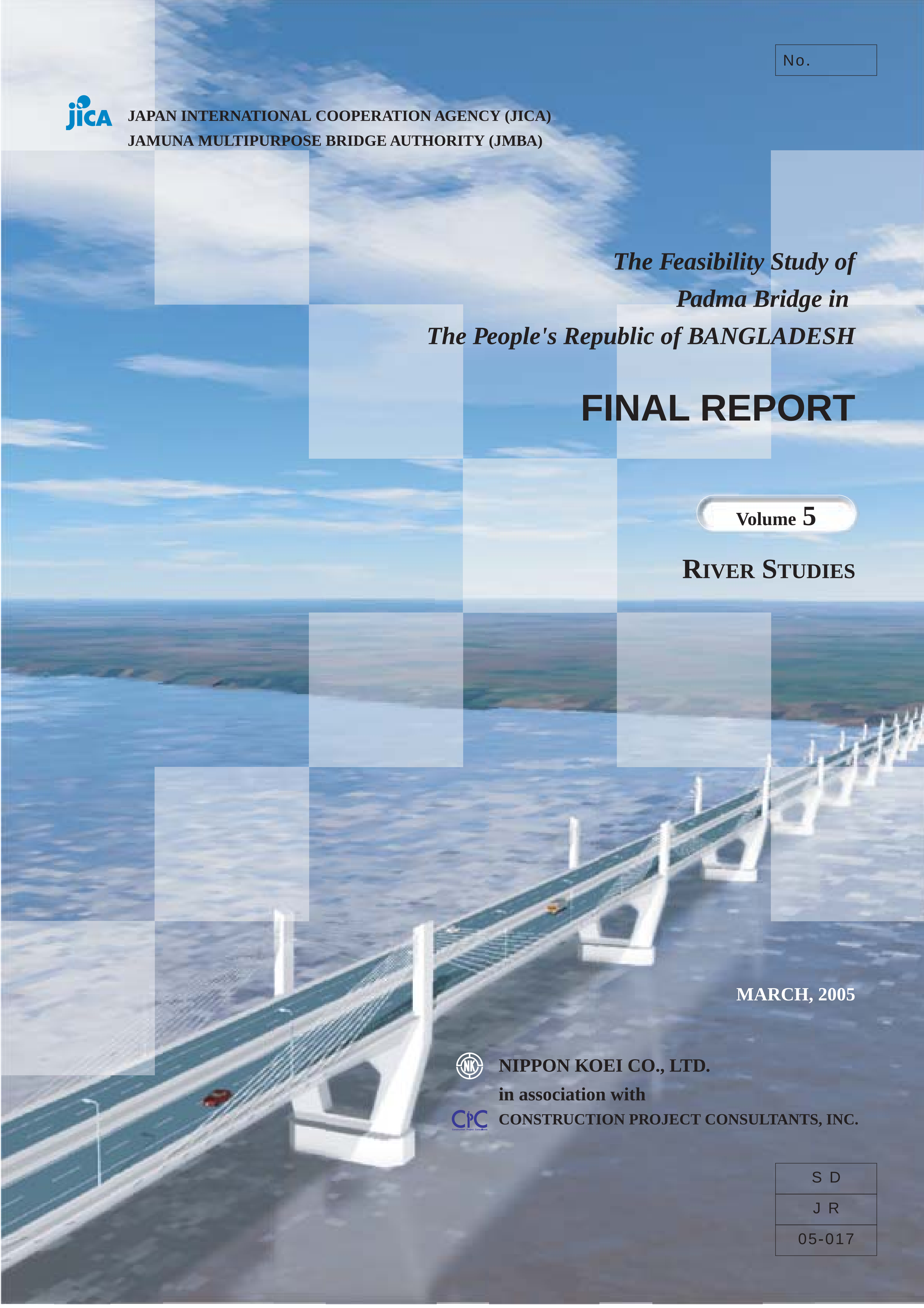

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JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)
JAMUNA MULTIPURPOSE BRIDGE AUTHORITY (JMBA)

The Feasibility Study of Padma Bridge in The People's Republic of BANGLADESH

FINAL REPORT

Volume 5

RIVER STUDIES

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STRUCTURE OF FINAL REPORT

The Feasibility Study of Padma Bridge
Final Report
(Vol. 4 Topographic Survey and Geotechnical Investigation)

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Appendix-5 River and River Morphology

5.1 RIVER AND BASIN FEATURES

General features of river and river morphology relevant to the Study Area were reviewed and introduced in this section based on the existing data and reference papers.

5.1.1 River and Basin

(1) Location

The territory of Bangladesh lies in the north eastern part of South Asia, between the latitude 20°34’N and 26°38’E, and the longitude 88°01’E and 92°41’E. As shown in Figure 5.1.1, the territory is bounded by India on the west to northeast, Myanmar on the southeast and the Bay of Bengal on the south. The area of the territory is 147,570 km2 mostly covered with the low-lying flood plain of the Ganges-Brahmaputra delta which is the largest delta in the world. The geographic location of the territory is a key factor to characterize the climate and hydrology of Bangladesh, surrounded by the Indian sub-continent to the west, the Himalayas and Tibetan Plateau to the north, and the Bay of Bengal and Indian Ocean to the south.

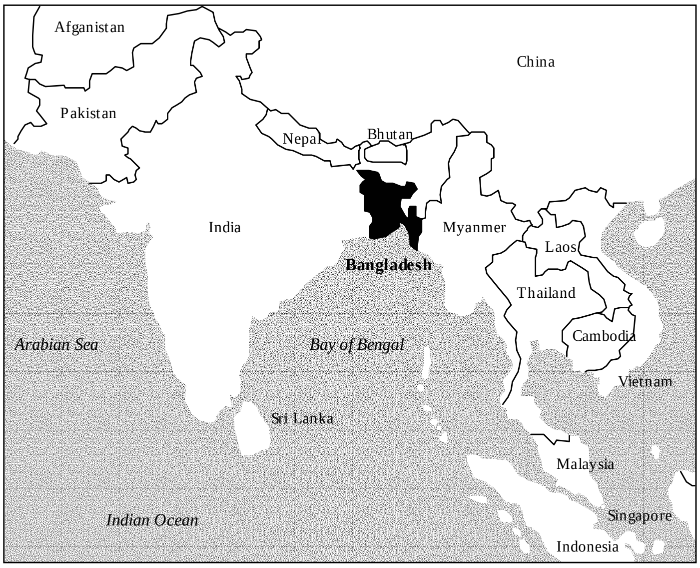


Figure 5.1.1 Location of Bangladesh

(2) Ganges-Jamuna-Meghna River System

The Ganges, the Jamuna and the Meghna rivers constitute the Ganges-Jamuna-Meghna (GJM) river system. Basin area of the GJM River is 1,740,000 km2 in total. Bangladesh is located in the lowest part of the GJM river basin.

The Ganges River (1,090,000 km2) and the Jamuna River (570,000 km2) meet each other near Goalundo and flow down to south and join the Meghna River (or the Upper Meghna, 77,000 km2) near Chandpur. The river stretch from the Ganges-Jamuna confluence to the Meghna River confluence is called as the Padma River in the present Study, though the Ganges River is also called by the name of Padma River. The main stream of the GJM river system downstream of the Padma-Meghna confluence is named as the Meghna River (or the Lower Meghna).

Basin map of the GJM River is shown in Figure 5.1.2 and overall longitudinal profile of the Ganges and Jamuna Rivers are shown in Figure 5.1.3. The drainage area in Bangladesh comprises only 5% of the total catchment basin area at Goalundo. Most of the upstream basin is located outside of Bangladesh, and river related interventions in the upstream countries may directly influence the flow conditions in Bangladesh. The Ganges, the Jamuna and the Meghna rivers have different hydrological characteristics due to their different basin sizes, locations and channel profiles.

(3) Ganges River

The Ganges River originates at the Gangotri Glacier at elevation 7,010 m in the Himalayas. Passing through Delhi, it flows to south southeastern direction, draining southern slope of the Himalayas in Nepal and Uttar Pradesh of India on the left banks, and the right bank basin in Rajasthan and Bihar in India. The river enters Bangladesh at Godagari.

At the confluence with the Jamuna near Goalundo, the drainage area of the Ganges River is 1,090,000 km2, of which 80% lies in India, 13% in Nepal, 4% in Bangladesh and the rest in Tibet. Total river length is about 2,520 km from the source to Goalundo.

(4) Jamuna River

The Jamuna River (Brahmaputra River) originates in the Great Glacier at about 5,150 m in Tibet. Draining snowmelt runoff and rainfall on the northern slope of the Himalayas, it flows eastward. Then the river abruptly turns south to emerge from foothills of the Himalayas and turns again westward. The river enters Bangladesh at Kurigram and changes flow direction to south. It meets with the Ganges near Goalundo.

The drainage area of the Jamuna River is 570,000 km2 at the confluence of the Ganges near Goalundo, of which 50% lies in Tibet, 34% in India, 8% in Bhutan and 8% in Bangladesh. Total river length is about 2,820 km from the source to Goalundo.

The Jamuna is a braided river having 4 to 6 channel segments in a across section.

(5) Meghna River

The Meghna River has a total drainage area of about 77,000 km2 at the confluence with the Padma River near Chandpur, of which 58% lies in Bangladesh and the rest in India. The river length is about 900 km from the source to Chandpur.

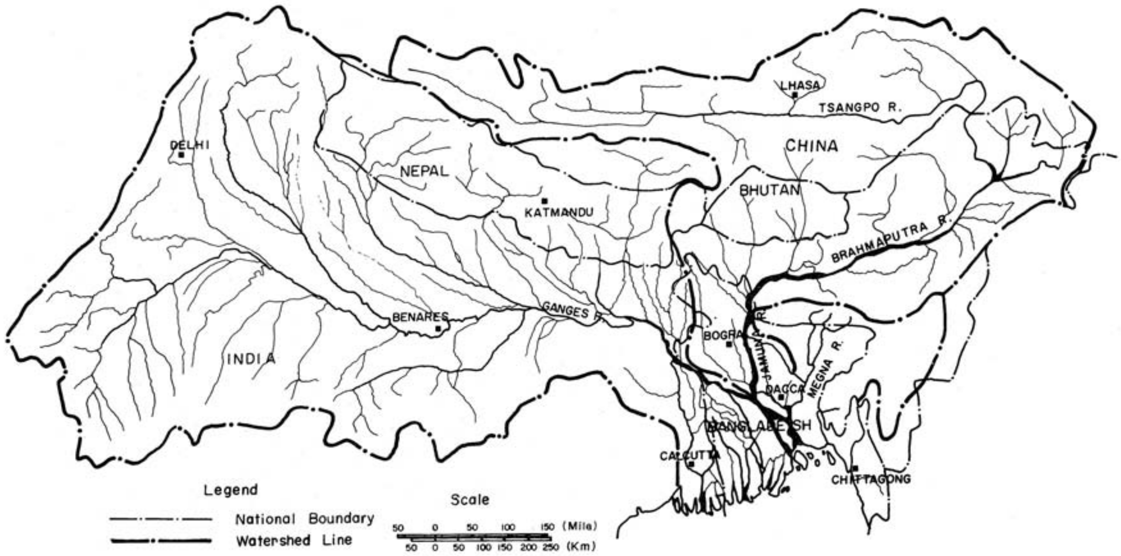


Figure 5.1.2 Ganges-Jamuna-Meghna River System

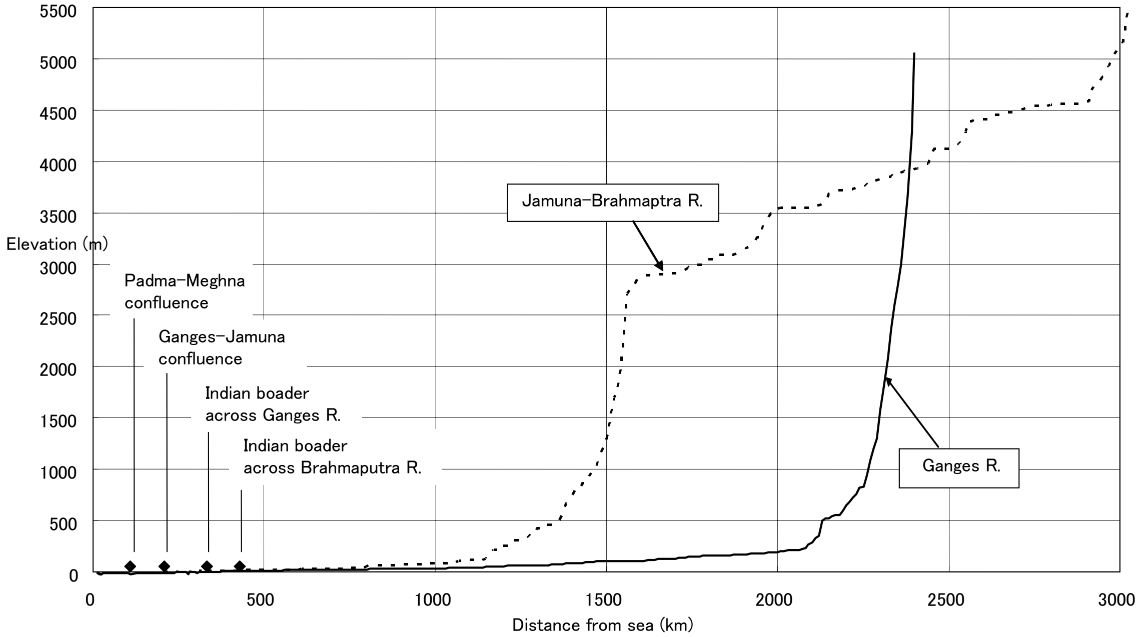


Figure 5.1.3 Overall Longitudinal Profiles of Ganges and Jamuna Rivers

(6) Padma River

The Padma River drains the combined flows of the Ganges and the Jamuna rivers. The river length is about 102 km from the Ganges-Jamuna confluence to the Padma-Meghna confluence. There is no major inflow from the tributaries until it meet with the Meghna River at Chandpur. The Arial Khan River branches at the upstream of Charjanajat Ghat.

River course of the Padma River is straight as a whole extending toward southeast holding some great islands (chars) within the river section.

(7) Other Tributaries and Distributaries

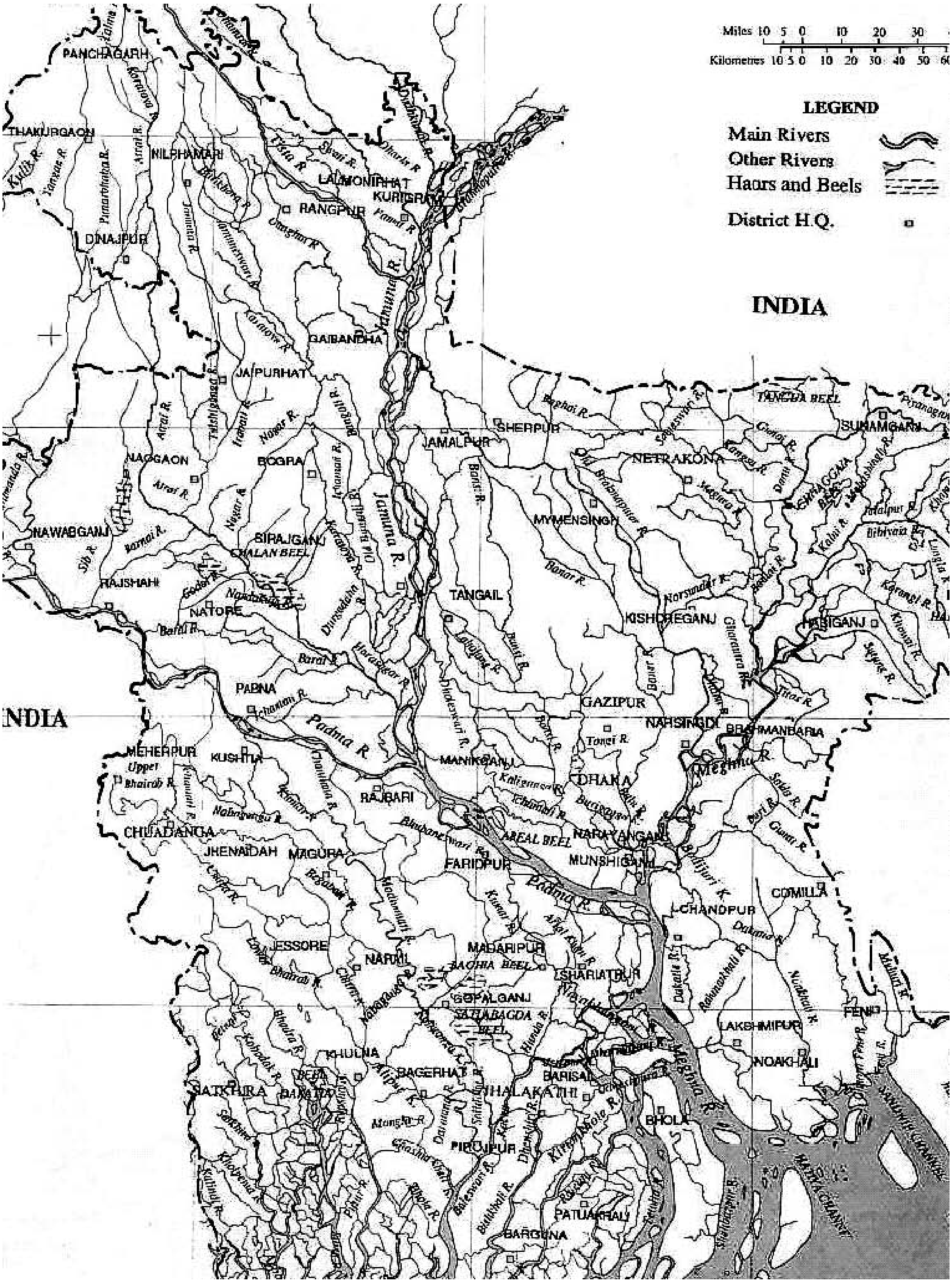
The above major rivers form the trunk river system in Bangladesh and other smaller rivers join or branch from the major rivers. These rivers also join or branch off each other and create the complex river network on the vast extent of the flood plain. Network of the main rivers in Bangladesh is shown in Figure 5.1.4.

The major tributaries are the Tista and Hurasagar rivers both on the right bank of the Jamuna River. The Tista River flows down across the northern border of India and joins the Jamuna near Sundarganj. The Hurasagar River drains mainly the northwestern region in Bangladesh and joins the Jamuna near Bera.

The Old Brahmaputra and Dhaleswari rivers are the major distributaries of the Jamuna River. The Old Brahmaputra branches off from left bank of the Jamuna River near Bahadurabad, flows down to the southeast, and debouches into the Upper Meghna River near Narsingdi. The Old Brahmaputra is known as the past main course of the Brahmaputra that shifted its course to the present Jamuna River around 200 years ago. The Dhaleswari River branching off from left bank of the Jamuna River near Tangail flows down almost in parallel with the Padma River until it joins with the Upper Meghna River near Munshiganj.

The Modhumati River (Gorai) is one of the largest distributaries of the Ganges and its off-take is located on the right bank downstream of the Harding bridge. The Modhumati River drains the southwestern region of Bangladesh jointly with some other distributaries, and pours into the Bay of Bengal.

The Arial-Khan branches from right bank of the Padma River near the existing ferry port at Charjanajat. After flowing down to the south, the Arial-Khan joins with the Lower Meghna River and finally empties into the Bay of Bengal. The Arial-Khan was the past main course of the Padma River until the time less than 170 years ago.



(Source: Graphosman World Atlas; 2003: SPARSO, BWDB)

Figure 5.1.4 Main Rivers in Bangladesh

(8) Flood Plains and Chars

The most of the territory of Bangladesh lies in the flood plains formed by the major rivers of the Ganges, Jamuna and Meghna, and adjoining tributaries and distributaries. The flood plains occupy about 80% of the territory. According to FAP-24 (River Survey Project, 1996), the flood plains in Bangladesh can be broadly classified into three physiographic zones as presented in the paragraphs below.

Active Flood Plain Comprising Natural Levee and Chars: The natural levee is a strip-shaped higher land formed with relatively coarse sediment deposited during flood along the riverbank. The vegetated chars or islands in the rivers are also classified into the same. The elevation of natural levee corresponds with a flood level in a range of 2- to 5-year return period. The natural levees are cut by sizable channels (crevasses) serving to route flood water from the main river channel to the flood plain. The active flood plains in Bangladesh are the dynamic regions in river morphology with high rates of riverbank erosion and channel migration.

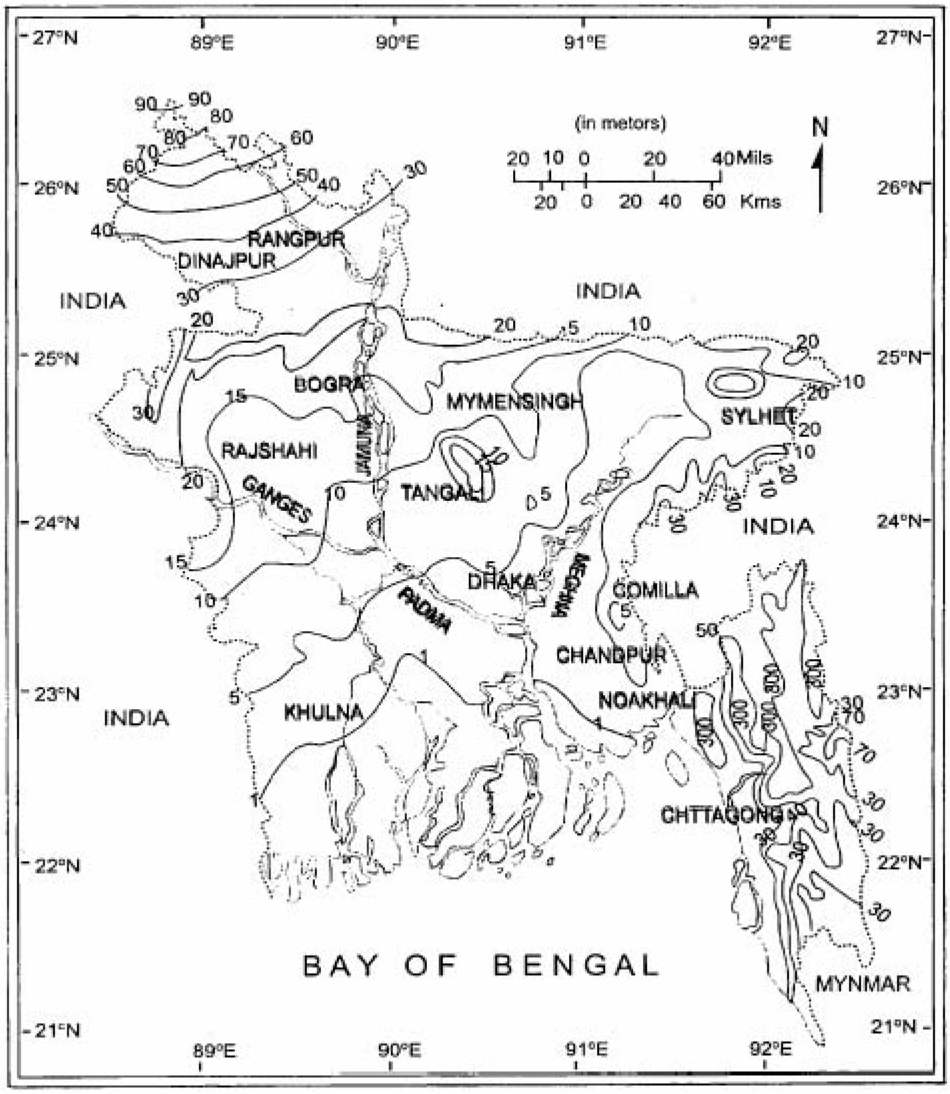
Seasonally Drained Flood Plains or Back-Swamps: The topographically lower areas than the natural levees serve as storage basins of flood water or runoff from the surroundings. Because of low flow velocity, these areas are formed with mostly fine sediments deposited through vertical accretion and are characterized by alluvial silt and clay deposits.

Standing Water Bodies or Marshes: Standing water bodies or marshes in the inland regions belong to the topographically depressed areas called as Haors, Boars, and Beels in Bangladesh. The majority of these areas are located in the northeastern region. Water flow is standing in these areas. These areas are mostly characterized by deposits of marsh clay and peat.

5.1.2 Physiography

(1) Topography of Bangladesh

General contour map of the ground elevation of Bangladesh is shown in Figure 5.1.5. The topography of Bangladesh is mostly flat slightly slanting toward south-southeast direction. Three quarters of the country is below 30m in elevation. It is noted that the ground elevation along the Upper Meghna River is markedly low forming a depression. The ground elevation around the Padma River ranges from 3m to 8m.

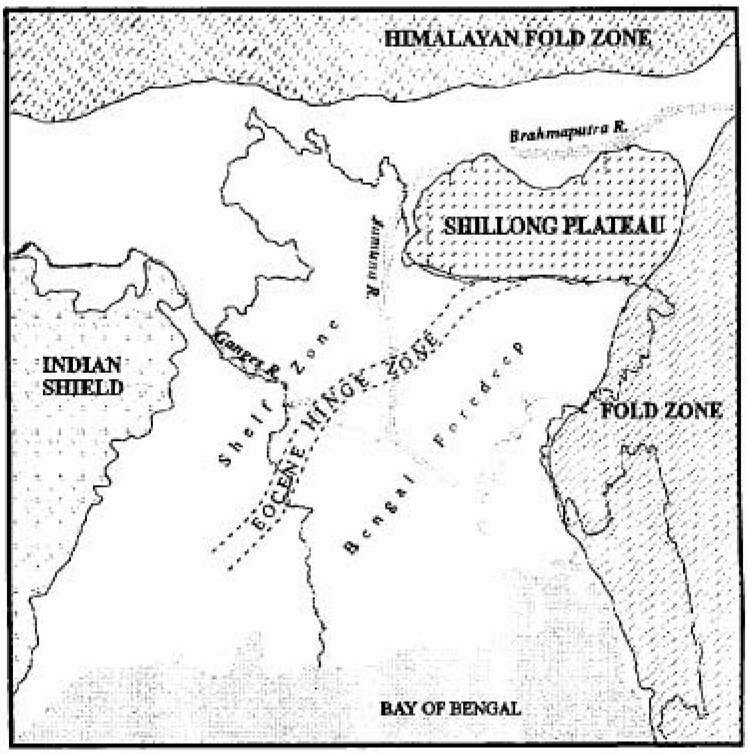


(Source: People's Report on Bangladesh Environment 2001)

Figure 5.1.5 General Contour Map of Bangladesh

(2) Physiographic Structure

Figure 5.1.6 shows physiographic structure of the Bengal Basin. The basin is bounded by Indian Shield in west and fold zone in east. Shillong Plateau is located in north on the international border. Eocene Hinge Zone, a 25- to 30-km wide flexure zone with a series of fault scarps, traverses the middle of the Bengal Basin toward south west direction passing by immediately south of Sirajganj. The hinge zone divides the basin into the Shelf Zone in the north and Bengal Fore-deep in the south. The Study Area is located in the Bengal Fore-deep.



(Source: Morphological Dynamics of the Brahmaputra-Jamuna River, 1997; EGIS)

Figure 5.1.6 Physiographic Structure of Bengal Basin

The Bengal Basin can be divided into three main physiographic sub-regions, i.e., Tertiary hills, Pleistocene uplands and alluvial lowlands (flood plain). The Tertiary hills are located in the north on and around the international border, Chittagong, etc. The Pleistocene uplands located in the northwest of Bangladesh are called as Barind tract, and those in the central Bangladesh are called as Madhupur tract on which City of Dhaka is located.

