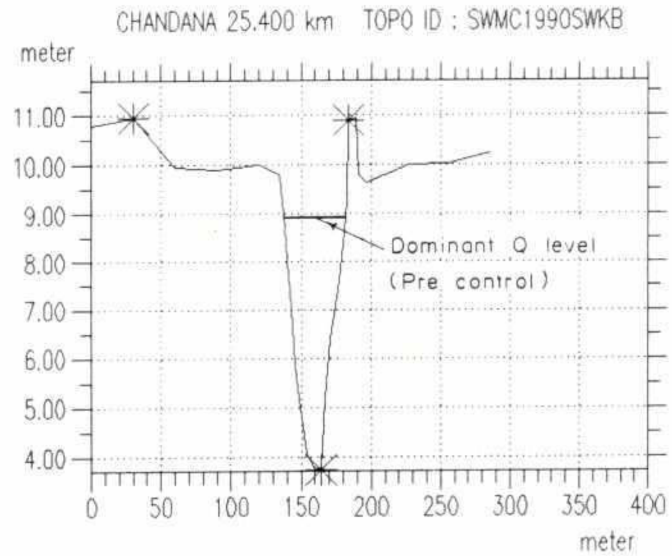
Figure 6.8

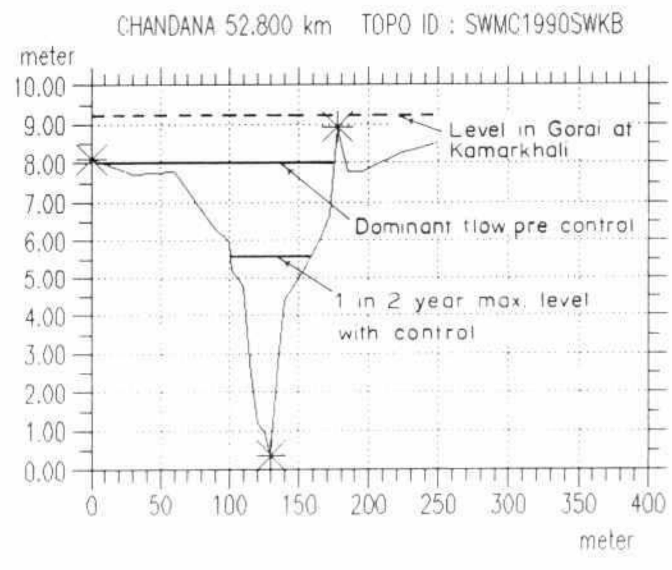


Long Profile of Chandana River

Figure 6.9







Cross Sections of Chandana

Rennells found the Chandana to be 250m wide and at least three metres deep in May 1764 though the river was already tortuous. It bifurcated to the Barasia and Kumar. The Barasia was 50m wide and 'excessively deep' in February 1767 which would indicate a high clay content in the banks.

There is now a 11 vent control structure in the Ganges right embankment near the head of the Chandana and this is used to allow controlled flow into the river during the monsoon period. Even before the construction of the structure the river seems to have been in continuing decline as can be seen from the specific gauge analysis (Figure 6.5). Prior to the closure of the Ganges right embankment the dominant discharge at the Chandana Rail bridge was around $50m^3/s$ as shown in Figure 6.6. At this time the river had negligible flow for 68% of the year which was also the case when the river was visited in 1992. Dominant flow was exceeded 6% of the time and is 87% of the mean annual flood. The cumulative sediment distribution as shown in Figure 6.7 shows that over 50% of the bed sediment transport occurred at flows between 40 and 80 Cumec.

The long profile of the river is shown in Figure 6.8 and cross sections in Figure 6.9. The cross sections show an underfit stream with a low section attuned to dominant discharge and natural levees attuned to flows of significantly higher flow.

It is known that the lower tidal reach of the Barasia is in decline and this would be consistent with the decline of the upper reach and further decline caused by controlling inlet flows. To maintain the channel naturally sufficient flow should be allowed to pass into the Chandana as consistent with drainage considerations.

6.4 River Chitra

There are no flow records for the Chitra but model runs indicate freshwater flows of around $20m^3/s$ in the monsoon season in the non-tidal river. The Chitra originally spilled from the Nabaganga but was blocked by a dam in 1840. The river rejoins the main Nabaganga flow downstream of Narail. Cross sections of the river are shown in Figure 6.10, these indicate that the channel is underfit to the banks as would be expected.

The river has been cut through by others as can be seen from the fragmented nature of the sections of river bearing the Chitra name as shown in Figure 6.11.

6.5 River Kaliganga

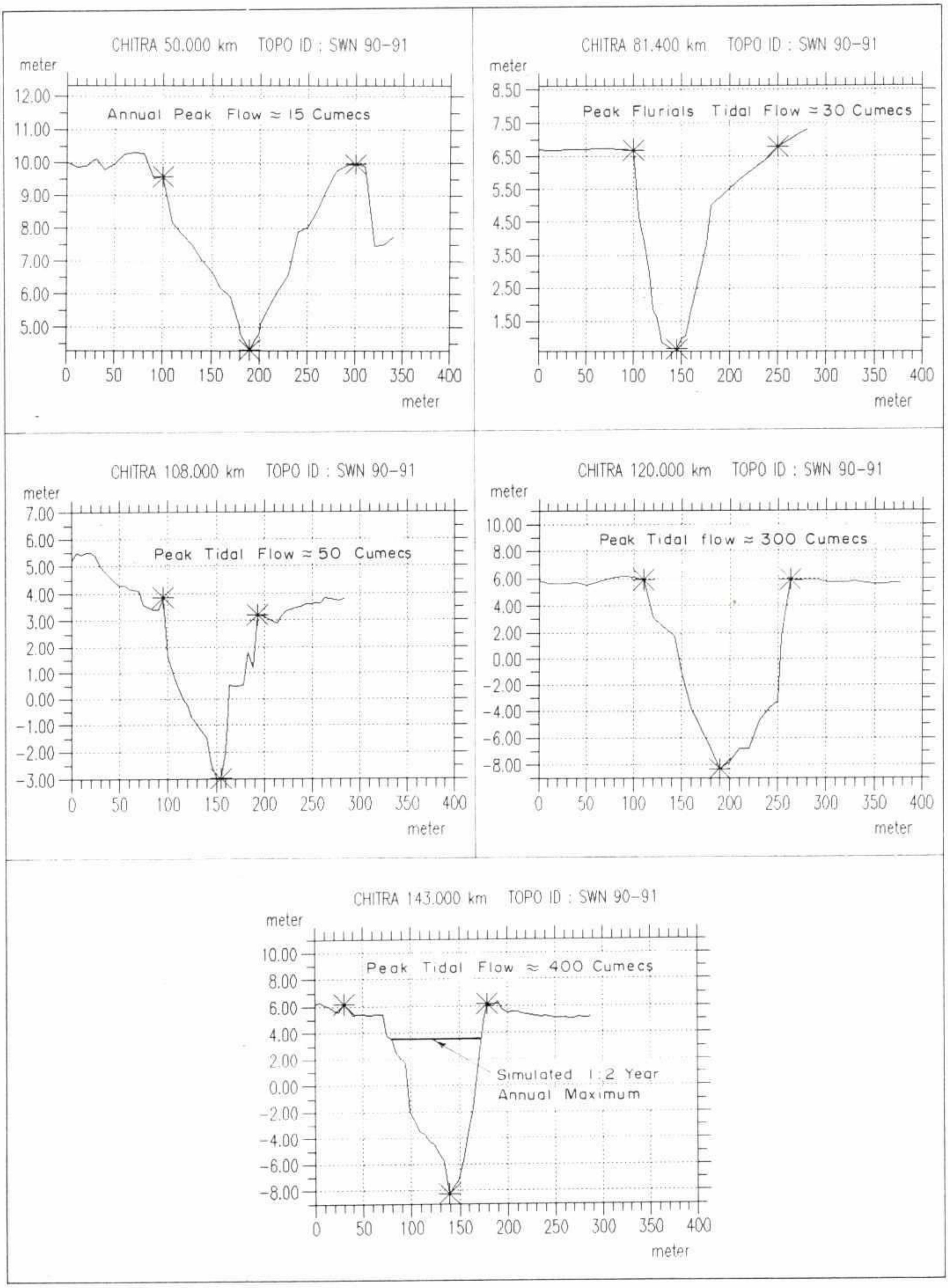
The Kaliganga is a spill river of the Gorai that off takes just downstream of the Gorai rail bridge. The river is included here as it has been considered as a supply route for dry season augmentation and thus was visited by the Consultants and a limited survey completed near the offtake (Figure 6.12).

The main part of the Kaliganga now falls within the G-K project and forms a drainage channel. The river is cut off by the main Kushtia canal and only two pipe inlets through the canal are allowed for. Upstream of the Canal the river is connected with an abandoned oxbow of the Gorai that was cut off at the upstream end by the railway embankment and now forms a fisheries area. The channel levels are high and there would seem to be little prospect of reconnection at the low levels in the Gorai currently experienced or expected without control of the Ganges. The long section and two cross sections are shown in Figure 6.13.

6.6 River Kobadak

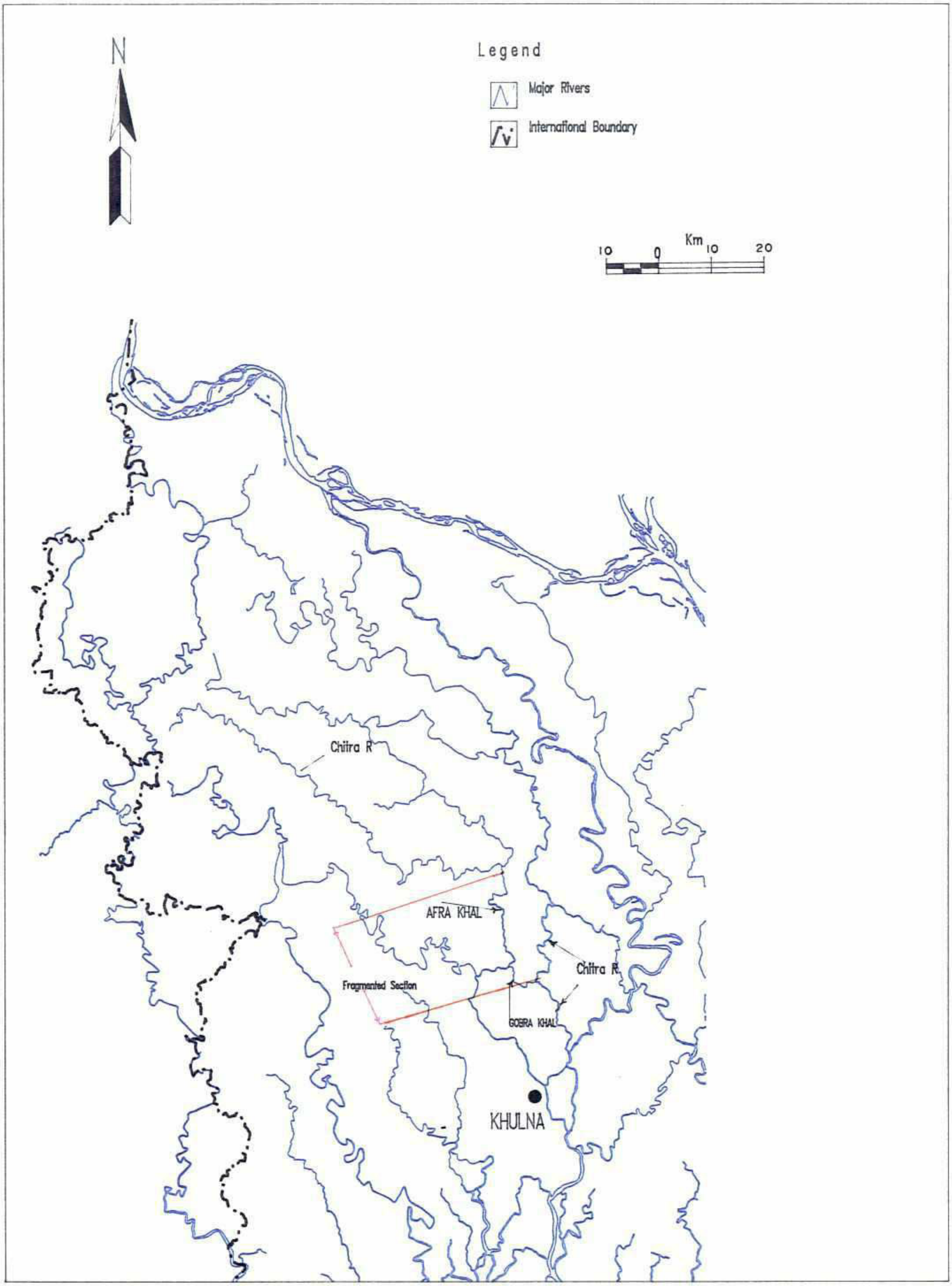
The Kobadak forms an important channel in the tidal areas and increases its section greatly in the seaward direction as shown in Figure 6.14. At the one flow gauging site at

Figure 6.10



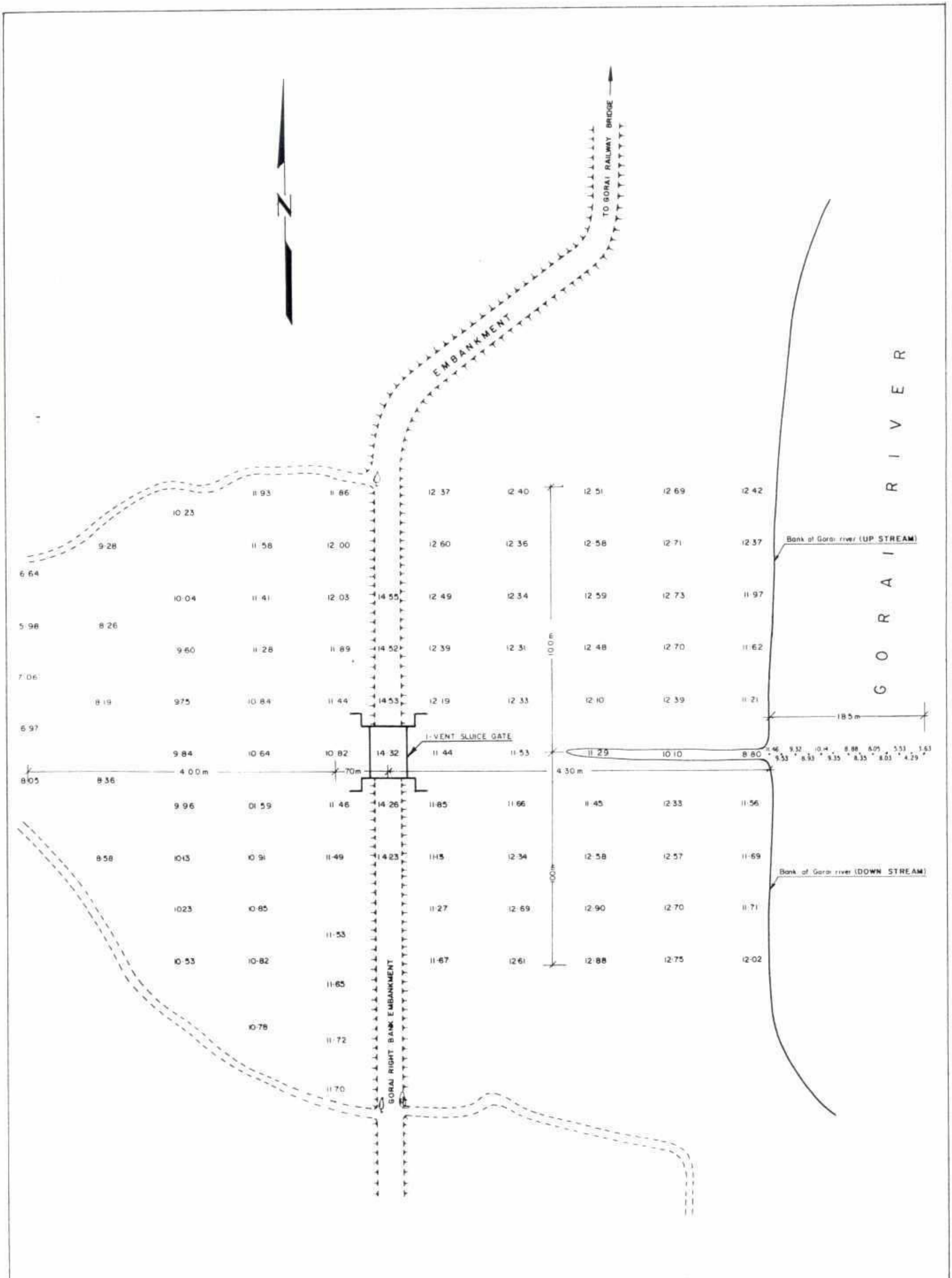
Cross Sections of Chitra

Figure 6.11



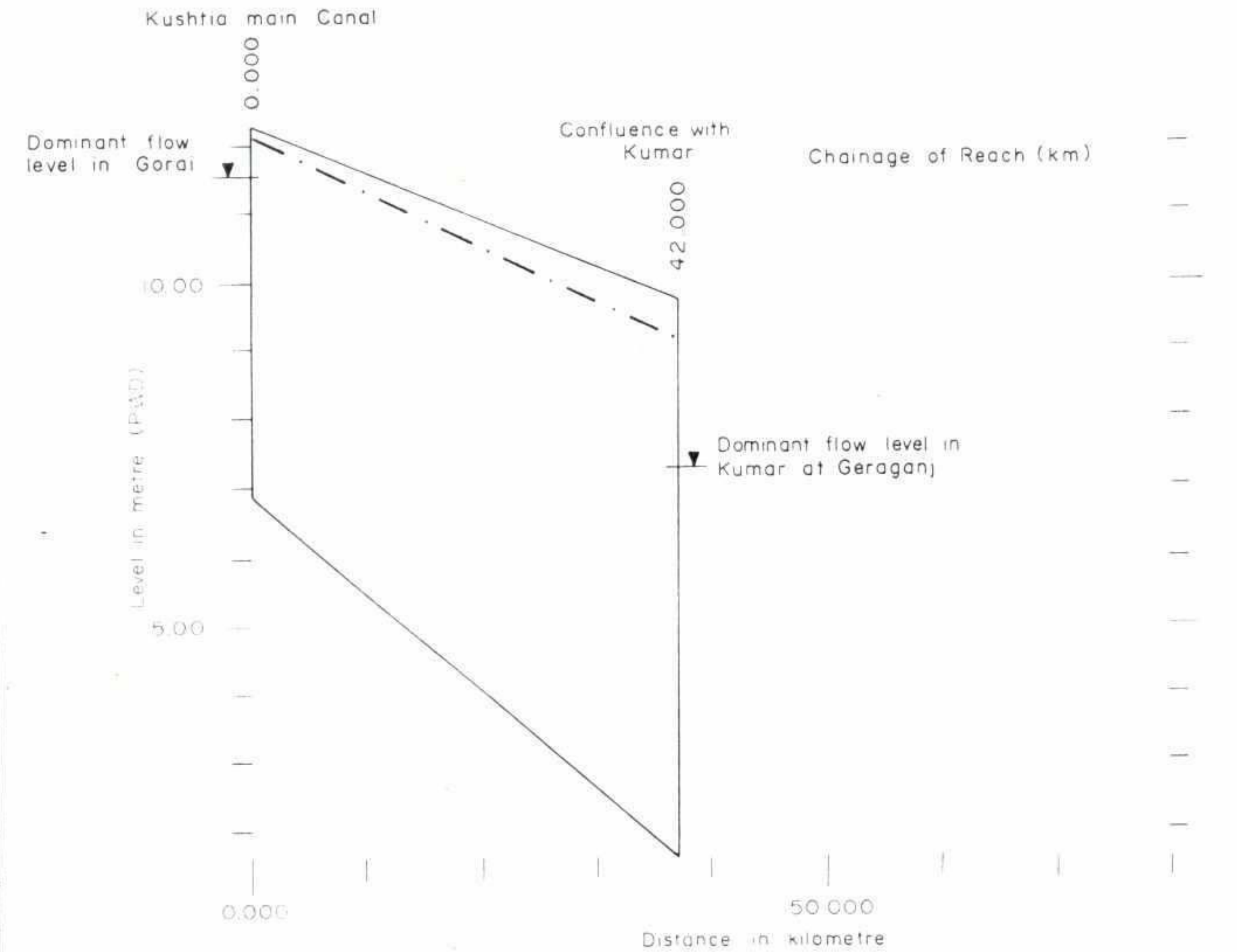
CHITRA RIVER (Fragmented section)

Figure 6.12

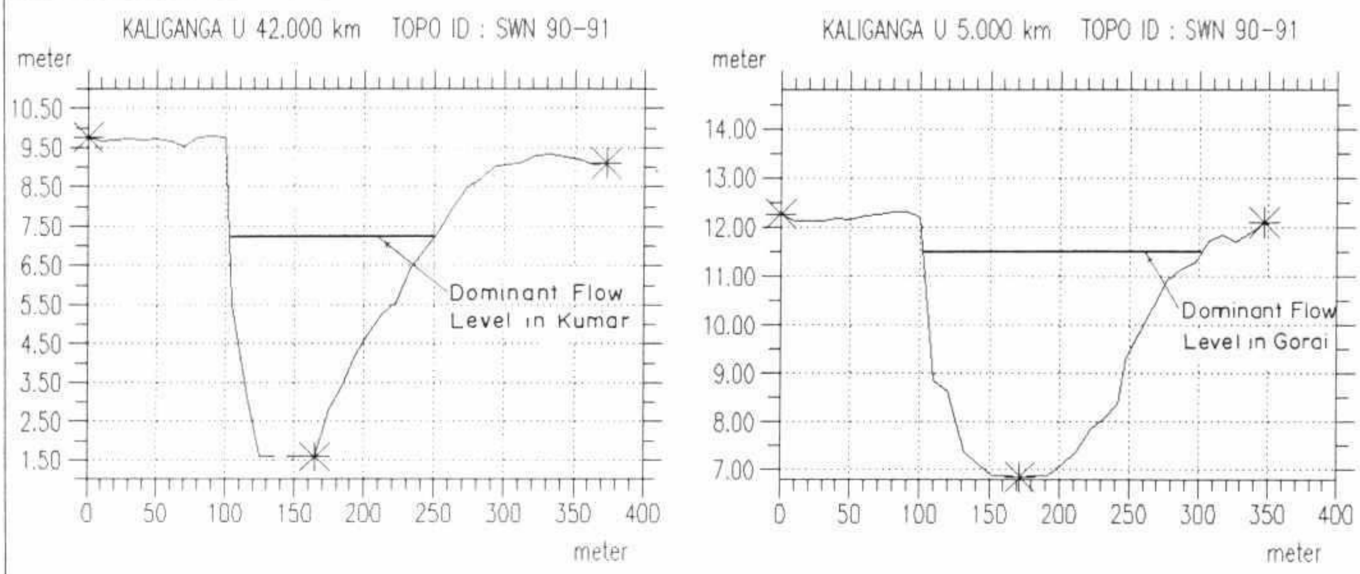


Survey Details: Bed Levels at Kaliganga Outfall, April 1992

Figure 6.13



Long Profile



Cross Section

Long Profile & Cross Sections of Kaliganga River (Kushtia)

Jhikargacha, the dominant flow as shown in Figure 6 .15 was found to be 25 m^3/s. The fresh water flow to the Kobadak came from the Matabhanga but was cut off as described in Section 6.2 and thus the section in the fluvial channel is underfit to the banks. The flow gauging site shows large scatter in the results and thus it is not possible to determine whether the channel has yet reached equilibrium. Regime analysis and re-survey of cross sections in the tidal reach indicates that there may still be some slow siltation.

6.7 Kumar (Magura)

The Kumar forms part of the river system that predates the development of the Gorai and in a similar fashion to the Bhairab, the Kumar formerly connected to the Ganges via the Matabhanga though it was probably only active in the monsoon season at Rennells' time. The river now forms the central drainage artery of the G-K project and joins the Nabaganga near Magura where the combined river is controlled.

The gauging site on the river is at Geraganj downstream of the confluence with the Kaliganga. Analysis of the flow frequencies and sediment flux gives a dominant flow of 25m3/s. At this flow the channel is relatively low indicating an underfit channel as illustrated in Figure 6.16. The gauging site shows significant variation between 1974 and later years possibly indicating intervention to improve drainage.

The connection of the Kumar with the Matabhanga is no longer evident, indeed Addams Williams (1918) reports attempts to cut off the link to the Matabhanga in 1819-1821. The additional spill from the Ganges directly to the Kumar has also been prevented and thus the Kumar can be expected to continue to decline though as it is now a part of the G-K irrigation system routine maintenance will probably prevent significant changes.

