FAP24

Government of the People's Republic of Bangladesh

Water Resources Planning Organization

European Commission

Delft Hydraulics

Danish Hydraulic Institute

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Osiris

RIVER SURVEY PROJECT

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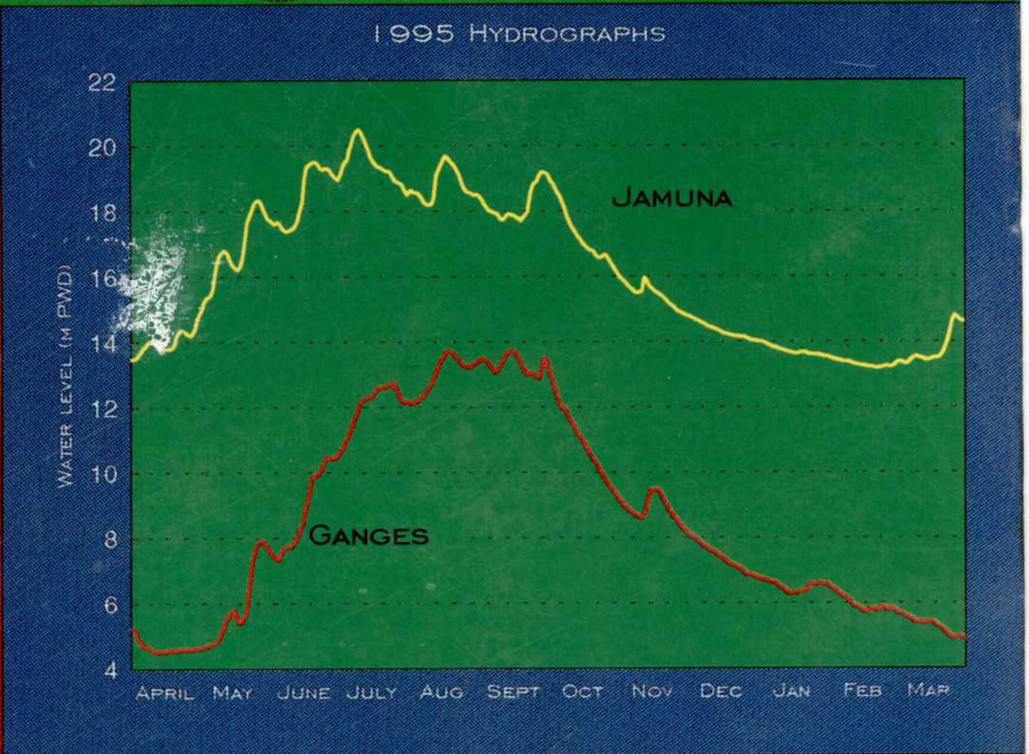

Final Report – Annex 3

Hydrology

November 1996

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1 Introduction

The main objectives of the River Survey Project according to the Terms of Reference are:

1. To collect reliable all season data on the hydrology and morphology of the main rivers in Bangladesh, see Figure 1.1 for a layout;
2. to undertake special studies regarding the behaviour of the river system based on both existing as well as new data;
3. to provide specialised on-the-job training to Bangladesh professionals, and
4. to provide benchmarks against which to assess changes in the river morphology and hydrology.

More specifically, with respect to hydrology, the activities should comprise (ToR, pg 20-22):

1 An assessment of the existing information, including:

- a compilation of the existing hydrological data and data-bases, as well as information collected in other projects as far as relevant for the current project;
- preparation of a well documented inventory of data, and
- an assessment of the current procedures for collection, processing and storage of hydrological data.

2 Investigations of water levels and surface profiles:

- a compilation, assessment and updating of water levels at the gauging stations;
- analysis of water-level time series to identify trends, inconsistencies and abnormal changes;
- analysis of correlations between gauges, when relevant;
- drafting and analysis of water surface profiles to identify possible abnormalities;
- verification of bench-marks and related documents;
- evaluation of the need for installation of new gauges and detailed studies, and
- setting up of a user-friendly, easy accessible water-level database matching the international standards, with proper storage, processing and retrieval options.

3 Analysis of discharge measurements:

- assessment of the uncertainty in the discharge measurements by the BWDB and by the Project, as a function of stage and other relevant parameters and suggestions for its reduction in a cost-effective way;
- introduction of a physically based methodology to fit and extrapolate discharge rating curves, and
- establishment of discharge rating curves for the gauging stations.

4 On-the-job training:

- guidance to local staff in acquisition, storage and processing of hydrological data.

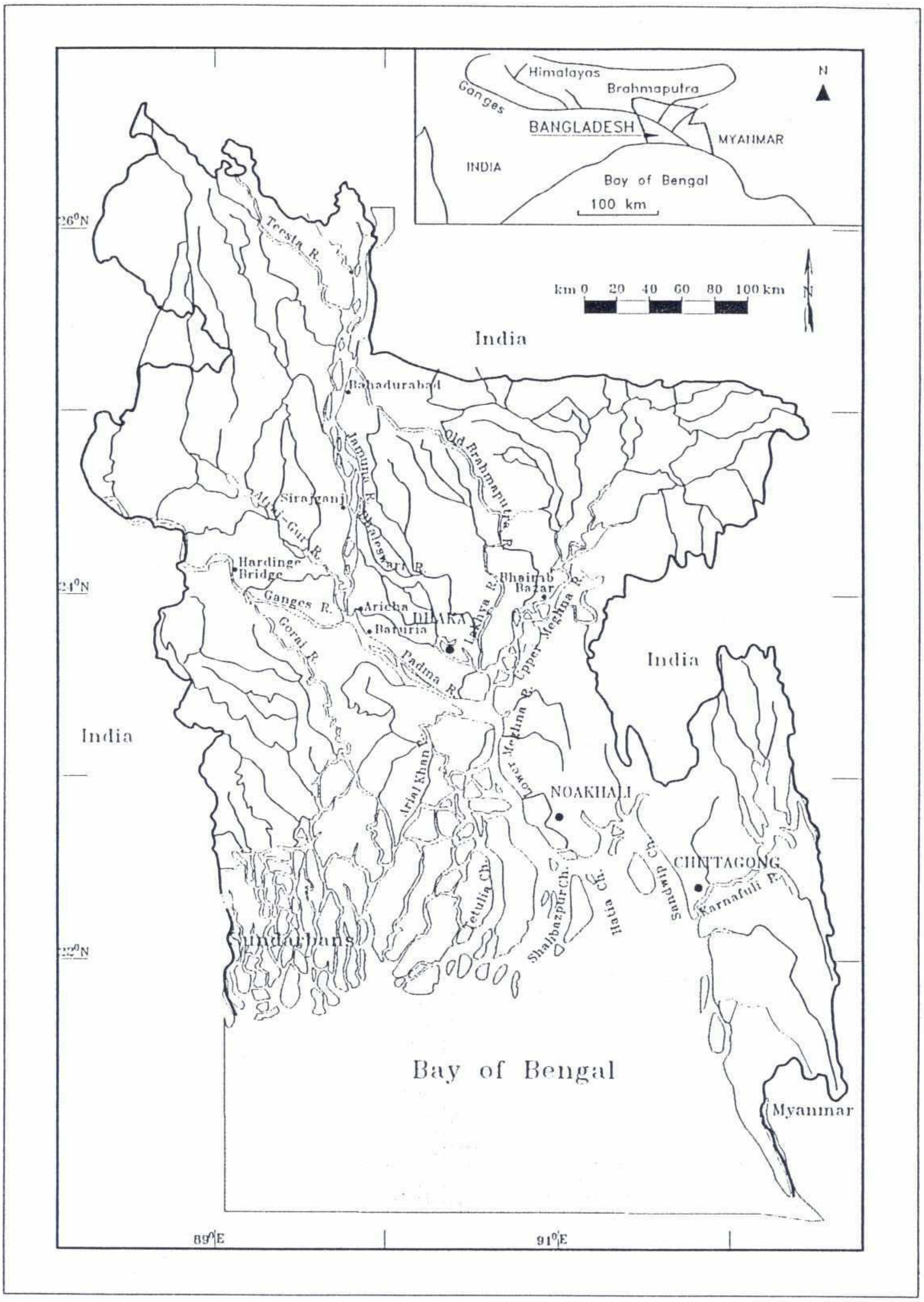


Figure 1.1 Layout of the main river system in Bangladesh

The Project has been executed in two phases:

- during Phase 1 attention was primarily focused on the collection of historical data, data validation, methodologies for the establishment of discharge rating curves and the setting up of a hydrological database,
- whereas in Phase 2, in addition to a further refinement of the processing procedures and updating of the hydrological database, special studies were undertaken.

The special hydrological studies comprised:

1. further refinement of the rating curves and estimation of peak flows at various flooding conditions;
2. further refinement of the profiles of the water surfaces at different discharges for the main rivers at different times of the year, as well as at different stages of implementation of various FAP projects, and
3. the characteristics of overland flow during flood stages.

In this Annexa the above requested activities and findings are presented, beginning with:

- A description of the characteristics of the main river basins in Chapter 2,
- followed by a summary of the hydrological investigations in Chapter 3.
- In Chapter 4 a summary is presented of the historical data available with the BWDB and other external sources and of the new data collected in the course of the Project.
- The current data collection, storage and processing procedures are described in Chapter 5,
- while the processing and storage procedures applied by the Project are presented in Chapter 6.
- In Chapter 7 attention is given to the specified analyses on water levels, water-level slopes, discharge measurements, on fitting and extrapolation of rating curves and on discharge series, including overland flow.
- Station-wise statistics and inter-station comparisons are presented in Chapter 8.
- In Chapter 9 conclusions about the hydrological studies and data requirements are drawn.
- In Chapter 10 final recommendations on data collection and storage, processing and analysis and further studies are presented.

2 Hydrological characteristics of the river basins

2.1 General

The River Survey Project activities concentrated on the main rivers in Bangladesh, viz:

- the Jamuna river
- the Ganges river
- the Upper Meghna river, and
- the Padma/Lower Meghna river

and their major distributaries, including:

- the Old Brahmaputra river
- the Dhaleswari river
- the Gorai river, and
- the Arial Khan.

The hydrological characteristics of these rivers are briefly described in this chapter, to provide background information for the hydrological investigations. Also attention is given to the tidal characteristics, which affect the river flows and stages in the lean season. A more in-depth description is presented in *Survey and Study Report 2: "Selection of study topics for Phase 2", FAP24, 1993.*

2.2 Main rivers

2.2.1 River basins

The layout of the river basins is presented in Figure 2.1. It shows that the Bangladeshi rivers drain almost the entire region of the Himalayas. Only the western slopes are not covered; there the melt and rainwater are conveyed through the Indus river and its tributaries.

Jamuna basin

The Jamuna river takes its rise on the northern slopes of the Himalayas as the Tsang-Po river. It runs first eastward, slightly north of the 29th parallel in southern Tibet, until it falls through a number of gorges. Embraced by the Salween river, at the 95th meridian it changes its direction first south and then south-west through Assam as the Brahmaputra. Finally, near the Bangladesh border, the river turns south until it meets the Ganges river at Aricha. From this confluence onward it flows on for some 120 km as Padma river in south-easterly direction until it is joined by the Upper Meghna river, a little north of Chandpur, after which it turns southward as Lower Meghna river until it reaches the Bay of Bengal. In Bangladesh the river is joined along its right bank by the tributaries Teesta and Atrai rivers that increase the river flow. Along the left bank the distributaries Old Brahmaputra, Arjam and Dhalewari rivers divert part of the Jamuna flow to the Upper Meghna river. At high river stages the Jamuna spills water to a vast floodplain along its left bank.

The total length of the river is about 2,700 km and its drainage area amounts to 560,000 km^2. From the Indian border to its confluence with the Ganges the river measures 240 km. In Bangladesh the average water-level slope of the Jamuna river is about 7.6 cm per km over the first 130 km and 6.5 cm per km further downstream. The riverbed consists of fine sands with D_{90} = 0.30 mm.

The most important river-flow gauging station in the river in Bangladesh is at Bahadurabad, just downstream of the offtake of the Old Brahmaputra river.

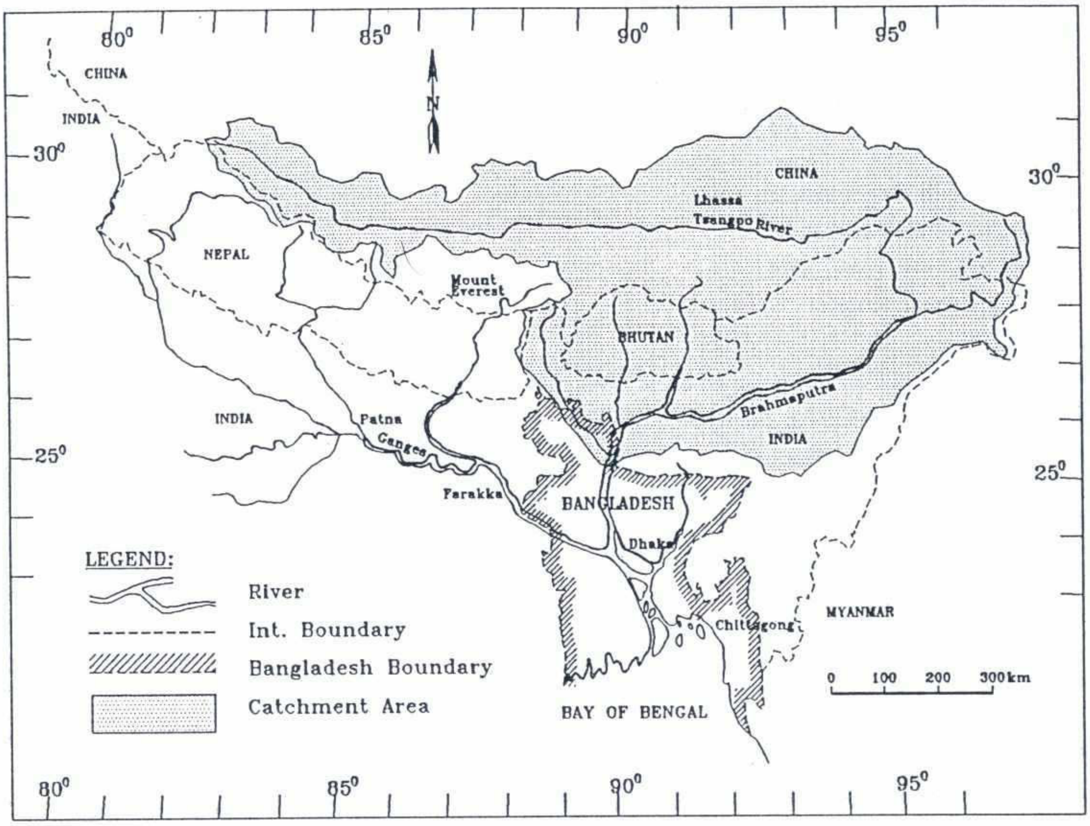


Figure 2.1 River basins of Jamuna/Brahmaputra, Ganges and Meghna

Ganges basin

The Ganges rises west of the Nanda Devi range in Himchal Pradesh and northernmost Uttar Pradesh, west of Nepal. The basin boundaries are roughly formed in the north by the Himalayas, in the south by the Tropic of Cancer, whereas the 75^{th} and 88^{th} meridians form its western and eastern borders. The Ganges basin includes the entire territory of Nepal and of Uttar Pradesh. The river drains the south-western slopes of the Himalayas, the eastern slopes of the Aravelli range in Rajasthan and the northern slopes of the Vindhya range in Madhya Pradesh. The river flows in south-easterly direction until it joins the Jamuna river at Aricha. In Bangladesh a number of right bank distributaries, like the Gorai river, divert flow from the river. The total length of the river from its westernmost sources to Aricha is 2,200 km. Its drainage area is about 980,000 km^2. The water-level slope near Hardinge bridge is approximately 5 cm per km. The characteristic bed material size D_{90} = 0.22 mm.

Hardinge Bridge is an old river gauging station with a long record, located upstream of the Gorai river offtake.

Upper Meghna basin

The Meghna river drains an area of 77,000 km^2, of which about 46,500 km^2 is located in Bangladesh. The major contributors to the river upstream of Bhairab Bazar are the Buolai, the Surma and the Kushiyara rivers, covering an area of roughly 63,000 km^2. Between Bhairab Bazar and the confluence with the Padma river the river flow is increased along its right bank by left bank spill from the Jamuna river, when the river is in flood, and by the Old Brahmaputra, Lakhya, Arjam and Daleshwari rivers, which convey water from the Jamuna and drain the local area. The river flow downstream of Bhairab Bazar is further increased by the left bank tributaries Titas and Gumpti rivers.

The water-level slopes in its lower reach during low flows are almost nil whereas during floods some 2 cm per km is measured. The characteristic grain size D_{90} of the river bed is 0.25 mm.

The principal river flow gauging station on the Upper Meghna river is located at Bhairab Bazar.

Padma/Lower Meghna river

Downstream of Aricha the combined Ganges and Jamuna flows are carried by the Padma river. It is 120 km long and joins the Upper Meghna river north of Chandpur, after which it is called Lower Meghna, which debouches into the Bay of Bengal at some 150 km from the confluence. So the Lower Meghna river conveys the melt and rain water from the Ganges and Jamuna basins as well as from the Upper Meghna river to the sea. Its total drainage area is about 1,600,000 km^2.

A rather important distributary from the Padma river is the Arial Khan, which branches off on the right bank between the discharge gauging stations Baruria and Mawa.

The average slope of the Padma river is around 5 cm per km. The slope of the Lower Meghna varies between 1 cm to 4 cm per km during respectively low and high flow conditions. The characteristic grain size of the bed material is similar to that of the Ganges: D_{90} = 0.22 mm.

2.2.2 Climate

The climate in the region is governed by the monsoon, which migrates annually northward with the movement of the Intertropical Convergence Zone in May-June and lasts till September. In Figure 2.2 the average annual rainfall pattern is shown. From this map it is observed that the rainfall on the northern slopes of the Himalayas is rather low and generally does not exceed 800 mm. On the southern slopes of the Himalayas the annual values range between 2,000 and 3,000 mm, which gradually reduces further southward to 1,000 mm and even less in the middle reaches of the Ganges basin. The highest annual totals are found in the middle and lower Brahmaputra/Jamuna reaches, where locally values far over 3,000 mm are found, with three extreme cells: the area of the Teesta and Shankoshi rivers to the west, the region of Dibang and Luhit to the east and more centrally the Shyllong-Cherrapunji area. The latter area holds the world records of seasonal and annual rainfall.

The variation of the rainfall throughout the year can be inferred from Figure 2.3, where for each month the percentage of catchment area with rainfall in excess of respectively 100 and 300 mm is shown. From this figure it is observed that in the Brahmaputra basin the rainy season last longer than in the Ganges basin and that the rainfall peaks occur earlier. A similar pattern is reflected in the river regime, see Sub-section 2.2.3.

Studies on regional rainfall in the Ganges-Brahmaputra basin indicate an east-west alternation: droughts over central and northwest India take place in years of excessive rainfall over northeast India/Bangladesh and vice versa (Rogers et al., 1989). A weak southwest monsoon, which is responsible for drought in central and northwest India, seems to coincide with the El Niño anomaly off Peru. The alternation makes Bangladesh a continuously flood-prone area.

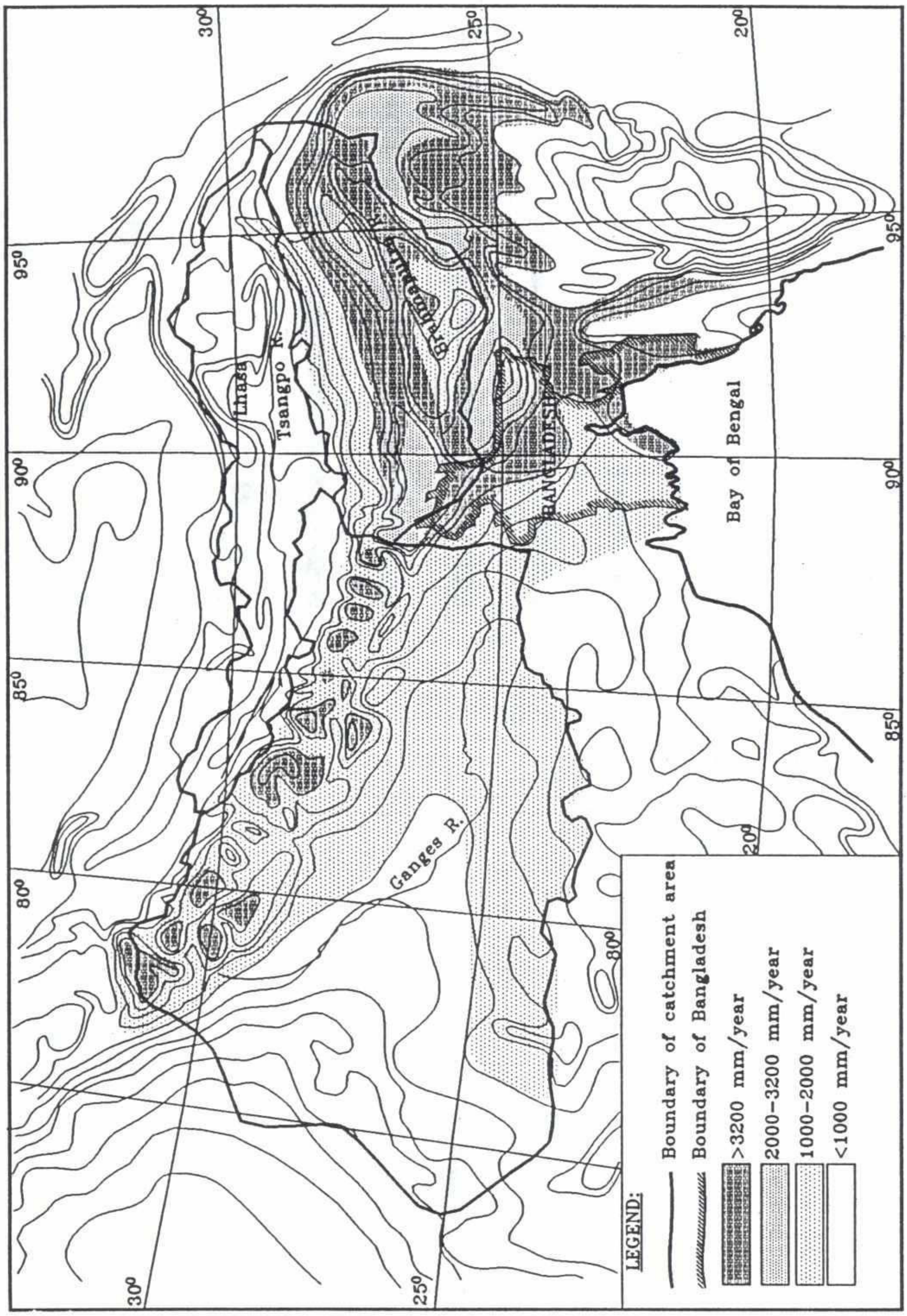
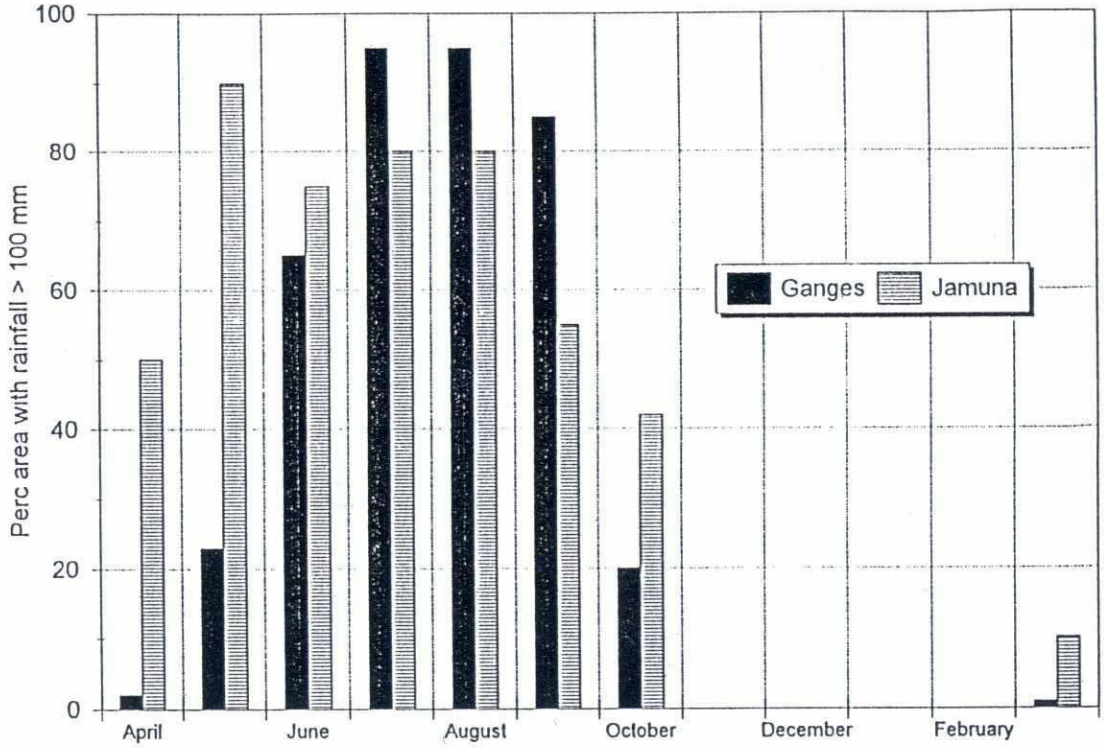


Figure 2.2 Isohyets of average annual rainfall in the Jamuna/Brahmaputra, Ganges and Meghna basins



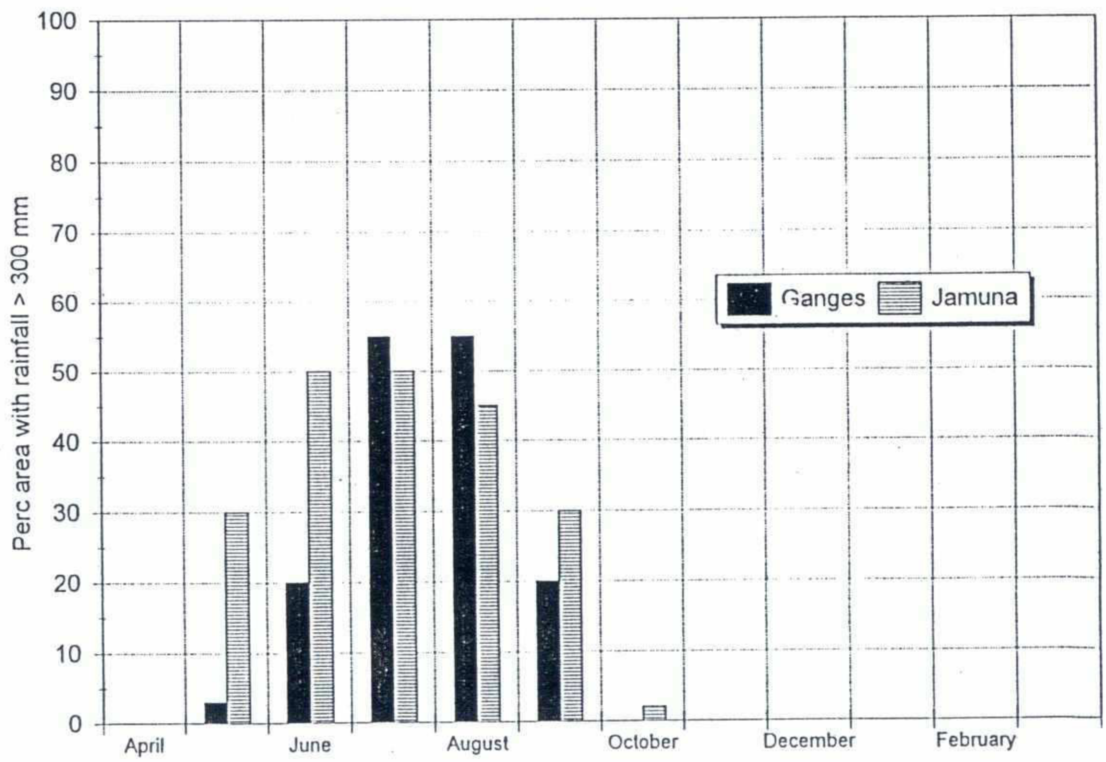


Figure 2.3 Area percentage in Jamuna and Ganges basins with monthly rainfall in excess of 100 and 300 mm

2.2.3 River flows

The river regimes of the three main rivers in Bangladesh are depicted in Figure 2.4, showing the 90, 50 and 10% exceedance flows for the period 1965-1995. Clear differences are observed between the Jamuna and Ganges river regimes: the Jamuna rises one and a half to two months earlier than the Ganges, whereas flow recession in the Ganges begins somewhat earlier. During August-September the river flows are on average similar. Consequently, the volume of Jamuna hydrograph is much larger than that of the Ganges.

The Jamuna river begins rising in April due to the melting of the snow in the Himalayas, which causes a first peak in May early June. Subsequent and largest peaks occur in July-August, in quick response to heavy monsoon rains in Assam and Bangladesh. Peak flows up to 100,000 m^3/s have been reported. The average discharge is approximately 21,000 m^3/s, which implies a runoff of 1,200 mm per annum.

The Ganges river flows increase gradually in May-June and attain peak levels on average early September. Since 1966 the highest peak flow amounted to 72,000 m^3/s. Although the peak flows in the Ganges are experienced about one month later than in the Jamuna, given the range in the occurrence of the peak flows, particularly in the Jamuna, there is a high probability that both phenomena coincide (FAP9B, 1992). The average flow at Hardinge Bridge of (1966-1995) is roughly 11,000 m^3/s, which is equivalent to a runoff of 350 mm per year. The annual flow volume is seen to be about half the Jamuna flow volume, whereas the runoff per unit area is less than 25% of that of the Jamuna. In the lean season the river flows are reduced at Farakka where part of the flow is diverted to the Hooghly river, creating inhomogeneities in the Hardinge Bridge low flow record.

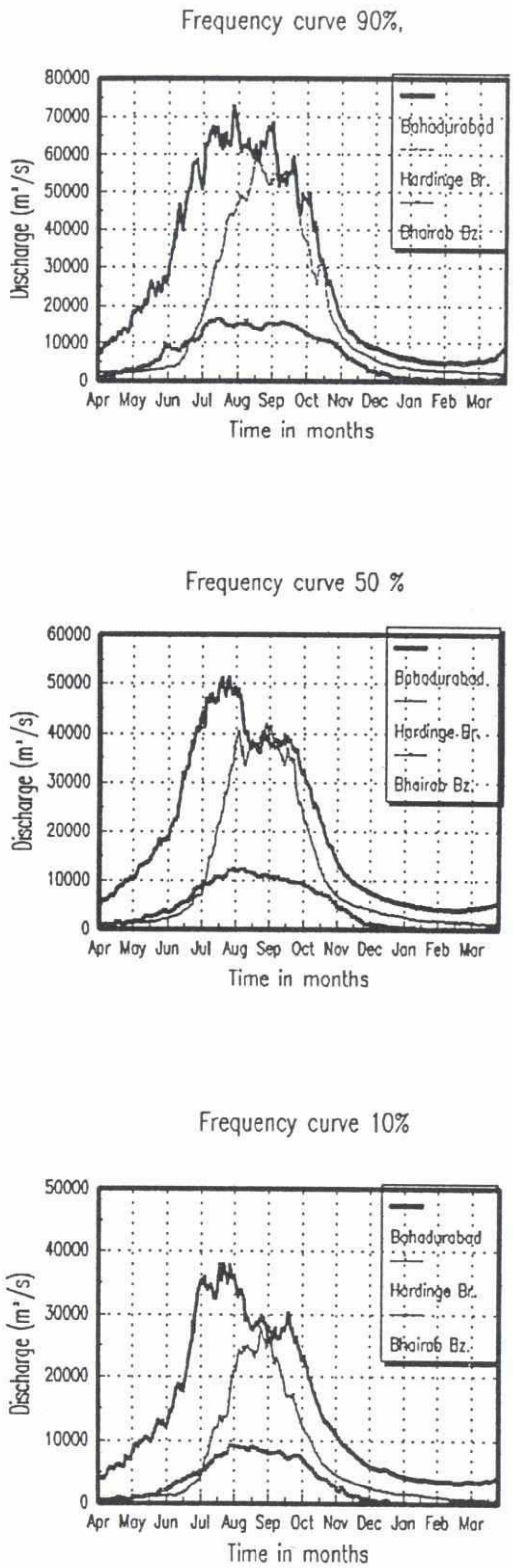


Figure 2.4

Frequency curves of 90%, 50% and 10% exceedance flows in the Jamuna at Bahadurabad, the Ganges at Hardinge Bridge and the Upper Meghna at Bhairab Bazar

The Meghna river is observed to begin rising somewhat earlier than the Ganges in response to early monsoon rains in May. Particularly the upper regions of the Surma river with annual rainfall totals of about 5,000 mm contribute significantly to the Meghna flows. Peak values of nearly 20,000 m^3/s have occurred a few times in the past three decades. The annual average discharge at Bhairab Bazar is approximately 4,800 m^3/s; this implies an annual runoff of 2,500 mm.

2.3 The distributaries

In this section some characteristic features of the distributaries of the Jamuna and Ganges rivers are described.

Old Brahmaputra river

The Old Brahmaputra is the first left bank distributary of the Jamuna, branching off at about 10 km upstream of Bahadurabad, see Figure 2.5. The river generates some of its own distributaries such as Sirkali, Sutia and Lakhya. It finally drains into the Meghna just south of Bhairab Bazar. The river is 220 km long from its offtake from the Jamuna to its outfall into the Meghna river. At Mymensingh the river flow is measured. Its regime is depicted in Figures 2.6a. Over the years the annual flows gradually reduce from about 800 m^3/s in 1965 to 500-600 m^3/s in the early nineties, which is equivalent to respectively 4% and 3% of the average Jamuna river discharge (see Figures 2.6b and 2.6c).

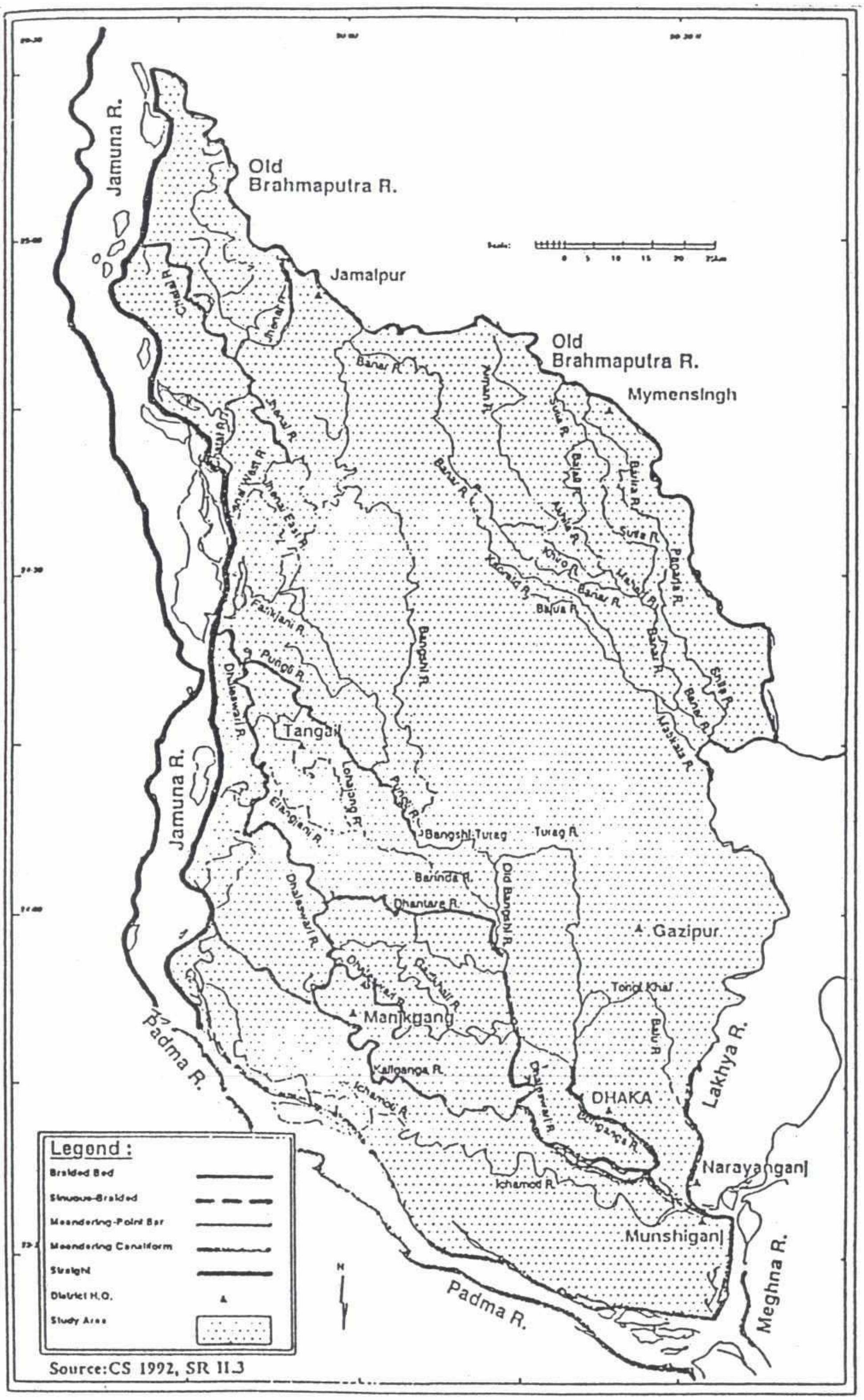
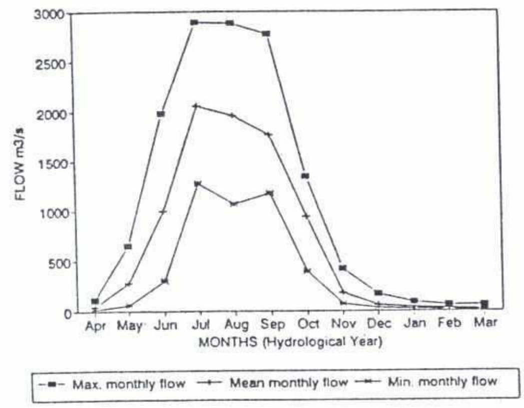
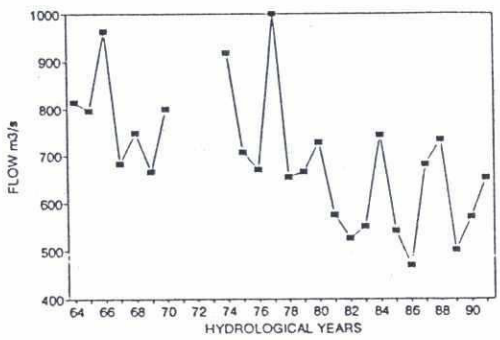


Figure 2.5 Left bank distributaries of the Jamuna





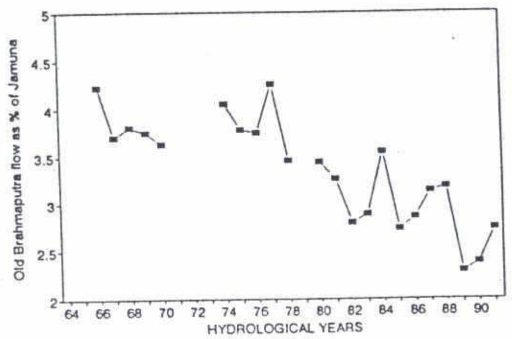


Figure 2.6a (above left): Monthly flow regime of the old Bramaputra at Mymensingh

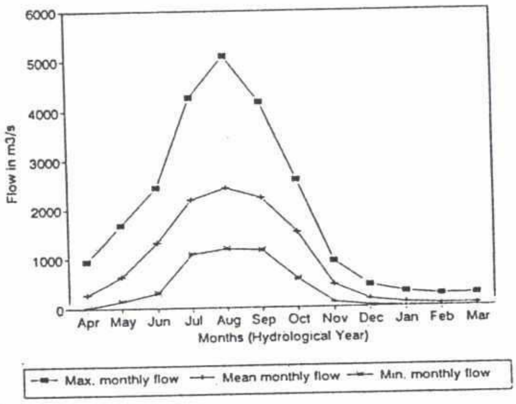
Figure 2.6b (above right): Trend of annual flow of the Old Brahmaputra at Mymensingh

Figure 2.6c (left): Trend of Old Brahmaputra flow as percentage of Jamuna

Dhaleswari river

At about 20 km downstream of Sirajganj the Dhaleswari branches off from the Jamuna river on the river's left bank, see Figure 2.5. At Tilly, some 48 km downstream from its offtake, the Dhaleswari bifurcates into the Dhaleswari and Kaliganga and reunite at Kalatia, before finally draining into the Meghna river near Munshiganj.

The river flows are gauged at Tilly. The river regime of recent years is shown in Figure 2.7a. Like the Old Brahmaputra, the annual flows in the Dhaleswari show a downward trend. In the past decades its conveyance of Jamuna water reduced from about 7% in the mid-sixties to 3 to 4% in the late eighties-early nineties (Figure 2.7b).



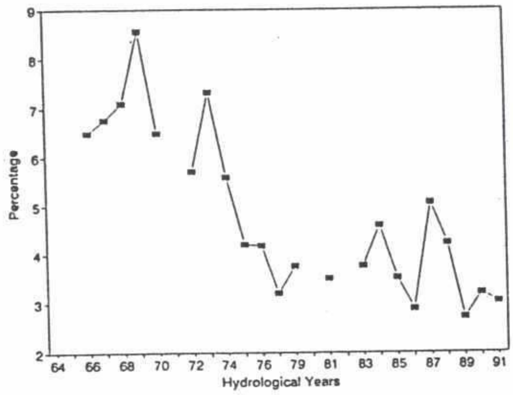


Figure 2.7a (left) : Monthly flow regime of the Dhaleswari

Figure 2.7b (right): Trend of annual flow of Dhaleswari as percentage of Jamuna flow

Gorai river

The Gorai is a major right bank distributary of the Ganges river, see Figure 2.8. It branches off some 15 km downstream of Hardinge Bridge. The river bifurcates into a number of branches before debouching into the Bay of Bengal. The Gorai is of extreme importance for the Southwest region of Bangladesh as it conveys fresh water in the saline zone around the city Khulna.

The Gorai river flows are measured at Gorai Railway Bridge. The flows in the river have been affected by flow diversion at Farakka and by the Ganges river morphology: a sandbar partly blocks the entrance to the Gorai river. The average river regime in recent years is shown in Figure 2.9a. The annual flows are declining. In the mid-sixties the Gorai river conveyed some 16% of the Ganges flow at Hardinge Bridge. This amount reduced to roughly 11% in the early nineties.

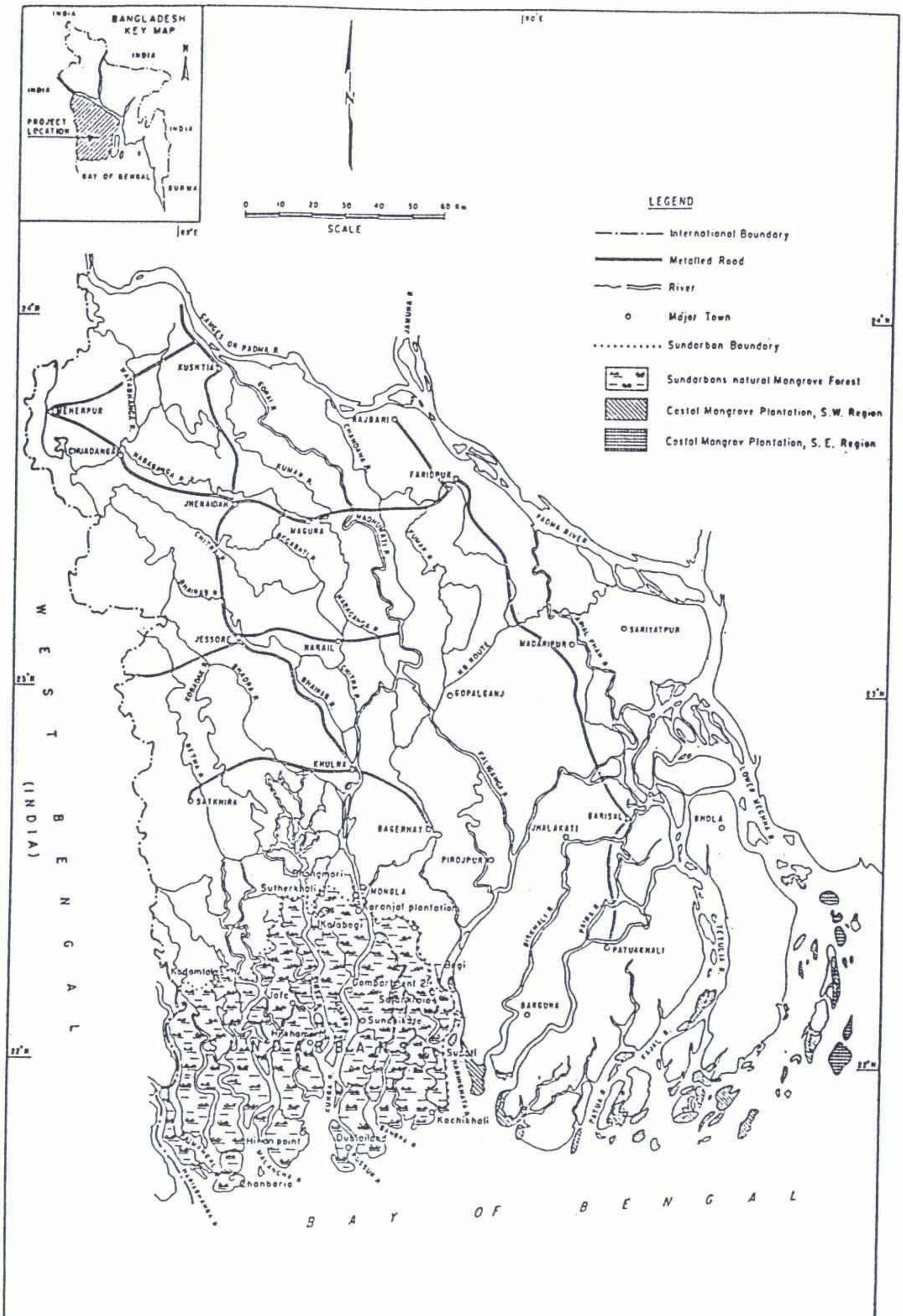
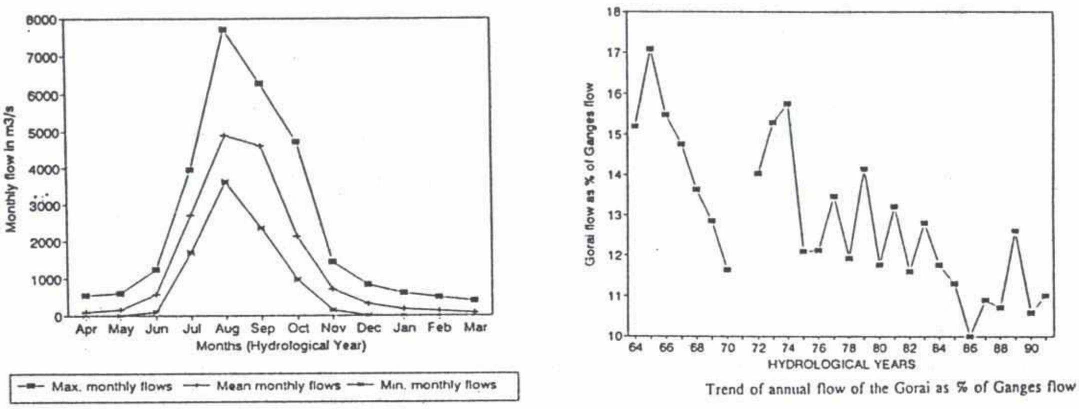


Figure 2.8 Distributaries of Ganges River



Trend of annual flow of the Gorai as % of Ganges flow

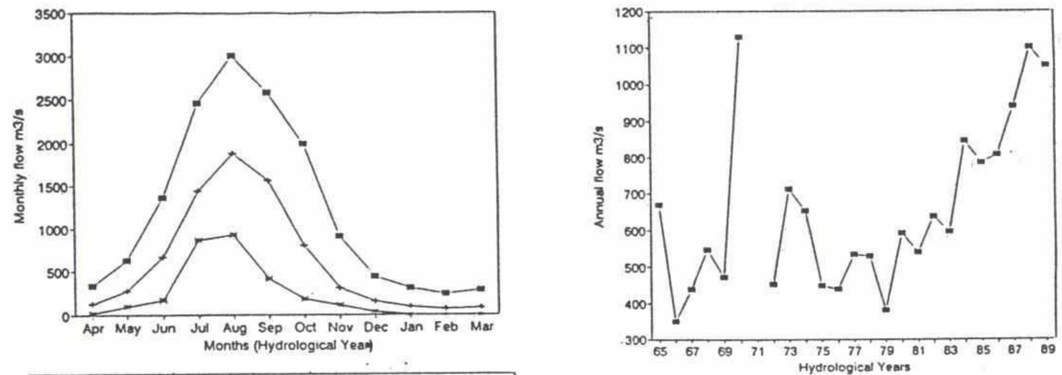
Monthly flow regime of the Gorai at Gorai Railway bridge

Figure 2.9 Characteristics of Gorai river flow at Gorai Railway Bridge

Arial Khan

The Arial Khan is a right-bank distributary of the Padma river, branching off at about 20 km upstream of Mawa, see Figure 2.8. The offtake is seasonally tidal. Similar to the Gorai river, the Arial Khan bifurcates at various places before reaching the Bay of Bengal.

The Arial Khan has more than one offtake, and the river is gauged at its main offtake at Chowdhury's char. The average flow regime in recent years is shown in Figure 2.10a. Different from the distributaries described above, the annual totals seem to increase: from about 500 m^3/s in the mid-sixties to over 1,000 m^3/s in recent years (Figure 2.10b). Since the river has more than one offtake, it is difficult to infer whether the total flow of the Arial Khan actually increases.



Trend of Annual flow at the offtake of Arial Khan

Monthly flow regime of the Arial Khan

Figure 2.10 Characteristics of Arial Khan river flow at offtake

2.4 Tidal effects

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

The tide originates in the Indian Ocean and travels past the deep Bay of Bengal, where it reaches Hiron Point and Cox's Bazar almost concurrently (NEDECO, 1967). Extensive shallowness and partial reflection along the northeastern bay increases the range of tide, while bottom friction, due to decrease of depth, distorts it. Flow friction and river flow decrease the tidal effect land inward. The tide in Bangladesh is predominantly semidiurnal with slight diurnal inequalities. The low atmospheric pressure during the monsoon season and high pressure in the winter season generates a seasonal variation in the mean sea-level, resulting in above average levels in the monsoon season and below average levels in winter. During the monsoon the levels are further increased by wind set-up as the prevailing wind direction in this time of the year counteract the river flow in the Lower Meghna.

The tidal effect on the Jamuna reaches about as far as the Ganges-Jamuna confluence. At Baruria still some tidal influence is felt in winter.

In the lean season the Meghna river is tidal up to Markuli, far upstream of Bhairab Bazar. During high flow the tidal influence is strongly reduced, but still some influence is felt as far upstream as Baidyer Bazar, i.e. around 20 km upstream of the Meghna-Padma confluence.

3 Summary of hydrological investigations

The hydrological investigations carried out during the River Survey Project included the following activities:

1. ***Assessment of historical hydrological information on river stages, discharge observations, stage-discharge relations and discharge series. It included:***

- Collection, validation, processing and analysis of daily mean water levels of the relevant river gauging stations along the main rivers. The historical data as compiled by the BWDB from three-hourly readings since 1964 have been considered.
- Collection, validation and processing of all historical stage-discharge data of the main river discharge station.
- Collection and analysis of processed daily average discharge series of the main river stations.

2. ***Creation of a reliable hydrological database based on validated BWDB water-level data and newly developed stage-discharge relations derived from BWDB flow measurements till 1988 and FAP24 measurements in the period 1993-1995. The activities comprised:***

- Collection, validation, processing and analysis of FAP24 water-level observations.
- detailed analysis of all river flow measurements of the period 1966-1995 carried out by BWDB and FAP24.
- Establishment of new annual discharge rating curves for the main river stations using BWDB and FAP24 discharge data. New parameter estimation procedures for the development of stage-discharge were introduced, which proved to result in more realistic values for the discharge at the highest water levels.
- Development of new and updated discharge series; the new series were based on the newly derived rating equations. For the project years preference was given to the discharge ratings derived from the FAP24 discharge measurements at most of the sites, provided sufficient FAP24 data were available.

3. ***Statistical analysis of improved water-level and discharge series of the main river stations along the Jamuna, Ganges, Padma and Gorai rivers. The statistics were based on the period 1965 to 1995 and comprise:***

- Annual mean, maximum and minimum water levels.
- Annual mean, maximum and minimum discharges.
- Statistics of annual maximum water levels.
- Statistics of annual maximum discharges.
- Frequency and duration curves of daily water levels.
- Frequency and duration curves of daily discharges.

4 *Special studies related to:*

- Stage-discharge relation of Bahadurabad, particularly in view of extrapolation of the discharge rating equation (a one or two channel rating equation) and an explanation of the inconsistency in the stage-discharge relation applied between 1 September 1988 and 1 April 1993.
- Analysis of the stage-discharge relation of Bhairab Bazar, where backwater from the Padma affects the stage-discharge measurements.
- Water balance analysis to investigate the consistency of flow data.
- Estimation of overland flow.
- Analysis of longitudinal water-level profiles for different flow conditions.
- Investigations into the reliability of the zero levels of the gauging stations.