The alluvial lowlands occupy greater part of Bangladesh including the Study Area. These lands were formed by massive sediment of the Ganges and the Jamuna rivers, influence of tectonic movement, heavy precipitations and floods on the young surface of alluvial lowlands/flood plains. Many micro-landforms are seen on the flood plain. They are the vestiges of former river channels, natural levees, point bars, back marshes, etc. Principal landforms of Bangladesh are shown in Figure 5.1.7.

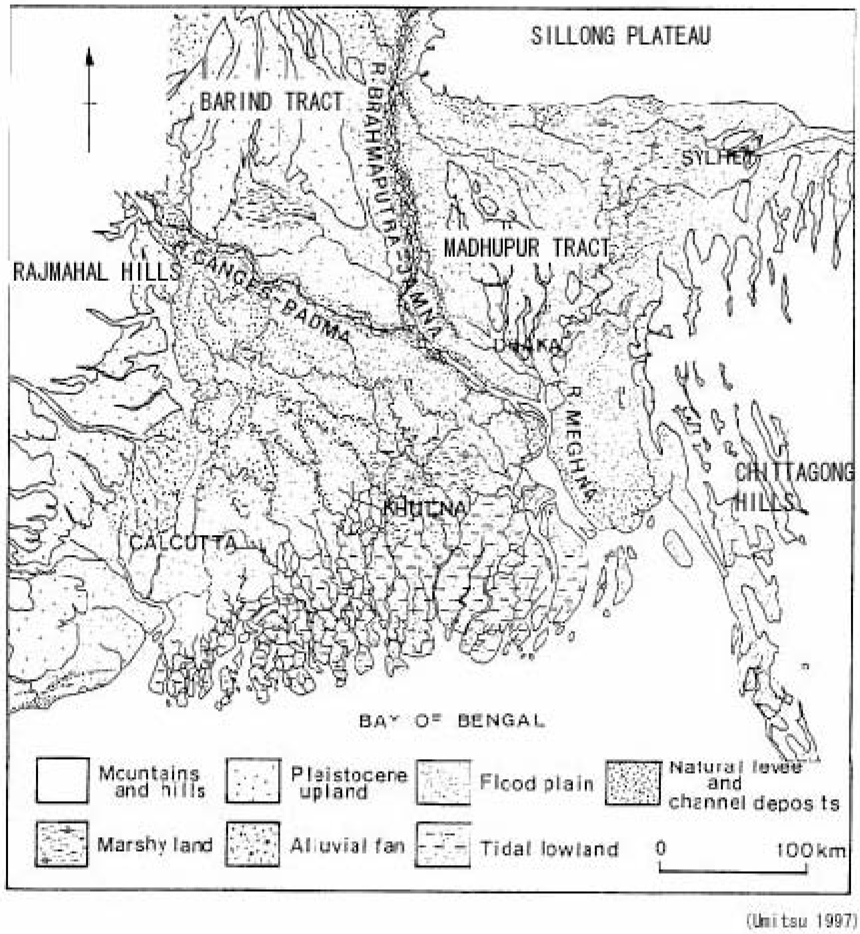


Figure 5.1.7 Landform of Bangladesh

(3) Geological Formation of Bengal Basin

The Bengal Basin was formed in the Tertiary and Quaternary period filled with heavy sediment transported by the Ganges and the Jamuna rivers from the tectonically active Himalayas. The thickness of the sediment cover above the pre-Cambrian basement rock is about 180m at Rangpur in the north. It increases toward south and amounts to more than 18,000m in the south eastern part of the country. In the Study Area, the sediment cover has been estimated as thick as 12,000m to 14,000m. The Bengal Basin is said subsiding and balanced with the deposition of sediment supplied from the rivers. Development of Bengal Basin is shown in Figure 5.1.8.

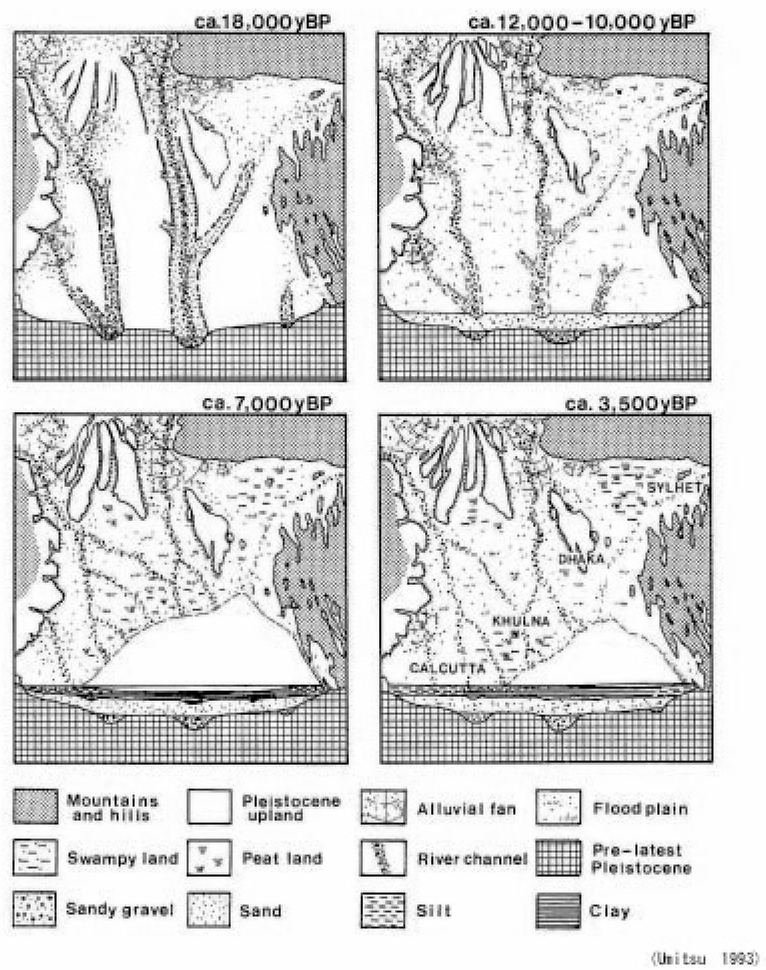


Figure 5.1.8 Development of Bengal Lowland

5.2 RIVER MORPHOLOGY AND SEDIMENT STUDY

In this section studies were made preliminarily on the river morphology, river channel and sediment flow conditions.

5.2.1 River Morphology

(1) Historical River Course Shifting

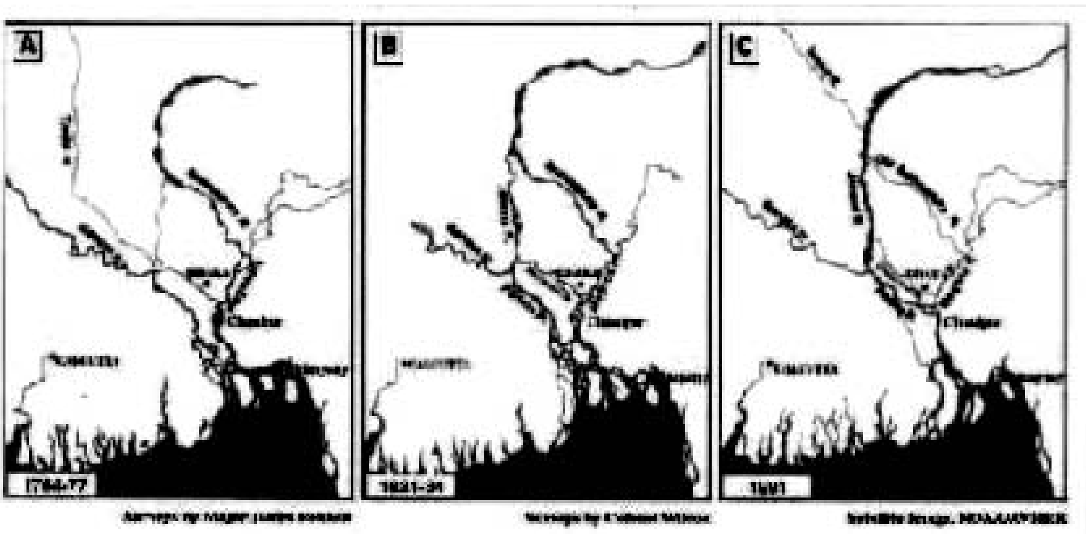
The Bengal Basin is tectonically active. The Madhupur and Barind tracts are Pleistocene alluvial deposits uplifted. The Sylhet Basin is subsiding at 1 to 3 mm/year because of over thrusting of the adjacent Shillong block. In most of the Bengal Basin, compaction and/or isostatically induced subsidence occurs including the coastal zone and offshore areas.

In addition to the tectonic activities, the formation of the Bengal Basin is strongly influenced by the huge input of sediments from the Ganges and the Jamuna rivers. These rivers spread huge sediments brought from Himalayas over the lowland in the Bengal Basin, changing their courses so often.

The river course shifting in the lower Bengal Basin is illustrated in Figure 5.2.1. Around 1770, the Ganges River took its course almost along the present course of the Arial Khan River and emptied into the Bay of Bengal separately from the Jamuna River. Meanwhile, the main flow of the Jamuna River then flew along the present course of the old Brahmaputra River in the east of the City of Dhaka or the Madhupur tract and drained into the bay through the Meghna River. There was only a small stream running along the present course of Jamuna.

According to the Wilcox's map around 1830, main course of the Jamuna River is found in the present river course and met with the Ganges almost at the present confluence. The joint flow, named as the Padma, discharged into the Bay of Bengal.

Some time between 1830 and 1860, the Padma River cut through the Chandina Alluvium at the downstream of Mawa and was connected with the Meghna River at the present confluence. The Padma River gradually shifted to the east and reached present location. The Padma River is a young river. Especially the Padma River downstream of Mawa is a new river channel formed less than 170 years ago.



(Source: Riverine Chars in Bangladesh; EGIS, 2000)

Figure 5.2.1 Historical River Shifting

(2) Trend of Eastward Shifting of Padma River

The eastward shifting of the Padma River has been pointed out by the FAP-19 study. The satellite image shown in Figure 5.2.2 endorses the eastward shifting clearly with the vestiges of old river courses. Numerous old river courses of similar scale of the present river channel are found in the flood plain on the west side bank, which implies that the west flood plain used to be the river course until recent years. On the other hand, the landforms in the east side flood plain show distinctively different features from the west one. On the east bank, vestiges of recent river courses are not found and the ground seems to be old and firm comparing to the west bank with relatively higher resistance to erosion.

From the above, trend of eastward shifting of the Padma River could be confirmed. However, the eastward shifting should be regarded as a long-term and gradual trend of yearly riverbank movements.

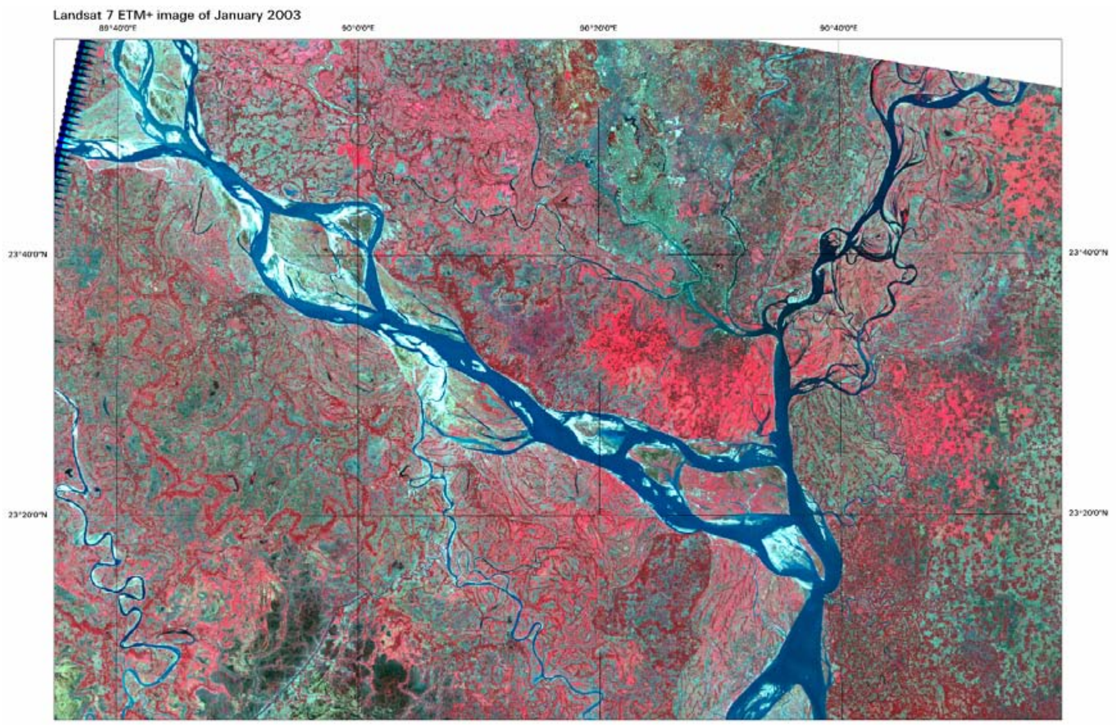


Figure 5.2.2 Landform Patterns on Satellite Image (Jan. 2003)

(3) Recent Changes of Riverbank

In order to overview the changes of riverbank in recent years, old topographic maps of scale 1/250,000 (published in 1926, 1965) and LANDSAT satellite images taken in dry season of 1973, 1984, 1993 and 2003 were collected and studied preliminarily. From the riverbank changes during the past 78 years since 1926, the following river morphologic features were found:

1) The Padma River alternated its plan-forms with and without big chars (islands) within the river channel. This alternation influences the changes of riverbank mainly on the right (southwest) bank.
2) The confluence of the Ganges and the Jamuna rivers shifted southwards (toward downstream) by about 6 km during the period from 1926 to 1973.
3) The Lower Meghna River changed drastically its channel features. The left bank is continuously eroded and the river width is gradually narrowed forming gradually a single channel section. These changes were more active in early years until 1973.

4) As a whole the left (east) riverbank is relatively stable, especially at Paturia-Goalundo and Mawa-Janjira sections. It was also confirmed that these two sites kept narrow (or nodal) sections at least during the past 78 years.
5) According to the latest satellite image taken in 2003, three big chars (islands) exist in the 102 km long Padma River. These chars, however, are not stable and young formed less than 30 years ago, since the river alternates conditions with and without chars.

(4) Stability of Riverbank

Furthermore, the satellite images taken in 1973, 1984, 1993 and 2003 were examined more precisely to evaluate the stability of riverbanks at the conceivable crossing locations. These satellite images are shown in Figure 5.2.3 and the changes of riverbanks during these three decades are shown in Figure 5.2.4 superimposing the bank lines each other.

Though the Padma River changes its width and plan-forms of riverbanks frequently, the river keeps relatively narrow and stable sections at the conceivable crossing locations. The left riverbanks are markedly stable especially at Paturia, Mawa and Chandpur.

Focusing on four crossing locations, historical riverbank changes in the past 30 years were studied and shown in Figure 2.5.5. From this Figure, it is clarified that Site-1 and Site-3 are by far stable comparing to remaining two sites as follows:

Site-1 (Paturia-Goalundo):
- Change in river width (W_{min} to W_{max}): 2.44 to 5.00 km
- Average river width (W_{ave}): 4.27 km
- Coefficient of variation = $(W_{max}-W_{min})/W_{ave}$: 0.61
- Maximum river extent during 30 years: 5.20 km

Site-2 (Dohar-Charbhadrasan):
- Change in river width (W_{min} to W_{max}): 3.56 to 8.48 km
- Average river width (W_{ave}): 5.25 km
- Coefficient of variation = $(W_{max}-W_{min})/W_{ave}$: 0.94
- Maximum river extent during 30 years: 8.88 km

Site-3 (Mawa-Janjira):
- Change in river width (W_{min} to W_{max}): 2.00 to 4.92 km
- Average river width (W_{ave}): 3.81 km
- Coefficient of variation = $(W_{max}-W_{min})/W_{ave}$: 0.60
- Maximum river extent during 30 years: 5.24 km

Site-4 (Chandpur-Bhedarganj):
- Change in river width (W_{min} to W_{max}): 2.68 to 9.60 km
- Average river width (W_{ave}): 5.31 km
- Coefficient of variation = $(W_{max}-W_{min})/W_{ave}$: 1.30
- Maximum river extent during 30 years: 9.60 km

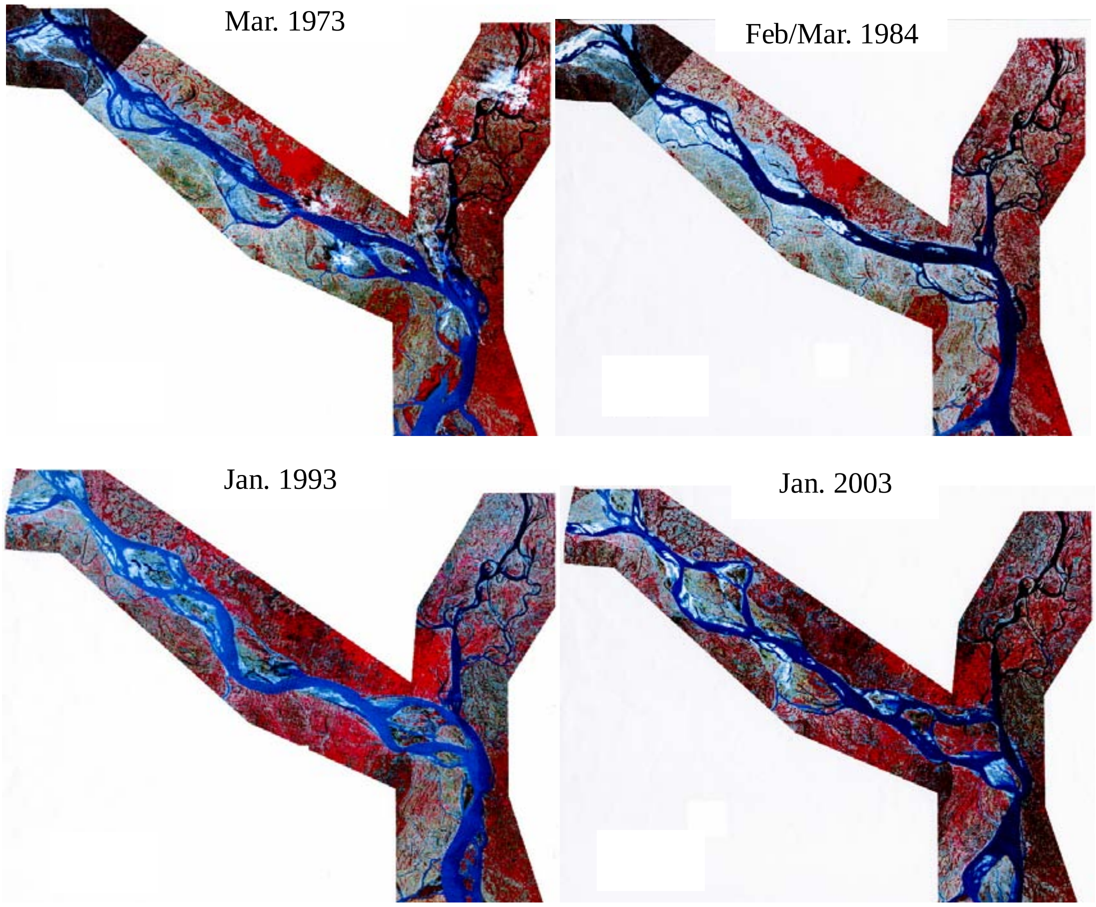


Figure 5.2.3 Landsat Images of Padma River (1973-2003)

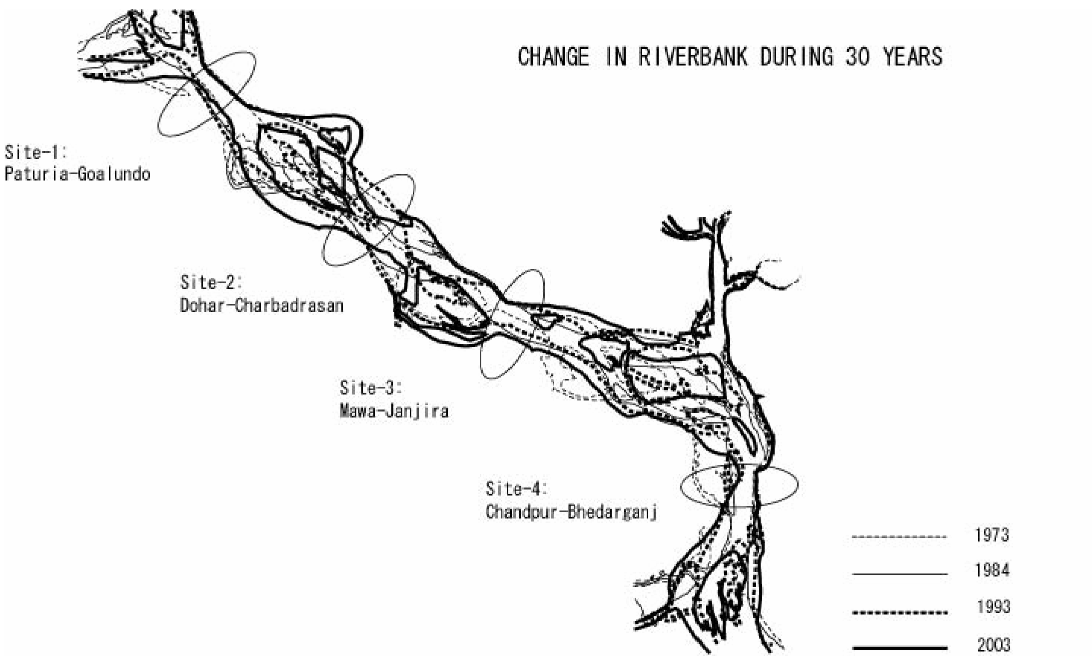
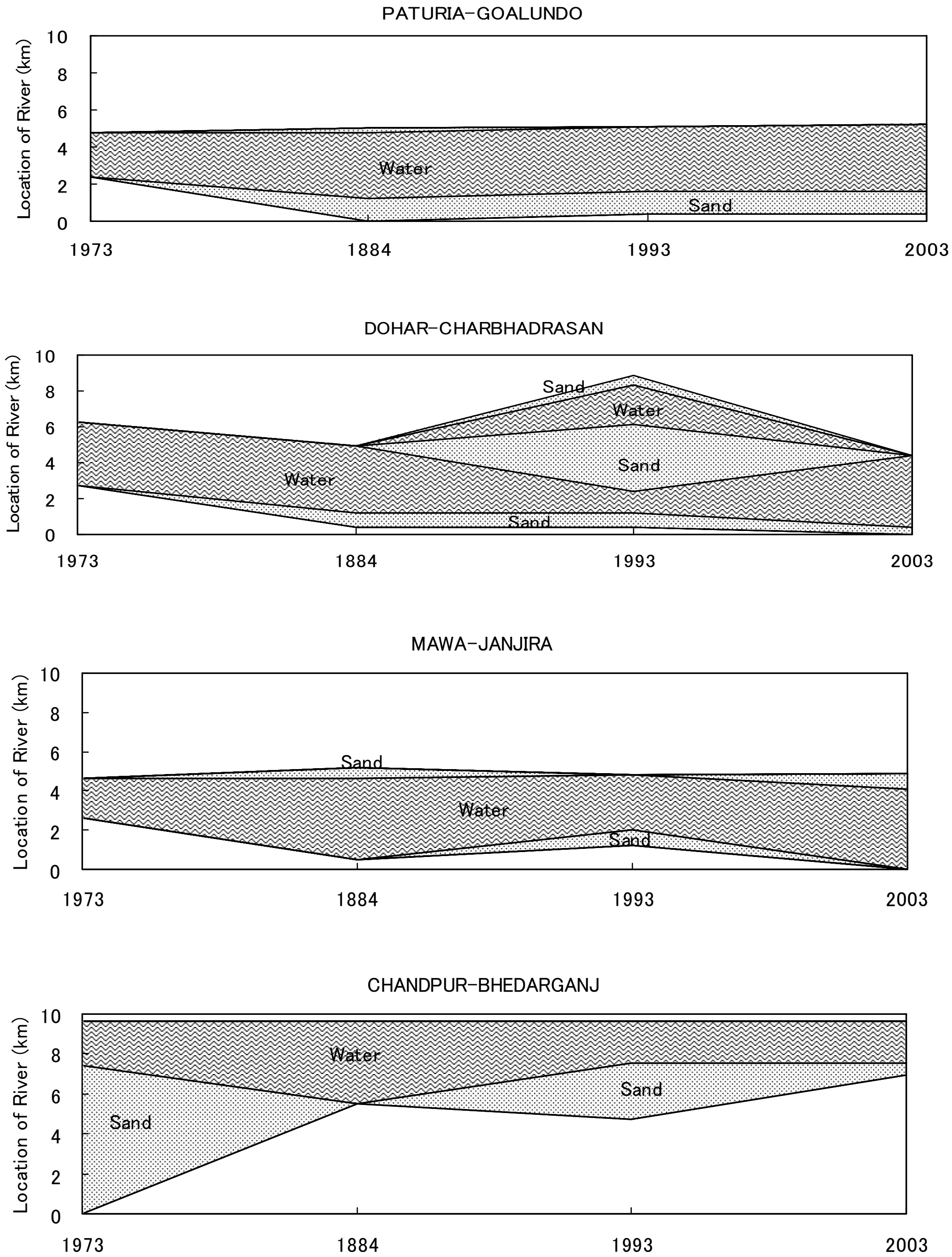


Figure 5.2.4 Change in Bank-lines



Note: Location of river indicates the historical locations of boundaries of river water and attached sand-bar along respective bridge crossing sections measured from fixed reference points on the right bank.

Figure 5.2.5 Changes in Riverbank Locations

5.2.2 River Channel Conditions

(1) Longitudinal Profiles

Longitudinal profiles of the Jamuna, Ganges-Padma and Meghna rivers were prepared and shown in Figure 5.2.6 based on the BWDW river survey for the year 1998/99.