6.8 Kumar (Faridpur)

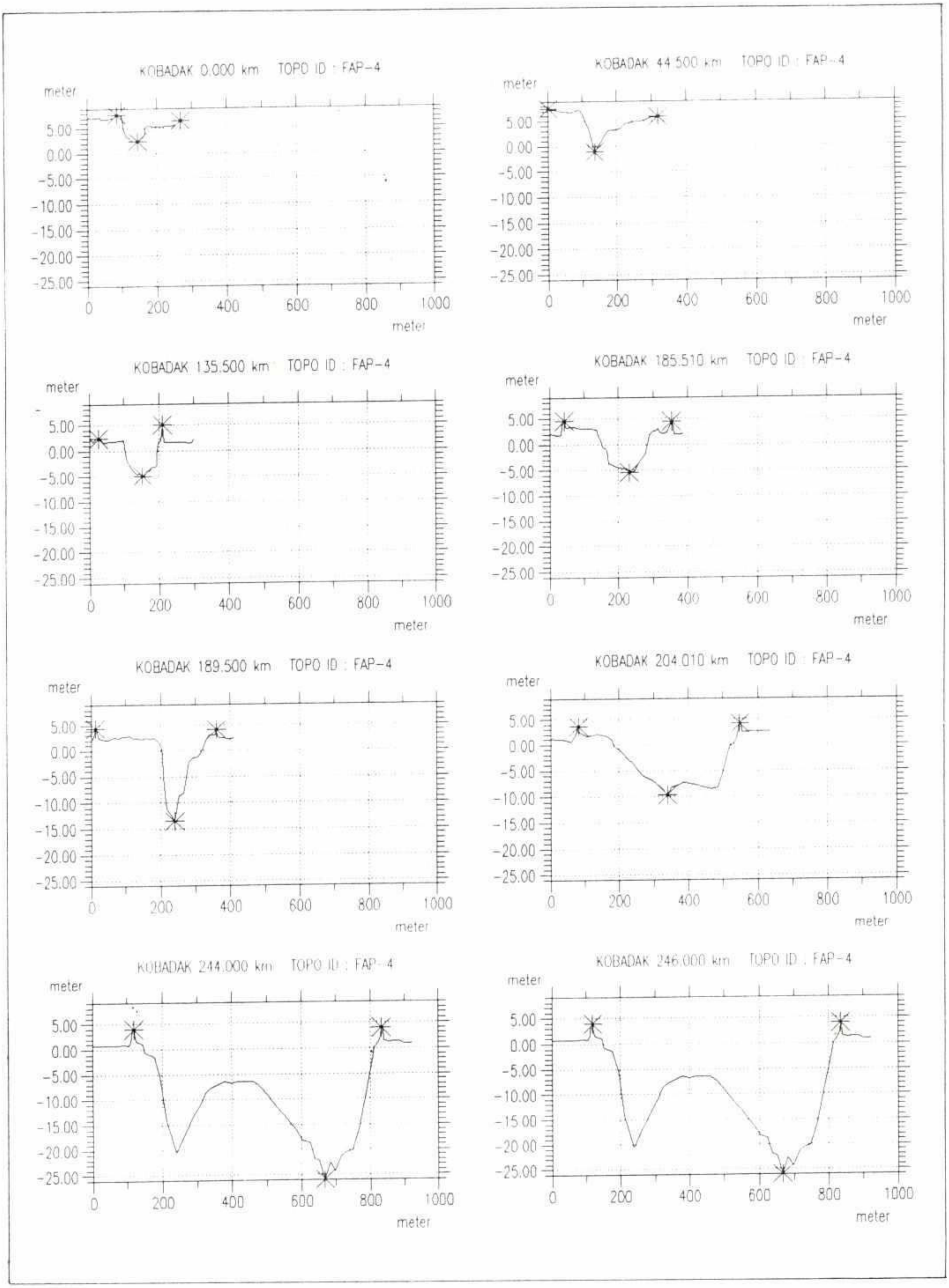
The flows in the Kumar at the connection to the Padma at Faridpur depend greatly on the alignment of the Padma and the vitality of the anabranch of the Padma. The movement of the Padma at this location is shown in Figure 6.17. The anabranch seems to have been active until recently as 1989 and in 1993 it is only a small channel.

During the 1992 dry season the channel was found to be dry for around 10Km and surveys showed bed levels between +2 and +4m PWD at the offtake (Figure 6.18). The inflow (and outflow) from the Kumar is controlled at the Padma embankment which connects to the anabranch via a 1.8 km channel.

The Kumar is traversed by a (now disused) branch of the East Bengal railway in Faridpur Town. The first railway bridge with a span of about 50m was undermined and dismantled; the replacement rail bridge is also dismatled and there is a large scour hole reportedly 20m deep and around 0.5Km wide downstream of the embankment. This would seem to suggest that the rail embankment was giving significant flood control even before the construction of the main embankment. The peak flow through the bridge must have been of the order of 250-500m^3/s and thus much greater than would be allowed to pass the 12 vent control structure now. Unfortunately there are no flow recording stations on the Kumar.

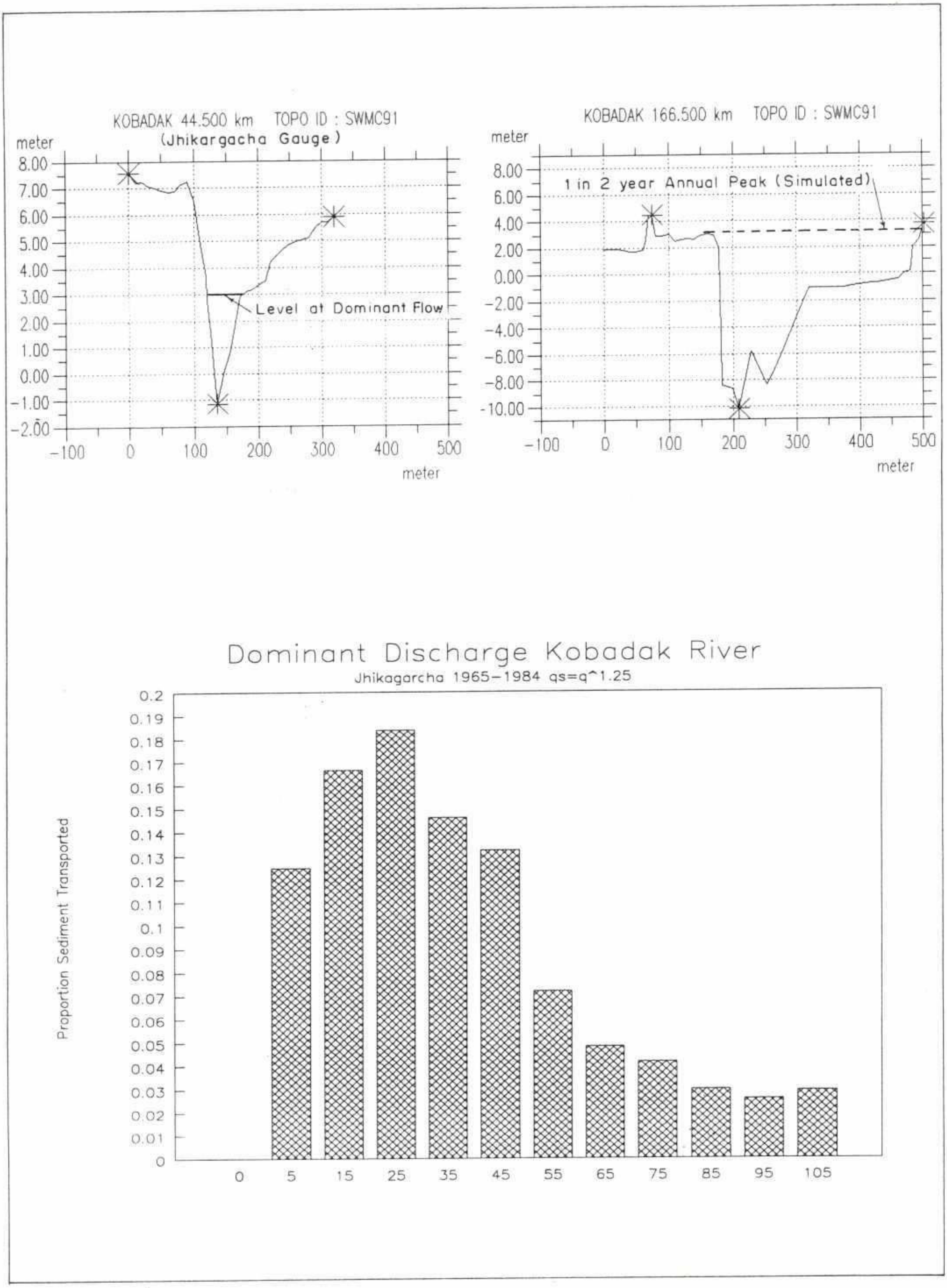
The Kumar was a channel that was dependant on spill flows from the Ganges and Padma. Now that the spills are controlled a gradual deterioration of the channel can be expected. The anabranch of the Padma from which the Kumar draws flow could be rejuvenated in the future but until this is the case the Kumar is a poor prospect for augmentation of dry season flow.

Figure 6.14



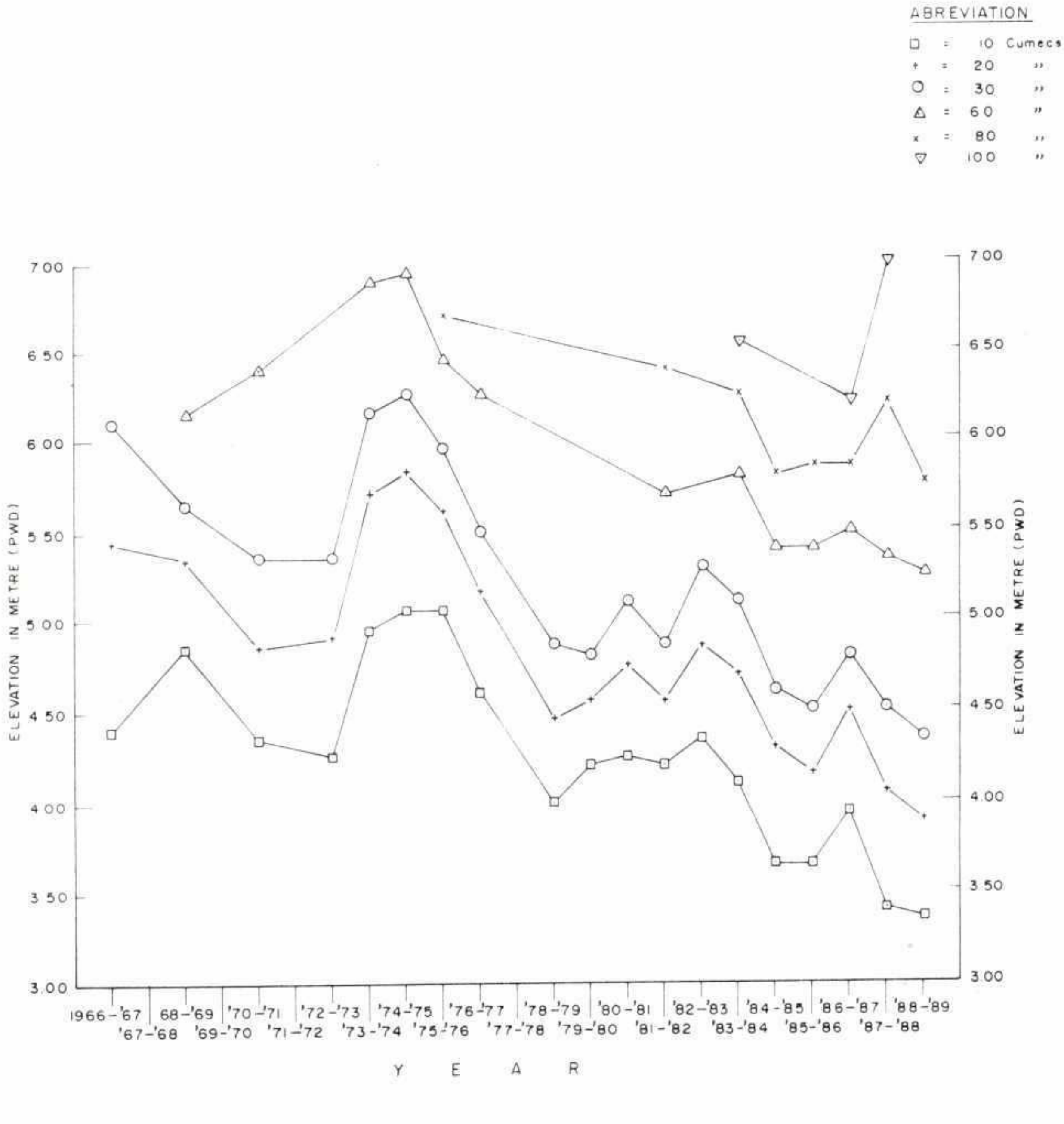
Cross Sections of Kobadak River

Figure 6.15



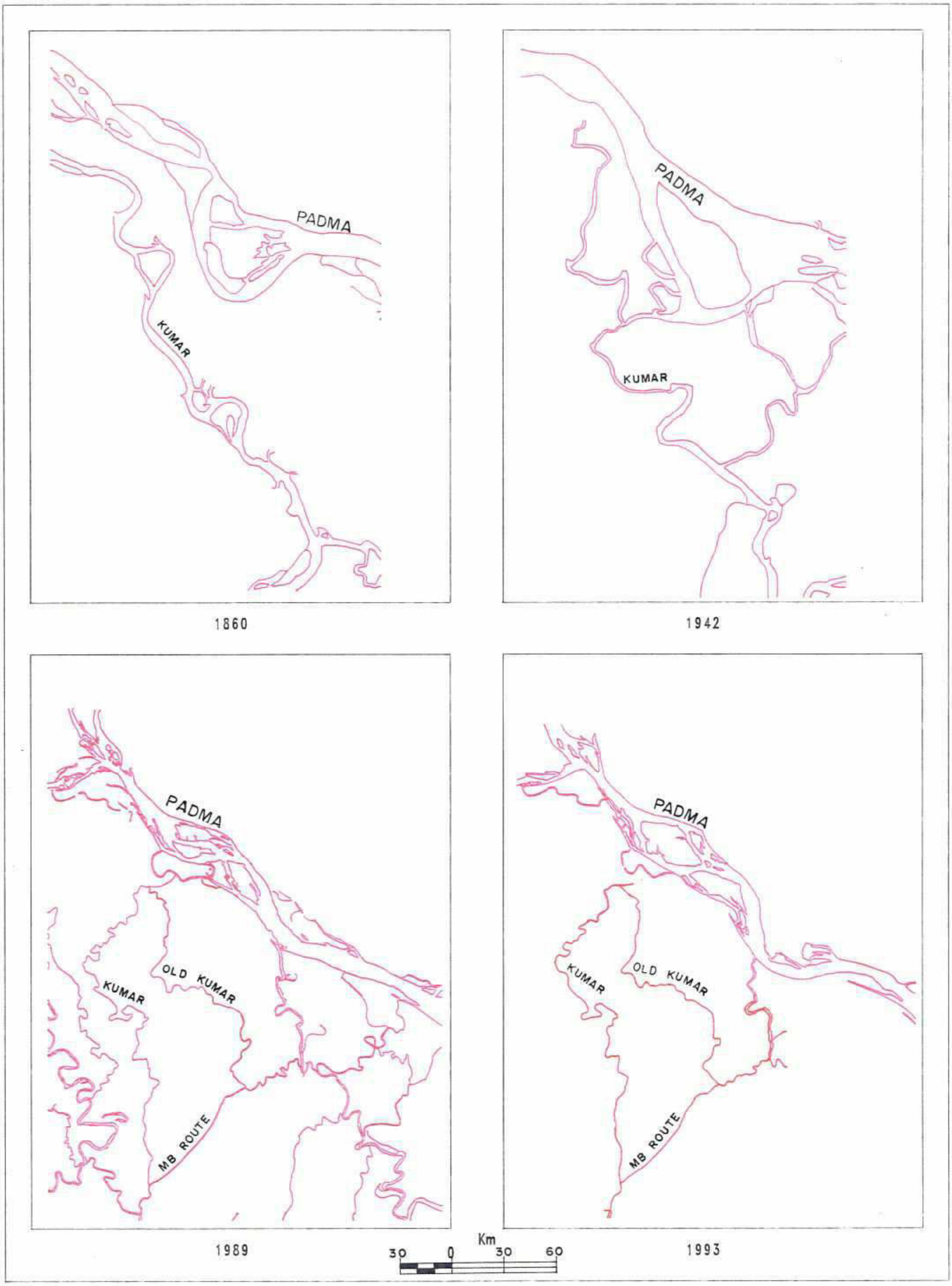
Dominant Discharge Kobadak River

Figure 6.16



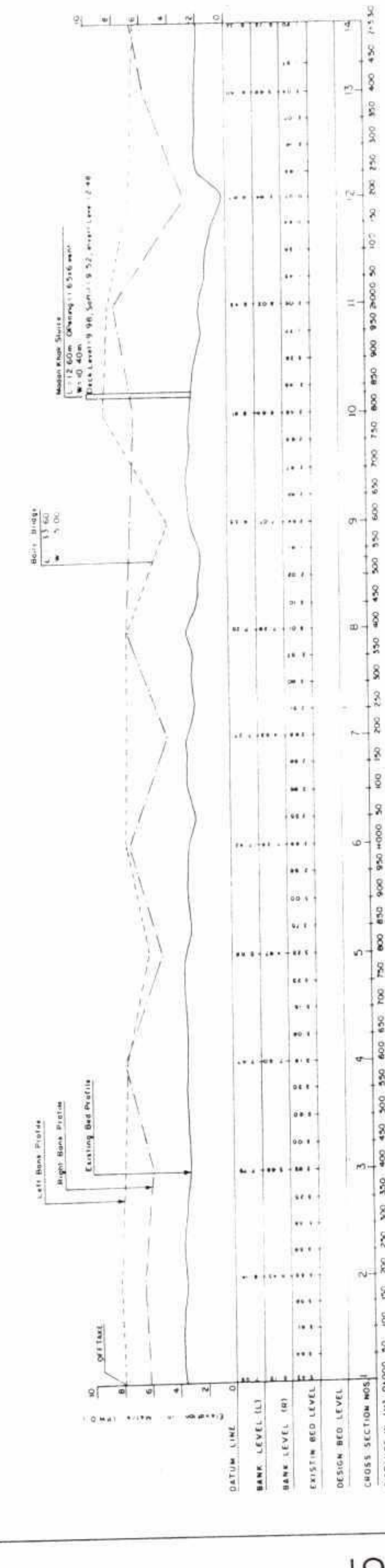
Low Flow Channel of Kumar

Figure 6.17



MOVEMENT OF PADMA AT KUMAR

Figure 6.18



1992 Dryseason Survey
Offtake of Kumar

6.9 Madaripur Beel Route (MBR)

The MBR was excavated across the Madaripur Beel using dredgers between 1905 and 1915 to a width of 150 to 170 feet. Problems of silting at the Gopalganj loop where the canal meets the Madhumati were overcome by embanking the southern side of the route and backing up flow in the Beel and Kumar rivers to ensure a continual throughflow out of the MBR into the Madhumati. Spill and navigation structures were provided at the junctions of the route with the main tranverse rivers and these have recently been replaced following damage caused in the 1988 flood.

A long section survey of the route in May 1992 as described in Section 3 revealed a number of shoals along the route but considering that very little maintainance has been done in the recent past there is surprisingly little siltation. The lower part of the route is tide dominated and the net flow is only a small part of the tidal flow during the dry period. During April the net flow is around 20 m^3/s but the peak tidal flow is 60 m^3/s. The tidal volume in the MBR helps to maintain the Lower Madhumati and as can be seen clearly from SPOT imagery, the size of the Lower Madhumati is significantly larger after the joining of the MBR. Increasing the flow down the MBR by dredging the Kumar river has been shown to be possible by modelling but almost certainly there would be a need for maintenance dredging as velocities are low in the upper Kumar and upper reach of the MBR. The bed material size was found to have a d_{50} grain size of 0.085mm.

6.10 Nabaganga

The present Nabaganga may be considered in three reaches: The upper portion which collects drainage flow in the G-K scheme and continues to a bifurcation with the Chitra near Narail where much of the flow goes into the Chitra. The middle reach to the Halifax cut is in decline and becomming weeded and silted up. The lower reach after the Halifax cut carries the bulk of the Gorai-Madhumati flow towards Khulna and is thus a major river which is also tidal. A long profile of the river is given in Figure 6.19 and typical cross sections in Figure 6.20.

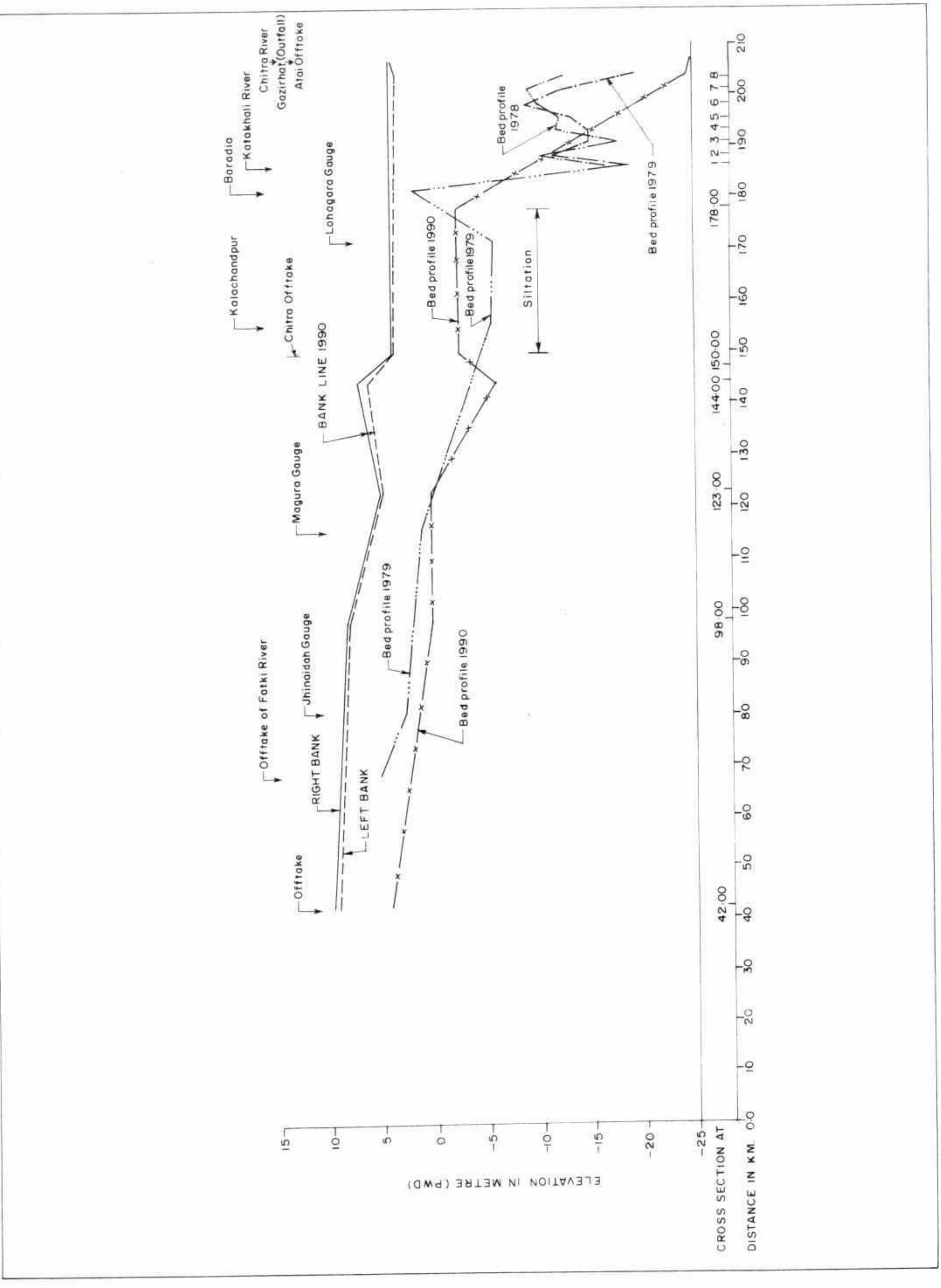
The Nabaganga was formerly connected with the Ganges via the Matabhanga and it also received significant spill from the Ganges and Gorai. In some years the spill was so great that in 1787, according to Addams Williams (1918), the depth of water over the land rose to seven to nine feet and consequently embankments were maintained along the south of the river by the Government at least until 1811. This spill is now contained by the Ganges right embankment and flood protection works associated with the G-K project.

Analysis of relatively short flow records for the gauging site at Magura (10 years) gives a dominant discharge of 120 m^3/s as shown in Figure 6.21, the return period of such a flow is around 1 in 1 year. Such a flow seems to be well within bankfull capacity suggesting that the river previously carried higher flows. The high degree of scatter found in the rating curves (Figure 6.22) is consistent with the finding of IECO (1980) that levels in the river are dependant on downstream conditions ie tidal levels and flows in the Gorai.

The middle reach after the bifurcation with the Chitra has a characteristic low flow channel within a much wider former river section that has silted up. The decline of this section is probably due to the increased flow through the Halifax cut and thus increased levels in the lower Nabaganga. The Chitra now offers a path of lower resistance and thus the middle reach of the Nabaganga can be expected to continue to decline.

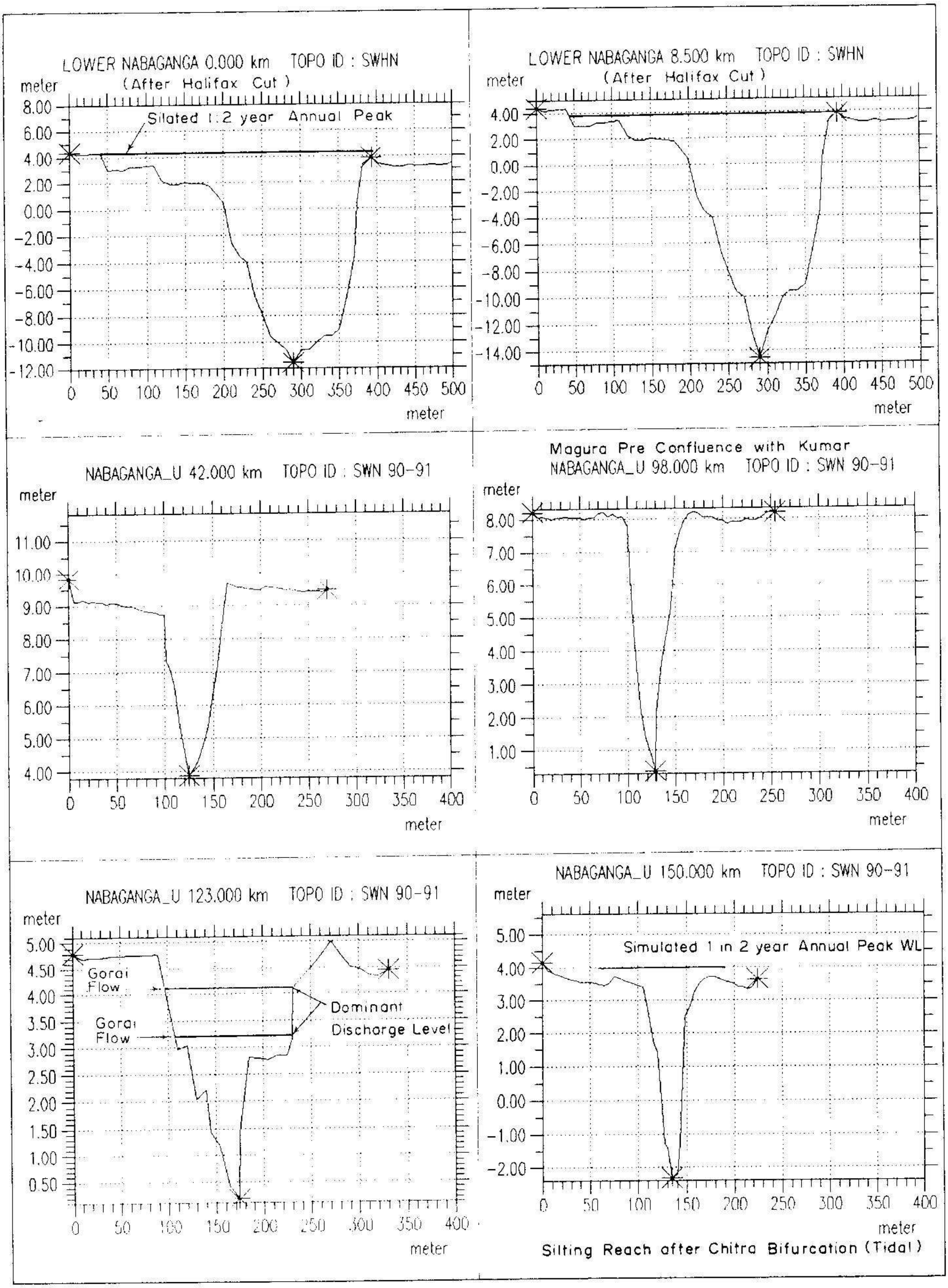
According to the hydrodynamic modelling with the current river geometry the Lower Nabaganga takes 94% of the average August flows in the Madhumati and is thus a major tidal river bearing little relation to the upper reaches.