5 ***Recommendations on future data collection, storage processing and analysis and on additional studies.***

6 ***Training of BWDB, WARPO and SWMC staff in hydrological data validation, processing and analysis using the database management and processing system HYMOS.***

4 Data availability

4.1 General

A number of agencies have been approached to obtain information on past and ongoing hydrological studies and projects related to the objectives of the FAP 24 hydrological studies.

The following agencies were visited:

1 Directorate of Surface Water Hydrology I (SWH-I) of the Bangladesh Water Development Board (BWDB).
SWH-I is responsible for the hydrological field work in connection with the BWDB network of hydrometric stations.

2. Directorate of Surface Water Hydrology II (SWH-II) of the Bangladesh Water Development Board (BWDB).
SWH-II is responsible for the processing of the field data measured by SWH-I.

3. Flood Modelling and Management (FAP25).
This project carried out a comprehensive study of existing hydrological data of the main rivers in Bangladesh. FAP25 developed an extensive hydrological database of BWDB data, processed by FAP25 standards (FAP25, June 1992).

4. Surface Water Modelling Center (SWMC).
The Center developed hydrodynamic models for the six regions in Bangladesh and a General Model covering the main rivers in the country, based on MIKE 11 (MPO, July 1992). Its hydrological database is based on BWDB data from 1985 onward. SWMC applies some additional checks on the supplied data to ensure physically consistent boundary conditions for modelling.

5. Brahmaputra River Training Studies (BRTS, FAP1).
FAP1 carried out a comprehensive hydrological study of the Jamuna river (FAP1, April 1991). It developed a hydrological database of the Jamuna river based on historic hydrological data collected by the BWDB. FAP1 data have been subjected to various data validation techniques. A detailed assessment of potential errors in discharge measurements on the Jamuna was made by FAP1 on the basis of own measurements.

6. Bank Protection and River Training (AFPM) Pilot Project (FAP21/22).
The hydrological studies carried out by the Project aimed at establishing hydrological design conditions at a few test sites along the Jamuna. The data used and the analyses carried out are similar to the FAP25 procedures (FAP21/22, July 1992).

7. Jamuna Bridge Project.
The project has carried out various hydrological analyses for the stations on the Jamuna to arrive at hydrological design conditions for the potential bridge project (JBP, August 1989). Its database includes data of water-levels station and discharge series for Bahadurabad.

8. Bangladesh Inland Water Transport Authority (BIWTA).
   The BIWTA operates 45 water-level gauges mainly in the tidal area of Bangladesh. The agency carries out tidal analyses and publishes tidal prediction charts.

9. Water Resources Planning Organization (WARPO).
   WARPO carries out studies and planning of water resources in the whole country, mainly on the basis of BWDB data on surface and groundwater observations.

The documents collected from the above agencies were used to provide background information for the studies dealt with in this annexa. Reports and available data were reviewed, and information on current procedures for collection, processing, validation and storage of data was obtained, see Hydrological Study, Phase 1 report (FAP24, June 1993).

The major source of hydrological information is the Directorate of SWH-II of BWDB. Most of the hydrological data required for the River Survey Project was, however, available in computerized form at FAP25, from which they were procured. The remaining data required, especially for the recent years after 1989 and some additional stations, were procured directly from the BWDB. A summary of the procured data is presented in Section 4.2.

Apart from the hydrological data from external sources, a large amount of hydrological data were obtained from the hydrological network operated by the River Survey Project, including water level data and observed river flow data. The extent of the observed data is summarized in Section 4.3.

4.2 Data from external sources

The hydrological data collected from FAP25 and BWDB comprised:

1 Mean daily water-level series
   Data of 40 water-level gauging stations were collected: 13 stations on the Jamuna, 6 on Ganges, 1 on Gorai, 6 on Padma, 7 on Upper Meghna, 3 on Old Brahmaputra, 3 on Dhaleswari and 1 on Arial Khan. The Location of the stations is shown in Figure 4.1. For about half of the stations the series covered the period 1964-1995, whereas for the remainder only the last 5 to 10 years could be made available. The data were partly obtained from FAP25 in computerized form. The BWDB data were all in hard copy. A summary of the data availability is given in Table 4.1.

2 Observed discharge data
   Processed stage-discharge measurements were collected for all stations on the main rivers and of the distributaries Gorai and Arial Khan, generally from 1966 until now, with some gaps, particularly for Gorai Railway Bridge, Bhairab Bazar and Chowdhury Char. A list of the data availability is presented in Table 4.2. The available BWDB-rating curves for these stations were also procured from the BWDB.

3 Mean daily discharge series
   Processed discharge series, based on the BWDB water-level series and established rating curves, available as from 1964/65 onward for Bhahadurabad, Hardinge Bridge, Baruria, Mawa, Gorai Railway Bridge and Bhairab Bazar were collected, Table 4.3.

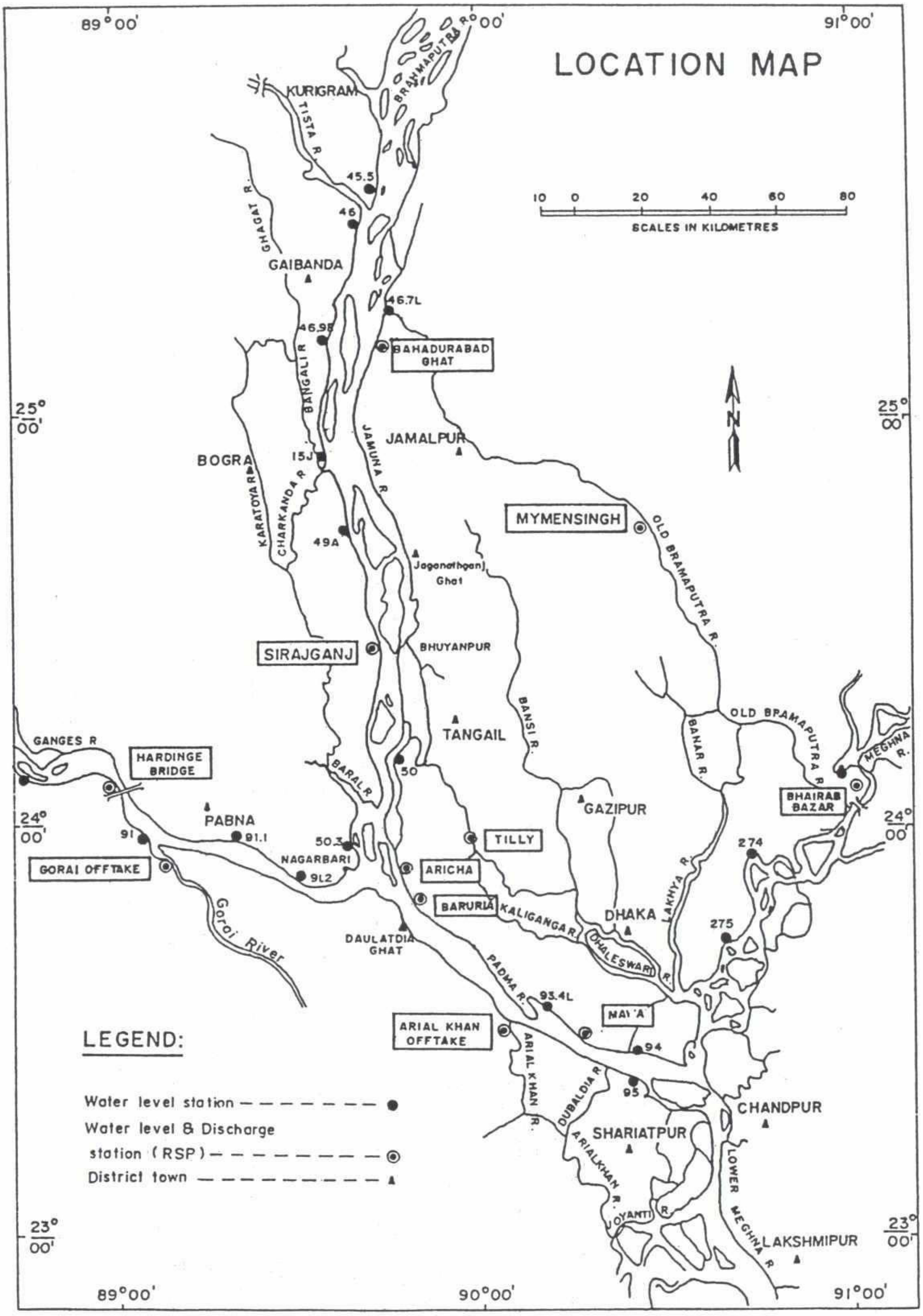


Figure 4.1 Location of the BWDB water level and discharge gauging station

MEAN DAILY WATER LEVEL DATA

STATION NO.	NAME OF STATION	TYPE	NAME OF RIVER	CHAINAGE	WATER YEAR (April 1 - March 31)																															
					64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95
								L				L				L				L				L				L				L				L
45	Noon khawa		Jamuna	0.0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	B	-	-	-	-	-	B	B	B	B	-	
45.5	Chilmari		Jamuna	37.1	-	F	F	F	F	F	B	B	F	F	F	F	F	F	F	-	F	-	-	F	F	F	F	F	F	B	B	B	B	B	B	B
46	Kamarjani		Jamuna	50.0	B	B	B	B	B	B	B	-	B	B	B	B	B	B	B	B	B	B	-	B	B	B	B	B	B	B	B	B	B	B	B	B
46.7L	Kholabarichar		Jamuna	75.0	-	F	F	F	F	F	F	-	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	B	B	B	B	B	-	
46.9R	Fulchari ghat		Jamuna	84.0	-	-	B	B	B	B	B	B	B	B	B	B	B	B	-	-	-	-	B	B	B	B	B	B	B	B	B	B	B	B	B	B
46.9L	Bahadurabad		Jamuna	84.7	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	B	B	B	B	B	B	B
15J	Mathurpara		Jamuna	115.0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	B	-	-	-	-	-	B	B	B	B	B	
49A	Kazipur		Jamuna	139.0	-	-	-	F	F	F	F	-	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	B	B	B	B	B	B	B
48	Jagannathagn		Jamuna	144.0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	B	B	B	B	-	
49	Sirajganj		Jamuna	162.4	F	F	F	F1	F	F	F	-	F	F	F	F	F	F	F	F	F	B	F	F	F	F	F	F	F	F	B	B	B	B	B	B
50	Porabari		Jamuna	188.2	F	F	F	F	F	F	F	-	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	B	B	B	B	B	B	B
50.3	Mathura		Jamuna	220.0	-	F	F	F	F	F	F	-	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	B	B	B	B	B	B	B
50.6	Teota		Jamuna	235.4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	B	B	B	B	B	
88	Rampur Boalia		Ganges	-33.0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	B	B	B	B	B	-	
89	Sardah		Ganges	-17.0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	B	B	B	B	B	
90	Hardinge Bridge		Ganges	35.2	F	F	F	F	F	F	F	-	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	B	B	B	B	B	B	B
91	Talbaria		Ganges	48.0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	B	B	B	B	B	B
99	Gorai Railway Bridge		Gorai	62.0	F	F	F	F	F	F	F	-	F	F	F	F	F	F	F	F	F	F	F	F	B	B	F	F	F	B	B	B	B	B	B	B
91.1	Sengram		Ganges	77.5	F	F	F	F	F	F	F	F	B	-	F	F	F	F	F	F	F	F	-	F	F	F	F	F	F	B	B	B	B	B	B	B
91.2	Mahendrapur		Ganges	97.2	B	F	F	F	F	F	F	F	-	F	-	F	F	F	F	F	F	F	-	F	F	F	F	F	F	B	B	B	B	B	B	B
91.9L	Baruria		Padma	11.6	F	F	F	F	F	F	F	-	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	B	B	B	B	B	B	B
91.9R	Galundo Transit		Padma	9.0	F	F	F	F	F	F	F	F	F	F	F	F	F	B	B	F	B	B	F	F	F	B	B	B	F	B	B	B	B	B	-	
93.4L	Bhagyakul	T	Padma	59.0	-	-	-	-	F	F	F	F	F	F	F	F	-	F	-	-	-	F	-	F	F	F	B	B	B	B	B	B	B	B	B	
93.5L	Mawa	T	Padma	71.5	-	F	F	F	F	F	-	-	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	B	F	B	B	B	B	B	B	B
94	Tarpasha	T	Padma	88.0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	B	B	B	B	B	
95	Sureshwar	T	Padma	88.0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	B	B	B	B	-	
273	Bhairab Bazar	T	Meghna	27.0	F	F	F	F	F	F	F	-	F	F	F	F	F	F	F	F	F	F	B	F	F	F	F	B	B	B	B	B	B	B	B	
230.1	Bhairab Bazar Rly. Br.	T	Old Brahmaputra	31.0	F	F	F	F	F	B	F	-	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	B	B	B	B	B	-	-	
274	Narsingdi	T	Meghna	57.0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	B	B	B	B	-	
275	Baidyer Bazar	T	Meghna	90.5	-	-	-	-	F	F	F	F	F	F1	F	F	F	F	-	F	F	F	F	F	F	F	F	-	F	B	B	B	B	B	-	
272	Madna	T	Meghna	96.1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	B	B	-	-	-	
272.1	Austagram	T	Meghna	109.0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	B	B	B	B	-	
275.5	Meghna Ferry ghat	T	Meghna	136.0	-	-	-	-	F	F	F	F	F	F	F	F	F	B	-	-	F	B	B	B	B	-	F	F	F	B	B	B	B	B	-	
4A	Chowdhury char		Arial Khan		-	-	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B
68.5	Jagir		Dhaleswari		-	-	-	-	-	-	B	-	-	B	B	B	B	B	B	B	B	-	-	B	B	B	B	B	B	B	B	B	B	-	-	-
137A	Taraghat		Kaliganga		B	B	B	B	B	B	B	-	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	-	-	-
74	Dialpur		Dhanu-Boulai Ghoru		-	-	-	-	-	-	-	-	-	-	-	-	-	B	B	-	B	B	-	-	-	B	B	B	-	-	-	B	B	B	-	-
228.5	Mymensingh		Old Brahmaputra		-	-	B	B	B	B	B	-	B	B	B	B	B	B	B	B	B	B	B	-	B	B	B	B	B	B	B	B	B	B	B	B
225	Jamalpur		Old Brahmaputra		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	B	B	B	B	B	B	B	B	B	B	-	-
68	Tilly		Dhaleswari		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	B	B	B	B	B	B	B	B	B	B	-	-

(shaded) = DISCHARGE/WATER LEVEL STATION
Type : T = Tidal station

WATER YEAR L = Leap Year
DATA AVAILABLE FROM : B = BWDB (with number of missing days)
[-] = DATA NOT AVAILABLE

F = FAP 25
(1st source mentioned is used for analysis)

Remarks : incase of incomplete years, additional data could not be found

Table 4.1 Availability of mean daily water-level data retrieved from external sources

OBSERVED DISCHARGE DATA

Hydrologycal Year	Station : 46.9L Bahadurabad				Station : 90 Hardinge Bridge				Station : 91.9L Baruna			
	Status	First od	Last od	Source	Status	First od	Last od	Source	Status	First od	Last od	Source
64	-	-	-	-	-	-	-	-	-	-	-	-
65	-	-	-	-	-	-	-	-	-	-	-	-
66	H	05 Apr	27 Mar	B48 (F39)	H	10 Apr	30 Mar	B48 (F48)	H	10 Apr	27 Aug	B21 (F21)
67	H	03 Apr	25 Mar	B53 (F39)	H	05 Apr	27 Mar	B54 (F54)	H	06 Apr	28 Mar	B53 (F53)
68	H	01 Apr	25 Mar	B52 (F38)	H	03 Apr	29 Mar	B77 (F77)	H	11 Apr	27 Mar	B50 (F50)
69	H	01 Apr	03 Mar	B49 (F38)	H	02 Apr	28 Mar	B79 (F79)	H	03 Apr	26 Mar	B53 (F53)
70	H	07 Apr	24 Mar	B49 (F38)	H	01 Apr	13 Feb	B61 (F61)	H	02 Apr	21 Jan	B34 (F34)
71	-	-	-	-	-	-	-	-	-	-	-	-
72	H	02 May	28 Mar	B33 (F33)	H	07 Apr	14 Mar	B41 (F41)	H	07 Apr	29 Mar	B41 (F41)
73	H	03 Apr	27Jan	B33 (F33)	H	05 Apr	27 Mar	B46 (F46)	H	05 Apr	28 Mar	B41 (F41)
74	H	03 Apr	23 Feb	B16 (F13)	H	03 Apr	23 Mar	B40 (F56)	H	04 Apr	27 Feb	B29 (F29)
75	H	01 Jul	17 Feb	B25 (F25)	H	02 Apr	15 Mar	B47 (F163	H	05 Apr	18 Mar	B29 (F29)
76	H	06 Apr	29 Mar	B49 (F38)	H	01 Apr	26 Mar	B60 F215)	H	01 Apr	31 Mar	B52 (F52)
77	H	05 Apr	20 Mar	B41 (F38)	H	02 Apr	29 Mar	B52 (F254	H	-	-	-
78	H	17 Apr	19 Mar	B35 (F35)	H	05 Apr	27 Mar	B51 (F174	H	-	-	-
79	-	-	-	-	H	03 Apr	22 Jan	B45 (F96)	H	05 Apr	24 Jan	B32 (F32)
80	H	08 Apr	16 Mar	B25 (F22)	H	01 Apr	30 Mar	B45 (F134	-	-	-	-
81	H	01 Apr	27 Mar	B31	-	-	-	-	H	09 Apr	25 Mar	B37 (F37)
82	H	07 Apr	28 Mar	B29 (F29)	-	-	-	-	H	08 Apr	31 Mar	B35 (F35)
83	H	12 Apr	19 Mar	B39 (F38)	H	07 Apr	31 Mar	B51 (F130)	H	13 Apr	29 Mar	B36 (F36)
84	H	04 Apr	25 Mar	B33 (F33)	H	07 Apr	31 Mar	B51 (F142)	H	12 Apr	29 Mar	B36 (F36)
85	H	08 Apr	24 Mar	B32 (F32)	H	17 Apr	31 Mar	B48 (F131)	H	11 Apr	20 Mar	B36 (F36)
86	H	07 Apr	30 Mar	B41 (F38)	H	02 Apr	25 Mar	B49 (F137)	H	03 Apr	28 Mar	B41 (F41)
87	H	12 Apr	21 Mar	B32 (F32)	H	02 Apr	29 Mar	B50 (F118)	H	11 Apr	31 Mar	B36 (F36)
88	H	11 Apr	20 Mar	B30 (F30)	H	06 Apr	30 Mar	B49 (F130)	H	14 Apr	30 Mar	B37 (F37)
89	H	03 Apr	19 Mar	B35 (F35)	H	05 Apr	31 Mar	B49 (F144)	H	13 Apr	22 Mar	B37 (F37)
90	H	02 Apr	25 Mar	B30 (F30)	H	01 Apr	31 Mar	B147	H	05 Apr	28 Mar	B36 (F35)
91	H	08 Apr	30 Mar	B32	H	01 Apr	30 Mar	B144	H	11 Apr	31 Mar	B37
92	H	13 Apr	8oct/10nov	B38	H	01 Apr	27 Dec	B139	H	16 Apr	24 Sep	B21
93	H	01 Apr	31 Mar	B126	H	01 Apr	31 Mar	B217	H	01 Apr	10 Feb	B35
94		02 Apr	30 Mar	B210	H	02 Apr	31 Dec	B141	H	07 Apr	29 Sep	B22
95		01 Apr	30 Nov	B116		01 Apr	31 Dec	B137		07 Apr	28 Dec	B30

Hydrologycal Year	Station : 93.5L Mawa (tidal)				Station : 99 Gorai Railway Bridge				Station : 273 Bhairab B.(tidal)				Station : 4A Chawdhury Char			
	Status	First od	Last od	Source	Status	First od	Last od	Source	Status	First od	Last od	Source	Status	First od	Last od	Source
64	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
65	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
66	H	02 Dec	31 Mar	F18	H	01 Apr	29 Mar	B46	-	-	-	-	H	13 Apr	25 Mar	B45
67	H	07 Apr	29 Mar	F52	-	-	-	-	H	24 Jun	11 Nov	F17	-	-	-	-
68	H	05 Apr	28 Mar	F52	H	02 Apr	31 Mar	B77	H	17 Jun	09 Nov	F22	H	06 Apr	29 Mar	B52
69	H	04 Apr	27 Mar	F52	H	03 Apr	30 Mar	B62	H	14 Jun	01 Nov	F20	H	05 Apr	28 Mar	B52
70	H	03 Apr	24 Mar	F52	H	06 Apr	22 Feb	B48	-	-	-	-	-	04 Apr	18 Mar	B51
71	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
72	H	06 Apr	28 Mar	F44	H	03 Apr	27 Mar	B34	H	03 Jun	30 Oct	F18	H	13 Apr	29 Mar	B24
73	H	11 Jul	26 Oct	F16	H	09 Apr	25 Mar	B32	H	29 May	06 Nov	F21	H	12 Jul	14 Feb	B31
74	H	13 Jun	13 Mar	F20	H	18 Jun	24 Mar	B37	H	27 Jun	06 Nov	F20	H	20 Jun	15 Mar	B22
75	H	09 Apr	31 Mar	F16	-	-	-	-	-	-	-	-	H	13 Apr	01 Feb	B8
76	H	07 Apr	09 Mar	F49	H	05 Apr	21 Mar	B53	-	-	-	-	H	25 Apr	31 Mar	B42
77	H	13 Apr	30 Mar	F47	-	-	-	-	-	-	-	-	-	-	-	-
78	H	12 Apr	21 Mar	F36	-	-	-	-	-	-	-	-	-	-	-	-
79	H	04 Apr	27 Mar	F52	-	-	-	-	-	-	-	-	-	-	-	-
80	H	02 Apr	19 Mar	F32	-	-	-	-	H	19 Apr	15 Nov	F28	-	-	-	-
81	-	-	-	-	-	-	-	-	H	17 Jun	07 Nov	F14	-	-	-	-
82	H	08 Apr	29 Mar	F32	-	-	-	-	H	19 Jun	04 Nov	F10	-	-	-	-
83	H	14 Apr	27 Mar	F28	H	11 Apr	28 Mar	B53	H	30 May	10 Nov	F13	H	16 Apr	29 Mar	B16
84	H	11 Apr	20 Mar	F25	H	04 Apr	27 Mar	B53	H	25 May	28 Mar	F16	H	26 Apr	25 Mar	B14
85	H	05 Apr	26 Mar	F23	H	04 Apr	26 Mar	B52	H	01 Apr	31 Mar	F22	H	06 Apr	27 Mar	B15
86	H	11 Apr	31 Dec	F32	H	02 Apr	30 Mar	B43	H	13 Apr	30 Mar	F24	H	12 Apr	26 Mar	B32
87	H	02 Jun	27 Oct	F19	H	16 Apr	30 Mar	B38	H	16 Apr	19 Mar	F28	H	09 Apr	24 Apr	B27
88	H	07 Jun	25 Oct	F19	H	13 Apr	29 Mar	B39	H	04 Apr	24 Dec	F29	H	07 Apr	26 Mar	B27
89	H	07 Jun	25 Oct	F19	H	12 Apr	28 Mar	B37	H	25 May	02 Nov	F23	H	07 Apr	29 Mar	B26
90	H	13 Jun	31 Oct	B20 (F21)	H	11 Apr	20 Mar	B37	H	24 May	29 Nov	B23 (F27)	H	13 Apr	28 Mar	B26
91	H	17 Jun	30 Oct	B14	H	10 Apr	20 nov/25 mar	B29/+11	H	16 May	28 Nov	B27	H	11 Apr	26 Mar	B25
92	H	03 Jun	28 Oct	B19	H	08 Apr	23 Dec	B32	H	04 Jun	26 Nov	B26	H	09 Apr	23 Mar	B27
93	H	04 Jun	27 Jul	B29	H	26 May	29 Dec	B32	H	05 Jun	25 Nov	B26	H	08 Apr	30 Dec	B20
94	H	01 Jun	26 Oct	B20	-	08 Jun	22 Mar	B33	-	31 May	24 Nov	B27	H	07 Apr	29 Dec	B20
95						05 Apr	15 Nov	B30		02 Jun	28 Sep	B18		06 Apr	16 Nov	B16

Status : H = Data transfered to HYMOS, with number of data if different from source :
Source : B = Data available from BWDB
F = Data available from FAP25
(1st source mentioned is used for analysis)

[-] DATA NOT AVAILABEL

Table 4.2: Availability of observed discharge data retrieved from external sources

MEAN DAILY DISCHARGE DATA

Hydrologycal Year	Station : 46.9L Bahadurabad		Station : 90 Hardinge Bridge **		Station : 91.9L Baruria		Station : 93.5L Mawa (tidal)		Station : 99 Gorai Railway Bridge		Station :237 Bhairab Bazar. (tidal)	
	Status	Source	Status	Source	Status	Source	Status	Source	Status	Source	Status	Source
64	-	-	H	F	-	-	H	F 186	H	F	H	F 170
65	H	F*	H	F	-	-	H	F	H	F	H	F
66	H	F*	H	F*	H	F*	H	F	H	F	H	B
67	H	F*	H	F*	H	F*	H	F	H	F	H	B
68	H	F*	H	F*	H	F*	H	F	H	F	H	B
69	H	F*	H	F*	H	F*	H	F	H	F	H	B
70	H	F*	H	F* 11	H	F*	H	F	H	F	H	B
71	-	-	-	-	-	-	-	-	-	-	-	-
72	H	F*	H	F*	H	F*	H	F	H	F	H	B
73	H	F*	H	F*	H	F*	H	F	H	F	H	B
74	H	F*	H	F*	H	F*	H	F	H	F	H	B
75	H	F*	H	F*	H	F*	-	-	H	F	H	B
76	H	F*	H	F*	H	F*	H	F	H	F	H	B
77	H	F*	H	F*	H	F	H	F	H	F	-	-
78	H	F*	H	F*	H	F	H	F	H	F	-	-
79	H	F	H	F*	H	Only parameter available	H	F	H	F	-	-
80	H	F*	H	F*	H	F*	H	F	H	F	-	-
81	H	F*	H	F*	H	F*	H	F	H	F	H	B
82	H	F*	H	F*	H	F*	H	F	H	F	H	B
83	H	F*	H	F*	H	F*	H	F 41	H	F	H	B
84	H	F*	H	F*	H	F*	H	F 43	H	F	H	B
85	H	F*	H	F*	H	F* 2	H	F 98	H	F	H	B
86	H	F*	H	F*	H	F* 39	H	F 90	H	F	H	B
87	H	F*	H	F*	H	F*	H	F 218	H	F	H	B
88	H	F*	H	F*	H	F*	H	F 224	H	F	H	B
89	H	F* (B)	H	F* (B)	H	F* (B)	H	B224	H	F (B)	H	B
90	H	B	H	B	H	F 13	H	B219	H	B	H	B
91	H	B	H	B	H	B	H	B	H	B	H	B
92	H	B	H	B	H	B	H	B	H	B	H	B
93	H	B	H	B	H	B	H	B	H	B	-	-
94	-	B	-	B	-	B	-	-	-	B	-	-

Status : H = Data transfered to HYMOS
Source : B = Data available from BWDB (with number of missing days)
F = Data available from FAP 25
(1st source mentioned is used for analysis)

| - | DATA NOT AVAILABEL
HYDROLOGYCAL YEAR : L = Leap Year

Table 4.3: Availability of compiled mean daily discharge data retrieved from external sources

4.3 FAP24 data

The main recurrent survey activities by FAP24 comprised discharge and sediment transport measurements at the following sites in and on the distributaries of the main rivers of Bangladesh, see Figure 4.2:

1 Jamuna river at Bahadurabad,

2 Jamuna river at Sirajganj,

3 Ganges river at Hardinge Bridge,

4 Padma river at Aricha,

5 Padma river at Baruria,

6 Padma river at Mawa,

7 Meghna river at Bhairab Bazar,

8 Old Brahmaputra at Mymensingh,

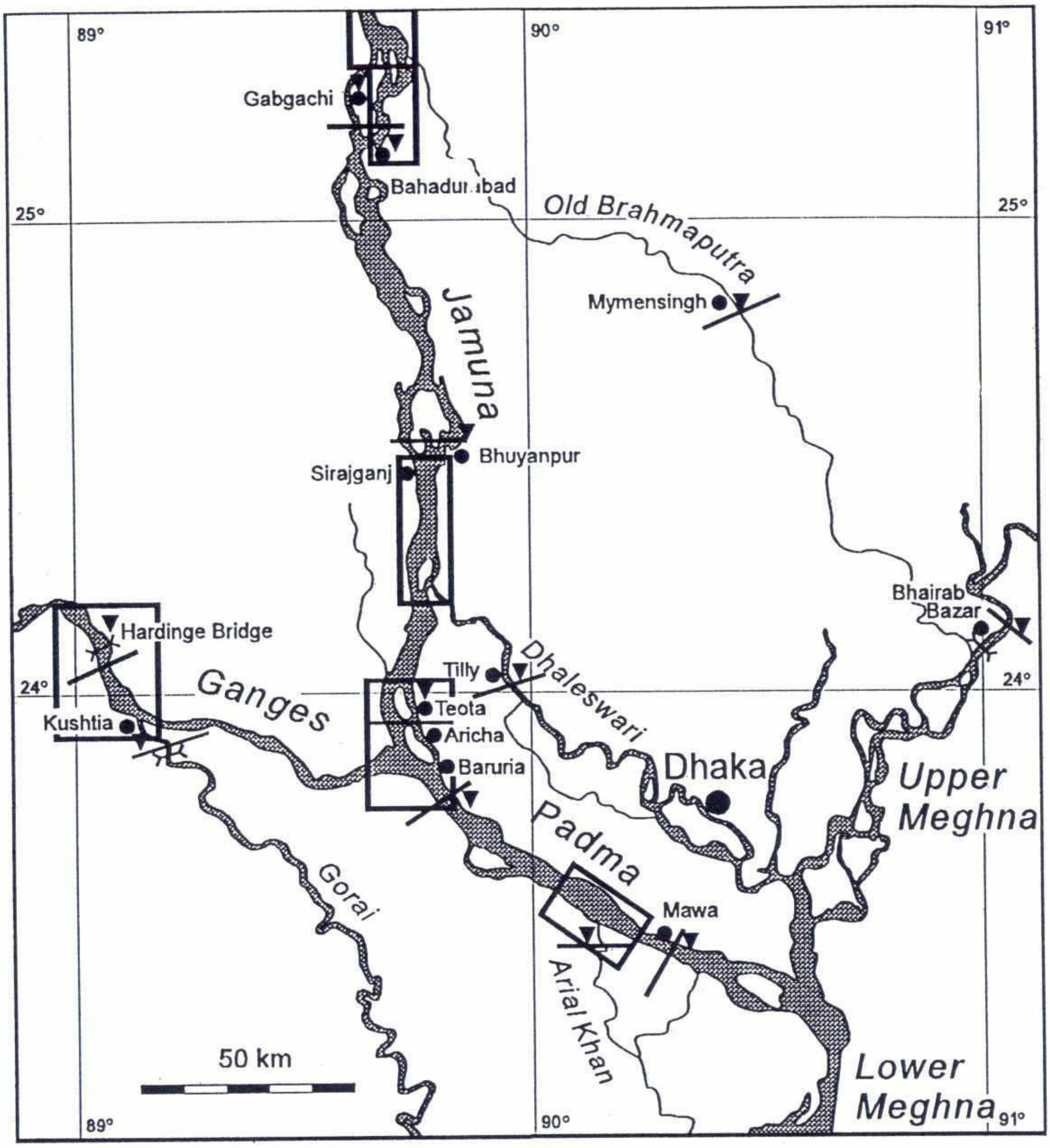
9 Daleshwari river at Tilly,

10 Gorai river at Gorai Offtake, and

11 Arial Khan at Arial Khan Offtake.

A total number of 276 flow measurements were carried out at these sites. A summary of the availability of the condensed flow measurement results is presented in Table 4.4.

In addition, at the selected discharge stations automatic water-level recorders gauging sites AWLRs were installed, together with staff gauges at 25 sites, see Figures 4.3 and 4.4 and Table 4.5, to support the various study activities. The lengths of the water-level records at these sites are presented in Table 4.6. The longest record is available for Bahadurabad where, since the first Project year, stages have been gauged. For the majority of the stations the records cover the years 1994 and 1995 only.



▼ Automatic water level recorder (AWLR)

—— Transect for routine gauging of flow and sediment transport

▭ Bathymetric survey area

Figure 4.2 Location of RSP discharge measuring sites

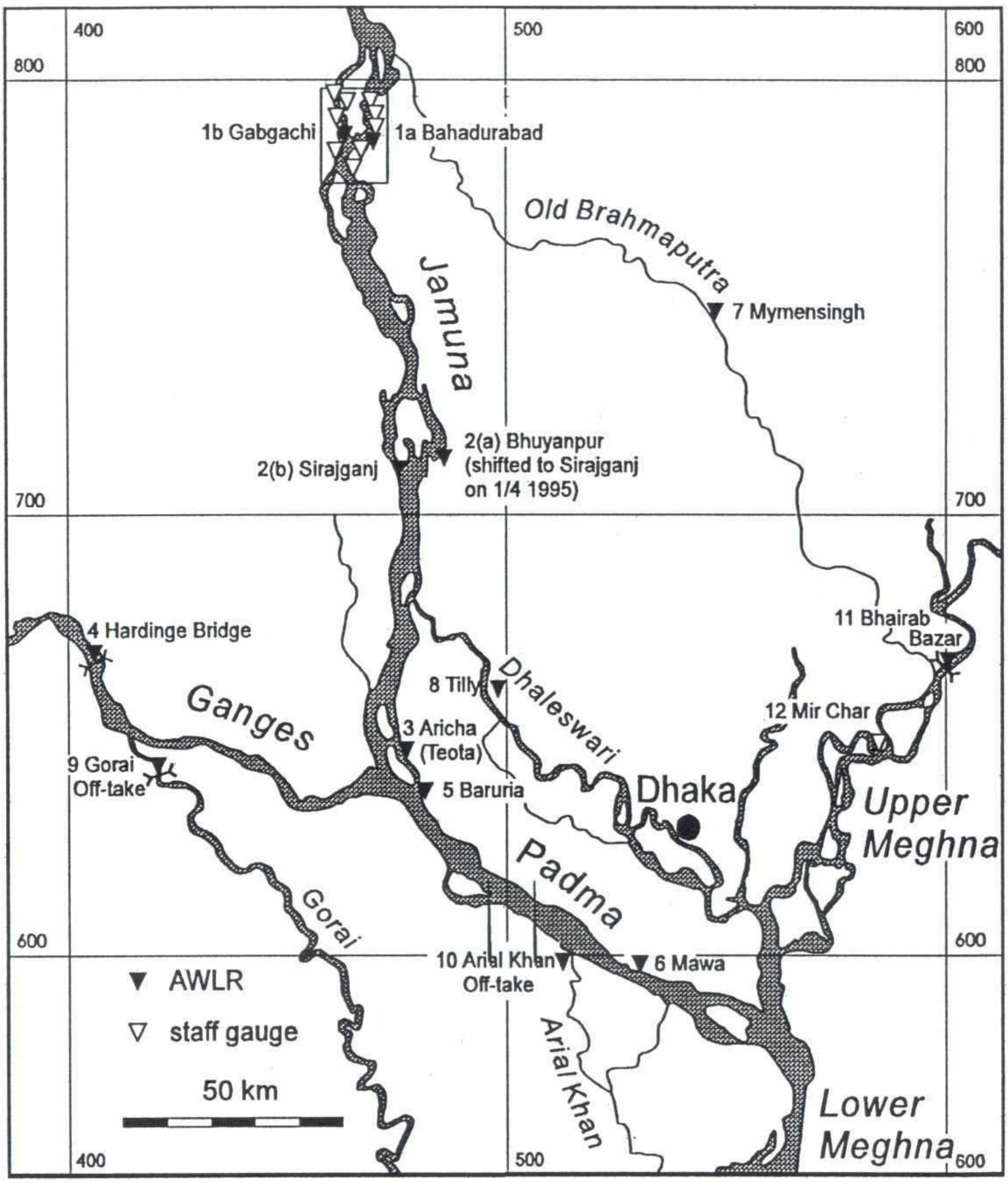


Figure 4.3 Location of RSP water-level gauging stations

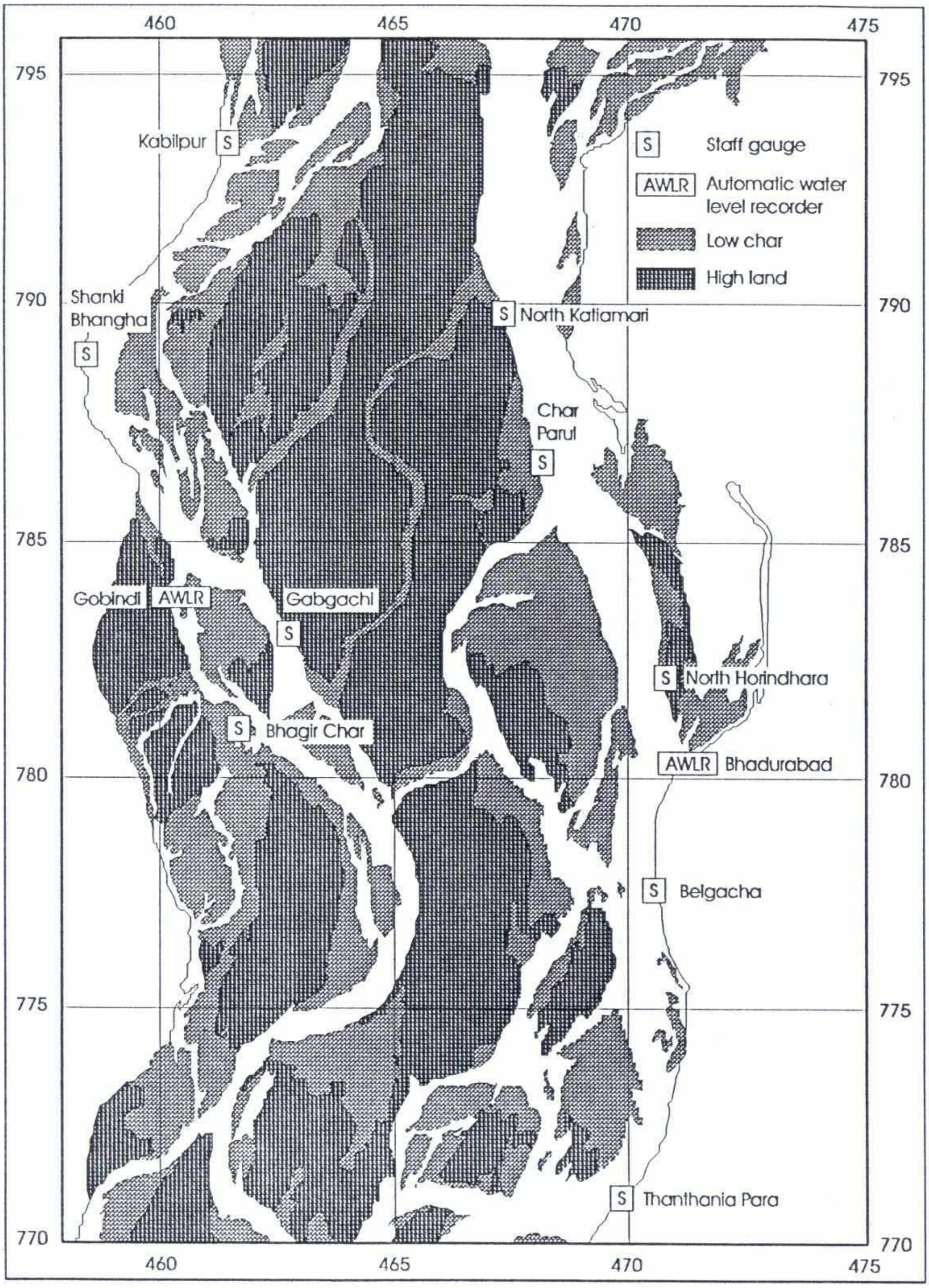


Figure 4.4 Location of RSP water-level gauging sites at Bahadurabad

OBSERVED DISCHARGE DATA (RSP)

HYDROLOGYCAL YEAR		Station : 46.9L Bahadurabad			Station : 90 Hardinge Bridge			Station : 91.9L Baruria			Station : 93.5L Mawa (tidal)			Station : 99 Gorai R. Bridge			Station : 228.5 Mymensingh		
		First od	Last od	Source	First od	Last od	Source	First od	Last od	Source	First od	Last od	Source	First od	Last od	Source	First od	Last od	Source
92		15 Sep	13 Mar	F05	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
93		06 Jun	17 Mar	F07	26 Sep	28 Mar	F07	05 Aug	21 Mar	F11	03 Oct	07 Oct	F04	30 Sep	06 Mar	F03	31 Jan	20 Mar	F03
94		02 Apr	28 Mar	F34	08 Apr	28 Mar	F14	09 Apr	22 Mar	F13	25 Jul	25 Aug	F02	05 May	01 Feb	F06	15 Jun	30 Nov	F05
95	L	29 Apr	29 Feb	F22	28 Apr	01 Mar	F14	14 Apr	10 Feb	F14	18 Sep	04 Oct	F02	05 May	12 Dec	F10	03 Apr	21 Dec	F09

HYDROLOGYCAL YEAR		Station : 273 Bhairab B.B (tidal)			Station : 4A Chawdhury Char			Station : 68 Tilly			Station : 49 Sirajganj			Station : 50.6 Aricha		
		First od	Last od	Source	First od	Last od	Source	First od	Last od	Source	First od	Last od	Source	First od	Last od	Source
92		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
93		12 Oct	24 Mar	F3	08 Oct	24 Mar	F03	16 Oct	24 Mar	F03	23 Jul	19 Mar	F07	19 Sep	19 Sep	F01
94		16 Apr	21 Feb	F06	18 Apr	23 Feb	F08	15 May	24 Mar	F07	06 Apr	25 Mar	F12	06 Jul	11 Sep	F02
95	L	20 Apr	28 Dec	F07	17 Apr	23 Dec	F08	19 May	16 Jan	F08	06 Apr	12 Dec	F15	14 Jun	17 Oct	F04

Source : F = Data available from FAP24

[-] DATA NOT AVAILABEL

HYDROLOGYCAL YEAR : L = Leap Year

Table 4.4: Availability of discharge measurements carried out by the RSP

Station	River	Appr. location	Easting	Northing
1 Kabilpur 1)	Jamuna, at Bahadurabad, right channel	7.5 km upstream of Fulchari	461260	792960
1 Shanki Bhangha		1 km upstream of Fulchari	458562	786874
1 Gobindi		2.3 km downstream of Fulchari	460335	782780
1 Gabgachi 2)		Mid char opposite of Fulchari	464053	782918
1 Bhagir Char		4.5 km downstream of Fulchari	461085	780474
1 North Kathiamari 3)	Jamuna, at Bahadurabad, left channel	10 km upstream of Bahadurabad	466678	789365
1 Char Parul		6.5 km upstream of Bahadurabad	468000	786500
1 North Horindhara 4)		1.5 km upstream of Bahadurabad	471652	781069
1 Bahadurabad 5)		0.7 km upstream of Bahadurabad Ghat	471447	780125
1 Belgacha 6)		3.5 km downstream of Bahadurabad	470889	776386
1 Thantania Para		9 km downstream of Bahadurabad	469549	771143
2 Bhuyanpur/ Sirajganj	Jamuna	Left channel, opposite of Sirajganj. Station moved to Sirajganj 1/4 95	479272 471146	702842 706938
3 Aricha (Teota)		2 km upstream of Aricha Ghat	477457	638242
4 Hardinge Bridge	Ganges	At bridge	401066	661668
5 Baruria	Padma	6 km downstream of Aricha	481094	629992
6 Mawa		Near ferry ghat	525840	595937
7 Mymensingh	Old Brahmaputra	At railway bridge	543466	736114
8 Tilly 7)	Dhaleswhari	10 km upstream of bridge	495655	648180
9 Gorai	Gorai	At railway bridge	416646	641622
10 Arial Khan	Arial Khan	Koshabhaya, 3 km downstream of off-take of Arial Khan	507819	590406
11 Bhairab Bazar	Upper Meghna	At railway bridge	601751	658881
12 Mirza Char		20 km downstream of Bhairab Bazar, right bank	593839	645104

1) Shifted from 463166 E, 794925 N on 02/05 95
2) Shifted from 462905 E, 782564 N on 09/06 95
3) Shifted from 467071 E, 789615 N on 02/08 95
4) Shifted from 471100 E, 781744 N on 10/11 95
5) Shifted from 471049 E, 779439 N on 30/06 94
6) Shifted from 471021 E, 776497 N on 10/11 95
7) Shifted from 495590 E, 648001 N on 29/05 95

Table 4.5: Location of water level gauges

RIVER SURVEY PROJECT FAP-24

Water level

		Year : 1992-1993												Year : 1993-1994												Year : 1994-1995												Year : 1995-1996											
Name of station	River	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M
Bahadurabad	Jamuna							X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Gabgachi	Jamuna															X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Charparul	Padma															X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Thanthanipara	Jamuna															X	X	X	X	X	X	X	X	X																									
North Khatiamari	Jamuna															X	X	X	X	X	X	X	X	X				X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
Mawa	Padma																											X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Aricha (Teota)	Dhaleswari																										X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
Tilly	Jamuna																											X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Baruna	Padma																										X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Bhuapur	Jamuna																											X	X	X	X	X	X	X	X	X	X	X											
Sirajganj	Jamuna																																					X	X	X	X	X	X	X	X	X	X	X	X
Arial Khan Off-Take	Arial Khan																											X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Mymensingh	Old Brahmaputra																											X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Hardinge Bridge	Ganges																												X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Gorai Rly. Bridge	Gorai																												X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Bhairab Bazar Bridge	Meghna																													X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
North Horindhara	Jamuna																											X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
Belgacha	Jamuna																											X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
Bhagirchaw	Jamuna																											X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
Shankibhanga	Jamuna																										X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
Kabilpur	Jamuna																											X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
Bheramara	Ganges																																							X	X	X	X	X	X	X	X		
Kustia	Gorai																																							X	X	X	X	X	X	X	X		
Shelaidha	Ganges																																							X	X	X	X	X	X	X	X		
Mirzachar	Meghna																																							X	X	X	X	X	X	X	X		

Table 4.6 Availability of water-level observations carried out by the RSP

5 Current procedures for data collection, processing and storage

5.1 General

The current procedures used by the BWDB for collection, processing and storage of hydrological data, including water levels, stage-discharge data and discharges are reviewed and discussed. Also the processing and storage procedures as used by FAP25 are briefly reviewed as most of the hydrological data were taken from its database. Possible sources of errors in each of the activities are analysed to design appropriate measures to improve the quality of the historical data and to suggest directions for future improvements.

5.2 BWDB procedures

5.2.1 Measuring practices and data collection

Water-level observations

SWH-I operates about 47 water-level gauging stations on the main rivers. At all these stations the water levels are measured from wooden staff-gauges. The observations are taken five times a day, at 06.00, 09.00, 12.00, 15.00 and 18.00 hours. Since the seasonal water-level variations exceed by far the reach of a staff gauge, its reach is regularly adjusted by fixing a new gauge close to the previous one. The relation between the data from the two gauges is obtained by simultaneous readings. Due to bank erosion or non-accessibility of the gauge site during high flows the gauge may be shifted to another location, sometimes up to one kilometre upstream or downstream of the old gauge site (FAP25, June 1992). Check-levelling of the gauge datum from a nearby benchmark is carried out weekly or fortnightly. Water-level corrections resembling from these checks are carried out at the field offices before the data are transferred to SWH-II for further processing.

In order to design effective procedures for validation of the water-level records an assessment is made of possible errors in the observation practice. The following error sources have been identified.

- The frequent raising and lowering of the staff gauges is likely to introduce errors, particularly if several shifts take place between two check-levellings. A shift of the gauge should immediately be followed by a relevelling.
- Even more serious is it to shift the gauge to a new location at some distance from the previous one. Average water-level slopes in the main rivers are about 5 to 8 cm per km. Hence, shifting the gauge over distances as far as one kilometres may introduce significant differences in simultaneous water-level readings.
- Regular shifts often implies loose fixation of the staff gauge. This may lead to gradual as well as sudden shifts, particularly if the gauge pole is used to anchor boats.
- Serious doubts are cast as to the frequency check-levellings are actually being carried out (FAP25, June 1992).
- Further errors in the readings are caused by inaccurate bench mark and gauge zero levels.

- As reported by FAP25 (FAP 25, June 1992) some readings are taken from gauges located on side-branches which are (temporarily) disconnected from the main river.
- At some sites the gauge is located at bridge piers or bridge abutments, where high velocities are experienced during floods. At those sites strong erosion and sedimentation may take place. It implies, that the velocity head for equal discharges will be different, dependent of the time in the year and hence a time varying stage-discharge relation results.

From the above it follows that inaccuracies are inherent to the field operation practice for water-level gauging. The inaccuracies are threefold:

1 Measurement errors, i.e. errors made in reading the water level from the staff gauge. Generally, this type of error is in the order of 1-2 cm when the current is low at the gauge location. When the current is high errors up to some 5 cm may occur. similar errors can be expected if wind waves disturb the water surface. This type of error has a random character.

2 Errors related to the location of the gauge. These errors refer to the poor representativeness of the readings (bridge piers, disconnected side-branches, etc.)

3 Errors related to the vertical position of the gauge. i.e. inaccuracies due to errors in the zero of the gauge due to:

- errors by infrequent levelling;
- errors in the levelling from the benchmark, and
- errors in the level of the benchmark

The first two sources lead to a temporary bias in the gauge readings, which are, generally in the order of less than one decimetre to some decimetres. The Land Survey Water Level Gauging of the BWDB staff-gauges (FAP24, June 1993) showed an average difference of 0.05 m (stdv = 0.08 m), with at three sites a difference of over 25 cm, see Table 5.1. In the long run the error has a random character as positive and negative biasses may occur. The last source is a systematic error, which may persist for several years. The levelling of the existing benchmarks showed an average difference of 0.16 m (stdv 0.15 m) between the BWDB benchmarks and those established by FINNMAP (FAP24, June 1993), see Table 5.2. Inaccuracies in the levels of the benchmarks affect the study and design parameters, which are dependent on the absolute value of the readings. Hence, errors of this kind do e.g. affect water-level slopes and design levels of embankments. The latter errors, however, have no consequences for stage-discharge relations.