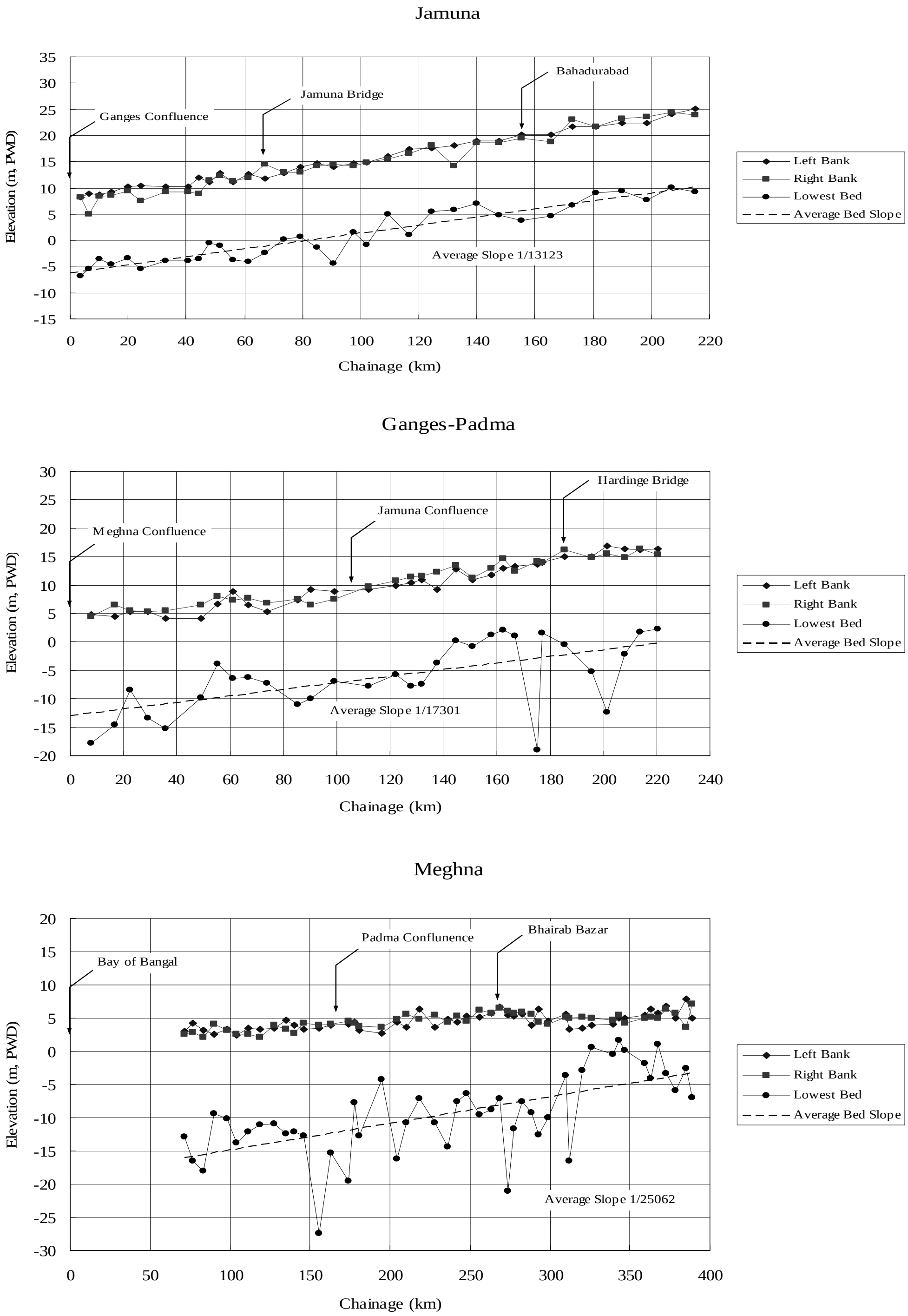


Figure 5.2.6 Longitudinal Profiles of Major Rivers

The average river bed slopes are 1/13,100 in the Jamuna, 1/17,300 in the Ganges-Padma, and 1/25,000 in the Meghna. In the Jamuna and Ganges-Padma rivers, the average slopes of the river banks are almost parallel with the average riverbed slope. The slope of river bank profile is very gentle along the Meghna River and the bank levels vary approximately from 3 to 7 m,PWD for the river stretch of about 320 km.

(2) Water Levels and Bank Levels

According to records of BWDB gauging stations the water level differences between high and low flow seasons in a year are 5 to 6 m in the Padma River, while they are 7 m in the Ganges and Jamuna rivers and 3.5 m in the Meghna River as shown in Table 5.2.1.

Table 5.2.1 Average Highest and Lowest Water Levels

River	Code	Gauge	Highest (m, PWD)	Lowest (m, PWD)	Difference (m)
Jamuna	50.3	Mathura	10.20	3.03	7.17
Ganges	91.2	Mohendrapur	10.67	3.23	7.44
Padma	91.9L	Baruia Transit	8.34	1.92	6.42
Padma	93.5L	Mawa	6.13	1.12	5.01
Meghna	276	Chandpur	4.46	0.88	3.58

As to topographic data of the flood plain, riverbank levels and some extent of flood plain levels are available from the cross-section survey results by BWDB. FAP-24 study estimated the bank level at each standard cross section. Along the Padma River, the average bank level varies from 8.3 to 5.0 m on the left bank and from 7.6 to 5.4 m on the right bank as shown in Table 5.2.2.

Table 5.2.2 Average Bank Levels of the Padma River

(Unit: m, PWD)

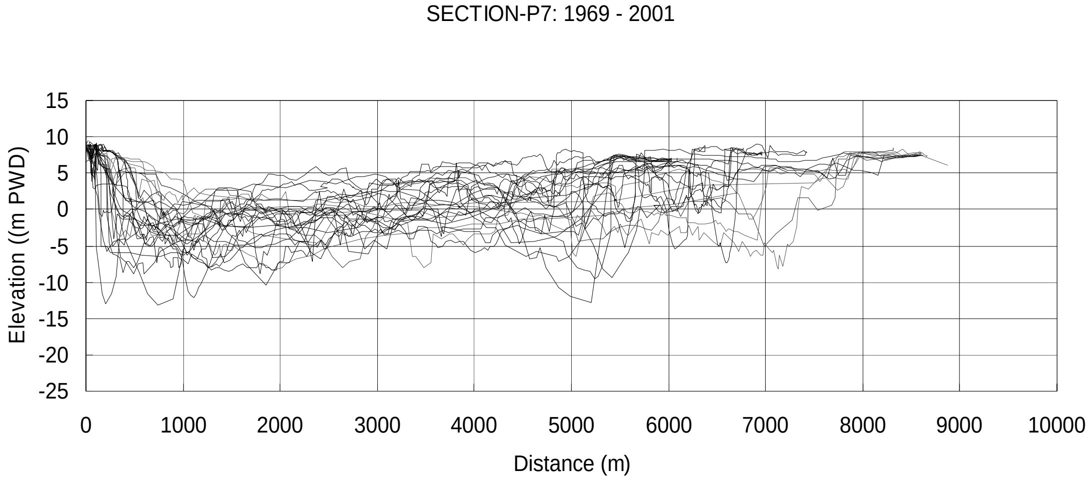
Cross section	P7	P6.1	P6	P5	P4.1	P4	P3.1	P3	P2	P1.1	P1
Left bank	8.26	7.01	6.68	6.83	6.67	6.67	6.50	5.51	5.00	4.91	5.10
Right bank	7.56	7.10	6.83	6.98	6.66	6.86	5.94	5.69	5.40	5.38	5.28

(Data: 1966-1993, Source: FAP-24)

(3) River Width and Sectional Patterns

Among the periodical survey sections by BWDB, two cross-sections located most close to the existing gauging stations were selected for study, i.e., Section-P7 about 4 km downstream of Baruria Station and Section-P2.1 almost at Mawa Station. At Section-P7 the survey data are available intermittently from 1969 to 2001 and at Section-P2.1 from 1968 to 1999.

The section data of these surveys are shown in Figure 5.2.7 superimposing them respectively. From the Figure, extent of river area during the data period is about 8.0 km at Section-P7, while at Section-P2.1 about 6.5 km. The extent of river area was assumed as the river area where ground elevation was lower and the elevation changed year by year.



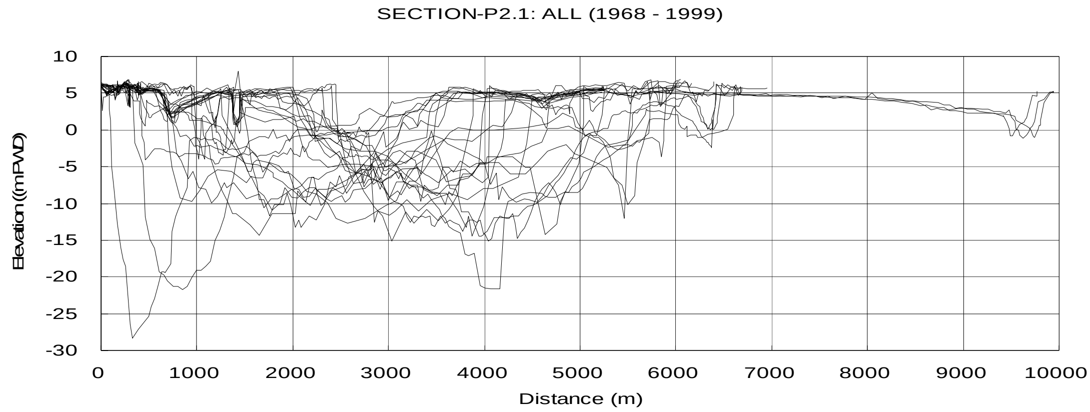


Figure 5.2.7 Superimposed River Sections at Sections P7 and P2.1

Looking into the changes of river sections year by year, it was found that the river kept a similar sectional pattern for some period and the changes of the patterns took place in relatively short period, during one or few flood seasons.

At Section-P7 near Baruria Station, historical river sections are divided into the following periods of similar sectional pattern as shown in Figures 5.2.8 (1/3) ~ (3/3):

1) River width: about 8.0 km from 1969 to 1973
2) River width: about 5.5 km from 1974 to 1986
3) River width: about 6.5 km from 1992 to 2001

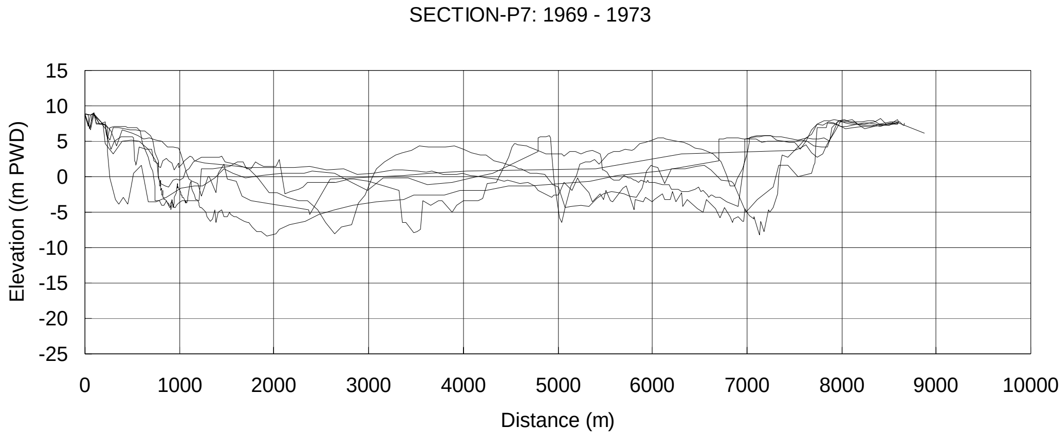


Figure 5.2.8 Changes in Sectional Pattern of Section P7 (1/3)

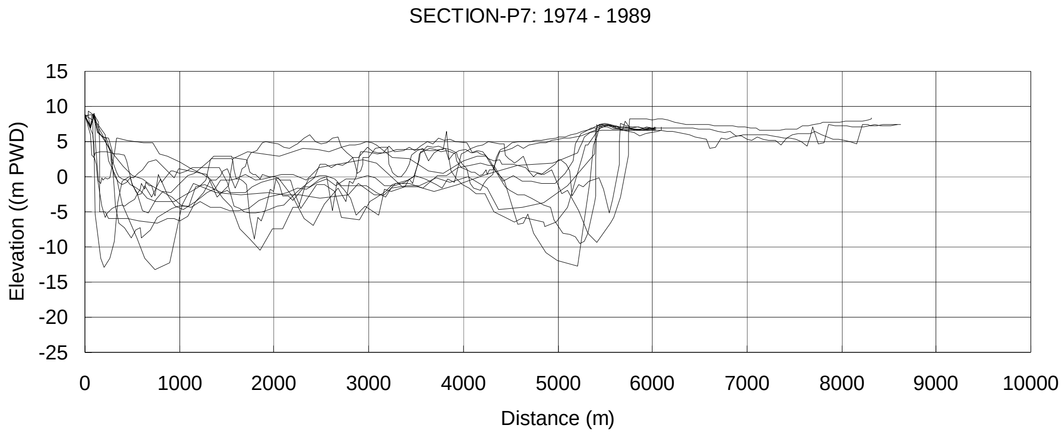


Figure 5.2.8 Changes in Sectional Pattern of Section P7 (2/3)

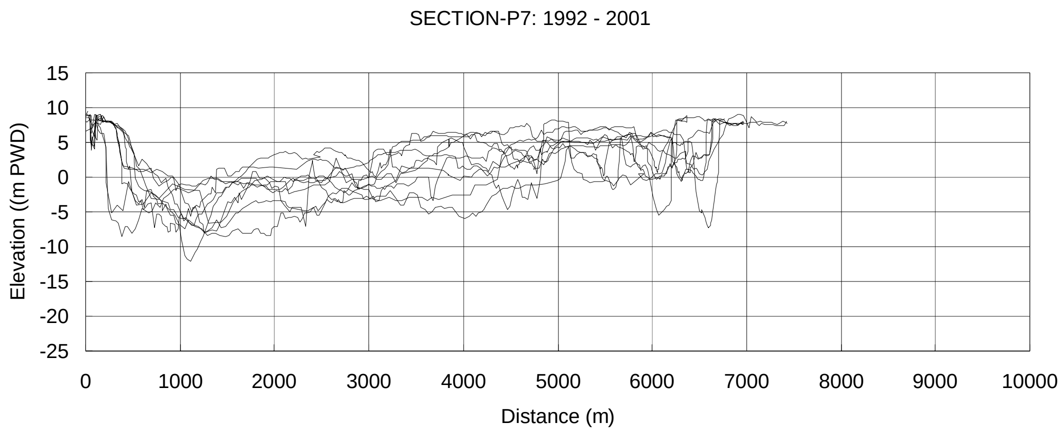


Figure 5.2.8 Changes in Sectional Pattern of Section P7 (3/3)

Likewise, the sectional patters at Section-P2.1 near Mawa-Janjira Site are similar during the following periods (see Figures 5.2.9 (1/4) ~ (4/4)):

1) River width: about 3.5 km from 1968 to 1976
2) River width: about 4.5 km from 1977 to 1989
3) River width: about 3.5 km from 1993 to 1995

4) River width: about 4.0 km from 1997 to 1999

It is noted that the river width at Section-P2.1 was kept within the range from 3.5 km to 4.5 km, though its location shifted within the extent of about 6.5km width.

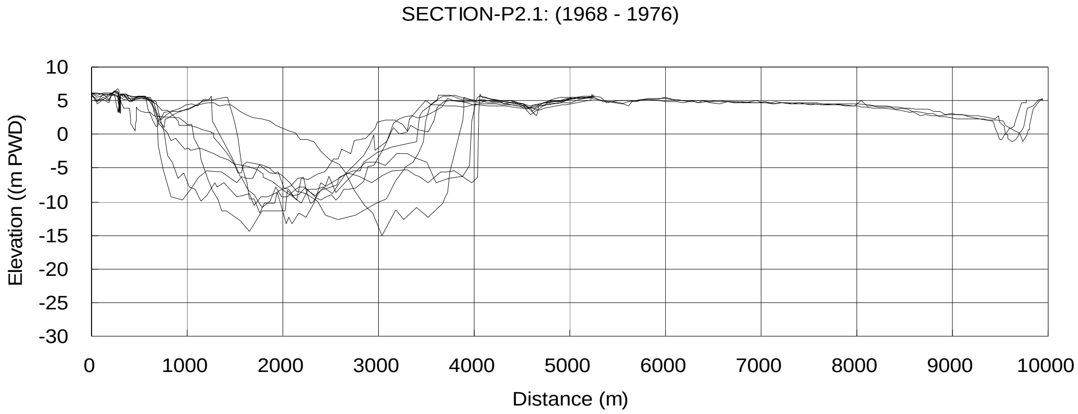


Figure 5.2.9 Changes in Sectional Pattern of Section P2.1 (1/4)

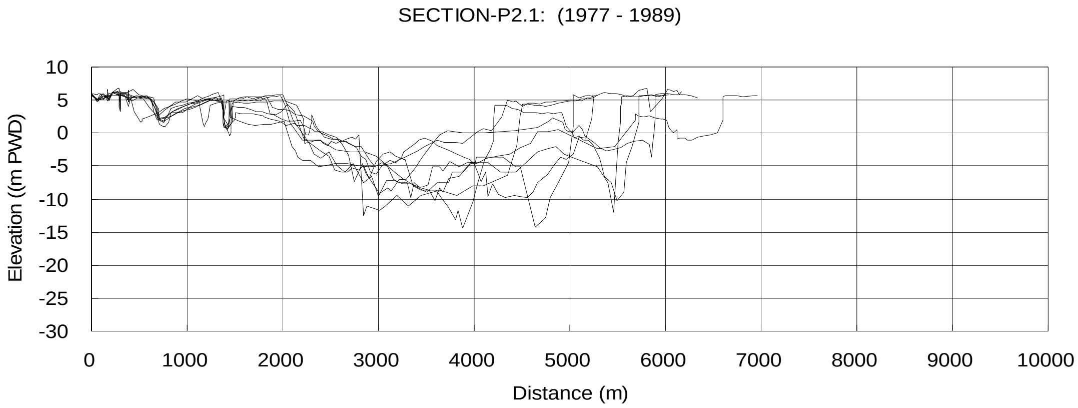


Figure 5.2.9 Changes in Sectional Pattern of Section P2.1 (2/4)

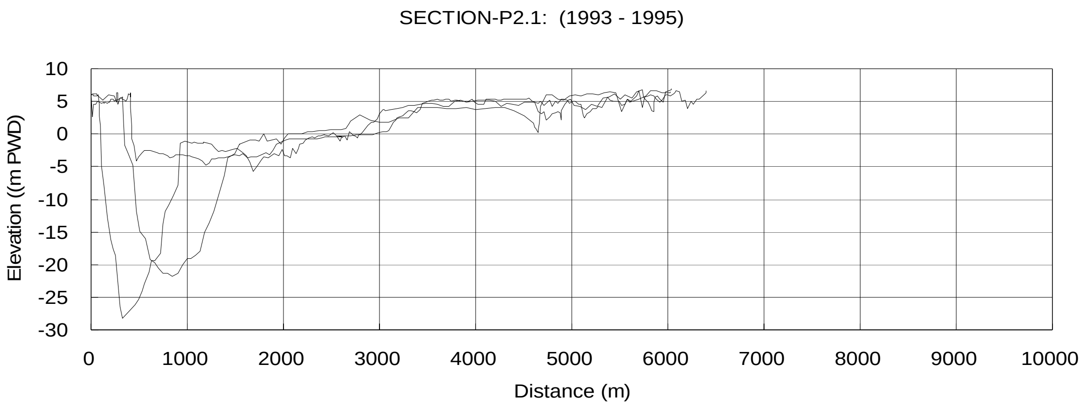


Figure 5.2.9 Changes in Sectional Pattern of Section P2.1 (3/4)

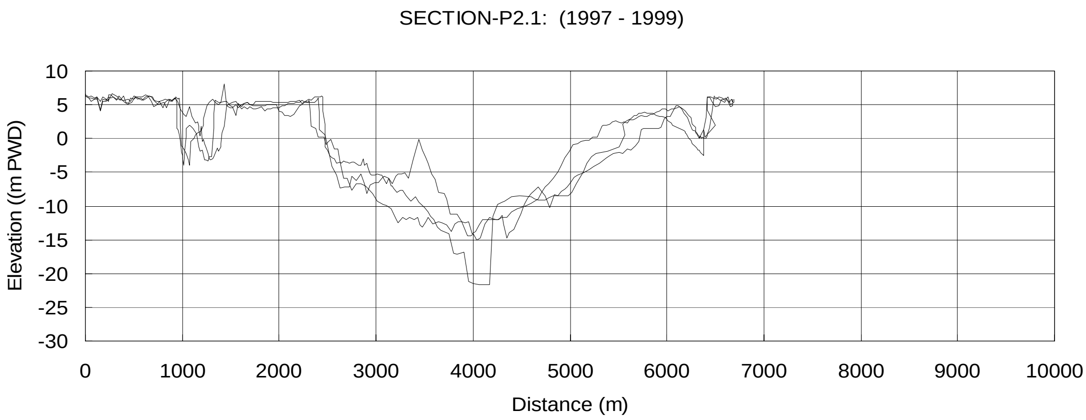


Figure 5.2.9 Changes in Sectional Pattern of Section P2.1 (4/4)

5.2.3 Sediment Flow Conditions

Riverbed material of the Padma is fine sand of about 0.15 mm in grain size. According to an estimate, the Padma River transports suspended load of about 0.6 to 1.2 billion tons per year, of which 60% is supplied from the Jamuna River and the remaining from the Ganges River. Although the river channel changes its features forming sandbars and eroding riverbanks in the course of sediment transport, the Padma River maintains its straight course toward south eastern direction from the Ganges-Jamuna confluence to the Padma-Meghna confluence.

(1) River Channel Conditions during Flood

River Section Data during Flood: Since the periodical BWDB surveys are conducted in principle during low flow period, the survey sections do not always represent flood season channel features. River channels during flood season were therefore studied using the discharge measurement records which were also carried out by BWDB periodically.

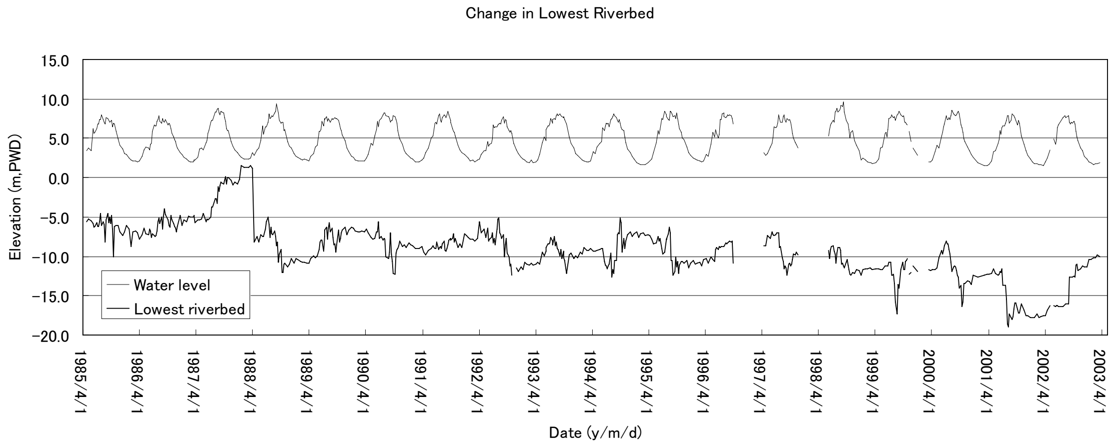
At Baruria Station the discharge measurement records are available from 1985 to 2003. The measurements are carried out in principle weekly for flood months and biweekly for the rest of the year. The measurement records include water level, discharge, flow area, river width, maximum water depth and its lateral location, etc. The discharge measurement records are also available at Mawa Station from 1997 to 2002 on the same data items, but measurements are limited only to flood months from June to October.

Changes in Lowest Riverbed at Baruria Station: Historical changes of the water level, lowest riverbed and lateral location of the lowest riverbed at Baruria Station are studied based on the discharge measurement data and shown in Figure 5.2.10. Location of the lowest riverbed of the Padma River swayed to the right and left bank sides frequently, but after 1988 it stayed at the right bank side. Sometime between 1997 and 1999, the lowest riverbed moved to the left bank side and remains until now. Since the year of 1988, the lowest riverbed shows lowering trend. The seasonal riverbed movements are not clear from the data.

In order to inspect the changes in riverbed throughout dry and flood seasons, a series of water levels measured periodically were plotted against the corresponding lowest riverbed elevations as shown in Figure 5.2.11. If the lowest riverbed does not change as the water level rises, the relationship would be expressed by the vertical movement of plot in the Figure. As seen in the Figure, the vertical movements of the plots seen during lower water period seem to change to the horizontal movements at the water levels higher than +6 m, PWD, which indicates the changes of riverbed elevations at higher water regime.

Changes in Lowest Riverbed at Mawa Station: Similarly to Baruria Station, historical changes of water level, lowest riverbed and lateral location of the lowest bed were studied and shown in Figure 5.2.12, though the dry season data are not available. Unlike Baruria station, the lowest riverbed of the Padma sways to right and left bank sides even in a flood season.

The relationship between water level and lowest riverbed is also shown in Figure 5.2.13. From the Figure, The lowest riverbed seems to move at the water levels higher than +5 m,PWD.