Figure 6.19



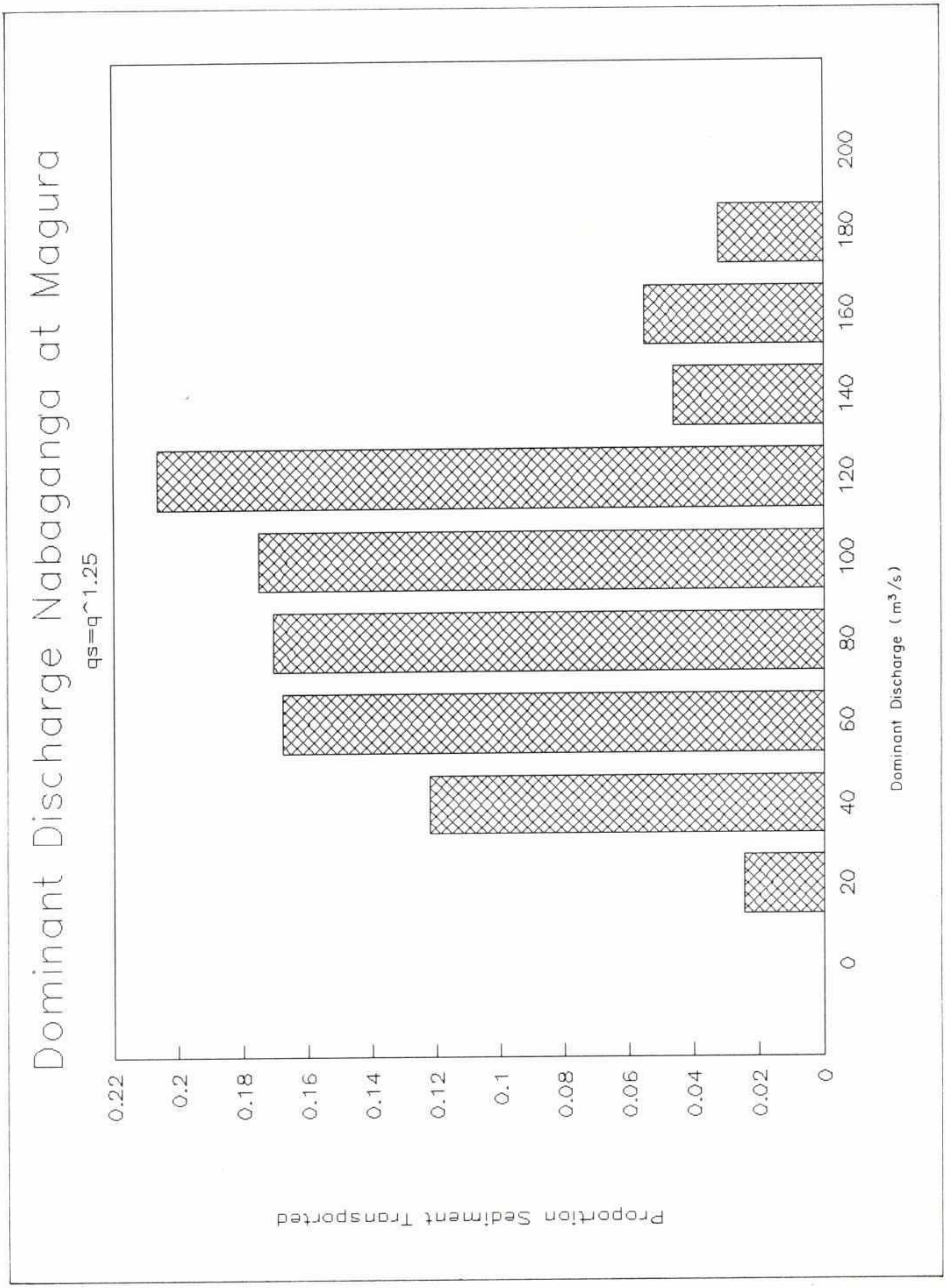
Long Profile of Nabaganga

Figure 6.20



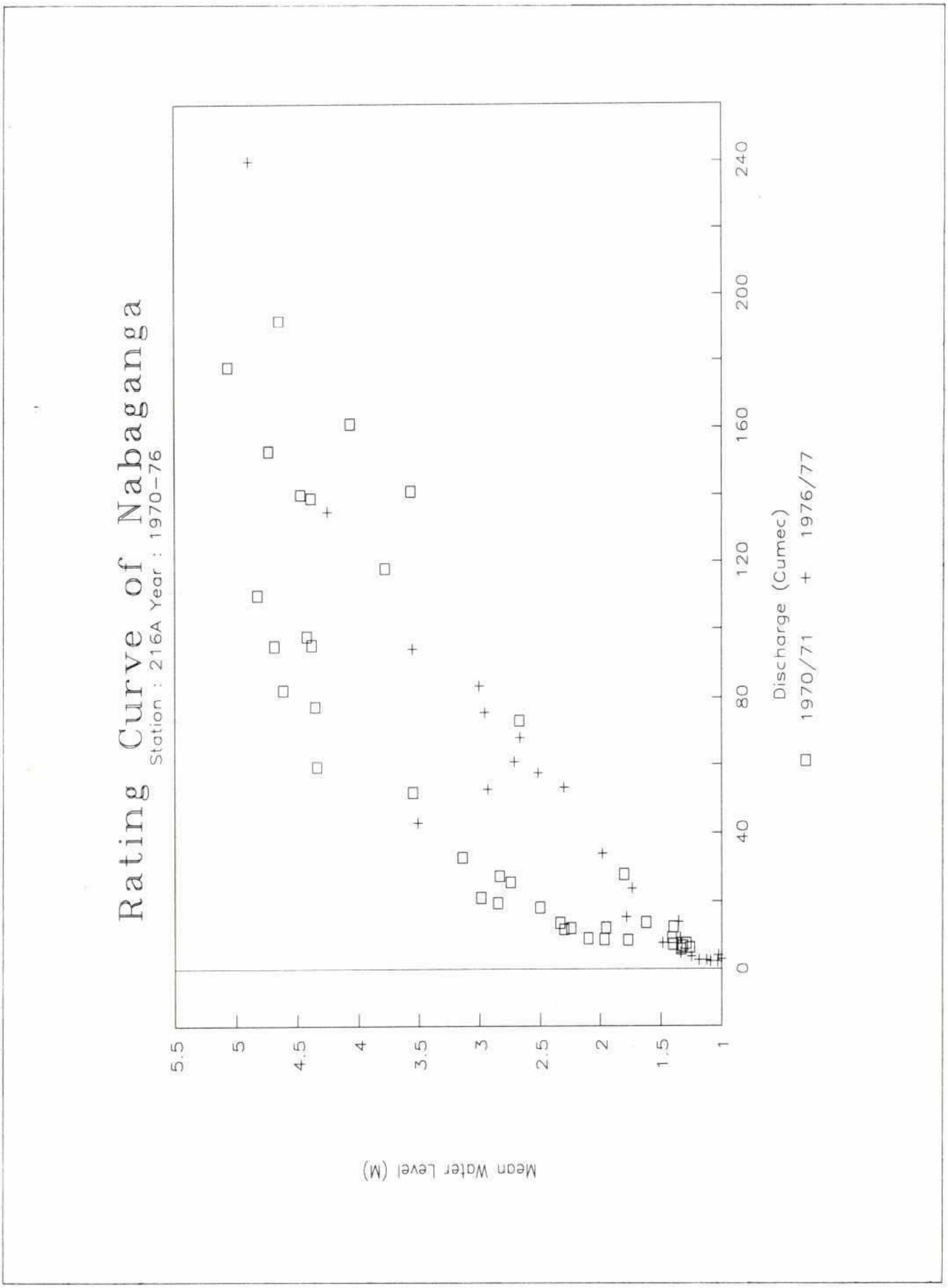
Cross Sections of Nabaganga

Figure 6.21



Dominant Discharge of Nabaganga at Magura

Figure 6.22



Rating Curve of Nabaganga

7 TIDAL INLAND RIVERS

7.1 Characteristics of Tidal Rivers

The coastal zone of the Area comprises the extensive, flat, coastal and deltaic land of the Ganges Delta which is crossed by large tidal rivers discharging into the Bay of Bengal. The form of the large estuaries and tidal rivers has been derived from many years of deltaic accretion controled by the major changes and movements of Ganges and Brahmaputra.

The major tidal rivers of the Southwest Area are shown in Figure 7.1 and include the major rivers from east to west:

Raimangal
Malancha
Sibsa
Pussur
Baleswar

The fresh water rivers of the South Central region were described in Sections 4 and 5. These major estuarial rivers are interlinked and fed by numerous smaller channels and in the Sundarban area there is mass of small tidal creeks each vitally important to the local forest area. Flow characteristics of selected rivers are given in Table 7.1.

TABLE 7.1

Characteristics of Selected Rivers

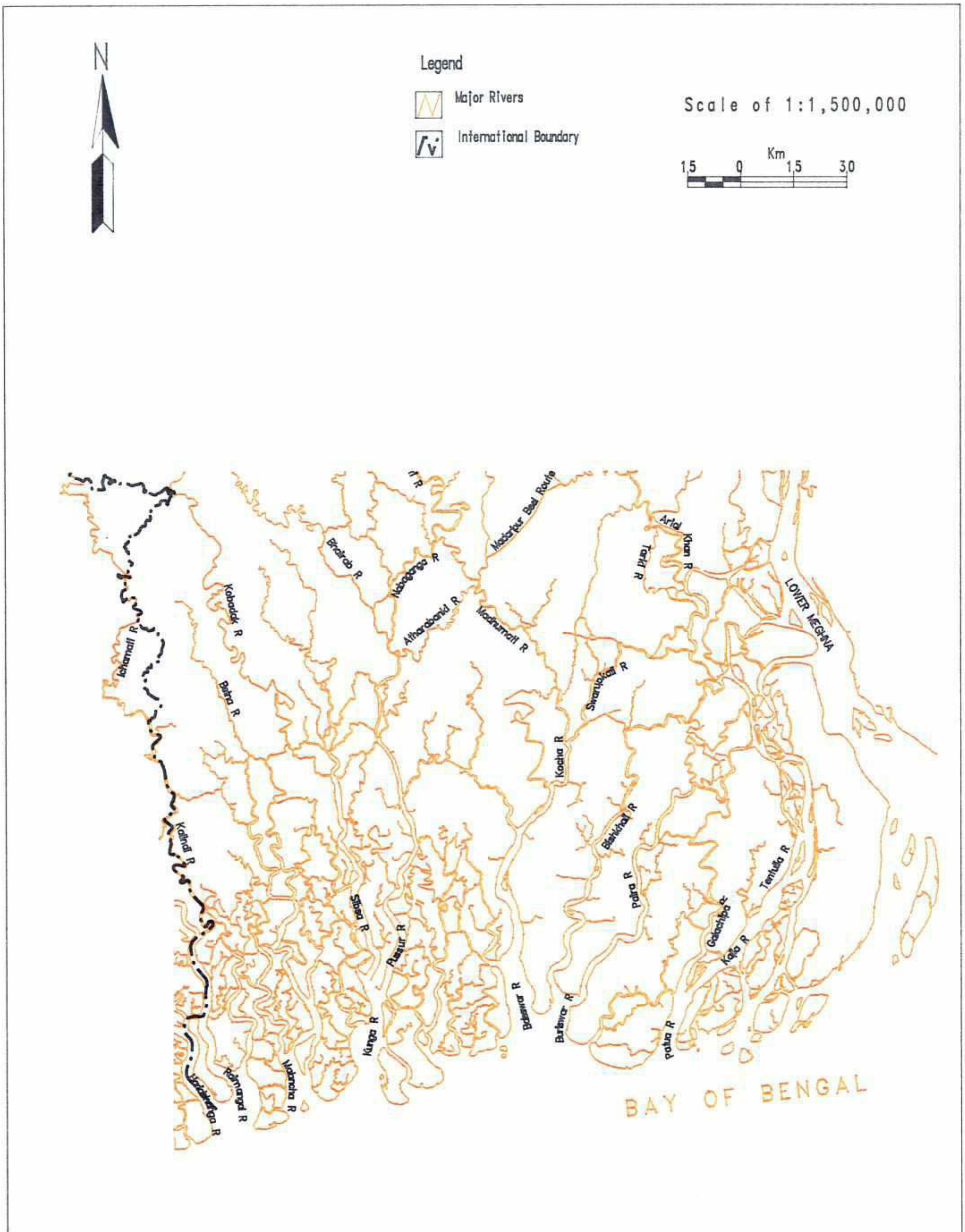
River Name	Tidal/Non-Tidal	Dominant Discharge (m^3/s)	Peak Tidal Flow		Nett Flow m^3/s		Width (m)
			August	April	August	April	
Arial Khan	N/T	2000	2900	300	2120	150	400
Swarupkati	T	-	16880	7120	3500	770	400
Buriswar	T	-	19340	9150	3070	620	1250
Biskhali	T	-	10990	8920	2400	360	1600
Tentulia	T	-	9020	4820	4380	1108	4000

Notes: (1) Tidal Flow given for spring tide 1991 from model simulation.
(2) Nett Flow derived from mean monthly flow of 25 year tidal simulation using current cross sections.
(3) Width at section for which flows given.
(4) Flows for Madhumati given just above Halifax cut, Lower Madhumati values given just below. Flow split indicated is subject to further studies.

As a consequence of the flat topography coastal processes have a major impact on the rivers of the area. These impacts are :

(i) reversal of freshwater flows due to tidal action is experienced up to 225 km inland in the wet season and 325 km inland in the dry season as shown on Figure 7.2.

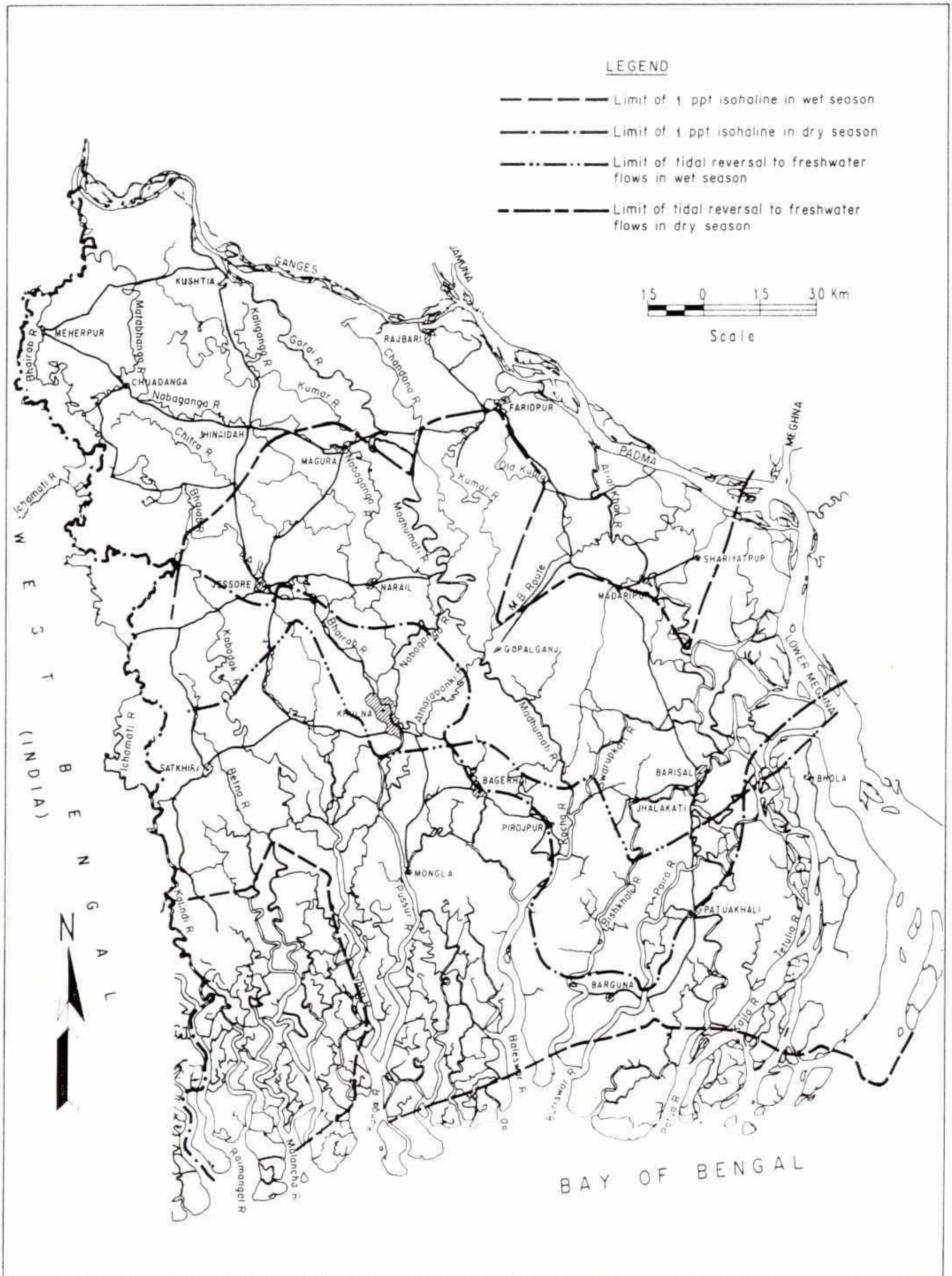
Figure 7.1



Major Tidal Rivers of South West Area

177

Figure 7.2



Tidal Boundary

(ii) the average tidal range in the area varies from approximately 3.0 m on the coast at Hiron Point to 0.5 m 275 km inland. The time difference between high water at Hiron Point and high water at Narail is approximately 7 hours. In addition to daily tidal fluctuations there are half yearly increases in sea level of 600 mm in the northern part of the Bay of Bengal due to the onset of the wet season and the NE Monsoon. These fluctuations combine with seasonal changes in river level caused by changes in freshwater flows.

(iii) a level of average saline intrusion likely to have an adverse effect on agriculture, 1 ppt (2000 mmhos), is experienced through 10% (4000 sq km) of the Area in the wet season and throughout 40% (16200 sq km) in the dry season as shown on Figure 7.2. In both seasons the extent of intrusion is greater in the southwest than the south central where intrusion is prevented by the fresh water flows entering the south central area from the Lower Meghna via the Arial Khan. In the southwest the 1 ppt isohaline is 75 km and 150 km inland in the wet and dry seasons respectively. In the south central the corresponding figures are 25 km and 45 km.

(iv) fine sediment is transported by tidal currents into the Area. It is probable that the sediment originates from the Meghna discharge during the wet season and is carried westwards by near shore currents created by the NE monsoon in the period July to November. Sediment is also carried into the Area by the freshwater rivers.

A combination of analysis methods were used to assess the state of the rivers in terms of siltation, the methods used comprised:

Surveys of Cross Sections and comparison with earlier surveys

Regime Analysis of Cross Sections

Examination of Satellite and Topographic Information

Hydraulic and Morphological Modelling using Sand Transport Model

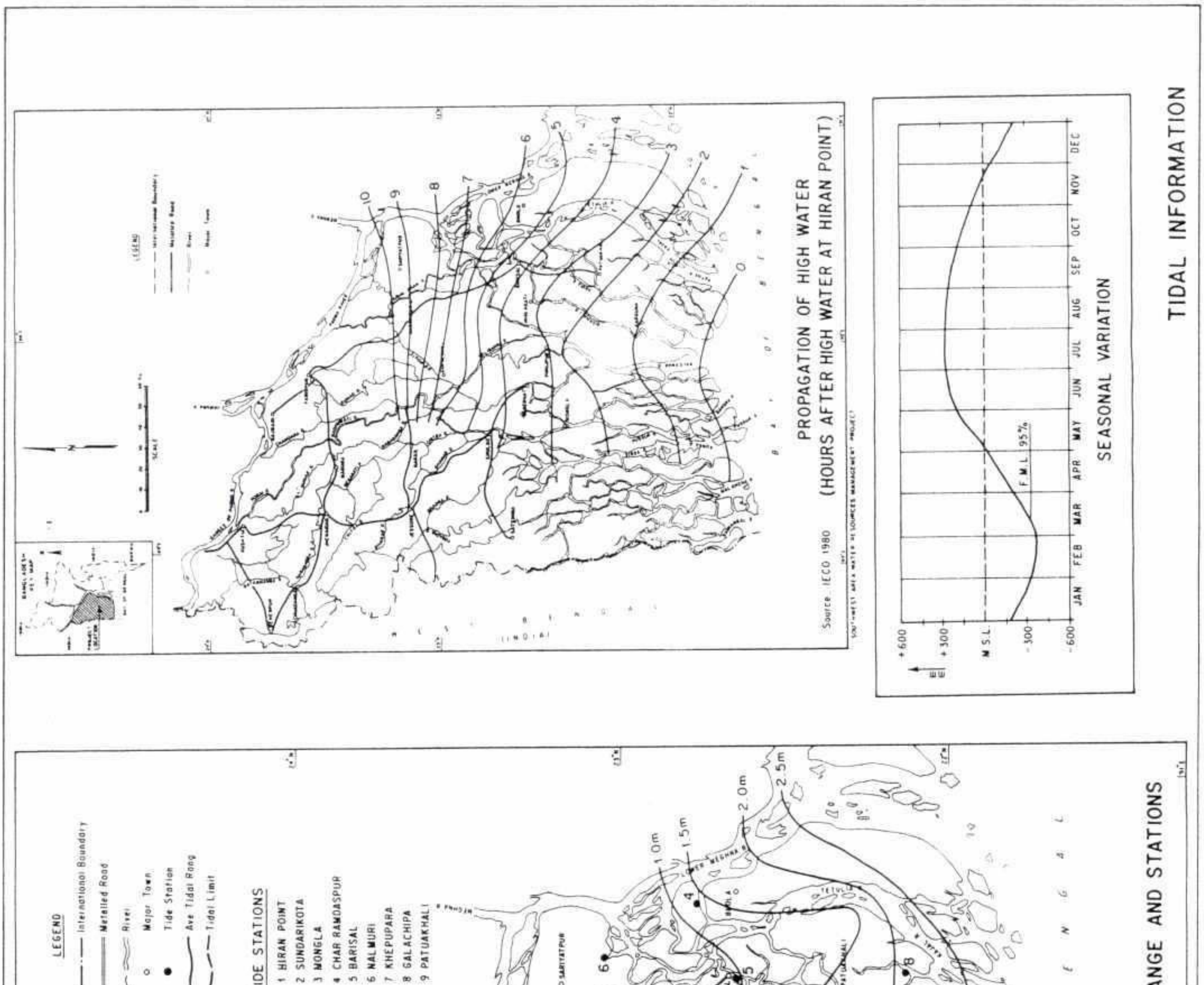
Questionaires and interviews with BWDB Executive Engineers and local people.

This information was used to derive an accurate picture of the current condition of the river system and then the regime analysis techniques were used to predict the impact of interventions.

7.2 Tides

The tides in the Bay of Bengal are predominantly semi-diurnal, that is the tidal period is 12 hours 25 minutes. As shown on Figure 7.3 it takes approximately 10 hours for the tide to propagate through the study area. The predicted ranges of tides for 1992, based on the BIWTA tide tables, are shown in Table 7.2. This should be compared with the lines of average tidal range shown on Figure 7.3. It is important to note that in the inland part of the Area the difference between extreme high and low water given in Table 7.2 is much greater than the average tidal range shown on Figure 7.3. The mean water level of the rivers changes between wet and dry season thus the extreme high water is high in the wet season and extreme low water is low tide in the dry season. The critical levels for structure and drainage design should therefore be based on the figures given in Table 7.2 and not the co-tidal ranges.

Figure 7.3



Tidal Flow Information

TABLE 7.2

Tidal Levels and Tide Station Information

TIDAL LEVELS							
STATION	LAT	MLWS	MLWN	ML	MHWN	MHWS	HAT
Hiron Point	-0.256	0.225	0.905	1.700	2.495	3.175	3.656
Sundarikota	-0.553	0.036	0.636	1.829	3.022	3.694	4.211
Mongla	-0.212	0.284	0.968	1.946	2.924	3.608	4.104
Char Ramdaspur	-0.261	0.189	0.763	2.036	3.309	3.883	4.333
Barisal	+0.134	0.434	0.692	1.539	2.386	2.644	2.944
Nalmuri	+0.078	0.370	0.722	2.195	3.669	4.021	4.313
Galachipa	-0.159	0.283	0.937	1.764	2.592	3.245	3.689
Patuakhali	-0.143	0.242	0.740	1.575	2.409	2.907	3.293

STATION INFORMATION					
STATION	RIVER	LATITUDE	LONGITUDE		
		NORTH	EAST	CD	PWD
Hiron Point	Pussur	21.48	89.28	3.784	
Sundarikota	Pussur	22.07	89.36	3.369	
Mongla	Pussur	22.27	89.36	4.657	
Char Ramdaspur	Meghna	22.48	90.39	5.137	
Barisal	Barisal	22.41	90.22	3.365	2.946
Nalmuri	Meghna	23.06	90.26	4.186	3.962
Galachipa	Lohalia	22.10	90.24	5.119	4.404
Patuakhali	Lohalia	22.22	90.19	3.785	2.889

LAT = Lowest Astronomical Tide
HAT = Highest Astronomical Tide
PWD = Public Works Datum
CD = Chart Datum
MLWS = Mean Low Water Spring
MHWS = Mean High Water Spring
MHWN = Mean High Water Neap
MLWN = Mean Low Water Neap
ML = Mean Level

Source: Bangladesh Tide Tables 1992 BIWTA

As the tidal wave propagates inland it loses its symmetrical shape due to the different hydrodynamic characteristics of the rivers and cross channels so the flood and ebb tide characteristics are different. The simulated tidal conditions (D.H.I. 1992) for various locations in the Pussur - Sibsa river system are given in Tables 7.3 and 7.4. It should be noted that the increase in ebb discharge for August compared with May is due to the fresh water flows.