Gauge station	BWDB BM		Zero value of gauge (m PWD)				
	BM No.	Height (m PWD)	Date	Time	BWDB	FAP24 survey	Differences
Noonkhawa	45	27.688	07.04.93	1440	19.60	19.65	+0.05
Chilmari	45.5	25.310	04.04.93	1025	17.30	17.32	+0.02
Kamarjani	46	24.690	02.04.93	1705	14.24	14.13	-0.11
Bahadurabad	46.9L	21.785	14.12.92	1620	13.00	12.98	-0.02
Fulchari	46.9R	19.330	13.12.92	1600	13.00	13.12	+0.12
Jagannathganj	48	16.732	22.02.93	1130	9.00	8.90	-0.10
Kazipur	49A	15.490	14.02.93	1045	8.00	8.00	0.00
Sirajgnaj	49	13.870	13.02.93	0940	6.53	6.48	-0.05
Porabari	50	12.270	12.02.93	1045	4.56	4.95	+0.39
Mathura	50.3	10.912	15.02.93	0935	2.65	2.61	-0.04
Teota	50.6	10.135	04.02.93	1340	2.17	2.24	-0.07
Mathurapara	15J	16.760	31.03.93	1550	10.30	10.35	+0.05
Hardinge Bridge	90	18.950	20.02.93	1240	3.24	3.27	+0.03
Talbaria	91	13.840	19.02.93	1200	2.51	2.59	+0.08
Sengram	91.1	12.550	20.04.93	1000	2.68	2.42	-0.26
Mahendrapur	91.2	11.050	11.02.93	1205	1.60	1.72	+0.12
Gorai Rly. Br.	99	13.728	18.02.93	1505	3.03	3.03	0.00
	91.9R	10.300	08.02.93	1135	2.00	1.94	-0.06
Jamalpur	225	18.530	21.02.93	1500	11.00	11.00	0.00
Mymensingh	228.5	14.338	19.02.93	1125	5.90	5.90	0.00
Tilli	68	9.409	04.02.93	1000	3.00	3.00	0.00
Rampur Boalia	88	20.086	01.02.93	0945	8.95	8.70	-0.25
Sardah	89	18.836	02.02.93	0935	8.00	7.97	-0.03
Baruria	91.9L	7.790	09.02.93	1000	0.68	0.65	-0.03
Bhagyakul	93.4L	6.931	25.01.93	1650	0.17	0.17	0.00
Mawa	93.5L	6.325	24.01.93	1135	-0.21	-0.15	+0.06
Tarpasha	94	5.575	28.01.93	1120	0.80	0.79	-0.01
Sureswar	95	5.276	15.04.93	1820	0.22	0.11	-0.11
Arial Khan Off-take	4A	7.140	27.01.93	1625	-0.94	-0.83	+0.11
Kanairghat	266	14.308	03.03.93	1040	5.78	5.79	+0.01
Sylhet	267	12.090	07.03.93	1600	0.09	0.09	0.00
Chattak	268	10.300	02.03.93	0920	3.60	3.57	-0.03
Sunamganj	269	8.450	28.02.93	1135	4.00	3.93	-0.07
Markuli	270	8.162	17.03.93	1300	2.93	2.93	0.00
Ajmiriganj	271	8.085	16.03.93	1635	2.95	2.92	-0.03
Madna	272	7.698	18.03.93	0720	1.20	1.20	0.00
Austogram	272.1	8.864	19.03.93	0900	0.60	0.54	-0.06
Bhairab Bazar	273	7.371	08.02.93	1555	0.77	0.76	-0.01
Narsingdi	274	6.814	08.02.93	0920	0.55	0.52	-0.03
Bauider Bazar	275	6.630	07.02.93	1455	1.46	1.42	-0.04
Meghna Ferryghat	275.5	6.985	12.04.93	1325	0.32	0.30	-0.02
Satnal	276	5.044	15.04.93	0805	-0.08	-0.80	0.00
Chandpur	277	5.410	14.04.93	0900	-0.28	-0.29	-0.01
Amalshid	172	17.590	05.03.93	1500	6.27	6.25	-0.02
Sheola	173	13.670	04.03.93	1040	6.80	6.83	+0.03
Fenchuganj	174	15.066	06.03.93	1215	5.00	5.03	+0.03
Sherpur	175.5	9.520	08.03.93	0930	3.00	3.00	0.00

Table 5.1 Zero values of gauges (BWDB BM)

Gauge station	FINNMAP BM		BWDB BM			Zero value of gauge (m PWD)				
	No.	Height (m PWD)	No.	Height (m PWD)	FAP 24 FMBM Connection (m PWD)	Date	Time	BWDB	FAP 24 w.r.t FMBM	Differences
Noonkhawa	1726	28.057	45	27.688	27.874	07.04.93	1440	19.60	19.83	+0.23
Chilmari	7612	23.882	45.5	25.310	24.985	04.04.93	1025	17.30	17.32	+0.02
Kamarjani	7602	21.910	46	24.690	24.685	02.04.93	1705	14.24	14.12	-0.12
Bahadurabad	GPS764	20.309	46.9L	21.785	21.768	14.12.92	1620	13.00	12.96	-0.04
Fulchari	GPS7	21.970	46.9R	19.330	19.843	13.12.92	1600	13.00	13.63	+0.63
Jagannathganj	5114	15.791	48	16.732	16.358	22.02.93	1130	9.00	8.53	-0.47
Kazipur	7209	15.155	49A	15.490	15.396	14.02.93	1045	8.00	7.90	-0.10
Sirajgnaj	7201	13.975	49	13.870	13.536	13.02.93	0940	6.53	6.14	-0.39
Porabari	6205	12.934	50	12.270	12.265	12.02.93	1045	4.56	4.95	+0.39
Mathura	GPS709	12.757	50.3	10.912	10.906	15.02.93	0935	2.65	2.60	-0.05
Teota	8122	10.202	50.6	10.135	9.947	04.02.93	1340	2.17	2.05	-0.12
Mathurapara	7215	16.763	15J	16.760	16.426	31.03.93	1550	10.30	10.01	-0.29
Hardinge Bridge	8236	23.140	90	18.950	18.868	20.02.93	1240	3.24	3.18	-0.06
Talbaria	8230	14.494	91	13.840	14.136	19.02.93	1200	2.51	2.88	+0.37
Sengram	8216	11.921	91.1	12.550	12.473	20.04.93	1000	2.68	2.42	-0.26
Mahendrapur	8212	11.216	91.2	11.050	10.903	11.02.93	1205	1.60	1.58	-0.02
Gorai Rly. Br.	8225	20.690	99	13.728	13.755	18.02.93	1505	3.03	3.02	-0.01
Jamalpur	5243	16.947	225	18.530	18.302	21.02.93	1500	11.00	11.77	-0.23
Mymensingh	6024	14.164	228.5	14.338	14.057	19.02.93	1125	5.90	5.62	-0.28
Tilli	6223	9.529	68	9.409	9.216	04.02.93	1000	3.00	2.81	-0.19

Table 5.2: Zero values of gauges (FINNMAP BM)

Discharge measurements

The discharge is measured at five locations in the main rivers, generally at intervals of one week during the monsoon season (May-November) and of one fortnight during the rest of the year. At Hardinge Bridge and, since 1 October 1992, also at Bahadurabad daily flow measurements are made during the lean season.

The BWDB uses the velocity-area method to determine the discharge. The flow velocities are measured from a survey boat by a non-directional Ott current-meter, exposed at 0.2 and 0.8 of the depth in the verticals. The measuring time in each point in a vertical is 100 sec. The survey boat is dynamically positioned, i.e. the boat is not anchored. Its location in the transect is determined with a sextant. The suspension cable with the current-meter is used to measure the depth in a vertical. The number of verticals varies according to the actual flow conditions.

The rule is that in one vertical no more than 10% of the total flow in a channel is measured. The required number of verticals becomes often very high (at Bahadurabad some 100 verticals) and it takes about two days to complete one measurement of the total discharge. The direction of the flow at the water surface is determined at each measurement point across the river by following the path of a floating bottle. The float positions are measured by sextants.

A detailed investigation on the possible sources of errors in measuring the average flow velocity, the flow direction and the depth in a vertical as well as the distance between successive verticals are discussed in Annexa 2. In summary, ISO (1983) identifies the following error types:

1. instrumental errors,
2. Type I error: exposure time of the local point velocity,
3. Type II error: number of points in the vertical,
4. Type III error: number of verticals in the cross-section.

Re 1. Instrumental errors:

- Current-meter behaviour deviates from the calibration curve.
  The calibration practice in BWDB seems to be that the current-meter is recalibrated annually. It is not known whether corrections are made if the rating tables in successive years deviate substantially. ISO (ISO/TR 7178-1983) reports relative standard deviations of 0.44 to 4.9% for screw-type current-meters in the velocity range 2.5 to 0.2 m/s, respectively.

- Application of incorrect flow angles relative to the normal to the transect.
  The transects taken by BWDB's field teams are generally not perpendicular to the flow in the river channels. Since use is made of non-directional current meters a correction of the flow angle is required. The corrections made are based on the flow direction at the surface. Directional flow measurements during the joint BWDB/FAP24 discharge measurements indicate that flow direction varies substantially in the vertical (up to 15°), hence the correction for oblique flow based on the surface flow direction introduces errors. The observed surface angle may either over- or underestimate the true angle in the vertical.

Re 2. Type I error: exposure time of the local point velocity:

- BWDB applies generally a measuring time of 100 sec. Test measurements on the Jamuna (see *Special Report 11: Optimization of Hydraulic Measurements* (FAP24, *June 1996*) that the standard pulsation error decreases with exposure time; values of 7% and 4% were found for exposure times of 50 and 100 seconds respectively.

Re 3. Type II error: number of points in the vertical:

- Use is made of the two-point method (0.2/0.8 of the depth). According to ISO 748-1979 (ISO, 1983) the average of the two values gives the mean velocity in the vertical, and no depth correction is required for the derivation of the discharge per unit width of the channel. According to ISO (ISO/TR 7178-1983) 1983) the relative standard deviation in estimating the average velocity in the vertical by the two-point method is 3.4%. Field investigations, based on detailed measurements in five verticals, indicated (see *Annex C, Special Report 11, FAP24, 1996)* that the two-point method performs poorly, and scores even worse than the one-point method. The report states that the best results are obtained with five points in the vertical. It is noted, however, that the conclusions are to a high extent determined by extreme outliers in one vertical.

- Dynamic positioning of the survey vessel.
Generally, by not anchoring the survey vessel inaccuracies in the velocity measurement are introduced by drifting of the vessel. However, field tests by FAP24 indicated that the applied dynamic positioning practice introduces less drifting than anchoring of the survey vessel.

Re 4. Type III error: number of verticals in the cross-section

- If the number of verticals is too low then neither the flow field nor the cross-sectional area, derived from the depth at the verticals and width between the verticals is accurately determined. In the Bahadurabad-transect a distance between the verticals of 100 m is used. Comparative measurements by FAP24 (FAP24, June 1996) indicate an average error of about 4% for intervals of 100 m.

- Inaccurate measurement of depths, when measured by a suspension cable.
BWDB does neither apply air- nor wetline corrections to the depth measured by the suspension cable. During the joint measurements by BWDB and FAP24 in 1995 vertical angles up to about 10° were measured. This implies corrections as small as 1.54% and 0.50% for air- and wetline respectively (see *Annexa to ISO 3454-1975, ISO 1983)*. The results from the joint measurements, however, indicated that depths measured with the suspension cable were generally less than the depth observed with the echosounder.

- Inaccurate measurement of the distances between verticals.
Distances from the river bank are measured using of a sextant, which requires great skill so as to be sufficiently accurate. The comparative measurements indicated that grave errors up to 15% are made in the present practice.

In the compilation of condensed discharge data from the flow velocity measurements additional errors are introduced due to:

- Total duration of the measurement.
Water levels on the Jamuna fluctuate occasionally up to some 50 to 80 cm per day. In 1995 the water levels at Bahadurabad differed from day to day more than 30 cm during 4% of the time. Also, during rising and falling stages, the bed may substantially change its configuration and hydraulic characteristics, owing to migration of

bed forms. BWDB practice is to take the average of the gauge reading at the beginning and at the end of the flow measurement. It is advised to take a weighted average water level (weighted according to the observed partial discharge relative to the total amount) if the difference between the start- and end reading is larger than 0.05 m, see ISO 1100/2-1982 (ISO, 1983).

- Random and systematic errors in the water level.
  The types of errors that may occur in the water-level readings, are discussed in Sub-section 5.2.1.

According to ISO/TR 7178-1983 (ISO,1983) the total stochastic error in the discharge estimated by the velocity-area method is to a large extent determined by the number of verticals as it determines the accuracy of the cross-sectional profile as well as the interpolation of the horizontal velocity profile.

5.2.2 Data processing

Water levels

The water levels received from the field are adjusted for the vertical shifts according to the check levellings and are subsequently keyed in for transfer to the computerized database. No validation is further made e.g. by intercomparison of hydrographs, etc. This implies that there is apparently no feed back from the data processing branch to the field offices.
To identify the reality of these staff gauge data and detection of errors, one can establish correlations between data from upstream and downstream stations, plotting the water-level differences between the two stations against time (Peters, 1994)[1)].

A thorough analysis by FAP25 revealed the following types of errors in the BWDB data (FAP25, June 1992):

- erroneous computation of daily averages,
- data shifted for a few days,
- data shifted for a few weeks,
- data shifted for longer periods,
- incorrect shift corrections,
- observations made in disconnected branches, and
- incorrect bench mark and gauge zero levels.

Stage-discharge data

The total discharge is calculated in the field by SWH-1 from the velocity measurements in the vertical at 0.2/0.8 of the depth. The mean flow velocity in the vertical is determined as the average of the two point flow velocities corrected for the flow direction at the water surface relative to the normal to the transect. The velocity-area mean-section method is subsequently applied to determine the total river discharge. The possible errors are discussed in Sub-section 5.2.1.

Stage-discharge relations

Discharge rating curves are developed for each hydrological year based on the actual stage-discharge (Q-h) measurements during that year. Some characteristic values from the previous years are added to the data for consistency and extrapolation purposes. The Q-h data are plotted on log-log paper, and the offset (stage of zero flow) is determined by trial and error until the lower Q-h observations form a straight line to the extent possible. Several segments of the curve are considered, but the offset derived for the lowest segment is assumed to be applicable for all other segments as well. The data are fitted by a power type equation, which has the following general form for segment i:

$$Q = c_i \, (h + a_1)^{b_i} \qquad \textbf{(5.1)}$$

where: Q = discharge [m^3/s]
h = water level [m+PWD]
c_i = coefficient for segment i
a_1 = offset, derived for segment 1 [m]
b_i = exponent for segment i

The parameters are determined by linear regression on the logarithms of Q and ($h+a_1$). At some sites the water levels are affected by backwater, for which no corrections are being applied.
Generally, the required offset is different for each segment. For the discharge gauging stations on the main rivers in Bangladesh, in absolute terms, the offset levels appear to increase for the higher segments, see Section 6.4 and *FAP24 Hydrological Study Phase 1, June 1993.*
For example, for the Ganges at Hardinge Bridge the required offsets for 1988 are respectively -3.00, -6.00 and -10.00 m for the first, second and third segments. Hence, by using a_1 for the higher segments as well, it implies that for these segments a too-low value is subtracted from h. The logarithmic plot of Q versus ($h+a_1$) for the higher segments is therefore convex shaped. When fitting this by a straight line the effects are that (see also Figure 5.1):

1. the observations will not be randomly distributed around the regression line, and
2. the extrapolation will always lead to overestimation.

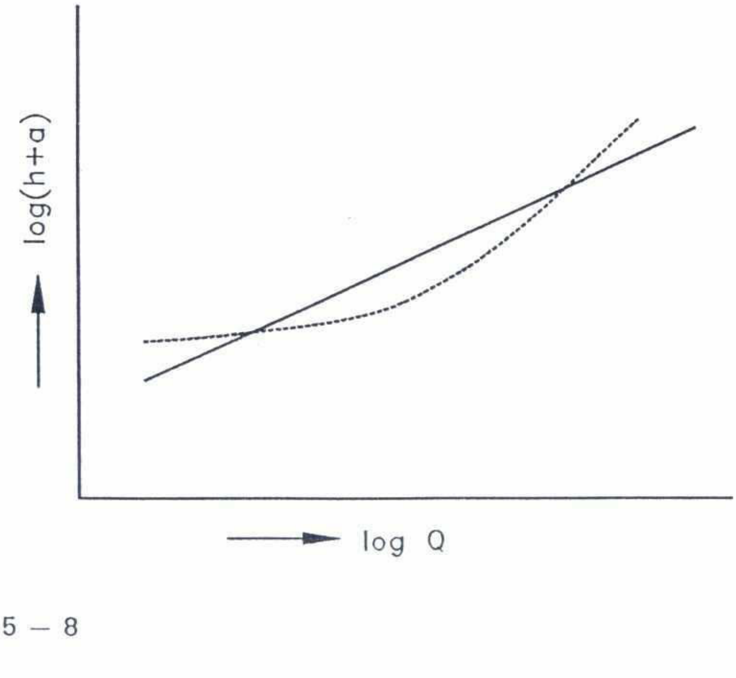


Figure 5.1:
Effect of applying first segment offset to curve fitting for the higher segments.

The above observations are illustrated in Figures 5.2a-c for the development of the stage-discharge relation for Hardinge Bridge on the Ganges river for the hydrological year 1988. One can see that the extreme high discharges may considerably be overestimated by the former practice, particularly so if one has to extrapolate far beyond the measured range, grave errors are made as dQ/dh is large at the extreme levels.

At backwater-affected sites normal or constant fall corrections are recommended. Reference is made to Sub-section 7.4.5 for further discussion on the BWDB discharge rating curves.

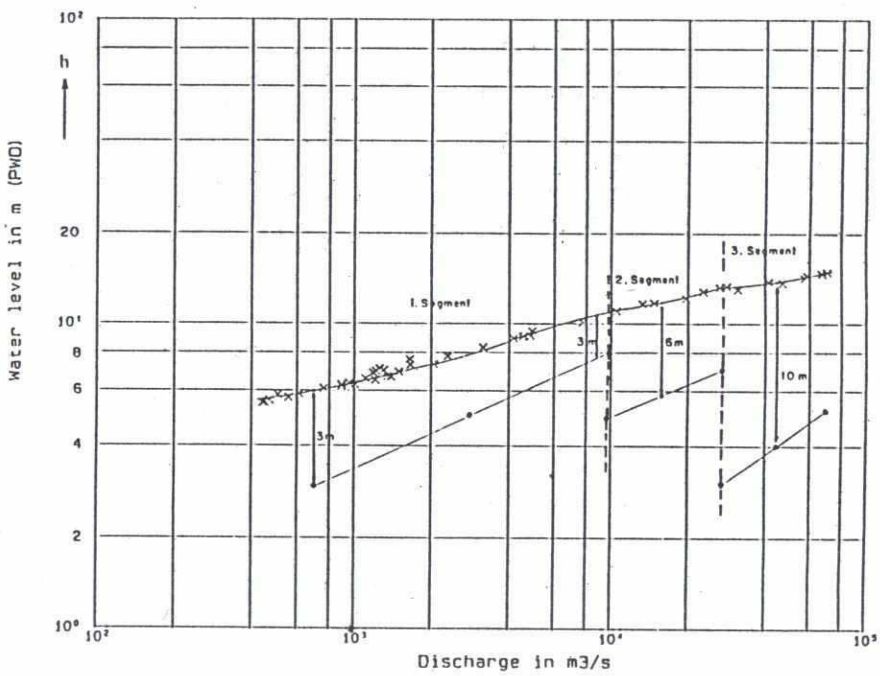


Figure 5.2a: Rating curve, Hardinge Bridge 1988. Illustration of procedure for estimation of Q-values.

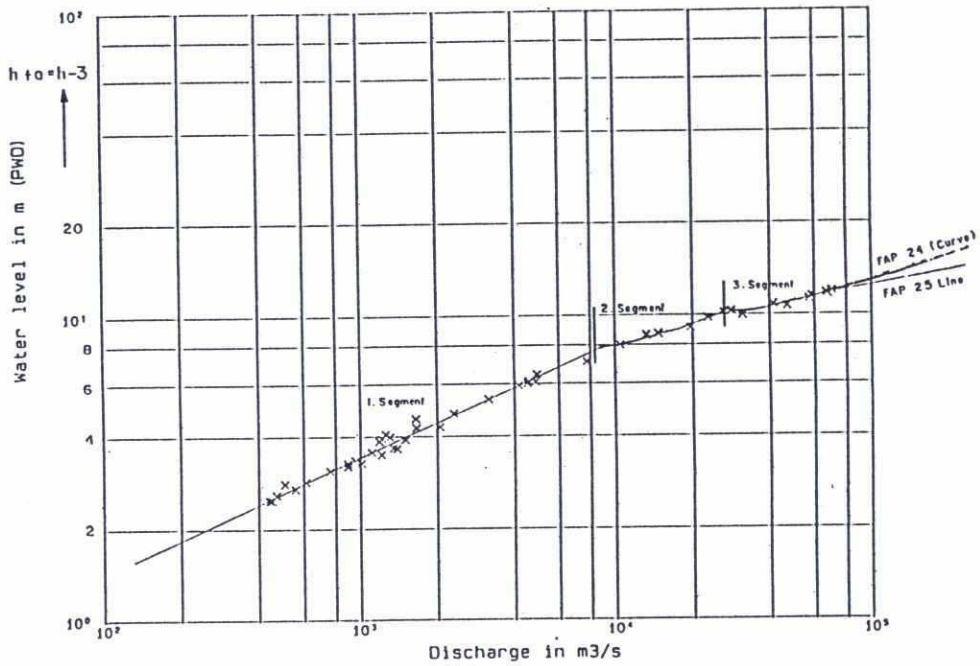


Figure 5.2b

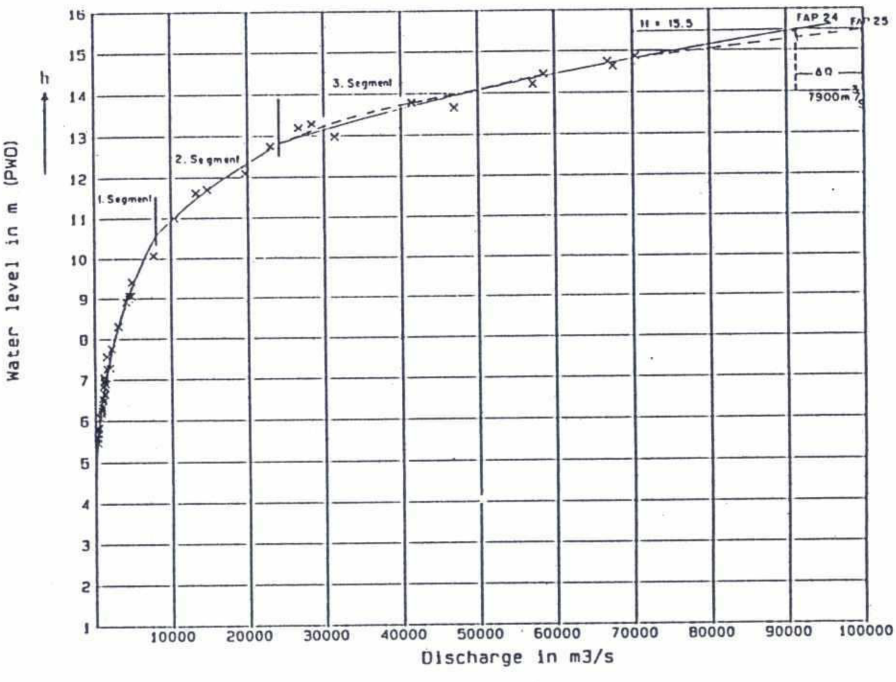


Figure 5.2c

Discharge series

The observed water levels are transformed to instantaneous discharge values by using the derived discharge rating curves. The instantaneous values are averaged over the day to produce daily mean values for final storage. When calculating the mean daily discharge from observed water levels BWDB regularly corrects for shifts. Usually a shift correction is applied when the rating curve changes with time due to changes in the cross-sectional characteristics along the control section. A shift correction is applied to the stage of a discharge measurement to bring it in accordance with the derived mean rating curve.

The shift correction procedure inherently assumes that the discharge measurements are true, without error. If this is not the case, application of shift corrections may introduce new errors. The *Flood Hydrology Study (FAP25, June 1992)* gives examples which illustrate that the current application of shift corrections by BWDB is questionable. A better procedure would to derive a new rating curve if a consistent rather than a random deviation from the mean curve is apparent.

5.2.3 Data storage

Most of the historical data on water levels and discharges are available at BWDB only on paper ("hard copy"). However, in recent years BWDB has introduced computerized databases for storage and retrieval of data. At present, only the most recent years of data are stored in the computer database at BWDB. A proper data directory is lacking (FAP 25, June 1992).

5.3 FAP 25 procedures

5.3.1 Data processing

FAP25 carried out a comprehensive study of existing hydrological data of the main rivers in Bangladesh. The data used and the study carried out by FAP25 are well documented in the *Main Report* of the *Flood Hydrology Study (FAP25, June 1992)*.

Water-level series

FAP25 processed BWDB's daily average water-level series of selected stations on the Jamuna and Ganges for the years 1964-1989, including:

- in the Jamuna river: Chilmari, Kholabari Char, Kazipur, Sirajganj, Porabari and Bahadurabad
- in the Ganges/Gorai rivers: Hardinge Bridge, Sengram, Gorai Railway Bridge and Kamarkhali.

Processing included systematic checking and correction of water-level time series using correlation methods. FAP25 carried out frequency analyses of annual peak water-levels for various stations and recommended on the types of probability distributions to be used. Analysis of the series by FAP24 revealed that, notwithstanding the reported data validation, still some inconsistencies were apparent in the series. Furthermore, it is noted that the application of frequency distributions to water levels is basically incorrect, when looking at return periods beyond the series range; water levels in rivers, different from levels at sea, cannot be considered as homogeneous quantities as the data depend on river flow and geometrical and hydraulic characteristics of control sections. For a series length of annual peak water levels of 25 years, using Gringorten's formula applicable to the Gumbel distribution, a water level with a return period of 45 years is about the maximum one can retrieve from the series. Reference is further made to Sub-section 7.4.2 and Section 8.2.

Stage-discharge relations

New annual rating curves (1965-1989) were established by FAP25 for three stations: Bahadurabad, Hardinge Bridge and Baruria. The procedure used was similar to the procedure used by BWDB (ref. Sub-section 5.2.2), and the new rating curves are not much different from the BWDB rating curves. The magnitude of shifts of the annual rating curves were analysed and appeared to be considerable. The exact reasons for these shifts were not analysed but were assumed to be caused by morphological changes, systematic errors in discharge measurements and long-term shifts in gauge locations.

The comments made to the derivation of rating curves by BWDB in Sub-section 5.2.2 (biassed fits and overestimation in the extrapolated range) apply also to the FAP25 rating curves in view of the used procedure.

Discharge time series

New discharge time series (1965-1989) were calculated for the stations Bahadurabad, Hardinge Bridge and Baruria on the basis of the corrected water level time series and the new rating curves. FAP25 found the BWDB correction procedure for shifting control questionable and did not apply any shift correction.
In addition to the frequency analysis on annual peak water levels, FAP25 carried out similar analyses of annual maximum discharges and average seasonal discharge for various stations and recommended on the probability distributions to be used for the various types of data in Bangladesh. Trend analyses and peak-frequency analyses indicate that the hydro-meteorological conditions in Bangladesh during the last 25 years are fairly representative for the longer term. It was concluded that the 1965-1989 period formed a slightly conservative basis for design, when compared to the last 50-100 years.

5.3.3 Data storage

Because a proper data directory of hydrological parameters was not available at BWDB, FAP25 developed such a directory based on BWDB data and other sources, e.g. WARPO. The directory contains useful information on station name, code and length of records for all water-level gauging stations and most discharge stations in Bangladesh (ref. FAP25, June 1992, Volume 2, Annexa 1).
FAP25 established a computerized database with the following data:

- Mean daily water levels: 25 years of data (1964-89) for 50 water-level stations including selected main stations in major rivers;
- Mean daily discharges: 25 years of data (1965-1989) for 22 discharge stations, including the six (FAP24) stations in the main rivers (Bahadurabad, Hardinge Bridge, Baruria, Mawa, Bhairab Bazar and Gorai Railway Bridge), and

- Observed discharges (i.e. the stage-discharge measurements): 25 years of data (1966-1990) from ten discharge stations including all stations in the main rivers, except Gorai Railway Bridge.

5.4 Assessment of current procedures

In the previous sections a detailed assessment has been presented on the current procedures of data collection, processing and storage applied by BWDB as well as by FAP25 on the latter two activities. In summary, the main conclusions are, with respect to:

1 water levels

- the field data include a number of inconsistencies, mainly due to frequent shifts in the vertical and horizontal positions of the staff gauges, for which was insufficiently corrected, and errors in benchmark elevations. Timely re-levellings are required;
- at bridge sites, gauge readings are affected by varying velocity head for equal flows. Relocation of those gauge to places with low velocities is recommended to improve the stability of stage-discharge relations;
- BWDB does not apply effective data validation procedures and the processed data still include a number of errors. Introduction of effective validation procedures with little delay between gauging and processing, including immediate feedback to the field, is strongly suggested to improve the quality of observations and stored data;
- BWDB's most recent historical data have been computerized, whereas older data are available on hard copy only. Its database lacks a proper data directory;
- FAP25 maintains a database with a clear data directory including 25 years of daily averaged water levels of 50 gauging stations. Although thorough validation was reported to have been carried out, still not all inconsistencies have been detected/eliminated.

2 discharge observations

- inaccuracies in BWDB flow measuring practice is mainly due to incorrect flow direction adjustment in oblique transects, flow area measurement and the long duration of the measurement. The use of a directional current-meter, an echosounder and a DGPS for proper survey vessel positioning is strongly recommended. Discharge weighted stage data should be connected to a flow measurement;
- FAP25's database includes stage-discharge data of ten discharge gauging stations covering a period of 25 years.

3 stage-discharge relations

- at most sites two to three segments are applied in the annual discharge rating curves. The application of one offset value for all segments leads to improper fits to the upper segments and overestimation of discharges in the extrapolated range. To each segment its appropriate offset should be applied in the derivation of the rating equation;
- backwater corrections are not applied to backwater-affected gauging sites, which leads to considerable scatter.

4 discharge series

- BWDB applies shift corrections in the computation of discharges. The correctness of this procedure is questionable. If clearly consistent shifts occur it is recommended to apply a new discharge rating equation;
- BWDB's stores daily average discharges of recent years in a computer. Data of more much older date are available on hard copy only;
- Discharge series of 22 stations of the period 1965-1989 are stored in FAP25's computerized database.

5 databases

- BWDB's hydrological database stores daily average water levels and discharge series of recent years on a computerized database. A proper data directory is lacking;
- FAP25 developed a database of daily average water levels and discharges of respectively 50 and 22 stations, covering 25 years of data. The database includes also discharge observations of ten stations. In addition, a well-documented data directory of the hydrological parameters was established.

6 Applied collection, processing and storage procedures

6.1 General

A summary of the hydrological data collected by the RSP is presented in Chapter 4. Two main external sources of data were used: BWDB and FAP25, to be compared with the data collected under this Project.

In this chapter the collection procedures for water levels and discharges as applied by the RSP are summarized. A description is given of the validation and completion procedures applied to the data collected under the Project and those obtained from external sources. Basically the procedures applied to the data of the different sources are the same. Where relevant, a distinction is made between the historical hydrological data and the RSP data.

The data processing has been carried out with the readily available extensive validation, completion and analysis options of the hydrological database and data processing package HYMOS.

6.2 Water-level data

6.2.1 Data collection

To collect reliable all-season water-level data for studying the hydrological and morphological characteristics of the rivers and to examine gauging strategies for water levels in the River Survey Project twelve AWLRs and 26 staff gauges were installed. Reference is made to *Special Report 2: Water-level Gauging Stations, November 1995* for full details about the location of the stations, the type of equipment used and station operation.
At all eleven RSP-discharge measuring sites AWLRs were installed. In the Jamuna river at Bahadurabad two AWLRs were installed, one in the right channel at Gabgachi and one at Bahadurabad along the left channel. The equipment used for sensing the water level comprised:

- pressure cell sensors mounted on custom-built platforms,
- acoustic sensors mounted on available fixed structures, and
- staff gauges at each station to supplement the auto-recorders.

The sensors sampled the water levels at 30 minutes intervals, whereas during daytime at the same location three-hourly manual observations were made. The recorded data were stored in a datalogger which were downloaded into an office PC at monthly intervals for further validation and processing. In the field a first validation was carried out by the inspection of a plot of the water level as a function of time to detect errors such as sensor over-range, recording of error codes and spikes in the data. Immediate action was taken if so required and if technically possible.
The staff gauges at the remaining sites were read at three-hourly intervals in accordance with the BWDB gauge reading practice for comparison reasons.
Near each gauge a temporary benchmark was established to allow quick and accurate levelling of the gauge. These benchmarks were tied to National Datum.

6.2.2 Data validation and completion

The types of errors present in the historical daily average water-level series have been discussed in Sub-sections 5.2.2 and 5.3.1. FAP25 carried out checking of water levels for a number of water-level stations and a few discharge stations in the main rivers. Screening of the time series for Bahadurabad revealed however that a number of errors had not been detected/corrected. A consistent check of the water-level series was therefore carried out, tuned to the type of errors to be expected in the gauge readings due to the observation and operation practice.
The validation of the water-level data collected by the RSP are described in *Special Report 6 Water-level Gauging, November 1995.*

In summary, the following systematic checking procedures were applied:

1 For the BWDB daily average water-level time series of 1965-1995 of the relevant stations on the main rivers and distributaries (see also Chapter 10):

- First, tables were prepared of the daily average water levels to serve as a reference. Differences between successive river stages were computed to carry out a first check on violation of estimated maximum rates of rise or fall of the water level.
- Next, plots were made of the water-level time series for each discharge station together with the time series of two adjacent water-level stations, to obtain a first visual impression of possible erroneous data or shifts in the gauges.
- The stations were subsequently subjected to pairwise examination by inspection of difference plots, combined with shifted time series plots to improve the comparison.
- Finally, a quantitative assessment was made of changes in the stage relation with adjacent stations: the regression line fitted to the data of one year was compared with data of other years. Where appropriate, time shifts were applied in the comparison of data to eliminate loopings in the relation curve caused by the travel time of the waves.
- Based on the above graphs, suspicious data were marked and double checked. Erroneous data were corrected by stage relations, interpolation or by adding or subtracting the value required to get the hydrograph in line with the reliable part.

2 For the RSP data the following, strictly formalised, procedure was used:

- Staff gauge and AWLR data were retrieved from their dedicated files. From a third file, the reference file, reference levels of staff gauge and AWLR, as well as the pre-set acceptance margin for differences between staff gauge and AWLR readings were read.
- Then, water-level time series graphs were produced for purpose of reporting and for assessment of data integrity. Any irregularities were, where possible, traced back to their cause.
- Next, checks were executed on the physical limits of the data.
- Subsequently, the data were subjected to a time test, to inspect the accuracy of the timing of an observation (30 min +/– 1.5 min).
- Further, difference tests between staff-gauge and AWLR observations were performed, for which the staff-gauge data were interpolated to coincide with the timing of the automatic gauge recordings.

- Finally, depending on the data source (staff gauge or AWLR) passing the test one of the sources was accepted. Preference was given to the AWLR data if both sources passed the tests.

The latter procedure is illustrated for water levels collected at a number of sites in the left channel of Jamuna River around Bahadurabad. Plots of the hydrographs observed at the gauging sites and of relation curves are presented in Figures 6.1 and 6.2.

From Figure 6.1 it can be seen that in November 1993 a shift is apparent in the Thanthani-para gauge observations. From the gauge history it was found, that this error coincided with a shift of the gauge. From the relation curves shown in Figure 6.2 one can see that at a level of 15 m+PWD the readings of the North Harindhara gauge start deviating from the general trend; the river branch used for the gauge had died off.

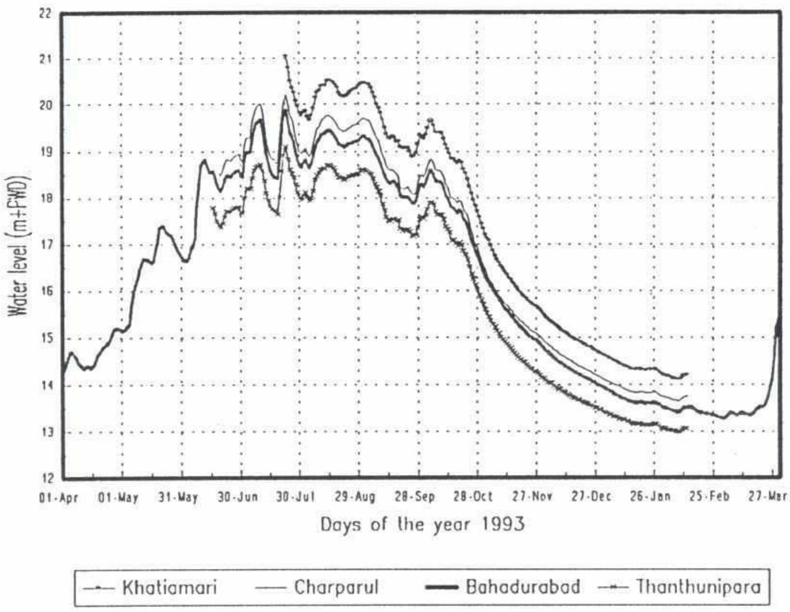


Figure 6.1

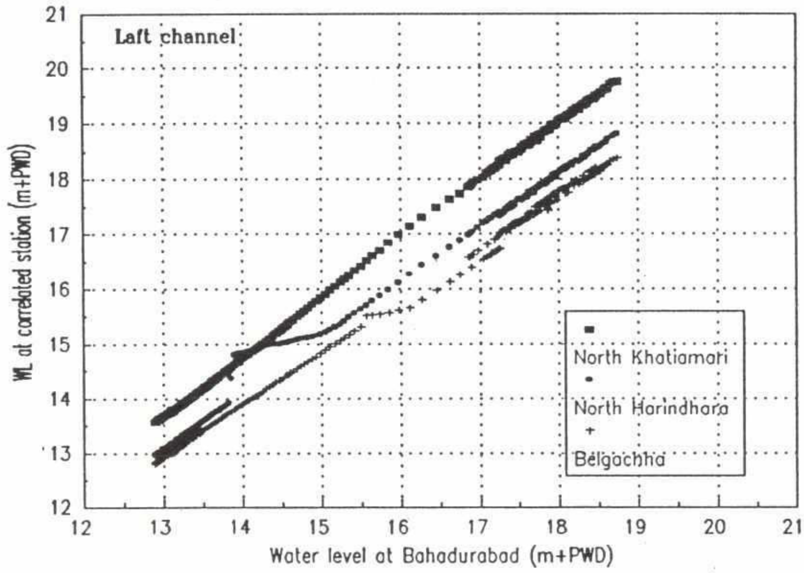


Figure 6.2

6.3 Discharges

6.3.1 Discharge measurements

Discharge measurements carried out by the RSP were made:

1. By moving boat method using an Acoustic Doppler Current Profiler (ADCP) in combination with an Electromagnetic Flow meter EMF. The ADCP transducer is positioned under the survey vessel, whereas the EMF is installed at a fixed level of 0.5-1.0 m in front of the vessel; see Figure 6.3. The actual measurements are carried out by crossing the river from one bank and during the sailing the system records high resolution vertical velocity profiles (discretised to depth-intervals of 0.5 m) for every 5-10 m along the transect while continuously presenting the profiles and calculating the discharge by integrating the velocity normal to the path taken by the survey vessel. The flow depth is measured with an echosounder. The ADCP can neither measure the velocity close to the riverbed due to transducer side loops, nor above the immersion depth of the transducer. Near the riverbed the velocity profile is extrapolated down to the bed, whereas for the upper part of the velocity profile use is made of the EMF measurements.

2. Conventional vertical profile measurements using a directional Ott current-meter used in shallow areas, sections inadmissible for the ADCP-survey vessel in view of its draft.

The moving boat method used by the RSP is a special application of the velocity-area method. Because the velocity profile is measured in detail, this method deviates from the conventional moving boat method, where the velocity is measured only at one depth below the water surface. The method is fast and can be used under adverse hydraulic conditions like during floods and for tidal areas. The method eliminates the most important error type III sources of the conventional flow measurement procedure: errors due to random sampling of the depth profile and due to random sampling of the horizontal velocity profile (ISO, 1983).
Limitations of the ADCP-EMF moving boat method are:

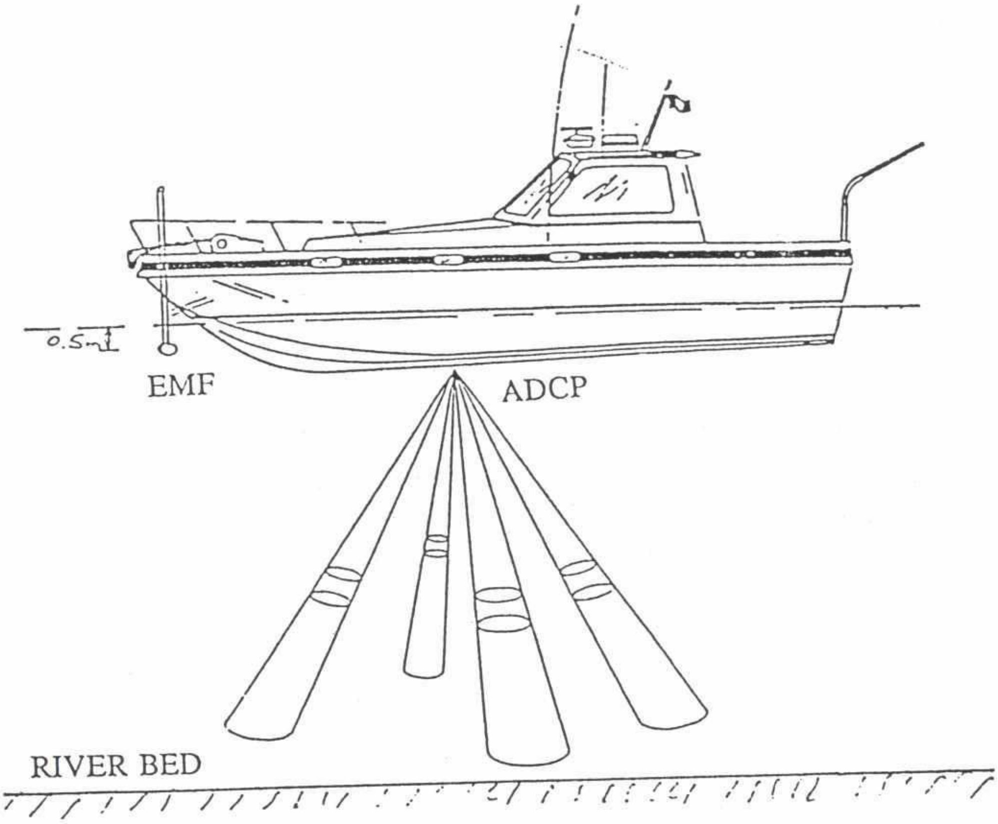
1. For mobile beds the system underestimates the flow because measurements are made relative to the mobile bed. Under such circumstances the vessel positioning is measured with a Differential Global Positioning System, which eliminates this error;

2. The ADCP underestimates the depth as it recognizes the mobile sediment layer as the bed. This error is, however, insignificant.

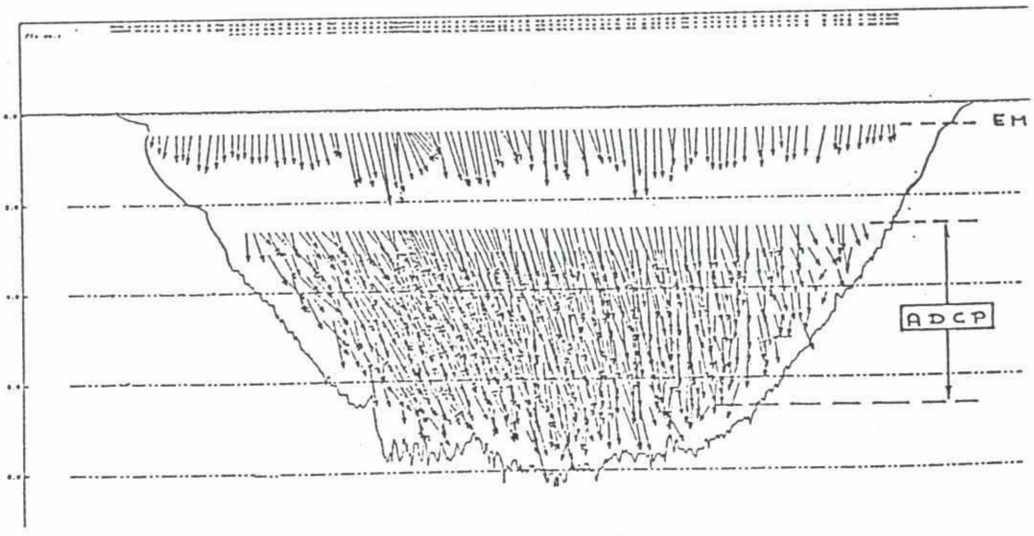
3. The system leaves unmeasured zones at the top and bottom of the transect. The top layer is therefore measured by an EMF, whereas the velocity distribution in the lower 6% of the cross-section is approached by a power curve profile.

4. At shallow depth the method is not applicable in view of the draft of the survey vessel. In such cases the conventional velocity-area method is used.

Reference is made to *Special Report 11: Optimization of Hydraulic Measurements*, for an overview of the accuracy of the various components of the RSP discharge measuring procedure compared to the conventional method.



Principle sketch of instrument installation for the recommended method with EMF and ADCP



Combined EMF and ADCP record

Figure 6.3

6.3.2 Stage-discharge relations

Due to the inadequate rating curve method currently applied in Bangladesh as described in Chapter 5, the RSP developed new rating curves for all the six discharge stations on the main rivers. Use was made of the following procedure for each discharge station:

1 First, listings were made of the available stage-discharge data per hydrological year.

2 The measurements were displayed in linear and double-logarithmic plots and a smooth curve was drawn through the data for each year. Clear outliers were eliminated from the data set.

3 The segmentation of the rating curve was determined from distinct breaks in the double logarithmic stage-discharge plots. The break-points were compared with changes in the cross-sectional profiles of the transects. The segment boundaries generally coincide with the levels where the conveyance suddenly increases; these boundaries are typically the levels of chars and of the flood plain.

4 The stage-discharge data for each segment were subsequently fitted by the following power type equation:

$$Q = c_i \left(h + a_i\right)^{b_i} \quad \mathbf{(6.1)}$$

where:	Q	=	discharge	[m³/s]
	h	=	water level	[m+PWD]
	c_i	=	coefficient for segment i	
	a_i	=	offset, derived for segment i	[m]
	b_i	=	exponent for segment i	

The difference with the BWDB and FAP25 procedure is that for each segment an offset value is determined. The final offset for each segment was finally adjusted by trial and error to obtain physically realistic values for the exponent b in equation (6.1). Values in the range of 1.5-3.5 were considered to be acceptable.

5 Comparisons were made between data of successive years to assess the possibility of representing more years of data by one stage-discharge relation.

The above procedure is explained in detail in Sub-section 10.2.2. The procedure was applied to all BWDB and RSP stage-discharge data. Separate rating curves were established for the two data sets for comparisons reasons.

In general, for each station it was necessary to develop a new rating curve for each year of record in view of the observed changes. Within most years the actual measurements provide a fairly consistent basis for development of reliable annual rating curves. It was pointed out (FAP25, June 1992) that the annual shift of the rating curves may be partly due to changes in the physical system (erosion, aggradation and moving bed forms) and partly from random or systematic errors in discharge measurements. Loop effects due to varying water surface slopes during rising and receding parts of the flood are not significant in the main rivers except for Bhairab Bazar; a minor backwater effect is present in the stage-discharge relation for Hardinge Bridge.

The parameters of the estimated rating curves for the six discharge stations on the main rivers are presented in Tables 6.1 to 6.5.

Analyses of the stage-discharge relations and methods for the extrapolation of the rating curves are presented in Section 7.4, where also methods for extrapolation of rating curves are discussed.

6.3.3 Discharge series

The following three discharge time series have been developed by the Project:

Set 1: original BWDB discharge time series, supplemented for the period 1993 to 1995 with discharges derived from the observed water levels and discharge ratings based on BWDB measurements in those years;

Set 2: adjusted BWDB discharge time series derived from observed water levels and discharge ratings based on BWDB's stage-discharge data, but using RSP's method for the fitting of the stage-discharge relation.

Set 3: The RSP discharge time series covering the period 1993-1995, derived from observed water levels and discharge ratings based on RSP's stage-discharge data.

DATA SOURCE	YEAR	INTERVAL - 1			Limit - 1	INTERVAL - 2			Limit - 2	INTERVAL - 3			STANDARD ERROR (%)
		a	b	c		a	b	c		a	b	c	
	1966	-9.00	2.163	230.337	15.113	-12.00	1.835	1438.860	18.978	-14.00	2.507	909.174	8.20
	1967	-10.00	2.591	158.741	15.721	-13.00	1.408	3560.180	17.800	-15.00	1.611	6155.130	11.40
	1968	-9.50	2.502	122.864	15.471	-11.50	2.162	544.405	18.687	13.50	2.554	578.192	11.17
	1969	-9.00	2.328	146.048	15.280	-11.00	2.128	477.455	18.943	-13.50	2.950	264.743	7.60
	1970	-9.00	2.914	58.731	14.998	-10.00	2.334	254.028	18.969	-13.50	2.814	357.149	5.25
	*1971												
	1972	-9.00	2.418	111.507	15.138	-11.00	2.331	327.488	18.044	-13.00	2.613	451.744	14.09
	1973	-8.00	1.285	412.034	13.683	-11.00	2.004	531.636	18.616	-15.00	2.807	843.172	10.92
	1974	-10.00	2.971	66.869	14.000	-10.00	2.828	79.248	19.000	-15.00	2.569	1164.940	11.00
	1975	-8.50	2.417	104.670	14.928	-11.00	2.129	509.813	18.952	-13.00	2.753	310.776	6.26
	1976	-10.00	1.709	650.338	15.075	-10.00	2.184	300.639	18.210	-14.00	2.306	1085.030	7.26
	1977	-9.00	2.065	255.796	15.816	-10.50	2.523	198.746	19.363	-14.50	2.735	646.017	9.17
	1978	-9.00	2.373	145.130	15.129	-10.00	2.501	179.671	18.306	-14.00	2.043	1812.120	7.90
	*1979												
	1980	-10.00	2.006	389.434	15.695	-10.00	2.410	192.765	17.786	-13.00	2.443	591.424	8.20
	1981	-10.00	2.170	296.965	16.153	-10.75	2.321	305.457	18.747	-15.00	2.278	1877.270	9.00
	1982	-8.00	2.847	37.807	15.842	-10.00	2.978	69.382	17.916	-13.00	2.374	749.649	7.60
BWDB	1983	-10.00	2.179	304.600	17.952	-13.00	2.260	750.930	19.064	-15.00	2.447	1426.830	6.90
	198'	-10.00	2.454	178.712	18.043	-13.00	2.371	643.588	19.116	-15.00	2.275	1884.260	5.60
	1985	-10.00	2.413	194.811	18.500	-15.00	2.022	2927.670					10.70
	1986	-10.00	2.340	228.315	17.800	-13.00	2.022	1182.580	18.613	-15.00	2.022	2927.670	6.46
	1987	-10.00	2.344	229.718	17.537	-12.00	2.780	224.407	18.160	-14.00	2.479	961.873	6.25
	**1988-19	-10.00	2.565	154.594	17.332	-13.00	1.906	1566.740	18.456	-15.00	1.909	3726.380	4.78
	1993	-8.75	2.651	75.337	17.533	-12.25	2.908	188.896	18.696	-13.50	2.535	654.191	5.00
	1994	-9.00	2.789	67.225	17.190	-10.50	2.467	217.735					3.10
	1995	-8.00	2.814	41.726	16.721	-11.50	2.678	221.340	18.117	-12.50	2.473	488.528	5.15
RSP	1993-1995	-8.00	2.843	35.184	17.013	-10.75	2.811	104.846	18.408	-13.75	2.773	449.930	7.57

Note :
1. Limit - 1 is the Upper limit Water level for interval - 1.
2. Limit - 2 is the Lower limit Water level for interval - 3.
3. Rating Equation : $Q = c(WL + a) ^ b$.
* . stage-discharge data not available
**. uncertainty in stage-discharge data in 1989-92

Table 6.1: Rating Parameters at Bahadurabad.