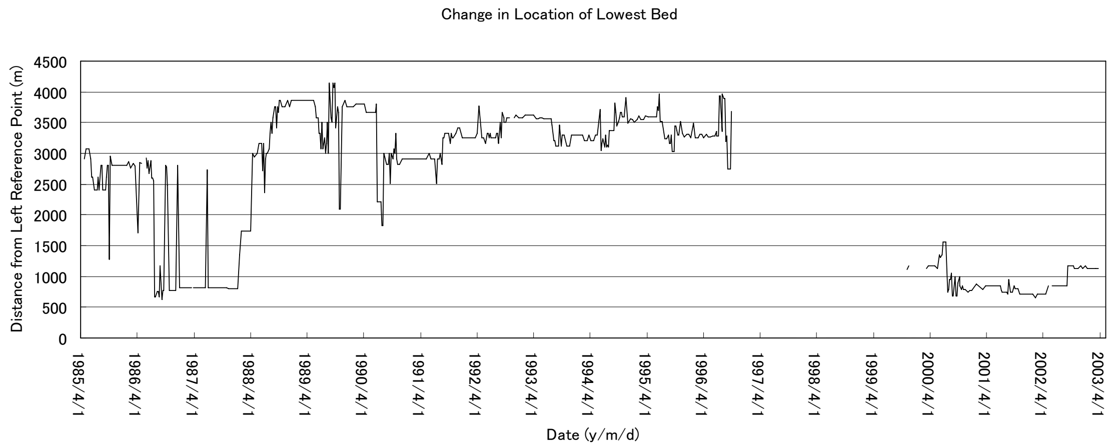


Figure 5.2.10 Changes in Lowest Riverbed at Baruria

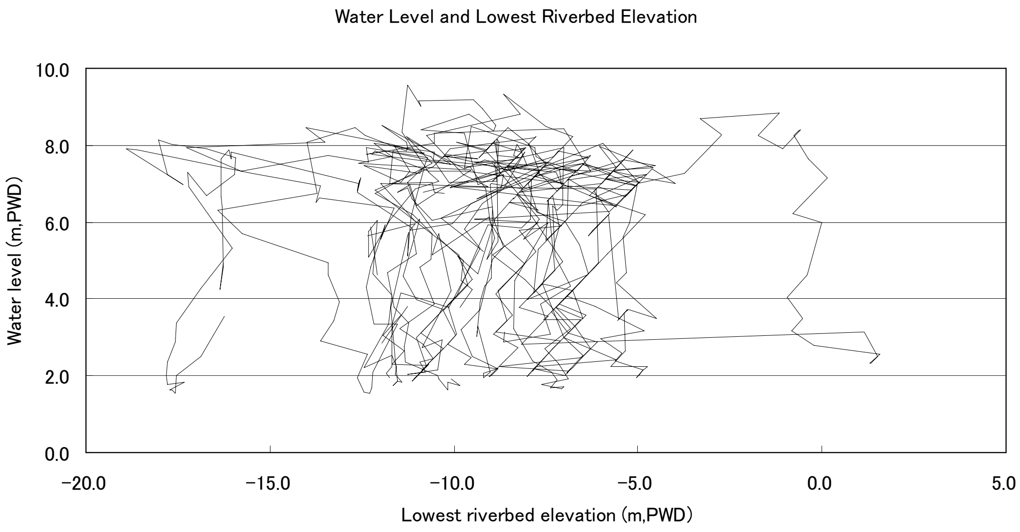


Figure 5.2.11 Water Level and Lowest Riverbed at Baruria

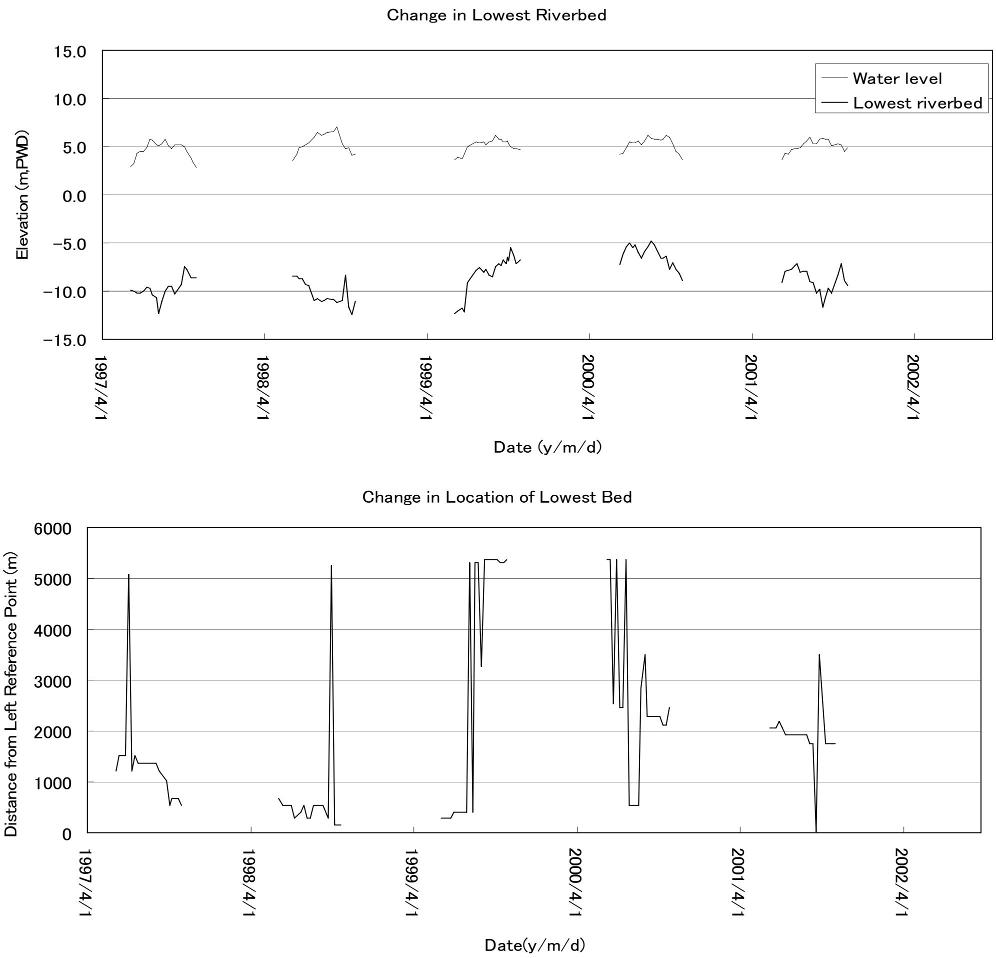


Figure 5.2.12 Change in Lowest Riverbed at Mawa

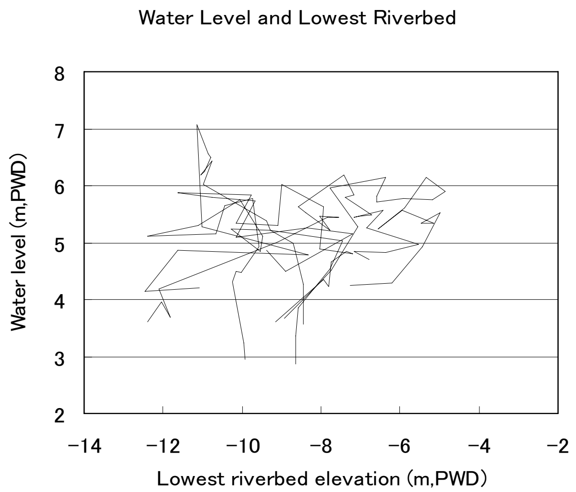


Figure 5.2.13 Water Level and Lowest Riverbed at Mawa

(2) Channel Roughness

Approach: Since sediment flow patterns and bed forms during flood are not visible, an attempt was made to have an insight on the sediment movements through the changes in roughness or resistance to flow based on the discharge measurement records at Baruria Station. For the discussions below, river slope was assumed to be 1/17,300 taking the average bed slope of the Ganges-Padma River, and mean diameter of bed material (d50) 0.015 cm. Riverbank elevation is around +8.0 m, PWD at the section of Baruria Station.

The roughness was worked out by the uniform flow formula using the discharge measurement records as follows:

$$n = A\,(A / B)^{2/3}\,I^{1/2} / Q$$

where n: Manning's coefficient of roughness, A: flow area (m2), B: surface width of river channel (m), I: river slope, and Q: discharge (m3/s).

Estimated Roughness: Figure 5.2.14 shows the relationship between water levels and corresponding channel roughness. The estimated roughness decreases as the water level rises, and at the bank-full level the roughness reaches more or less n = 0.015. It is noted that some changes in trend of roughness are observed around at +5.5 m, PWD of water level.

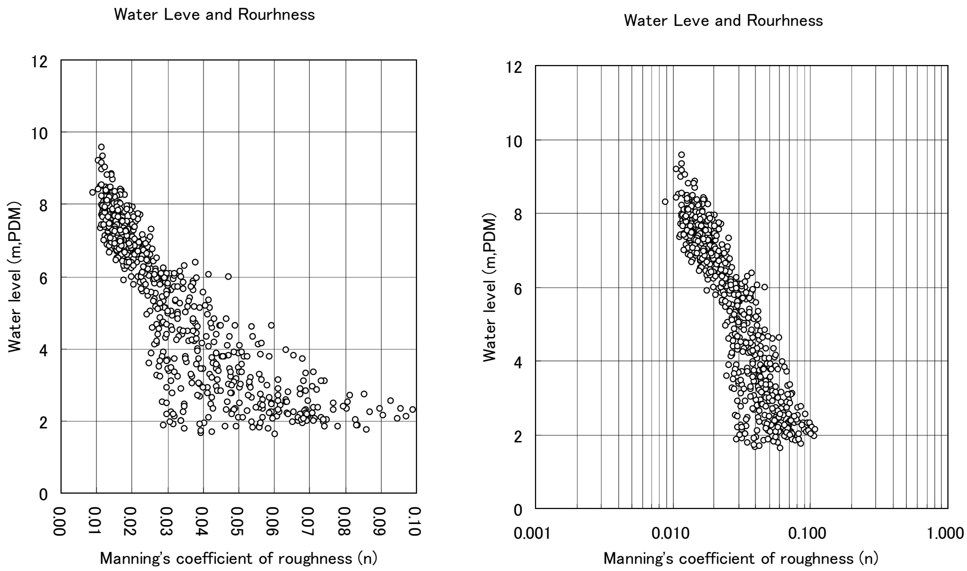


Figure 5.2.14 Water Level and Channel Roughness

Resistance to Flow: In order to look into the change in trend observed in the above Figure, relationship between dimensionless shear stress (τ_*) of flow and velocity coefficient (ϕ) which represents resistance to flow was examined using the same discharge measurement records. Figure 5.2.15 shows the relationship between τ_* and ϕ, which are defined as follows:

τ_* : Dimensionless shear stress = $u_*^2 / (s\ g\ d) = h\ I / (s\ d)$

ϕ : Velocity coefficient = v_m / u_*
$= h^{1/6} / (n\ g^{1/2})$ (n: Manning's coefficient of roughness)
$= C / g^{1/2}$ (C: Chezy's coefficient of roughness)
$= F_r / I^{1/2}$ (F_r: Froude number)

where

- h : Water depth
- I : River slope (I = 1/17,300)
- v_m : Mean velocity
- u_* : Shear velocity = $(g\ h\ I)^{0.5}$
- s : Specific gravity of bed material in water (assumed as s = 1.65)
- g : Acceleration of gravity (g = 9.80 m/sec^2)
- d : Particle size of bed material (d_{50} = 0.015 cm)

From the Figure it is clearly identified the difference in velocity coefficient or resistance to flow depending on the magnitude of shear stress. The shear stress represents the tractive force of flow and largely depends on the water depth. The relationship between τ_* and ϕ were further reproduced dividing the data into two, i.e., water-level group lower than +5.5 m, PWD and water-level group higher than that. These relationships were illustrated in Figures 5.2.16 and 5.2.17.

The velocity coefficients (ϕ) for the lower water-level group distribute horizontally around ϕ = 10. Referring to the empirical relations derived from river data in Japan, the lower water-level group seems to be under the bed-form of dune, bringing about high channel roughness. On the other hand the higher water-level group indicates the state of transition from dune-bed to flat-bed, and further to anti-dune bed. The channel roughness is very small under the flat-bed condition and sediment load is much. The boundary of dune-bed to flat-bed seems to be at around water level H = +5.5 m, PWD.

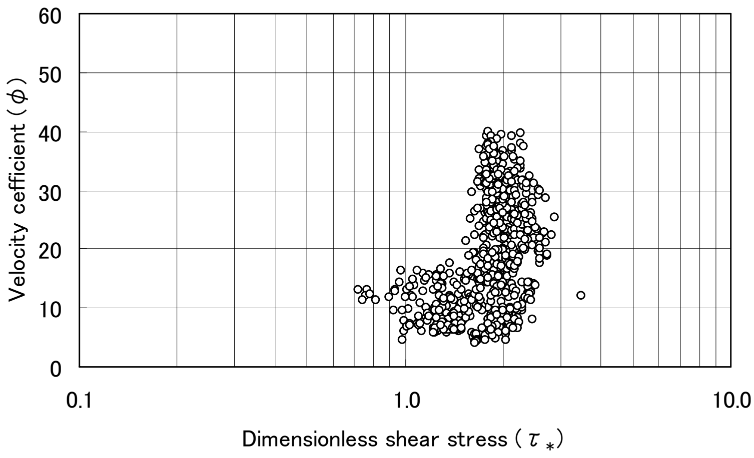


Figure 5.2.15 Relationship between τ· and ϕ at Baruria

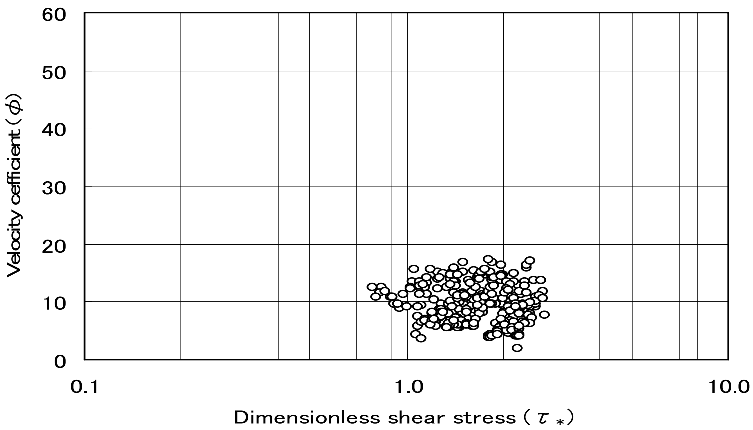


Figure 5.2.16 τ· - ϕ Relationship at Baruria (H < +5.5 m,PWD)

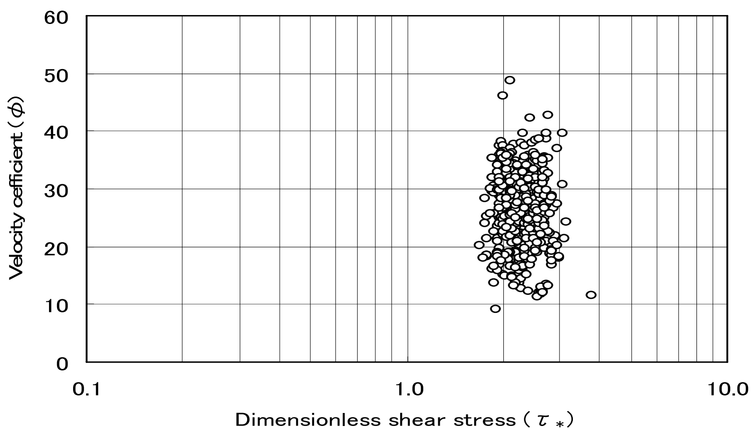


Figure 5.2.17 τ· - ϕ Relationship at Baruria (H > +5.5 m,PWD)

(3) Sediment Flow Conditions

General Process of Sediment Flows: The process of sediment flow in the river can be generalized by the relationship of shear stress of flow and the resistance to flow represented by the roughness (n) or velocity coefficient (ϕ). The bed materials start to move when the shear stress of flow exceeds critical value particular to the materials. As the water level rises increasing the shear stress, resistance to flow of river channel also increases forming ripples on riverbed. If the shear stress continues to increase, the resistance to flow increases further forming dunes on the riverbed. Under the dune-bed condition the resistance to flow reaches to the maximum. The high resistance to flow abruptly turns to low, when the riverbed changes to flat-bed or unti-dune conditions as the shear velocity increases.

Sediment Flow in Padma River: Because of fine bed material, the bed material of the Padma River can start to move even under the water flow of 30 to 40 cm in depth. Most of the sediments are transported as suspended load even during the rising period of water level. During the flood season the riverbed forms dune increasing the resistance to flow, and at the water level of around +5.5 m, PWD the dune-bed starts to turn to flat-bed. Under the bank-full flow condition, the riverbed at Baruria Station would be flat-bed and/or unti-dune with roughness of around n = 0.015.

5.3 ADDITIONAL RIVER AND MORPHOLOGIC STUDIES

Additional studies were made in this section mainly for Patria-Goalundo site (PG-site) and Mawa-Janjira site (MJ-site), in order to compare river and river morphologic features to select an optimum crossing location for Padma Bridge.

5.3.1 Displacement of Left and Right Banks

Displacement of riverbanks at PG-site and MJ-site was studied based on the old topographic maps in 1926 and 1960; and satellite images taken in 1973, 1984, 1993 and 2003. Locations of historical bank-lines were superimposed and shown in Figure 5.3.1. In the Figure, left bank-lines are shown in white lines and right bank-lines in yellow lines. Approximate crossing locations are also shown in the Figure.

Probably due to the eastward shifting, the left bank (eastern bank) of the Padma River seems to sticks to the eastern land where the Padma River has not flowed yet. Especially near Paturia and Mawa the bank-lines were superimposed on one line, which indicates that the left banks at these sites are markedly stable showing invisible bank-line movement at least during the data period of 78 years.

On the other hand, the right bank of the Padma River is changeable as a whole located on the unconsolidated past river course of the Padma River. It seems that the right bank moves to absorb the river width changes due to fluctuation of water and sediment flow conditions of the Padma River.

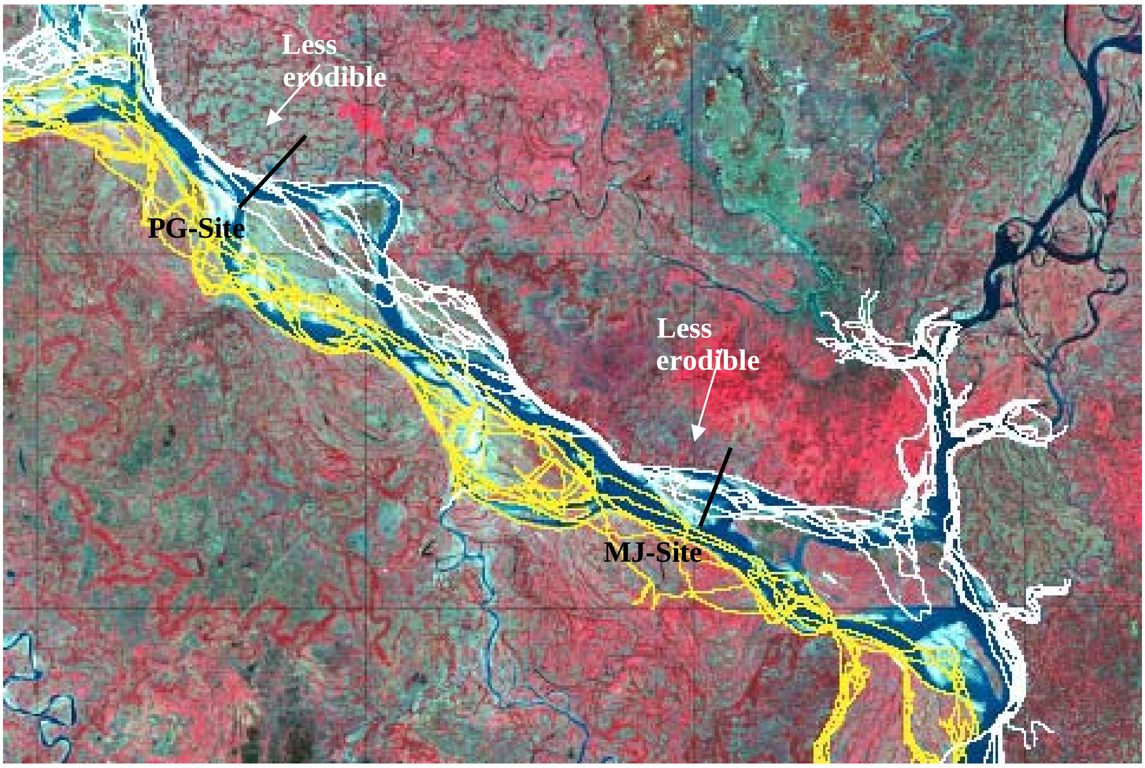


Figure 5.3.1 Displacement of Riverbanks along Padma River

5.3.2 Identification of Erosion Resistant Banks

Bank line shift of the Padma River is very active and its erosion rate is high as a whole. However, the erosion rate of the bank line is not uniform for its entire 100 km long stretch. In some locations the bank erosion rates are relatively low (5 to 20 m/year), and further there are a few locations where the bank erosion is markedly low (1 to 5 m/year) as mentioned earlier. The locations of low erosion rate are found even where the main flow of the Padma is along the bank. The bank erosion rate mainly depends on the texture of the bank materials, consolidation and mineralogical composition.

It is important to investigate different types of bank materials and their extent along the riverbanks of the Padma River, prior to the layout plan of the bridge, approach roads and river works for Padma Bridge.

In order to identify erosion resistant banks, Asian Institute of Technology (AIT, Bangkok) conducted a study under sublet contract with JICA Study Team. The study was carried out jointly with AIT and Center for Environmental and Geographic Information Services (CEGIS, Dhaka).

Major findings brought about by the study are summariz ed as follows:

1) The soil materials of floodplain and riverbank along the right bank are nearly uniform and composed of recently deposited unconsolidated sediments mostly consisting of fine sand and silt. The right bank is highly erodible, while any channel of the Padma River attacks the bank. The rate of bank erosion often reaches in the range of several hundred meters per year. The only exception is a patch of 'Tippera Surface' as designated by Coleman (1969), which consists of clay and silt, and relatively consolidated sediment. Rate of bank erosion in this area is much less compared to that of the unconsolidated floodplain.
2) Unlike the right bank, floodplain along left bank of the Padma River was not uniform in

terms of erodibility. Most of the floodplain is composed of Atria-Gur and 'Tippera Surface' sediments and less erodible. Ages of these flood plains are probably several hundred to several thousand years. Borehole data show that the sediments consist of clay, silt and find sand.

3) The exception is the left floodplain near Harirampur, which recently suffers from severe erosion in the scale of hundred meters per year. The left floodplain downstream of the Mawa, although it appears to be composed of 'Tippera Surface', was also found susceptible to erosion. Average rate of bank erosion is 20 to 40 m/years during the last three decades, which is between the observed erosion rates in the recently formed and the older floodplains upstream of Mawa.

As a result of the AIT-CEGIS study, Figure 5.3.2 was prepared to show the extent of the different categories of erodibility levels in consideration of bank materials and their distributions.

In the Figure, all the riverbanks of the Padma River are divided into three categories of erodibility levels; highly erodible, moderately erodible and less erodible. When the main channel of the Padma River attacks the bank, erosion rate would be more than a hundred meters per year along the highly erodible bank (red line), 20 to 50 m/year along the moderately erodible bank (yellow line), and 0 to 15 m/year along the less erodible bank (green line). It should be mentioned that even a moderately erodible bank can act as erosion resistant bank for a number of decades due to having a thin patch of clay deposits or while the bank is not attacked by an aggressive bend.

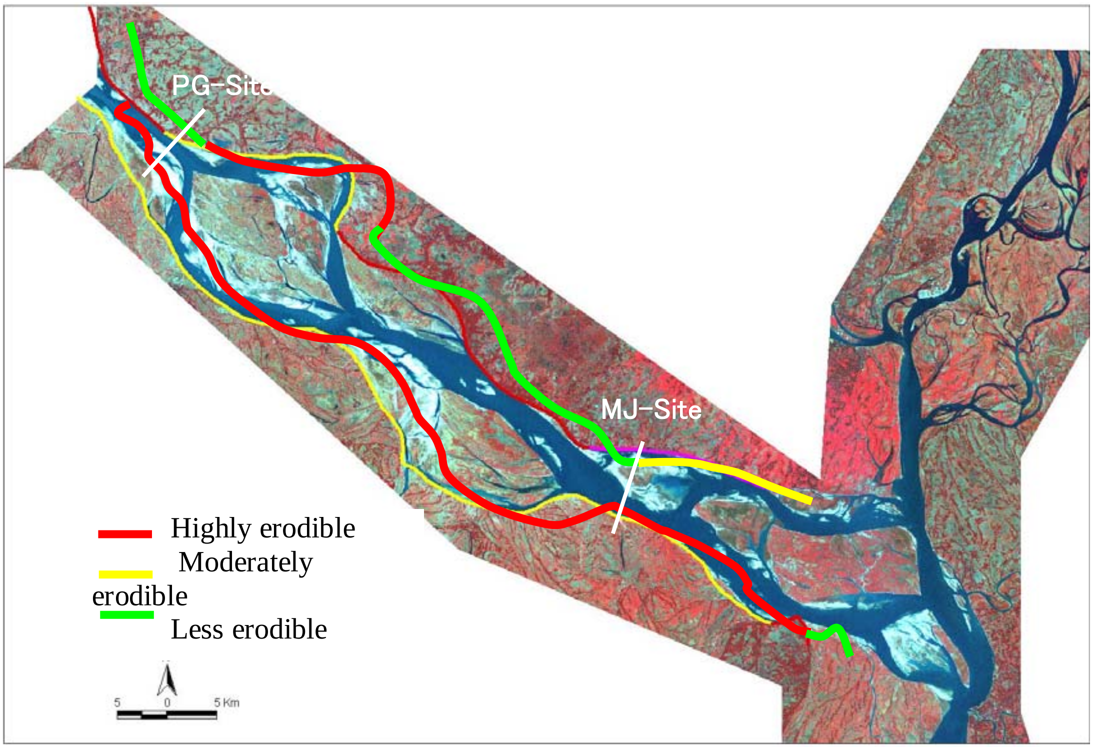


Figure 5.3.2 Distribution of Erodibility Levels of Riverbanks

5.3.3 River Channel

(1) Longitudinal Profile

Based on the cross sections surveyed in 1998/99, longitudinal profiles of the lowest riverbed, left and right riverbanks, and mean riverbed were prepared along the Padma River as shown in Figure 5.3.3.

Since the mean riverbed generally represents hydraulic sectional characteristics of the river, riverbed slope was delineated on the profile of the mean riverbed. The riverbed slope is 1/15,800 (or 6.3 cm/km) from Hardinge bridge of the Ganges River to about 1.3 km downstream of MJ-site of the Padma River. Within the stretch, PG-site and MJ-site are included. In the downstream reaches of the stretch, the Padma and the Lower Meghna rivers have very gentle bed slope as 1/50,200 (or 2.0 cm/km).

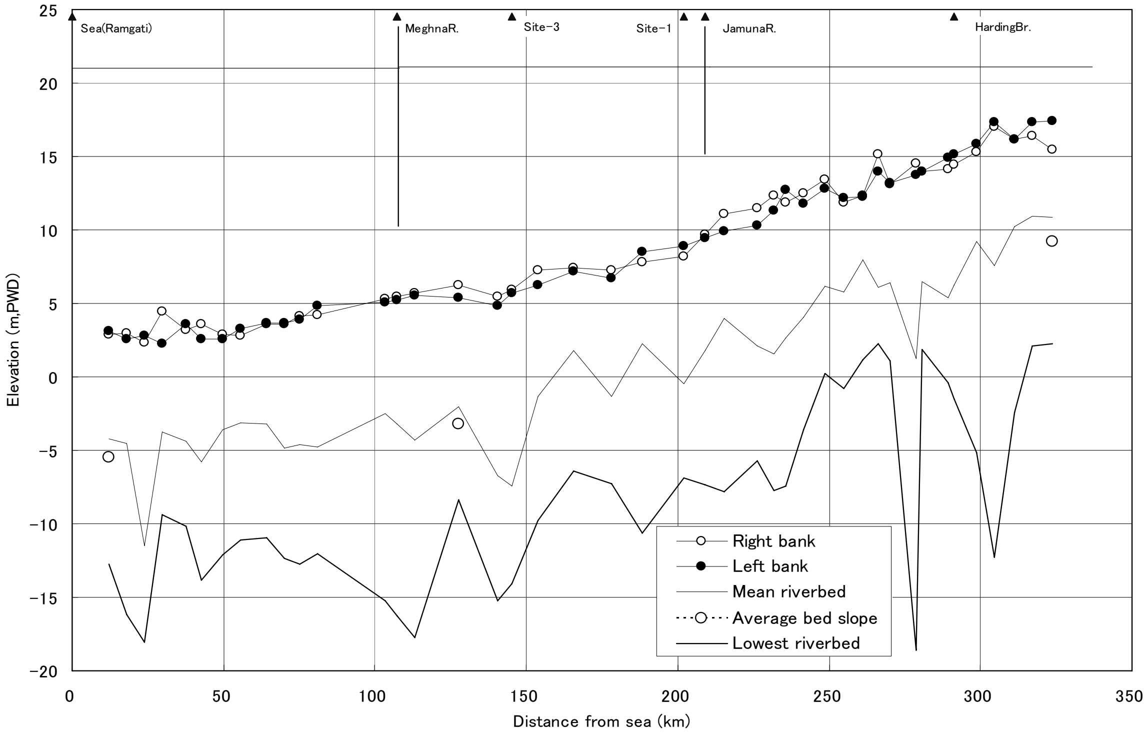


Figure 5.3.3 Longitudinal Profile of Meghna-Padma-Ganges River: 1998/99

(2) Study on River Section Data

According to periodical survey data of the BWDB, the river section nearest to PG-site is CS-P7 at about 4 km downstream of PG-site, and that nearest to MJ-site is CS-P2.1 almost at MJ-site. Historical changes and hydraulic characteristics of these river sections were studied as presented below.