The overall picture in the dry season is that the system is flood dominated with peak discharges, and hence sediment transport, greater during flood than ebb. In the wet season the situation is less pronounced or reversed. Annually the dry season effects appear to exceed the wet season effects making the system a net importer of sediment but this important topic requires further verification with the aid of the sediment transport model.

TABLE 7.3
Hydrodynamic Simulation
Present Conditions Spring and Neap Tide, May 1990

Date : 11th May 1990 Tide : Spring

River	Location	Rising Tide (Flood Current)		Falling Tide (Ebb Current)		Water Level Range (m)
		Peak velocity (m/s)	Peak Discharge (m^3/s)	Peak velocity (m/s)	Peak Discharge (m^3/s)	
Sibsa	Easy Point	1.007	30347	0.964	26555	2.78
Pussur	Sundarikota	0.919	17485	0.959	15592	2.54
Mongla M.	Mongla	0.864	2244	0.696	1516	2.86
Pussur	Mongla	0.920	5956	0.860	5253	2.93
Chunkuri	--	0.597	1093	0.555	626	3.07
Old Pussur	--	0.976	2035	0.619	1447	3.09
Jhapjhapia	--	1.030	1349	1.290	1150	3.05
Kazibacha	--	0.574	2691	0.627	2250	2.86
Solmari	--	0.457	668	0.756	719	2.87
Sibsa	Malianala	1.424	18651	1.223	14984	3.32

Date : 17th May 1990 Tide : Neap

River	Location	Rising Tide (Flood Current)			Falling Tide (Ebb Current)		Water Level Range (m)
		Peak velocity (m/s)	Peak Discharge (m^3/s)	Total Volume (10^6 m^3)	Peak velocity (m/s)	Peak Discharge (m^3/s)	
Sibsa	Easy Point	0.795	23782	353.33	0.697	19362	2.00
Pussur	Sundarikota	0.749	13973	213.14	0.696	11423	1.82
Mongla M.	Mongla	0.716	1811	28.78	0.567	1197	2.38
Pussur	Mongla	0.770	4903	72.27	0.653	3830	2.42
Chunkuri	--	0.605	931	14.55	0.445	490	2.60
Old Pussur	--	0.742	1589	21.66	0.520	1147	2.62
Jhapjhapia	--	0.924	1196	19.47	0.964	883	2.60
Kazibacha	--	0.564	2489	37.78	0.458	1618	2.51
Solmari	--	0.504	665	11.20	0.571	549	2.52
Sibsa	Malianala	1.095	14577	216.34	0.913	11035	2.52

Source: DHI 1992

TABLE 7.4
Hydrodynamic Simulation
Present Conditions Spring and Neap Tide, August 1990

Date : 21st August 1990 Tide : Spring

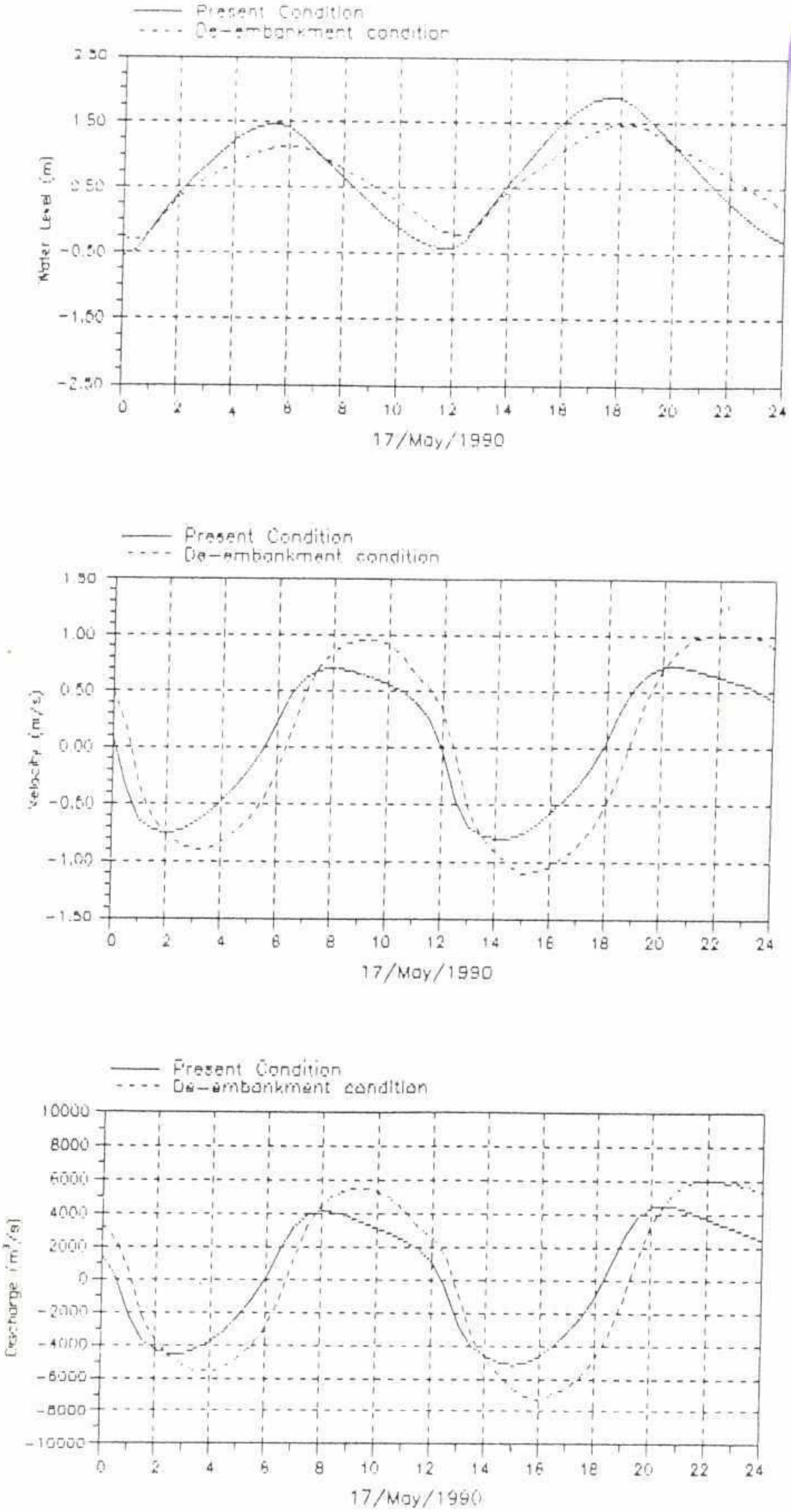
River	Location	Rising Tide (Flood Current)		Falling Tide (Ebb Current)		Water Level Range (m)
		Peak velocity (m/s)	Peak Discharge (m^3/s)	Peak velocity (m/s)	Peak Discharge (m^3/s)	
Sibsa	Easy Point	1.045	33023	1.134	32987	2.77
Pussur	Sundarikota	0.880	17954	1.026	18260	2.60
Mongla M.	Mongla	0.935	2765	0.765	1821	2.93
Pussur	Mongla	0.864	6226	1.073	7460	3.00
Chunkuri	--	0.502	838	0.756	999	3.04
Old Pussur	--	1.021	2496	0.651	1686	3.05
Jhapjhapia	--	0.382	580	1.517	1592	2.89
Kazibacha	--	0.067	355	0.960	4095	2.55
Solmari	--	0.008	15	0.975	1092	2.54
Sibsa	Malianala	1.520	21552	1.451	20260	3.36

Date : 30th August 1990 Tide : Neap

River	Location	Rising Tide (Flood Current)		Falling Tide (Ebb Current)		Water Level Range (m)
		Peak velocity (m/s)	Peak Discharge (m^3/s)	Peak velocity (m/s)	Peak Discharge (m^3/s)	
Sibsa	Easy Point	0.354	10440	0.545	15943	1.28
Pussur	Sundarikota	0.279	5104	0.561	10123	1.25
Mongla M.	Mongla	0.356	922	0.451	1006	1.62
Pussur	Mongla	0.204	1285	0.642	4143	1.66
Chunkuri	--	0.089	132	0.543	704	1.75
Old Pussur	--	0.341	784	0.411	987	1.77
Jhapjhapia	--	--	--	1.025	1116	1.70
Kazibacha	--	--	--	0.727	2946	1.54
Solmari	--	--	--	0.725	823	1.53
Sibsa	Malianala	0.475	6224	0.752	9898	1.75

Source: DHI 1992

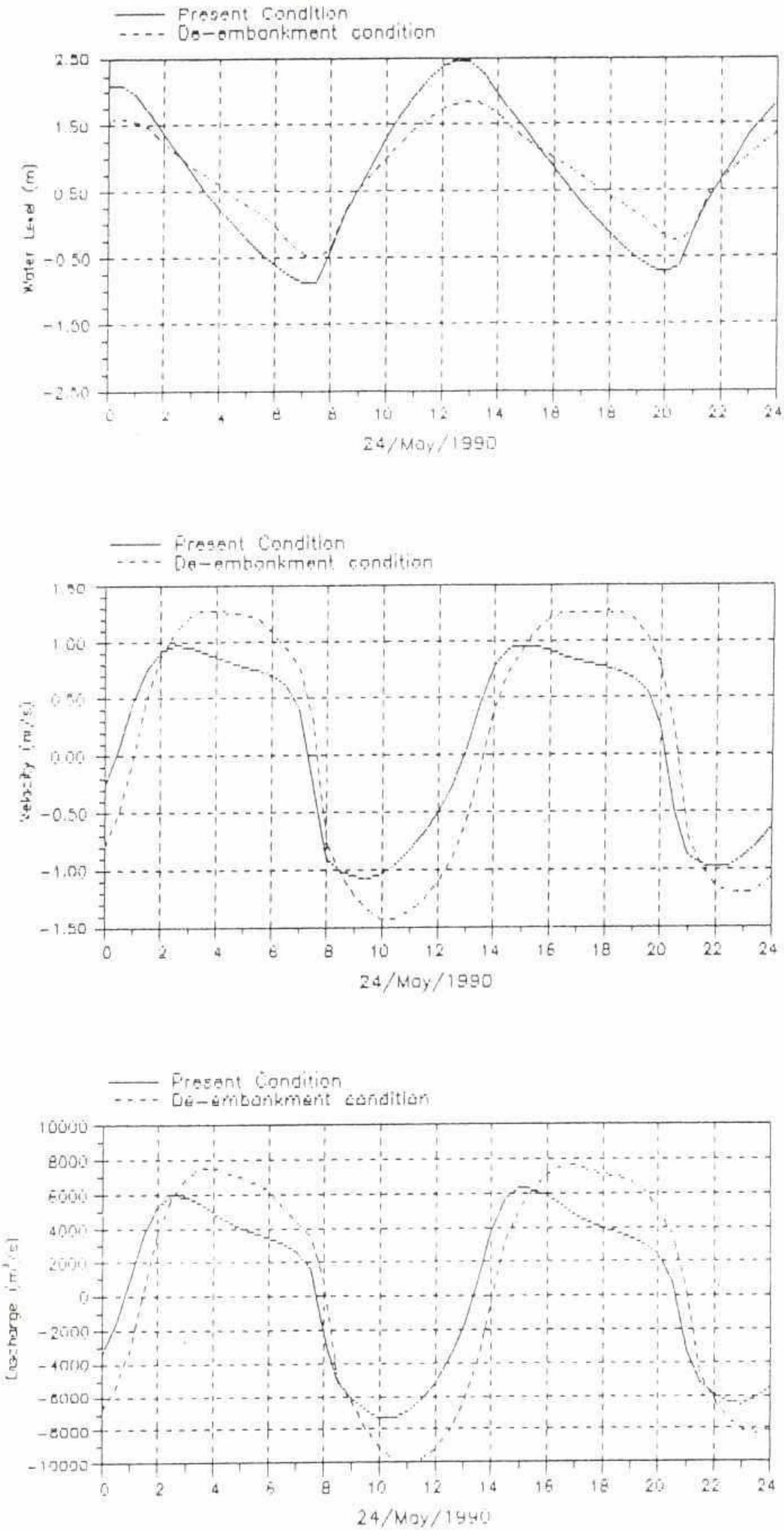
Figure 7.4



Source : DHI 1992

Comparison of Tidal Range, Velocities and Discharges Neap Tide at Mongla

Figure 7.5



Source : DHI 1992

Comparison of Tidal Range, Velocities and Discharges Spring Tide at Mongla

The inland tidal condition is also subject to changes caused by major intervention in the river system. Simulations verified by historic measurements for Mongla (DHI 1992) show that the tidal range has increased and tidal discharge decreased following the large scale construction of polders under the Coastal Embankment Protection (CEP) scheme in the 1960s and 70s. These results are reproduced in Figures 7.4 and 7.5 but it should be noted that the results for the de-embankment condition are based on present day channel dimensions which will generally be different to those that originally existed.

7.3 Tidal Characteristics of Rivers

The tidal wave propagates into the Area along the major tidal rivers. The speed of propagation in the rivers varies due to their different cross sectional area and in consequence water levels in adjacent rivers can differ. This results in flow from one river to another through the cross channels and rivers (cross rivers are particularly prevalent in the southwest). Where the tidal wave from one river meets the wave from another river there are tidal meeting points which are characterized by periods of low or stagnant flow and consequential siltation. Where there are no tidal meeting points the tidal flow is continuous and the conditions for siltation are less severe.

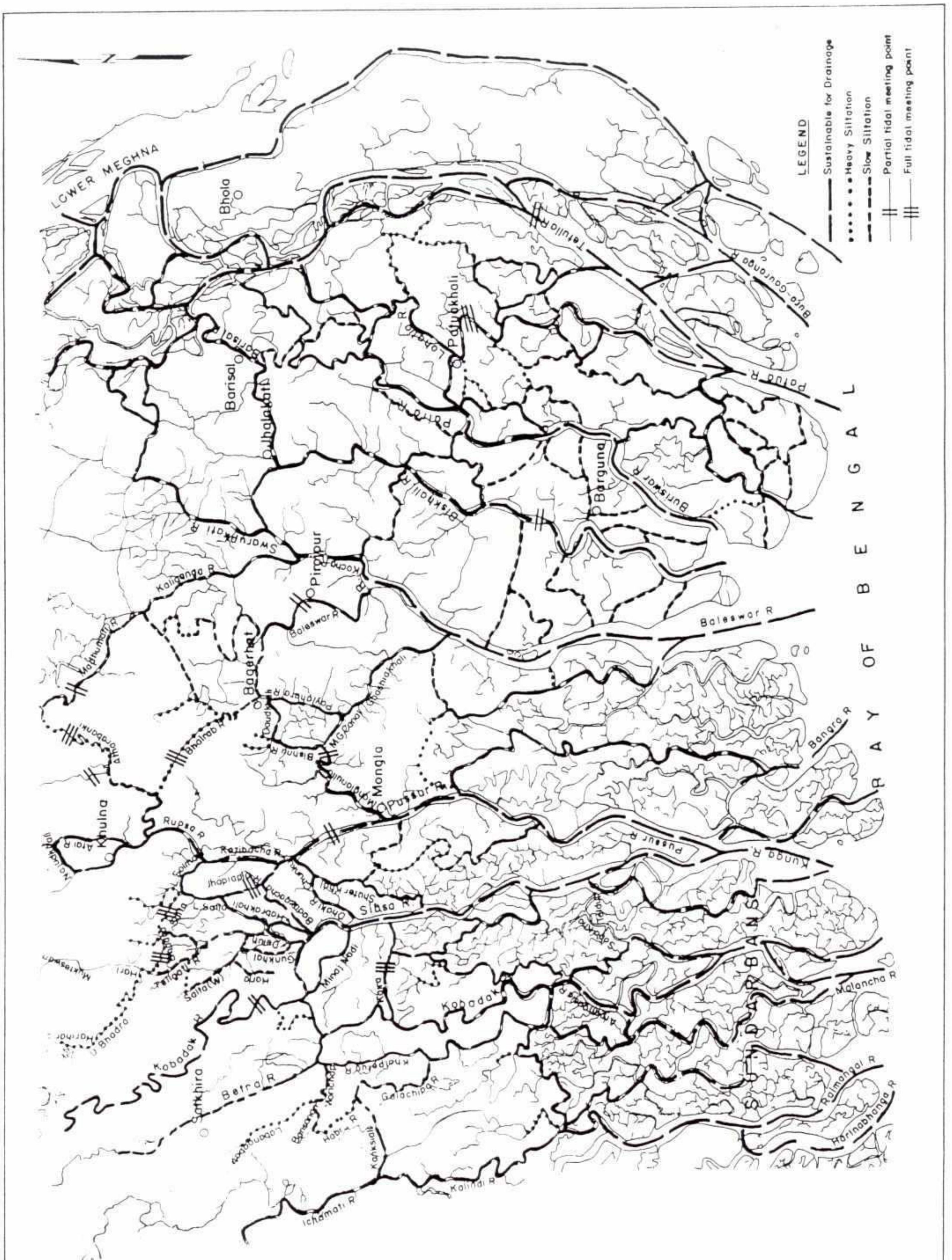
The tidal meeting places are known to be areas of accretion and these were identified using the hydrodynamic model. Tidal meeting points are more evident during spring tide than neap tide. Stagnation zones are also predicted where the flow is dampened due to the interaction of flows from different directions. Both tidal meeting and stagnation places are detrimental factors causing siltation in the channel. The following are the rivers where tide meeting and stagnation take place as shown in Figure 7.6.

Tidal meeting
- Koira and Hudda rivers
- Salta
- Bhadra
- Haria, upstream end of Sibsa
- Jhapjhapia
- Bhairab at Bagerhat
- U. Atharobanki
- Lohalia near Patuakhali

Stagnation places
- Kobadak
- Pussur, upstream of Mongla Port
- Pussur (for a short duration), downstream of Mongla Port
- Athorobanki
- Baleswar
- M.G. Canal (non very evident)
- L. Modhumati
- Bishkhali (not very pronounced)
- Tentulia (not very pronounced)

Notwithstanding the effect of cross channel flows the tidal wave propagates to the upstream limits discussed in Section 7.2 where tidal movement ceases and siltation is likely to occur. Unless freshwater flows are present at this upstream boundary siltation will continue until the estuary reaches equilibrium. Where fresh water flows exist the channel will tend to be flushed clear during the ebb tide but the success in clearing or sustaining the channel will depend on the relationship between the ebb discharge, freshwater plus tidal volume, and the channel cross section. The model results also provide peak ebb discharges and channel cross sections throughout the river system which may be used in

Figure 7.6



Tidal Meeting Place

the appropriate empirical regime relationship to assess whether or not the channel is stable, accreting or eroding. The results of this regime analysis are also shown on Figure 7.6 and are discussed in greater detail in Volume 4.

Following construction of the Coastal Embankment Project, the volume of tidal over-spill was greatly reduced with the result that the tidal became insufficient to sustain the pre polder channel cross section and siltation occurred. This situation has not occurred to such a large extent where freshwater flows or tidal circulation patterns are dominant.

The manner in which the tidal wave propagates through the major rivers is as follows:

(i) Kobadak-Sibsa

The Malancha/Kobadak and Sibsa have the same tidal phase. These two rivers are exchanging flow through Koira, Minajnadi and Haria (upper stretch of Sibsa). Tide meeting is occurring in Koira and Haria and causing siltation to these channels. The tidal flow in the upper Kobadak is both the action of Sibsa via Minajnadi and L.Kobadak rivers. This phenomenon indicates that the Minajnadi is free from tide meeting. The Minajnadi is under the process of siltation which is the consequence of the deterioration in the U.Kobadak. The flood tide pushes the flow from Kobadak to Sibsa through Koira and reverses at the beginning of ebb tide. In the dry period, both for ebb and flood condition, the tidal meeting is for longer duration in the Koira river. Another linkage between Kobadak and Sibsa is the Sonakhal-Taldup river. Through this river,the flood movement is toward Sibsa and ebb direction towards Kobadak. This linkage is morphologically stable and sound.

(ii) Pussur-Sibsa

The Sibsa has an earlier tide than the Pussur. The flow from Sibsa, at its upstream end, is diverted firstly toward Gangrail and later to L.Bhadra during flood tide. The wide corridor of Gangrail allows the main sediment flux to move upward and create siltation in the upper reaches of its system. In the dry season, the flow in L.Bhadra combines with the flow from Kazibacha.

The Sibsa is linked with the Pussur through the Badurgacha, Dhaki-Chunkuri and Shuterkhali-Chunkuri rivers.

As the Sibsa has earlier tide, more prominent during wet season, the flow from Shuterkhali, Badurgacha together with the upland fresh flow create a "Flow Stagnation Zone" in the upper reach of Pussur. In the dry neap tidal period the Pussur at its upper reach has dampening in flow due to interchange of tide with its connecting channels. This phenomenon is causing siltation in the Pussur but the extent is not significant. All the connecting channels have south-west to north-east alignment which make them less prone to siltation and therefore these rivers such as the L.Bhadra and L.Solmari are dynamic and stable.

(iii) Pussur-Baleswar

The exchange of flow between these rivers is mainly through the Monglanulla-M.G.Canal-Gashiakhali connection.

For a short while, during flood tide, the flow is from Baleswar to Pussur river. But the ebb tide drops much earlier in Baleswar which initiates flow from Pussur to this river. The net flow is toward Baleswar. The flow from Pussur and Baleswar through the connecting channel enters the loop of Poylahara, Bishnu and Daudkhali rivers and finally moves into the upper reaches of Poylahara where it fades and causes silting to this channel. The siltation is gradually propagating downward. It is important to note that the flow in the Poylahara is mainly dominated by the flow from Baleswar river.

(iv) Central region

The rivers in the central region are very active. Cross flow between the rivers is, however, small. The flow is mainly governed by the substantial fresh water flow originating from the Lower Meghna and tidal flow from downstream. The small internal channels are tending to silt up. Any change in the upstream conditions will drastically change the morphology of this area.

7.4 Cross Section and Regime Analysis

A comparison between each of the 77 cross sections measured and previous surveys was carried out. Bench marks in the area sometimes have systematic errors and although care was taken to use the same benchmarks as the original surveys, this was not always possible and for comparison purposes the embankment levels were used to correct for gross errors.

The difficulty in modelling morphological processes lies in the fact that it is a constantly changing evolutionary process. The channel cross-section geometry, which has taken a considerable effort to obtain, can only be a snapshot in time so, in turn, the representation of sediment transport processes can only relate to that channel geometry unless a morphological model that makes progressive adjustments to that geometry is employed. The tidal system in the project area is complex with many interconnecting channels and consequently there are sensitive sediment and flow divisions at each junction. The current state of knowledge and modelling capability is such that at present a suitable comprehensive morphological model does not exist.

An alternative approach to detailed sediment transport modelling is to apply a regime model which although it does not to represent the processes in any detail, it empirically relates the ideal tidal river cross-sections to some measure of the flow conditions. McDowell and O'Connor(1977) show that many estuaries which have unrestrained boundaries exhibit a strong correlation between the maximum tidal discharge on a mean spring tide and the channel cross-section so that

$$Q_m = A_m C (t_s/p)^{½}$$

where Q_m (m^3/s) is the maximum tidal discharge, A_m (m^2) the cross-sectional area at mean tide level, t_s an average cross-sectional shear stress which may vary between 0.35 and 0.5 kg/m^2, p is water density and C is a Chezy coefficient which can be approximated by

$$C = 30 + 5 \log(A_m) \; m^{½}/s$$

If however the river is in a state of transition it follows that a flow greater than Q_m will cause the cross section to erode until a new stable cross-section is created. Conversely a flow lower than Q_m will cause siltation. Whilst the conditions in the tidal rivers in the study area do not exactly match those for which this relationship is known to be valid for example the Hooghly in India, it can be checked as a valid means of approach by comparison with field observations and data obtained from SPOT imagery. The hydrodynamic model can also be used to generate results for use in a regime type equation. The usefulness of this type of approach has been proven over many years. At a planning level it gives a simple analysis tool that can be applied over a wide area to identify areas for which further detailed study is required. The hydrodynamic model may then be run to give results that can quickly be analysed to give predictions of the effects of interventions for example.

The hydrodynamic model can be used to calculate Q_{max} at specified locations in the river system. The value of the cross-sectional area at mean tide level, A_m, can be approximated by Q_{max}/V_{max} and the corresponding value of Q_m determined. If the ratio $Q_{max} : Q_m$ is greater than unity this implies erosion and if less than unity the siltation is occurring. The manner in which this method has been used predict the condition of the tidal rivers is discussed in Chapter 6, 7 and 9.

For the purposes of river classification the morphological process has been defined as given in Table 7.5.

TABLE 7.5

River Classification

River Classification	Ratio $Q_{max} : Q_m$
Heavy Siltation	< 0.05
Moderate Siltation	0.36 - 0.70
Slow Siltation	0.71 - 0.95
Equilibrium	0.96 - 1.05
Slow Erosion	1.06 - 1.25
Moderate Erosion	1.26 - 1.50
Heavy Erosion	>1.51

The main value of this type of classification is as a means of comparing river conditions rather than the absolute conditions. The model was run for monsoon season conditions (August 1991) and dry season conditions (April 1991) to check the variation of silting and scouring that may be seen throughout the year. The results were then compared with those from other methods and are given in Table 7.6. It was concluded that the technique of regime analysis gave a sufficiently good representation of the known situation to use for prediction purposes.