DATA SOURCE	YEAR	INTERVAL - 1			Limit -1	INTERVAL - 2			Limit - 2	INTERVAL - 3			STANDARD ERROR (%)
		a	b	c		a	b	c		a	b	c	
	1966	-3.00	2.577	45.317	10.748	-5.50	2.781	88.128	13.598	-8.50	2.798	310.332	7.38
	1967	-3.00	2.552	46.959	10.250	-5.00	2.846	64.970	12.900	-8.00	2.843	249.367	7.34
	1968	-25.00	2.805	21.666	10.071	-5.00	2.811	78.979	12.872	-7.00	2.845	169.768	10.10
	1969	-3.00	2.122	128.830	9.970	-5.00	2.813	89.063	13.408	-7.00	2.499	342.353	8.81
	1970	-1.00	2.678	18.878	9.810	-5.00	2.836	75.158	13.100	-7.00	2.951	137.766	11.66
	*1971												
	1972	-2.00	2.593	40.977	9.895	-4.00	2.865	53.987	12.552	-7.00	2.570	308.679	11.80
	1973	-1.00	2.823	16.437	8.440	-3.00	2.643	54.435	11.901	-6.25	2.984	100.103	12.39
	1974	-1.00	2.680	20.125	8.051	-3.00	2.937	32.457	12.227	-7.00	2.537	333.950	8.80
	1975	-2.00	2.576	37.421	9.099	-4.00	2.958	47.098	12.310	-6.00	2.574	215.675	9.80
	1976	-2.00	2.553	29.574	9.200	-5.00	2.864	77.818	12.367	-8.00	2.176	959.866	3.00
	1977	-3.00	2.597	49.161	10.064	-5.00	2.869	75.112	13.335	-9.00	2.418	948.592	6.30
BWDB	1978	-2.50	2.877	27.088	10.803	-5.50	2.620	151.032	12.733	-8.00	2.284	772.768	8.90
	1979	-2.00	2.954	17.074	9.300	-4.00	2.673	70.350	12.390	-7.00	2.799	185.719	5.40
	1980	-2.00	2.684	24.307	8.916	-5.00	2.642	118.432	12.355	-6.00	2.778	135.428	11.30
	*1981												
	*1982												
	1983	-3.00	2.461	63.012	10.258	-5.00	2.611	108.668	13.051	-8.00	2.994	197.125	
	1984	-3.00	2.548	54.856	11.430	-6.00	2.799	112.121	13.700	-9.00	2.925	376.545	9.49
	1985	-3.00	2.571	58.995	10.627	-6.00	2.533	226.016	13.694	-7.00	2.985	136.158	10.90
	1986	-2.50	2.857	30.125	11.003	-5.00	2.837	84.432	12.347	-7.00	2.702	260.818	7.06
	1987	-2.00	2.809	18.630	8.977	-5.00	2.702	104.810	13.286	-9.00	2.500	834.676	12.50
	1988	-3.00	2.605	41.077	10.640	-6.00	2.752	123.801	12.930	-10.00	2.002	3019.930	10.00
	1989	-2.00	2.939	17.913	10.639	-5.25	2.802	90.339	12.627	-8.00	2.281	741.880	12.10
	1990	-2.00	2.652	27.073	9.163	-5.00	2.830	88.584	13.407	-8.00	3.097	196.843	10.00
	1991	-2.00	2.862	18.858	10.520	-5.50	2.683	114.336	12.926	-8.00	2.718	325.609	12.18
	1992	-1.80	2.809	20.323	9.478	-3.75	2.739	52.271	11.684	-7.20	2.699	264.565	10.89
	1993	-1.75	2.769	20.060	10.500	-6.00	2.875	112.557	12.908	-7.50	2.533	405.774	7.00
	1994	-2.25	2.790	26.009	10.303	-5.75	2.834	119.284	13.298	-6.00	2.003	684.850	7.50
	1995	-2.25	2.736	32.328	10.220	-6.00	2.556	238.360	13.169	-8.75	2.905	487.843	7.40
RSP	1993-1995	-2.75	2.868	23.070	10.000	-5.75	2.800	118.167	13.091	-7.25	2.801	223.525	5.40

Note : 1. Limit - 1 is the Upper limit Water level for interval - 1.
2. Limit - 2 is the Lower limit Water level for interval - 3.
3. Rating Equation : Q = c(WL + a) ^ b.
*. stage-discharge data not available

Table 6.2: Rating Parameters at Hardinge Bridge

DATA SOURCE	YEAR	INTERVAL - 1			Limit -1	INTERVAL - 2			Limit - 2	INTERVAL - 3			STANDARD ERROR (%)
		a	b	c		a	b	c		a	b	c	
	1966	2.00	2.802	96.836	4.784	0.00	2.166	697.588	7.668	-2.00	2.923	361.212	7.20
	1967	2.00	2.460	155.330	4.505	0.50	2.492	280.957	7.050	-1.50	2.799	357.483	6.20
	1968	1.50	2.147	330.648	5.341	0.50	2.858	132.368	7.191	-1.50	2.972	256.807	6.50
	1969	2.00	2.314	202.920	4.972	0.50	2.889	133.845	7.548	-1.50	2.931	283.296	5.70
	1970	2.00	2.630	119.251	4.982	0.00	2.547	331.027	7.452	-2.00	2.607	662.862	7.70
	*1971												
	1972	2.00	2.640	118.320	4.830	0.00	2.846	213.663	6.133	-1.00	2.556	569.453	7.77
	1973	1.50	2.606	150.005	5.446	-0.50	2.885	232.570	7.470	-1.75	2.978	349.669	11.00
	1974	1.50	2.693	135.564	5.472	-0.50	2.871	253.427	6.544	-1.75	2.717	627.418	7.65
BWDB	1975	1.00	2.072	481.652	4.625	0.00	2.598	323.189	7.129	-2.50	2.798	730.427	7.80
	1976	2.50	2.654	103.916	5.606	-0.25	2.984	179.177	7.279	-1.75	2.864	450.816	7.00
	*1977												
	*1978												
	1979	2.00	2.410	217.323	5.852	-1.50	2.785	518.673	7.115	-1.50	2.683	619.263	7.60
	*1980												
	1981	2.00	2.463	186.595	4.829	0.00	2.712	295.724	7.061	-1.00	2.962	285.573	9.00
	1982	2.00	2.026	459.875	5.748	-1.00	2.641	475.699	7.186	-1.50	2.987	325.783	7.50
	1983	0.00	1.571	1968.960	5.200	0.00	2.363	533.930	7.293	-2.00	2.775	573.221	8.00
	1984	1.75	2.266	314.788	5.660	-1.00	7.629	515.119	7.914	-1.50	2.751	500.350	7.80
	1985	2.00	2.638	137.250	4.983	0.00	2.868	230.883	6.803	-1.00	2.545	642.488	9.50
	1986	0.00	1.706	1277.560	5.418	-1.00	2.839	335.776	7.400	-2.00	2.754	622.289	6.90
	1987	2.00	2.681	113.486	5.567	0.00	2.932	167.950	7.806	-1.00	2.870	282.978	6.60
	1988	2.00	2.742	108.968	5.835	-0.50	2.850	261.021	7.594	-1.00	2.916	283.668	5.00
	1989	2.00	2.626	143.283	5.785	0.00	2.819	222.704	7.256	-1.00	2.801	349.442	5.90
	1990	2.00	2.695	122.294	5.475	0.00	2.756	255.097	7.416	-1.00	2.595	512.857	5.80
	1991	2.00	2.620	140.057	5.765	-0.50	2.929	231.782	7.615	-1.00	2.916	294.278	5.50
	1992	1.20	2.156	439.399	4.426	0.50	2.623	278.040	7.428	-1.75	2.897	414.378	5.00
	1993	1.25	2.319	329.680	5.579	-2.00	2.353	1232.700	7.039	-2.00	2.353	1232.740	4.00
	1994	2.00	2.848	88.520	5.031	1.50	2.924	94.637	6.866	-1.50	2.712	495.283	5.50
	1995	2.50	2.563	124.149	5.617	0.25	2.914	153.224	7.174	-1.50	2.736	457.325	7.70
RSP	1993-95	2.25	2.719	97.629	5.780	0.25	2.898	154.299	7.489	-2.00	2.563	7390.400	6.35

Note : 1. Limit - 1 is the Upper limit Water level for interval - 1.
2. Limit - 2 is the Lower limit Water level for interval - 3.
3. Rating Equation : Q = c(WL + a) ^ b.
*. stage-discharge data not available

Table 6.3: Rating Parameters at Baruria

DATA SOURCE	YEAR	INTERVAL - 1 a	INTERVAL - 1 b	INTERVAL - 1 c	Limit -1	INTERVAL - 2 a	INTERVAL - 2 b	INTERVAL - 2 c	Limit - 2	INTERVAL - 3 a	INTERVAL - 3 b	INTERVAL - 3 c	STANDARD ERROR (%)
	*1966												
	1967	2.00	2.536	281.618	4.397	-5.00	2.755	734.864	5.341	-2.00	2.402	3125.600	15.00
	1968	2.00	2.143	2182.262	3.650	0.00	2.724	591.546	5.598	-1.00	2.653	1126.590	14.90
	1969	2.00	2.505	340.875	4.961	0.00	2.901	422.271	5.916	-2.00	2.578	2171.320	10.00
	1970	1.00	2.030	1044.510	4.701	0.00	2.722	529.105	6.012	-2.00	2.488	2205.400	13.30
	*1971												
	1972	2.00	3.001	140.964	4.067	0.00	2.561	868.704	21.682	0.00	2.775	624.232	14.40
	1973	1.00	2.140	938.306	4.103	-0.50	2.728	929.614	4.525	-1.00	2.299	2293.610	13.00
	1974	2.00	2.731	223.566	3.773	0.00	2.406	1100.420	5.223	0.00	2.707	669.117	12.77
	*1975												
	1976	2.00	2.891	167.770	3.663	0.00	2.616	844.252	4.782	0.00	2.699	741.284	16.45
	1977	2.00	2.807	207.775	4.450	-0.50	2.742	925.131	5.355	-1.00	2.869	1033.450	15.57
	1978	2.00	2.570	322.584	3.929	0.00	2.868	616.955	5.188	0.00	2.712	798.039	16.16
	1979	2.00	2.467	359.399	4.862	0.00	2.867	446.793	5.821	-1.00	2.486	1396.450	12.40
	1980	2.00	2.603	254.083	3.687	-1.00	2.087	2974.860	5.727	-1.00	2.180	2575.450	13.50
	*1981												
	1982	1.50	2.765	295.009	3.723	0.50	2.607	665.787	5.089	0.00	2.820	601.728	16.10
BWDB	1983	2.00	2.326	411.624	3.355	0.50	2.559	645.705	4.802	0.00	2.873	508.373	14.37
	1984	2.50	2.972	125.000	3.848	0.00	2.628	880.235	4.803	-0.50	2.559	1298.330	15.74
	1985	1.50	2.823	289.875	2.897	1.00	2.643	520.737	4.724	0.00	2.839	479.691	10.39
	1986	2.00	2.016	667.029	3.906	0.00	2.792	533.155	4.772	-1.00	2.631	1850.750	14.40
	1987	1.00	2.754	315.304	5.084	-1.00	2.928	740.152	5.873	-2.00	2.453	2756.520	14.00
	1988	1.50	2.822	258.675	4.411	1.00	2.254	866.744	5.722	0.00	2.419	933.444	10.60
	1989	0.00	2.555	905.242	4.690	0.00	2.555	905.242					8.90
	1990	0.00	2.272	1442.320	5.375	0.00	2.280	1415.730					4.10
	1991	0.00	2.165	1904.200	5.744	0.00	2.041	2365.470					7.00
	1992	0.00	2.832	780.328	4.625	0.00	2.593	1126.430	4.962	-0.50	2.292	2327.070	10.00
	1993	1.50	1.660	2395.950	4.150	1.50	1.660	2395.950	4.702	-0.50	2.636	1126.720	12.00
	1994	2.00	2.669	297.863	4.210	0.00	2.530	1026.310					13.70
	1995	0.10	2.997	429.192	5.218	0.00	2.442	1137.310					12.50

Note : 1. Limit - 1 is the Upper limit Water level for interval - 1.
2. Limit - 2 is the Lower limit Water level for interval - 3.
3. Rating Equation : Q = c(WL + a) ^ b.
*. stage-discharge data not available

Table 6.4: Rating Paramaters at Mawa

DATA SOURCE	YEAR	INTERVAL - 1 a	INTERVAL - 1 b	INTERVAL - 1 c	Limit -1	INTERVAL - 2 a	INTERVAL - 2 b	INTERVAL - 2 c	Limit -	INTERVAL - 3 a	INTERVAL - 3 b	INTERVAL - 3 c	STANDARD ERROR (%)
	1966	-2.50	1.898	53.936	10.539	-3.00	2.528	17.071	11.118	-3.30	2.769	11.442	9.10
	1967												
	1968	-3.65	1.537	147.070	10.244	-3.75	2.217	42.222	10.950	-4.00	2.362	35.044	12.38
	1969	-3.50	1.852	85.081	11.674	-4.25	2.791	15.463					3.00
	1970	-3.75	1.935	65.743	11.270	-4.00	2.534	21.390	11.733	-4.50	2.828	14.176	
	*1971												
	1972	-3.25	2.842	17.275	7.221	-3.50	2.515	51.558	10.419	-3.50	2.563	23.213	16.80
	1973	-3.00	2.273	34.702	10.258	-3.50	2.416	31.082					15.00
	1974	-2.75	1.846	62.964	9.505	-3.50	2.789	14.429	11.950	-4.00	2.605	25.251	13.70
	*1975												
	1976	-3.25	1.987	50.811	10.184	-3.40	2.839	10.383	11.881	-5.00	2.465	38.690	11.30
	*1977												
	*1978												
	*1979												
	*1980												
	*1981												
	*1982												
	1983	-3.00	2.255	27.288	9.516	-3.75	2.312	32.524	11.853	-4.50	2.872	13.317	15.00
BWDB	1984	-2.75	2.305	20.436	10.591	-4.00	2.719	13.979	12.421	-5.20	2.952	13.399	14.54
	1985	-25.00	2.199	22.368	9.682	-4.75	2.517	30.738	11.969	-5.00	2.887	16.387	13.67
	1986	-2.40	2.255	17.234	9.432	-4.00	2.992	8.859	11.204	-4.00	2.816	12.553	14.30
	1987	-3.00	2.142	32.928	9.439	-4.00	2.414	29.797	12.181	-4.00	2.779	13.837	14.20
	1988	-3.75	1.782	75.122	9.468	-4.50	2.319	40.802	11.772	-5.00	2.679	24.198	13.00
	1989	-4.00	2.437	27.790	9.578	-4.00	2.623	20.160	10.771	-5.00	2.183	66.291	10.00
	1990	-3.75	2.137	37.723	9.703	-4.00	2.891	11.129	10.863	-4.50	2.686	20.214	6.57
	1991	-3.75	2.315	28.785	10.570	-4.50	2.602	22.469	11.872	-5.00	2.917	14.692	14.00
	1992	-4.00	2.517	28.243	7.500	-4.10	2.179	44.534	10.988	-4.50	2.657	20.767	17.00
	1993	-3.00	2.430	27.200	7.424	-3.20	2.378	32.801	10.545	-5.00	2.004	121.542	14.00
	1994	-3.75	2.509	29.011	10.020	-4.50	2.760	25.990					8.00
	1995	-4.00	2.986	13.458	7.813	-4.10	2.159	43.095	11.043	-5.00	2.774	19.243	10.00
RSP	1993-95	-3.50	2.803	6.780	9.562	-6.00	2.257	60.244					16.00

Note : 1. Limit - 1 is the Upper limit Water level for interval - 1.
2. Limit - 2 is the Lower limit Water level for interval - 3.
3. Rating Equation : Q = c(WL + a) ^ b.
*. stage-discharge data not available

Table 6.5: Rating Parameters at Gorai Railway Bridge

Note that in Set 2 for station Bahadurabad, BWDB rating curve for the period 04/01/1987-31/08/1988 was applied for the period 1988-1992 in view of inconsistencies in the stage-discharge data for latter period.

To investigate the consistency of the data, water-balance analyses and double mass analyses have been carried out on the data sets.

6.4 Hydrological database

The processed water level, stage-discharge data and parameters as well as the three discharge time series of the BWDB and of the RSP data sets are stored in the final FAP24-HYMOS database.

7 Analyses

7.1 General

In the course of the Project a number of special studies have been formulated, including:

- stage-discharge relation of Bahadurabad, particularly in view of extrapolation of the discharge rating equation,
- analysis of the stage-discharge relation of Bhairab Bazar, where backwater from the Padma affects the stage-discharge measurements,
- water balance analysis to investigate the consistency of flow data,
- estimation of overland flow, and
- analysis of longitudinal water-level profiles.

These topics are are discussed in this chapter together with a comparison between the BWDB and RSP water-level and discharge data.

7.2 Water levels

7.2.1 Accuracy of measurements

In Sub-section 5.2.1 a summary is given of the errors present in the BWDB water-level series; these consist of reading errors and errors caused by incorrect gauge zeros. To quantify the errors in the water levels a comparison was made between the daily average values of 1994 and 1995, derived from the BWDB observations and those by the RSP using the same observation procedure. The results are summarized in Table 7.1 and illustrated in Figure 7.1. From the results it can be concluded that:

- the differences for Bahadurabad are small and fairly random;
- a systematic difference is found between the readings at Hardinge Bridge. The gauges at this site are not exactly at the same location and the readings at both sites are influenced by differences in velocity head. Sudden changes in the differences are observed, indicating gauge shifts without proper relevelling;
- the BWDB readings for Baruria are on average slightly lower than the RSP readings. The deviations are fairly random in nature;
- the differences for Mawa are considerable and amount to about 10 cm with occasionally differences up to 30 cm, caused by gauge shifts;
- the differences for Gorai Railway Bridge show a sudden change at the end of October 1994. Thereafter, the readings at the BWDB gauge are about 3 cm less than the RSP observations.

In summary, the comparison of gauge readings support the findings of FAP25 about the untimely re-levelling of gauges, see Chapter 5.

Station	Year	Mean abs. diff.(m)	Stdv.abs.diff.(m)
Bahadurabad	1994	0.02	0.01
	1995	0.05	0.04
Hardinge Bridge	1994	0.07	0.02
	1995	0.06	0.03
Baruria	1994	0.03	0.02
	1995	0.04	0.03
Mawa	1994	0.08	0.04
	1995	0.10	0.06
Gorai Railway Br.	1994	0.03	0.01
	1995	0.03	0.02

Table 7.1 Summary of accuracy of water-level observations: mean and standard deviation of absolute difference between daily average gauge readings of BWDB and FAP24

7.2.2 Water-level slopes

Water-level slopes provide important information about the hydraulic and morphological behaviour of rivers. The appropriate longitudinal scale of the water-level slopes to be considered depends on the type of study. When looked at it in detail, it provides information about the local river hydraulics and can be used to explain the small-scale morphological developments. For calibration of one-dimensional mathematical hydraulic and morphological models a larger scale is required. Under RSP both far-field and near-field investigations of water-level slopes have been carried out, including:

- a study of longitudinal water-level profiles in the main rivers, and
- studies of local water-level slopes in the Jamuna river around Bahadurabad and between Bahadurabad and Sirajganj.

Longitudinal water-level profiles

Longitudinal water-level profiles have been determined for the main rivers for various flow conditions. The results are shown in the Figures 7.2 to 7.4. In the upper parts of the two main rivers in Bangladesh, the slopes appear to be fairly constant: 7.6 cm and 5.5 cm per km for the Jamuna and Ganges rivers respectively. Further downstream, the slopes vary considerably with river discharge. In the Padma river during the flood season the slope is about 4 cm per km and almost nil during the lean season. The slopes in the Meghna river are even less: 2.2 cm per km to about zero for flood and lean-season flow conditions. Apart from providing relevant information for backwater and sediment transport computations, the longitudinal profiles give clear indications of possible errors in the gauge zeros. The results of the overall slope analysis has been the trigger of a full-scale re-levelling of gauge zeros and benchmarks, see Sub-section 5.2.1.

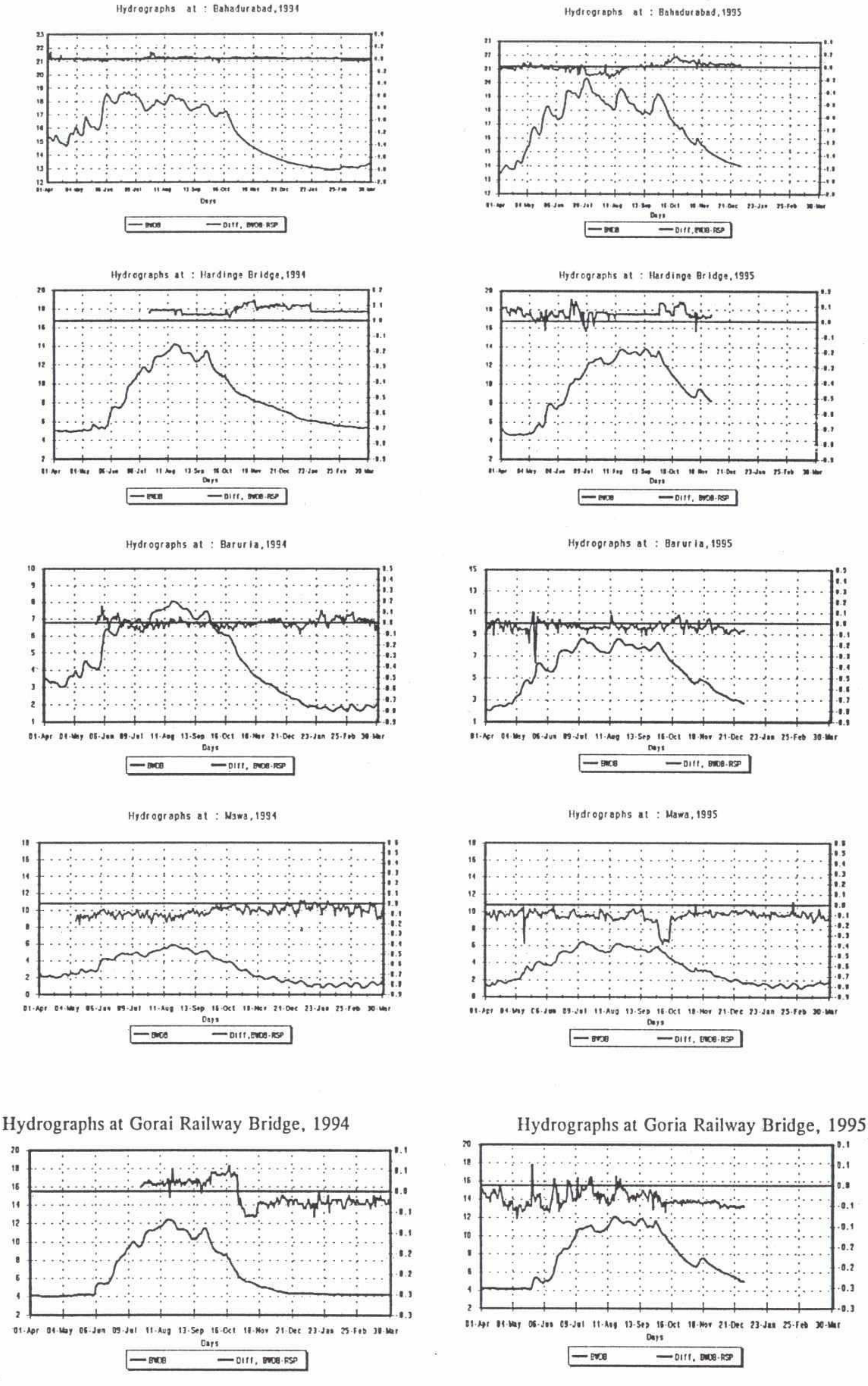


Figure 7.1 Differences between BWDB and FAP24 daily average water levels

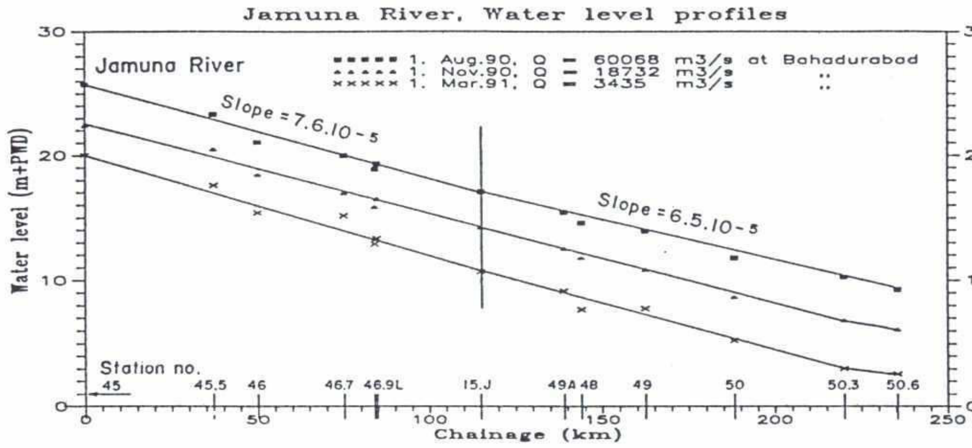


Figure 7.2 Water-level profiles in the Jamuna river

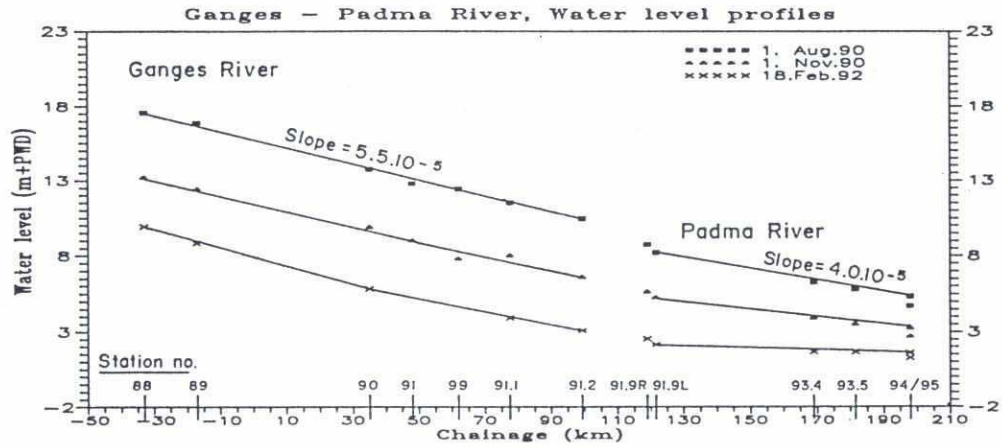


Figure 7.3 Water-level profiles in the Ganges and Padma rivers

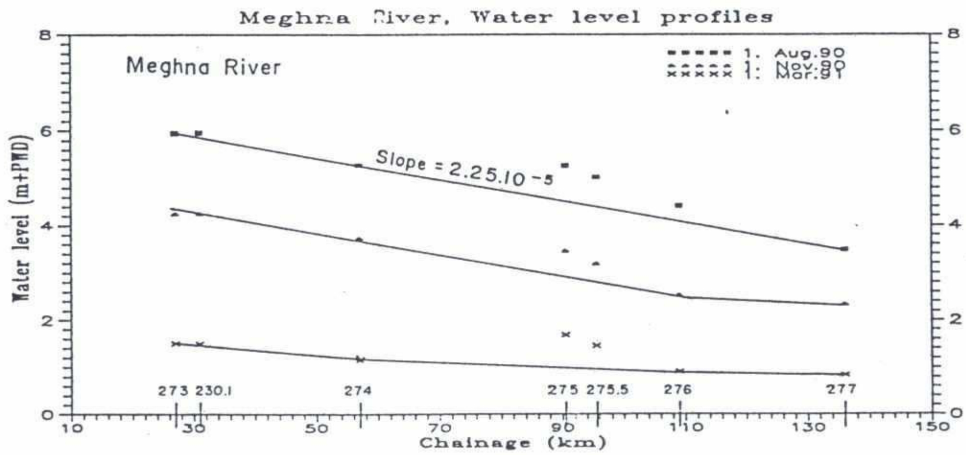


Figure 7.4 Water-level profiles in the Meghna river

Local water-level slopes in the Jamuna River near Bahadurabad

To investigate in detail the development of the local water-level slopes at Bahadurabad, nine staff gauges and two automatic water-level recorders were installed along the left and right channel of the Jamuna, see Figure 4.4. Water-level differences between stations upstream and stations downstream of the Bahadurabad flow-measuring transect for the year 1994 are presented in Figure 7.5. From the figure it can be seen that in the range of observations for that particular year the water-level differences and hence the water-level slopes increase with river stage/discharge, both in the left and in the right channel. Apparently, in that reach of the Jamuna River the conveyance increases in downstream direction. However, 1994 was a relatively dry year and the river stages hardly reached the level of the flood plain.

By plotting the water-level differences between the two stations as a function of stage, one can have a idea of the change in local water-surface slope with stage (Peters, 1994). The power of studying local water-level slopes for assessment of morphological developments is illustrated by means of the left channel water-level data and their differences of 1995. In 1995, high stages were recorded in the Jamuna River. From satellite images of the left channel configuration prior to, during, and after the 1995 flood (Figure 7.6), it can be deduced that for some time the channel was partly blocked near the basr studied by the University of Leeds (see SPR 9, Bars and bedforms in the Jamuna River: during the flood the channel west of the island silted up. From the images of the area after the flood period one can observe that the river responded to the temporary blockage by expanding the channel east of the island. The development of this process in time can be read from the Bahadurabad hydrograph in combination with the water-level differences between Bahadurabad and Khatiamari on the one hand, and between Bahadurabad and Belgacha, on the other, as displayed in Figure 7.7. Until early July the water-level differences are observed to follow the general pattern: the differences increase with stage. One can see that during the occurrence of the 1995 flood peak the water-level difference between the upstream stations had been reducing (see also Figure 7.8, right-hand side relation curve). The reduction indicates a sudden increase of conveyance at the upstream side. The water level at which the reduced water-level difference takes place corresponds to the approximate floodplain level at Bahadurabad of 19 m+PWD. After the occurrence of the peak, the water-level differences upstream and downstream of Bahadurabad are seen to behave differently: downstream of Bahadurabad the general pattern is unchanged, whereas upstream of Bahadurabad the differences have increased compared to the same water levels prior to the flood. Increased water-level differences imply larger hydraulic resistance; apparently, between Khaliamari and Bahadurabad the river flow is obstructed. A likely explanation is that the sedimentation of the west channel around the bar studied by the University of Leeds took place at that time, possibly induced/accelerated by an increased sediment supply from the flood plain or by a change in the local flow pattern. This situation continued until the occurrence of the last flood wave on the Jamuna, end of September 1995. After that flood wave a sharp drop in the water-level difference between Khatiamari and Bhadurabad is observed. This indicates that at that time the blockage in the channel was lifted and the new channel east of the bar studied by the University of Leeds was established.

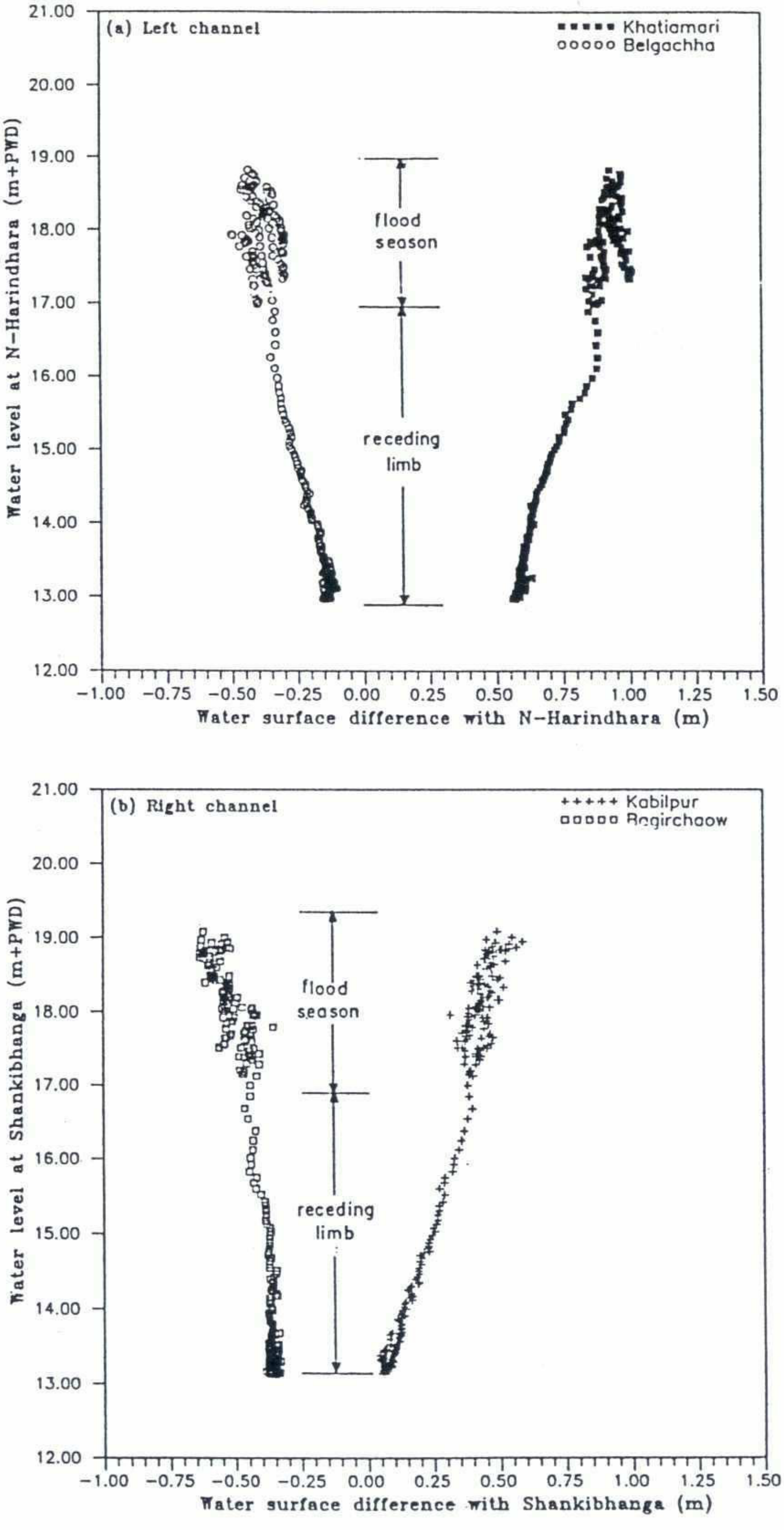


Figure 7.5 Water-level differences (1994) in the left and right channel of the Jamuna river at Bahadurabad as a function of river stage.

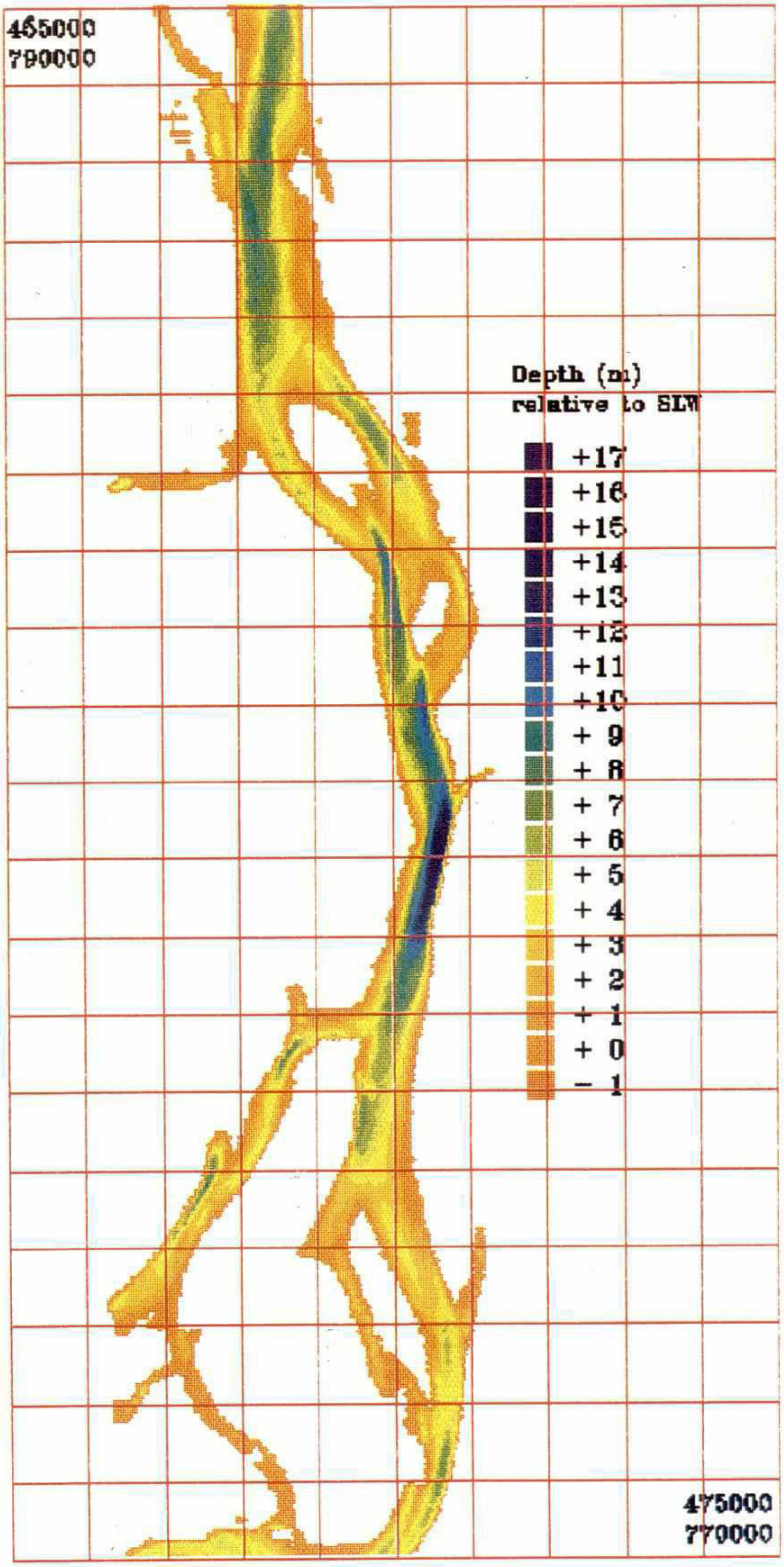


Figure 7.6a: Development of the left channel of the Jamuna river west and east of Jim's Island: Contour slice of the River Bathymetry Surface February 95 Bahadurabad left channel of Jamuna.

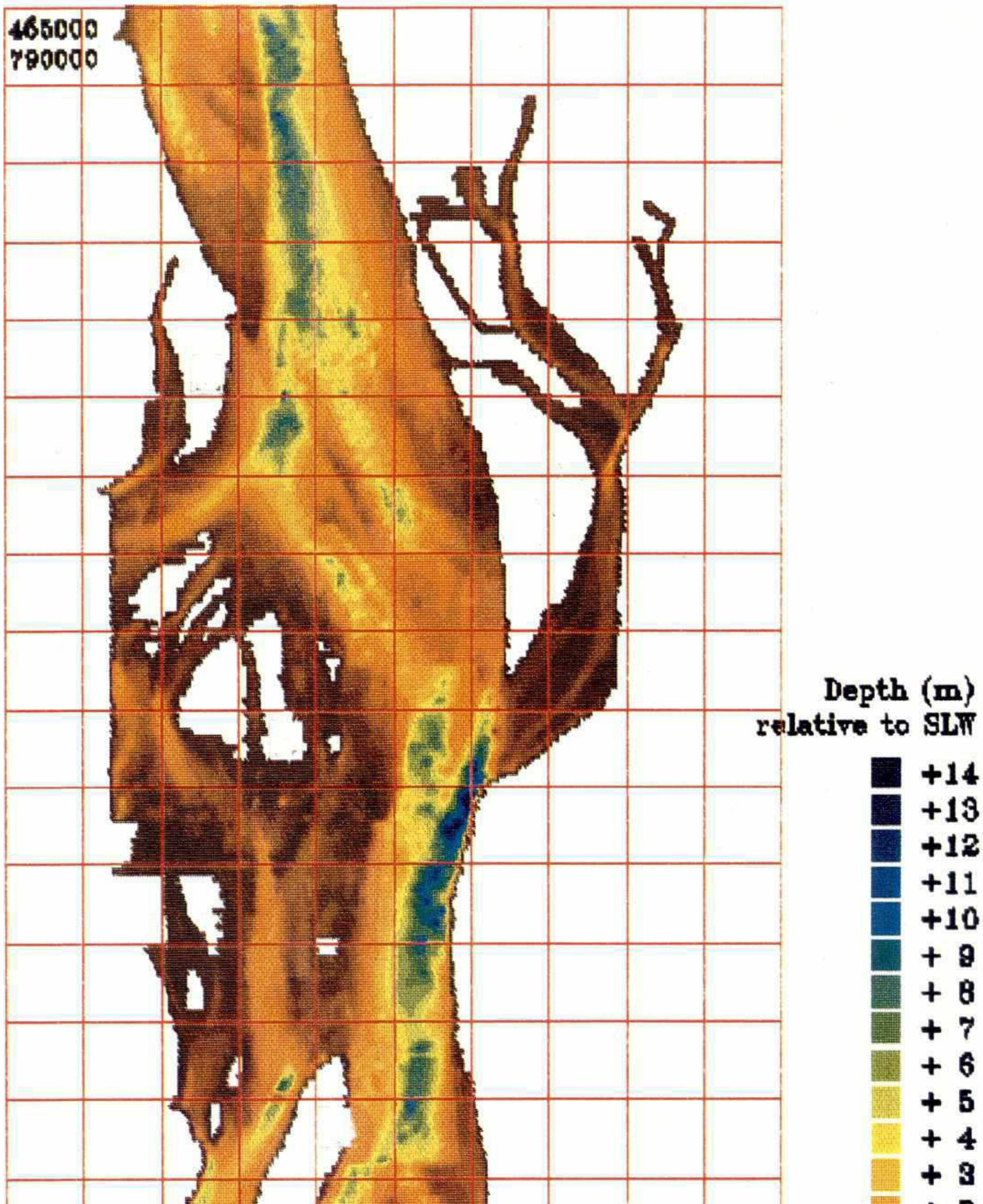


Figure 7.6b: Development of the left channel of the Jamuna river west and east of Jim's Island: Contour slice of the River Bathymetry Surface July 1995 Bahadurabad left channel of the Jamuna.

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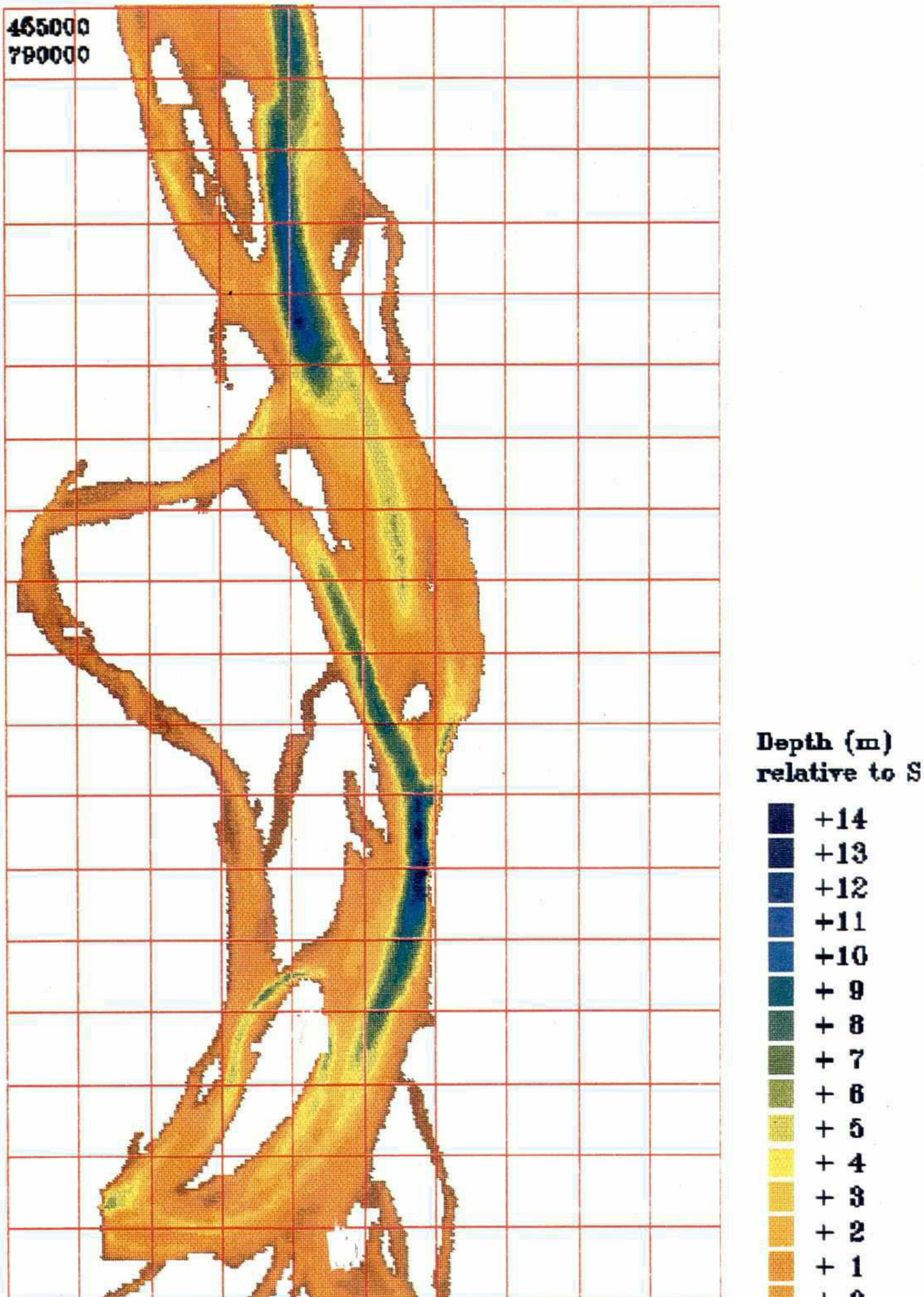


Figure 7.6c: Development of the left channel of the Jamuna river west and east of Jim's Island. Contour slice of the River Bathymetry Surface November 95 Bahadurabad left channel of Jamuna.

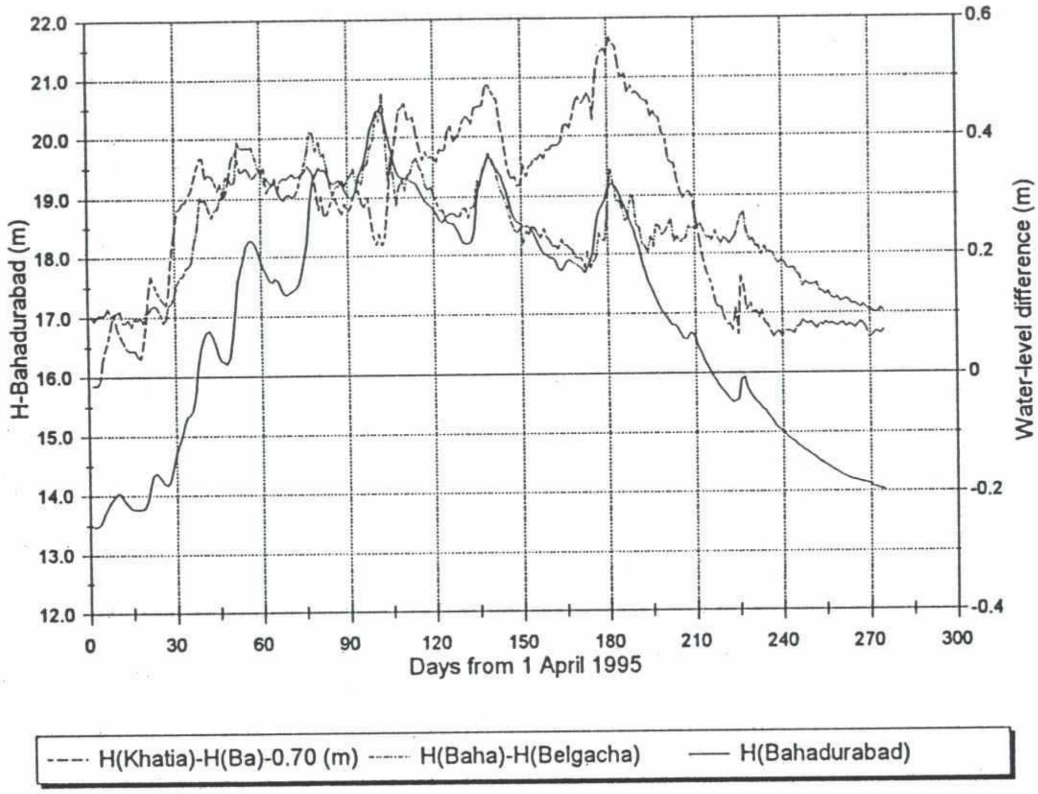


Figure 7.7 1995-hydrograph of the Jamuna river at Bahadurabad and water level differences upstream and downstream of the Bahadurabad flow measuring transect.

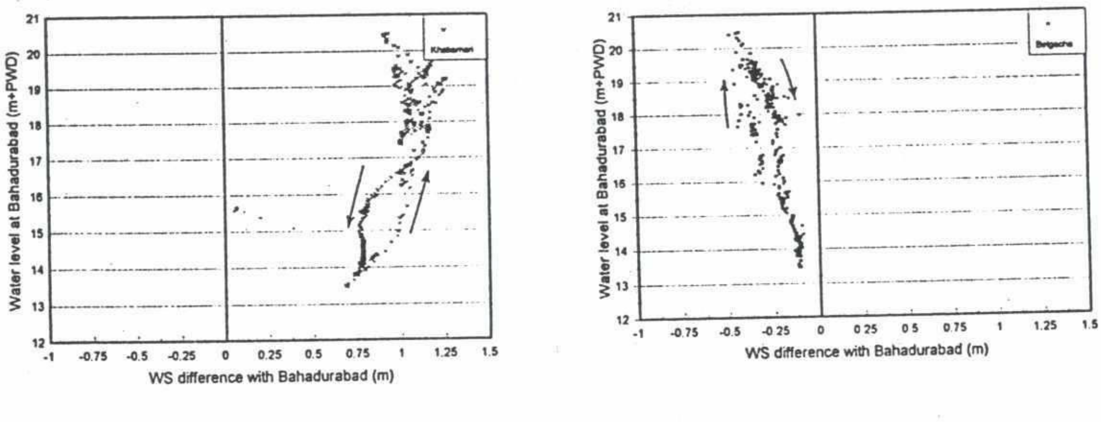


Figure 7.8 Water-level differences (1994) in the left channel of the Jamuna river upstream and downstream of the Bahadurabad flow-measuring transect, as a function of river stage.

Local water-level slopes in Jamuna river between Bahadurabad and Sirajganj

An interesting development of water-level slopes takes place annually between Bahadurabad and Sirajganj. In Figure 7.9 the water-level difference between the two stations is shown based on average values, derived from differences of daily levels averaged per month for the entire period of record at the stations (1965-1995). The Figure shows that from January until July the water-level difference is higher than for the rest of the year. A similar looping is obtained if only the last seven years (1989-1995) are considered. Possible reasons for the observed looping may be:

1. dynamic hydraulic effects,
2. backwater effect from the Ganges,
3. varying hydraulic roughness, and
4. morphological effects causing bed-level changes.

If a flood wave travels down a river, some looping will occur in the stage-relation curve as the water-level gradients before the passage of the peak are higher than after that. This effect is conveniently eliminated by accounting for the travel time of the wave (upstream levels are compared with the levels at the downstream site some time later, equal to the distance between the stations times the wave celerity). Investigations show that this effect affects to some extent the observed looping in Figure 7.9, (see Figure 7.10), particularly in the months when the levels rise (April to June) or fall (October to December) more or less continuously. However, during July to September rises and falls alternate frequently, and here this dynamic effect is seen to be of no importance in the explanation of the looping.

Also important is the backwater effect. The water levels at Sirajganj are during part of the year affected by backwater from Ganges river. It implies that when the Ganges is in flood the water levels at Sirajganj are slightly increased by it. From the hydrograph and discharge rating curve at Baruria the backwater effect by the Ganges at the mouth of the Jamuna river is easily obtained, see Figure 7.11. To transfer the setup at the river mouth properly to Sirajganj, and to assess the morphological implications of it, a one-dimensional hydraulic/ morphological model would have been required. Unfortunately, no allowance was received for the development of such a model. Therefore, a simplified first-order analysis was embarked upon to analytically estimate the backwater effect on the water levels at Sirajganj. The result is also shown in Figure 7.11. From this figure one can observe that from July to October roughly one to two decimetres backwater on the gauge-readings at Sirajganj can be expected. But as shown in the Figures 7.12 and 7.13 this effect is still insufficient to explain in full the looping in the water-level differences and consequently the water-level slopes.

A further cause may be an increase of hydraulic roughness, induced by backwater effect. Such effects are reported also elsewhere. E.g. at the transition of the river Waal to the river Merwede in the Netherlands where the water levels begin to be set up by backwater, the hydraulic roughness increases whereas, according to existing theories on grain size and hydraulic conditions, a decreasing roughness is expected (DELFT HYDRAULICS, 1984). In the case of the Jamuna a similar effect could develop each year from July onward in the river reach downstream of Sirajganj to affect the stage-discharge relation during part of the year. To investigate this aspect in detail, year-round measurements of bedforms in the lower Jamuna river reach would be required.

Another possibility is an annual variation in the riverbed geometry downstream of Sirajganj due to sedimentation and erosion as a consequence of varying backwater effect. For comparable river flows, when the Ganges river is in flood, the sediment transport capacity in the lower reaches of the Jamuna river will be less than prior to the rise of the Ganges as a consequence of reduced water-level slopes. Hence, sedimentation will occur if backwater becomes apparent. Furthermore, due to backwater it is likely, that in the lower reach more frequently than upstream the floodplain is inundated and may form an extra source of sediment supply. However, due to the absence of a hydraulic-morphological model of the main river system a quantitative assessment of the above mentioned factors cannot be given. The development of such a model is recommended to improve the understanding of the complex processes governing the hydraulic-morphological behaviour of the main rivers.