Historical Changes of CS-P7: Section data are available for 33 years from 1969 to 2001 for CS-P7. The maximum extent of river is about 8.0 km during the data period. Left bank of the main stream almost stayed at the same location during the past 33 years, and the river sections could be divided into three periods of similar sectional patterns mainly depending on the location of right bank as shown in Table 5.3.1.

Table 5.3.1 Historical Changes of CS-P7

Period (year)	River width (km)	sand bar on left bank	Lowest riverbed (m,PWD)	Lowest riverbed Location
1969-73	8.0 (wide)	Small	– 8.34	L, C or R
1974-86	5.5 (narrow)	Small	–13.20	L or R
1992-01	6.5 (medium)	Small	–12.14	L

(Remark) L, C and R stand for left, center and right side of the channel section.

Considering the close location to PG-site, the river section at the crossing location would be similar to CS-P7 with a little narrower width.

Historical Changes of CS-P2.1: River sections at CS-P2.1 could be divided into four periods of similar sectional patterns, according to the BWDB data available for 32 years from 1968 to 1999. Although the locations of perennial channel move to left and right within the maximum extent of river of about 6.5 km, the river keeps relatively narrow width ranging from 3.5 to 4.5 km as summarized in Table 5.3.2.

Table 5.3.2 Historical Changes of CS-P2.1

Period (year)	River width (km)	sand bar on left bank	Lowest riverbed	
			(m,PWD)	Location
1968-76	3.5	Medium	–15.09	C
1977-89	4.5	Large	–14.42	C or R
1993-95	3.5	Small	–28.31	L
1997-99	4.0	Large	–21.66	C

(Remark) L, C and R stand for left, center and right side of the channel section.

The left riverbank stayed almost at the same location during the data period. It is noted that the sections from 1993 to 95 showed markedly different sectional pattern from others with extremely deep water depth close to the left bank. During this period, the main flow of the Padma River took almost along the present South Channel behind Char Kawrakandi.

Sectional pattern of MJ-site would be the same as those of CS-P2.1, since the locations are close each other.

Hydraulic Characteristics: Hydraulic channel characteristics of CS-P7 near PG-site and CS-P2.1 near MJ-site were analyzed using the same data discussed in the above. Results of the analysis are shown in Table 5.3.3 for CS-P7 and Table 5.3.4 for CS-P2.1.

Table 5.3.3 Hydraulic Channel Characteristics (CS-P7)

Y･M･ CS	Bankfull	MeanBed	LowestB	Area	Width	Dmean	Dmax	Qlow	Qtotal	hx/hm
	m,PWD	m,PWD	m,PWD	m^2	m	m	m	m^3/s	m^3/s	
6902P7	7.56	0.28	-8.03	56,386	7,744	7.282	15.590	112,000	112,000	2.14
7003P7	7.56	-0.03	-8.20	59,080	7,779	7.595	15.764	121,000	121,000	2.08
7012P7	7.56	1.39	-5.25	47,191	7,653	6.166	12.813	84,000	84,000	2.08
7202P7	7.56	-0.64	-8.34	63,779	7,775	8.203	15.905	138,000	138,000	1.94
7301P7	7.56	0.51	-7.98	54,325	7,710	7.046	15.539	106,000	106,000	2.21
7312P7	7.56	1.28	-6.48	48,534	7,728	6.280	14.042	88,000	88,000	2.24
7412P7	7.56	1.33	-4.61	47,633	7,650	6.227	12.170	86,000	86,000	1.95
7512P7	7.56	-0.28	-8.79	41,608	5,310	7.836	16.347	87,000	88,000	2.09
7707P7	7.56	-1.63	-13.20	49,179	5,351	9.191	20.764	114,000	115,000	2.26
7712P7	7.56	-0.27	-7.06	42,095	5,379	7.826	14.624	88,000	88,000	1.87
7911P7	7.56	-1.31	-10.45	47,334	5,339	8.865	18.005	108,000	108,000	2.03
8104P7	7.56	0.62	-8.80	37,829	5,453	6.937	16.362	73,000	73,000	2.36
8202P7	7.56	0.78	-6.05	36,297	5,352	6.783	13.612	69,000	69,000	2.01
8311P7	7.56	-0.16	-12.91	41,372	5,360	7.718	20.465	86,000	86,000	2.65
8412P7	7.56	-0.63	-9.52	44,544	5,440	8.188	17.075	96,000	96,000	2.09
8702P7	7.56	0.30	-5.73	41,566	5,727	7.259	13.290	83,000	83,000	1.83
8904P7	7.56	-1.07	-9.37	48,876	5,663	8.631	16.929	109,000	109,000	1.96
9208P7	7.56	0.46	-6.67	43,330	6,102	7.101	14.227	85,000	85,000	2.00
9305P7	7.56	1.49	-8.62	37,428	6,163	6.072	16.181	66,000	66,000	2.66
9501P7	7.56	2.86	-1.95	29,362	6,250	4.698	9.509	44,000	44,000	2.02
9602P7	7.56	0.04	-12.14	45,872	6,104	7.515	19.700	93,000	93,000	2.62
9711P7	7.56	0.91	-7.92	42,107	6,330	6.652	15.480	79,000	79,000	2.33
9802P7	7.56	-0.88	-8.06	53,490	6,340	8.437	15.620	118,000	118,000	1.85
9812P7	7.56	0.52	-6.88	44,420	6,310	7.040	14.440	87,000	87,000	2.05
0001P7	7.56	0.27	-7.94	47,446	6,510	7.288	15.500	95,000	95,000	2.13
0201P7	7.56	0.81	-8.51	39,847	5,900	6.754	16.070	76,000	76,000	2.38
Ave	7.56	0.27	-8.06	45,805	6,324	7.292	15.616	91,962	92,038	2.15

Table 5.3.4 Hydraulic Channel Characteristics (CS-P2.1)

Y･M･ CS	Bankfull	MeanBed	LowestB	Area	Width	Dmean	Dmax	Qlow	Qtotal	hx/hm
	m,PWD	m,PWD	m,PWD	m^2	m	m	m	m^3/s	m^3/s	
6812P21	5.71	-3.37	-14.39	28,952	3,187	9.083	20.103	67,000	71,000	2.21
7001P21	5.71	-5.24	-10.56	32,917	3,005	10.952	16.274	86,000	89,000	1.49
7102P21	5.71	-4.66	-10.89	33,966	3,274	10.373	16.597	86,000	89,000	1.60
7205P21	5.71	-3.65	-10.24	27,917	2,982	9.362	15.948	66,000	66,000	1.70
7303P21	5.71	-3.67	-12.68	31,652	3,376	9.376	18.393	75,000	75,000	1.96
7402P21	5.71	-4.74	-15.09	26,175	2,505	10.450	20.798	66,000	67,000	1.99
7504P21	5.71	-6.16	-13.21	31,317	2,638	11.869	18.923	86,000	87,000	1.59
7602P21	5.71	-6.01	-9.17	32,805	2,800	11.717	14.878	90,000	91,000	1.27
7704P21	5.71	-4.05	-12.54	30,850	3,161	9.759	18.250	75,000	76,000	1.87
7802P21	5.71	-3.08	-14.28	32,879	3,741	8.790	19.990	74,000	74,000	2.27
7912P21	5.71	-3.91	-9.83	29,893	3,108	9.618	15.536	72,000	73,000	1.62
8102P21	5.71	-4.03	-12.05	35,354	3,631	9.736	17.765	85,000	86,000	1.82
8203P21	5.71	-1.59	-10.21	28,665	3,924	7.304	15.920	57,000	57,000	2.18
8403P21	5.71	-2.47	-14.42	33,209	4,061	8.178	20.131	71,000	72,000	2.46
8501P21	5.71	-2.75	-10.18	39,075	4,621	8.455	15.887	86,000	87,000	1.88
8905P21	5.71	-1.51	-5.13	22,068	3,057	7.219	10.835	44,000	45,000	1.50
9301P21	5.71	-2.48	-21.74	35,700	4,361	8.187	27.445	77,000	77,000	3.35
9401P21	5.71	-4.66	-28.31	35,908	3,464	10.366	34.022	91,000	92,000	3.28
9510P21	5.71	-1.21	-4.70	21,859	3,161	6.916	10.412	42,000	43,000	1.51
9703P21	5.71	-6.23	-21.66	47,331	3,965	11.937	27.370	131,000	132,000	2.29
9803P21	5.71	-5.29	-15.09	44,361	4,032	11.002	20.800	116,000	117,000	1.89
9907P21	5.71	-4.91	-14.10	44,371	4,178	10.619	19.810	114,000	115,000	1.87
Ave	5.71	-3.89	-13.20	33,056	3,465	9.60	18.91	79,864	80,955	1.98

River Sections Surveyed by Study Team: JICA Study Team conducted leveling survey in August 2003 along the proposed routes of approach roads and bridge across the Padma River at PG-site and MJ-site. The survey results are shown in Figures 5.3.4 and 5.3.5 for PG-site and MJ-site, respectively. In the figures, water levels such as DHWL, SHWL, MWL and SLWL are also shown in comparison.

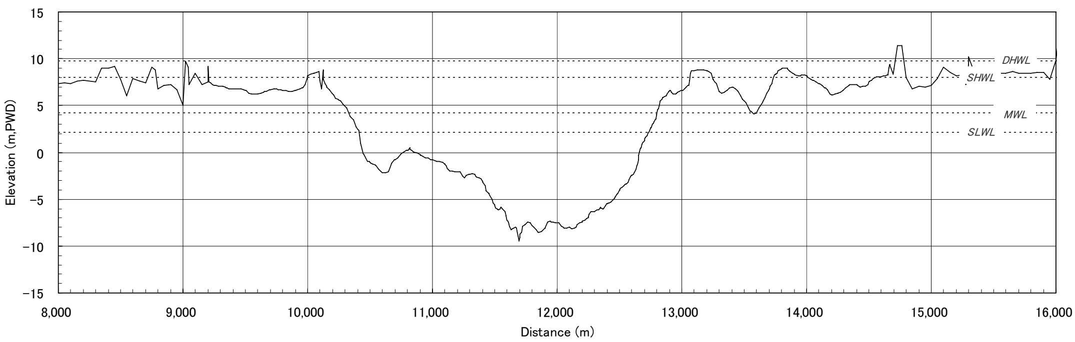


Figure 5.3.4 Cross Sectional Survey across PG-site

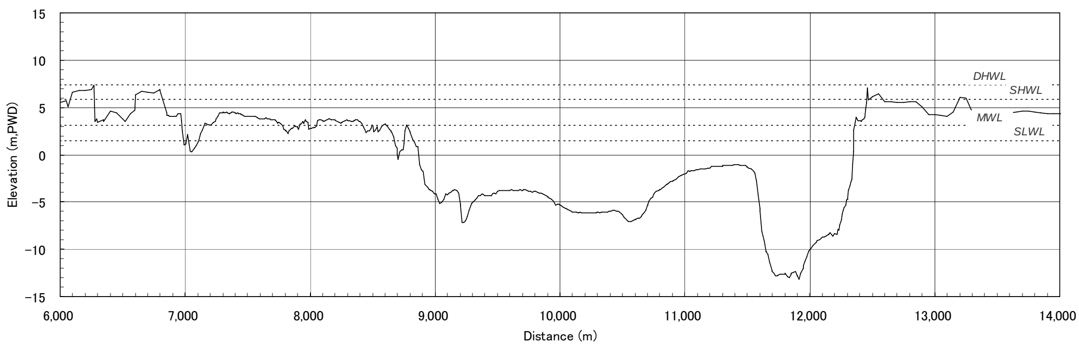


Figure 5.3.5 Cross Sectional Survey across MJ-site

(3) Normal River Width

Lacey's Formula: The following formula gives minimum stable river width of alluvial rivers. The formula was originally proposed by G. Lacey based on studies on rivers in India and Pakistan:

$$W = C\sqrt{Q}$$

in which W is the net surface river width corresponding to design discharge Q, and C is a coefficient originally proposed C=4.84 (in meter-second units) by Lacey for sand-bed river. According to the preliminary estimate, bank-full discharge is 92,000 m3/s at CS-P7 and 80,000 m3/s at CS-P2.1. Design discharge estimated for 100 year probable flood is 151,400 m3/s at CS-P7 and 134,400 for m3/s at CS-P2.1.

Applying Lacey's formula to the Padma River, the stable river widths were estimated as shown below. On the other hand, low-water channel width of the surveyed section is 6,300 m for CS-P7 ranging from 5,300 to 7,800 m, and 3,500 m for CS-2.1 ranging from 2,500 to 4,600 m. Actual river width of the Padma River is far wide comparing to the estimated stable width.

Cross section	Lacey's stable width (W)			
	For bank-full discharge (Q_b)		For design discharge (Q_{100})	
	Q_b (m^3/s)	W(m)	Q_{100} (m^3/s)	W(m)
CS-P7	92,000	1,500	151,400	1,900
CS-P2.1	80,000	1,400	134,400	1,800

Coefficient C for Padma River: In order to find out the Lacey's coefficient corresponding to the conditions of the Padma River at the candidate bridge sections, the coefficient C were estimated under the bank-full flow conditions as follows:

Cross section	Bank-full Qb (m^3/s)	LW ch. width Ave. (range: m)	Coefficient C Ave. (range: m)
CS-P7 (BWDB section)	92,000	6,300(5,300-7,800)	20.8(17.5-25.7)
CS-P2.1 (BWDB section)	80,000	3,500(2,500-4,600)	12.4(8.8-16.3)
PG-site (JICA survey)	81,000	3,000	10.5
MJ-site (JICA survey)	99,000	3,700	11.8

The C-value estimated for CS-P7 is quite different from those of CS-P2.1 and PG- and MJ-sites. The C-values for PG-site and MJ-site were assumed commonly at C = 12. Applying this to the design discharge, the normal river widths were estimated as follows:

Site	Design discharge	Normal width
PG-site	151,400 m^3/s	4,700 m
MJ-site	134,400 m^3/s	4,400 m

5.3.4 Preliminary Estimate of Maximum Scour Depth

(1) Recorded Lowest Riverbed

Periodical river survey results of CS-P7 and CS-P2.1 were used for the study of the maximum scour depth at the crossing location.

These survey results, however, are mostly of dry season. In order to clarify the difference of riverbeds between dry and rainy seasons, the deepest water records at Baruria and Mawa stations obtained during the time of discharge measurements were also studied, though these depths are of approximate ones. Locations of these survey sections and flow gauging stations are shown below.

Crossing location	Survey section	Flow gauging station
PG-site	CS-P7: About 4 km downstream of the site	Baruria: Almost the same location with the site
MJ-site	CS-P2.1: Almost the same location with the site	Mawa: Almost the same location with the site

Historical lowest riverbed data are plotted in Figures 5.3.6 and 5.3.7, respectively for PG-site and MJ-site for both data from river survey and discharge measurements.

Records at CS-P7 near PG-site: As to CS-P7 near PG-site, river survey and discharge measurement data accord relatively well up to the year 1996, but after the year the discharge measurement data show lower riverbed elevations than those of river survey due to unknown reasons.

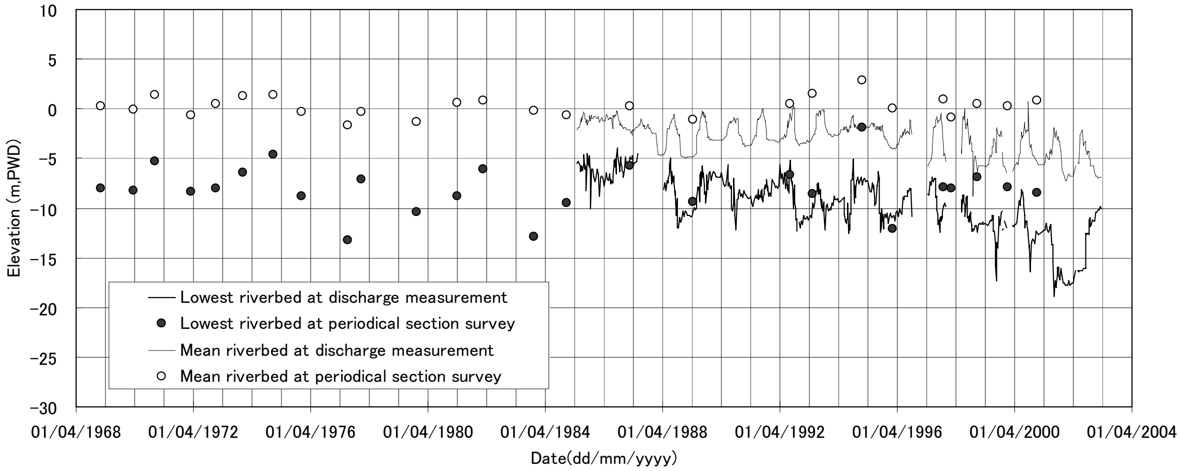


Figure 5.3.6 Historical Lowest Riverbed at CS-P7

The lowest riverbed elevation during the data period (Table 5.3.1) was -13.2 m,PWD according to the river survey data, and that of discharge measurement was -20 m,PWD.

Records at CS-P2.1 near MJ-site: As to CS-2.1 near MJ-site, riverbed elevations from two sources could not be compared, since river survey data were available mostly in low water season and discharge measurements were not conducted during the low water season at Mawa Station.

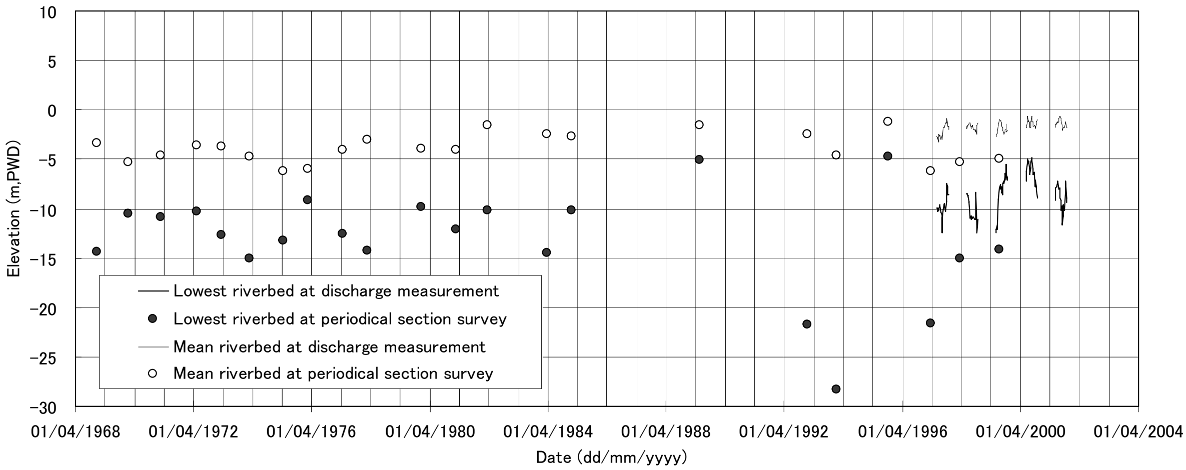


Figure 5.3.7 Historical Lowest Riverbed at CS-P2.1

According to the river survey data by BWDB (Table 5.3.2), the lowest riverbed was recoded as low as -28.3 m,PWD followed by two records of -21.7 m,PWD. These low riverbeds were recorded in the period from 1993 to 1997. Except for this period, the lowest riverbed at Mawa was -15.1 m,PWD.

(2) Preliminary Estimation of Maximum Scour Depth for Alternative Study

Method of Estimation: Maximum scour depth was estimated preliminary for the facility design necessary for the alternative study to select an optimum crossing location. The same method and standards adopted for the design of Jamuna Bridge and pre-feasibility study of Padma Bridge were applied for this purpose, considering the confluence scour, bend scour and local scour around river works and bridge piers.

The bend scour is considered for the riverbed adjacent to riverbank and the confluence scour for the other portion of the riverbed. The bend scour is caused by the possible stream bend, and the extent of scour is assumed to be 300 m wide from the riverbank. The confluence scour is caused by the turbulence of flows generated by the confluence of two streams, i.e., the Ganges and Jamuna rivers at PG-site and the southwestern and northeastern channels of Char Kawrakandi at MJ-site.

The scoured riverbed due to bend would be scoured further when riverbank is provided by bank protection works (BPW). Furthermore, the riverbed around the bridge pier would be scoured locally.

Result of Estimation: Maximum scour depths estimated by the empirical formulas are summarized in Table 5.3.5. The estimated maximum scour depths are deep enough comparing to the recorded lowest riverbeds.

Table 5.3.5 Preliminarily Estimated Maximum Scoured Depth

Location	Items	PG-Site Q_{100} = 151,400 m^3/s H_{100} = 9.72 m,PWD		MJ-Site Q_{100} = 134,400 m^3/s H_{100} = 7.35 m,PWD	
		Depth (m)	El. (m,PWD)	Depth (m)	El. (m,PWD)
Near bank	Scour due to bend & BPW	43.5	-33.8	44.9	-37.5
	Scour due to pier (Φ3m)	49.0	-39.3	50.4	-43.0
Middle river	Scour due to confluence	32.8	-23.1	33.7	-26.4
	Scour due to pier (Φ3m)	38.3	-28.6	39.2	-31.9

(Remarks) Depth: Water depth below DHWL; EL: Scoured riverbed elevation

The scour depths estimated in this sub-section are to be applied to the preliminary facility design for selection of an optimum site only. The scour depth shall be studied further for the optimum site selected finally.

5.4 FURTHER STUDIES ON ERODIBILITY OF RIVERBANK

Further studies on the erodibility of riverbank were made specifically for Mawa-Janjira site (MJ-site) finally selected for crossing of Padma Bridge.

5.4.1 Historical River Course Shifting

(1) Data and Methodology

Historical maps and satellite images were collected additionally as shown in Table 5.4.1. The historical maps collected cover the period from 1776 to 1963 and the satellite images from CORONA in 1967 to LANDSAT in 2003. In addition to these, aerial photos taken in December 1998 and November 1989 were also referred.

Adjusting the coordinates and clear land marks carefully, maps and satellite images were superimposed each other and historical plan form changes of the Padma River were studied for the neighboring stretch of crossing location at MJ-site.

Table 5.4.1 Old maps and Satellite Images Collected

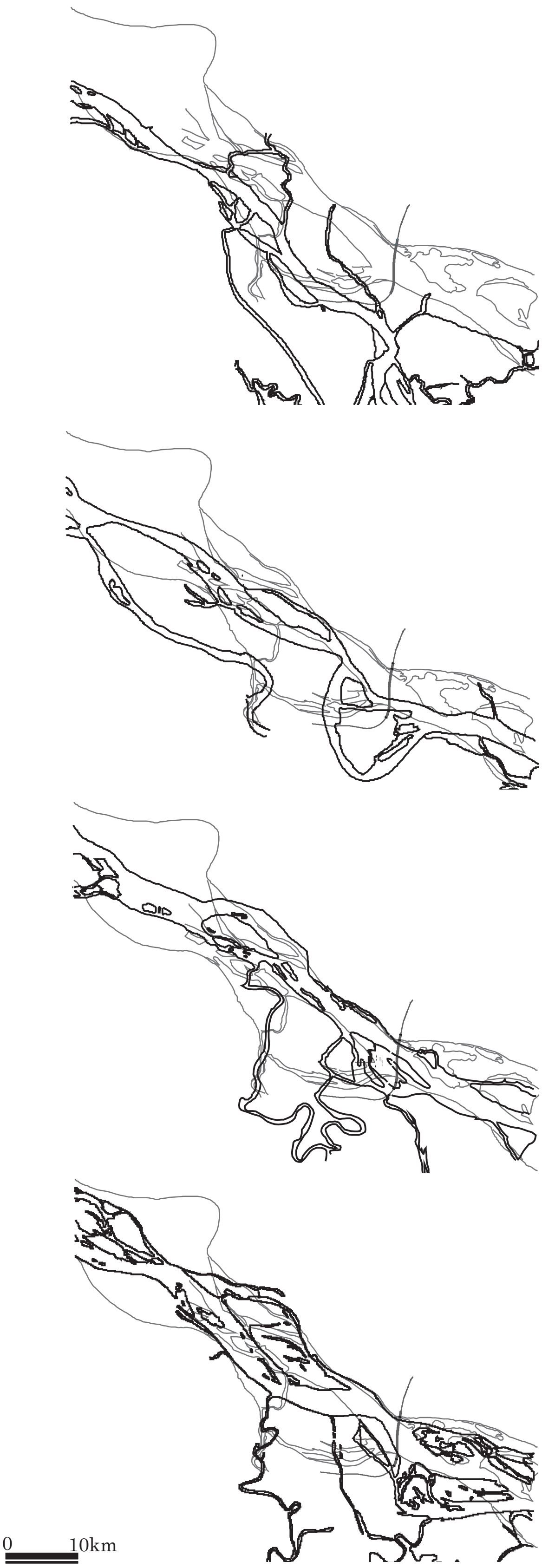
Year	Date	Type
1776	(Published year)	
1860	(Published year)	
1914	(Published year) 1904-1913:surveyed	Topography
1938-42		Bank line survey
1952/53	Dec/1952 - Jan/1953	Bank line survey
1960		Topography
1963		Bank line survey
1967		CORONA
1973	10 Mar. & 21 Feb.	Landsat
1980	02 Feb. & 21 Feb.	Landsat
1984	19 Mar. & 23 Feb.	Landsat

Year	Date	Type
1989	Feb.	Landsat
1989	04 Nov.	Landsat
1993	15 Jan.	Landsat
1996	18 Feb.	Landsat
1997	26 Jan. & 18 Feb.	Landsat
1998	Dec.	Aerial photo
1999	01 Feb. & 28 Mar.	Landsat
2000	28 Feb.	Landsat
2001	29 Jan.	Landsat
2002	Feb.	Landsat
2003	19 Jan.	Landsat

(2) Long-Term River Course Shifting

Figure 5.4.1 shows the long-term river course shifting since 1776 (228 years ago) based on the historical topographic maps in reference to plan-form in 2003. From this figure, one can find the following:

1) In 1776-map, the old Padma River took river course almost along the present Arialkhan River and it changed to the present river course as seen in 1860-map.
2) Since 1860, the Padma River shifted gradually toward northeast.
3) Since 1914 at latest, main stream of the Padma River has kept present river course at the crossing location, stuck to the less erodible left bank.