TABLE 7.6

River Characteristics-Comparison of Regime Analysis with alternative Methods of Analysis

X-section No.	River Name	Regime Analysis	Sediment Model	X-section Comparison	Maps & spot Image Analysis
1	KOBADAK U	Moderate siltation	Slow siltation	Slow siltation	Slow siltation
2	KOBADAK M	Slow siltation	Slow siltation	Slow siltation	Slow siltation
3	KARULLA	Erosion	Erosion		Equilibrium
4	CONNECTION	Slow siltation	Slow siltation		Equilibrium
5	KATAKHALI-K	Erosion	Erosion	Erosion	Equilibrium
6	KOBADAK L	Slow siltation	Equilibrium	Equilibrium	Equilibrium
7	KOIRA	Slow siltation	Slow siltation		Slow siltation
8	HADDA	Slow siltation	Slow siltation		Slow siltation
9	BETNA	Moderate siltation	Slow siltation	Slow siltation	Slow siltation
10	BETNA	Slow siltation	Equilibrium	Equilibrium	Slow siltation
11	MORIRCHAP	Equilibrium	Slow siltation		Slow siltation
12	LABANGABATI	Heavy siltation	Heavy siltation	Heavy siltation	Heavy siltation
13	BANSANA	Equilibrium	Heavy siltation	Slow siltation	Heavy siltation
14	HABRA	Heavy siltation	Heavy siltation	Heavy siltation	Heavy siltation
15	KANKSIALI	Heavy siltation	Erosion	Heavy siltation	Heavy siltation
16	GALGHASIA	Slow siltation	Moderate siltation	Slow siltation	Moderate siltation
17	KHOLPETUA	Slow siltation	Moderate siltation	Equilibrium	Slow siltation
18	LINK-KK	Equilibrium			Equilibrium
19	ARPANGASIA	Equilibrium			Equilibrium
20	ARPANGASIA	Equilibrium			Equilibrium
21	CHALKIGANG	Equilibrium			Equilibrium
22	BAL	Equilibrium			Equilibrium
23	BARAPANGA				Equilibrium
24	BETMARAGANG	Equilibrium			Equilibrium
25	MALANCHA	Equilibrium			Equilibrium
26	MALANCHA-E	Equilibrium			Equilibrium
27	SONAKHAL	Equilibrium	Erosion		Equilibrium
28	TALDUP	Equilibrium	Erosion		Equilibrium
29	HARIHAR	Heavy siltation	Heavy siltation		Heavy siltation
30	BURIBHADRA	Heavy siltation	Heavy siltation		Heavy siltation
31	U-BHADRA	Heavy siltation			Heavy siltation
32	MUKTESWARI	Heavy siltation	Moderate siltation		Heavy siltation
33	HARI	Heavy siltation	Erosion		Heavy siltation
34	M-BHADRA	Moderate siltation	Equilibrium	Slow siltation	Moderate siltation
35	HAMKURA	Moderate siltation	Slow siltation		Moderate siltation
36	BHADRA	Heavy siltation	Slow siltation		Moderate siltation
37	BHADRA	Moderate siltation	Erosion	Erosion	Moderate siltation
38	TELIGATI	Slow siltation	Erosion		Slow siltation
39	SALTA(W)	Slow siltation	Slow siltation		Slow siltation
40	HARIA	Slow siltation	Slow siltation	Slow siltation	Slow siltation
41	GHENGRAIL	Slow siltation	Slow siltation	Slow siltation	Slow siltation
42	BHANGARIA	Heavy siltation			Heavy siltation
43	GUNAKHALI	Slow siltation	Heavy siltation		Slow siltation
44	U-SOLMARI	Moderate siltation	Slow siltation		Moderate siltation
45	L-SOLMARI	Equilibrium	Erosion	Equilibrium	Equilibrium
46	SALTA	Moderate siltation	Erosion		Heavy siltation
47	L-SALTA	Equilibrium	Equilibrium	Equilibrium	Equilibrium
48	L-BHADRA	Equilibrium	Erosion	Slow siltation	Equilibrium
49	HABARKHALI	Equilibrium	Equilibrium	Equilibrium	Equilibrium
50	DELUTI	Erosion	Erosion		Equilibrium
51	MINAJNADI	Slow siltation	Slow siltation		Equilibrium
52	SIBSA	Slow siltation	Slow siltation		Equilibrium
53	SIBSA	Erosion	Erosion		Equilibrium
54	SIBSA	Erosion	Equilibrium		Equilibrium
55	JHAPJHAPIA	Heavy siltation	Heavy siltation	Heavy siltation	Heavy siltation
56	BADURGACHA	Erosion	Erosion	Equilibrium	Equilibrium
57	MANGA	Erosion	Slow siltation		Equilibrium
58	JHAPJH-MANGA	Heavy erosion	Erosion	Erosion	Equilibrium
59	CHUNKURI	Equilibrium	Equilibrium		Equilibrium
60	DHAKI	Erosion	Erosion		Equilibrium
61	SUTARKHALI	Equilibrium	Slow siltation		Equilibrium
62	SUTARKHALI	Equilibrium	Slow siltation		Equilibrium
63	BHAIRAB U	Moderate siltation			Heavy siltation
64	BHAIRAB U	Slow siltation	Equilibrium		Moderate siltation
65	NABAGANGA-M	Equilibrium			Equilibrium

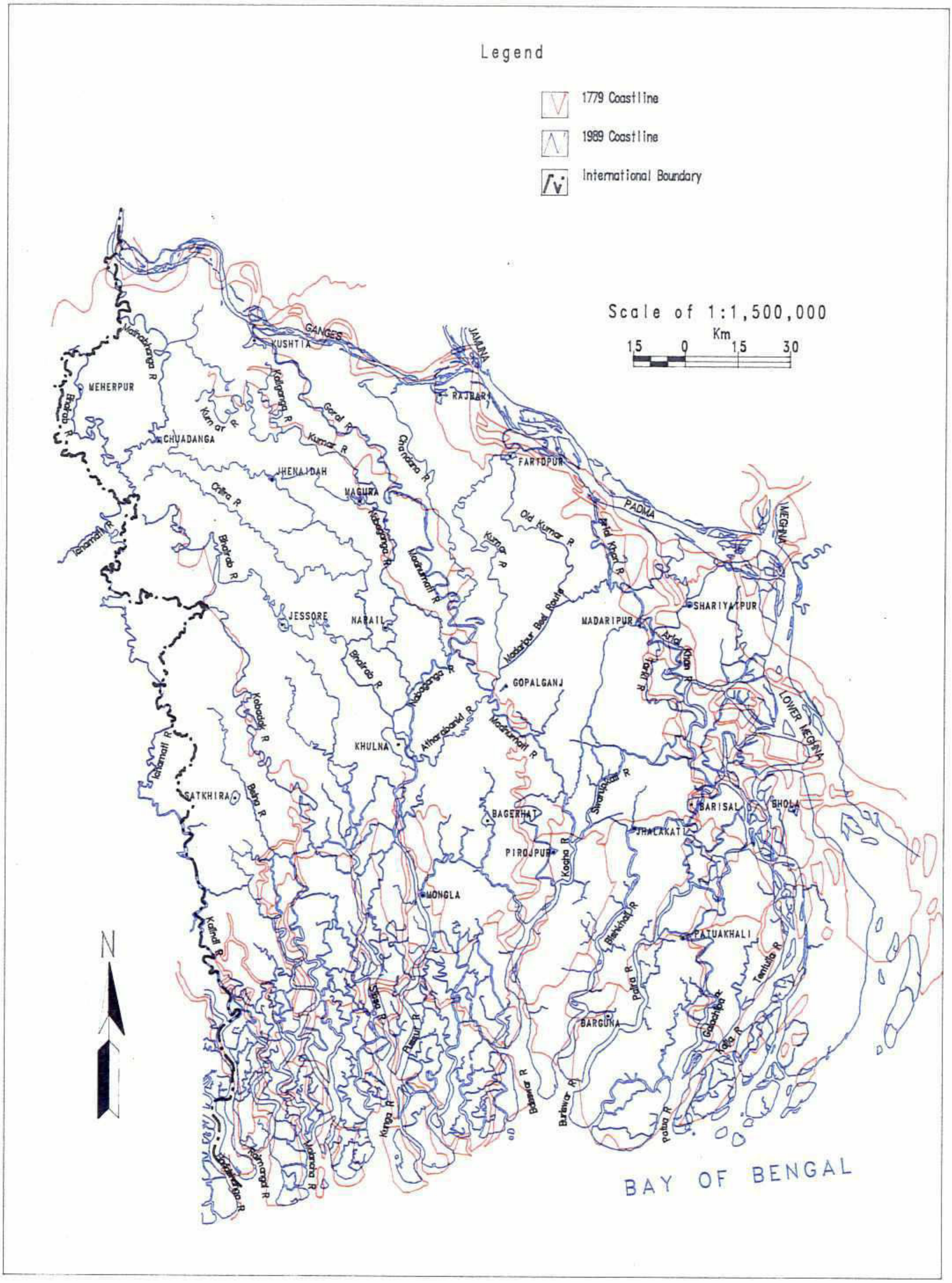
X-section No.	River Name	Regime Analysis	Sediment Model	X-section Comparison	Maps & spot Image Analysis
66	ATAI	Equilibrium			Equilibrium
67	NABAGANGA-M	Slow siltation	Low flow		Slow siltation
68	RUPSA	Erosion	Equilibrium		Equilibrium
69	KAZIBACHA	Equilibrium	Equilibrium	Equilibrium	Equilibrium
70	NALUANULLAH	Slow siltation			Equilibrium
71	PUSSUR	Slow siltation			Equilibrium
72	PUSSUR	Equilibrium	Equilibrium		Equilibrium
73	PUSSUR	Slow erosion	Equilibrium		Equilibrium
74	MONGLANULLA	Equilibrium	Slow siltation		Equilibrium
75	BISHNU	Slow siltation	Erosion		Slow siltation
76	DAUDKHALI	Slow siltation	Erosion		Slow siltation
77	M.G.CANAL	Slow siltation	Erosion		Equilibrium
78	GASHIAKHALI	Slow siltation	Erosion	Erosion	Equilibrium
79	ATHAROBANKI	Heavy siltation	Low flow	Equilibrium	Heavy siltation
80	ATHAROBANKI	Moderate siltation	Slow siltation	Equilibrium	Moderate siltation
81	BHAIRAB	Heavy siltation	Low flow		Heavy siltation
82	POYLAHARA	Heavy siltation	Heavy siltation	Slow siltation	Moderate siltation
83	BHAIRAB L	Slow siltation	Heavy siltation	Slow siltation	Moderate siltation
84	KUMAR	Moderate siltation			
85	MADHUMATI	Heavy siltation	Slow siltation	Slow siltation	Slow siltation
86	BALESWAR	Heavy siltation	Now flow	Heavy siltation	Heavy siltation
87	BALESWAR	Moderate siltation	Heavy siltation	Heavy siltation	Moderate siltation
88	BALESWAR	Slow siltation	Equilibrium	Equilibrium	Equilibrium
89	BALESWAR	Equilibrium	Equilibrium	Slow siltation	Equilibrium
90	KALIGANGA	Moderate siltation	Moderate siltation		Slow siltation
91	KOCHA	Erosion	Moderate siltation		Equilibrium
92	SHIKARPUR	Equilibrium			Slow siltation
93	UZIRPUR	Equilibrium			Equilibrium
94	SHANDHA	Equilibrium			Equilibrium
95	AMTALI	Equilibrium			Equilibrium
96	NAYABHANGANI	Equilibrium			Slow siltation
97	DHARMAGANJ	Slow siltation			Equilibrium
98	KALABADAR-1	Slow siltation			Equilibrium
99	KALABADAR-2	Equilibrium			Equilibrium
100	ILSHA				Equilibrium
101	RANGAMATIA	Slow siltation		Slow siltation	Slow siltation
102	KIRTONKHOLA	Slow siltation		Slow siltation	Equilibrium
103	KIRTONKHOLA	Equilibrium		Equilibrium	
104	KATAKHALI	Equilibrium			Slow siltation
105	BISHKHALI	Equilibrium		Equilibrium	Equilibrium
106	PANDAB-1	Slow siltation			Slow siltation
107	PANDAB-2	Erosion			
108	DHULIA	Equilibrium			Equilibrium
109	PAIRA	Equilibrium		Equilibrium	Equilibrium
110	BURISWAR	Equilibrium			Equilibrium
111	PATUAKHALI	Erosion			Equilibrium
112	LOHALIA	Slow siltation		Heavy siltation	Slow siltation
113	LOHALIA	Equilibrium			Equilibrium
114	SWARUPKATI	Erosion			Equilibrium

7.5 Planform Changes

The changes in rivers of the coastal area are shown in Figures 7.7 for 1779 to 1989. A comparison of 1973 and 1989 from satellite imagery showed little change to the rivers.

The most notable aspect of the historic mapping is that the coastline of the Southwest region has barely moved indicating relative equilibrium between siltation, erosion, subsidence and changes in sea level.

Figure 7.7



Coastline Changes in 1779-1989

7.6 Current Condition of Rivers

The current condition of the rivers is shown graphically Figure 7.6 and the results of different methods in Table 7.6. The main points of the analysis nmay be summarised:

(i) Kobadak River

The Kobadak river is slowly deteriorating. Historical maps (1778) show the Kobadak connected via the U. Bhairab and Ichamati to the Ganges. The wide corridor near Morirchap reflects the past potential of the river. The present reduced fresh water flows come only from the local catchment area. Saline intrusion has increased but may now have stabilised. During dry season heavy siltation occurs and during the monsoon period siltation is reduced but not flushed out of the system.

(ii) Betna River

The Betna was a tributary of the Ichamati and Kobadak system but many of the past branches are now disconnected. The regime analysis indicates rapid siltation upstream and slow siltation in the lower reaches.

(iii) Lower Solmari River

The L. Solmari is a crucial river connecting the upper reaches of the Sibsa-Pussur system. Although slow siltation is indicated in the dry season the river can be considered as active or in equilibrium.

(iv) Pussur upstream of Mongla Port

The regime analysis clearly shows that the Pussur upstream of Mongla port is slowly silting. The siltation is acute in the dry period when the Pussur is dominated by tidal flows. The reason for siltation is a stagnation stretch of dampened flow created by the intersection of flows between the Sibsa and Pussur rivers.

(v) Other Rivers

The rivers Bishnu, M.G. Canal, Gashiakhali and Daudkhali are correctly shown as undergoing slow siltation but some of the channels in the Sundarban area do not appear to be correctly represented by the regime analysis.

7.7 Saline Intrusion

Salinity Conditions in the Bay of Bengal

During monsoon large amount of fresh water flows into the Bay, mainly through the Lower Meghna, rendering the water in the northern part of the Bay more or less brackish. Records on resulting salinity concentrations are available at a number of stations along the coast, but not much data are available on the salinities in the Bay. Two sets of salinity measurements in the Meghna estuary (the NE part of the Bay), one from the end of the dry season and one from the end of the wet season, by the Land Reclamation Project, are available, (see Figures 4.1.1 to 4.1.4 in Volume 2). After the wet season, water is fresh (salinity below 1 ppt) out to at least the 20 m contour of the Meghna estuary. Both in dry and wet season salinity is well mixed over the depth by the tidal movement and stratification is present.

In order to describe salinity over a larger part of the Bay, a simulation on salinity was performed using a two dimensional hydrodynamic model of the Bay. In this, typical discharges of fresh water from the rivers (as obtained from the one dimensional hydraulic modelling of the river System) was introduced in the Bay having a constant salinity of 33 ppt, and the resulting distribution of salinity was calculated taking into account dispersion and advection by the outflow and tidal movement derived from the hydrodynamic calculations of the model.

The calculations show that the salinity never reaches a steady state: during dry season the "plume" of fresh water decreases, but does not reach the level it would have reached if dry season flows continued for a longer time. Similarly, the distribution in wet season never reaches the state that would be reached if wet season flows persisted for a longer time. This means that the salinities in the Bay are governed by the total outflow of fresh water during wet and dry seasons, and not so much on the variation of outflows during each season. It also means that a change of total outflow into the Bay during a wet season will affect salinities during the following dry season and even the salinities in the following wet season.

7.8 Salinity Intrusion in Rivers

Isohalines of simulated salinities for dry and wet seasons (April and August 1991) are presented in Figures 7.8 and 7.9. The general pattern of simulated salinity intrusion in the study area matches well with reported measurements. It should be noted that the salinities simulated by the SWAM model at the south east corner of the South Central Region in the Meghna estuary are not representative. This is due to the fact that the more saline estuaries of Meghna on the eastern side (eg. Hatia, and Sandwip channels) are not included in the model. The salinities in the Tentulia, the Lower Meghna and its distributaries are affected by circulation of more saline waters from the eastern part of the Meghna estuary. The isohalines in this area have been drawn correlating the simulated results of GM-SALT [see Volume 2]. The low salinities in the South Central Region are clearly due to the large freshwater supplies from the Padma and the Lower Meghna rivers through the Arial Khan system in the northern part and through the numerous distributaries in the eastern part of the region.

High salinities in the southwest corner and along the Pussur-Sibsa system of the area are associated with the decreasing upstream freshwater flow as well as silting of the major channels. It is clear that any measure to be taken to alleviate the salinity problem in this area should consider augmenting the freshwater inflow during the dry season to the upper reaches of the Pussur-Sibsa system, specifically increasing the flow significantly near Khulna. Further details on salinity intrusion in the South west Region and the impacts of low flow augmentations are presented in Sections 6.1 and 6.2 of Volume 2.

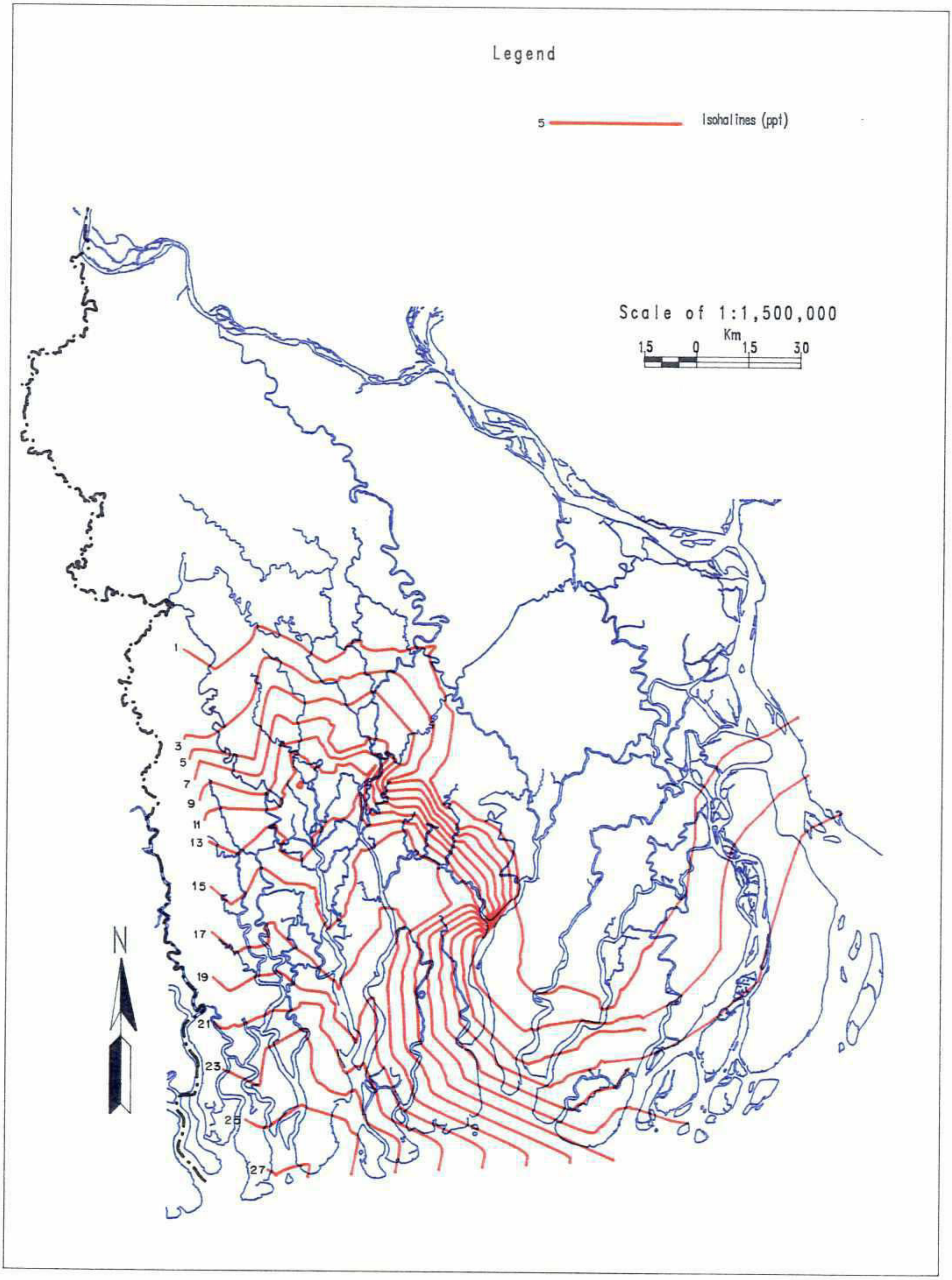
7.8.1 Historical Changes in Salinity Intrusion

Comparison of 1966 and 1991 isohaline for April shows that the 1 ppt boundary has moved northwards approximately 20 km in the Khulna Region. Modelling results discussed in Volume 2 show that augmentation of the present April Gorai flow by 100 cumec would be sufficient to return Khulna salinity to the 1966 levels. In the area to the east of Bagerhat the 1 ppt isohaline has moved eastwards probably as a consequence of dredging the M.G. canal connection in 1970. This cut provides a pathway for salt to migrate from the Pussur to Baleswar with potentially adverse effects on the fresh water dominated South Central Region.

7.9 Sea Level Rise and Land Settlement

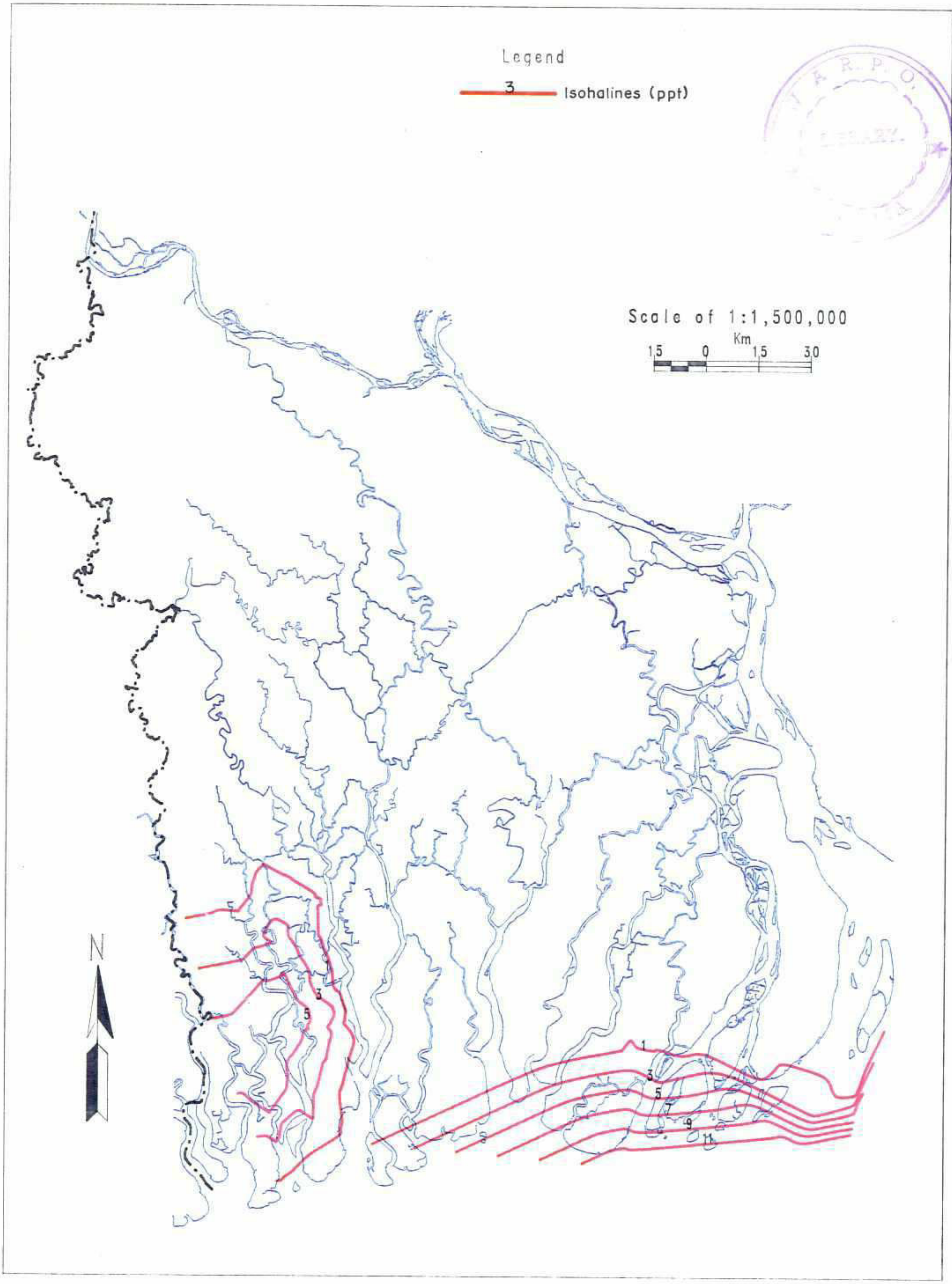
Morphologically it is apparent that where the tide is allowed to spill over the land, the changes due to sea level change, subsidence etc seem to be made up by accretion. Now

Figure 7.8



Simulated Dry Season Salinity (ppt)

Figure 7.9



Simulated Wet Season Salinity(ppt)

that much of the area is embanked under the CEP thus spilling is not possible and changes in sea level is of greater concern.

The Region will be affected by the combined impact of future sea level rises and land settlement. As discussed in Section 2 the rate of settlement indicated in the Khulna area in between 1mm and 5mm annually with rates of between 0.75mm and 1.4mm annually in the Sundarbans. The combined effects of sea-level rise (1992 values) and land subsidence (at Khulna) is given in Table 7.7 using the latest estimates of the IPCC (1992) who have revised downwards the earlier estimates of sea level rise.

TABLE 7.7

Estimate of Sea Level Rise and Land Subsidence (Year 2050, 2100)

Year	2050			2100		
Estimate	High	Best	Low	High	Best	Low
Absolute Sea Level Rise (cm)	43	23	7	90	48	17
Subsidence (cm)	29	17	6	54	32	11
Relative Sea Level (cm)	72	40	13	144	80	28

A simplified simulation of the sea level rise scenario has been carried out for preliminary impact analysis. A general increase in the sea level of 35 cm has been assumed and incorporated in the coastal water level boundaries. The present channel geometry has been used for this case also.