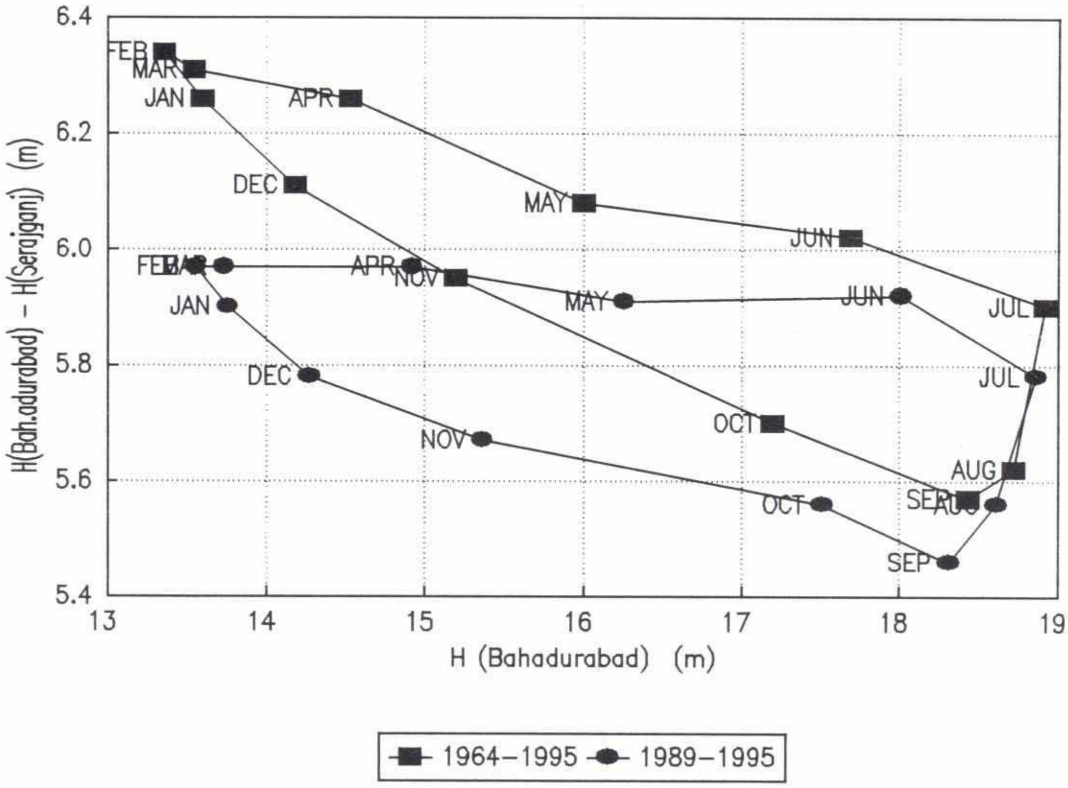


Figure 7.9 1964-1995 and 1989-1995 monthly average water-level differences between Bahadurabad and Sirajganj as a function of river stage

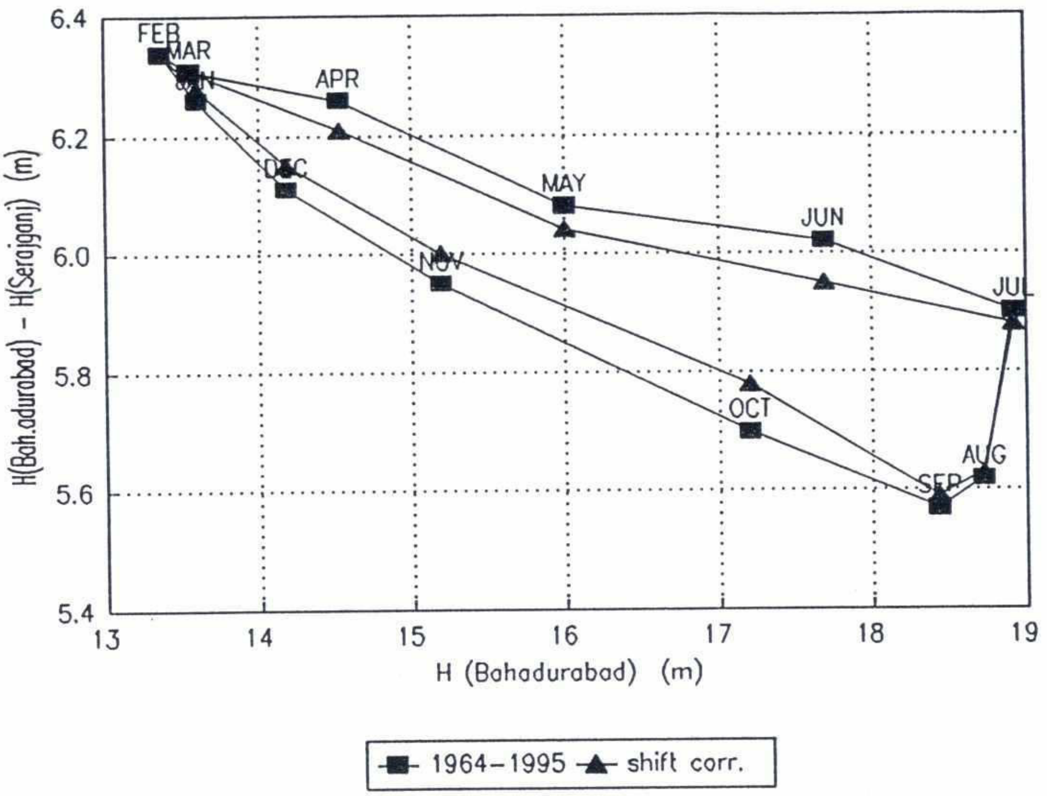


Figure 7.10 Effect of correction for time shift on the 1964-1995 monthly average water-level differences between Bahadurabad and Sirajganj

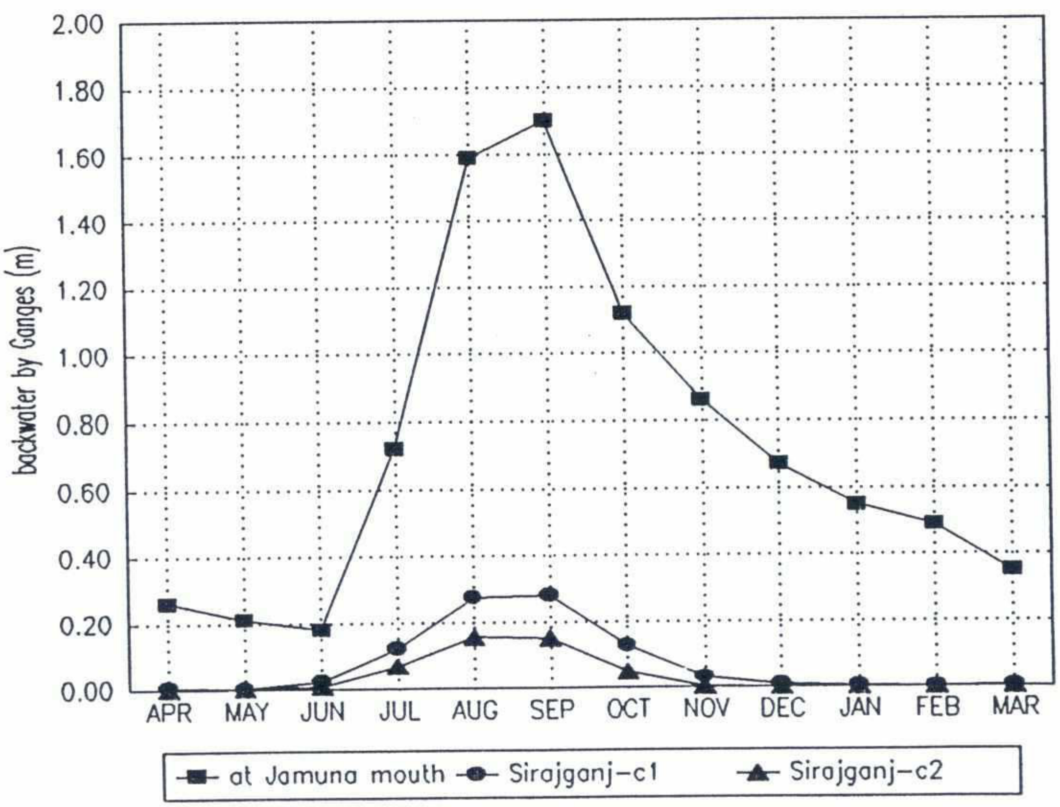


Figure 7.11 Approximate backwater effect of Ganges river on water levels at Jamuna river mouth and at Sirajganj according to two scenarios (c1 and c2)

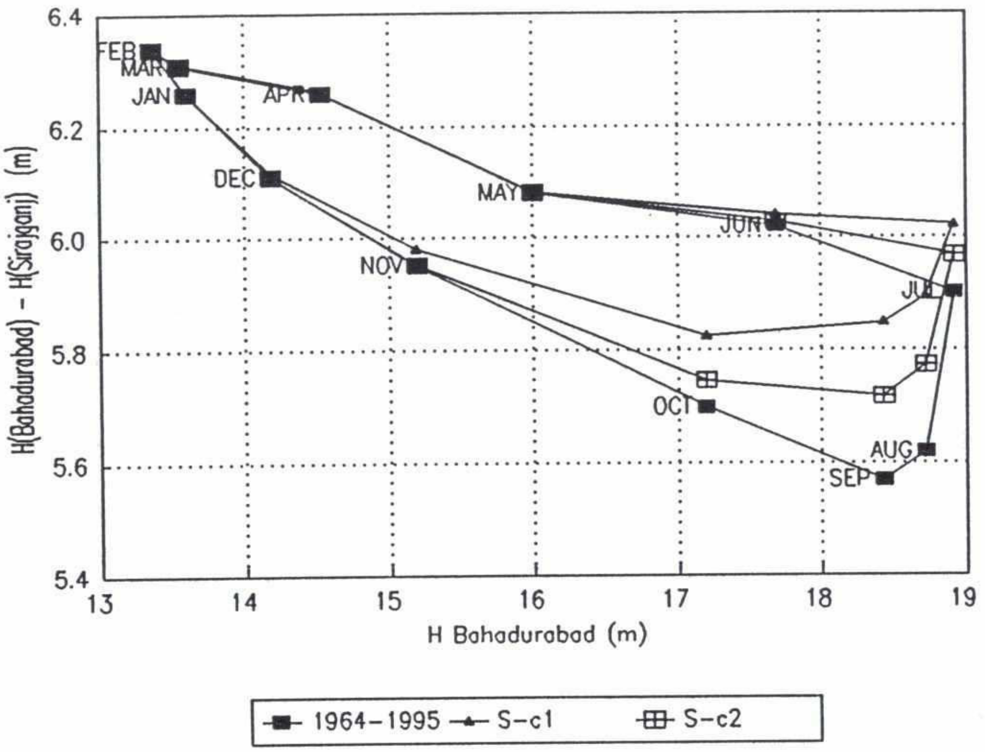


Figure 7.12 Effect of backwater corrections on the looping in the "water-level difference — river stage" relation curve for Bahadurabad and Sirajganj, period 1964-1995.

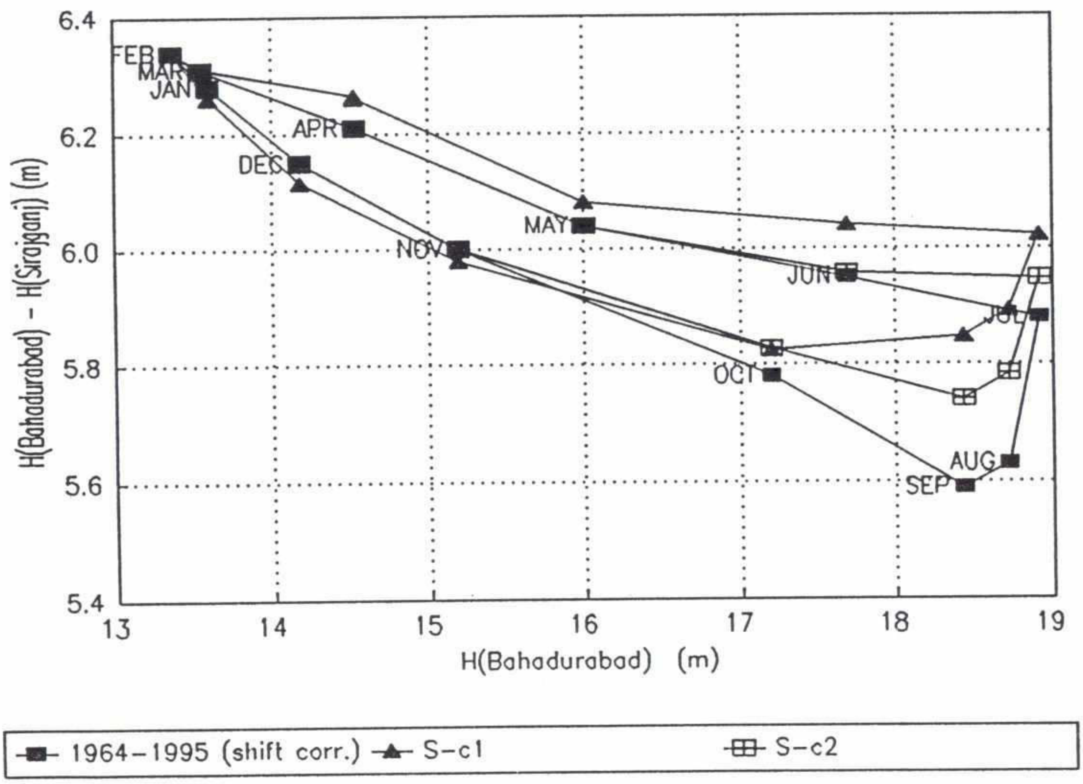


Figure 7.13 Effect of backwater corrections on the looping in the "water-level difference (corrected for wave travel time) — river-stage" relation curve for Bahadurabad and Sirajganj, period 1964-1995.

7.3 Discharge measurements

The discharge measurement procedures are discussed in Chapters 5 and 6. Test measurements carried out by the RSP at Bahadurabad in the right channel of the Jamuna river revealed that the ADCP-EMF moving boat method gives very reproducible results; crossing the river and back gave differences within a few percent. Comparison of the method with the conventional velocity-area method, based on point-flow velocity measurements in a large number of verticals, also showed a good match: the ADCP-EMF moving boat method gave 1 to 2% higher discharges than the velocity-area method, *(Annex C: Optimization of Hydraulic Measurements, FAP24, 1996)*. Compared to the conventional propellor-type current-meter the ADCP appears to give systematically approximately 5% lower velocities. Manufacturers of the acoustic equipment suggest that propellor-type flow meters overestimate the flow velocity as turbulence supplies extra energy to the rotation of the propellor: propellor-type current-meters are calibrated by towing it through stagnant water without turbulence (see SPR 19, Joint measurements BWDB/RSP Hydrology, page 17). Others argue that with acoustic devices the speed of the particles in the water rather than the flow velocity itself is measured. At present, no definite answer can be given as to the exact absolute velocity.

Possible error sources in the BWDB procedure have been summarized in Sub-section 5.2. From the combined measurements the following sources of error have been quantified:

- flow direction (differences ranging from -5 to +5%),
- flow velocities (BWDB measures up to 12% higher velocities),
- flow depth (BWDB measures 1-5% lower depth), and
- flow width (errors up 15%).

As a consequence deviations occur in the measured discharges as is shown in Table 7.2. In general, the measurements by BWDB give higher discharges, with values up to 13%. The above figures, however, refer only to the joint measurements, which were limited in number. A far better picture of the differences between the outcomes of the discharge mesurements is obtained from comparison of discharge rating equations. For this reference is made to Sub-section 7.4.5.

date of measurement	River	Location	Discharge by BWDB	Discharge by FAP24	Difference
			(m^3/s)	(m^3/s)	%
Oct 1994	Jamuna	Bahadurabad	24335	22265	9.3
Oct 1994	Jamuna	Bahadurabad	18470	17807	3.7
Jul 1995	Jamuna	Bahadurabad	55300	55100	0.4
Oct 1995	Ganges	Hard. Bridge	36800	32631	12.8
Oct 1995	Padma	Mawa	33680	34640	-2.8
Nov 1995	Jamuna (lc)	Bahadurabad	8737	8152	7.2

Table 7.2 Summary of results of discharge measurements during joint measurement

7.4 Stage-discharge relations

7.4.1 Fitting of discharge rating curves

In Section 6.4 the procedure applied by the RSP for fitting discharge rating curves is discussed. The procedure includes a segmentation of the rating curve, where the segment boundaries coincide with changes in the cross-sectional geometry. For each segment the data are fitted by a power type equation. Essential to the RSP procedure is that the value for the power remains within physical limits and that the offset applied to the stage is unique for each segment. With respect to the offset it deviates from the presently applied procedure by BWDB and FAP25, in which the offset for the lowest segment is applied to the higher segments as well. By selecting a unique offset for each segment the fit to the data improves as the data will be randomly distributed around the fitted line. Due to this its potential for extrapolation improves. However, it is noted here that extrapolation beyond the measured range based on an empirically derived curve should be avoided and that the procedure presented in the next sub-section is strongly preferred.

In the following the rating curves developed for the RSP data are discussed.

Bahadurabad

Under this project special attention was given to the stage-discharge relation of Bahadurabad as inconsistencies in the discharges of this station were detected for the period August 1988 to March 1993. Water-balance checks indicated that the discharges for this period were too high. All steps in the process were carefully examined on possible errors. Apart from the normal inaccuracies inherent to the velocity-area method one source of error is prominent: measuring in an oblique transect, without proper correction for the direction of the velocity. It appeared that after the flood of 1988 a new transect was used.

Since 1993 flow measurements have been carried out by the RSP. The measurements, with the curve fitted to the data, are shown in Figure 7.14. In view of the reported variation in the BWDB-rating equations year by year, it is remarkable that the data for the three successive years could accurately be fitted by one curve. It shows, that, notwithstanding the significant morphological activities at a local scale, the effect on the stage-discharge relation is apparently limited. One reason is that, due to the small river slopes, a large reach downstream of the station controls the backwater on the gauge readings. Hence, large-scale morphological changes for example a cut-off, are required to significantly affect the stage-discharge relation.

For some years (e.g. 1995) BWDB discharge measurements show different relations for the first and the second half of the hydrological year. An easy conclusion would be to establish two rating curves for such years. The RSP measurements, however, do not indicate a change in the relation through the year. The apparent change should therefore be attributed to inaccuracies in the measurements.

Possible improvements by applying separate rating curves for the left and for the right channel at Bahadurabad were investigated, as an alternative to the single relation. Neither the BWDB data for 1987 nor the results based on the RSP data show significant improvement of the stage-discharge relation (RSP, May 1996). It is likely that such an approach would require more often an adjustment than the single curve approach as presently in use, due to small scale morphological changes, and is therefore disencouraged.

To investigate the consistency of the discharge relation found for Bahadurabad, the flow measurements carried out by RSP at Sirajganj have been transferred to the former station by using the stage relation curve adjusted for wave travel time effects. The result is presented in Figure 7.15. The Figure shows that the data fit well to the discharge rating curve, supporting the validity of the established relation for Bahadurabad.

Hardinge Bridge

Another key station in the hydrometric network of Bangladesh is Hardinge Bridge on the Ganges river. The results of the measurements are shown in Figure 7.16. One can observe that for the low flows there is considerable scatter in the data, likely caused by backwater from the Jamuna on water levels at Hardinge Bridge. Data of stations downstream of Hardinge Bridge would have been required to compute the water-level slope for correction of backwater effects. Since these data were not available no such correction was applied. We advise to analyse the effectiveness of such a correction on the stage-discharge relation for Hardinge Bridge.

No clear change is observed in the stage-discharge relation for the remainder of the data, hence one single stage-discharge relation is established for the full period of record 1993-1995.

A further improvement of the stage-discharge relation is likely obtained by relocation of the gauge. At present, at the gauge site the flow velocities are high and the riverbed erodes and considerably silts up seasonally. This will give different velocity heads through the season for equal discharges while forming a potential source of scatter in the stage-discharge relation. Establishment of the gauge at a more quiet location is recommended.

Baruria

A remarkable stable stage-discharge relation is also observed for Baruria, as is shown in Figure 7.17, and hence one curve has been applied for the period 1993 to 1995. Discharge observation made at Mawa were used to verify the reliability of the curve. The data of Mawa were transferred to Baruria by means of a stage relation curve with shift adjustment. The result is presented in Figure 7.18. One can see that the flow measurements at the latter station fit acceptably to the discharge rating curve of Baruria. Note that no correction was made for the off take to the Arial Khan as this amount (ranging from 100 to 2700 m^3/s) is far within the measurement error of the flow in the main stream.

Mawa

At Mawa only a small number of measurements were carried out by the RSP, too few to establish a stage-discharge relation as can be observed from Figure 7.18. Discharges measured by BWDB at Mawa show generally a large scatter, also because of tidal effects. In view of this noise in the data, exceeding by far the scatter in the data of Baruria, as well as the limited off-take from the river between Baruria and Mawa, the usefulness of continuation of measurements at this site is questionable. We advise to derive in future the stage-discharge relation from Baruria by making use of the stage relationship between the two stations.

Gorai Railway Bridge

The discharge measurements in the Gorai river at Gorai Railway Bridge as a function of the water level is presented in Figure 7.20. The discharge is seen to vary from virtually nil to some 4000 m^3/s. For water levels in excess of 11 m+PWD the capacity of the river appears to increase very rapidly. As before, the data do not indicate any change in the stage-discharge relation for the period 1993-1995 and, therefore, one discharge rating equation was fitted to the data.

Bhairab Bazar

The results of the discharge measurements carried out by the RSP at Bhairab Bazar are presented in Figure 7.21. The Figure shows a considerable scatter in the data as a result of backwater effects by the Padma river. Similar scatter is present in the historical stage-discharge data of this station. An analysis to make a correction for backwater effects has been carried out for the rating curve data of some selected years. Firstly, a neighbouring water-level station was selected from which the fall or gradient could be calculated. In absence of reliable stations downstream of Bhairab Bazar, station Dilalpur, 20 km upstream, was chosen. Figure 7.22 shows the gauging data for 1988 with the fall. It appears that the data can nicely be grouped according to the fall. A correction for constant fall was applied using the option available in the HYMOS software package. The result is shown in Figure 7.23. From this Figure a significant improvement is observed in the stage-discharge relation with the fall correction. Similar improvements were found for other years. It is therefore strongly recommended to make the RSP gauge, installed along the Meghna in 1995, a permanent one. Furthermore, the historical discharge series of Bhairab Bazar should be recomputed by accounting for backwater, using this technique.

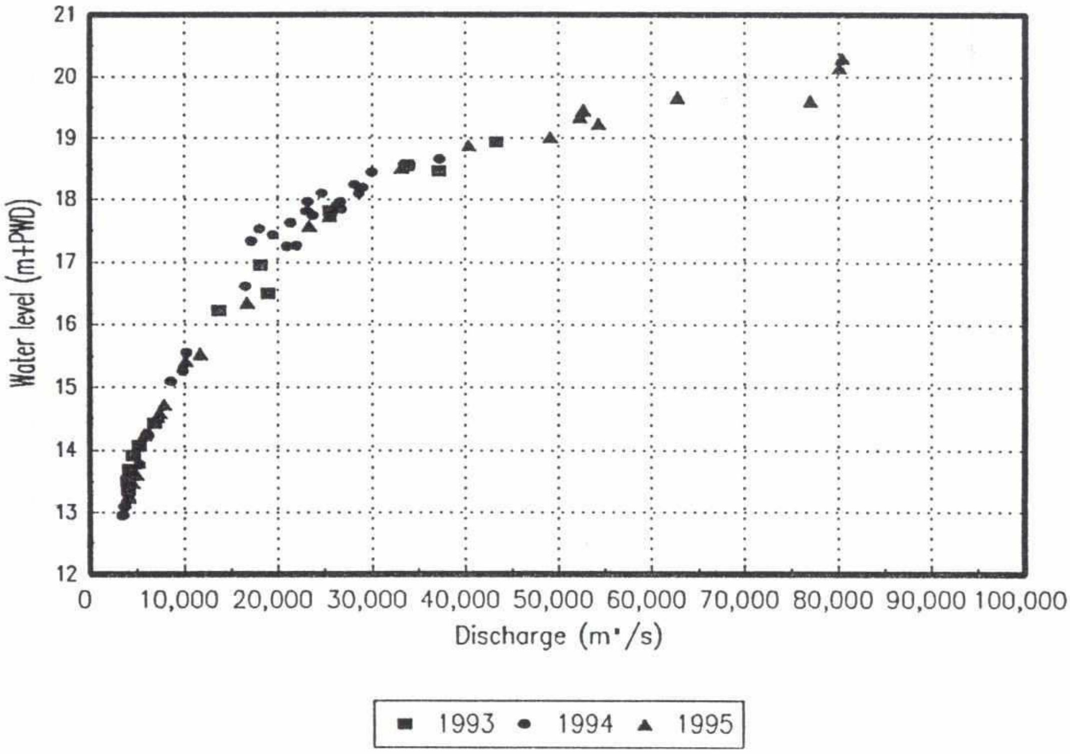


Figure 7.14 Observed discharges and rating curve for the Jamuna at Bahadurabad, RSP data

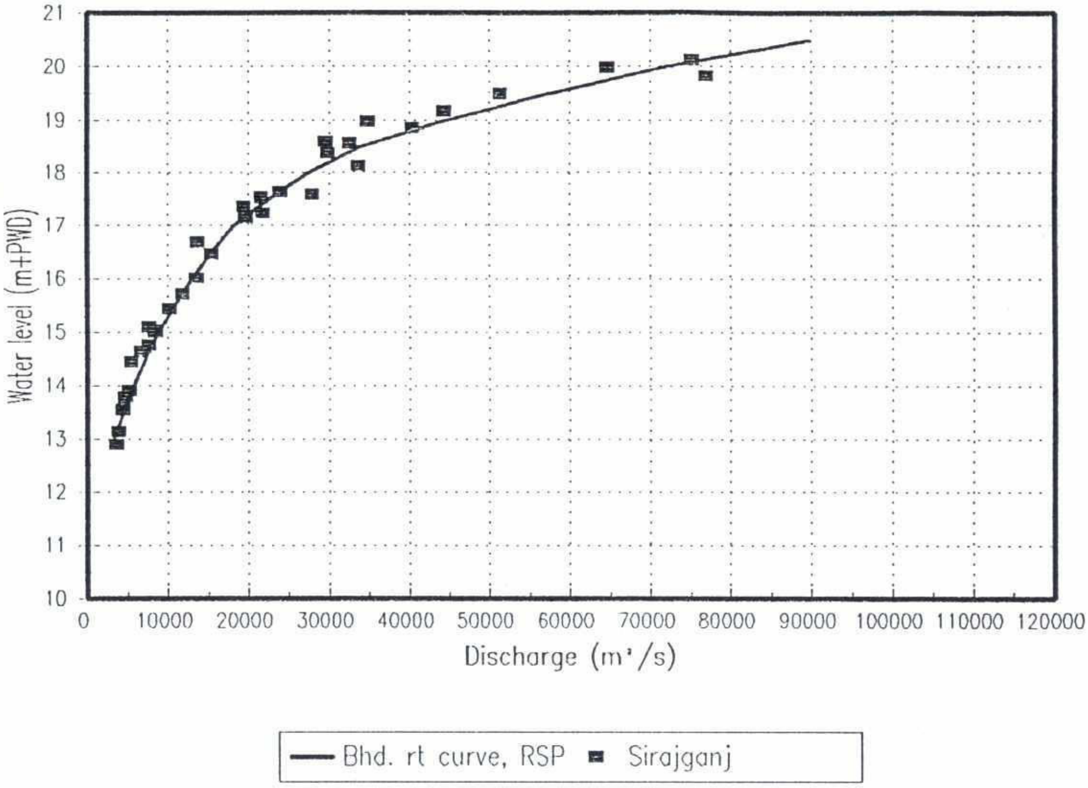


Figure 7.15 Comparison of Sirajganj discharge data with the Bahadurabad rating curve

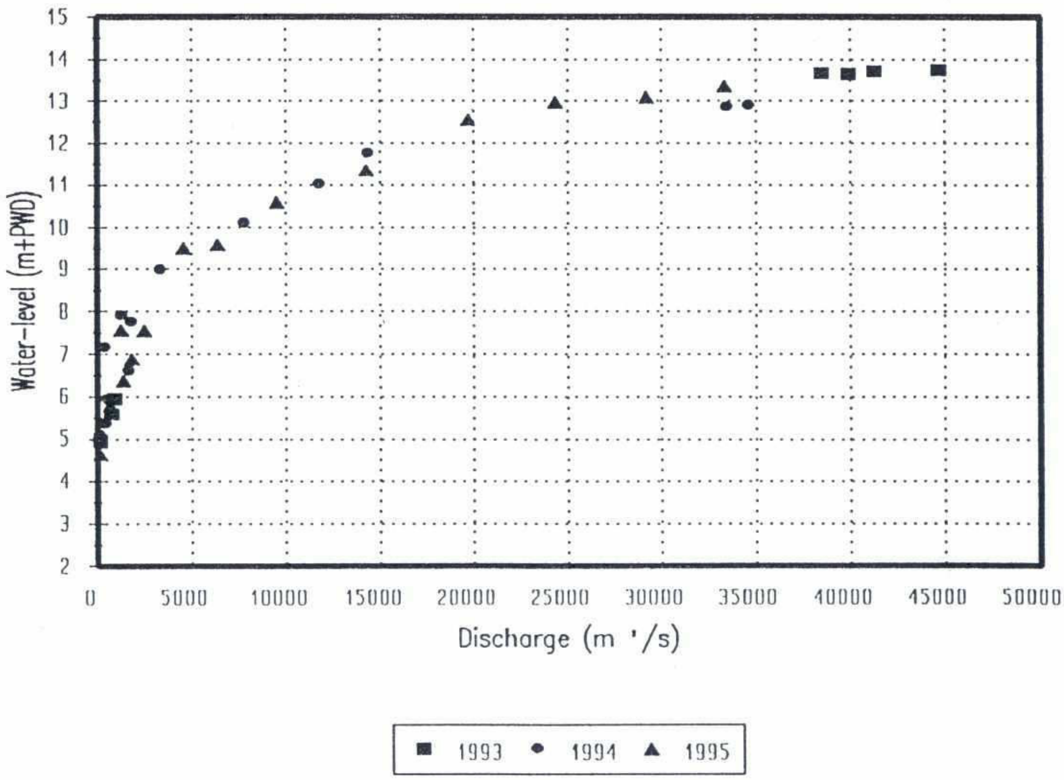


Figure 7.16 Observed discharges and rating curve for the Ganges at Hardinge Bridge, RSP data

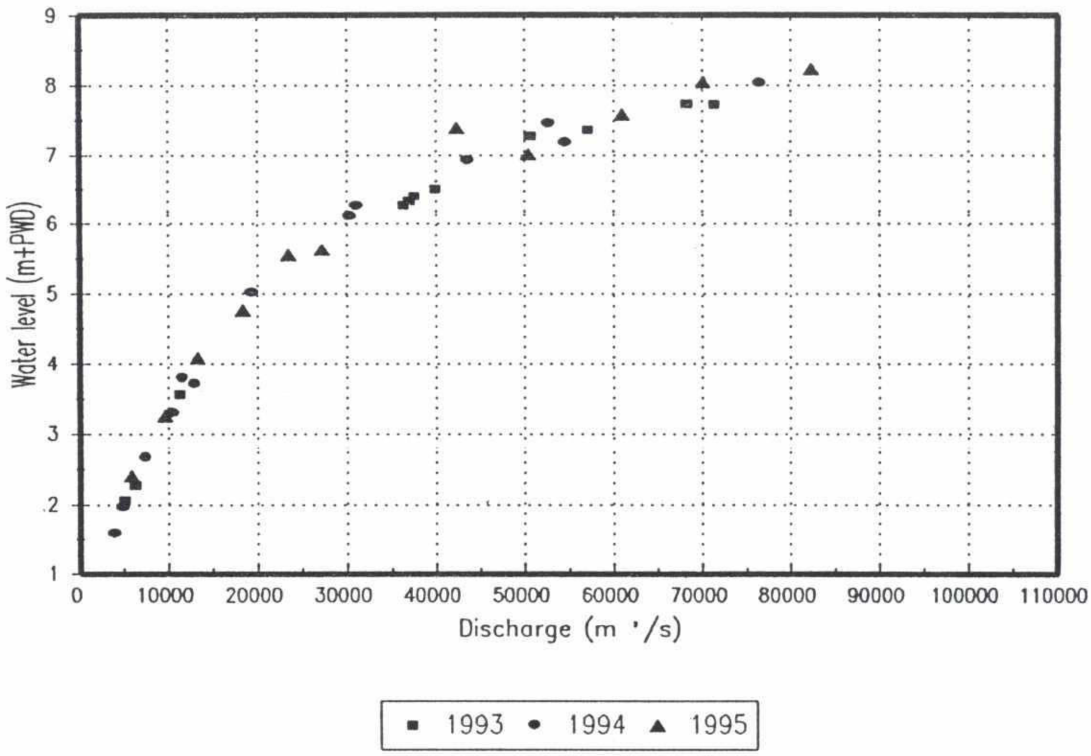


Figure 7.17 Observed discharges and rating curve for the Padma river at Baruria, RSP data

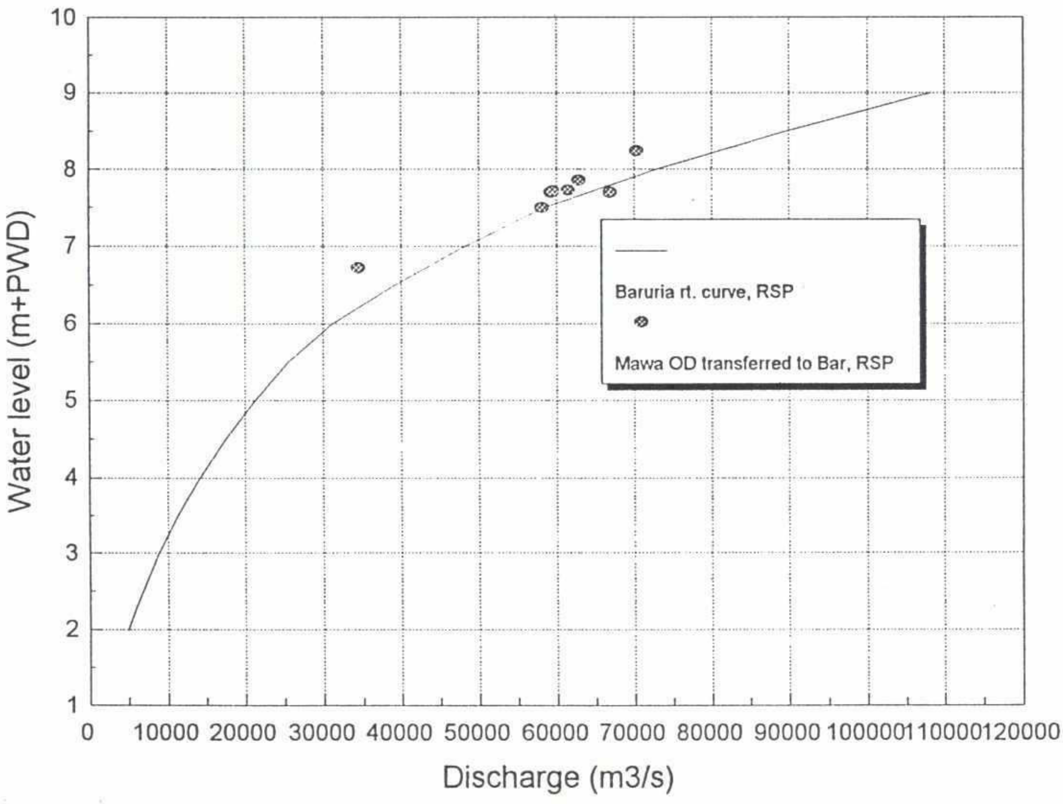


Figure 7.18 Comparison of Mawa discharge data with the Baruria rating curve

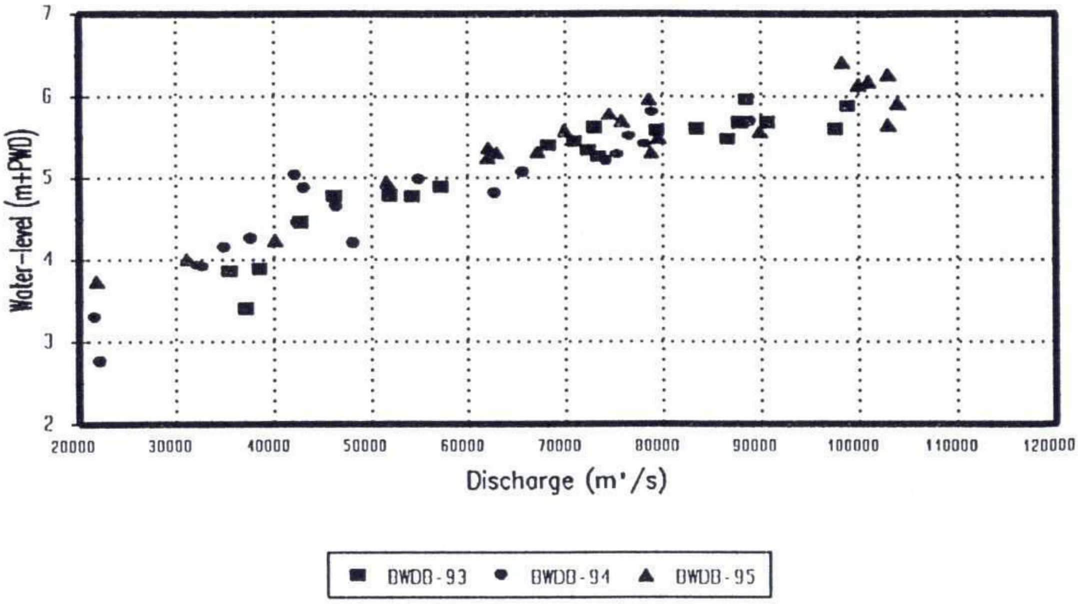


Figure 7.19 Observed discharges for the Padma river at Baruria, BWDB data

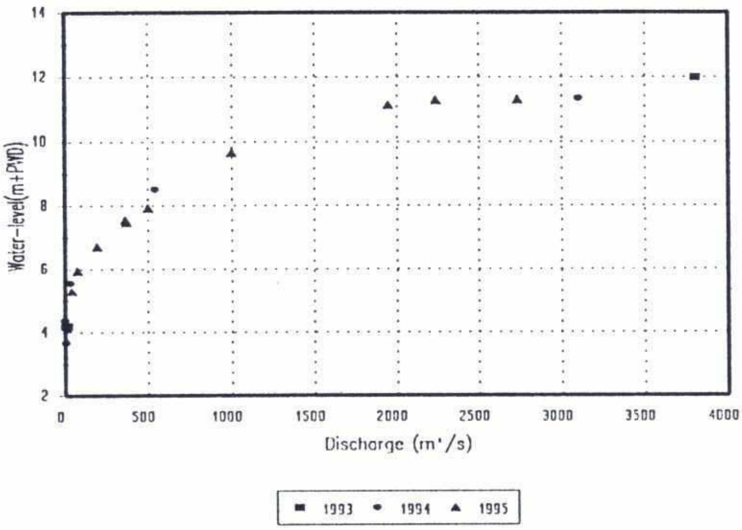


Figure 7.20
Observed discharges and rating curve for the Gorai river at Gorai Railway Bridge, RSP data

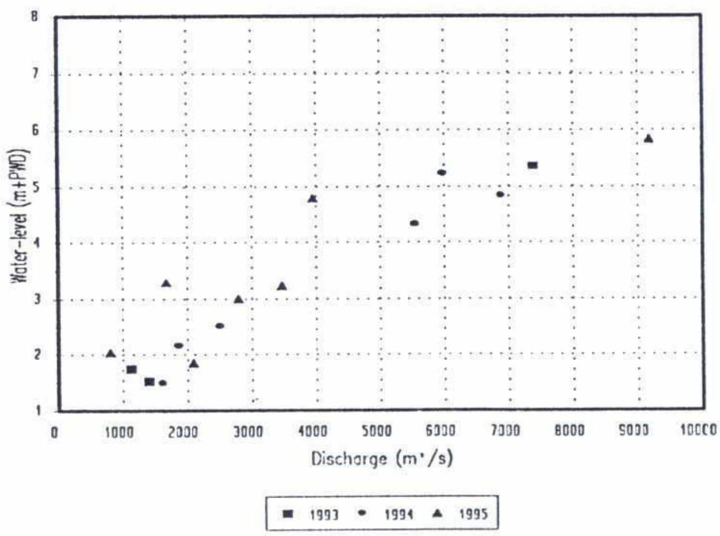


Figure 7.21
Observed discharges for the Meghna river at Bhairab Bazar, RSP data

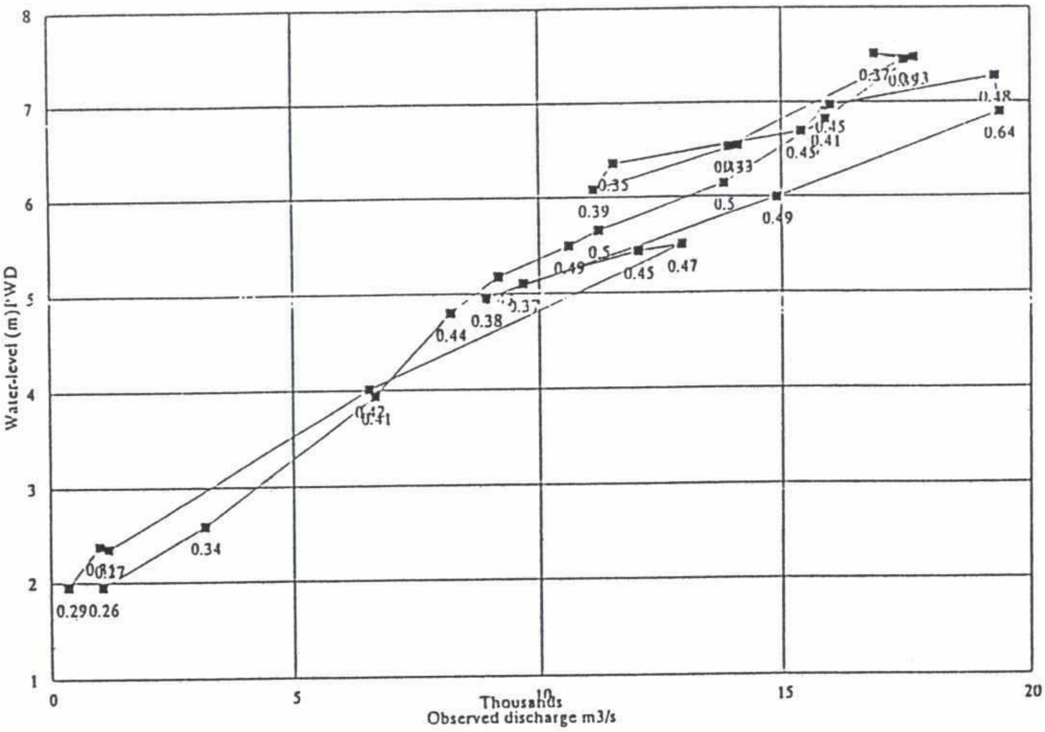


Figure 7.22 Observed discharge as a function of the water level for Bhairab Bazar, 1988, with the fall indicated

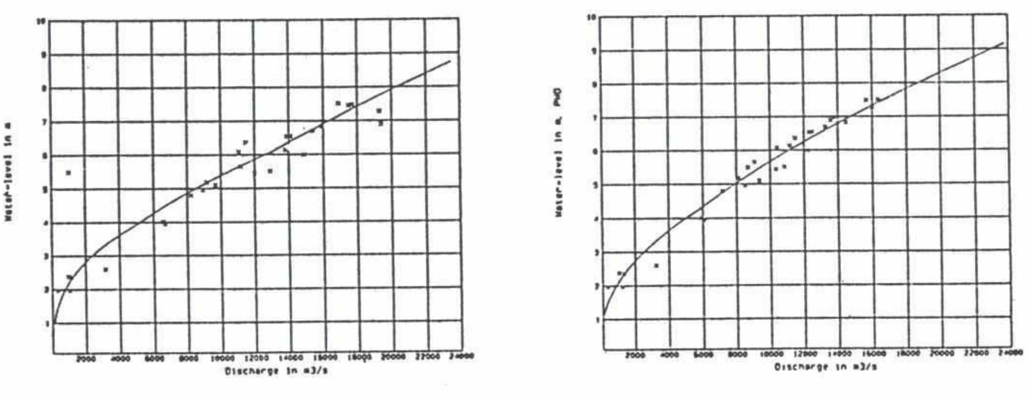


Figure 7.23 1988 rating curves for Bhairab Bazar, (a) without and (b) with correction based on constant fall

7.4.2 Extrapolation of discharge rating curves

The range of observed water levels generally exceeds the range of water levels for which discharge measurements are available. Hence, the stage-discharge relation has often to be extrapolated beyond the measured range. Extensive investigations were carried out by the project to the most adequate extrapolation procedure *(Study Report 4, FAP24, 1996)*.

The following procedures were considered:

1. direct extrapolation of the upper segment of the fitted rating curve,
2. Stevens method,
3. conveyance-slope method,
4. slope-area method of peak discharge determination, and
5. the method based on steady flow formula.

Investigations carried out for the Bahadurabad transect gave best results with the conveyance-slope method. It should be noted that the investigations were carried out with 1994 and 1995 flood data. In 1994 the discharge did not reach extreme high levels, but in 1995 the discharge was the second largest over the last forty years. Furthermore, the analysis was strongly based on the geometry of the transect itself, which is too limited. Nevertheless, the conveyance-slope method is a physically based approach, including parameters which can easily be obtained from field observations.

To design a sound procedure for extrapolation of the stage-discharge relation, it should be kept in mind that the control reach for the water levels gauged at a station for a particular discharge is, in the mildly sloped, rivers in Bangladesh quite substantial (the impact of a disturbance at a distance of $h_eS/2$ away from the station is still 20 to 25% (h_e=equilibrium depth and S is river slope)). Furthermore, the dimensions of the channels in braided rivers like the Jamuna vary considerably from place to place. Hence, concentrating on the dimensions of one single cross-section is an over simplification. Average cross-sectional profiles of the first 20 to 40 km downstream of the station is more appropriate. Once an average cross-sectional profile is established, a horizontal segmentation is applied to differentiate between river and floodplain. For the vegetated floodplain one can assume a constant hydraulic roughness, whereas in the river the hydraulic roughness of the dune-covered bed varies. Based on the assumed floodplain roughness and the water-level slope as a function of stage, the amount of water discharged by the floodplain can be determined. The discharge through the river is then obtained as the difference between the rated discharge and the computed floodplain flow. With Chézy's or Manning's equation, given the river flow, geometry and water-level slope, the development of the hydraulic roughness as a function of stage can be determined. Depending on the development of the dune dimension, estimates can be made about the trend in and value of the roughness in the extrapolated range.
Van Rijn (1987) established the following relation between Nikuradse's equivalent sand-roughness k_N, the characteristic grain size dimension D_{90} and the dune length L and dune height H:

$$k_N = 3D90 + 1.1H(1 - e^{(-25H/L)}) \tag{7.1}$$

The relation between k_N and the Chézy coefficient C is given by Colebrook-White's formula:

$$C = 18\log\left(\frac{12R}{k_N}\right) \qquad (7.2)$$

From equation (7.1) it is observed that there is a physical lower limit to the equivalent sand-roughness: $k_N = 3D_{90}$ in natural conditions. Measurements in natural channels showed a very large variation of k_N between 1 and 10 D_{90} in only ten measurements. In a laboratory an artificial bed of glued grains can be rather smooth without irragularities: $k_N = 2\ D_{50}$. During high stages in the Jamuna River the riverbed can become very smooth with a high sediment transport of silt and fine sand. It is uncertain if under these special circumstances these simple rules for the grain roughness still apply. Hence the upper limit to the Chézy value is given by the grain roughness and the hydraulic radius.

The above procedure has been applied to the Jamuna at Bahadurabad for the 1988 river and flow conditions. The schematized cross-sectional area of the Jamuna is presented in Figure 7.24. It shows an average and a maximum profile to investigate the sensitivity of the results for the assumptions made. In the computations a maximum width of the alluvial river of 4500 m was assumed; the remainder was considered to be vegetated flood plain having a Manning roughness ranging from 0.025 (using the maximum profile) to 0.03 (for the average profile). The resulting Chézy value and Nikuradse's equivalent roughness as a function of stage is shown in the Figures 7.25 and 7.26 respectively. From these figures it is observed that, based on the average profile and the smallest floodplain capacity, at a level of 19.75 m+PWD at Bahadurabad the physical limit of the hydraulic roughness is already reached. Using maximum cross-sectional dimensions and maximum floodplain capacity this level would be reached at a level of 21.20 m+PWD. In 1988 the maximum water level was 20.63 m+PWD, whereas in 1995 the maximum was only a few decimetres lower. This analysis thus shows that under extreme high flow conditions nearly flat bed conditions or dunes with mildly sloped leeward faces (and hence producing no form resistance) are to be expected. It also shows that, because the physical limits of hydraulic roughness are approximately reached, the stage-discharge relation will behave differently in the extrapolated range, see Figure 7.27. Particularly for the design of embankments this phenomenon should be taken into consideration.

With respect to the conditions at Bahadurabad it is further mentioned that due to breaches in the embankments overland flow occurred in the past. Due to this, the water level slope locally increased creating a higher discharge capacity. It should be kept in mind that, if these breaches would not have occurred, the water levels at Bahadurabad could even have been higher during these extreme discharges. Hence, one should be very careful in extrapolating discharge rating curves; all elements determining the stages should be examined thoroughly.

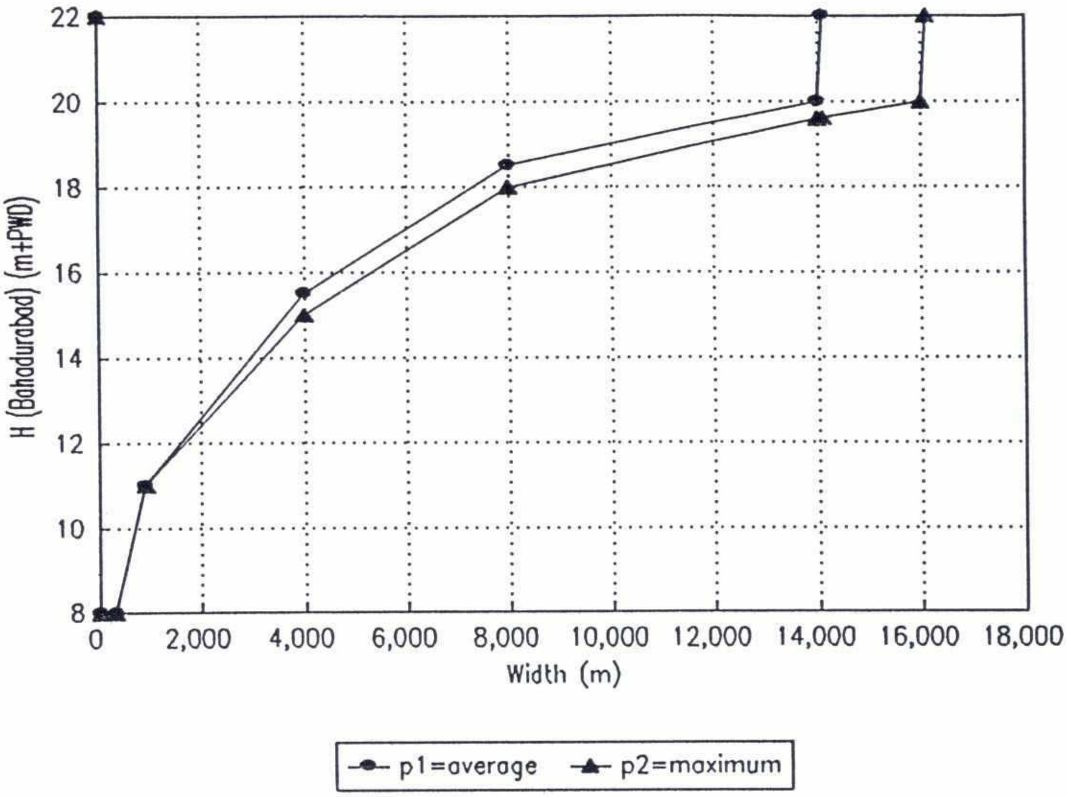


Figure 7.24 Average and maximum cross-section of the Jamuna river downstream of Bahadurabad

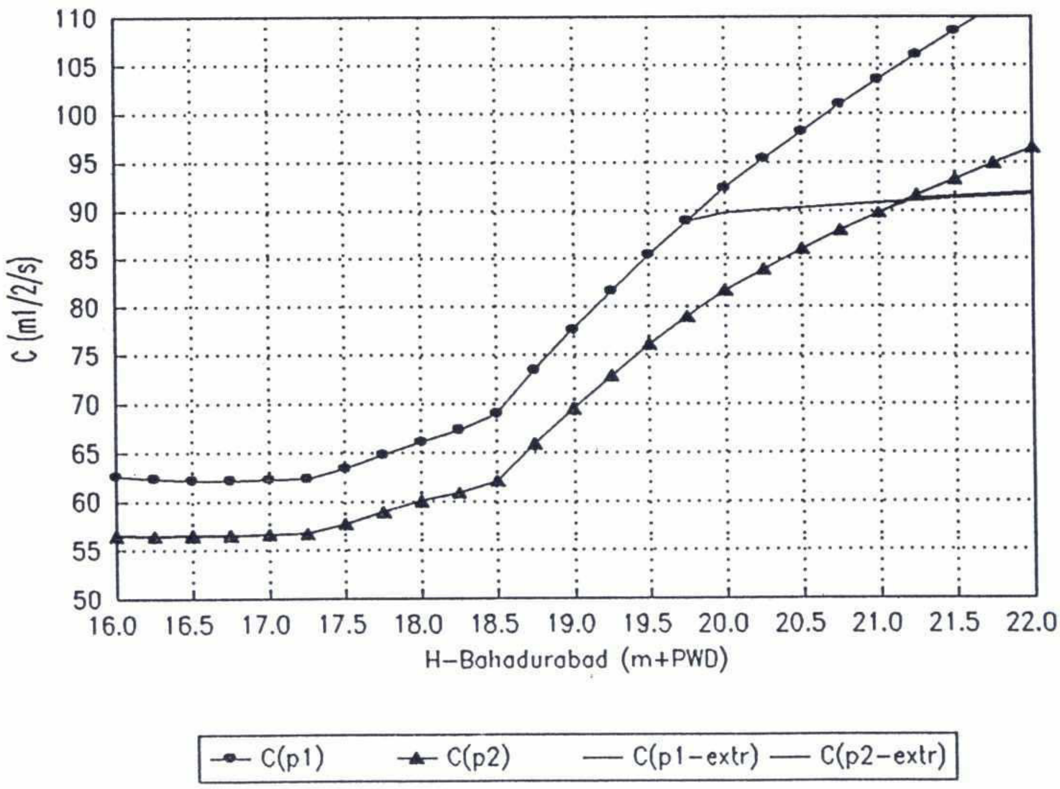


Figure 7.25 Chézy-value of Jamuna riverbed as function of river stage at Bahadurabad

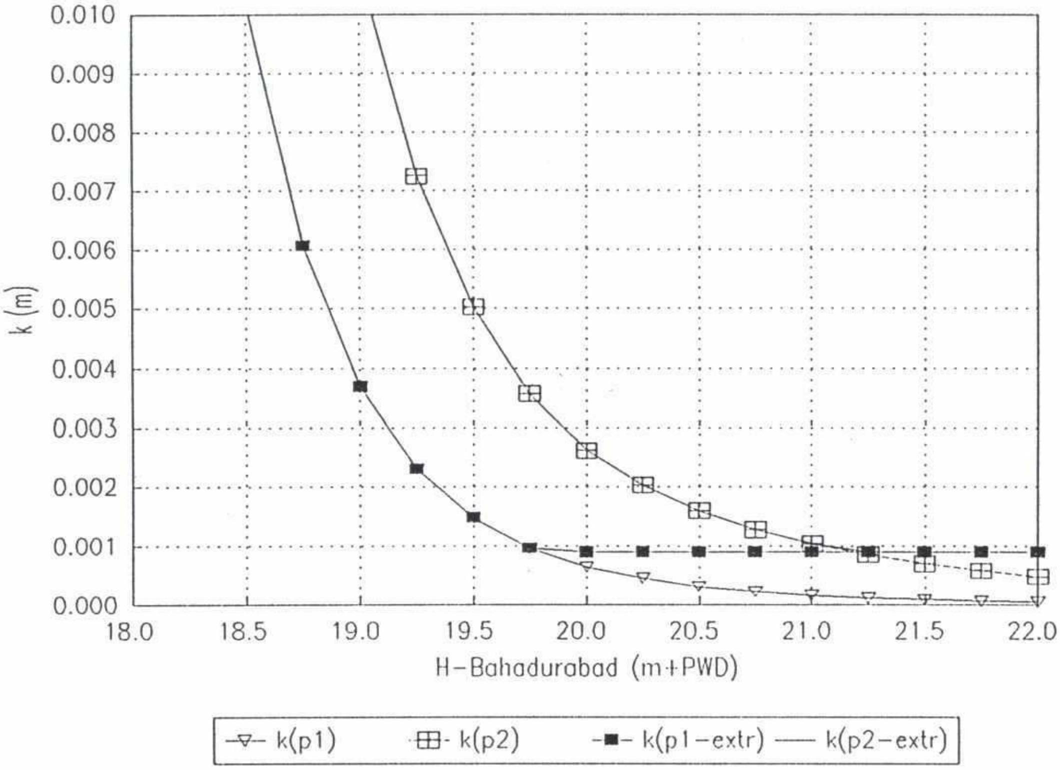


Figure 7.26 Nikuradse equivalent and roughness of the Jamuna riverbed as a function of river stage at Bahadurabad

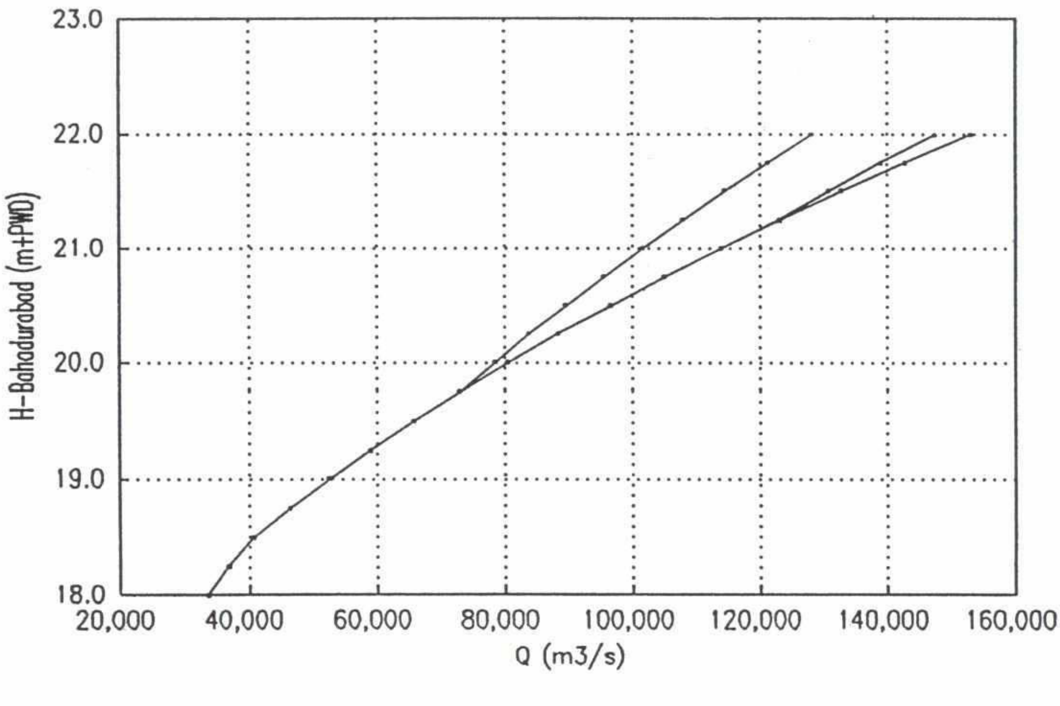


Figure 7.27 Extrapolation of the rating curve of the Jamuna river at Bahadurabad based on average (p1) and maximum (p2) geometric and hydraulic conditions

7.4.3 Accuracy of discharge rating curves

In the previous analysis for the main river stations single discharge rating curves have been fitted to the discharge measurements.