1776 (228 years ago)

1860 (144 years ago)

1914 (90 years ago)

1963 (31 years ago)

Figure 5.4.1 Long-Term River Course Shifting

(3) Recent River Course Shifting

Figure 5.4.2 shows changes and evolutions of riverbanks, main stream and sand bar (char) during recent years since 1960 with shorter time intervals. From the figure, following behaviors of the Padma River were found:

1) Since 1960, the Padma River at MJ-site has maintained a single channel section with no char. Though the period of data is limited, the Padma River seems to alternate meandering river and straight river courses, having node at the crossing location.
2) The meandering river develops gradually as the main stream upstream from the crossing location moves westward. The development peaks of meandering took place in around 1967 and 1993 when the South Channel got most active.
3) The straight river course appears when the meandering channel becomes inactive or extinct and the straight channel along the less erodible left bank becomes active. The most typical straight river course is found in around 1980.
4) According to the above data, it took about 13 years to change from the peak of meander river (1967) to that of straight river (1980) and took another 13 years to return to the peak of meander river (1993) with a cycle time of 26 years.
5) Along with the alternate process of meandering and straight river courses, riverbanks of the Padma were eroded or sand bars/islands were developed as outlined below.
   - **1960-1967:** The Padma River upstream from the crossing location gradually activates meandering, eroding right bank and developing sand bar on left side bank.
   - **1967-1980:** Upstream from the crossing location, former straight channel along the less erodible left bank was activated and became main stream with straight plan form, while the meander channel was gradually buried with sediment.
   - **1980-1993:** In response to the development of sand bar upstream from Narisha, the main stream started to meander again. Due to the channel meandering toward right bank upstream from the crossing location, left bank downstream from the crossing location was eroded and sandbar developed on the opposite bank (right bank).
   - **1993-2003:** The left sub-channel along the less erodible bank gradually became active upstream from the crossing location. Until the year around 1997, erosion on the left bank and development of sand bar on the right bank downstream from the crossing location are still active. In around 2000, flow of the straight channel prevails over that of the meander channel and sedimentation on the left bank and erosion on the right bank downstream from the crossing location were started.
   - **Present:** Judging from the findings mentioned above, the Padma River around the crossing location would be in the transition from the meandering to straight river course. Downstream from the crossing location, the right bank erosion and the left bank sedimentation are continuing. This tendency would continue for several years.
6) The Padma River experienced big flood events in 1987, 1988 and 1989. However, significant influences were not identified with regard to the plan-form change by these flood events.

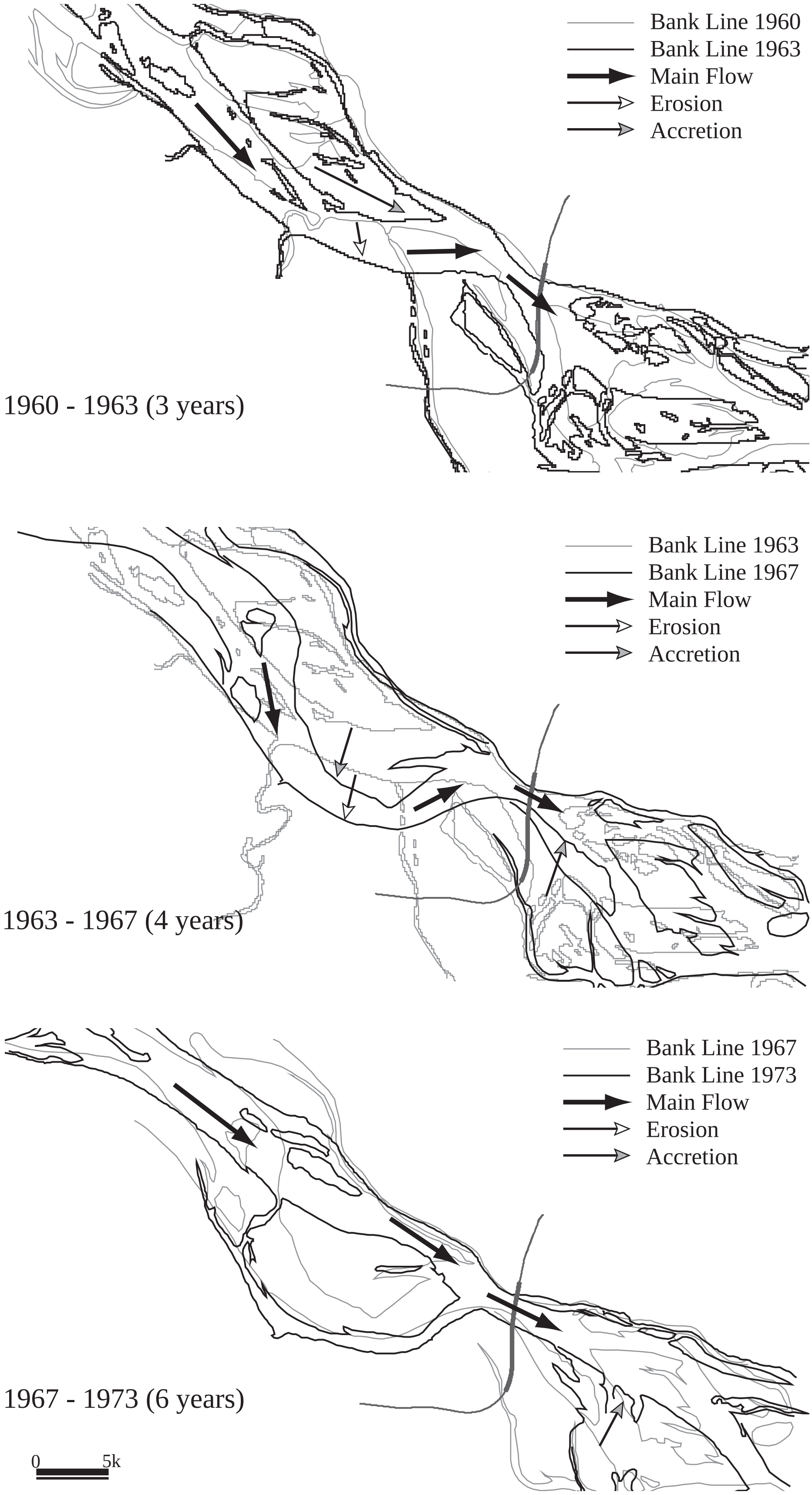
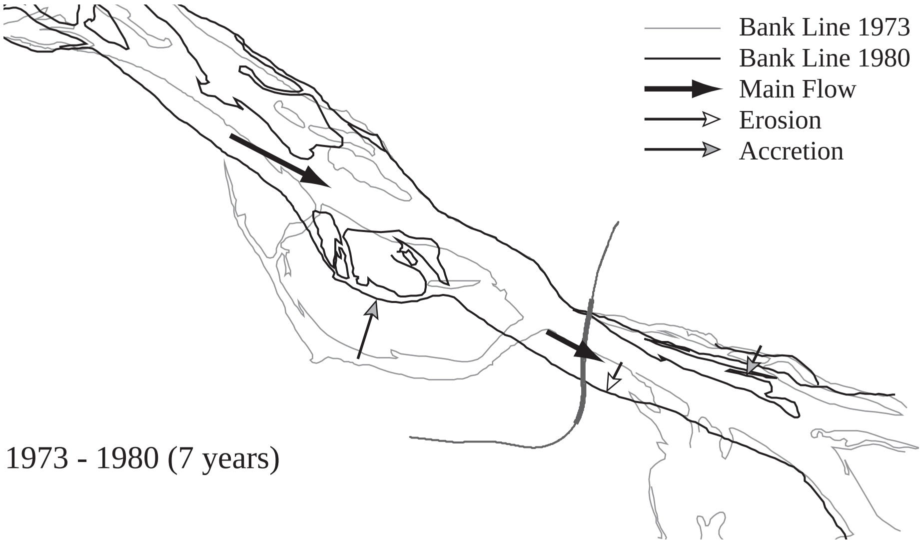
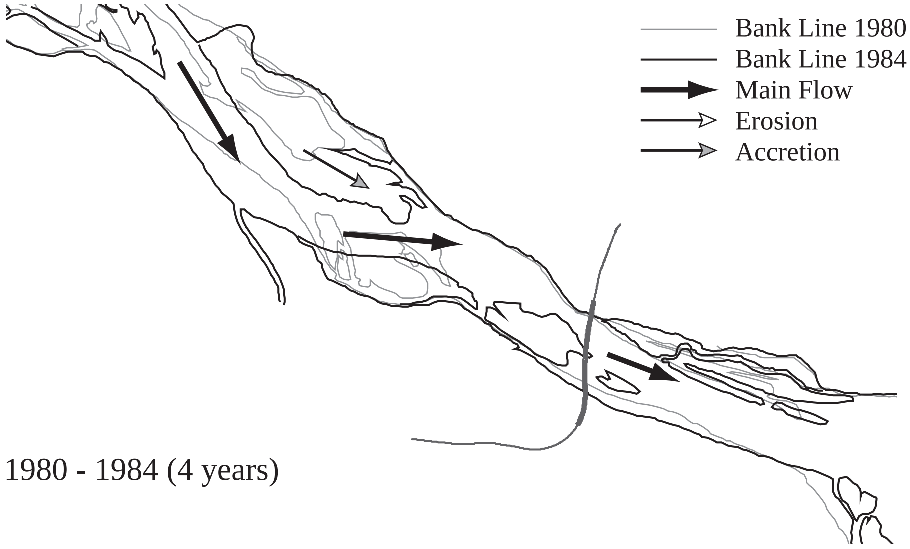


Figure 5.4.2 Recent River Course Shifting (1/4)





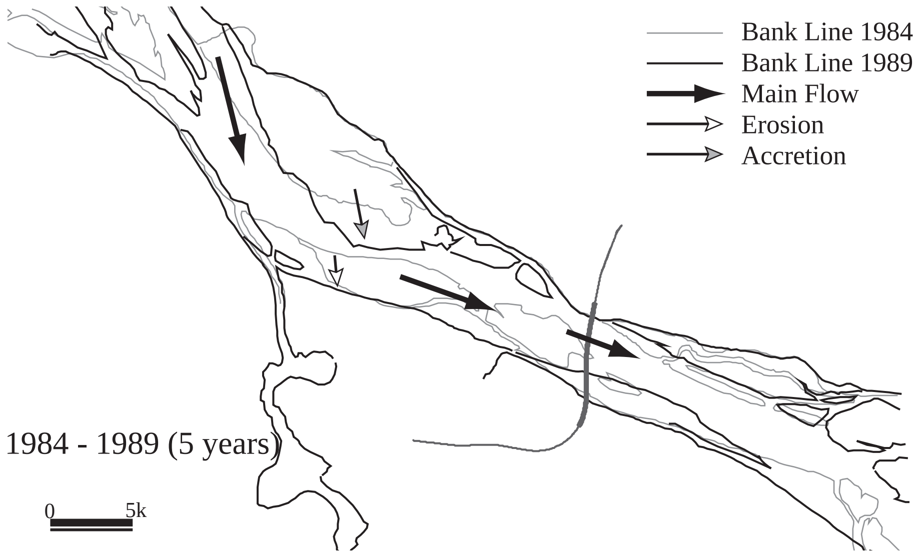


Figure 5.4.2 Recent River Course Shifting (2/4)

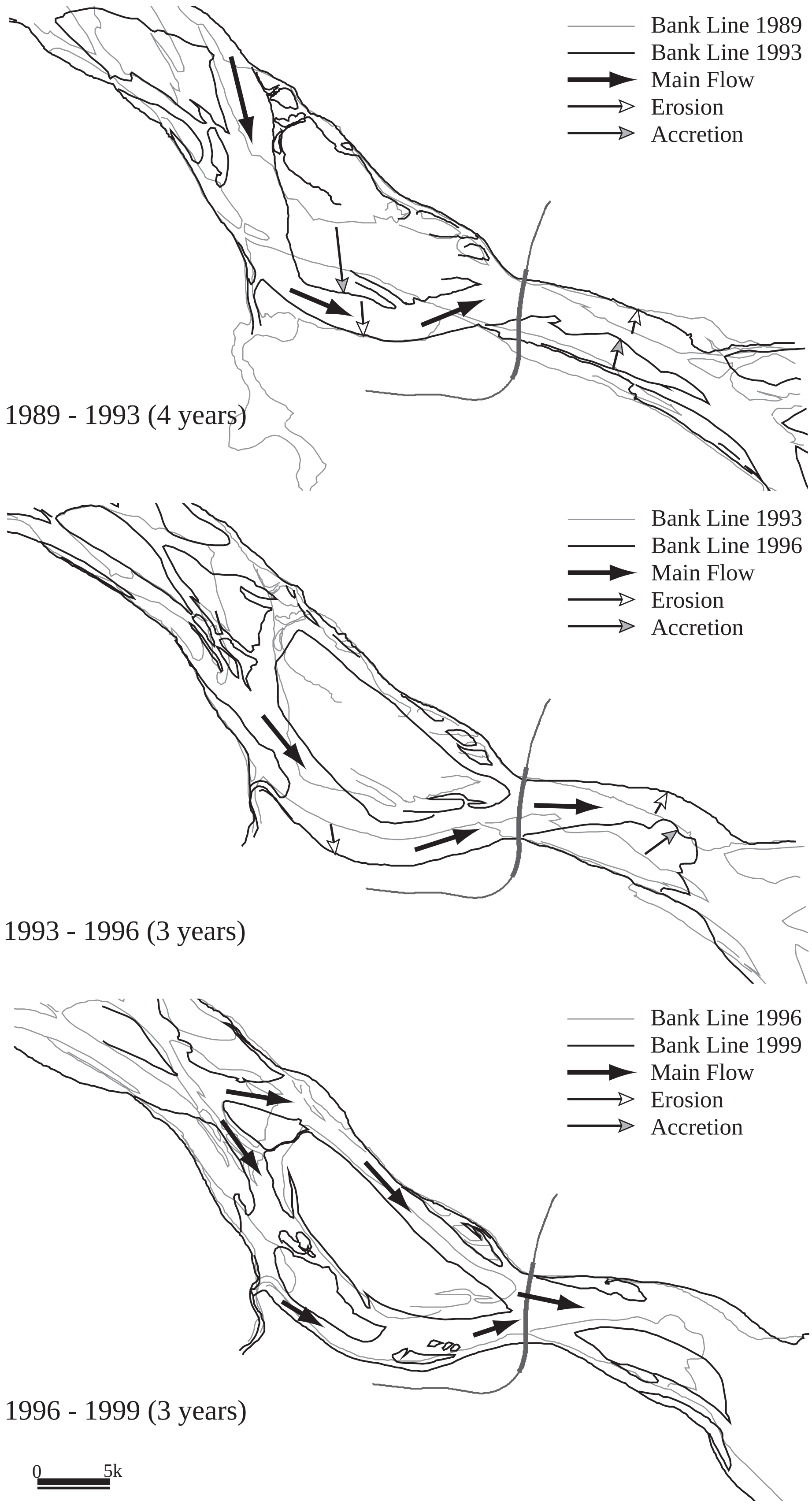


Figure 5.4.2 Recent River Course Shifting (3/4)

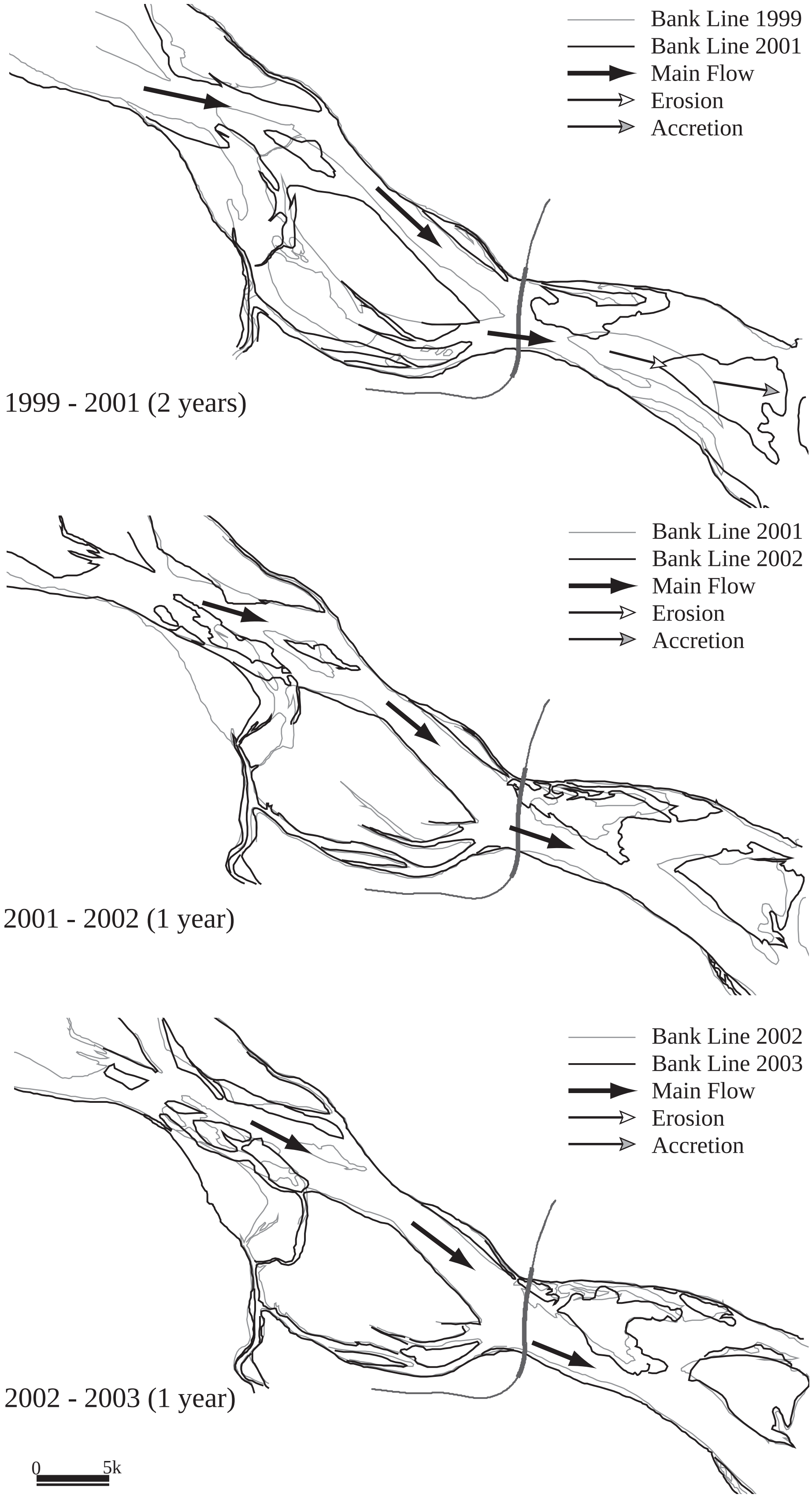


Figure 5.4.2 Recent River Course Shifting (4/4)

5.4.2 Rate of Riverbank Change

(1) Data and Methodology

In order to estimate the erosion rate of the riverbanks around the crossing location, periodical river survey data by BWDB were studied. Cross sections selected for the study are CS-P2.0 and CS-P2.1 located downstream from the bridge site, and CS-P3.0, CS-P3.1 and CS-P4.0 upstream from the bridge site, for the period of 33 years from 1968/69 to 2000/01. Locations of the selected survey sections are shown in Figure 5.4.3.

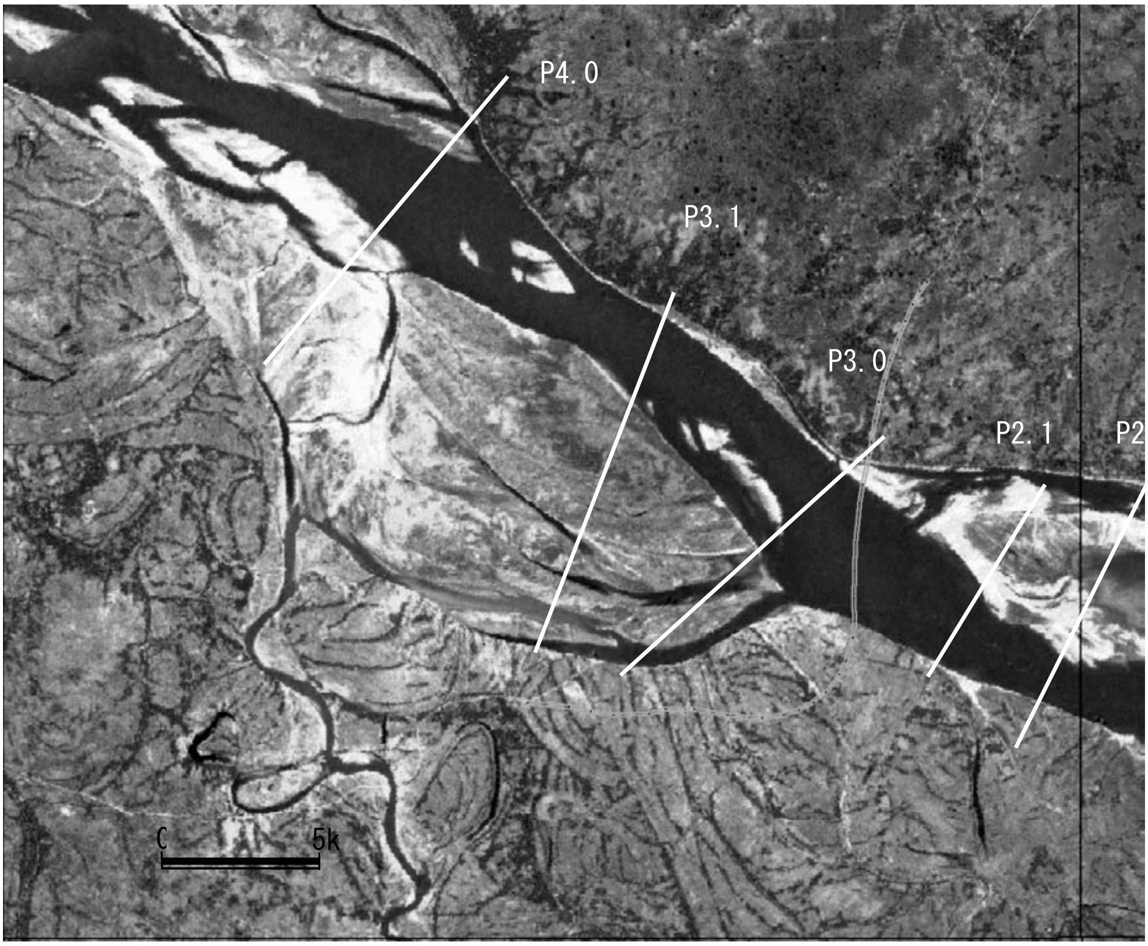


Figure 5.4.3 Periodical Survey Sections by BWDB near Crossing Location

Locations of survey stakes were examined and extent of survey and sectional forms of river were checked with maps and satellite images. Then the locations of riverbank were identified and summarized in the following diagrams:

1) Rate of riverbank changes
2) Yearly changes of riverbank

(2) Erosion Rate of Left Bank

For the selected sections, erosion rate of less erodible riverbank was studied. For this purpose locations of left bank (natural levee) regardless of attached bars were identified and shown in Figure 5.4.4 setting the reference year in 1972. From the figure, following are found:

1) Historical change of left riverbank at CS-P3.0 which is most close to the crossing

location on left bank indicates average erosion rate of 5 m/year for the whole data period, though it is 8 m/year for early 13 years until 1985 and 1.5 m/year for recent 15 years. Judging from the plan forms of the Padma River, the higher erosion rate seems to be caused by collision of meander flow from the South Channel and protrusion of riverbank to straight river flow.

2) The bank erosion at CS-P3.1 located upstream from the crossing location is small. The riverbank at P4.0 did not suffer from erosion during the data period because of the existence of sand bars in front.
3) The bank erosion at CS-P2.1 downstream from the crossing location was large for the period from 1989 to 1993 probably caused by collision of meander flow from the South Channel, though the natural levees are not always distinct for CS-P2.1 and CS-P2.0.

Figure 5.4.5 shows the yearly changes of left riverbank. According to the figure, the maximum amount of erosion during a flood season is more or less 20 m.

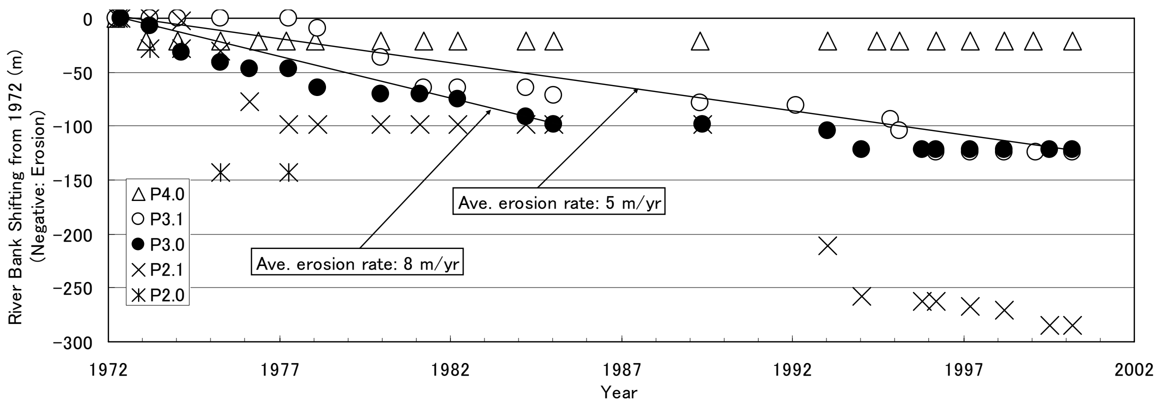


Figure 5.4.4 Average Erosion Rate of Left Bank

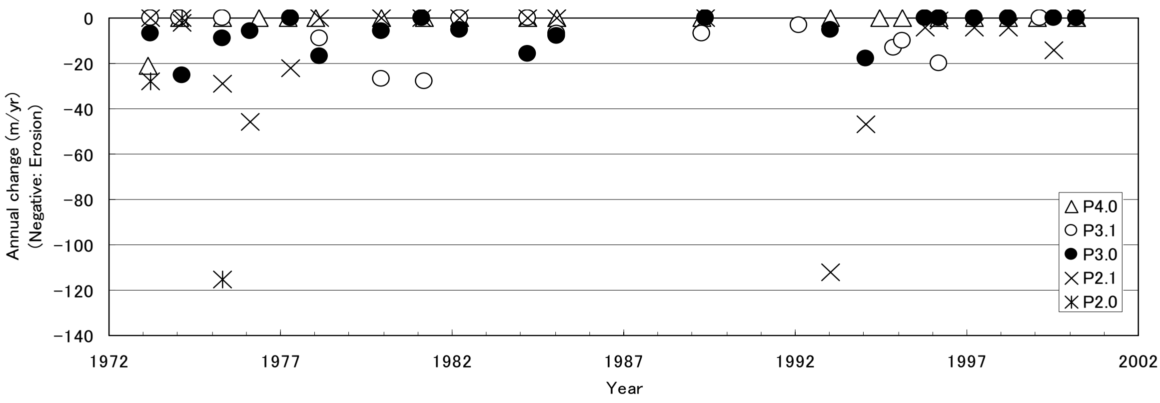


Figure 5.4.5 Yearly Changes of Left Bank

(3) Rate of Right Bank Changes

Existing right bank is formed of recent sediment deposit and is highly vulnerable to erosion. Similarly to the left bank, rate of riverbank changes were studied based on BWDB survey data. CS-P2.0 and CS-P2.1 were used for this study, since other sections upstream from the crossing location are influenced by the evolution of char. Changes of right bank location are shown in Figure 5.4.6 in reference to the riverbank in 1972. Erosion rate of riverbank was markedly high until 1985 showing average annual rate of about 240 m/yr at CS-P2.1. After 1985, the high erosion rate seems to be terminated and the riverbank location remains the same, though it fluctuates within the range of about 1000 m.

Figure 5.4.7 shows the yearly changes of right bank, in which negative value shows the erosion from the previous year and positive value the deposit of sediment. According to the figure, yearly erosion amount to as high as 500 m/yr at maximum at CS-P2.1 which is the nearest section to the crossing location on right bank.