The impact of the assumed sea level rise on flooding has been assessed by simulating the increased flooding during the peak flood time of August - September. Also, since a major part of the study area is tide affected, the increased flooding due to high tide under the sea level rise scenario is assessed during the dry season, ie. the month of April.

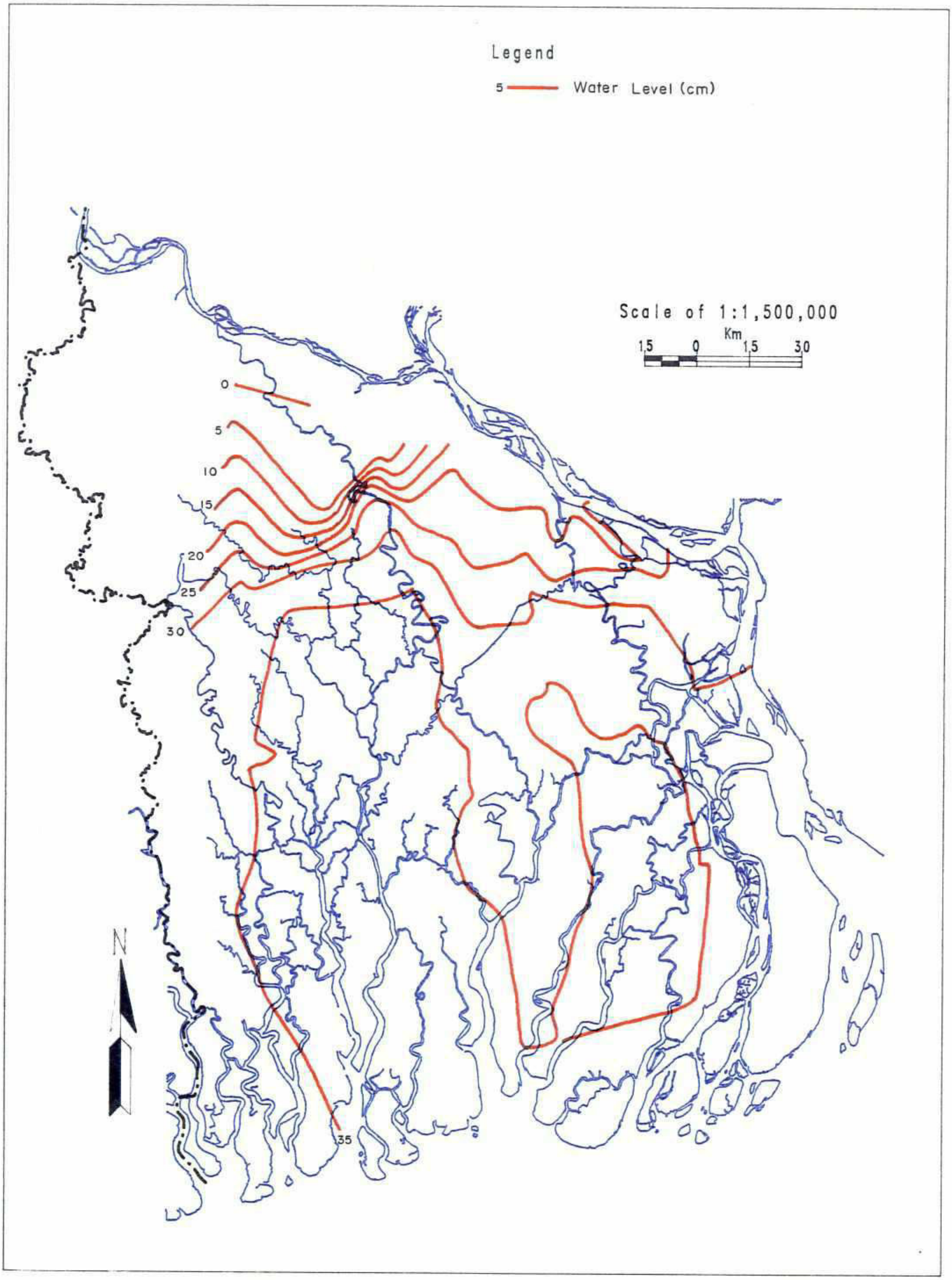
The extent of the impact of sea level rise in study area as a whole is presented in Figures 7.10 and 7.11, which show the contours of increase in water level in April and August, respectively. During the dry season, the impact on high water level is seen to extend far upstream along the Gorai - Madhumati river as well as in the South Central Region. More than two thirds of the area will experience a 30 cm increase in water level during a high tide if the sea level will rise by 35 cm. The impact during the flood time is less extensive as can be seen in Figure 7.11.

Simulation of the maximum salinity in April show little change to the saline front for a sea level rise of 35 cm (Figure 7.12).

7.10 Morphological Changes in Tidal Rivers

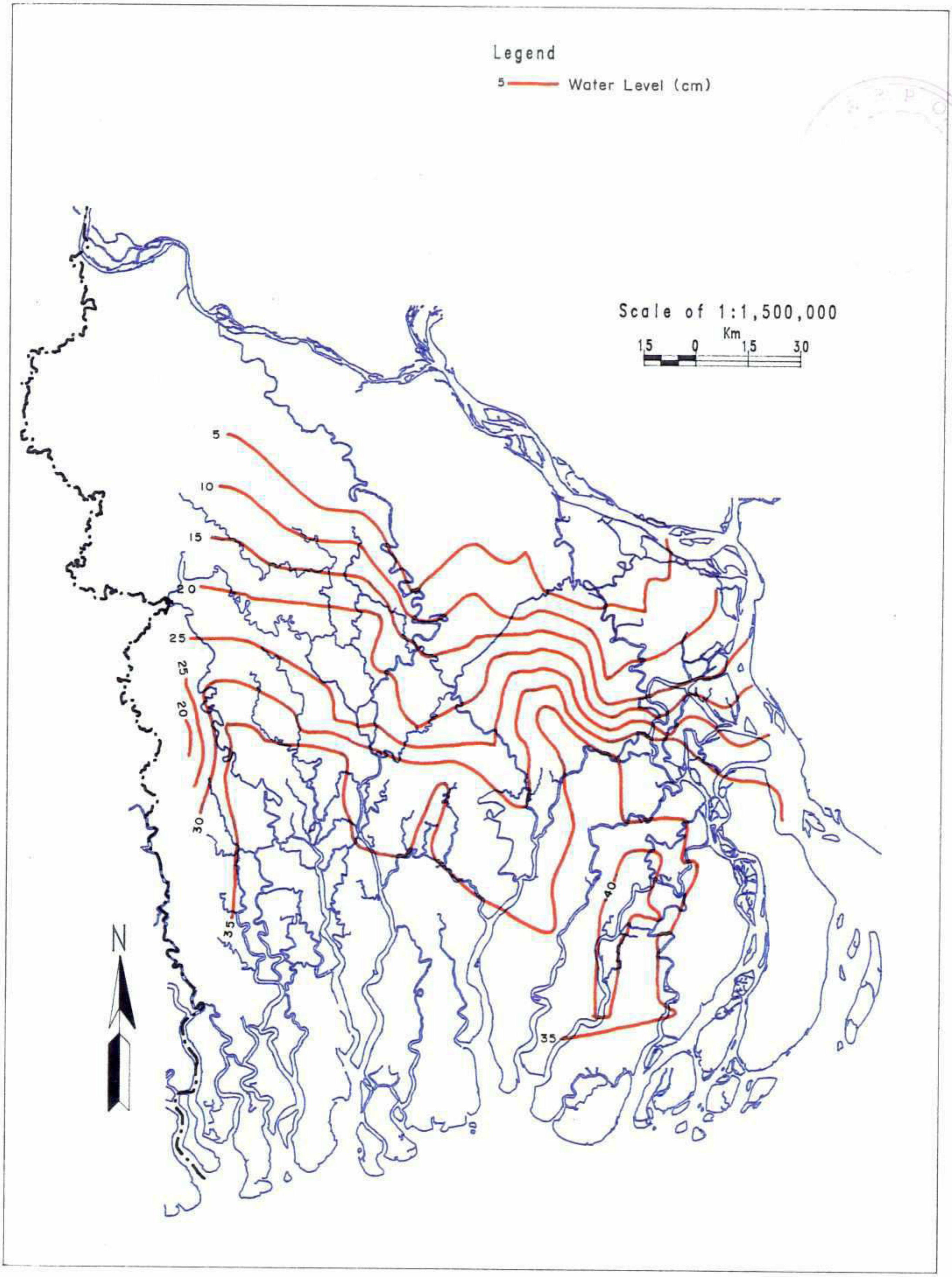
The changes in the rivers observed and described above indicate that the region is in the process of continuing morphological change. Rivers are for the most part silting up, some only slowly as would be consistent with the general trend of eastward migration of the delta, but others particularly the smaller rivers seem to have silted up at an alarming rate. The impact of these changes is to make drainage of low lying lands progressively more difficult. The consequences of this are studied further in Volume 4 Coastal Studies and a regional strategy for improving the situation is given. If no action is taken then the deterioration of the rivers will continue until a new equilibrium is reached taking account of the reduced tidal spills. This implies further deterioration of the channels identified as silting including slow deterioration of the Pussur even.

Figure 7.10



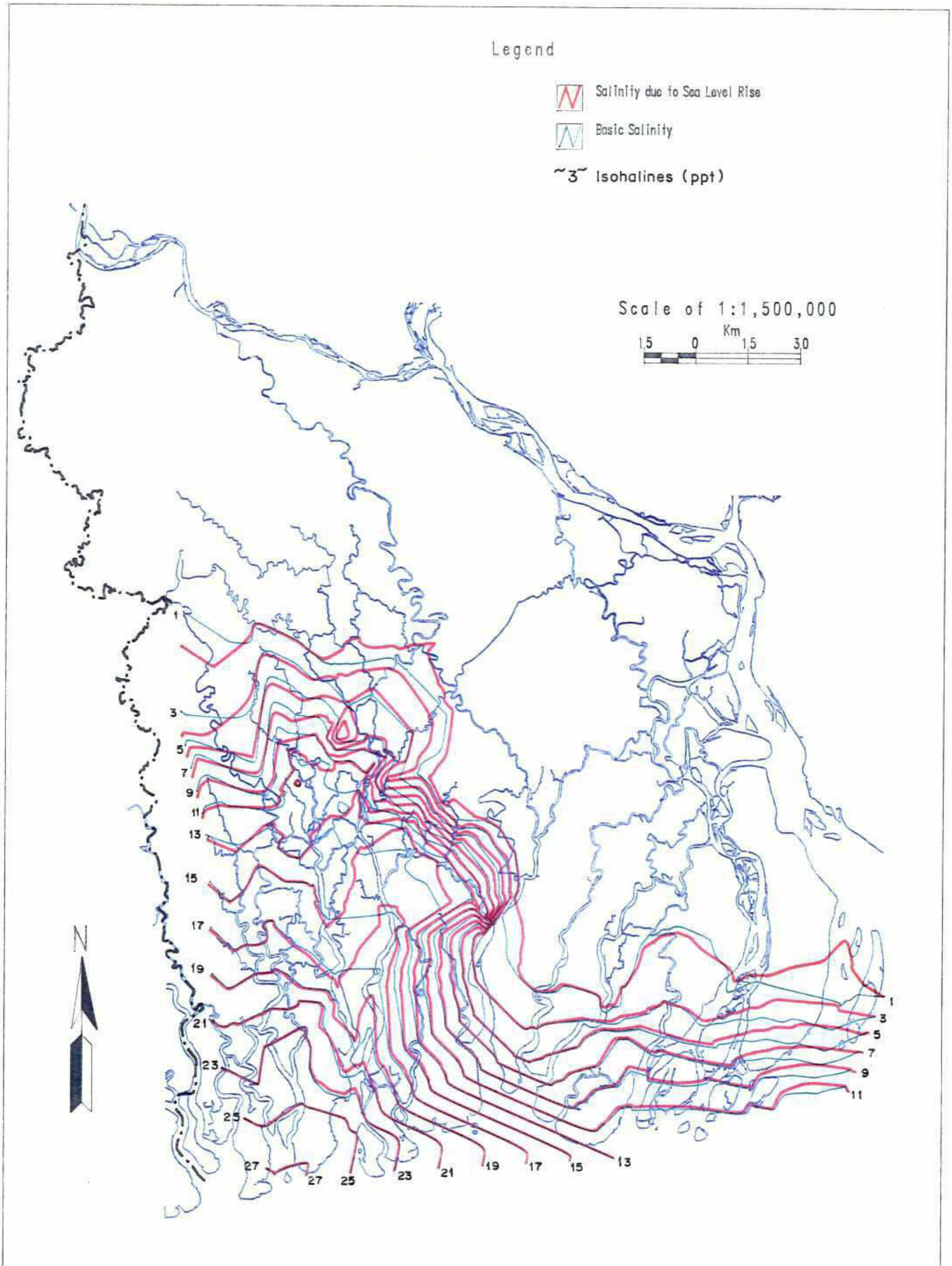
Increase in High Water Level due to 35 cm Sea Level Rise (April)

Figure 7.11



Increase in High Water Level due to 35 cm Sea Level Rise (August)

Figure 7.12



Impact of 35 cm Sea Level Rise on Salinity Intrusion

8 COASTAL STUDIES

8.1 Coastline Changes

As discussed previously the coastline as shown on historic mapping from 1779 to the present day shows very little change in the western part and accretion around the Meghna estuary. Further examination of navigation charts for 1879 and 1985 give further information on sedimentation and erosion.

Between 1879 and the present day the coast line in the western zone is more or less stable with an erosion of 1-2 km where as the central part indicates gradual migration of delta towards south west. The erosion in the western part is due to the less upstream flow and strong flood tidal movement. The changes in the coastal belt are very complicated and complex. The comparison of Chart data for the years 1879 and the Chart data published in 1985 give some impression about the changes in the Bay of Bengal. The changes usually taken place between the shore line and the 10 metre contour line. Between Zulfiquar and Haringhata channel, the 5m contour line is more or less stable. The entrances from bay to Tentulia and Shabazpur channel were deep in the order of 6-9 meters. The 5 metre contour was showing as if the extension of the Bhola and other polders and in between, the channels were defined and deep. The recent chart map indicates the filling of these channels and the 5 metre contour extended uniformly in the coast from the Shabazpur channel up to Bhangra river entrances without showing any deep entrances. The entrance of Baleswar and Harianghata were shallow and did not change considerably.

The channels between Zulfiquar, Malancha and Raimangal were deep and these are still deep. The 5 metre contour line did not change over 100 years. The 10 metre contour line just follows the old contour line in the study region with little progress toward the bay in the western region. It can be concluded that sediment transport through Lower Meghna is partly utilised for filling the deep holes and channels in the coastal belt of the study region up to approximately 10 metre contour and a considerable amount is carried towards the Swatch of No Ground into the deep sea. The deep channels in the western part indicate that the sediment which is coming from Meghna is not significantly transported to this area. The islands along Tentulia and Shahbazpur channels are eroding at the eastern bank and silting in the western bank which indicates the island development towards the western direction.

8.2 Sediment Movement

Fine sediment and silt is transported by tidal currents into the western area. It is probable that the sediment originates from the Meghna discharge during the wet season and is carried westwards by near shore currents created by the NE monsoon in the period July to November. Coarse sediment and sand is carried into the Area by the freshwater rivers.

8.3 Waves and Cyclones

Cyclones originating in the Bay of Bengal can cause storm surges which have a devastating impact on the coastal region. Although the predominant passage of cyclones is to the east of the Meghna the Area coastal boundary has suffered from storm surge attack in the past. The main areas of vulnerability are the sea facing coastal embankment areas in the south-central and the lands adjacent to the main rivers. The Sundarbans forest dampens the impact of surges in the south west but surges have propagated up the main rivers. A surge value of 2.8 m above normal tide levels was recorded at Mongla in 1988. The measures required for protection against cyclones have been studied under the Cyclone Protection Project -II (FAP 7) and are therefore not considered further in this study.

202

In addition to storm surges, storm waves impact on the coast. Where there is no protection from storms by Sundarbans Forest, sea facing coastal embankments are generally set back from the coast and waves break before reaching the embankment. However the effect of sea level rises due to surges or global warming may allow waves to propagate as far as the embankment. Because embankments are normally unprotected they may soon be eroded by wave action. In the absence of long term measured records the FAP-7 study has derived wave heights for offshore and near shore conditions. The offshore waves are generated by travelling depressions and storms in the Bay of Bengal and the near shore waves are the result of offshore waves shoaling and breaking as they approach the shore over a 1:200 sea bed slope. The results of the study are presented in Table 8.1 and 8.2.

TABLE 8.1

Offshore Significant Wave Heights and Wave Periods

Return Period (Years)	2.5	5	10	20	50	100
Offshore Significant Wave Height (m)	6.9	7.6	8.2	8.8	9.6	10.2
Offshore Significant Wave Period (s)	1.1	11.7	12.2	12.5	13.1	13.6

TABLE 8.2

Approximate Nearshore Significant Wave Heights

Water Depth (m)	1.0	2.0	3.0	4.0	5.0	6.0
Nearshore Significant Wave Height (m)	0.8	1.50	2.10	2.70	3.3	3.6
Nearshore Significant Wave Period (s)	7	8	8.5	9	9	9

The morphological impact of such storms is connected with the redistribution of sediments recently deposited. The moribund delta of the south west region is protected from storms by the dense growth of the Sundarbans vegetation which helps to prevent erosion. The South Central coastline which does not have the same protection is fortunately in a zone of accretion and therefore there is rarely any overall retreat of the coastline.

8.4 Currents

Currents in the northern part of the Bay of Bengal comprise ocean currents which vary seasonally and tidal currents which vary daily.

The ocean currents are largely generated by the monsoons. During the period January to March the ocean currents are generated by the SW monsoon and flow clockwise with the near shore current running eastwards at approximately 0.25 knots. During the period July to November the currents are generated by the NE monsoon and flow anticlockwise with the nearshore currents running westwards at 0.5 to 0.75 knots. This is also the period when sediment discharge from the Meghna is greatest. It is likely that this current carries material from the Meghna to the entrances of the tidal rivers to the west. The south-westerly direction of sedimentation on the island of Bhola would support this concept.

Tidal currents off the mouth of the Pussur River are predominantly north-south. The values quoted on Admiralty Chart No. 859 for a point 36 km south of Hiron Point, are given in Table 8.3.

TABLE 8.3

Tidal Currents at Hiron Point

Time relative to high water at Chittagong (hours)	Direction of current (degree N.)	Current (knots)	
		Spring Tide	Neap Tide
-6	343	1.5	0.6
-5	349	1.6	0.6
-4	359	1.5	0.6
-3	015	0.8	0.3
-2	102	0.5	0.2
-1	143	1.2	0.5
0	158	1.8	0.7
1	172	1.9	0.7
2	174	1.6	0.6
3	175	1.0	0.4
4	280	0.1	0.0
5	334	1.0	0.4
6	341	1.4	0.5

Tidal streams 36 km south of Hiron Point

9 INTERDEPENDENCE AND LINKAGES BETWEEN UPLAND RIVERS AND THE COASTAL AREAS

9.1 Regional and Boundary Rivers

The linkage between changes in the boundary rivers and impacts on the regional rivers has been clearly illustrated in preceding sections. The Ganges follows a wandering course and as the main Ganges channel moves away from a distributary such as the Chandana (or the Padma in the case of the Faridpur Kumar), then the channel declines. The Ganges at Hardinge Bridge periodically occupies a westerly embayment causing the Gorai to be disfavoured with the result that dry season flows are reduced. The Arial Khan mouth at Chowdhury Hat only developed in this century with the decline of the Bhubaneswar offtake at Faridpur and this is also disfavoured by the Padma periodically.

The tidal rivers of the South Central area are dependant on the difference in the time for the tide to travel up the deeper Lower Meghna channel which results in a significant net flow down the Jayanti, Hilsa and other spill rivers during the dry period. In geological terms it is inevitable that these channels will decline as the delta develops and siltation is readily apparent at the mouth of the Jayanti and in the Tentulia channel west of Bhola. The rate at which these rivers decline will also depend on the salinity and the supply of sediment. Higher salinity leads to a more rapid rate of settling of fine sediment.

Therefore if a river has a tendency to silt up, higher salinities will tend to give a more rapid rate of siltation depending on the sediment size and mineralogy.

9.2 Linkage between Fluvial and Tidal Rivers

There is no standard method for estimating the impact that changes in the fluvial river system will have on the estuarial rivers but observations recorded over a period of centuries allow certain conclusions to be drawn and predictions made. The available morphological models are at a relatively early stage of development and though useful insights can be gained through modelling, the models are a long way from representing all the processes that are important in the deltaic areas of Bangladesh. Assessing the important linkages between fluvial and tidal sediment transport is a particularly difficult aspect to model as most developments have concentrated on either unidirectional flows or tide dominated channels.

The processes identified as being important are shown in Table 9.1.

TABLE 9.1

Processes important in interaction between Fluvial and Tidal Rivers

Process	Linkage
Fresh Water Flow in Monsoon	Determines Dominant discharge and flushing out of salinity
Dominant Discharge of fresh water river	Determines size of fluvial channel and hence tidal volume in upper reach of tidal channel
Tidal Volume	Determines size of tidal channel
Sediment Load in Monsoon	Influence siltation rates
Salinity	Influences rate of settlement of fine silts and clays
Fresh Water Flow in Dry Season	Determines Position of saline front and influences scouring of bars in reaches on the boundary between tidal and fluvial flows. Influences nett flows of sediment and hence siltation rates.

The importance of the linkages are evident to people in the area, for example where a river such as the Nabaganga downstream of the Halifax-cut has a large freshwater flow during the monsoon a large channel is maintained and after the monsoon an active tidal channel allows early drainage of the land. Where the freshwater flow declines such as in the Nabaganga upstream of the Halifax cut, tidal action during the rest of the year quickly silts up the channel. The Atharabanki near Gopalganj and the Lower Madhumati near Bardia also seem to be following a similar trend. Siltation in the Barasia may also be expected following the reduction of flow into the Chandana and reduced spill from the Ganges and Padma.

The impacts of such changes are not universally detrimental as smaller rivers can be more controllable for the construction of bridges, bank protection etc, the silted bed offers cultivable land, and if the surrounding land is at a high elevation then land drainage is possible. Generally the secondary changes such as decreasing meander wavelength, increased thalweg levels etc can cause problems that are expensive to solve.

The Gorai, Madhumati, Nabaganga, Atai, Rupsa, Pussur line of flow which now dominates the Southwest region is a good example of the complexities of the regional rivers. The Pussur estuary upon which Mongla is located has long been one of the most active estuaries though it is only in recent years that it has received flow directly from the Gorai. Previously the Bhairab, Nabaganga and Chitra were the main sources of freshwater flow though these received spill from the Ganges and Madhumati. As these rivers declined the estuary was still maintained by significant tidal spill over low lands between Jessore and Khulna as well as in the Sundarbans. With the gradual reduction of the tidal spill areas and the more rapid reduction during the implementation of the Coastal Embankment Project, the connection of the estuary with the Madhumati developed to a great extent such that the Nabaganga now conveys most of the flow from the Gorai. The consequence of this has been to prevent serious deterioration of the Pussur, but the estuary and the associated tidal linking channels are now dependent on the continued vitality of the Gorai and Madhumati.

9.3 Movement of Sediment

The general trend for movement of sediments in the river systems shows that the bulk of the sand size sediment must be deposited in the area of the Meghna estuary where there has been a significant increase in land area. Fine silts and clays are widely dispersed into the Bay of Bengal during the monsoon season and may be returned landward by tidal action during the dry season. There is little data available to quantify the movement of fine sediments throughout the year and this will be an important outcome of the results of ongoing field measurements (FAP 24) and the cohesive model development proposed at SWMC.

9.4 Effect of Salinity

The fluvial flow of the Meghna in the monsoon season flushes saline water out of the estuary during the monsoon and causes a measureable reduction of salinity in the Bay of Bengal. It has long been established that where freshwater and saline water mix, an area of accretion occurs due to the nature of the density currents generated.

Clay sized particles carried in suspension in water normally carry an electrostatic charge. The particles therefore repel each other helping to remain in stable suspension. When the salinity increases, the electrolytic potential of the particles decreases differentially depending on the mineralogy with the result that some particles become mutually attractive and flocculation occurs. Flocculated particles have a settling velocity of possibly 200 times the unflocculated clay particle. The critical salinity at which flocculation increases rapidly is dependent on mineralogy but 2ppt for most minerals has a significant impact.

The estuaries of the Southwest Area may be taken as well mixed and salt wedge penetration is not found due to the relatively high level of tidal activity. Flocculation is suppressed in the moving flows and of particular relevance is that flocculated particles may be broken down and resuspeded when fresh water conditions return during the monsoon season. This reinforces the arguments for maintaining high fresh water flows in the Gorai during the monsoon which flush salinity and fine sediment from the system.

9.5 Delta Building Processes

Examining the historical changes in the landform of the Southwest Area it is clear that the continuing change in the active delta is significant even in engineering timescales. Interventions through engineering works can accelerate or retard changes but generally the tendency to morphological change will remain.

There is a delicate balance between land subsidence and accretion due to siltation as floods subside. The potential accretion in a fluvial area is small as only a relatively small amount of the silts and sands carried by the river spill over the banks. If this spill only occurs a limited number of times per year, the accretion rates may only just keep up with land subsidence. The many beel areas in Bangladesh testify to this slow rate of accretion and proposals for reclaiming land through fluvial flooding may be discounted on this basis. In the tidal areas, water may spill over the land two times per day giving a much greater potential for accretion. The increased tidal range in the Southwest Area due to empoldering can therefore be expected to increase siltation in unprotected areas.

In the Meghna estuary which is the active delta, accretion takes place through sediment deposition in the channel and movement of bars both of which are closely linked as found by FAP 1. The estuary is becoming longer and has changed from having multiple channels to be concentrated in one at the upper end of the Meghna and former large branches such as the Tentulia are becoming silted.