Apart from inaccuracies in the measurements itself and changes in the river geometry and hydraulic roughness, scatter in the stage-discharge plots may be due to:

1. unsteady flow effects, and
2. backwater effects.

Flashy floods in flat rivers can produce considerable scatter in the stage-discharge plot. The size of the unsteady flow effect can be estimated with Jones' formula:

$$Q_{unsteady} \approx Q_{steady} \sqrt{1 + \frac{1}{Sc}\frac{\partial h}{\partial t}} \qquad (7.3)$$

where: S = slope of the riverbed
c = flood-wave celerity

The rate of change of the water level in one day at Bahadurabad is at maximum 0.8 m. Assuming a wave celerity of 3 m/s and a river slope of 7.6 cm per km, the maximum deviation from a single rating curve is 2%. So, unsteady flow effects do not contribute to the scatter observed in the stage-discharge plots for the main rivers in Bangladesh.

As discussed in Sub-section 7.4.1 at some stations (Hardinge Bridge, Bhairab Bazar) back-water is to some extent responsible for the sometimes large scatter in the stage-discharge plots. By applying fall corrections improvements can be achieved. Sofar, no corrections for backwater have been implemented.

The standard error s_e in the stage-discharge relations, as presented in the Tables 6.1 to 6.5 is computed from:

$$s_e^2 = \frac{\sum(\Delta Q_i - \overline{\Delta Q})^2}{N-2}$$

$$where:\ \Delta Q_i = \frac{Q_i - Q_c}{Q_c}.\,100\% \qquad (7.4)$$

with: ΔQ_i = percentage difference
Q_i = measured discharge
Q_c = computed discharge
N = number of observations

The standard errors in the fit of the rating curves based on BWDB measurements for the various sites are summarized in Table 7.3. From the Table it is observed that substantial noise is present in the curves for Mawa and Gorai Railway Bridge and, to a lesser extent, also in the curves for Hardinge Bridge. As stated in Sub-section 7.4.1 the continuation of the measurements at Mawa should be re-examined as with the scatter observed, its contribution to the information about the Padma river discharge already received through Baruria is almost nil. Special attention should be given to the measurements at Gorai Railway Bridge. Not only is the scatter in a particular year considerable, but also the changes in the relation from one year to another is large, a characteristic not included in the standard error as presented in Table 7.3. For the latter reference is made to the next sub-section.

Station	average s_e	stdv s_e
Bahadurabad	7.86	2.59
Hardinge Bridge	9.00	2.30
Baruria	6.99	1.49
Mawa	12.70	2.90
Gorai Railway Bridge	12.13	3.60

Table 7.3 Average and standard deviation of the standard error in the discharge rating curves based on BWDB discharge data

7.4.4 Trend analysis of stage-discharge relations

A simple but illustrative way to present the shift of the annual rating curves, is to plot the time series of water levels derived from the annual rating curves for selected fixed discharges (Specific Gauge Analysis). This procedure was applied to the rating curves derived from the BWDB discharge measurements. The time series plots are shown in Figures 7.28 to 7.32. For each selected discharge a trend line through the corresponding water levels have also been estimated by simple linear regression.

Bahadurabad

The results for Bahadurabad in Figure 7.28 show insignificant trends for the period of record, which indicates that the Jamuna River appears to be in dynamic equilibrium.

However, the changes from year to year are considerable, up to a maximum of about 0.5 meters. According to BRTS, (BRTS, Dec. 1991) stage changes like this are characteristic for a large, braided river with a highly mobile bed. The passage of macro-scale bed forms such as sand waves, and the shifting of braid bars and chars can radically alter the resistance characteristics and water surface topography, so altering the stage-discharge relationship. The degree of variability observed in the rating curves is, therefore, to be expected. The results obtained by the RSP do show a more moderate picture of changes: in the period 1993-1995 no shifts in the stage-discharge relation were apparent. It is therefore likely that the variation to some extent has no physical background but a measurement inaccuracy one.

Note that for the period 1988-1992 the same rating equation have been used, due to inconsistencies in the data for the period August 1988-March 1993.

Hardinge Bridge

Figure 7.29 shows no trends in the water levels for low and medium flows, but a slightly decreasing trend for high flow conditions. It might be an effect of local morphological changes at or downstream of, the bridge itself. The maximum change from year to year is also in this case about 0.5 meters.

Baruria

Figure 7.30 shows insignificant trends in the development of the stages for a particular discharge. This indicates that Padma River is in dynamic equilibrium as well. The maximum change from year to year is about 0.5 meters.

Mawa

Figure 7.31 shows no clear consistent trends at Mawa. The variations from year to year are in some cases very high, about 0.75 m, e.g. from 1978 to 1979 and from 1987 to 1988. This is probably due to uncertain rating curves/discharge measurements during years with high flows.

Gorai Railway Bridge

For this station the trends are very different from the trends in the major rivers. The pronounced increasing trends in the water levels for all discharge conditions, see Figure 7.32, indicate that the Gorai river is aggredating due to deposition of sediments. The effect on the water levels of such an aggredation is, as expected, highest for low-flow conditions. Then the flow is confined to the deeper parts of cross-sections, where the sediments will be deposited first.

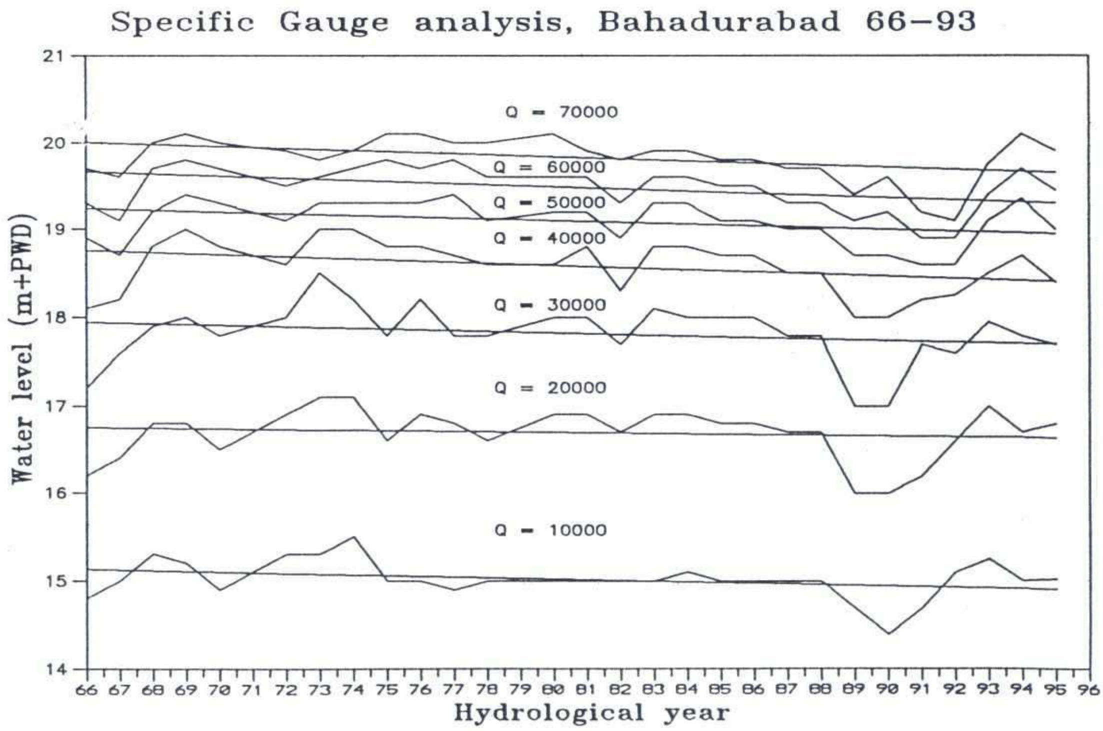


Figure 7.28

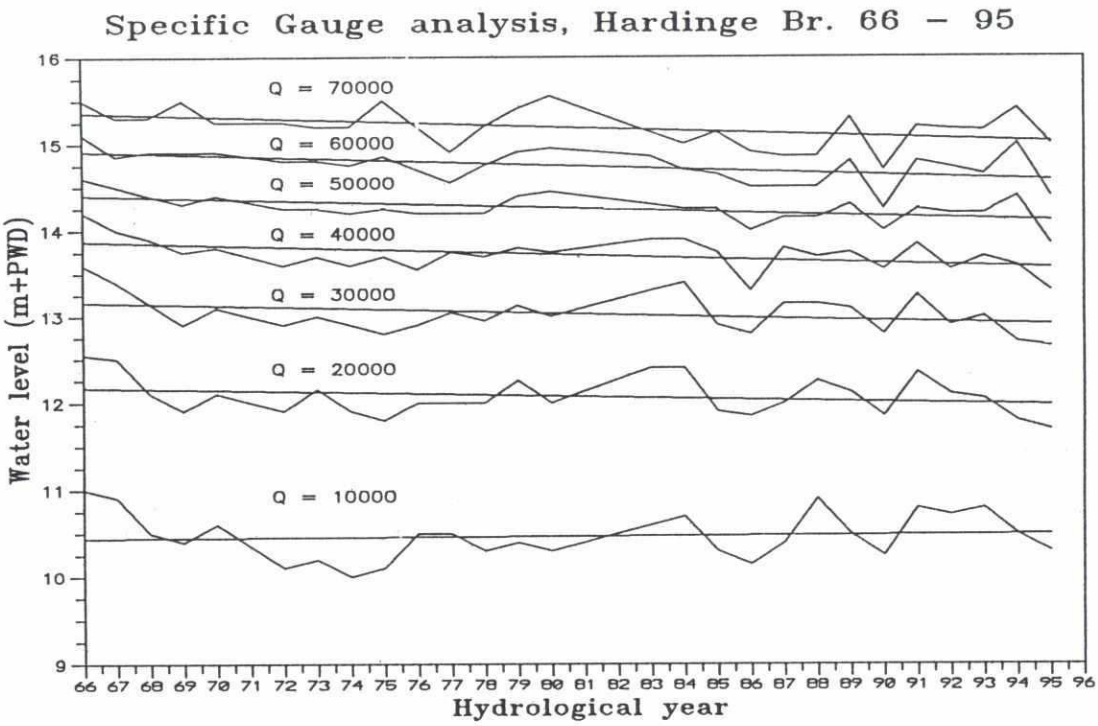


Figure 7.29

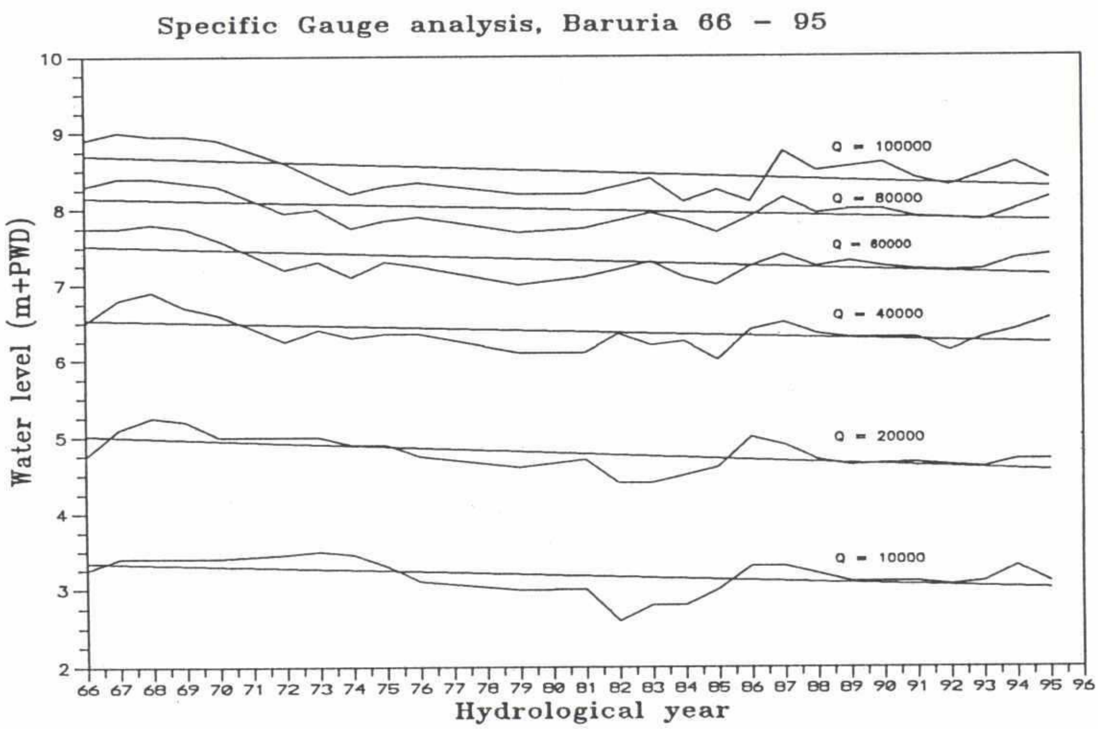


Figure 7.30

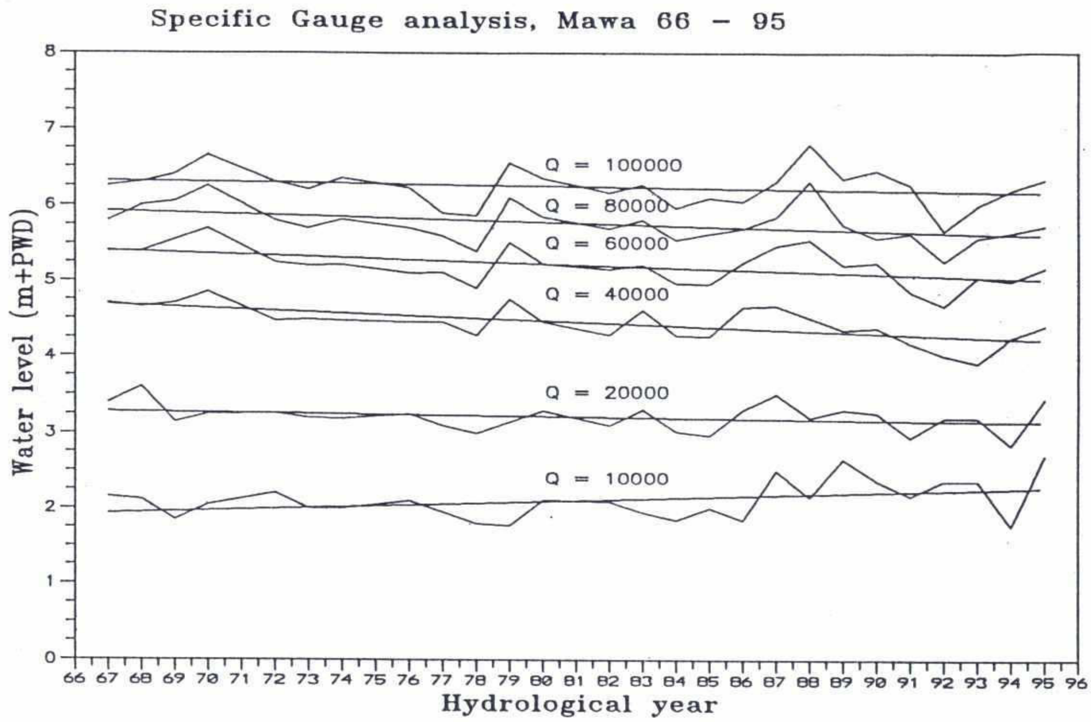


Figure 7.31

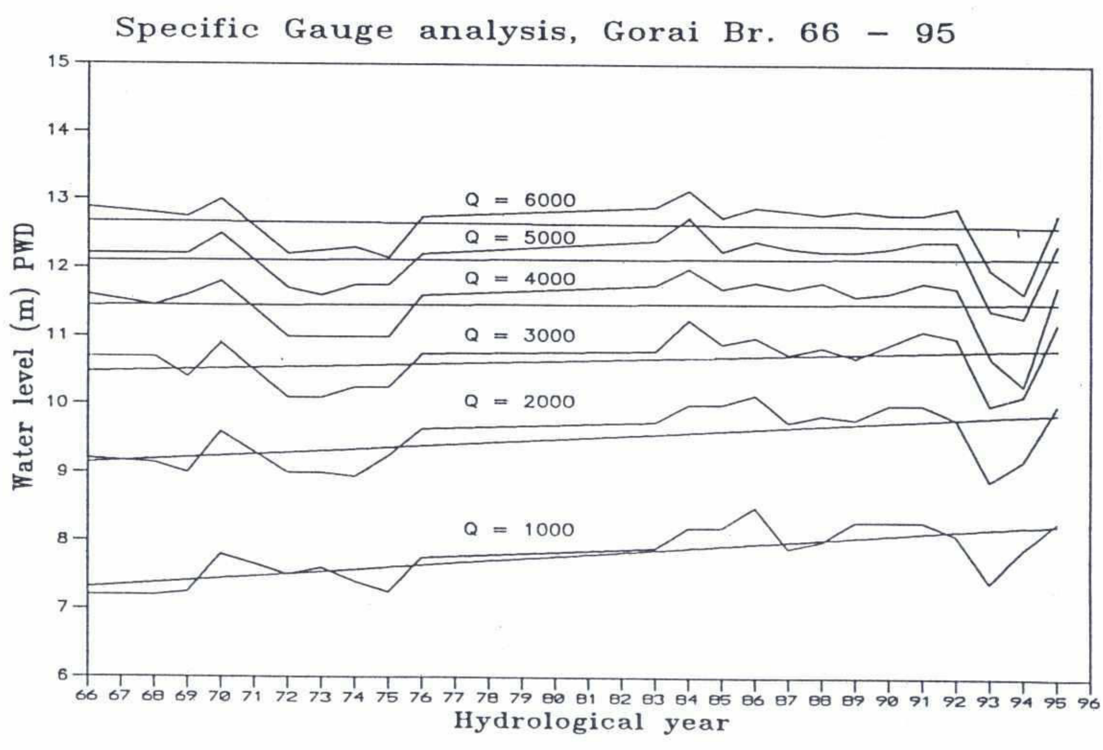


Figure 7.32

7.4.5 Comparison of BWDB and RSP discharge rating curves

The stage-discharge data measured by BWDB and the rating curves have been compared with the discharge rating equations derived from RSP measurements. The results are shown in the Figures 7.33 to 7.36 and includes year-by-year comparison of BWDB data with the RSP curve as well as the percentage difference in the computed discharges according to the annual rating curve derived from BWDB data and the RSP curve as a function of river stage. The results show that in all cases the BWDB data lead to higher discharges.

Bahadurabad

Figure 7.33 shows that the 1993 BWDB-curve approaches best the RSP Bahadurabad rating, with differences of the order of 10%. The deviation for the remaining years range between 10 and 25% on average.

Hardinge Bridge

Large deviations are shown in Figure 7.34 between the two rating curves, particularly for the low flow stages. For the higher flows the resemblance is much better.

Baruria

Best resemblance between the BWDB and RSP ratings is obtained for Station Baruria. Here the differences are generally less than 15% and for most water-level reaches less than 10%.

Mawa

Since for Mawa no rating curve was established for RSP data, here only the actual measurements have been compared. The location of the RSP measurements in the plot presented in Figure 7.36 is conformable to the trend observed for the other stations: the RSP discharges are less than the BWDB data. From the plot the great scatter in the Mawa data becomes apparent.

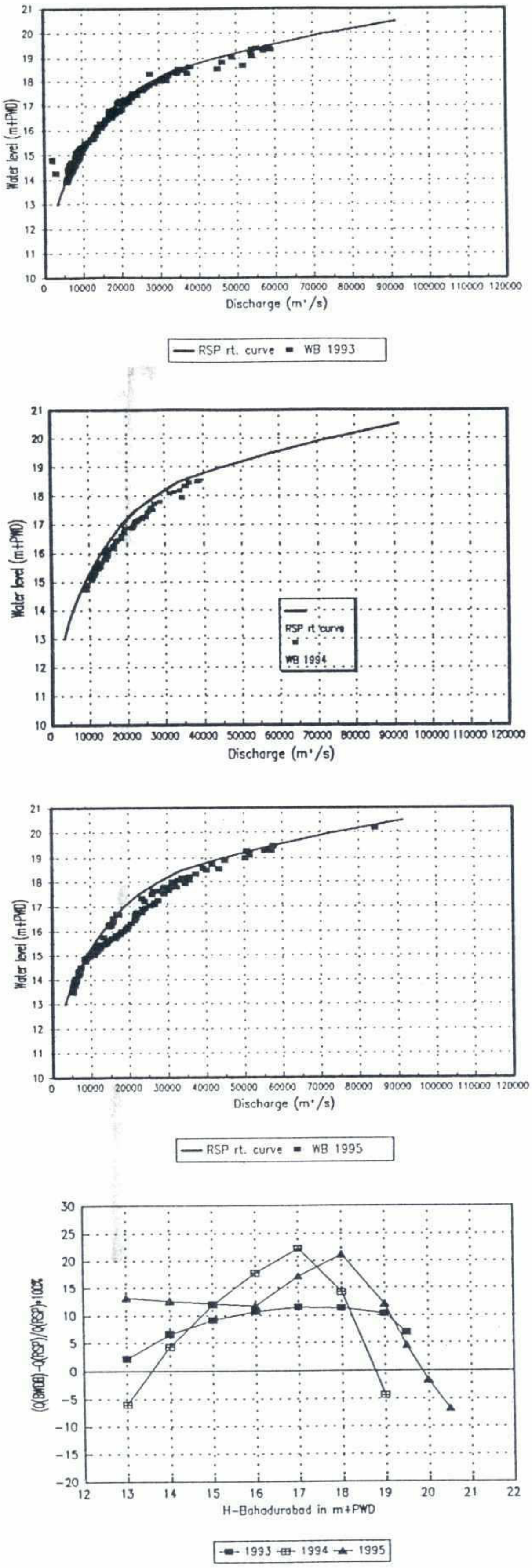


Figure 7.33
Comparison of BWDB discharge data and rating curves with FAP24 rating curve for the Jamuna river at Bahadurabad

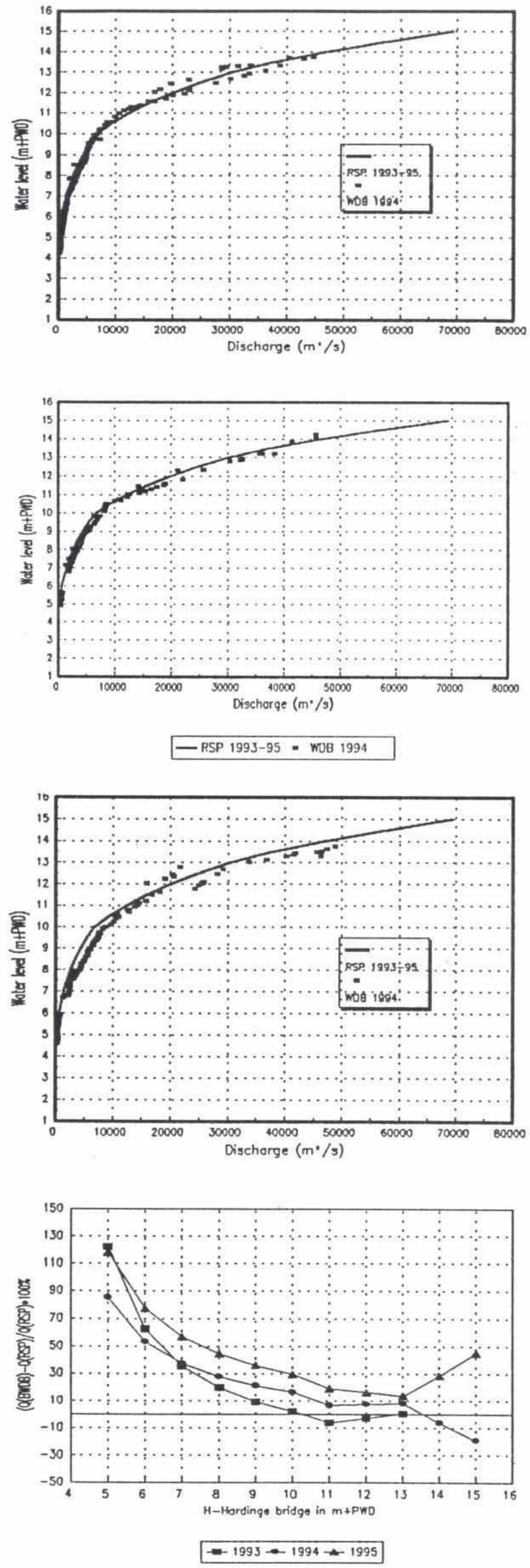


Figure 7.34

Comparison of BWDB discharge data and rating curves with FAP24 rating curve for the Ganges river at Hardinge Bridge

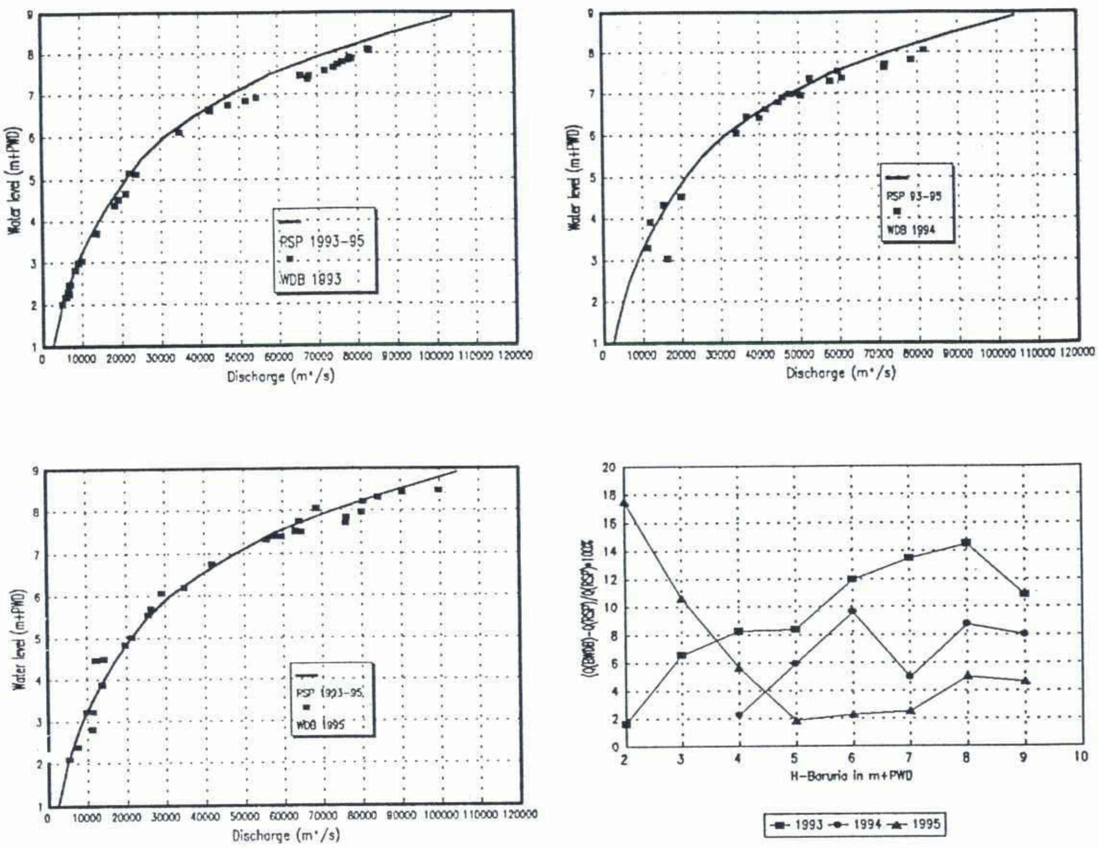


Figure 7.35 Comparison of BWDB discharge data and rating curves with FAP24 rating curve for the Padma river at Baruria

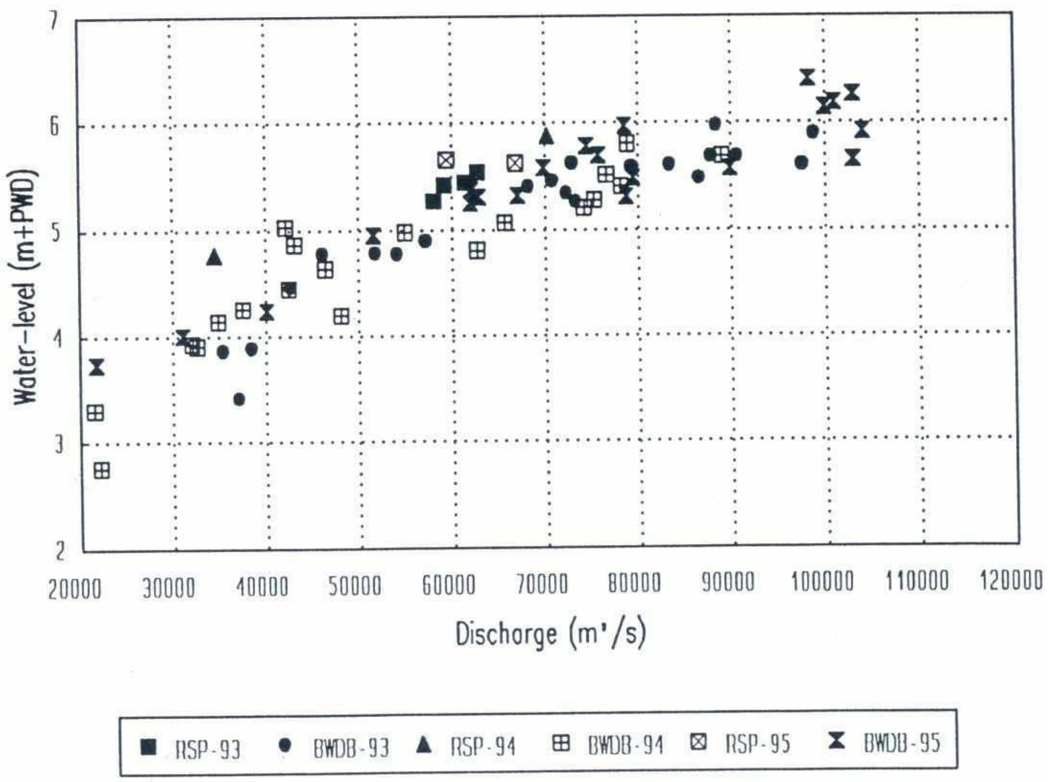


Figure 7.36 Comparison of BWDB discharge data with FAP24 data for the Padma river at Mawa

7.5 Discharges

7.5.1 Water balances

To investigate the consistency of the discharge series water balances of monthly flow data were considered. In Figures 7.37 to 7.39 the observed discharge at Bahadurabad is compared with the computed discharge at Bahadurabad relative to the discharge at Baruria. The computed discharge at Bahadurabad is derived from:

$$Q\ (Bahadurabad) = Q\ (Baruria) - [Q\ (Hardinge\,Bridge) - Q\ (Gorai)] \quad (7.5)$$

In this equation it is assumed that the discharges in the rivers are below the bankfull discharge. If, during flood, the discharge exceeds the bankfull discharge then the overland flow can be added as a separate term in that equation. The results from the original BWDB discharge series is shown in Figure 7.37. The Figure shows two periods with clear inconsistencies: 1966-1971 and September 1988-1992. The first inconsistency is due to the discharge series of Baruria as mentioned in the Hydrological Study Phase 1 (FAP24, June 1993). For that period in the Baruria discharge measurements a bypass was not included in the measurements leading to too-low discharges at Baruria. The second period results from overestimation of the discharge at Bahadurabad. If corrections are made for this by applying the discharge rating curve of 1988, based on stage-discharge data from April up to and inclusive August 1988), is applied for the period September 1988-1992 a consistent result with the flows on Ganges and Padma rivers is found, see Figure 7.38. The differences in the observed and computed flows for the remainder of the series shows a random character with deviation ranging, generally, between +15 and -15% of the discharge at Baruria.

A similar analysis on the discharge series, based on the same BWDB stage-discharge data but fitted by the procedure developed by the RSP, is presented in Figure 7.38. Apart from the inconsistency caused by the underestimation of the discharge at Baruria in the period up to 1971, this series shows no consistent deviations.

Finally, in Figure 7.39 the same balance is shown for the discharge series derived from the stage discharge data measured by the RSP, using one single relation for the full period of record. It is observed that the differences are generally well within 10%. For comparisons reasons also the differences resulting from the RSP discharge rating procedure applied to BWDB measurements is shown. Both series are seen to bahave equally well. Note, however, that the latter is derived from annual rating curves instead of one as in the case of the RSP series. From the above it can be concluded:

1. The discharges in the BWDB series for Bahadurabad from September 1988 to March 1993 are inconsistent with the flows on observed flows on Ganges and Padma rivers. The discharges for this period are too high.
2. The discharge series produced by the RSP based on BWDB stage-discharge data are consistent, with the exception of the series for Baruria prior to 1971. This period in the series of Baruria should therefore be disregarded.
3. The discharges series derived from the RSP discharge measurements using one single rating curve for the period 1993-1995 balance equally well as the series derived from the annually adjusted discharge rating curves using BWDB stage-discharge measurements. This supports the reliability of the RSP stage-discharge measurements and indicates that part of the variation in the historical stage-discharge relations is due to inaccuracies in the discharge measuring procedure as applied by the BWDB.

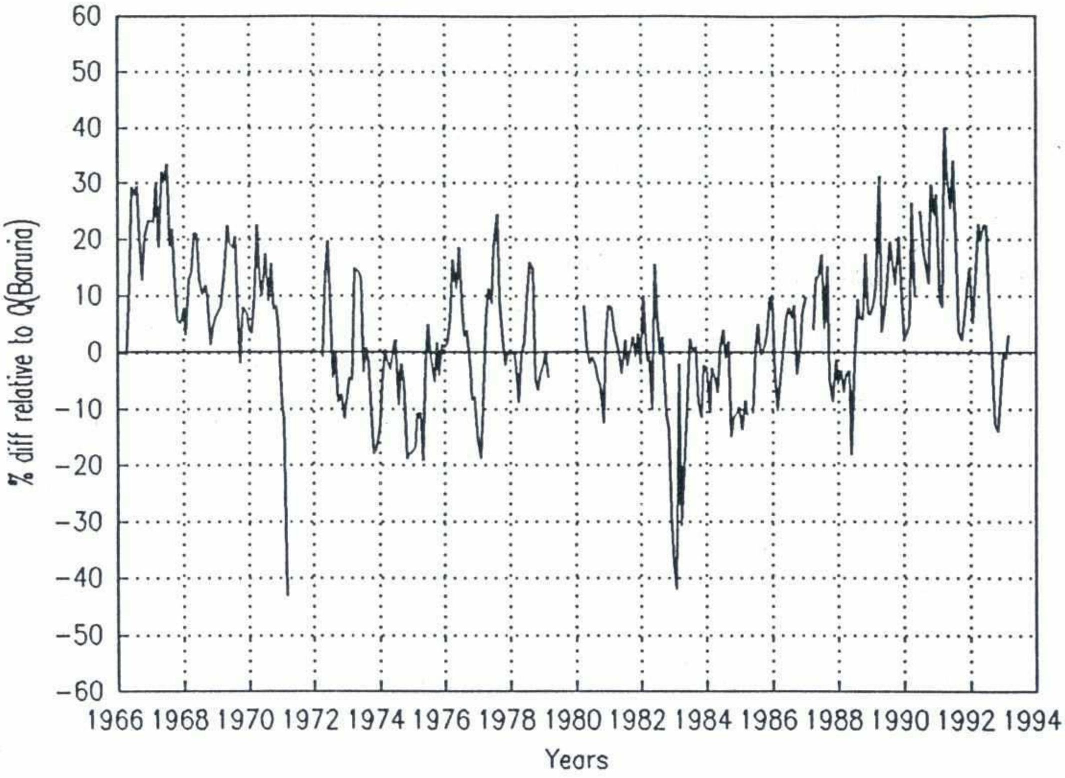


Figure 7.37 Difference of observed and computed monthly flows at Bahadurabad as a percentage of the observed discharge at Baruria based on BWDB discharge series

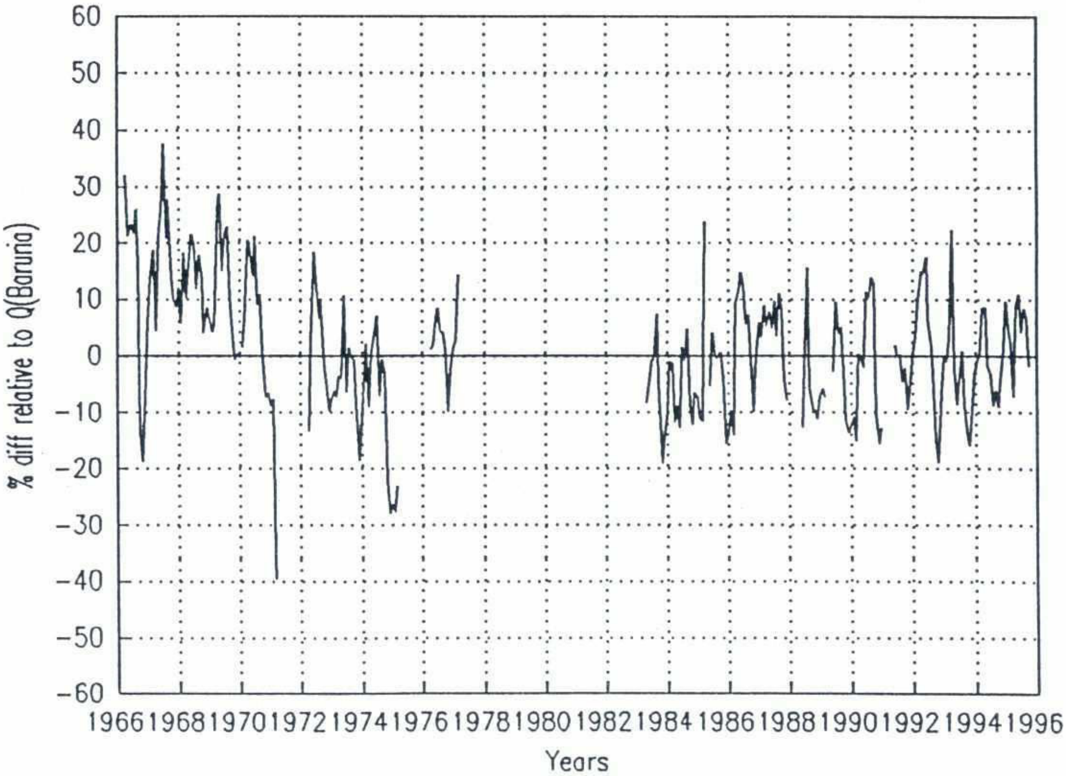


Figure 7.38 Difference of observed and computed monthly flows at Bahadurabad as a percentage of the observed discharge at Baruria based on RSP rating curves

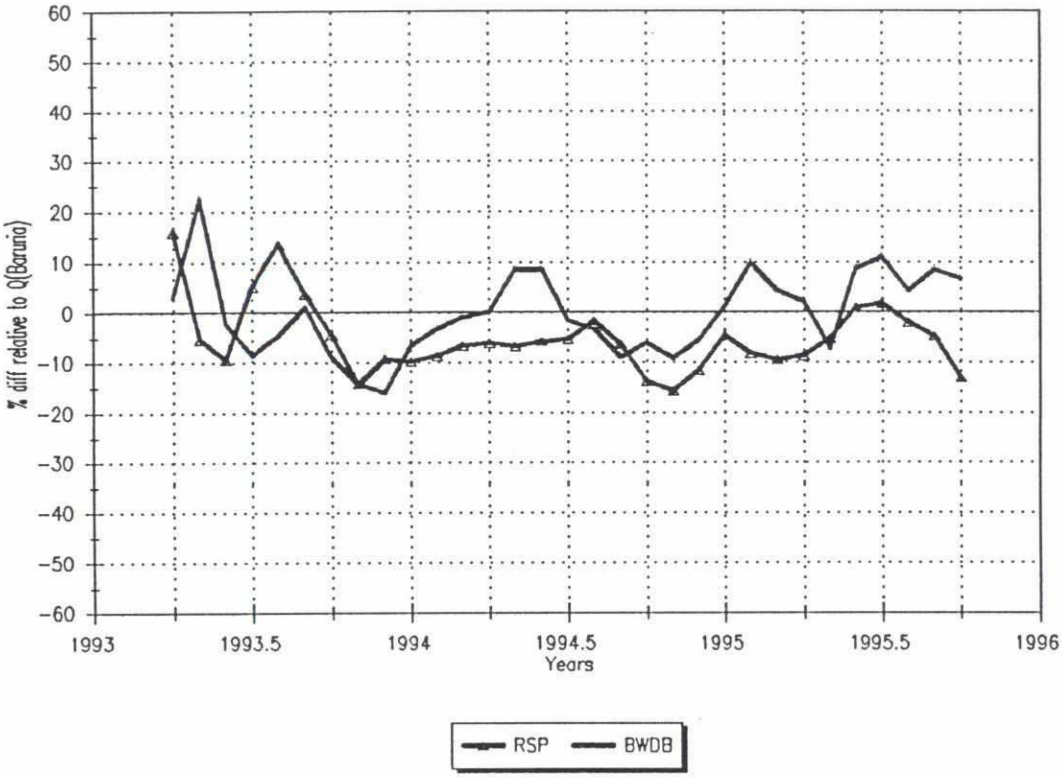


Figure 7.39 Comparison between difference of observed and computed monthly flows at Bahadurabad as a percentage of the observed discharge at Baruria based on RSP rating curves derived from BWDB stage-discharge data (BWDB) and RSP stage-discharge data (FAP24)

7.5.2 Overland flow

The bankfull discharge of the Jamuna varies between 44,000 and 48,000 m^3/s (see *Study Report 6, FAP24, 1995)*. Beyond that discharge, at a number of locations water spills to the plains particularly along the left bank of the river. Part of the spill does not return to the Jamuna and is conveyed to the Upper Meghna via the Old Brahmaputra and Dhaleswari rivers and adjacent planes. The volume of overland flow downstream of Bahadurabad can in principle be determined from the difference between the discharges at Bahadurabad and Baruria on Padma, corrected for the net inflow from the Ganges *(Q (Hardinge Bridge) - Q (Gorai)*. Corrections are further required for inflow from the Atrai river and outflow through the Dhaleswari. Assuming that the latter flows balance, the overland flow during the flood peak of July 1995 downstream of Bahadurabad amounted to 6250 m^3/s. This value, however, is less than 9% of the discharge at Bahadurabad during the flood. Consequently, its standard error is extremely large (130%). Hence, from water-balance computations including main river stations, no reliable estimate can be obtained for overland flow. The only way out is to measure the overland flow proper, as was carried out for the Jamuna river near Bahadurabad, *(see Study Report 15, FAP24, May 1996)*.

8 Station statistics

8.1 General

The updated historical water-level and discharge series were subjected to statistical analysis. In this chapter the statistics are presented in graphical and tabular form for the stations on the main rivers, Bahadurabad, Hardinge Bridge, Baruria, Mawa and Gorai Railway Bridge. Comparisons are presented of the annual extreme water levels and discharges between those derived from the FAP24 (RSP) series with those derived by FAP25. The latter are based on data up to 1989, whereas the FAP24 series ends in 1995.

8.2 Statistics used

The following statistics have been considered:

- annual mean, maximum and minimum water levels
- annual mean, maximum and minimum discharges
- statistics of annual maximum water levels
- statistics of annual maximum discharges
- frequency and duration curves of daily water levels
- frequency and duration curves of daily discharges

Frequency analysis requires homogeneous data. All series have been checked on possible trends.

Analysis of extremes revealed that all annual maximum water-levels and discharges fitted well to the log-normal three-parameter distribution. It appeared that the Extreme Value Type I or Gumbel distribution, advocated by FAP25 for annual extreme discharge, fitted poorly to the data.

A convenient way of showing the variation of the water levels and discharges throughout the year for a given station, is by means of frequency curves where each frequency curve indicates the magnitude of the water-level/discharge for a selected specific probability of non-exceedance. In all cases the 90%, 50% and the 10% probabilities were selected together with the maximum and minimum values in the years considered. The frequency curves presented are based directly on the corrected and updated mean daily time series for all the years available, i.e. using a time-step of one day. The corresponding average duration curve gives the average number of days that a given value was not exceeded in the years considered.

The results of the analyses are presented in the following section.

8.3 Summary of station statistics

8.3.1 Jamuna river at Bahadurabad

The annual minimum, mean and maximum water-level and discharge time series are presented in Figures 8.1 and 8.2. Figure 8.1 shows a slightly upward trend for the minimum water levels while the maximum water levels decline somewhat. Both trends are, however, insignificant and the series allow for subjection to frequency analysis. The annual minimum, mean and maximum discharges series show no trend.

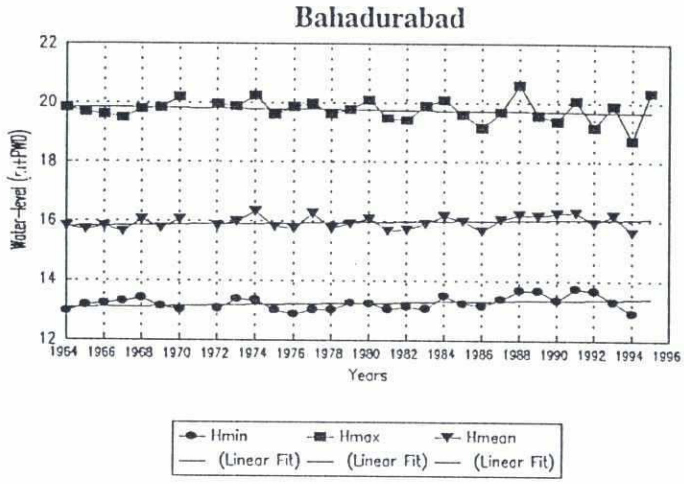


Figure 8.1
Annual minimum, mean and maximum water levels at Bahadurabad

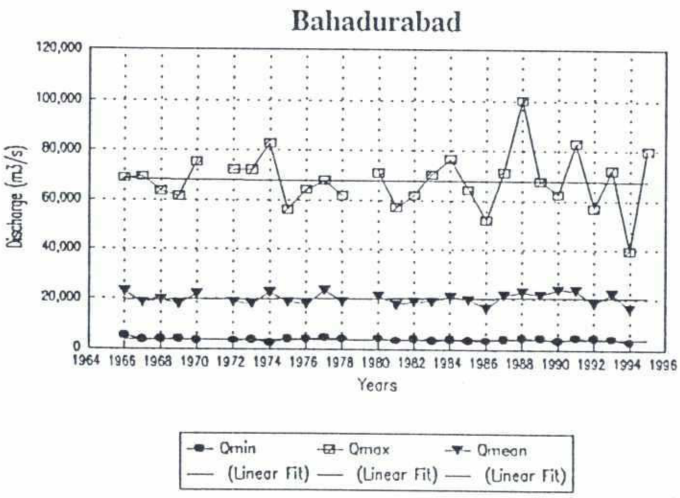


Figure 8.2
Annual minimum, mean and maximum discharges at Bahadurabad

The fit of the three-parameter log-normal distribution to the observed frequency distribution is shown in Figures 8.3 and 8.4. A proper fit is observed in both figures. The extreme water levels and discharges for selected return periods are presented in Tables 8.1 and 8.2. For reasons of comparison also the results earlier obtained by FAP25 are presented in these Tables. The difference between the two estimates for the extreme water levels is within a few centimetres. However, the extreme discharges do differ considerably, mainly due the application of different types of frequency distributions (log-normal – this study – versus Gumbel distribution (FAP25)).