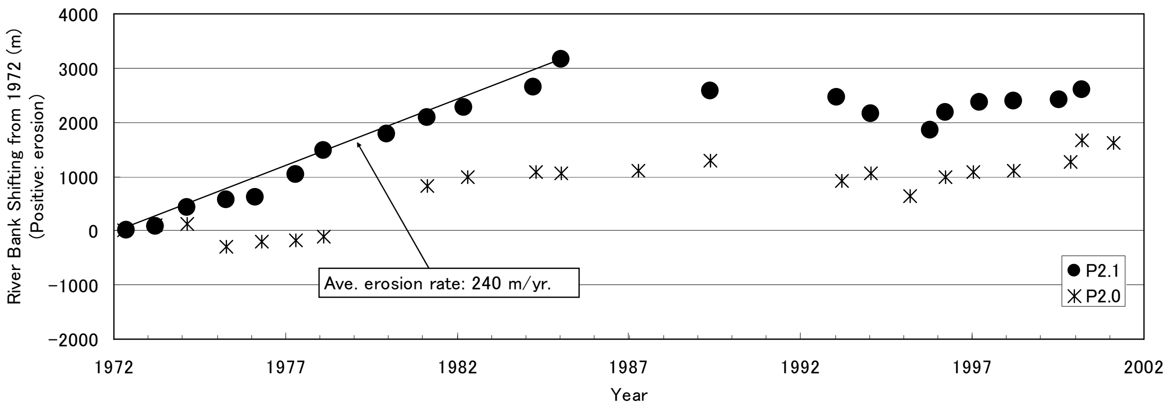


Figure 5.4.6 Rate of Right Bank Changes

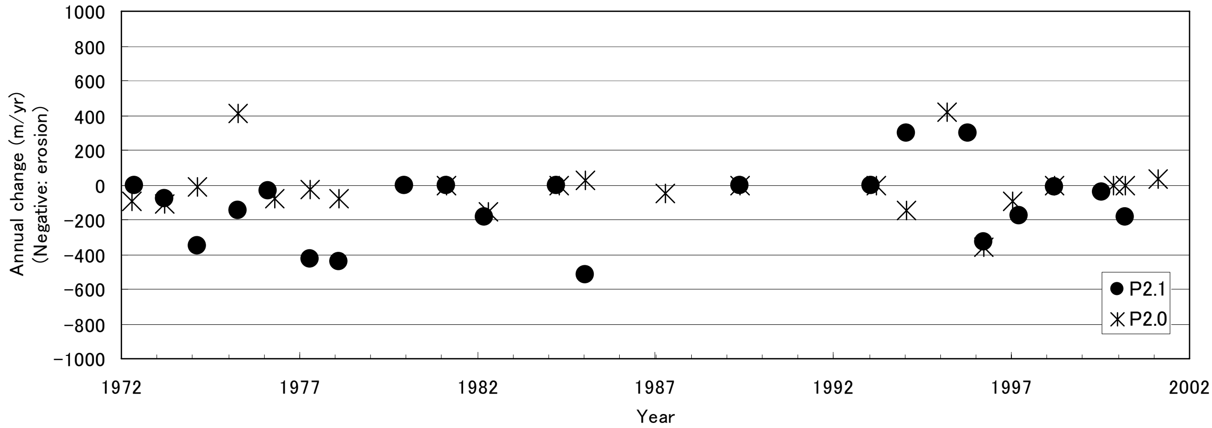


Figure 5.4.7 Yearly Changes of Right Bank

5.4.3 Limit of River Course Shifting

The existing left bank composed of geologically older soil layer covered with natural levee is less erodible and can be considered as the left limit of river course shifting.

On the other hand, the existing right bank is formed of young and loose deposit and susceptible to change. However at about 10 km land side from the existing right bank, there exist a boundary of recent active flood plain and high land (old flood plain). The high lands are made up with natural levee eroded by old river movements as shown in Figure 5.4.8.

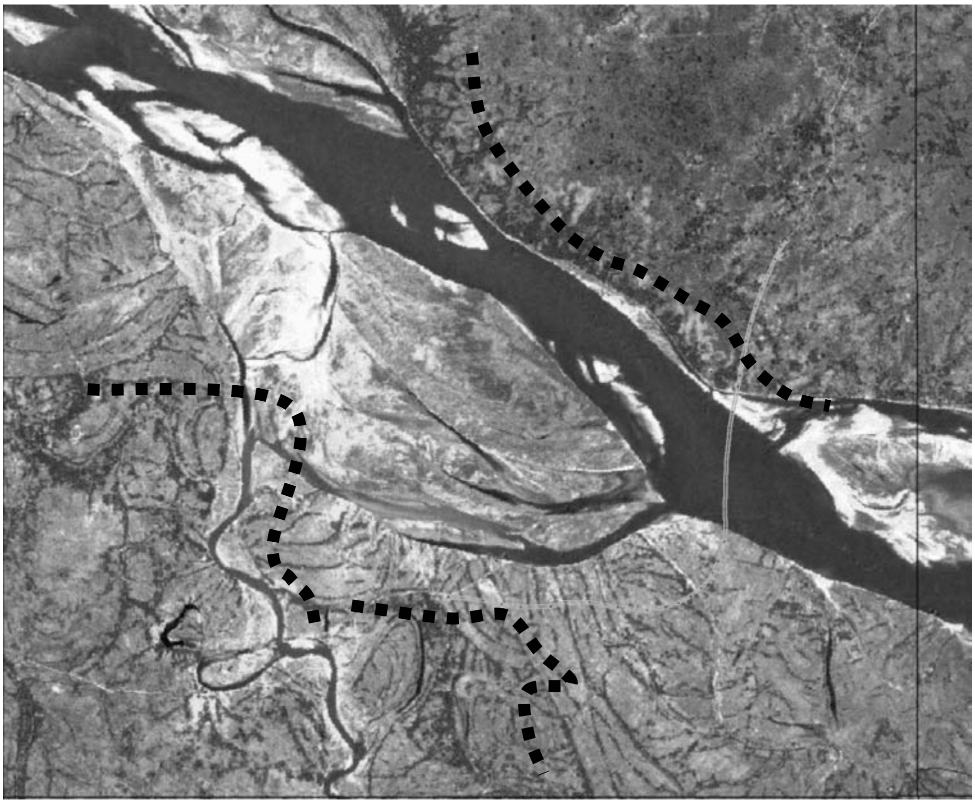


Figure 5.4.8 Limit of River Course Shifting

Examining the historical bankline changes, the old flood plain on the south-west of the boundary was found not to have experience of erosion due to the main Padma River at least these 90 years since 1914. The boundary can be considered as the right limit of river course shifting.

The Padma River has a long-term tendency to shift toward north-east and is apt to flow aside along the less erodible left bank. The Padma River flows between the left and right limits frequently changing the right bank-line probably due to temporal changes of water and sediment flow of the Padma River.

5.4.4 Geotechnical Structure of Riverbanks

Geotechnical data were collected and analyzed to clarify the cause of the less erodibility of left bank and its vertical and spatial distribution. The following data were collected and analyzed for the study:

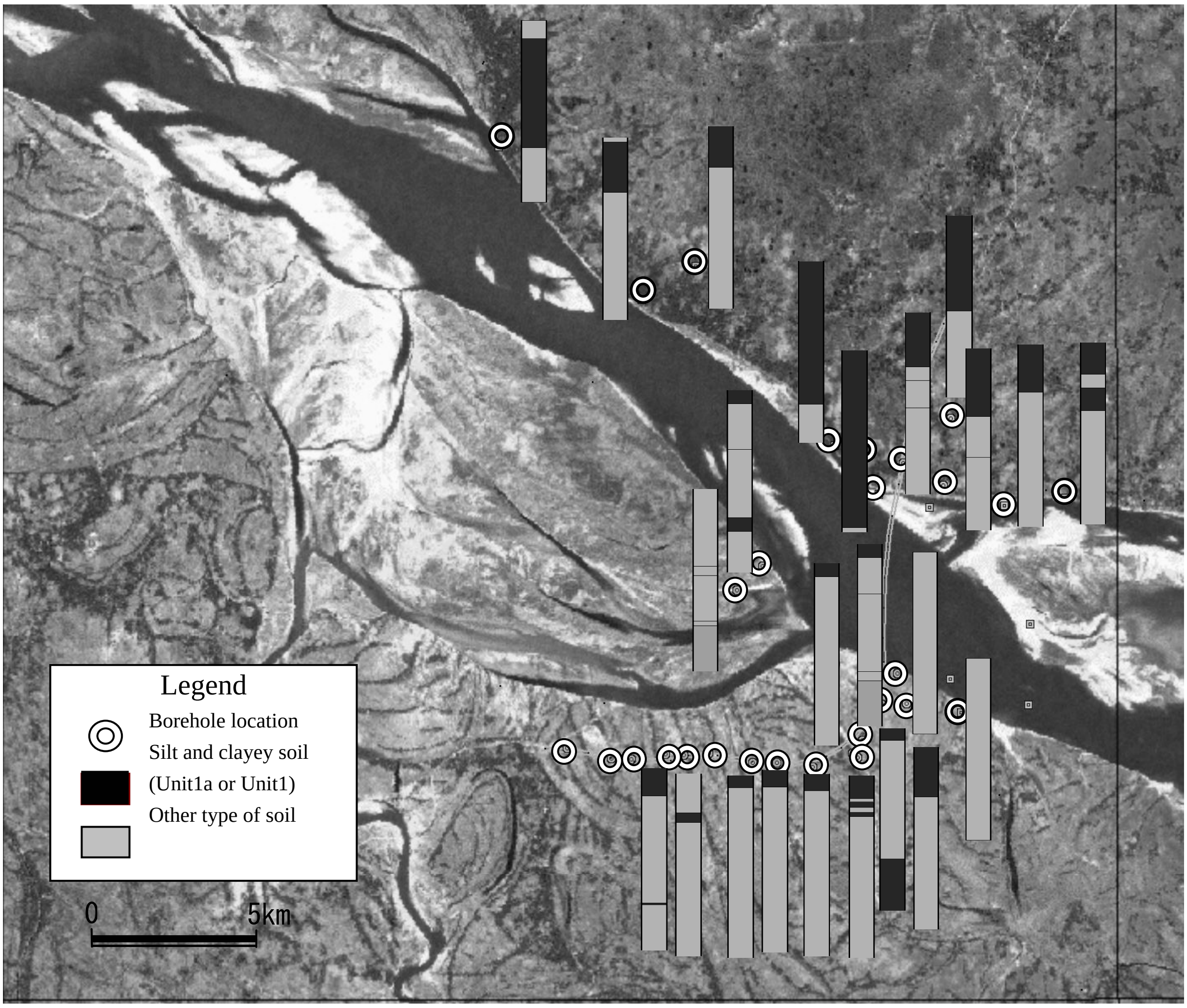
1) Geotechnical investigation conducted for Pre-F/S: 4 boring data on left bank, 3 boring data on right bank and 1 boring data on char downstream from the crossing location.
2) Geotechnical investigation by JICA Study Team for the 1st stage study: 2 boring data each on the left and right banks.
3) Geotechnical investigation by JICA Study Team for bridge and approach road design during the period of 2nd stage study: 1 boring data on right bank, 13 boring data (including 4 boring of 20 m depth) on right bank and 2 boring data on char upstream from the crossing location.
4) Geotechnical investigation by JICA Study Team for mathematical modeling during the period of 2nd stage study: 5 boring data on left bank and 1 boring data on right bank.

Location of these data are shown in Figure 5.4.9. Boring data up to 40 m from the ground were used for the study considering the possible depth influenced by the river flow. According to the riverbank investigation made so far it has been found that the silt and clayey soil play an important role to resist erosion due to river flow. The boring logs were, therefore, simplified classifying into two types of soil materials to show up the characteristics of erodibility as follows:

1) Silt and clayey soil: Regarded relatively resistible against erosion. Soils of Unit-1 layer classified by Pre-F/S and Unit-1a layer classified by our geologist fall under this category. Definitions of Unit-1 and Unit-1a are as follows:
   - Unit-1: Variable near-surface deposits ranging from silt of variable clay and sand content to very silty fine sand with occasional layers of silty clay.
   - Unit-1a: Clay or silt with fine sand in which silt and clay of 50% or more are contained.
2) Other soil: Soil material other than the above which are regarded susceptible to erosion.

The simplified boring logs are shown in Figure 5.4.9. From the figure, following matters are considered:

1) On the left bank, the thickness of the silt and clayey soil cover is 12 m to 25 m for the most part, while on the right bank the thickness of the soil and clayey soil is as thin as 5 m, more or less. The thicker silt and clayey soil layer would be the main reason of less erodibility of the left bank.
2) As for the width of the silt and clayey soil along the left bank, significant differences were not found between the boring log at river bank and that at about 1 km inland. Judging from the borehole data and distribution of natural levee, the width of the less erodible layer along the left bank would be more than 1 km, though further investigations are necessary to obtain the spatial distribution definitely.



(Note) Boring logs are plotted for 40m long from the surface

Figure 5.4.9 Geotechnical Conditions of Riverbanks

5.5 ESTIMATION OF MAXIMUM SCOUR DEPTH

The maximum scour depth necessary for the design of river and bridge facilities was estimated specifically for Mawa-Janjira site (MJ-site) finally selected for the crossing of Padma Bridge.

5.5.1 Methodology

(1) Types of Riverbed Scour

Various types of riverbed scours are conceivable for estimation of scour depth around the structures related to bridge and river training works as follows:

Natural Scour:

1) Long-term degradation
2) Bend scour
3) Confluence scour
4) Scour due to bed-form

Structure-induced Scour:

5) Constriction scour
6) Scour around bank protection works
7) Scour around bridge pier

The maximum scour depth was worked out combining the component riverbed scour listed above, and the scour depth of each component was estimated mainly referring to the following data:

1) Guidelines and Design Manual for Standardized Bank Protection Structures; Bank Protection Pilot Project FAP-21, December 2001; WARPO (FAP-21 Manual)
2) Padma Bridge Study; Phase 1: Pre-feasibility Report, February 2000; JMBA (Padma Pre-F/S Report)
3) Scouring; IAHR Hydraulic Structures Design Manual, 1991; H.N.C. Breusers and A.J. Raudkivi
4) Study on Bridge Problems Relevant to Flood Mitigation (Japanese version); Public Work Research Institute Data #3225 November 1993; T. Uda et al

Further explanations for each component riverbed scour are given below in brief.

(2) Long-Term Degradation

Lowering due to long-term degradation occurs because of decrease in sediment supply from the upstream reaches or increase in river discharge.

Trend of Long-term Riverbed Changes

According to Study Report of FAP-24, the Jamuna and Ganges rivers have a trend of aggradations with an annual sedimentation rate of 0.01 m/year. Riverbed of the Padma, located downstream from the confluence of both rivers, may also have rising tendency due to long-term morphological development.

Therefore, the long-term degradation is not necessary to be considered as far as the maximum scour depth is concerned.

Bifurcation of Arialkhan River in Future

Just upstream of MJ-site, the Arialkhan River bifurcates. The Arialkhan River was a main stream of the Padma River until about 150 years ago and now conveys about 10 percent of floodwater of the main Padma River. Considering geomorphologic evolution of the river at MJ-site, no one can deny the complete closure of the Arialkhan River in future temporarily or permanently. The complete closure of the Arialkhan would bring about the increase of river discharge and lowering of riverbed at JM-site.

In view of this, the maximum scour depth was estimated for the following two cases:

1) Case 1: Under present conditions of the Arialkhan River (Present Arialkhan R.)
2) Case 2: Under assumed conditions of complete closure of the Arialkhan River (Closed Arialkhan R.)

(3) Bend Scour

Riverbed is scoured in general at the outer side and raised at the inner side of the channel bend. The bend scour can occur at any part of river section.

The scour depth at bend can be calculated by the empirical formula by Thorne.

$$h_s / h_m = 2.07 - 0.19 \log (r_c / B - 1.5)$$

where,

h_s : Total water depth at thalweg below Design High Water Level (DHWL)
h_m : Mean water depth below DHWL
B : Channel width
r_c : Radius of channel bend centerline

Assuming rc = 2.5 x B under which the largest scour would occur, the above formula is expressed simply as;

$$h_s = h_m + y_{s\text{-}bend} = 2.07 \times h_m, \text{ or } y_{s\text{-}bend} = 1.07 \times h_m$$

where,

$y_{s\text{-}bend}$: Scour depth at bend defined as the difference between h_s and h_m.

(4) Confluence Scour

Confluence scour occurs where two channels meet, namely the main Padma River and the south channel an anabranch behind Char Kawrakandi.

The FAP-21 Manual proposes following empirical relation to calculate confluence scour in line with the approach by Klaassen and Vermeer as follows:

$$y_{s\text{-}confl} = h_{SLW} (0.292 + 0.037 \varphi)$$

where,

$y_{s\text{-}confl}$: Confluence scour (m)
h_{SLW} : Upstream water depth below SLW (m)
φ : Angle of incidence of anabranches (degree). It is recommended to use a

representative value of 45° for channels wider than 1 km and 70° for channels narrower than 1 km.

Assuming φ = 45° for the Padma River at MJ-site;

$$y_{s\text{-}confl} = 1.957 \times h_{SLW}$$

(5) Scour due to Bed-form

According to the result of our study on sediment flow of MJ-site, it was confirmed that the sediment was transported in the flat bed conditions during flood flow period. The scour due to bed-form was not taken into account for the estimation of the maximum scour depth.

(6) Constriction Scour

If the river section at the crossing location is constricted to reduce the bridge length, the concentration of flow at the constriction would bring about an increase in flow depth. The increase in flow depth is defined as constriction scour.

Since river training works proposed for Padma Bridge intend to maintain existing river and flow conditions giving less impact to the river, existing river channel would not be constricted and the flood water in flood plain would not be influenced significantly by the approach roads. Therefore, the constriction scour was not considered for the estimation of the maximum scour depth.

(7) Scour around Bank Protection Works

<u>Scour around Groynes</u>

Around the permeable groynes various scour phenomena take place, i.e., scour downstream from the tip of groyne, scours around the groyne piles, scour upstream from the groyne due to protrusion. Among these, scour downstream from the tip of groyne is most important for the design of the structure.

FAP-21 Manual proposes to calculate the scour depth behind the tip of the groyne by the following empirical relation based on the formula of Ahmad:

$$h_i + y_{s\text{-}groyne} = K\,\{h_i \cdot u_i \cdot B/(B - b)\}^{2/3}$$

where,

$y_{s\text{-}groyne}$	:	Maximum scour depth at the tip of groyne (m)
h_i	:	Water depth upstream from scour hole (m)
u_i	:	Upstream depth-averaged flow velocity (m/s)
B	:	Channel width upstream of the groyne (m)
b	:	Protrusion length (m)
K	:	Empirical coefficient ($m^{-1/3}\ S^{2/3}$)

K = (K for groyne) · (K for bed protection) · (K for floating debris)

K for groyne

- Impermeable : K = 2.4
- Permeability 50% : K = 1.6 to 2.0
- Permeability 60% : K = 1.5 to 1.8
- Permeability 70% : K = 1.4 to 1.6
- Permeability 80% : K = 1.2 to 1.3

K for bed protection:
Without bed protection: K = 1.0
With bed protection: K = 1.1
K for floating debris:
Without floating debris: K = 1.0
Floating debris ≤ 1 m in thickness: K = 1.2
Floating debris > 1 m in thickness: K = 1.3

The formula can be simplified as follows:

$$y_{s\text{-}groyne} = K (h_i \cdot u_i)^{2/3} - h_i$$

For the standardized groynes proposed by FAP-21 Manual, permeability at the tip of groyne is 80%. Then, K-value was assumed to be 1.3 under the conditions without bed protection and floating debris.

Scour around Revetment Works

The local scour induced by revetment works can be treated as the local scour at the abrupt transition at the tip of impermeable structure in combination with bed protection. The FAP-21 Manual recommends to use Ahmad's formula for this case, too.

As to K-value, the following is recommended by the Manual:

K = 2.4 (impermeable) x 1.1 (bed protection) = 2.6

The above K-value would be considered as that for vertical wall. It is generally known that the scour depth at the foot of revetment reduces as revetment slope becomes milder. According to the result of additional model test for FAP-21/22 (Technical Report No.5, Mar. 1996), scour depth for vertical wall would reduce as follows depending on the revetment slope:

Slope	Scour depth	Ratio to Vertical
Vertical	15.5 m	1.00
1V : 1H	13.3 m	0.86
1V : 3H	9.1 m	0.59
1V : 4H	7.1 m	0.46

Revetment and guide bund works proposed for Padma Bridge are designed as a composite work of slope pavement, launching apron, and falling apron works. The revetment slope will be formed naturally by the river flow. For the estimation of the maximum scour depth at the foot of revetment, following K-value was used, assuming overall revetment slope as 1V : 3H:

K = 2.6 x 0.59 = 1.6

As a summary, the scour depth at the foot of revetment works including guide bund works can be calculated using following equation:

$$y_{s\text{-}revet} = K (h_i \cdot u_i)^{2/3} - h_i$$

where,

$y_{s\text{-}revet}$: Maximum scour depth at the foot of revetment (m)
h_i : Water depth upstream from scour hole (m)
u_i : Upstream depth-averaged flow velocity (m/s)

K : Empirical coefficient ($m^{-1/3} S^{2/3}$)
K = 2.6 for vertical wall
K = 1.6 for revetment and guide bund works

(8) Scour around Bridge Pier

Local scour around cylindrical bridge pier was estimated using the following empirical formula:

$$y_{s\text{-}pier} = K \times D$$

where,

$y_{s\text{-}pier}$: Scour depth around pier
D : Diameter of cylindrical bridge pier
K : Empirical coefficient, assumed to be K = 1.8 for single cylindrical pile pier.

Scour around Group Piles

In case bridge pier consists of plural piles, scour depth around the pile may be influenced by adjacent piles each other. The K-value to yield maximum scour depth should be adjusted as follows:

$$K = K_s \times K_{g\text{-}long} \times K_{g\text{-}lat}$$

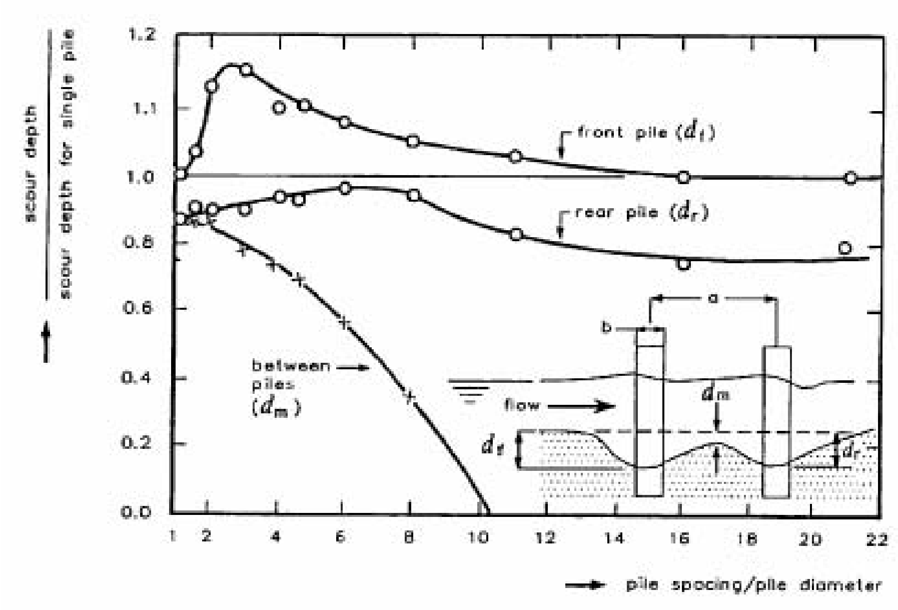
where,

K : Composite K-value for estimation of maximum scour depth around group pile pier
K_s : Empirical coefficient for single pile pier (= 1.8)
$K_{g\text{-}long}$: Adjustment factor for the influence of group piles placed longitudinally
$K_{g\text{-}lat}$: Adjustment factor for the influence of group piles placed in lateral

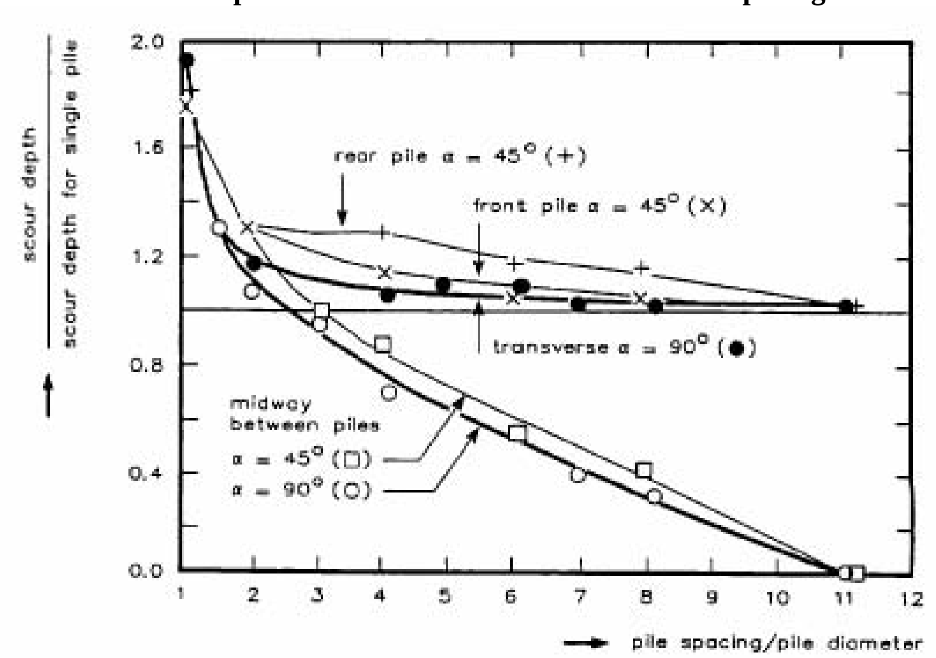
As to the scour around pile group, empirical diagrams are available investigated by Hannah as shown in Figure 5.5.1. Maximum scour around group pile pier can be estimated in the following procedures:

1) To get ratios S_{long}/D and S_{lat}/D, where S_{long} and S_{lat} are spacing of longitudinal and lateral pile at original riverbed, and D is pile diameter.
2) To find adjustment factors $K_{g\text{-}long}$ and $K_{g\text{-}lat}$ using empirical diagram shown in Figure 5.5.1 for S_{long}/D and S_{lat}/D.
3) To calculate scour depth as follows: $y_{s\text{-}gpier} = K_s \times K_{g\text{-}long} \times K_{g\text{-}lat} \times D$

Scour Depths for Two Piles in Line as a Function of Pile Spacing



Scour Depths for Two Piles as a Function of Pile Spacing



Note: Solid lines: transverse piles, Dashed lines: Angle of attack 45°
(Source: Scouring, H.N.C.Breusers, A.J.Raudkivi; IAHR/AIRH, 1991)

Figure 5.5.1 Empirical Relation Showing Influence of Pile Group

5.5.2 Component Scour Depth

(1) Fundamental Setup

FAP-21 Manual presents regime relations of the Padma River section at the bank-full flow conditions as follows:

$$h_{mb} = 0.28 \times Q_b^{0.30}$$

$$B = 4.76 \times Q_b^{0.62}$$

where

h_{mb} : Average water depth below bank elevation (m)
B : Channel width between the banklines at bank elevation (m)
Q_b : Bankfull discharge (m^3/s)

The above relation was derived based on the survey sections of BWDB by FAP-24 study (Special Report No.7: River Survey Project, Delft Hydraulics and DHI).