10 RIVER MAINTENANCE AND RIVER CHANNEL CHANGES

10.1 Management of Rivers

The long term maintenance and management of the river system covers not only the localised dredging currently carried out but also strategic management of the river system in a planned and coordinated manner. Over the next fifty years the prospect of sea level rise, land subsidence and the tendency for the Ganges to move eastward abandoning former distributories must be taken into account in formulating long term water management options. The system will also continue to adjust to recent developments such as construction of the Ganges left embankment, poldering and regulation of rivers such as the Chandana and Kumar. The development of the delta system can be modified as the intervention at the Halifax Cut demonstrates and the natural processes can be delayed by intervention such as dredging. The requirements for maintaining the vitality of the existing river system fall into several categories:

- Land Drainage
- Flood Control
- Salinity Control
- Navigation
- Urban Drainage
- Erosion Control
- Potable Water Supply and Public Health

These maintenance activities are implemented by a number of agencies and the objectives may be achieved in a variety of ways. The development of the delta system can also be expected to have positive effects such as the creation of new land and opportunities. Whilst the implementation of capital works under the regional water resources plan will consider maintenance costs in general the aim is to provide sustainable development without major maintenance wherever possible.

10.2 Different Programmes

The different programmes for maintenance of the river system may be divided into strategic capital works, long term development works and maintenance works. The development of schemes must consider the various impacts that can be expected and though prediction techniques are useful, uncertainties about the impacts of different measures are bound to remain in such a complex network of channels as is found in the Southwest Area. This indicates that prudence in designs and continuous monitoring during implementation of major works is needed and the works should be adapted if this is indicated.

Strategic Capital Works

The major regional rivers are critical to the development of the southern part of the study area and all should be carefully monitored and timely action taken as once a major spill river starts to silt up the decline accelerates after which piecemeal measures to keep open the mouth of the river are ineffective and a major programme of rehabilitation will be needed. The morphological studies have indicated that the Gorai may be in decline which would have a major impact on the downstream channels. In 1980 the dredging requirement for the Gorai was estimated as 3 million m^3, this was not taken up and the requirement is now estimated as 20 million m^3.

The concept of active river management (dredging and low cost measures as being studied under FAP 21/22) rather than construction of groynes and revetment should be followed as far as possible. For example rather than constructing groynes to protect existing infrastructure a cut off channel should be considered. There are obviously cases where this is not feasible but the principle of looking at the larger picture of upstream flow conditions, bars, historical developments etc should be followed to minimise the use of hard protective works which tend to have further adverse effects downstream.

Long Term Development Works

The major requirements for maintenance dredging tend to be concentrated in a short period at the end of the monsoon recession. For other parts of the year plant is under utilised. To combat long term effects such subsidence and slowly silting rivers such as the Kobadak etc, longer term development requirements should be addressed making use of the available plant and under-utilised human resources. This programme might include the accelerated creation of new land through active interventions in the Bhola island area and actions to raise land levels at risk from inundation elsewhere.

Routine Maintenance

The routine dredging and maintenance of river channels in the Southwest Area seems to be increasingly neglected despite the facilities being available as described in section 2.8. Maintenance of land drainage facilities as an interim measure until capital works can be implemented as part of the long term development of the polder areas as described in Section 5.5 will be considered as part of a phased implementation. Schemes that seem to come under this heading are:

- Gorai Rehabilitation
- Drainage improvement in polders of the Southwest Region

Rivers that need to be closely monitored are:

- Arial Khan
- Swarupkhati
- Bishkhali
- Pussur/Sibsa
- Lower Meghna

It is important to consider the wider effects of any scheme to ensure that the improvements in one area are not to the detriment of other areas. Tidal cubature in particular has been drastically reduced and any measures that further reduce cubature would need particularly careful examination. This would include cutting off smaller channels from tidal influence, which though insignificant alone, on a large scale the effect becomes apparent. These aspects are discussed in more detail in Volume 4. A policy of active river management is to be preferred to piecemeal construction of groynes or revetment.

10.3 Declining Rivers

The changing form of the rivers of the Southwest Area has been described at length elsewhere in this report and the case of the Gorai has been examined in detail. The most apparent symptom of decline is decreasing low flows and the decline in higher flows may not be apparent for some time. The importance of timely action where appropriate has been emphasised in the study.

10.4 Alternatives to hard structures

The pressure on engineers to control river erosion can be great but due to the high cost of the works required for bank protection there are relatively few places where such work is justified. Bank protection works at one position also often cause erosion at other sites and the total cost escalates.

The choices left to the engineer are therefore:

(a) Allow ersoion to continue
(b) Adopt temporary measures to slow down erosion rates and allow relocation of infrastructure.
(c) Adopt Active River management through dredging of pilot channels, Bandaling etc.

The active measures possible on the main rivers have been studied under FAP 21/22 though in most cases erosion and accretion of the Padma and Lower Meghna will continue with very little intervention possible. The planning for retirement of embankments should be an on-going activity with support from satellite imagery in a timely manner. The development of marginal embankments in areas of accretion which will not be eroded for a significant period could be coordinated at the same time.

The more active meandering rivers such as the Arial Khan, the lower reach of the Gorai-Madhumati etc, are most active when morphological changes are taking place, the source of the change should be studied and active measures such as realignment of bends and the approach to erosion sites should be attempted. In general the construction of bank protection by mattresses and blockwork is to be preferred to construction of T-head groynes.

11 BURNING ISSUES AND PROJECT IMPACTS ON REGIONAL MORPHOLOGY

11.1 Gorai Augmentation

The decline of the Gorai has been hastened by upstream withdrawal of water particularly at Farakka. Although the Gorai Augmentation project has been principally concerned with improving conditions for dry season flows, improvement of the whole river will be achieved at the same time preventing a terminal decline which is otherwise likely within the next fifty years.

Extensive excavation and dredging will be used to restore the bed levels in the upper reach to those appararent previously. Morphologically positioned training works in the upper reach are also proposed and these attempt to use the natural processes inherent in meandering to improve the low flow channel.

Building a control structure at the mouth of the Gorai will reduce the sediment input to the river as well as reducing the sediment transporting capacity. The two should broadly be in balance though the siting of the intakes will be critical in ensuring that greater sediment concentrations are not passed into the Gorai than pass at present. It is recommended that gates are opened such that there is no significant change in the dominant flow and hence channel form.

The loop cutoff at Kamarkhali that has been considered would be beneficial to the long term condition of the river and though not proposed at present, it could be reconsidered in the future if monitoring of the Gorai indicates that it would be feasible.

Operation of a control weir in the Madhumati at Mohamadpur should ensure that the recession flows are able to scour out the crossing points between bends and thus the pond level should initially be allowed to fall before gates are closed to maintain levels for diversion.

The operation of the intake control structure should be studied further at feasibility stage to consider extending the recession curve of flow by closing gates and reducing flow earlier than in the Ganges.

The impact of controlling the Gorai on other rivers such as the Ganges and Padma should be small as the dominant annual floods will be unaffected by operation of the structure and for extreme events the Ganges is insensitive. The change in flow would be of the order of 5000 m^3/s in 87000 m^3/s for 1 in 100 year flood which would probably result in some additional scouring of the Ganges bed but this would quickly recover during subsequent years. The impact on the Padma would be less. It is relevant to note that the Ganges embankments on both sides have not as yet produced a detectable change in the river.

Without intervention at the Gorai mouth it can be expected that the river will decline at an accelerating rate as the sediment concentrations from the Ganges for a particular flow in the Gorai increase with the decline of the river and transporting capacity. Because of the size of the river and the large range of water level in the Ganges the decline will take place over a period of decades with the mouth eventually becoming cutoff and the river will become an inland drainage route.

11.2 Ganges Padma Embankments

The Ganges and Padma embankments are largely in place and their completion is recommended under FAP 4. This recommendation is made after engineering studies using a detailed survey of the existing embankment. In light of the morphological studies a strategy for completing the embankments has been derived.

This includes completion of inlet structures and limited resectioning of the existing embankment from the Indian border to the Arial Khan. After this point on the Padma and on the Lower Meghna, the rivers are too large and the structures required too expensive to continue with a main embankment and controlled inlet structures. Protection is instead to be by progressive empoldering by constructing embankments as required out of the active corridor of the regional rivers. Recent developments of the Arial Khan have lead to a large increase in flow through the main Chowdhury Hat channel and a decline in the Dubaldia. The relative balance of flow between the various channels is likely to continue to change as the Padma continues to develop and therefore control of these channels should not be contemplated at this stage.

The Flood Policy Study suggested that the changes in flow regime due to embankments upstream may have a significant morphological impact on the Padma. FAP 25 studied the hydraulic effects of embankments on the main rivers and these results have been used to consider likely morphological impact in more detail. The FAP25 results are obtained using a fixed bed model of the major rivers with a limited representation of the complexities of spill occurrences particularly as regards the Padma right bank. Simulation results should therefore be interpreted with care for two reasons:

- The model may not actually be representing changes in spill patterns or magnitudes. Relatively crude spill channels have been used particularly regarding the Padma right bank.
- The BRTS studies show that though a fixed bed model may represent the initial response of the system to a flood event occurring immediately after an intervention, the channel will alter in the longer term and the response will differ. The changes can be expected to begin to have effect quickly (5-10 years) in the case of the Padma.
- Dominant discharge analysis and research has shown that the principal channel forming discharges correspond to frequent bank full discharge which could be expected to be largely unaffected by proposed interventions. There is very little data presented for such cases though from the data given small changes to the mean annual flood peak are apparent.

Some statistics are given for two cases, Scenario 3 and Scenario 5 which consider Jamuna embankments alone and final development respectively as shown in Figures 11.1 and 11.2.

The changes in peak water levels given are reproduced in Table 11.1.

TABLE 11.1

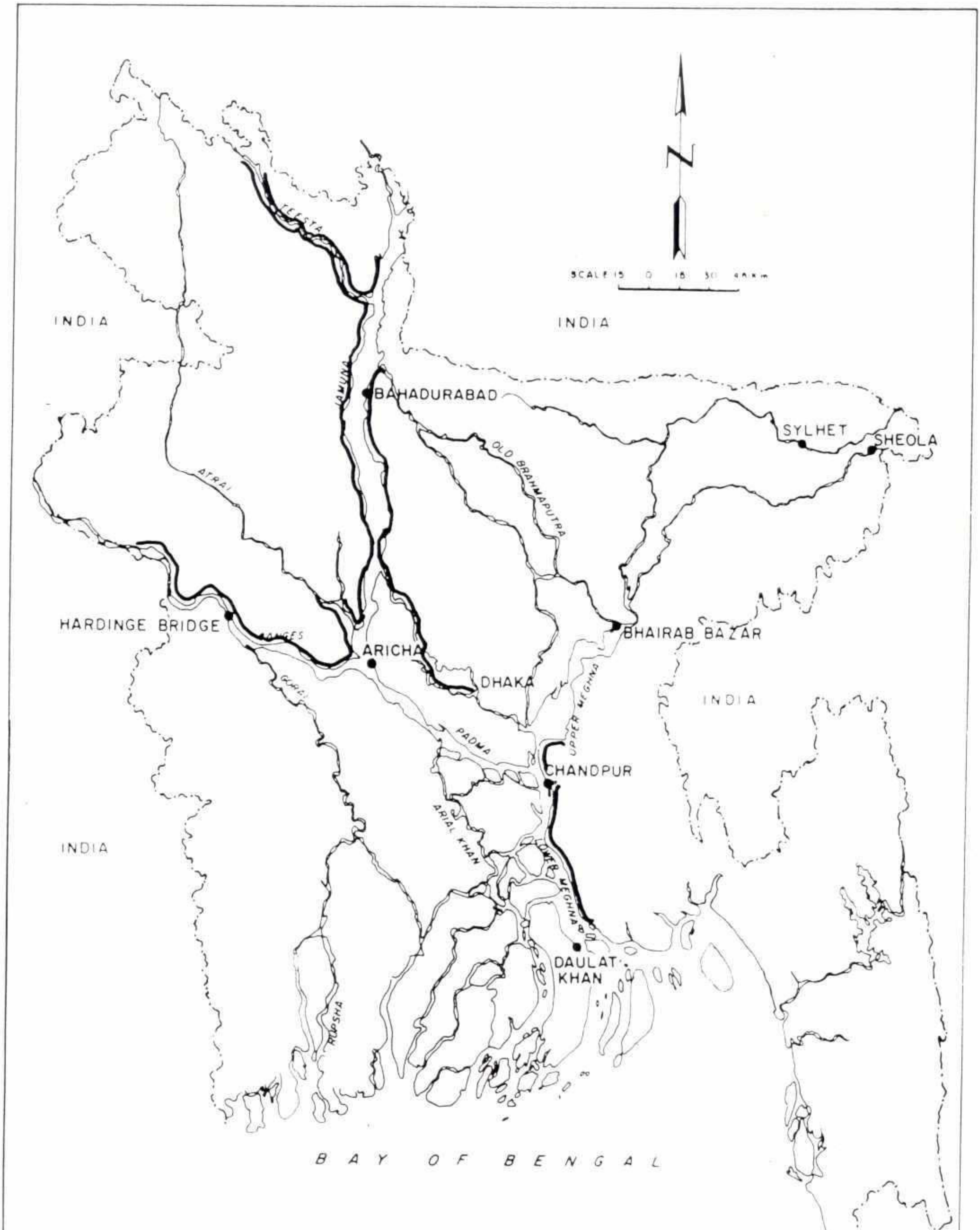
Changes in Peak Water Levels (Scenario 3 and 5)

Station	Water level change (m) Scenario 3			Scenario 5		
	86	87	88	86	87	88
Baruria	0.07	0.14	0.23	0.11	0.19	0.33
Mawa	0.04	0.08	0.17	0.10	0.17	0.34

These changes are smaller than those occurring on the Jamuna (up to 0.87m at Sirajganj) though greater than those predicted for the Ganges. The change in Peak discharges for 1988 flood are shown in Table 11.2.

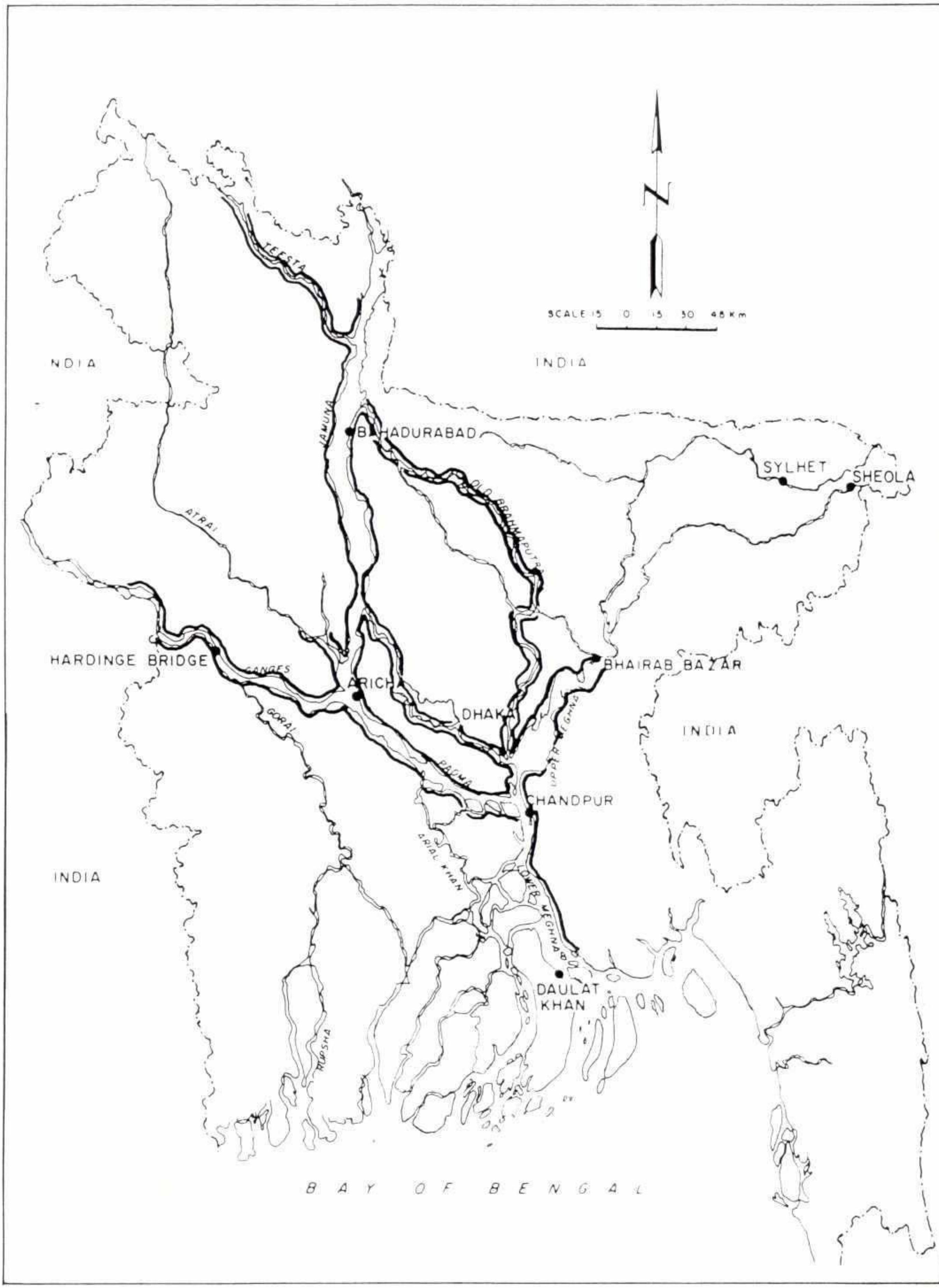
212

Figure 11.1



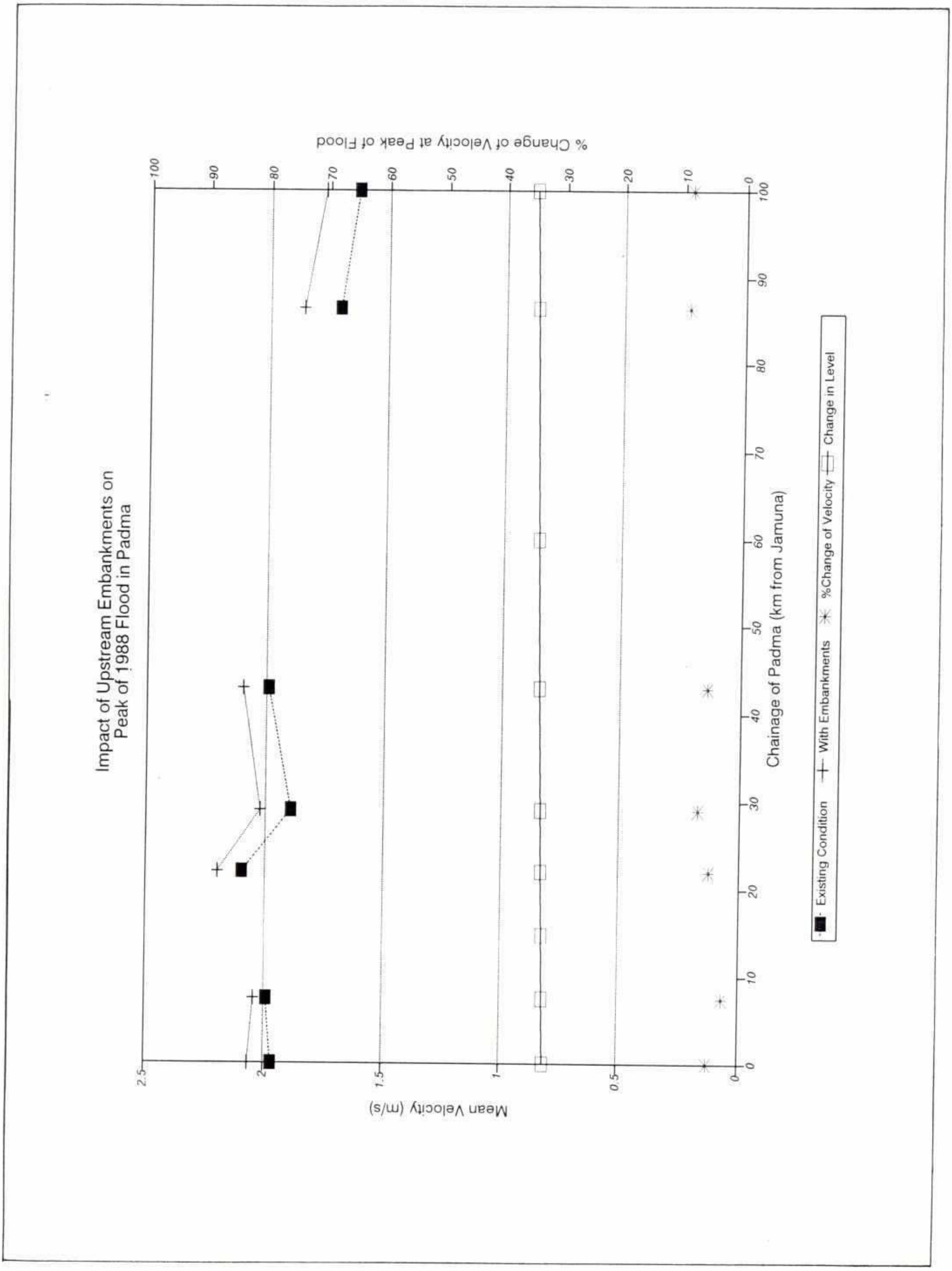
Scenario 3 FAP 25 Study

Figure 11.2



Scenario 5 FAP 25 Study

Figure 11.3



Impact of Upstream Embankments

TABLE 11.2

Changes in Peak Discharge in Scenario 3 and 5 for 1988 Flood

Station	Change in Peak Discharge (m^3/s)				
	1988 Base	Scenario 3		Scenario 5	
		Q	% increase	Q	% increase
Baruria	135300	147000	8.6	149000	10.1
Mawa	123200	132500	7.5	139800	13.5

Using the water levels and discharges given above the change in mean velocities in the Padma at the peak of the 1988 flood were calculated for Scenario 5 (full embanking). These are presented in Figure 11.3 which shows a general trend for decreasing mean velocity towards the Meghna confluence in both cases. For the fully embanked case the initial increase in velocity averages 5% and is greatest (up to 10%) at the confluence.

The average annual peak discharge for 25 years simulation increases by 6% at Baruria for scenario 3 the most extreme scenario. Data is not given by FAP25 for scenario 5. A morphological response to the marginally increased discharges and velocities can be expected in terms of channel enlargement. For a single thread channel such as the Padma W $Q^{0.6}$ where W = Total Width and Q = Dominant Flow. For the fully embanked case assuming a 10% increase in dominant discharge, the width may be expected to increase by approximately 5%. Considering the cross sections of the Padma such a slight increase is small compared to the natural variation in sections. The time scale for such changes may be gauged from those predicted by BRTS for the Jamuna which takes 50 to 100 years to adjust to constrictions though nearly one third of the total change occurs in the first five years.

It is therefore concluded that the initial concern about the morphology of the Padma is justified to the extent that the river is much younger and less predictable than the Ganges and therefore embankments are at greater risk of erosion. However FAP 4 find no reason to delay construction for reasons of possible morphological change due to construction of embankments upstream.

11.3 Coastal Embankment Interventions

The strategy behind the interventions proposed is:

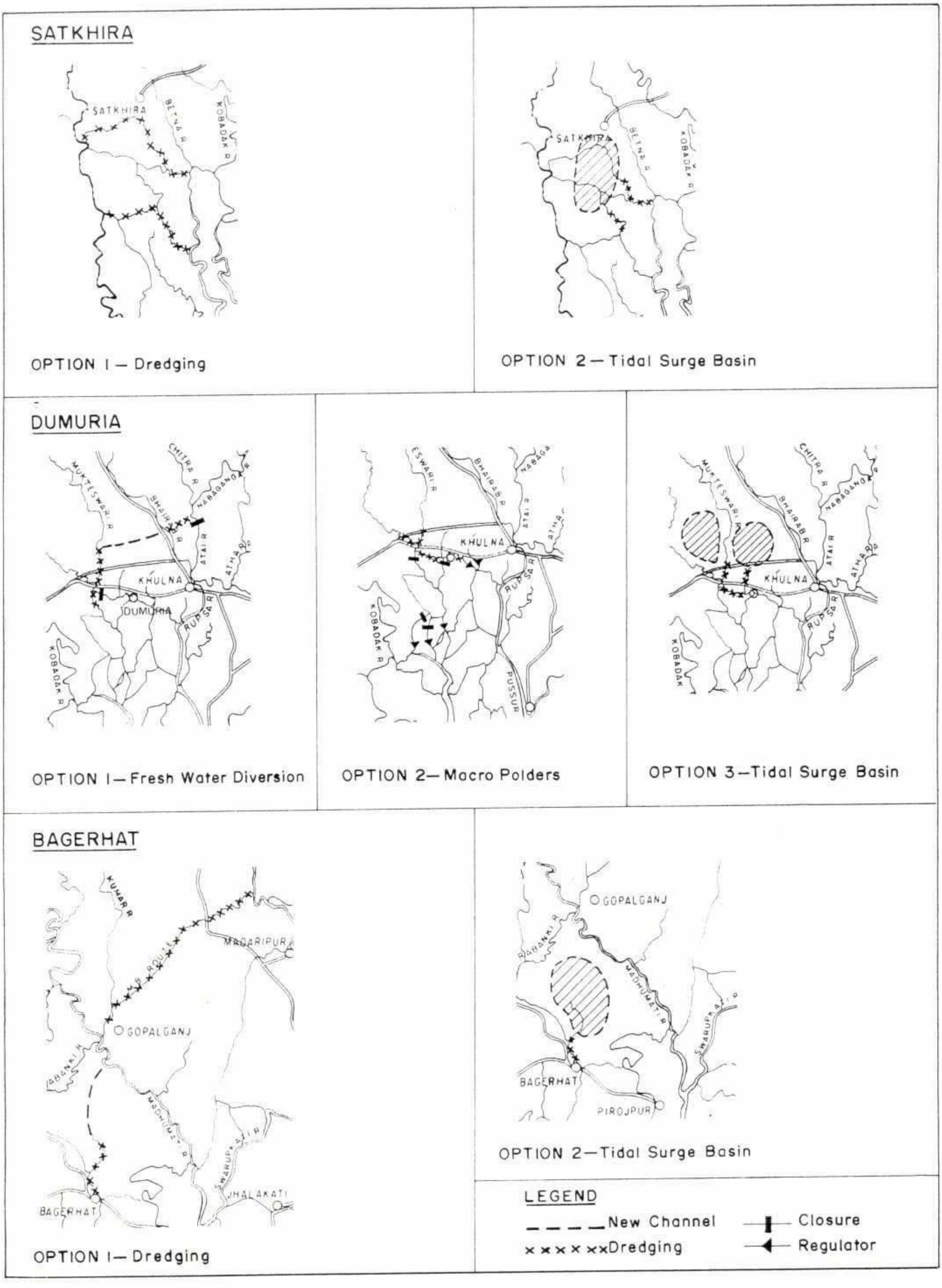
(a) To maintain tidal flows in the area

(b) All new works should drain to sustainable rivers

(c) To intervene to help create sustainable rivers through tidal interchange where necessary.