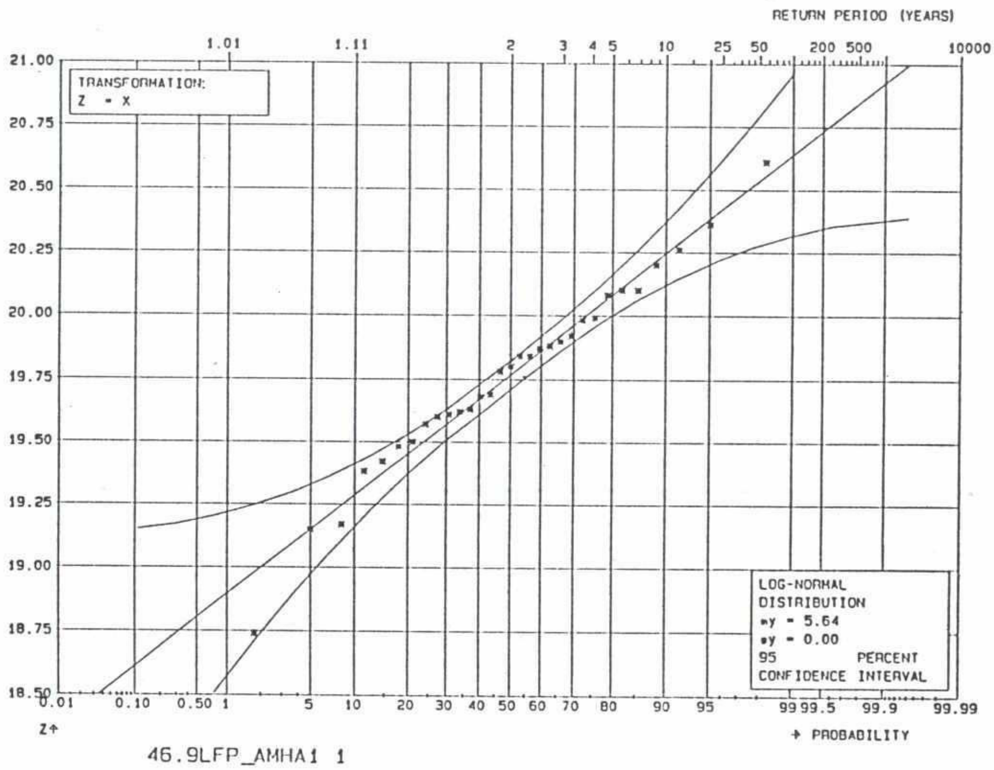


Figure 8.3 Fit of log-normal distribution to annual maximum water levels at Bahadurabad

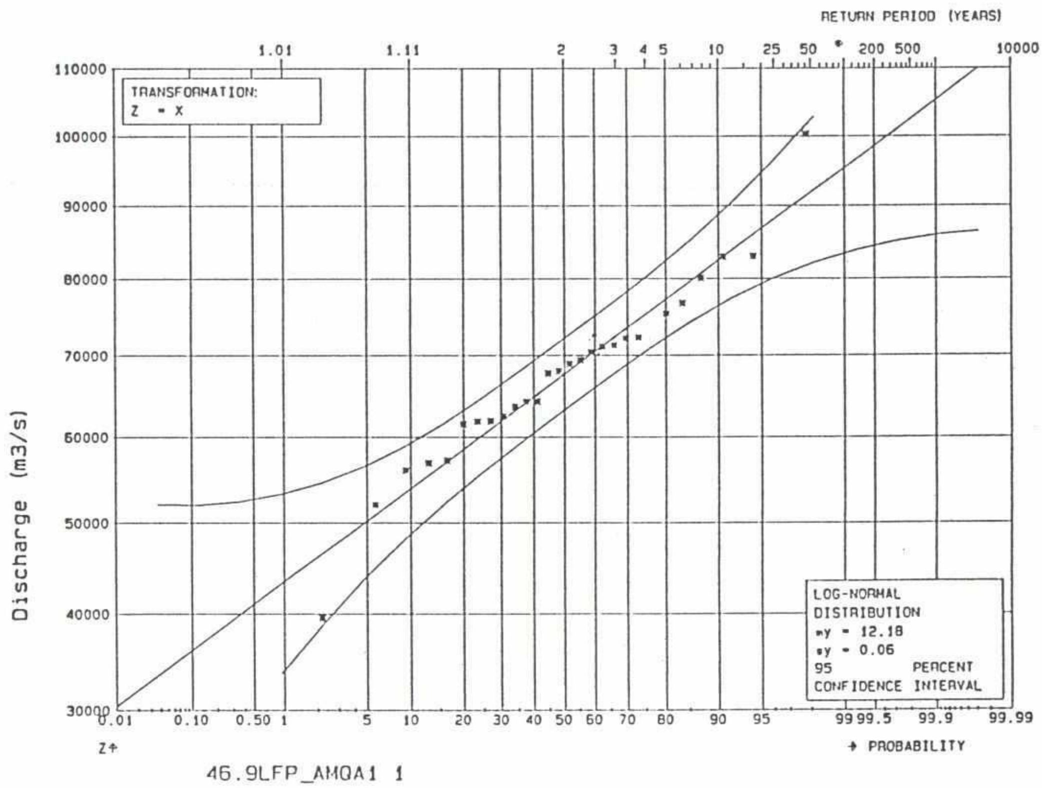


Figure 8.4 Fit of log-normal distribution to annual maximum discharges at Bahadurabad

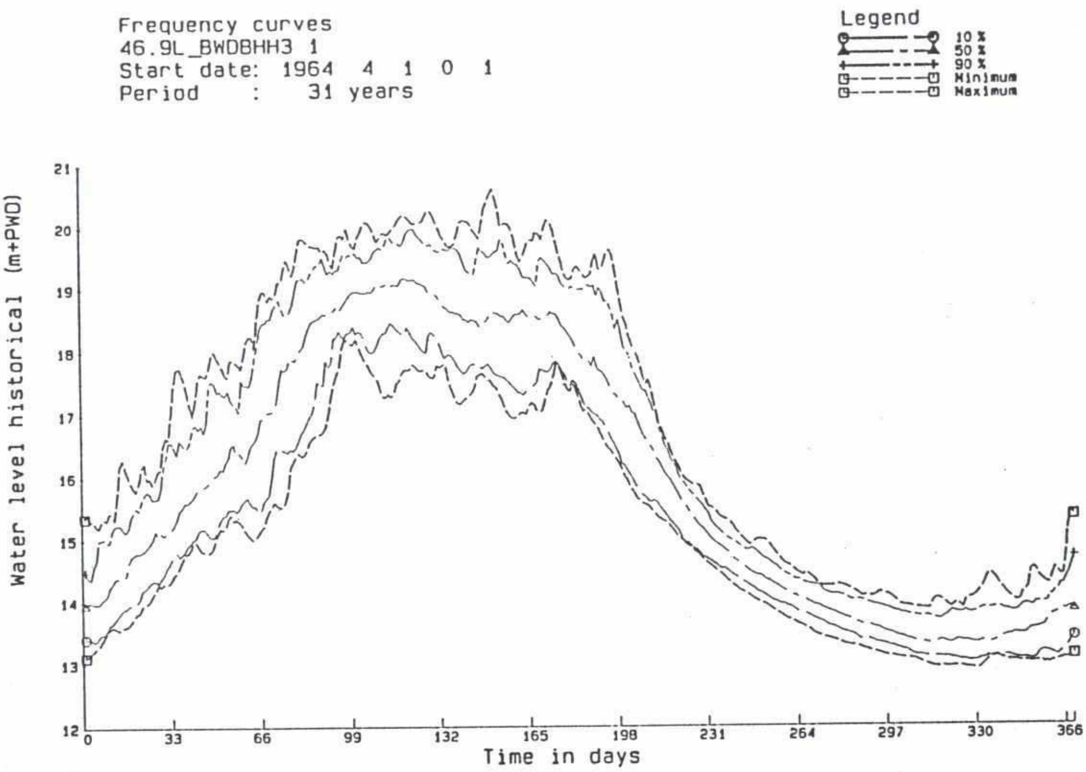
Station	Source	Return Period (year)				
		2	5	10	25	50
Bahadurabad	FAP 24 FAP 25	19.77 19.78	20.08 20.04	20.25 20.21	20.42 20.42	20.54 20.57
Hardinge Bridge	FAP 24 FAP 25	- 14.72	- 14.80	- 14.85	- 14.92	- 14.97
Baruria	FAP 24 FAP 25	8.18 8.14	8.52 8.51	8.75 8.76	9.03 9.08	9.23 9.32
Mawa	FAP 24 FAP 25	5.93 5.91	6.24 6.22	6.45 6.44	6.70 6.76	6.88 7.01
Gorai Rlw.Bridge	FAP 24 FAP 25	12.80 12.91	13.22 13.30	13.44 13.51	13.68 13.73	13.83 13.88

Table 8.1 FAP 24 and FAP 25 calculated peak water levels for selected return periods

Station	Source	Return Period (years)					
		2	5	10	25	50	100
Bahadurabad	FAP 24 FAP 25	67500 67000	77500 78000	82500 85000	88000 94000	92000 100500	95500 107000
Hardinge Bridge	FAP 24 FAP 25	50000 49000	58000 59500	62500 66500	67500 76000	71000 82500	74000 89000
Baruria	FAP 24 FAP 25	90000 86000	103500 101000	112000 110500	123500 123000	132000 132500	140500 141500
Mawa	FAP 24 FAP 25	90000 -	100500 -	106000 -	112000 -	116000 -	120000 -
Gorai Rlw.Bridge	FAP 24 FAP 25	6250 -	7250 -	7800 -	8350 -	8750 -	9100 -

Table 8.2 FAP 24 and FAP25 calculated peak discharges for selected return periods

The frequency curves and average duration curves for water levels as well as discharges are presented in Figures 8.5 and 8.6.



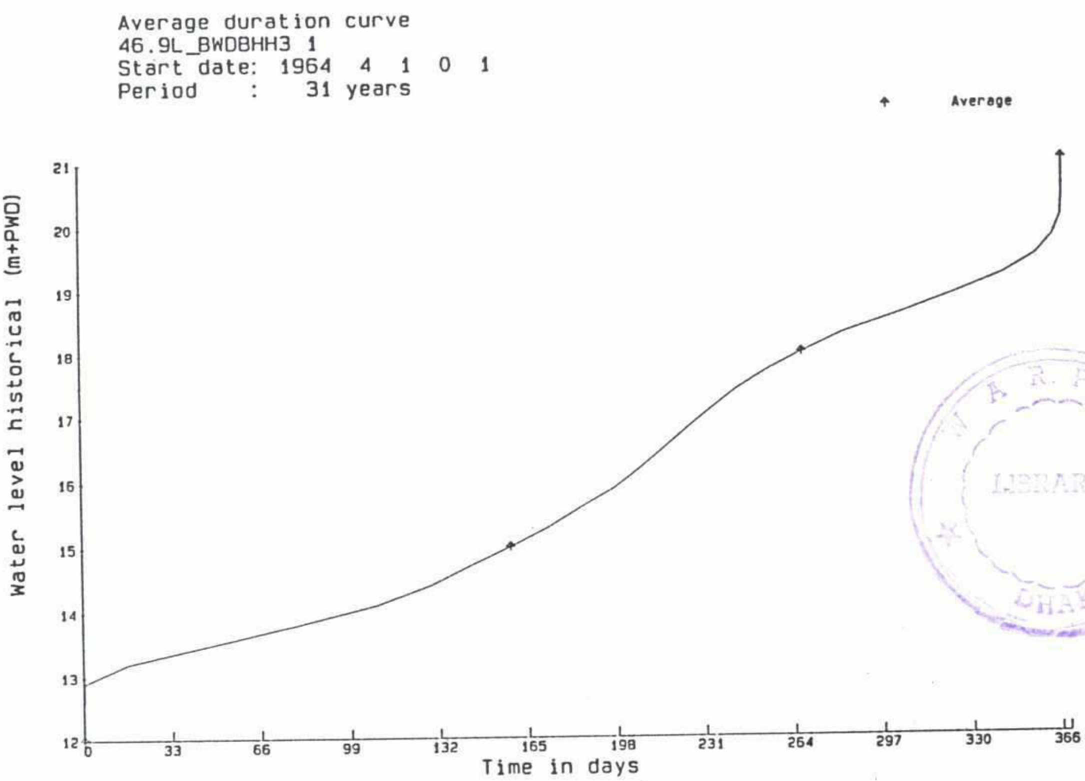
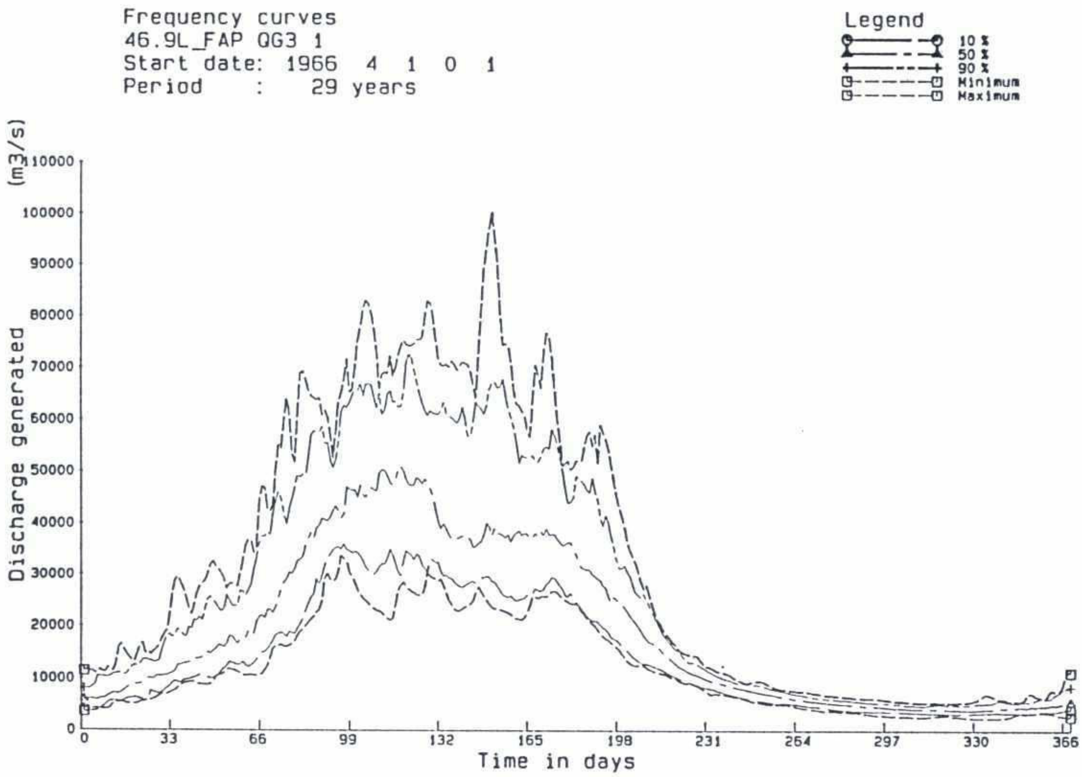


Figure 8.5 Frequency curves and duration curves of daily average water levels at Bahadurabad



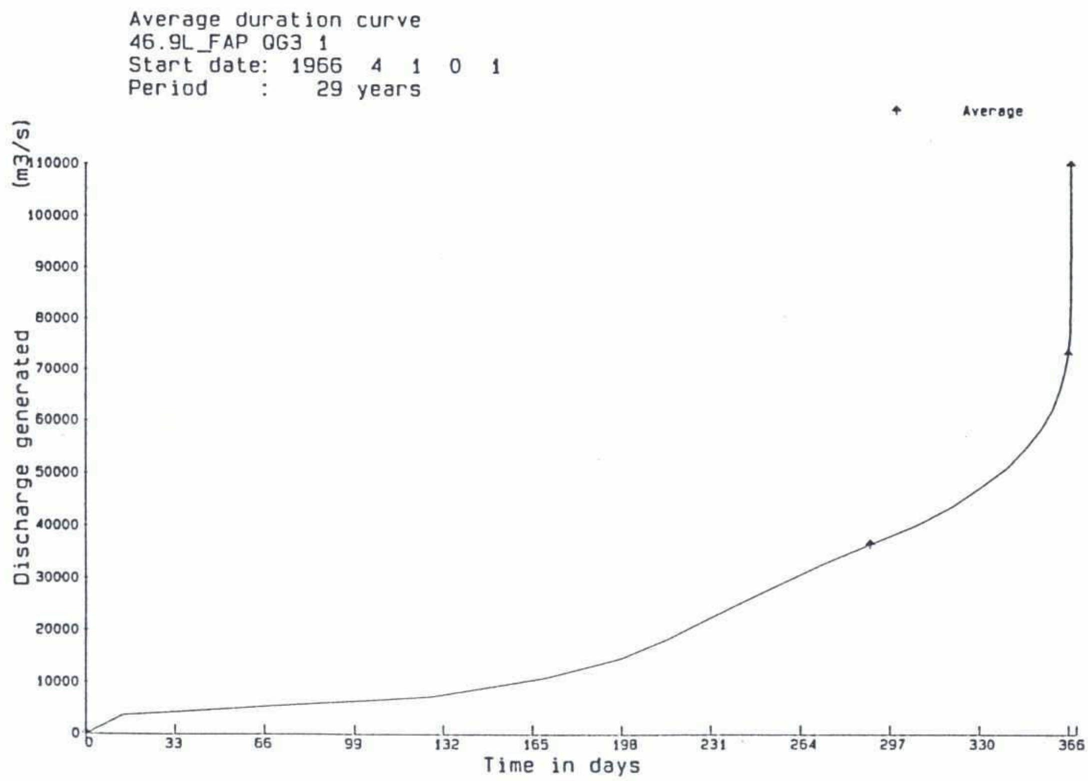


Figure 8.6 Frequency curves and duration curves of daily average discharges at Bahadurabad

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8.3.2 Ganges river at Hardinge Bridge

The annual minimum, mean and maximum water-level and discharge time series are presented in Figures 8.7 and 8.8. Figure 8.8 shows a slightly downward trend for the minimum and mean water levels whereas the maximum water levels do not show a trend. The downward trend in the water-level series results from water withdrawal at Farakka, beginning in the mid-seventies. The annual minimum and mean discharges series show a similar downward trend, whereas the maximum discharges go up slightly (but statistically insignificant).

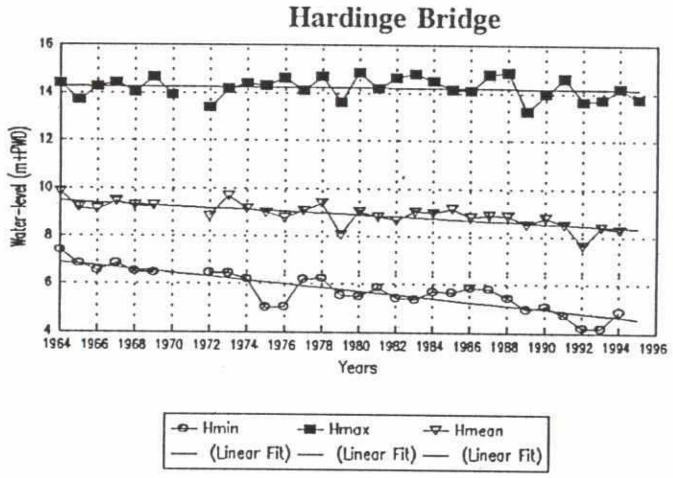


Figure 8.7
Annual minimum, mean and maximum water levels at Hardinge Bridge

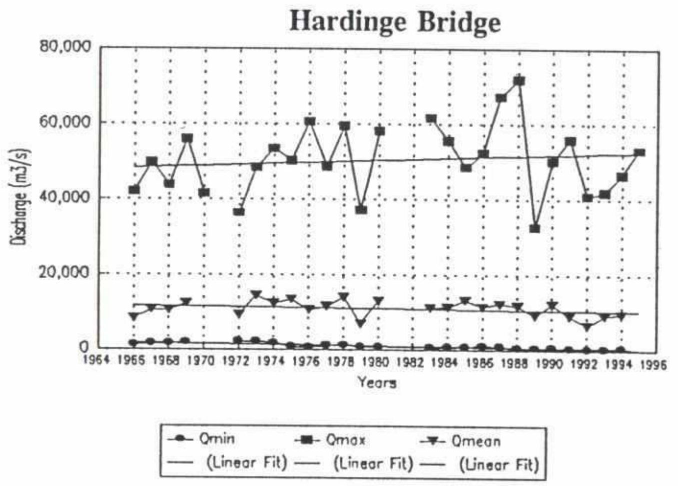


Figure 8.8
Annual minimum, mean and maximum discharges at Hardinge Bridge

The fit of the three-parameter log-normal distribution to the observed frequency distribution is shown in Figures 8.9 and 8.10. In Figure 8.9 one can see that the highest stages deviate from the distribution function. Apparently, the conveyance capacity of the river in the back-water reach of the station increases here rapidly and shows that the large one should take in the application of frequency distributions to extreme water levels. The annual maximum discharges fit well to the log-normal distribution. Reference is made to Table 8.2 for the discharge values for selected return periods.

The frequency and duration curves for Hardinge Bridge are shown in Figures 8.11 and 8.12. At comparing the frequency curves for Bahadurabad and Hardinge Bridge it is obvious that the Jamuna River is generally topping before the Ganges River, and that the flows in these two rivers are not in phase.

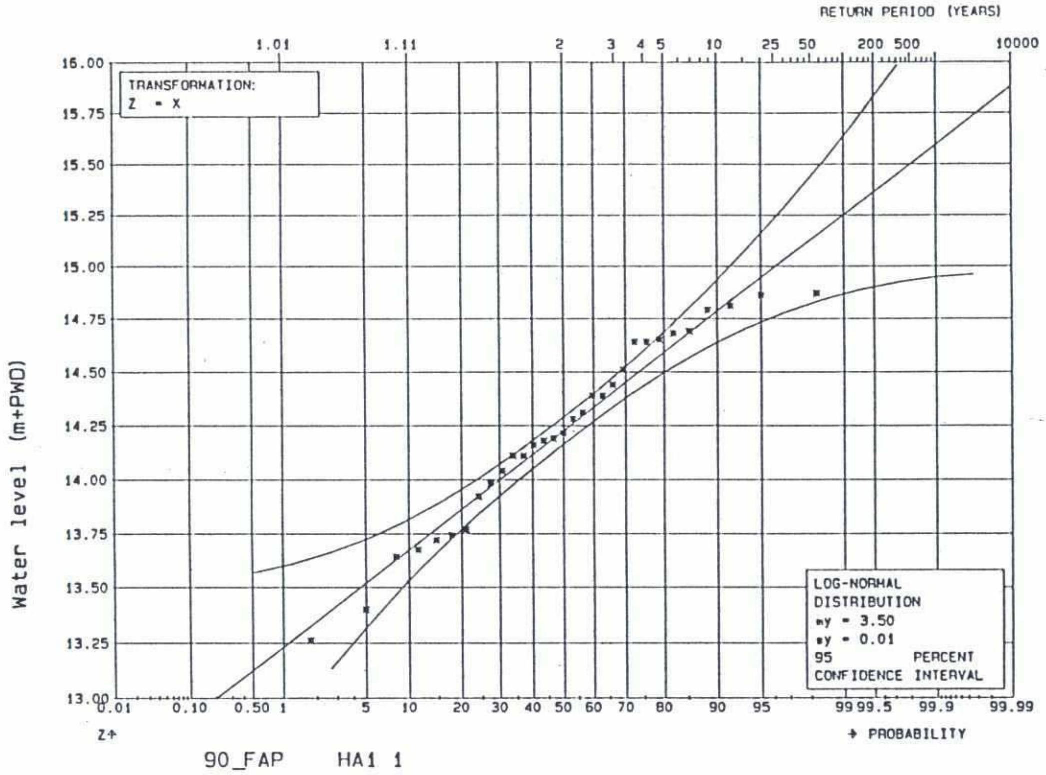


Figure 8.9 Fit of log-normal distribution to annual maximum water-levels at Hardinge Bridge

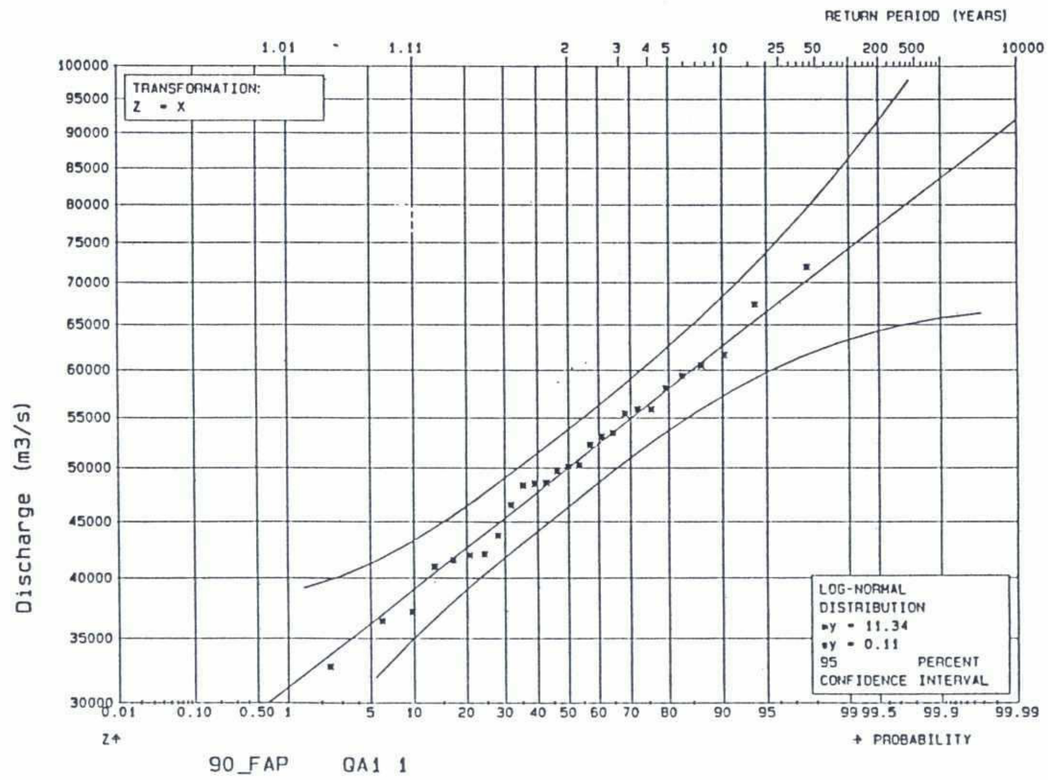
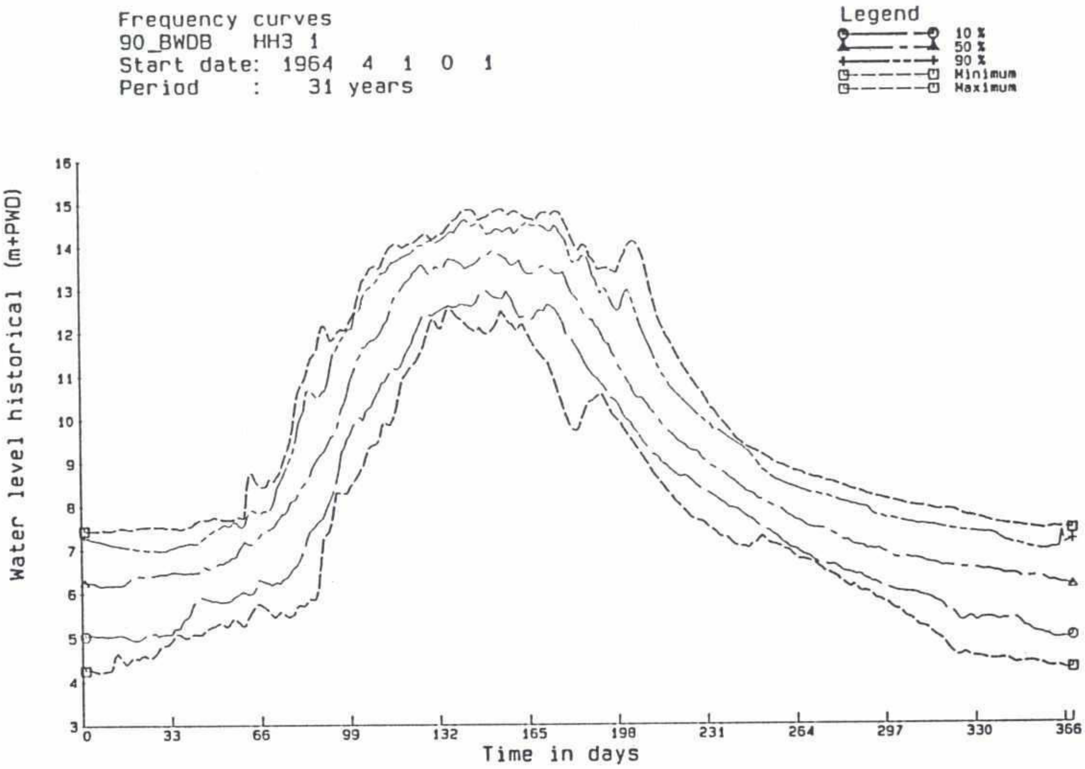


Figure 8.10 Fit of log-normal distribution to annual maximum discharges at Hardinge Bridge



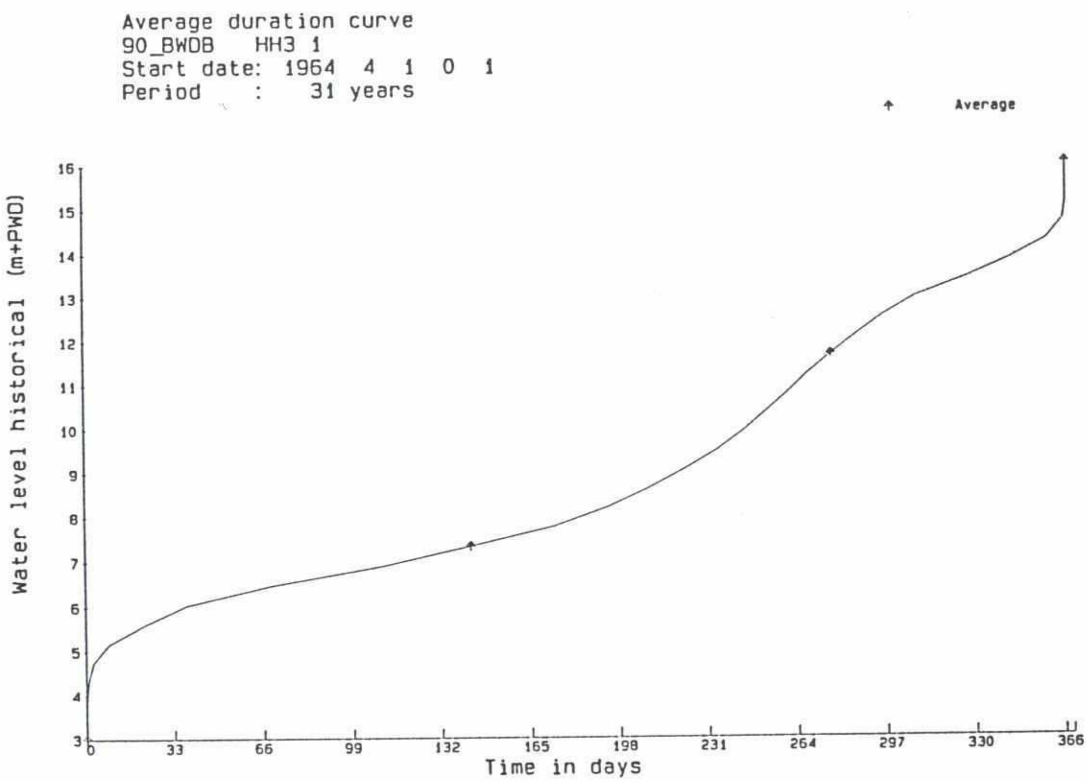
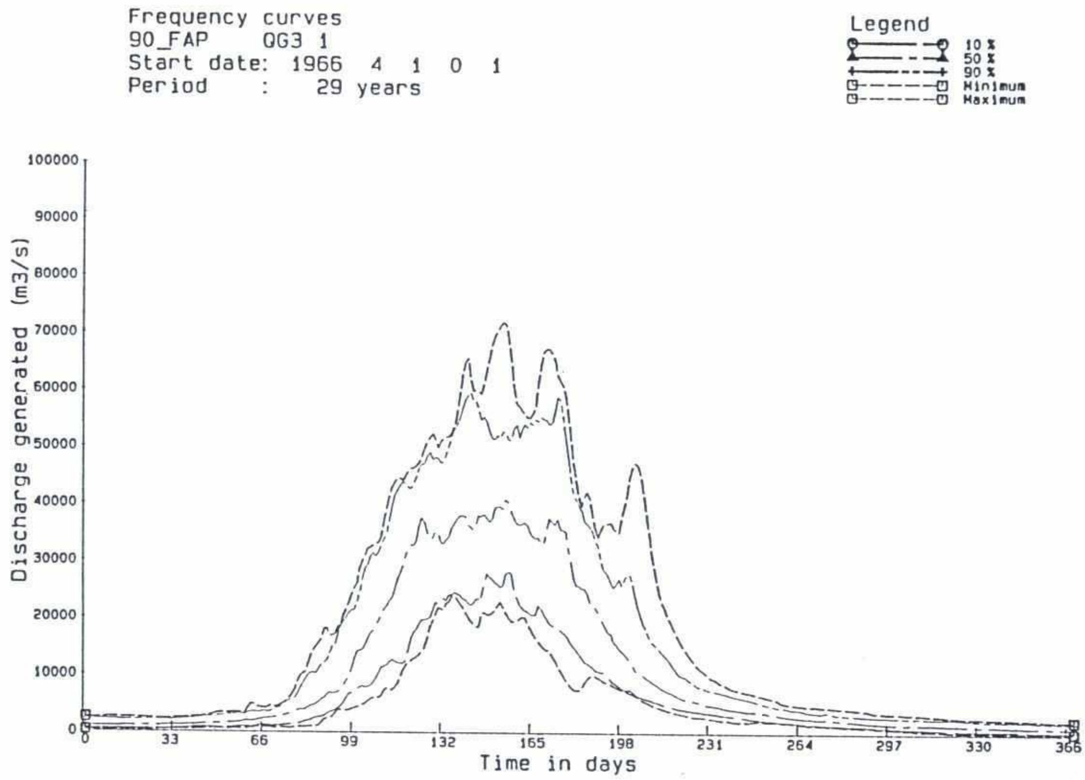


Figure 8.11 Frequency curves and duration curves of daily average water-levels at Hardinge Bridge



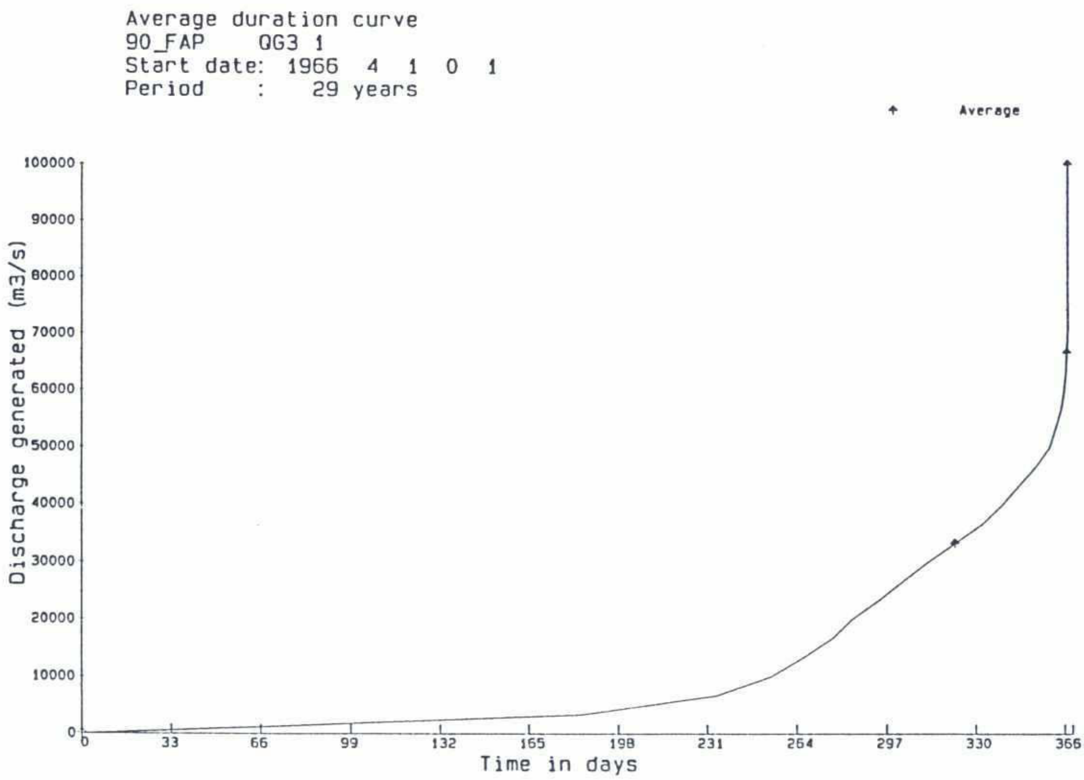


Figure 8.12 Frequency curves and duration curves of daily average discharges at Hardinge Bridge

8.3.3 Padma river at Baruria

The annual minimum, mean and maximum water-level and discharge time series are presented in Figures 8.13 and 8.14. The Figures show that in neither the water levels nor the discharges trends are present for the Padma river at Baruria. Note that the discharge series begins in 1972. Prior to that date, the discharges appeared to be inconsistent with the surrounding stations and have therefore been omitted; see also Chapter 7.

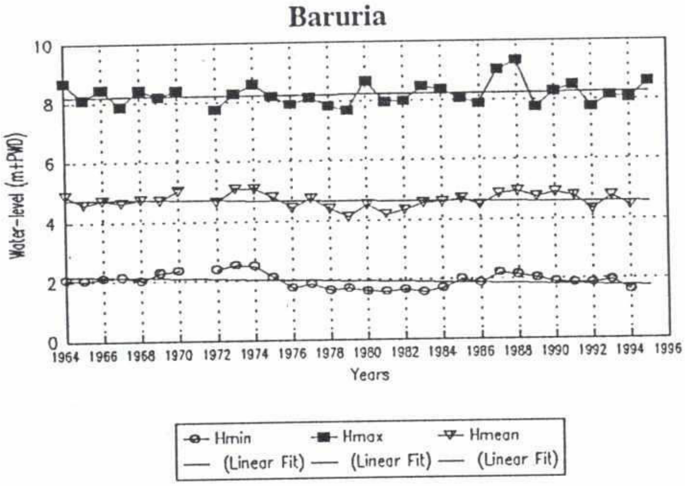


Figure 8.13
Annual minimum, mean and maximum water levels at Baruria

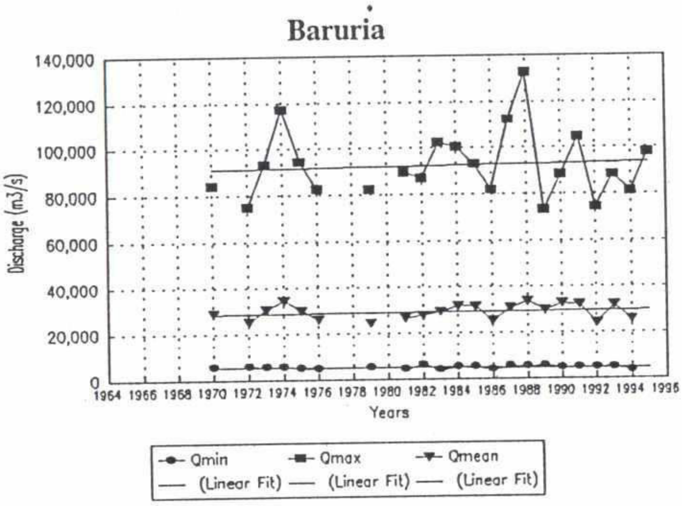


Figure 8.14
Annual minimum, mean and maximum discharges at Baruria

The fit of the three-parameter log-normal distribution to the observed frequency distribution is shown in Figures 8.15 and 8.16. In these Figures it is revealed that the log-normal distribution fits well to both the extreme water levels as well as the annual maximum discharges. Reference is made to Tables 8.1 and 8.2 for the extreme values at selected return periods, as well as for a comparison with the FAP25 extremes. The differences in the extreme water levels are seen to be within 1 decimetre. Also the discharges for the selected return periods are very similar.

The frequency and duration curves for Baruria are shown in Figures 8.17 and 8.18.

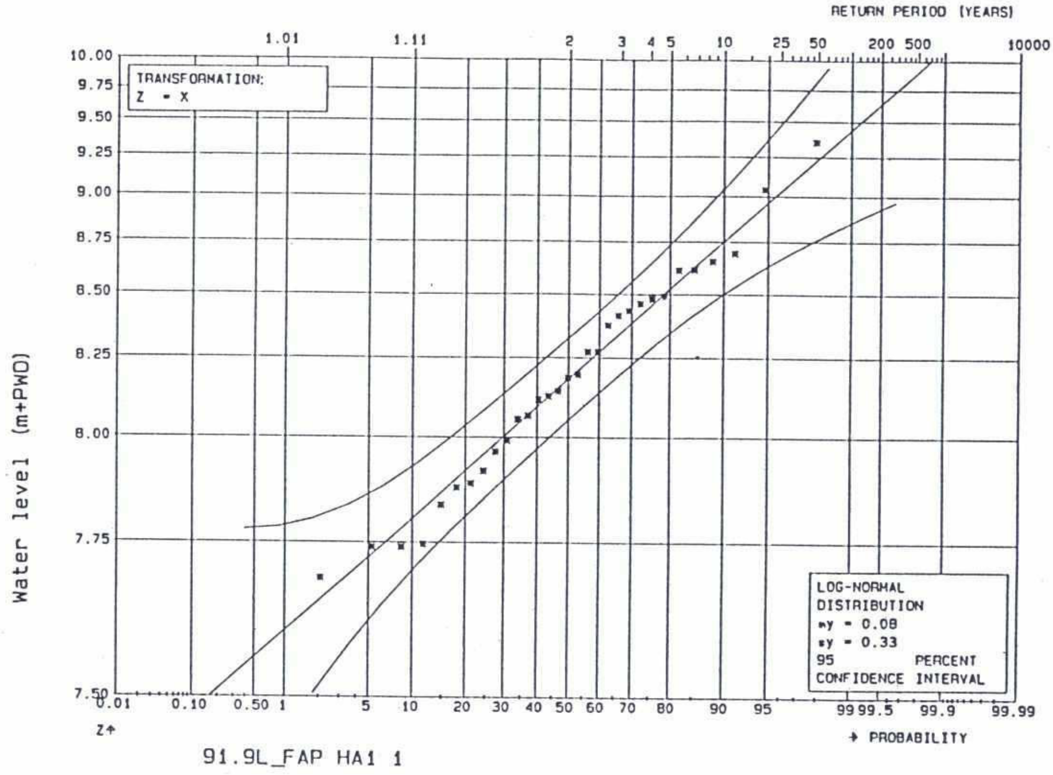


Figure 8.15 Fit of log-normal distribution to annual maximum water-levels at Baruria

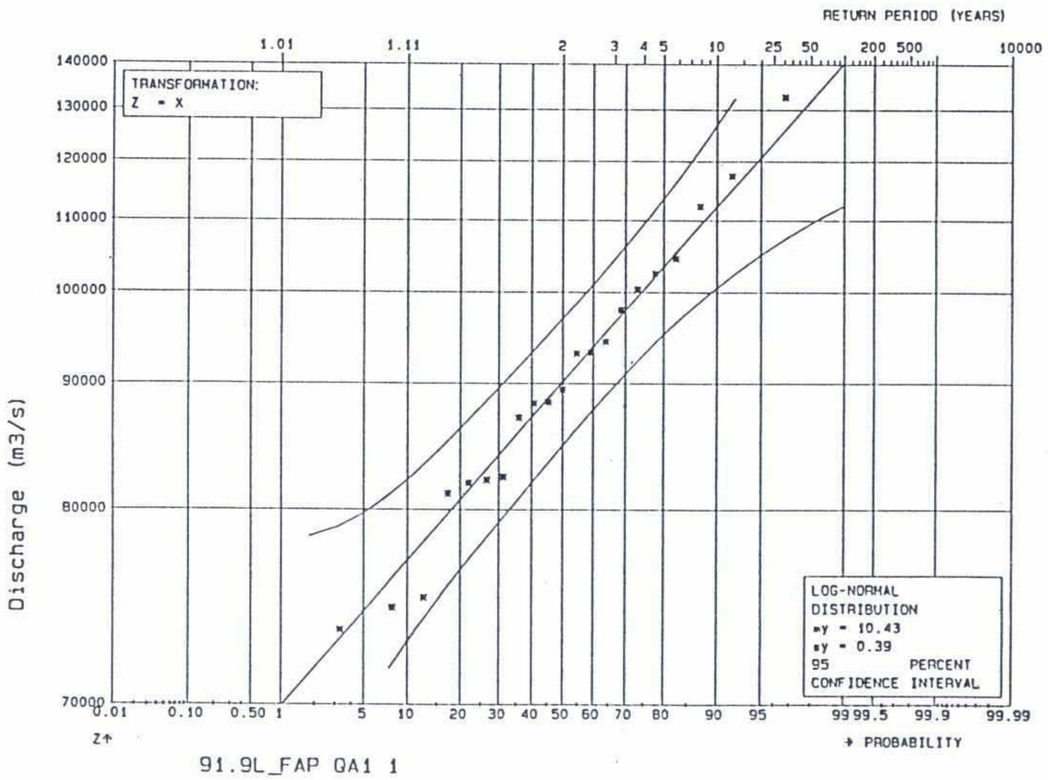
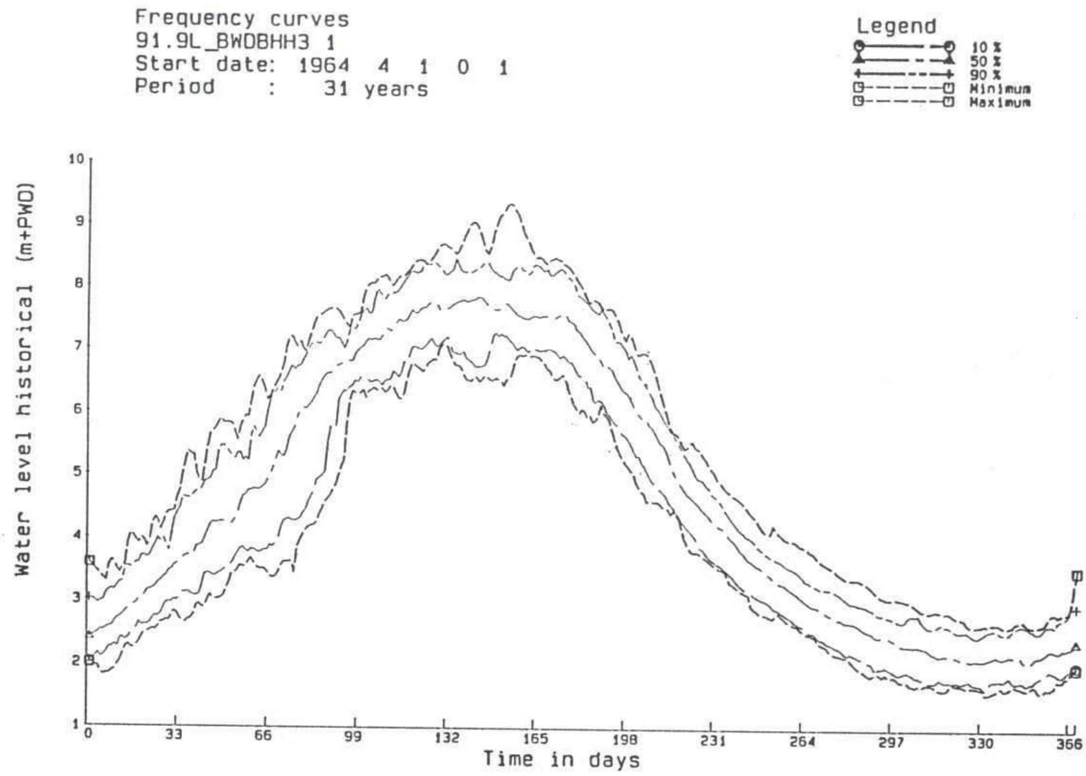


Figure 8.16 Fit of log-normal distribution to annual maximum discharges at Baruria



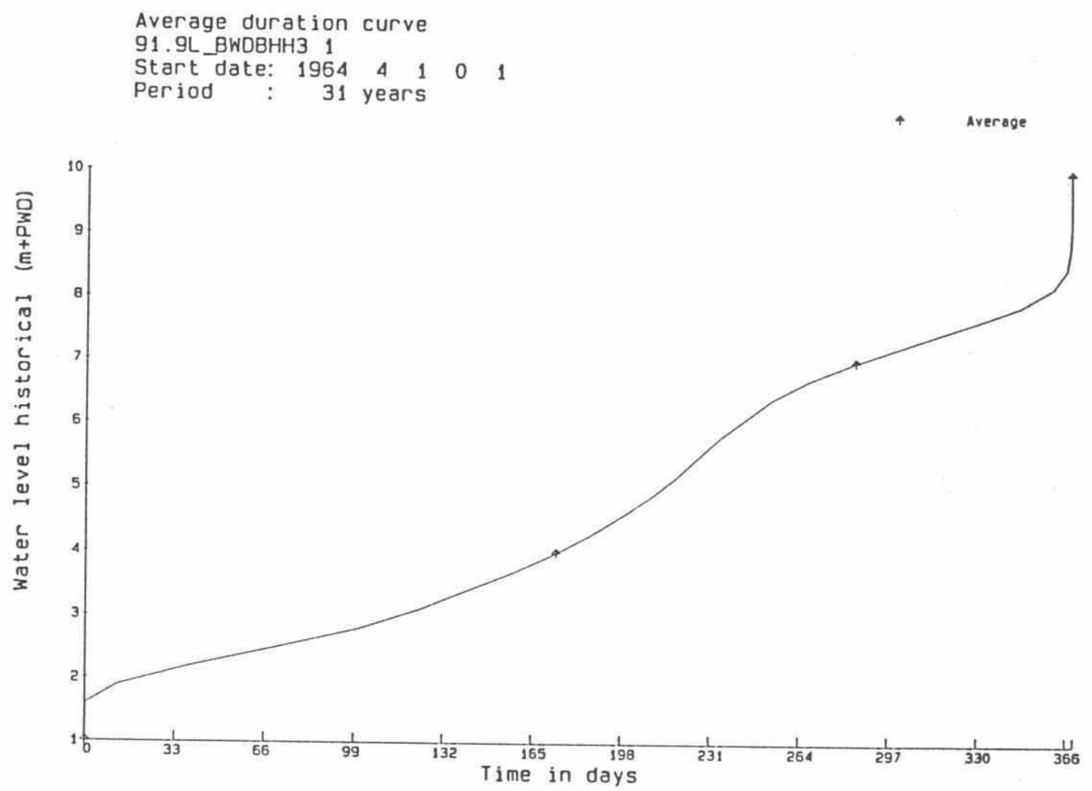
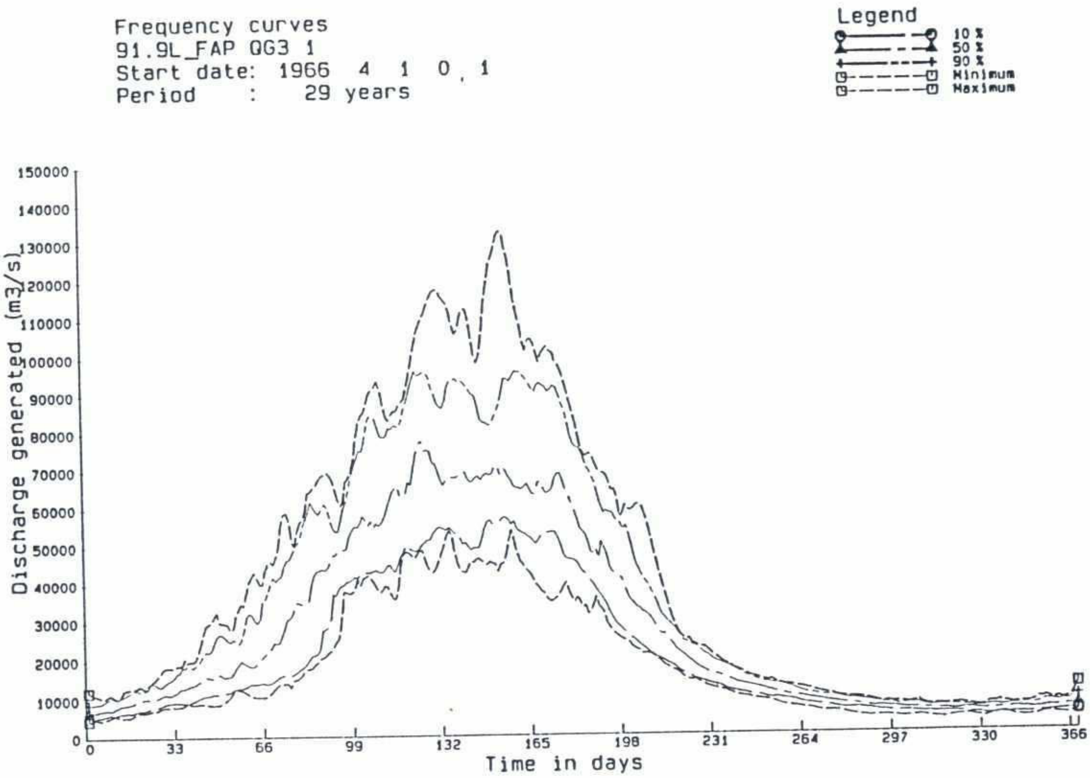


Figure 8.17 Frequency curves and duration curves of daily average water levels at Baruria



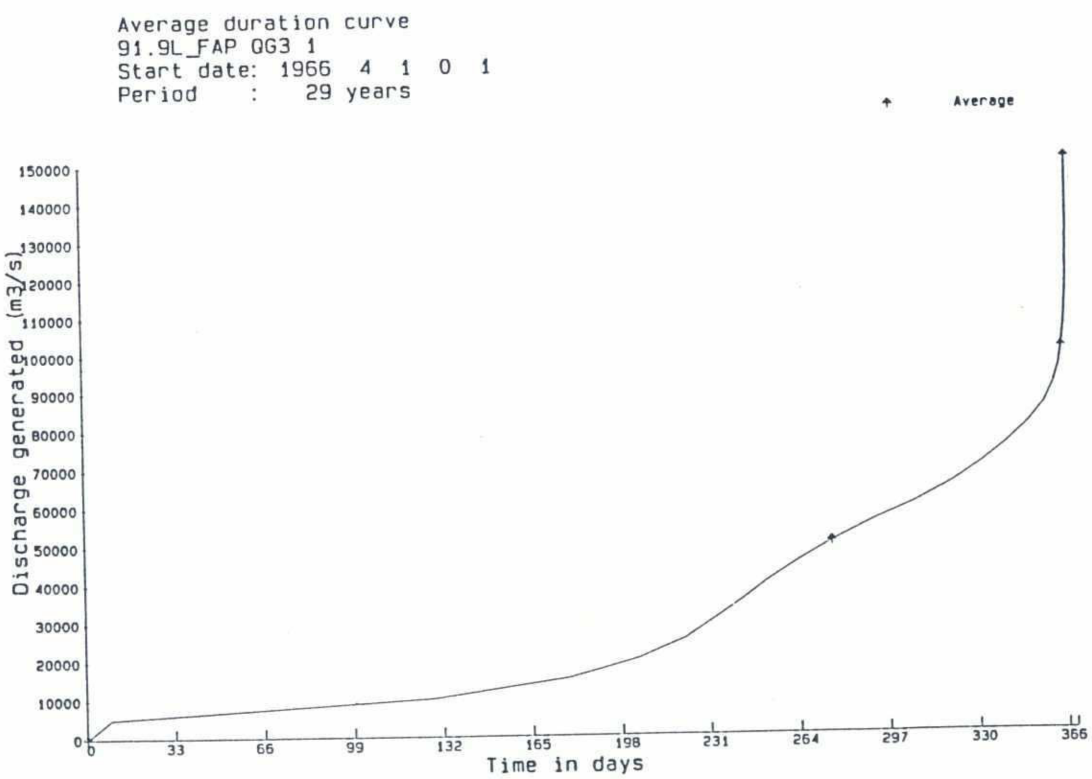


Figure 8.18 Frequency curves and duration curves of daily average discharges at Baruria

8.3.4 Padma river at Mawa

The annual minimum, mean and maximum water-level and discharge time series are presented in Figures 8.19 and 8.20. The Figures show a slightly downward trend for the minimum water levels, whereas the mean and maximum discharge go up slightly. In view of the latter, one is tempted to attribute this to a decreasing spill into the Arial Khan as Baruria showed no change. It is noted, however, that the discharge series for Mawa has many gaps, which frustrates a proper comparison with Baruria.