The bankfull discharge (Qb) and other hydraulic parameters necessary for the estimation of scour depth was estimated by the following equation, applying the regime relations to Manning's uniform flow formula:

$$Q_d = Bh_m^{5/3}\ I^{1/2}/n = (I^{1/2}/n) \times 4.76Q_b^{0.62} \times (0.28\ Q_b^{0.30} + dh)^{5/3}$$

where

Q_d : Design discharge (m^3/s)
Q_b : Bankfull discharge (m^3/s)
h_m : Average water depth below design high water level (DHWL)
dh : Difference between DHWL and bank elevation (BEL)
I : Channel slope ($I = 1/15,800$)
n : Manning's coefficient of roughness ($n=0.015$)

Hydraulic parameters calculated for the study cases are shown in Table 5.5.1 together with other fundamental parameters necessary for the estimation of the scour depth.

(2) Calculation of Scour Depth

The following types of scour depth were calculated according to the methodology mentioned above.

1) Natural scour:
   - Bend scour
   - Confluence scour
2) Structure-induced scour:
   - Scour around groyne
   - Scour around revetment
   - Scour around bridge pier

Results of calculation are shown in Table 5.5.1. In estimating the scour depths, following arrangements were made:

1) Natural scour was estimated as a total scour of bend and confluence scours that could

occur at the same time for the worst.

2) Structure-induced scour was calculated under the flow conditions of natural scour.

3) The scour depth (y_s) is further divided into normal scour (y_n) and incremental scour (y_s’), i.e.;

   $y_s = y_n + y_s'$

   The total water depth (h_s) subject to plural types of scours is estimated as follows:

   $h_s = h_m + y_n + \sum y_s'$

4) The normal scour is defined as the difference between the maximum water depth and average water depth of the river section under the straight and normal flow conditions not subject to specific scours mentioned earlier. The normal scour (y_n) was assumed as

   $y_n = 0.25\ h_m$

   taking the lowest ratio of the maximum water depth and the average water depth based on the periodical survey sections of BWDB.

Table 5.5.1 Estimation of Maximum Scour Depth

Items	Unit	100-year Case-1: Present Arialkhan River	100-year Case-2: Closed Arialkhan River	25-year Case-1: Present Arialkhan River	25-year Case-2: Closed Arialkhan River
FUNDAMENTAL SETUP					
Design discharge (Qd)	m3/s	134400	151400	120100	131000
Bankful discharge (Qb)	m3/s	84640	94900	81240	88210
Mean water depth below B.EL	m	8.42	8.72	8.32	8.53
Design High Water Level (DHWL)	m,PWD	7.35	7.35	6.94	6.94
Bank elevation (B.EL)	m,PWD	5.71	5.71	5.71	5.71
Standard Low Water Level (SLWL)	m,PWD	1.43	1.43	1.43	1.43
Manning's coefficient of roughness (n)	m-sec	0.015	0.015	0.015	0.015
Channel slope (1/I)	1/I	15800	15800	15800	15800
Mean water depth below DHWL (hm)	m	10.06	10.36	9.55	9.76
Normal scour (yn)	m	2.52	2.59	2.39	2.44
NATURAL SCOURS					
1. Bend scour					
ys_bend = 1.07 * hm	m	10.76	11.09	10.22	10.44
ys'_bend = ys_bend - yn	m	8.25	8.50	7.83	8.00
2. Confluence scour					
hb″ = mean water depth below SLW	m	4.14	4.44	4.04	4.25
deg = angle between anabranches	deg	45	45	45	45
ys_confl = hb″ * (0.292+0.037*deg)	m	8.10	8.69	7.91	8.32
ys'_confl = ys_confl - yn	m	5.59	6.10	5.52	5.88
3 Total natural scour					
ys_natural = yn + ys'_bend + ys'_confl	m	16.35	17.18	15.74	16.32
ys'_natural = ys_natural - yn	m	13.84	14.59	13.35	13.88
STRUCTURE-INDUCED SCOURS					
1. Scour around permeable groynes					
hi = hm + yn + ys'_natural	m	26.41	27.54	25.29	26.08
ui = hi^(2/3)*I^(1/2)/n	m/s	4.70	4.84	4.57	4.66
ys_groyne = 1.3*(hi*ui)^(2/3) - hi	m	5.96	6.37	5.55	5.84
ys'_groyne = ys_groyne-yn	m	3.44	3.78	3.16	3.40
2. Scour around revetment/guide bund					
hi = hm + yn + ys'_natural	m	26.41	27.54	25.29	26.08
ui = hi^(2/3)*I^(1/2)/n	m/s	4.70	4.84	4.57	4.66
ys_revet = 1.6*(hi*ui)^(2/3) - hi	m	13.42	14.19	12.67	13.20
ys'_revet = ys_revet-yn	m	10.91	11.60	10.28	10.76
3. Scour around single pile pier *					
D = Diameter of pile (3m)	m	3.00	3.00	3.00	3.00
ys_pier = 1.8 * D (for single pile)	m	5.40	5.40	5.40	5.40
DESIGN MAXIMUM SCOUR DEPTH (DMSD) **					
1. Scour around permeable groyne works					
ys = 1.2*(yn+ys'_natural+ys'_groyne)	m	23.75	25.16	22.68	23.66
hs = hm + ys	m,PWD	33.81	35.52	32.23	33.42
Zs = DHWL-hs	m,PWD	-26.46	-28.17	-25.29	-26.48
2. Scour around revetment/guide bund works					
ys = 1.2*(yn+ys'_natural+ys'_revet)	m	32.71	34.55	31.22	32.50
hs = hm + ys	m,PWD	42.77	44.91	40.77	42.26
Zs = DHWL-hs	m,PWD	-35.42	-37.56	-33.83	-35.32
3. Scour around bridge structure ***					
Scour in the middle of river section					
ys = 1.2*(yn+ys'_natural)	m	19.62	20.62	18.88	19.58
hs = hm + ys	m,PWD	29.68	30.98	28.43	29.34
Zs = DHWL-hs	m,PWD	-22.33	-23.63	-21.49	-22.40
Adjacent to riverbank (within 300m)					
ys = 1.2*(yn+ys'_natural+ys'_revet)	m	32.71	34.55	31.22	32.50
hs = hm + ys	m,PWD	42.77	44.91	40.77	42.26
Zs = DHWL-hs	m,PWD	-35.42	-37.56	-33.83	-35.32

(Notes)

* For the effect of group piles, adjust using attached empirical diagram.

** Case-1(closed Arialkhan River) was adopted for DMSD.

*** Local scour around bridge pier is not included.

5.5.3 Design Maximum Scour Depth

Assuming the worst combination of the relevant types of scour, total maximum scour depth was calculated.

In order to account for extra scour which may be induced by unforeseen behavior of river channel and compound influence of the structures, the total scour shall be multiplied by a factor of 1.20 to determine design maximum scour depth (DMSD).

Adopting the case of closed Arialkhan River, DMSD was decided for 100- and 25-year flood as shown below. In the table below:

h_s : Total scoured water depth below DHWL
Z_s : Elevation of scoured riverbed

(1) DMSD for Permeable Groyne

	(100-yr.)	(25-yr)
$h_s = h_m + y_s$	35.5 m	33.4m
$Z_s = DHWL - h_s$	-28.2 m,PWD	-26.5 m,PWD

(2) DMSD for Revetment/Guide Bund

	(100-yr.)	(25-yr)
$h_s = h_m + y_s$	44.9 m	42.3 m
$Z_s = DHWL - h_s$	-37.6 m,PWD	-35.3 m,PWD

(3) DMSD for Bridge Structure: Scour around bridge pier is not included

<u>In the middle of river section</u>

	(100-yr.)
$h_s = h_m + y_s$	31.0 m
$Z_s = DHWL - h_s$	-23.6 m,PWD

<u>Adjacent to riverbank (within 300 from riverbank)</u>

	(100-yr.)
$h_s = h_m + y_s$	44.9 m
$Z_s = DHWL - h_s$	-37.6 m,PWD

5.5.4 Comparison with Historical Riverbed Records

Design maximum scour depth (DMSD) estimated in the previous Subsection was compared with the historical lower bed around the crossing location. The historical riverbed scours and their characteristics of seasonal changes are shown below. From these data, proposed DMSD is deemed appropriate.

(1) Historical Riverbed Scour

Figure 5.5.2 shows historical river sections periodically surveyed by BWDB at CS-P2.0, CS-P2.1, CS-P3.0, CS-P3.1 and CS-P4.0 that are located in the neighboring river reaches of the crossing location (see Figure 4.2.3 for their locations). These river sections were surveyed mainly during low water season and are available for a period of 35 years from 1968 including some lack of survey. The lowest riverbeds surveyed at each section are shown in Figure 5.5.3 and in Table 5.5.2.

Table 5.5.2 Lowest Riverbed Surveyed Periodically by BWDB

Year[1]	CS−P2.0			CS−P2.1			CS−P3.0			CS−P3.1			CS−P4.0		
	Yr.	M.	Lowest bed (m,PWD)	Yr.	M.	Lowest bed (m,PWD)	Yr.	M.	Lowest bed (m,PWD)	Yr.	M.	Lowest bed (m,PWD)	Yr.	M.	Lowest bed (m,PWD)
1968/69	1969	1	−14.11	1968	12	−14.39	1968	12	−17.60	1969	1	−14.13	1968	12	−10.19
1969/70	1970	1	−13.68	1970	1	−10.56	1970	1	−37.01	1970	1	−14.59	1970	1	−7.87
1970/71	1971	2	−9.80	1971	2	−10.89	1971	2	−25.24	1971	2	−10.90	1971	2	−7.23
1971/72	1972	5	−7.62	1972	5	−10.24	1972	5	−23.28	1972	5	−9.49	1972	5	−7.16
1972/73	1973	3	−9.47	1973	3	−12.68	1973	3	−15.50	1973	3	−13.53	1973	3	−9.55
1973/74	1974	2	−13.16	1974	2	−15.09	1974	2	−18.84	1974	2	−10.00	1974	2	−10.82
1974/75	1975	4	−8.52	1975	4	−13.21	1975	4	−17.84	1975	4	−14.47	1975	4	−13.43
1975/76	1976	2	−7.02	1976	2	−9.17	1976	2	−22.07	1976	2	−7.05	1976	2	−8.36
1976/77	1977	4	−6.80	1977	4	−12.54	1977	4	−15.79	1977	4	−8.84	1977	4	−6.55
1977/78	1978	2	−8.31	1978	2	−14.28	1978	2	−12.31	1978	2	−7.82	1978	2	−5.77
1978/79	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
1979/80	−	−	−	1979	12	−9.83	1979	12	−13.63	−	−	−	1979	12	−7.79
1980/81	1981	2	−9.78	1981	2	−12.05	1981	2	−20.20	1981	2	−11.22	1981	2	−10.36
1981/82	1982	4	−9.33	1982	3	−10.21	1982	3	−12.54	1982	4	−10.60	1982	3	−11.69
1982/83	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
1983/84	1984	4	−15.63	1984	3	−14.42	1984	3	−24.81	1984	4	−22.91	1984	3	−13.87
1984/85	1985	2	−9.37	1985	1	−10.18	1985	1	−31.73	1985	2	−19.59	1985	1	−12.91
1985/86	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
1986/87	1987	4	−10.75	−	−	−	−	−	−	1987	4	−6.78	−	−	−
1987/88	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
1988/89	1989	5	−14.79	1989	5	−5.13	1989	5	−13.76	1989	5	−13.37	1989	5	−7.52
1989/90	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
1990/91	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
1991/92	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
1992/93	1993	3	−16.16	1993	1	−21.74	1993	1	−12.39	1993	3	−16.90	1993	1	−9.19
1993/94	1994	1	−25.00	1994	1	−28.31	1994	1	−9.20	1994	1	−7.47	1994	1	−14.50
1994/95	1995	3	−10.06	−	−	−	−	−	−	1995	3	−11.51	−	−	−
1995/96				1995	10	−4.70	1995	10	−4.94				1995	10	−4.94
	1996	3	−13.57	1996	3	−15.46	1996	3	−11.48	1996	3	−11.89	1996	3	−14.01
1996/97	1997	1	−16.99	1997	3	−21.66	1997	3	−8.62	1997	1	−8.71	1997	3	−10.95
1997/98	1998	3	−14.51	1998	3	−15.09	1998	3	−12.93	1998	3	−3.86	1998	3	−6.43
1998/99	−	−	−	1999	7	−14.10	1999	7	−9.76	−	−	−	1999	7	−6.42
1999/00	1999	11	−15.21	2000	3	−12.50	2000	3	−13.20	1999	11	−7.67	2000	3	−6.60
	2000	3	−12.84												
2000/01	2001	2	−10.35												

(NOTE) 1) Yr: Year starting from September to August next year(e.g., 1968/69: Sep. 1968 to Aug. 1969); Mn: month
2) Riverbed elevation shown in box indicates deep scour lower than −20.0 m,PWD

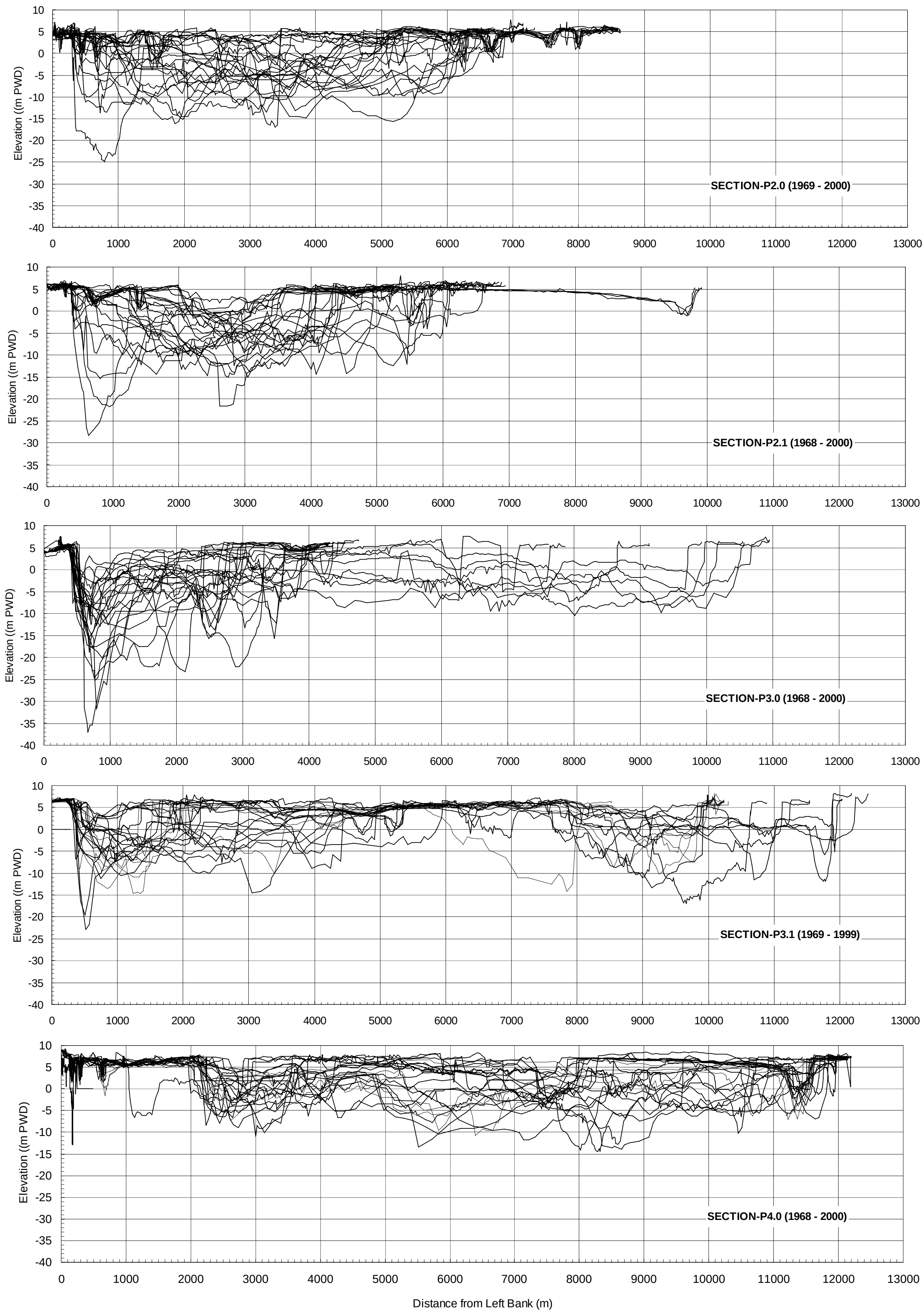


Figure 5.5.2 Historical River-Section Surveyed by BWDB

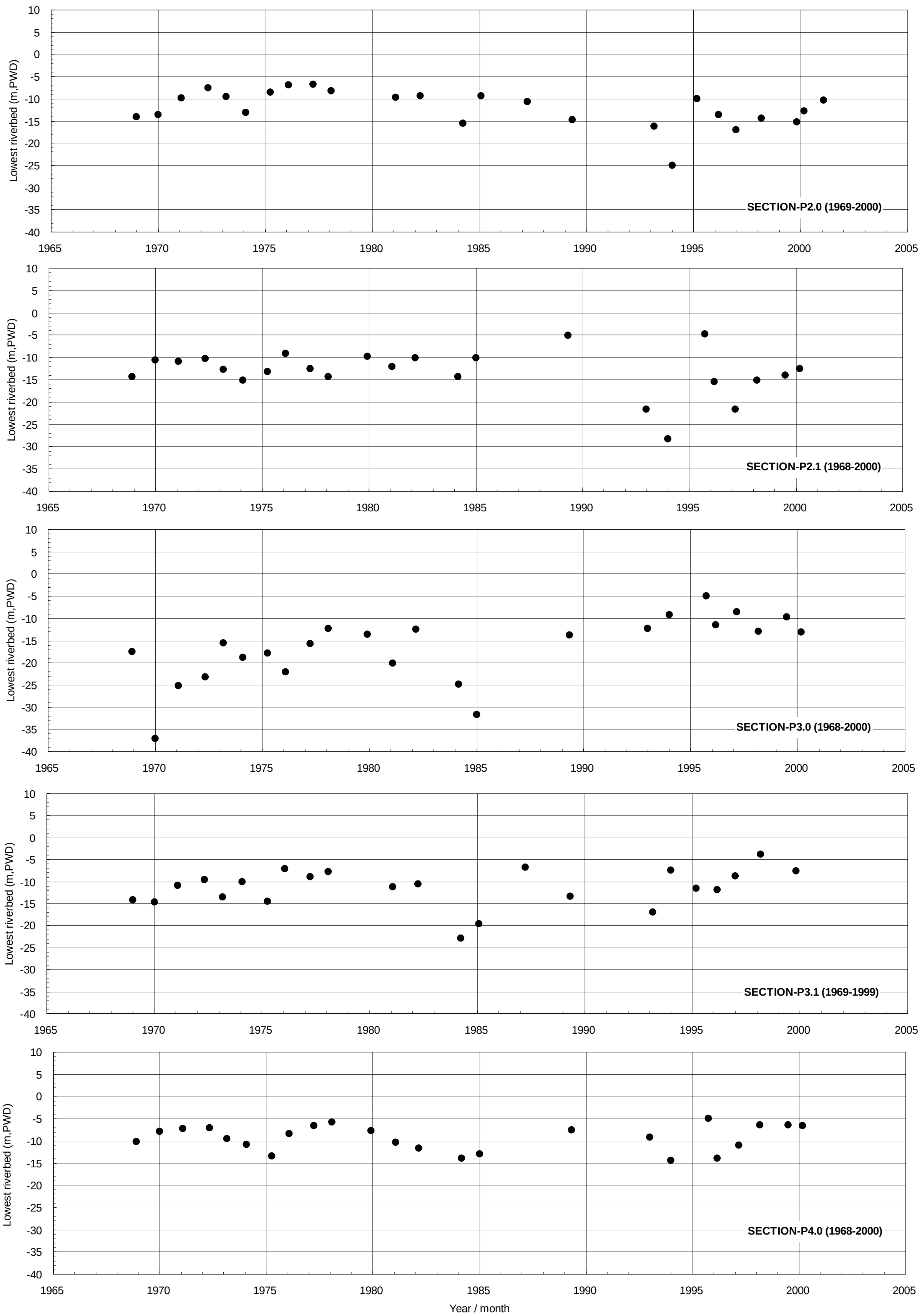


Figure 5.5.3 Historical Lowest Riverbed Surveyed by BWDB

According to the Table, deep riverbed scours lower than -20 m,PWD were extracted and shown below. The recorded lowest riverbed was -37.01 m,PWD in 1970 followed by -31.73 m,PWD in 1985 both at CS-P3.0.

Section Year Month	Depth (m,PWD)	Scoured place	Estimated Main cause
CS-P2.0			
1994 Jan.	-25.00	Left bank	Bend/flow attack
CS-P2.1			
1993 Jan.	-21.74	Left bank	Bend/flow attack
1994 Jan.	-28.31	Left bank	Bend/flow attack
1997 Mar.	-21.66	River center	Bend/flow attack, confluence
CS-P3.0			
1970 Jan.	-37.01	Left bank	Bend/flow attack
1971 Feb.	-25.24	Left bank	Bend/flow attack
1972 May	-23.28	River center	Bend/flow attack, confluence
1976 Feb.	-22.07	River center	Bank protrusion, confluence
1981 Feb.	-20.20	Left bank	Bank protrusion, confluence
1984 Mar.	-24.81	Left bank	Bank protrusion, confluence
1985 Jan.	-31.73	Left bank	Bank protrusion, confluence
CS-P3.1			
1984 Apr.	-22.91	Left bank	Bend/flow attack
CS-P4.0	(None)	-	-

The deep scours took place mostly near the left bank and some in the river center. Judging from plan-form of river and stream flow lines shown in the satellite images, main causes of scours at the foot of left bank are due to bend or flow attack to less erodible bank of the South Channel and protrusion of riverbank near Mawa Ghat. Some deep scours in the river center are deemed to be caused by flow turbulence due to confluence of channels downstream from the char.

(2) Seasonal Changes in Riverbed

The historical riverbed sections discussed above were surveyed mostly during low-water season. It should be noted that the lowest riverbed does not always occur during flood season. The following data show the fact that the lowest riverbeds in low-water season were lower than those in flood season:

1) The lowest riverbed data surveyed at CS-P2.1 in low-water season were compared with corresponding lowest riverbeds surveyed in flood season at Mawa discharge measurement station as shown in Figure 5.5.4. The discharge measurements are carried out only in flood season and the section is located about 2 km upstream of CS-P2.1. The figure indicates that the lowest riverbeds of low-water season are lower than those of flood season, probably due to bed-form change.

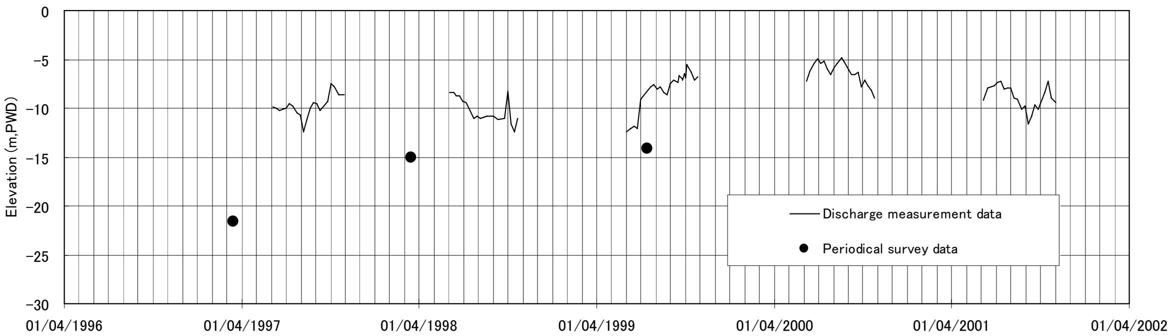


Figure 5.5.4 Lowest Riverbeds by Periodical Survey and Discharge Measurement

2) The similar tendency was found in BWDB survey data in 1995/96 at CS-P2.1, P3.0 and P4.0 (see Table 5.5.2 and Figure 5.5.5). In this low-water season, two surveys were conducted, i.e., in October 1995 just after the flood season and in March 1996 just before the start of rainy season. The lowest riverbeds surveyed just before the start of rainy season are lower than those surveyed just after the flood season, even though the river did not experience major flood flows between two surveys. The riverbeds just after the flood season (the October section) are flatter as a whole.

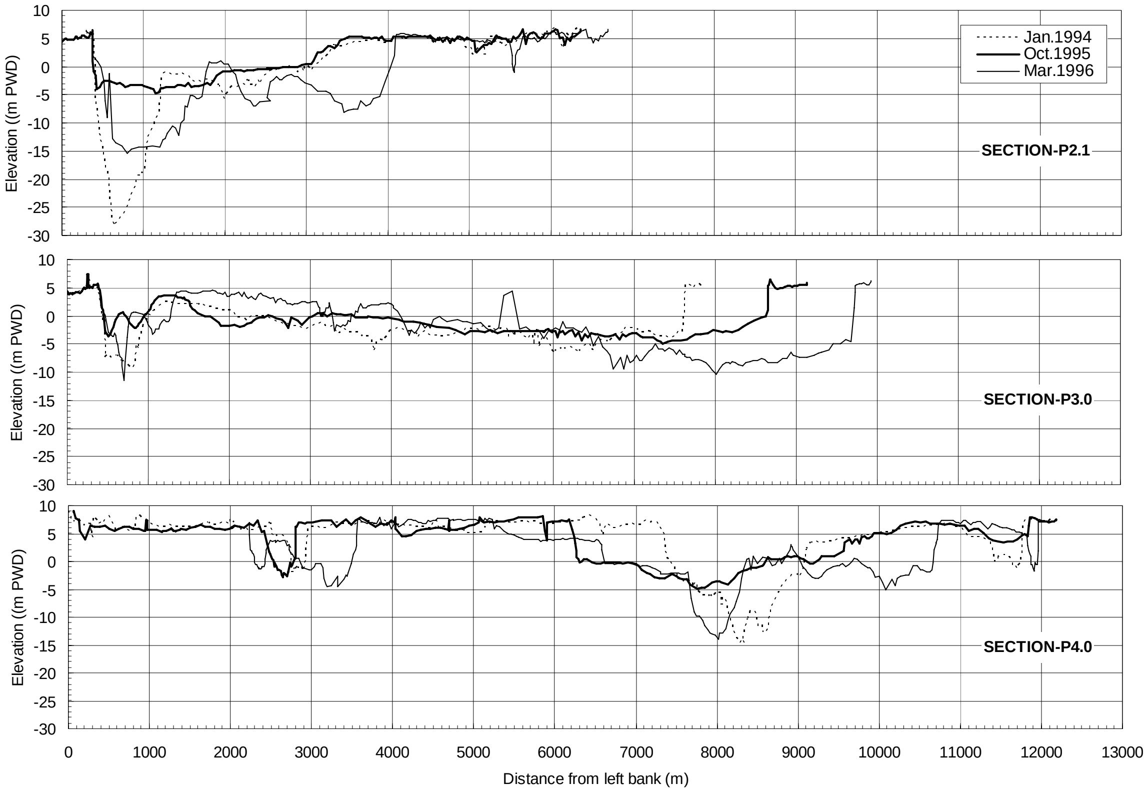


Figure 5.5.5 Seasonal Changes of River Sections