The interventions proposed are shown in Figure 11.4 and the full morphological assesment is given in Volume 4 Coastal Studies. The interventions have been tested using hydrodynamic modelling and regime analysis to predict impacts and derive schemes without major adverse effects away from the problem area under study.

Figure 11.4



Interventions Proposed in the C.E.P

The main conclusions of the coastal studies may be summarised as:

- Drainage congestion in the CEP area should be resolved as part of an overall long term coastal strategy
- The long term strategy is based on the premise that the coastal zone will remain as a tidal delta
- Sustainability of the tidal delta depends on sustained wet season flows in the Gorai and sustained non-saline dry season fresh water flows from the Arial Khan and Lower Meghna
- The near term intervention programme proposes that the present drainage congestion problems can be tackled by dredging at Satkhira, implementation of CERP II and amalgamating certain Polders at Khulna, dredging at Bagerhat and completion of unfinished polders in the Mongla, Bagerhat and Khulna area
- The performance of each intervention will require monitoring and subsequent design will depend on the nature of the monitoring results
- The proposed long term strategy involves a new approach to evaluating interventions in the coastal zone.

11.4 Ganges Barrage

Detailed morphological studies of the Ganges barrage will be required at feasibility stage and only an initial appraisal can be presented here. The proposal is to build a barrage with a clear opening of 1674m near Pangsa or between Pangsa and Rajbari. The final site selection must depend on site surveys and detailed layout studies.

The long term impact of the barrage on bed levels upstream will be greater than that of a bridge such as Hardinge Bridge or the proposed Jamuna Bridge as the gate sill will prevent scouring of the bed and thus greater headloss through the structure. This headloss will cause siltation upstream and some erosion downstream. However the headloss through the structure at the barrage is relatively low at dominant flow (of the order of 0.3m) and consequently the maximum upstream deposition will be of the same order. Due to confinement of the channel there would be an area of erosion downstream where the channel flow is constricted followed by an associated sandbar. Because the confluence with the Jamuna is close to the site the downstream effects are unlikely to be significant.

11.5 Lower Meghna Bank Protection Works (FAP 9B)

It is proposed in FAP 9B that the towns of Eklashpur, Chandpur, and Haimchar on the left bank of the Lower Meghna should be protected from erosion by bank protection works. The likely impact of such works on the right bank are not considered. Given the restricted width and the past movements of the Meghna it would seem to be likely that significant impacts could be expected resulting in erosion on the right bank and possibly affecting the intake channels to the South Central rivers. Any such works should take account of the impacts on the whole reach of the river.

11.6 Previous Interventions

Pre-1900 Works

Various early river works have been described in this report such as :

- The early embankment on the Kumar which was rebuilt around 1800
- Attempts to cut off the Kumar from the Mathabanga
- An unsuccesful attempt to dam the Kobadak and rejuvenate the Bhairab in 1794
- Cut off of the Kobadak and Bhairab from the Mathabanga
- Construction of the East Bengal Railway embankment from Goalundo to Calcutta including bridging the Gorai near Kushtia and the Chandana near Pangsa in late 1800s. Repair of embankment where breached between Calcutta and Jessore due to high spills from Ganges and connecting rivers. Extension of the line to Faridpur.

Pre-Independance Works

- Construction of Hardinge Bridge and guide banks and later remedial works. The bridge is sited at a natural constriction in the Ganges. There is a strong tendency for scouring at the constricted section and consequent sediment deposition downstream. The impact could be expected to be greatest after high flows such as in 1987 and 1988.
- Dredging of Madaripur Beel Route and construction of an embankment on the southern side of the route.
- Dredging of Halifax cut from Nabaganga to Madhumati near Bardia.
- Reclamation of land in coastal areas by clearance of the forest and building of dwarf bunds to reduce tidal spillage.

The impact of these works on the locality has been described in the relevant sections and they are mentioned again here only to illustrate the history of human interventions over the last two centuries, some of which were successful and others which have gone on to have important impacts to the present day.

Coastal Embankment Project

The Coastal Embankment Project was planned in the 1950s and involved an ambitious programme of construction of over 3700 Km of embankment with associated drainage sluices. The project benefited 860,000 Ha but resulted in approximately halving the tidal volume in the main rivers with the consequence that there are now a number of rivers that are silted or deteriorating. Increased tidal levels and higher channel bed levels have caused some low lying land to become undrainable without intervention.

Ganges Right Embankment

There are as yet no adverse morphological impacts of building embankments on both sides of the Ganges. Some slight degradation of the bed might have been expected but the analysis of rating curves at Hardinge Bridge does not show such an effect. The withdrawal of water at Farakka causing a faster recession curve after the monsoon and reduced dry season discharges has had a far stronger influence on the river.

The G-K project

The G-K irrigation system forms flood embankments along part of the Gorai right bank and flow is controlled in the Kumar, Kaliganga and Nabaganga. The upper reaches of these rivers have therefore become drainage channels that are part of the project. The project seems to have suffered from the natural morphological changes in the Ganges and the

Gorai but as abstractions are relatively small there has been no measurable impact on the main rivers. Erosion of the Kushtia main canal on the outside of a bend on the Gorai led to retirement of the canal embankment and recent bank protection works.

T-Head Groynes on the Gorai

Three T-Head groynes have been constructed at Kushtia, two at Kumarkhali and one at Khoksa. The large groynes at Kushtia seem to have been effective at protecting Kushtia though as discussed in Section 5.3 the impact on the flow in the channel has been unfavourable resulting in an unstable channel course without clear crossing points. The consequences of this have been higher bars to low flow and a poor approach to the Gorai rail bridge resulting in erosion and greater headloss. At Kumarkhali the two groynes have not been sufficient to stop erosion of the town but have only localised effects.

M-G Canal

The M-G canal linking the Pussur and Baleswar rivers established year round navigation from Mongla and seems to have been successful for navigation. The canal seems to have caused some decrease in flows through other routes linking the two estuaries which all show some siltation. The main concern is that the net flow from the Pussur to the Baleswar has increased the salinity in the eastern side of the link as the salinity of the Pussur is higher than that in the Baleswar.

12 FUTURE ACTIONS AND RECOMMENDATIONS

12.1 Overview

This study has used the existing data on landforms, fluvial rivers, tidal rivers and coastal morphology together with additional data collected in the field and acquired by remote sensing to produce a coherent and reasonably thorough overview of the area. The studies have covered the geologic background, historical evolution and current status of the Southwest area including the major Boundary Rivers, Regional Spill Rivers, Inland Rivers, Tidal rivers and Coastal Zone. Special emphasis has been placed on key locations and issues, including the condition of notable regional spill rivers such as the Gorai and the Arial Khan, the current status and implications of planned completion of the Ganges and Padma right embankments and the morphological aspects of drainage problems being encountered in the empoldered region.

However, the great complexity of the fluvial and coastal systems operating in the Southwest Area means that the overall level of knowledge and understanding attainable in an 18 month study cannot be entirely complete. Particularly, field observations of important processes and features are not available and could not be obtained within the Terms of Reference for this study. For example, improved data on sediment movement in both fluvial and tidal environments is an essential component to fully understanding and explaining channel form and evolution in the Southwest Area. While sediment transport data are to be collected under FAP-24 (River Surveys) for selected locations on rivers with uni-directional flow, there are no plans to measure sediment fluxes in any of the tidal rivers. Also, when assessing channel dynamics and process-response to either human intervention or environmental change, it would be very useful to be sure of the source of the sediment involved in channel changes. Questions remain concerning the roles of terrestrial and marine sediments in silting channels at and around the tidal limit and a lack of certainty over the relative importance of sediment sources and dynamics will continue to hamper the clear resolution of some management issues. There are no plans at present to undertake any sediment tracing or sourcing.

In this concluding section, the main findings of the morphological studies are summarised and recommendations for future work are listed.

12.2 Conclusions of the Morphological Studies

12.2.1 Regional Morphology

The Southwest Area is located in the geologically controlled Bengal Basin, which is a depositional of Eocene age. Major faults criss-cross the Area and there is seismic activity, although not to the extent experienced to the north. The Area is subsiding, rates being fastest in the east and southeast. Sedimentation over the last 54 million years has produced the World's largest alluvial fan, which is over 3,000km long and up to 18km thick. The portion of the alluvial fan above sea level constitutes the Ganges Delta, with an area of around 60,000 km^2.

The Southwest Area consists entirely of the active and moribund sections of the Ganges Delta. In the Southwest Region the Delta is moribund, having been abandoned by the Ganges as it has migrated eastwards during historic time. This portion of the Delta is believed to have been formed about 500 years ago. There is a shortage of freshwater flows, especially in the dry season and little deltaic accretion along the coast. Lack of freshwater and siltation in the lower courses of rivers in the South Central region may be partly responsible for ecological problems in the Sundarbans mangrove forest. In the South Central Region the Delta is presently active, with copius freshwater flows and continuing net growth through accretion along the Lower Meghna Estuary and in the coastal zone.

The Ganges and Padma Rivers form the major boundary rivers to the Southwest Area. These great waterways receive snowmelt and monsoon runoff from vast catchments of which the Southwest Area constitutes only a small fraction of the land area. These great boundary rivers have right bank distributary offtakes that feed regional rivers which are themselves large water courses. Notable regional spill rivers include the Matabhanga and Gorai-Madhumati in the Southwest Region and the Arial Khan and Tentulia in the South Central Region.

Historically, spill rivers are known to have finite life spans. After a period distributaries become disconnected from the parent stream, so that spill flow ceases and the river conveys only local rainfall. Disconnection is followed by a marked diminution of the channel through heavy siltation. Generally, the age of spill rivers increases from east to west across the area, so that old, long disconnected streams such as the Hisni are found close to the Indian Border, while younger, energetic spill rivers such as the Arial Khan are found to the east.

Local rainfall is drained via a complex network of inland rivers. The generally flat terrain makes it very difficult to define watersheds and drainage during the wet season is often poor. Low areas called beels collect surface run off and are water logged for long periods. Beels provide important wild life habitat.

Because of the low terrain, tidal influence extends well inland. Flood tides travel upstream at variable rates depending on the size and geometry of the channel. Differences between tidal rates leads to complex flow paths sedimentation and tidal pumping between rivers. Of particular importance are fresh water flows from the Lower Meghna driven into the South Central Region in this way during and following flood tides.

12.2.2 River Ganges

The Ganges has been following its present course along the northern boundary of the South West Area for several hundred years. Analysis of flow and sediment records at Hardinge Bridge indicates that it has a dominant discharge of about 38,000 cumecs. This corresponds to a high, in-bank flow which overtops braid and point bars, but does not inundate the flood plain. Expected "regime" dimensions at dominant flow are 4.3km width and 6.7m mean depth. These dimensions are similar to those observed from BWDB cross-sections.

The planform of the Ganges may be classified as wandering, with elements of both meandering and braiding patterns being evident. The river usually has one or two active channels which swing and bifurcate within the active river corridor with a periodicity of perhaps 40 to 50 years. Upstream of Hardinge Bridge a meandering pattern predominates, but downstream the river is more braided. There are several nodal points in the braid pattern where the width is relatively narrow. The planform is fixed at the Hardinge Bridge where training works have established a single channel for the last 80 years. Talbaria point on the southern edge of the active corridor just upstream of the Gorai offtake appears to be a nodal point and has experienced deep flow against it for some considerable time.

Specific gauge analysis of historical stage-discharge records does not show any systematic trend of aggradation or degradation over the last 60 years.

Hydrological analysis reveals clear and significant changes in the flow regime due to the operation of the Farakka Barrage. Dry season flows are reduced and the rate of recession at the end of the summer monsoon is accelerated. These changes have not materially altered the dominant flow, but have altered the sediment regime associated with lesser flows. These changes appear to be causing changes in bed and bar topography and the form of the low flow channel with negative impacts on spill channels, notably the Gorai.

Taking all of this evidence together, it may be concluded that the Ganges in this reach is broadly in a state of dynamic meta-stable equilibrium. On this basis it should be expected that the alignment of the present right embankment is secure, since it lies mainly to the south of the active corridor of the river. There is, however, little allowance for flood plain erosion at some locations and the situation should be monitored annually to allow time for embankment retirement when necessary. As the embankment is located outside the morphologically active corridor it should not have major impacts on channel form and process over engineering time scales.

12.2.3 River Padma

The Padma is a much younger river than the Ganges and was formed less than 200 years ago by the avulsion of the Brahmaputra (Jamuna) to form a junction with the Ganges near Rajbari. The dominant discharge is around 72,000 to 76,000 cumecs. Cross-sectional analysis indicates that dominant flow corresponds to bankfull flow, suggesting that the cross-sectional form is adjusted to the flow regime.

The planform displays elements of both meandering and braiding. In geomorphic terms it is "wandering". Large meander loops and braid embayments have in the past cut deeply into the flood plain on either side of the river, enlarging the width of the active morphological corridor as they do so. This may be happening again as the river develops from its current, surprisingly straight alignment. Such planform dynamics lead to offtake distributaries being favoured or abandoned with important implications for fresh water supply to the South Central region.

It appears that the active corridor is still adjusting to the avulsion of the Brahmaputra and this may continue for some years. However, the course of the Padma is constrained by outcrops of erosion resistant Chandina Alluvium in higher terraces both to the north and south of the river near Shariatpur. Hence, major avulsive shifts are not expected.

The practical implications are that great care must be taken over the positioning of embankments as the edge of the active corridor is more liable to attack than along the Ganges. The situation is further complicated by the existence of energetic and active offtake channels on the right bank which could not easily be controlled with structures. It is probably acceptable to place an embankment along the southern edge of the active corridor leaving gaps around the offtakes, but the margin of safety is less than along the Ganges.

Specific gauge analyses for Baruria and Mawa give some indications of a possible aggradational trend, which if real would have serious implications for the Southwest Area. However, the period of record (25 years) is too short for firm conclusions to be drawn. The analysis should be continued to keep this situation under review, but at the moment there is no clear evidence of progressive raising or lowering of the bed.

12.2.4 Lower Meghna

The Lower Meghna is younger still than the Padma having been formed when the Padma broke through a band of Chandina Alluvium to confluence with the Upper Meghna less than 200 years ago. The river is tidal, especially during the dry season and so dominant discharge analysis is less reliable than for a uni-directional flow. The river carries the combined sediment loads of the Ganges, Brahmaputra and Upper Meghna Rivers to the Bay of Bengal and is actively building the Gangetic Delta at this time. Island building and extension are on-going, although planform evolution also involves significant re-erosion. The estuary is subsiding, and this together with projected sea-level rise will tend to limit the rate of delta growth and the creation of new land.

A salient feature of the Lower Meghna is the large right angle bend just downstream of the Upper Meghna confluence. The outer (east) bank has experienced severe erosive attack in recent years that is on-going. This has led to bank protection works, especially at Chandpur. The impacts of bank stabilization (and also land reclamation along the left bank lower downstream) are not yet clear, but may well be significant for the South Central Region.

Large spill channels on the right bank bring significant amounts of water into the South Central Region. In the natural course of events these channels would be expected to diminish due to eastward migration of the Lower Meghna, but interventions on the left bank that are attempting to halt this migration could potentially lead to instability and unpredictable changes.

Given the youth and dynamism of the Lower Meghna, it would be very difficult to site a right embankment with any degree of confidence. Hence, on morphological grounds it is recommended that the construction of a Lower Meghna right embankment be delayed until the river matures morphologically.

T2.2.5 River Gorai

The channel dynamics of distributary channels are driven by the inputs of water and sediment from the parent river. These have been found to depend upon:

- Planform of the main boundary river;
- Shape of offtake mouth;
- hydrology of the boundary river and particularly the rate of recession at the end of the summer monsoon;
- channel planform and sinuosity of the distributary river;
- energy slope into the distributary river and particularly any backwater effects cause by poor alignment or constriction.

In the case of the Gorai there is strong evidence that the combined effect of these controls is to produce a cycle of growth and decline with a periodicity of roughly 50 years. The primary control is the position of the low flow channel in the Ganges adjacent to the offtake. Movement of this channel is constrained 15km upstream of the offtake by Hardinge Bridge and an apparent node or hard point at Talbaria Point, just upstream of the offtake. Although the position of the Ganges deep water channel is now somewhat fixed, its orientation still varies. Recently, the channel has swung away from the offtake, reducing the input of water to the Gorai. This situation is likely to persist or worsen for the next ten years at least, after which a more favourable approach alignment may develop.

However, there is also evidence of an underlying declining trend in the cyclical variation of the Gorai over the last 150 years that may lead to its complete abandonment as a Ganges distributary and conversion to an inland river in the near to medium future.

Currently, the Gorai has a dominant discharge of 4,250 cumecs. The flow regime has changed in the post-Farakka, period with a marked decreases in the effectiveness of both low and high flow in forming the channel since 1975. Dominant discharge is just less than bankfull stage in the upper course of the river, indicating cross-sectional adjustment of morphology, but further downstream dominant flow is an overbank event, suggesting that the channel is unstable. This finding is consistent with the results of flow and morphological modelling.

A specific gauge analysis for the Railway Bridge site shows a clear raising of flow levels for low discharges leading to a reduced energy slope and reduced sediment transport capacity. This trend is also evident but is less pronounced at Kamarkhali.

Long profiles confirm that the bed has been aggrading since at least 1963, especially in the mouth and the first 12 to 15km of the river. In the first 15km poor alignment, possibly aggravated by T-Head groynes at Kushtia have produced poorly defined crossings with high bars. In fact, very high crossing bars are also found at several points along the river and particularly at the Kamarhali bends. An analysis of planform spacing of bends and crossings indicates that the natural periodicity of the river calls for crossings at 2 to 2.5km intervals in low sinuosity reaches and 4 to 4.5km spacings in highly sinuous reaches. This is consistent with the observed stable meander wavelength of 9km (ie. twice the crossing spacing).

The planform of the upper course of the river has been remarkably stable in the last twenty years. The bends at Kamarkhali are a prominent feature for nearly 200 years. Their form and evolution strongly suggest a geologic or topographic control that is interfering with the natural progression of the meandering planform. In the lower course sinuosity has increased. A tortuous channel (lower reach sinuosity = 2.3) was identified by earlier researchers as being a sign of impending demise as a distributary river (Fergusson, 1863; Addams-Williams, 1918).

The mouth of the Gorai has become extremely wide and funnel-shaped. This development was described in detail by Addams-Williams (1918) as leading to either abandonment of the mouth and establishment of a new offtake, or permanent disconnection of the distributary from the boundary river. In the case of the Gorai the establishment of a new mouth is precluded by the Ganges right embankment.

The Gorai is vital to the natural ecosystem, water resources and commercial navigation of the Southwest Region because it flushes salt from the Pussar each year during the wet season and it maintains the channel size necessary to produce a sufficient tidal volume at the head of the Pussar-Sibsa system that prevents siltation and decline of the tidal rivers. Reductions in dry season flows are already impacting the Region and the Sundarbans are particularly at risk. If marked declines in wet seasons flows were to become a reality, the consequences in terms of salinity intrusion and morphological adjustment would be dire.

Continued decline of the Gorai can be expected unless there is intervention to restore the river and secure its future as a Ganges distributary.

12.2.6 Arial Khan

The Arial Khan is a strong and growing right bank distributary of the Padma. It has a dominant flow around 2,000 cumecs, ranking it second only to the Gorai as a regional river.

Specific gauge analysis at Chowdury Hat indicates a degradational trend, leading to channel enlargement and a high level of morphological activity.

The river is highly mobile, with rapidly evolving meander bends and frequent cut-offs producing an active meander belt. The river has three offtakes, which vary in importance, depending on planform changes in the Padma.

This high level of morphological activity precludes engineering structures at the mouth(s) of the Arial Khan. It is recommended that flood embankments be placed well back from the channel behind the edge of the active corridor as defined by the meander belt.

The Arial Khan is connected to the Gorai-Madhumati system via the Kumar River, Madaripur Beel Route and Atharabhanki River. While a transfer of fresh water to the dry Southwest Region along this route could be feasible the lack of topographic slope limits the amount of water that could be carried. Tidal pumping and control of the lower Madhumati by a weir would be necessary to develop this route.

12.2.7 Tidal Rivers

The condition of many of the Area's tidal rivers is a grave cause for concern. Morphological analyses support the findings of the hydro-dynamic and morphological models that many channels are suffering chronic siltation. External changes due to sea level rise may exacerbate the situation.

Intervention in the drainage system of the coastal zone is probably essential to protect the natural environment and allow sustainable development of existing water and land resources. This will centre on identifying sustainable watercourses for drainage purposes and cutting off other channels.

12.3 Recommendations

1. Continued study and monitoring of the Gorai-Madhumati is essential to better establish the process-form inter-relationships in this complex system. The river is of pivotal importance to the ecology, water resources, industry and commercial navigation of the South Central Region and any accelerating trend in its decline must be identified immediately if irreversible changes are to be avoided.

2. Studies of the Gorai performed by FAP-24 must be sufficient to allow a full and comprehensive understanding of the controls on river regime to be built up. In particular it is vital that the different roles of deep water channel alignment in the Ganges, condition at the offtake mouth and the form of the distributary channel downstream of the mouth be established. This requires, as a minimum, studies of:

   - Detailed examination of flow processes and channel forms in the entire fluvial system around the offtake at Kushtia.
   - The intensive study area must extend in the Ganges from the bend at Sara (upstream of Hardinge Bridge) to at least 10km downstream of Talbaria Point, and in the Gorai downstream at least as far as the Railway Bridge.
   - Less intensive studies should cover the entire Gorai-Madhumati system at least as far as Bardia and ideally, along the Nabaganga to Khulna.
   - Specific studies and monitoring programmes in the intensive area should include:

     Bed topography before, during and after the monsoon;
     Bed material size distributions and variations across and along the channels;
     Water levels and local slopes along the Ganges and into and along the Gorai;
     Flow fields and flow patterns by laser-doppler measurements ideally, or at least by float tracking;
     Sediment transport measurements using the best available and appropriate technology.

- Studies in the less intensive area should include geomorphic reconnaissance (as described earlier in this Volume), echo sounder profiling, bed and bank material sampling and water level recording along the distributary system.

While the amount of effort required to secure this data will be considerable, the importance of the Gorai to the South West Area makes it imperative that a detailed field study be performed.

3. The monitoring of cross-sections by BWDB should be extended to cover major regional rivers including those in the South Central Region. The monitoring needs to be accompanied by analysis and interpretation of results to document trends and types of channel change. Better position fixing of the sections using GPS or even Decca navigation systems is required.

4. Continued monitoring of the Padma is needed to determine the trends and patterns of planform developments that could threaten the right embankment and directly affect the distributary offtakes. For example, the Arial Khan is an important water course and supplier of fresh water and changes that impact on its stability have implications for large parts of the South Central Region. Also, any move by the river to re-occupy the right bank embayment at Faridpur could potentially improve prospects for using the Old Kumar for fresh water transfer into the Southwest Region. Early identification and confirmation of such a trend would allow time for plans to be made to take advantage of this situation.

5. Continued monitoring of the Lower Meghna is essential to keep a close watch on planform changes in response to bank protection and land reclamation on the left bank. The Meghna is highly dynamic and changes of flow alignment and position could have major impacts on right bank spill channels feeding fresh water into the South Central Region.

6. Sediment source identification and sediment tracing studies should be performed for selected key rivers in the coastal zone. Tried and tested techniques using sediment mineralogy, particle size analysis and the magnetic susceptibility of sediments could be used to resolve questions relating to the sources of sediments responsible for siltation and congested drainage. Armed with this information, the management approach recommended elsewhere in the FAP-4 Final Report could be further verified and, possibly, new and innovative approaches based on the full understanding of sediment pathways might be employed.

7. Further investigations of the impacts of river regulation on instream and riparian zone environments, sedimentary features and ecological habitats should be performed on the Ganges. It is important to document and quantify the river response to operation of the Farakka Barrage and other human impacts in a scientific manner in order to build up a thorough and defensible catalogue of real and measurable effects.

8. Where river training works are essential full account must be taken of upstream and downstream morphological impacts. Works must be designed to work in harmony with natural periodicities and harmonics in the channel form. For example, it is vital that the correct morphological spacing of pools and crossings be maintained or restored and that the alignment, geometry and length of bends mimic those of stable bends on the river in question. As a rule linear revetment is to be preferred to "T-Head" groyne for the protection of outer banks in bendways.

12.4 Predicting future Morphological Changes

The tools that can be used for predicting changes in the major rivers of Bangladesh have improved significantly over recent years with the development of numerical modelling, satellite imagery and GIS processing and research in river morphology. However the uncertainties are still high and a prudent practical approach is required. The predictions that have been made under FAP 4 include:

Future Conditions of Tidal Rivers to identify sustainable drainage paths.

Likely Planform Changes in the Ganges near to the Gorai mouth.

Modelling of the morphological changes following a cutoff of the Kamarkhali bend on the Gorai

Future Predictions of morphological impact of interventions proposed including Gorai Augmentation works, Interventions in the Poldered areas and predicting the impact of upstream embankments on the regime of the Padma.

Morphologically based predictions of maintenance dredging requirements for Gorai Augmentation.

Other predictors that should be developed during feasibility studies are:

> River Course predictors as developed for the Jamuna by FAP 1 for future embankments along the Arial Khan and Padma.
>
> Impact Studies for the Ganges Barrage
>
> Prediction of the effect of works on the left bank of the Meghna upon the South Central spill rivers and the right bank.

The impact of relatively small works can have a wide reaching impact particularly in areas close to the physical intervention. The development of models at the Surface Water Modelling Centre has been proven as a useful tool for planning purposes and continued development should be focussed towards aiding designers to predict impacts and formulate policy. Given the uncertainties regarding predicted impacts large scale interventions should be monitored closely and planning adapted accordingly. The development of a cohesive sediment transport model as proposed by SWMC should help to improve the understanding of sediment movement in the tidal areas and enable better predictions of the timescale of changes to be made.

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