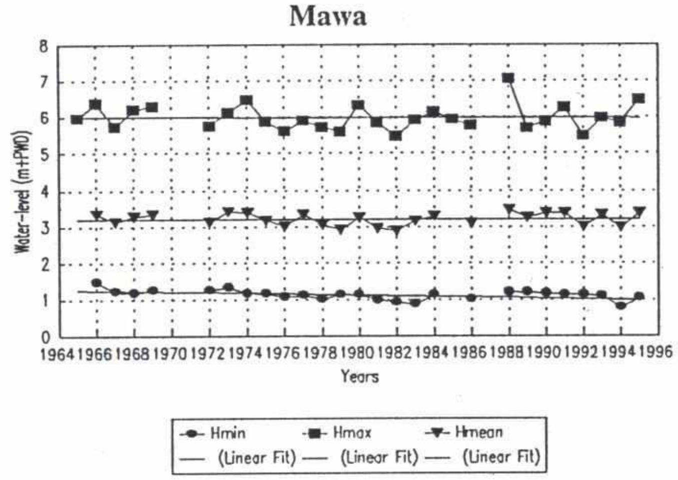


Figure 8.19
Annual minimum, mean and maximum water levels at Mawa

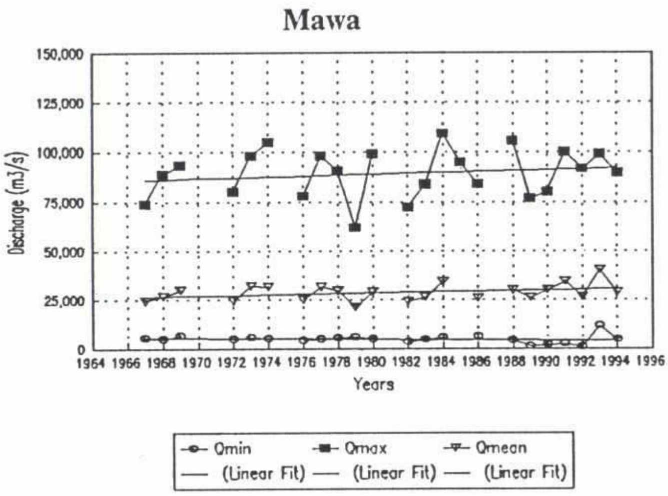


Figure 8.20
Annual minimum, mean and maximum discharges at Mawa

The fit of the three-parameter log-normal distribution to the observed frequency distribution is shown in the Figures 8.21 and 8.22. In the Figures it is revealed that the log-normal distribution fits well to both the extreme water levels as well as the annual maximum discharges. Reference is made to Tables 8.1 and 8.2 for the extreme values at selected return periods as well as for a comparison with the FAP25 extremes. The FAP24 series differ by about 1 decimetre (lower) with the FAP25 extreme for a return period of fifty years.

The frequency and duration curves for Mawa are shown in Figures 8.23 and 8.24.

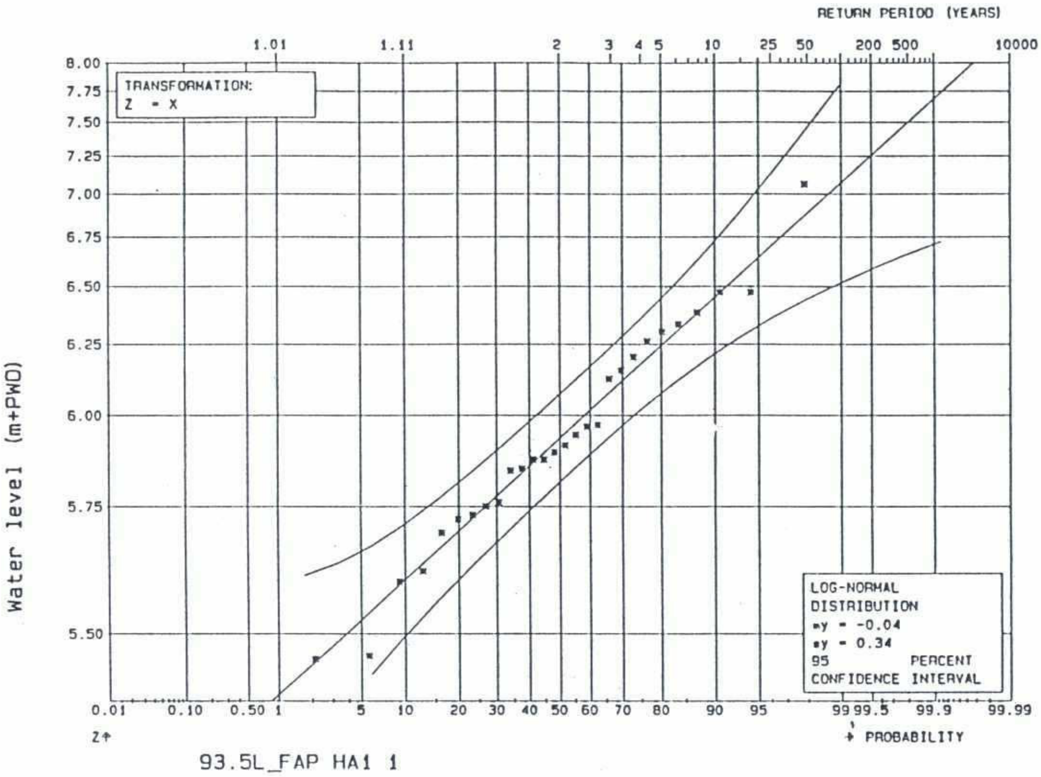


Figure 8.21 Fit of log-normal distribution to annual maximum water levels at Mawa

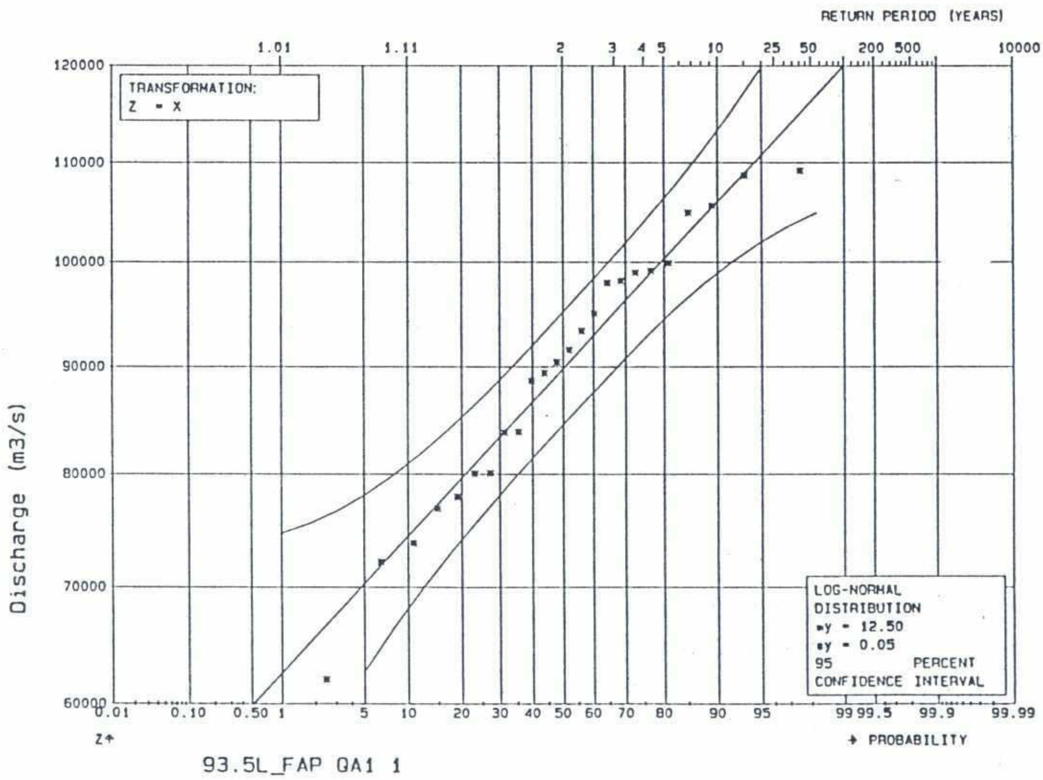
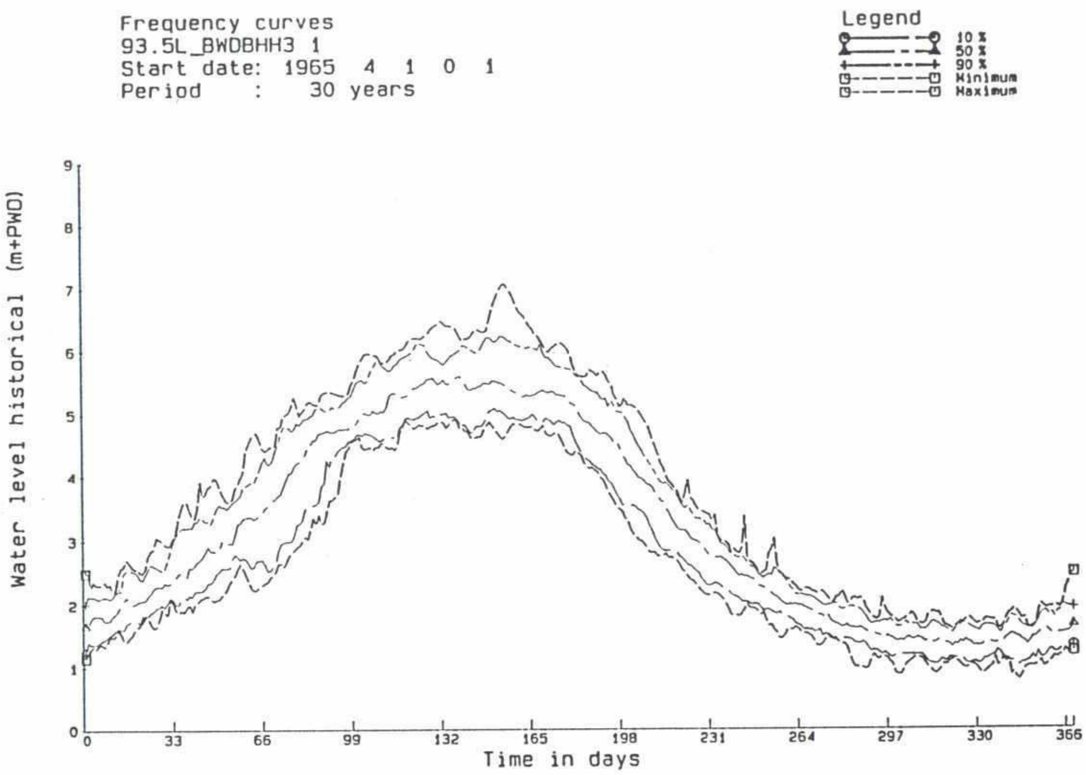


Figure 8.22 Fit of log-normal distribution to annual maximum discharges at Mawa



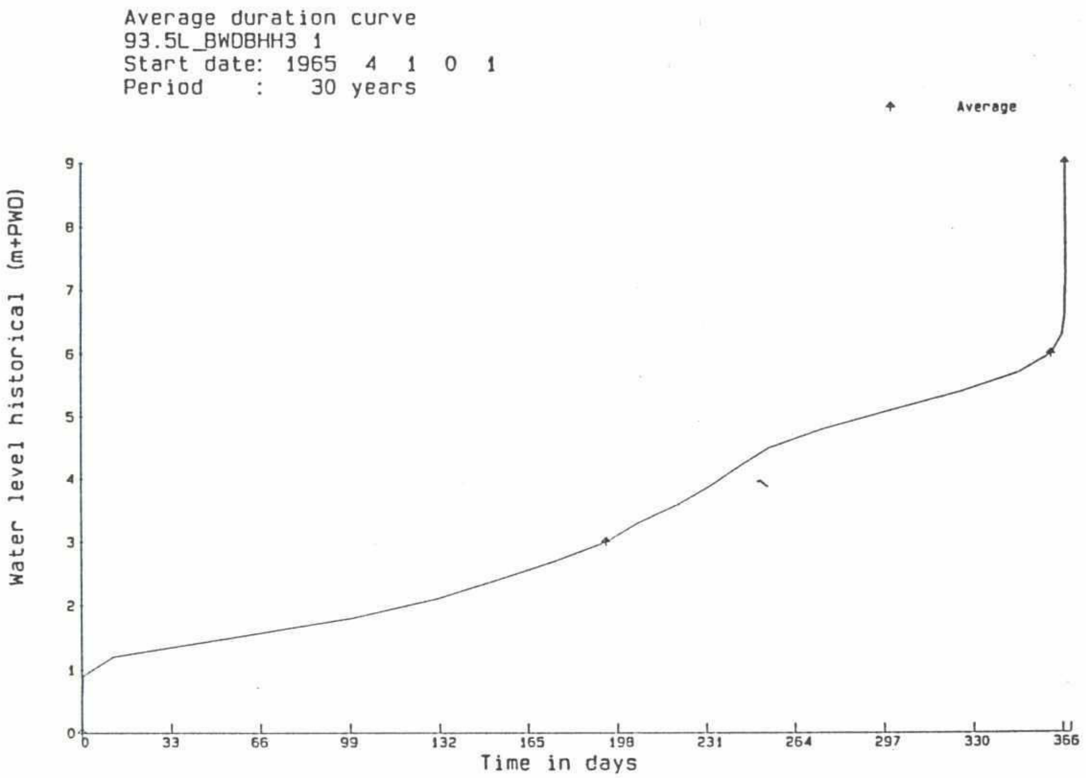
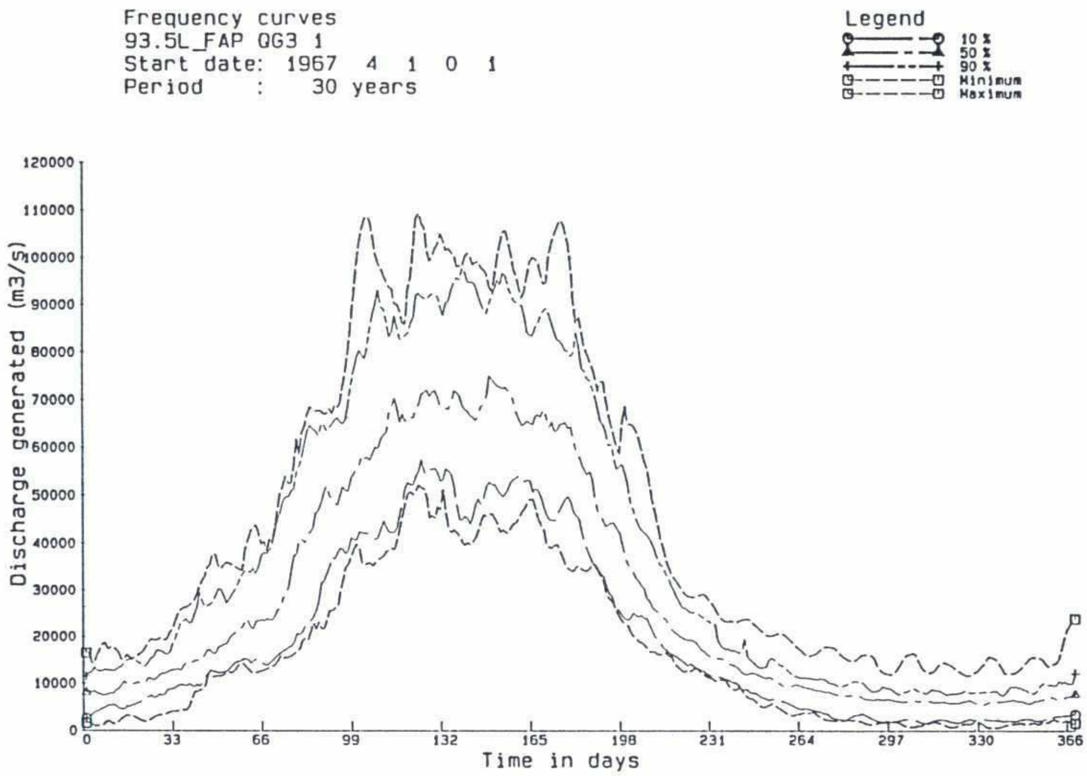


Figure 8.23 Frequency curves and duration curves of daily average water levels at Mawa



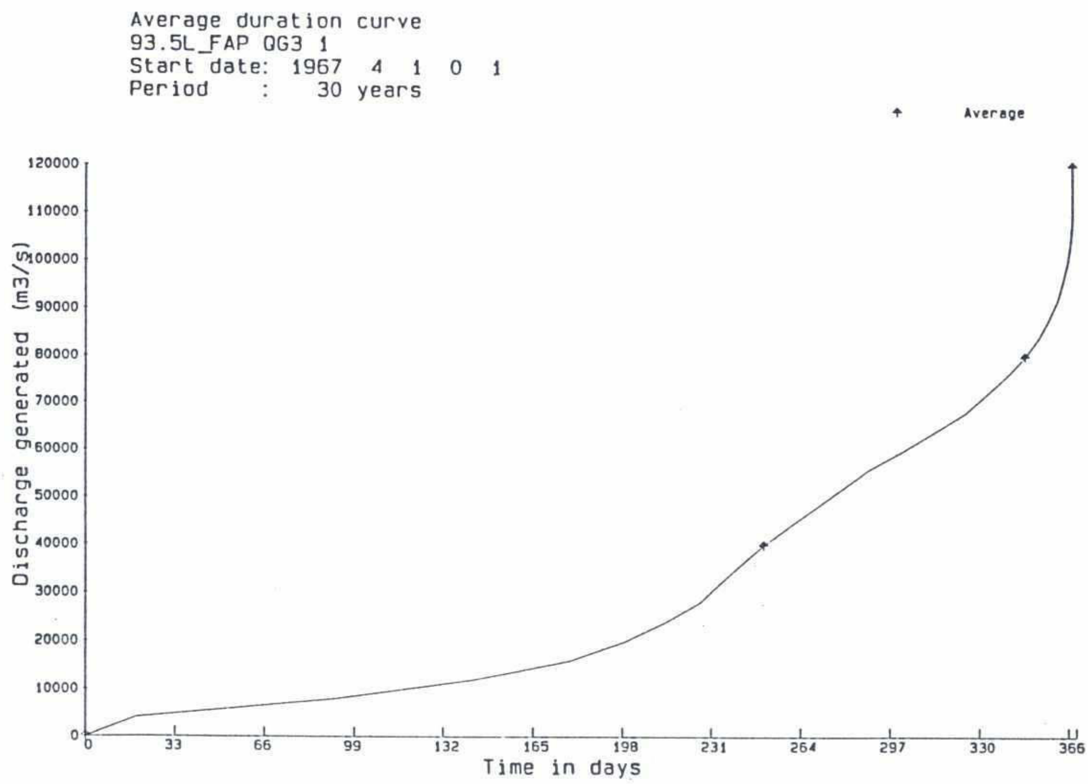


Figure 8.24 Frequency curves and duration curves of daily average discharges at Mawa

8.3.5 Gorai river at Gorai Railway Bridge

The annual minimum, mean and maximum water-level and discharge time series are presented in Figures 8.25 and 8.26. The Figures show a downward trend for the minimum, mean and maximum water levels as well as discharges.

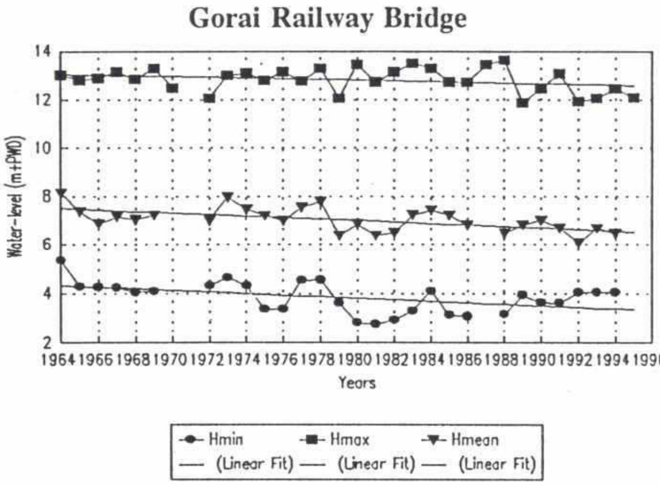


Figure 8.25
Annual minimum, mean and maximum water levels at Gorai Railway Bridge

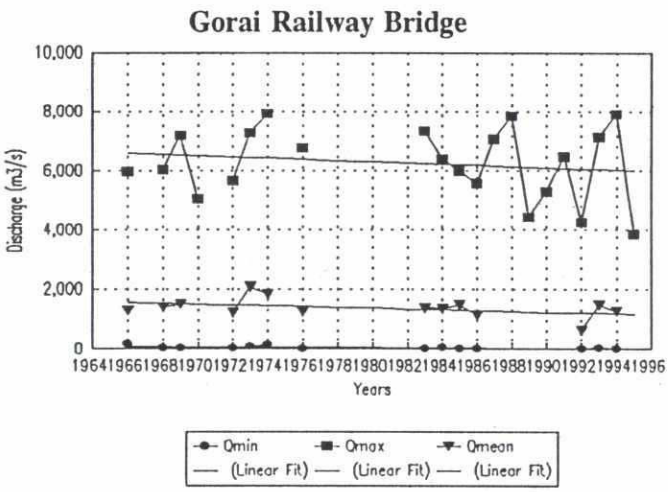


Figure 8.26
Annual minimum, mean and maximum discharges at Gorai Railway Bridge

The fit of the three-parameter log-normal distribution to the observed frequency distribution is shown in Figures 8.27 and 8.28. In the Figures it is revealed that the log-normal distribution fits well to both the extreme water levels as well as the annual maximum discharges. Reference is made to Tables 8.1 and 8.2 for the extreme values at selected return periods as well as for a comparison with the FAP25 extremes. The FAP24 series differ by about 1 to 0.5 dm (lower) with the FAP25 extremes.

The frequency and duration curves for Mawa are shown in Figures 8.29 and 8.30.

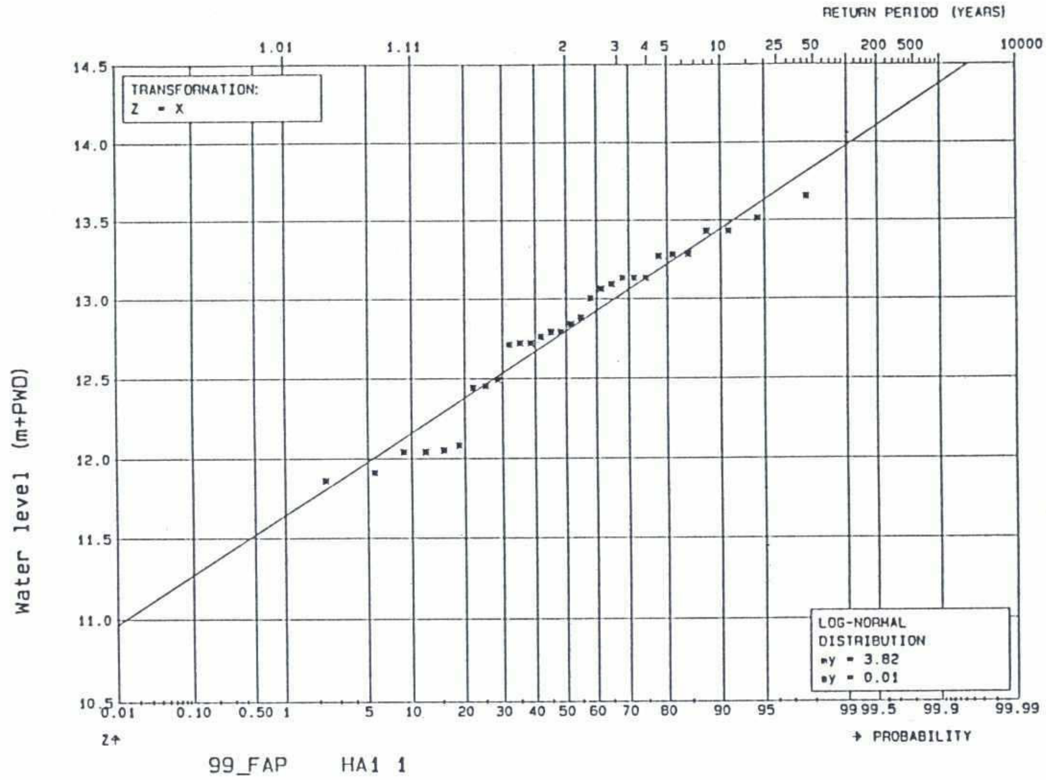


Figure 8.27 Fit of log-normal distribution to annual maximum water levels at Gorai Railway Bridge

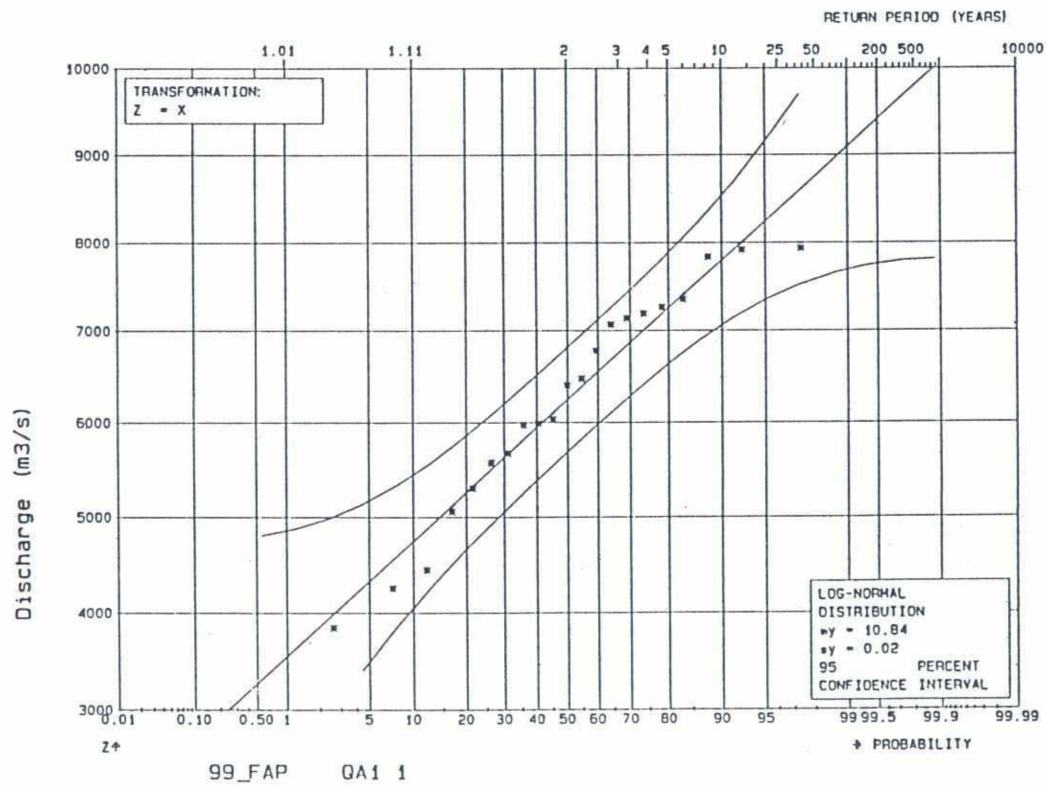
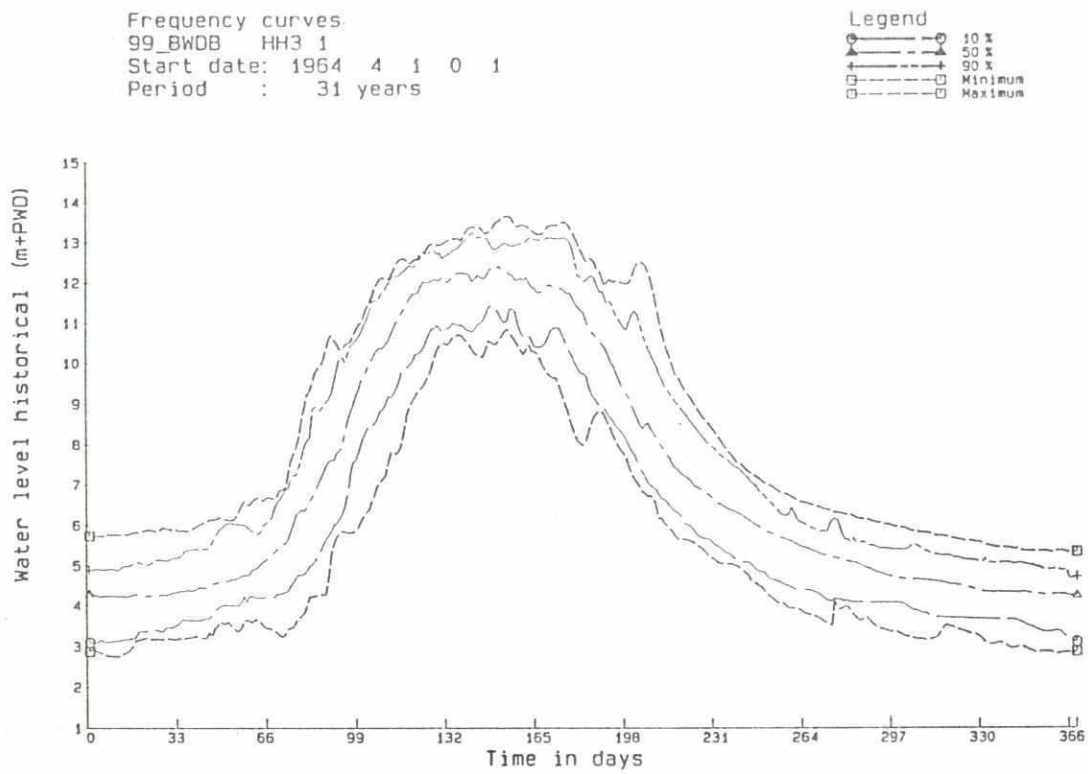


Figure 8.28 Fit of log-normal distribution to annual maximum discharges at Gorai railway Bridge



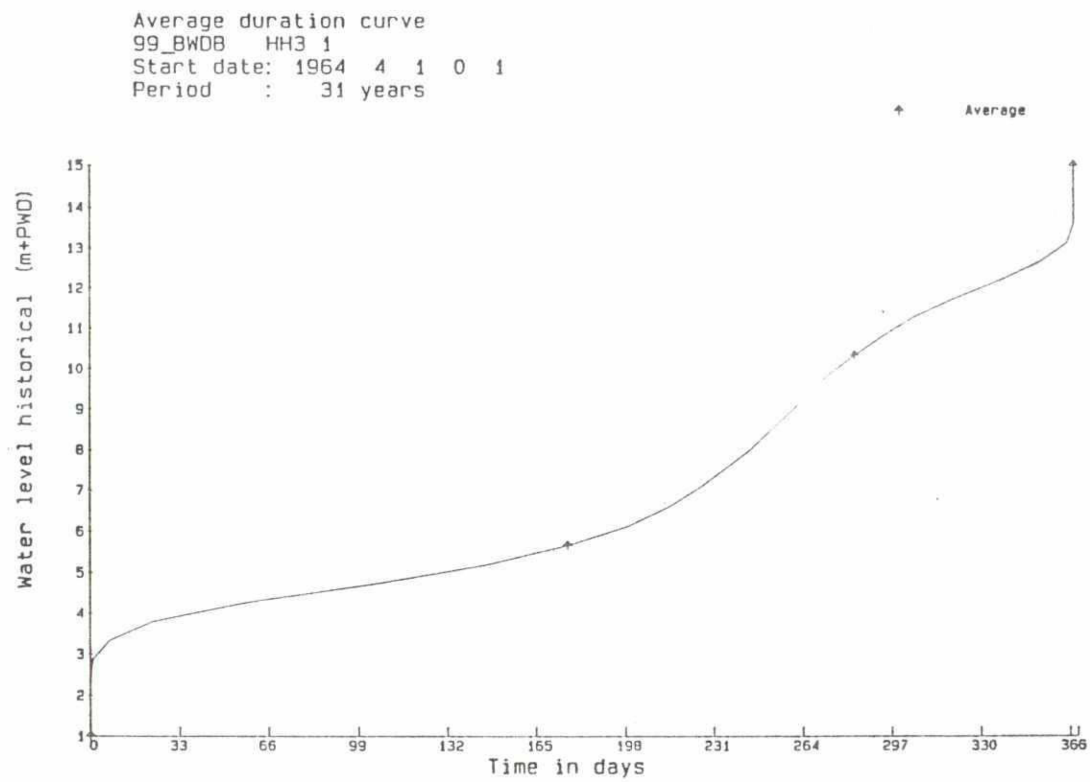
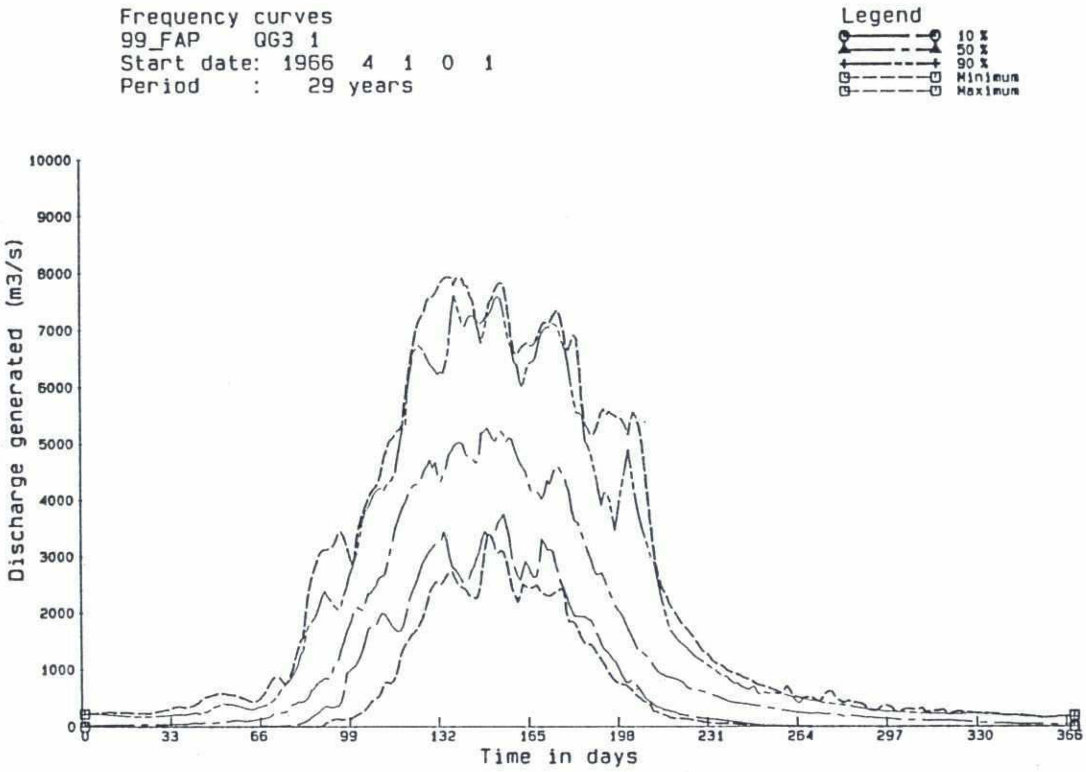


Figure 8.29 Frequency curves and duration curves of daily average water levels at Gorai Railway Bridge



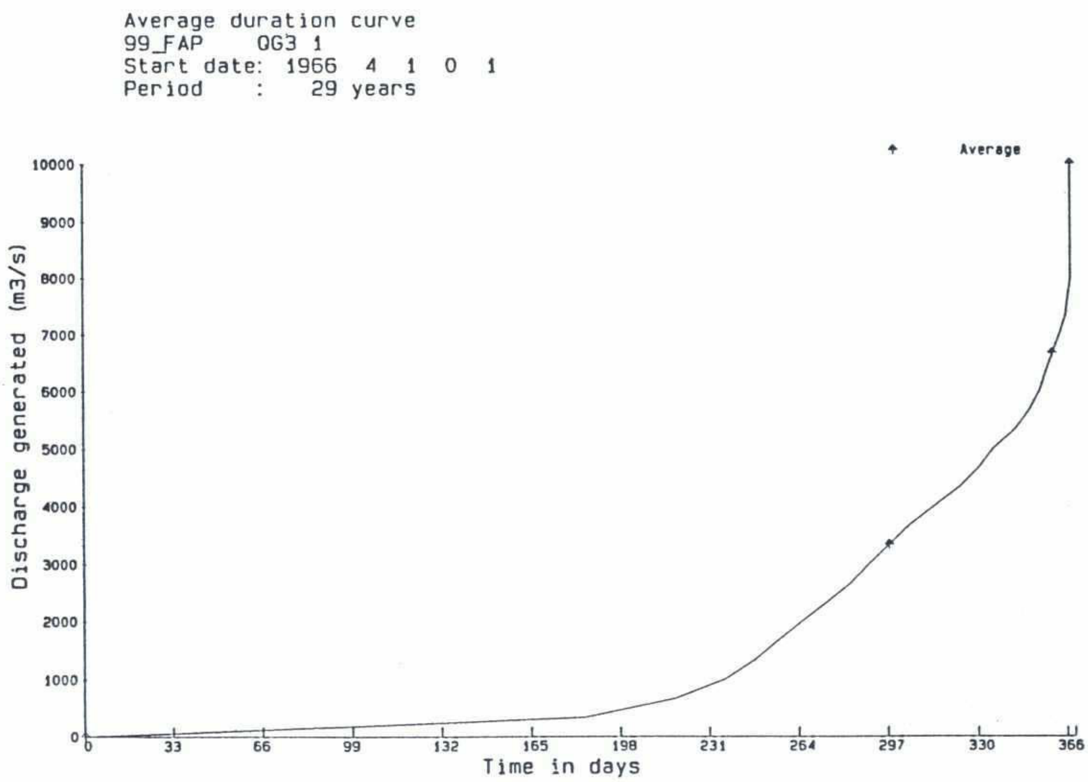


Figure 8.30 Frequency curves and duration curves of daily average discharges at Gorai Railway Bridge

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9 Conclusions

From the study of documents and analysis of hydrological data, as presented in Chapters 5 to 8, the following conclusions can be drawn.

Water levels

1 - The historical daily average water-level series include errors caused by frequent shifting of staff gauges and errors in benchmark elevations.

2 - Application of effective data validation procedures is not common practice in the BWDB data processing of water levels.

Water-level slopes

3 - Investigation of local water-level slopes appears to be a powerful tool to identify morphological changes in river sections. These changes are typically the development of a cut-off, or a redistribution of the discharge over the outflowing channels of a bifurcation: one channel gains importance and in another channel the discharge will decrease.

4 - A seasonal variation is present in the water-level slope between Bahadurabad and Sirajganj, which is partly due to morphological effects and/or seasonal changes in the hydraulic roughness downstream of Sirajganj.

Discharge observations

5 - Inaccuracies in BWDB's flow measuring practice occur due to incorrect flow direction adjustment in oblique transects, flow-area measurement and long duration of the measurement.

6 - Discharges measured by the ADCP-EMF moving boat method are consistently less than those measured by the conventional velocity-area method using propellor type current-meters.

7 - The usefulness of executing discharge measurements at Mawa is questionable. The scatter in the measurements is considerable, due to tidal effects mainly in the lean season. The combination of discharge measurements at Baruria and at Arial Khan offtake is likely to provide more accurate discharges in the lower Padma.

Stage-discharge relations

8 - The use of one offset value in a multiple segment stage-discharge relation, as practised by BWDB and FAP25, leads to improper fits to the upper segments and overestimation of the discharge in the extrapolated range.

9 - An improved method for fitting stage-discharge relations was introduced by FAP24, by using a unique offset for each segment.

10 - To fit BWDB stage-discharge data annual adjustment of the stage-discharge relation is required. This variation is mainly caused by changes in the river geometry and hydraulic roughness of the backwater reach of the gauging station.

11 - The discharges measured by the ADCP-EMF moving boat method show less variation from year to year than the BWDB stage-discharge data, indicating that part of the variation in the historical stage-discharge relations can be attributed to inaccuracies in the BWDB-discharge data.

12 - Corrections for unsteady flow effects (Jones effect) are not required for fitting the stage-discharge relation for the main river stations.

13 - Application of separate discharge rating curves for the left and right channel at Bahadurabad gives no improvement over a single stage-discharge relation.

14 - Correction for backwater effects improves the stage-discharge relation for Bhairab Bazar. Part of the variation in the stage-discharge data for Hardinge Bridge can also be attributed to backwater.

15 - The conveyance-slope method and horizontal segmentation of the river cross-section is required to arrive at reliable extrapolations of the stage-discharge relation at Bahadurabad. Extrapolations based on fitted stage-discharge relations will likely overestimate the discharge as the physical lower limit of the hydraulic roughness of the alluvial river bed will approximately be reached during extremely high discharges.

Discharge series

16 - The BWDB-discharge series for Bahadurabad for the period September 1988 to March 1993 are inconsistent with the discharge at Baruria corrected for the Ganges. The discharges for this period are too high. Application of the discharge rating curve, based on early 1988 stage-discharge data, produces a consistent discharge series for that period.

17 - The discharge series for Baruria prior to 1972 gives too-low values and should be excluded from the historical records.

18 - Water balances for the river reaches enclosed by Bahadurabad on the Jamuna, Hardinge Bridge on the Ganges and Baruria on Padma river, based on the corrected discharge series, show no anomalies in the discharge series.

Overland flow

19 - A proper assessment of overland flow requires detailed flow measurements in the distributaries and floodplain. Estimation of the overland flow from water balances between the main river stations leads to values with standard errors of over 100%.

Extremes

20 - The three-parameter log-normal distribution fits well to the annual maximum water levels as well as discharges. Generally, poor fits were found with the Extreme Value Type I or Gumbel distribution for the annual maximum discharges.

10 Recommendations

10.1 General

Based on the findings during this study and the conclusions drawn, the following recommendations are made.

1 – The setting up of a Hydrological Information System is proposed according to the guidelines presented in Section 10.2 and using the processing procedures as outlined in Section 10.3. The proposed procedure is recommended to be applied to the historical water-level and stage-discharge data of all stations in the hydrological network.

2 – An AWLR-station downstream of Bhairab Bazar is recommended to be established to correct the stage-discharge relation for Bhairab Bazar for variation in slope.

3 – It is recommended to investigate the additional value of the execution of discharge measurements at Mawa relative to flow measurements at Baruria and at the Arial Khan offtake.

4 – Studies are recommended on the extent of backwater effects on the stages at Hardinge Bridge to investigate possible reduction in the scatter of the stage-discharge data. At the same time a relocation of the gauging site is recommended to eliminate morphological effects on the gauge readings due to seasonal variation in the velocity head for equal discharges.

5 – The application of the conveyance-slope method for the extrapolation of the stage-discharge relation beyond the measured range according to the procedure outlined in sub-section 7.4.2 is strongly recommended.

6 – To support studies on the dynamic behaviour of the main river system and to be able to explain the variation in the stage-discharge relations at the various sites, the development of a one-dimensional mathematical hydraulic/morphological model of the main river system is imperative.

10.2 The setting up of a Hydrological Information System

For the purpose of planning, design, operation and execution of hydrological and morphological studies the development of a reliable Hydrological Information System is of the utmost importance. Based on long-term experience with information systems it is recommended to set up a four-stage database system:

1 – **Field data database**
This database should contain all and only field data to serve as a backup for the other databases. It is important that this database does not include any processed data so as to ensure that at all times one can get back to the source, in case confusion or disagreement arise on the method of validation or processing. Each month this database should be updated with the data transferred from the field offices. At fixed times a backup of this database should be made.

2 - **Mid-stage database**
This database is used for data validation, correction and completion purposes, and has therefore a temporary character. This database is updated each month by transferring the data loaded to the Field database. As soon as the data have fully been processed for a certain period up to dissemination level, the data are transferred to the Final database. Processing of yearbooks can best be done from this database as all relevant information and particulars are readily available. From this database no data should be retrieved to be supplied to users.

3 - **Final database**
This database contains only fully processed data of all stations in the network. Neither any processing nor analysis activities should be carried out in this database to ensure its integrity. In addition to its regular updating, only retrieval activities should be allowed for transfer of data to the User database or user storage device. At fixed times a backup of this database should be made.

4 - **User database**
For analysis purposes or data compilation activities the User database is available. This type of database has only a temporary character. Only the data required for the analysis are retrieved from the Final database. As soon as the analysis is completed this database may be deleted.

The above set will ensure an organised system of databases while avoiding the dissemination of information which is at various stages of processing. By structuring the database and data processing activities properly, the following benefits are easily obtained:

- immediate feedback to the field if errors are encountered in first-stage data validation,
- availability of the original data,
- improved quality of the processed data, and
- a unique set of data to ensure consistent design.

In the next section for each parameter recommendations on the various steps required for the development and operation of the Hydrological Information System will be discussed:

10.3 Data processing and analysis

10.3.1 Water-level data

Based on the type of errors to be expected in the gauge readings due to the observation and operation practice, the following systematic checking procedure is recommended (see Figures 10.1-a to 10.1-l):

- For each discharge station to be checked at least two adjacent water-level stations have to be selected for comparison (in Figure 10.1 station Bahadurabad (46.9L) is compared with Sirajganj (49) and Chilmari (45.5)). Annual tables should be made of the data to serve and to carry out a first check on violation of estimated maximum rates of rise or fall (HYMOS option 'Screening' under 'Validation');

- Water-level time series for each discharge station should be plotted for every year together with the time series of two comparison stations, see Figure 10.1-a. This gives a first visual impression of possible erroneous/shift data (HYMOS option 'time series' under 'Time series graphs' from the main menu option 'Validation';

- Next the stations are pairwise examined by inspection of difference plots in combination with shifted time series plots to improve the comparison, (see Figures 10.1-b and -c for Bahadurabad-Sirajganj and Figures 10.1-h and -i for Bahadurabad-Chilmari). By plotting more years in one graph, the change from one year to another can qualitatively be assessed (HYMOS options 'balance' and 'time series' under 'Time series graphs' from the main menu option 'Validation'. Note that sudden peaks or troughs in the difference graph does not necessarily imply erroneous data. If $|dh/dt|$ is large, then due to differences in the time of the rise or fall at successive sites, the difference graph will show peaks or troughs;

- Finally, stage-stage relation curves are made to assess quantitatively the change year by year: the regression line fitted to the data of one year is compared with data of other years (HYMOS option 'computation' under 'Relation curves' from the main menu option 'Validation'. When stages are plotted for the same day at both sites the graph may show a looped relation, caused by hydraulic and/or morphological effects. Looping caused by hydraulic effects is easily eliminated by applying a time shift between the data to be compared based on the wave travel time between the stations (compare Figure 10.1-d with 10.1-e). HYMOS provides under 'Relation curves' an option to identify the optimum shift based on cross-correlation maximization. Because the celerity of the wave is dQ/dA, the optimum shift is investigated for different reaches of stage. The relation curve analysis is shown in Figures 10.1-e,-f,-g and 10.1-j, -k, and -l. In the latter group of graphs the relation can be seen to change from year to year, of which some are clearly the result of gauge shifts.

- Based on the above graphs suspicious data have to be marked in the data tables and double-checked. Erroneous data should be corrected by stage relations, interpolation or by adding or subtracting the value required to get the hydrograph in line with the reliable part.

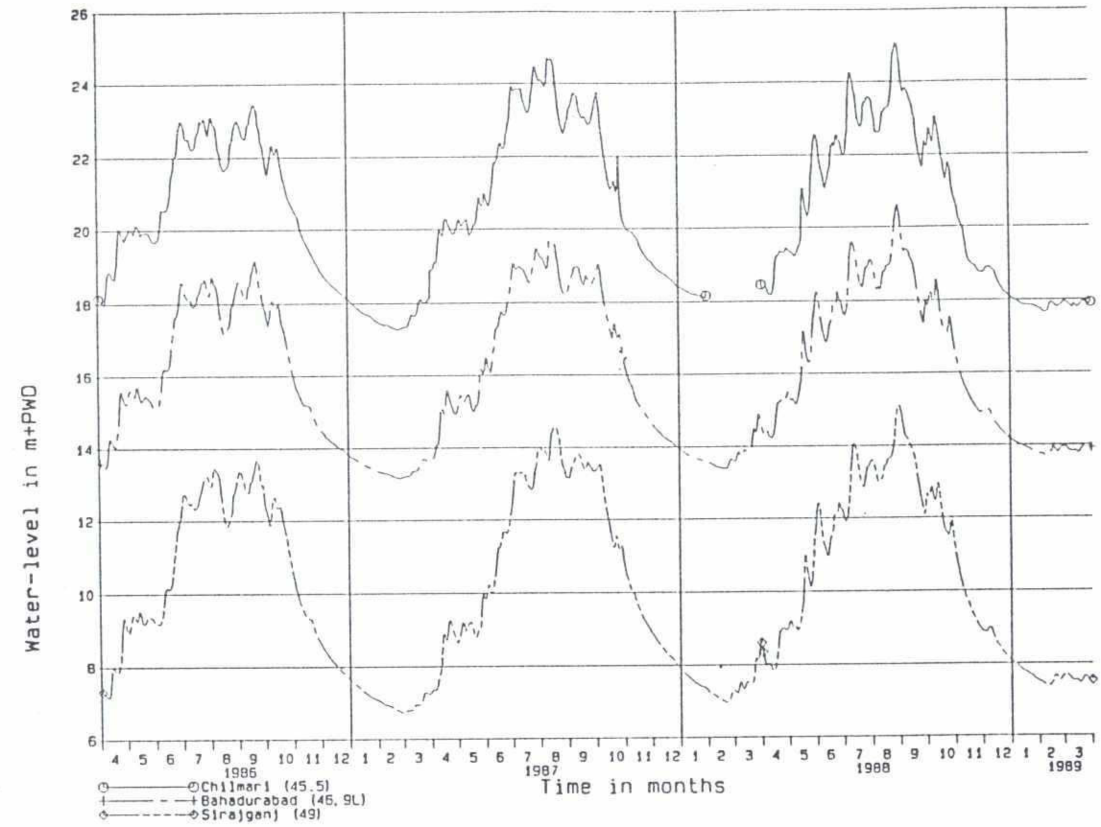

Figure 10.1-a

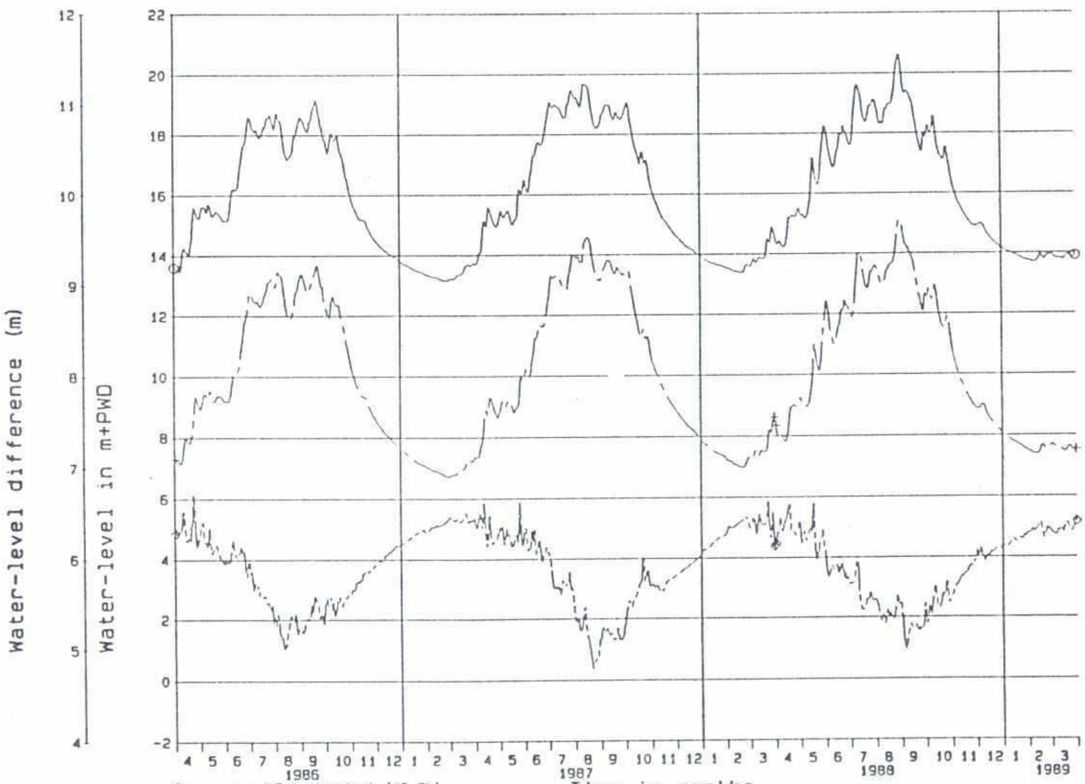

Figure 10.1-b

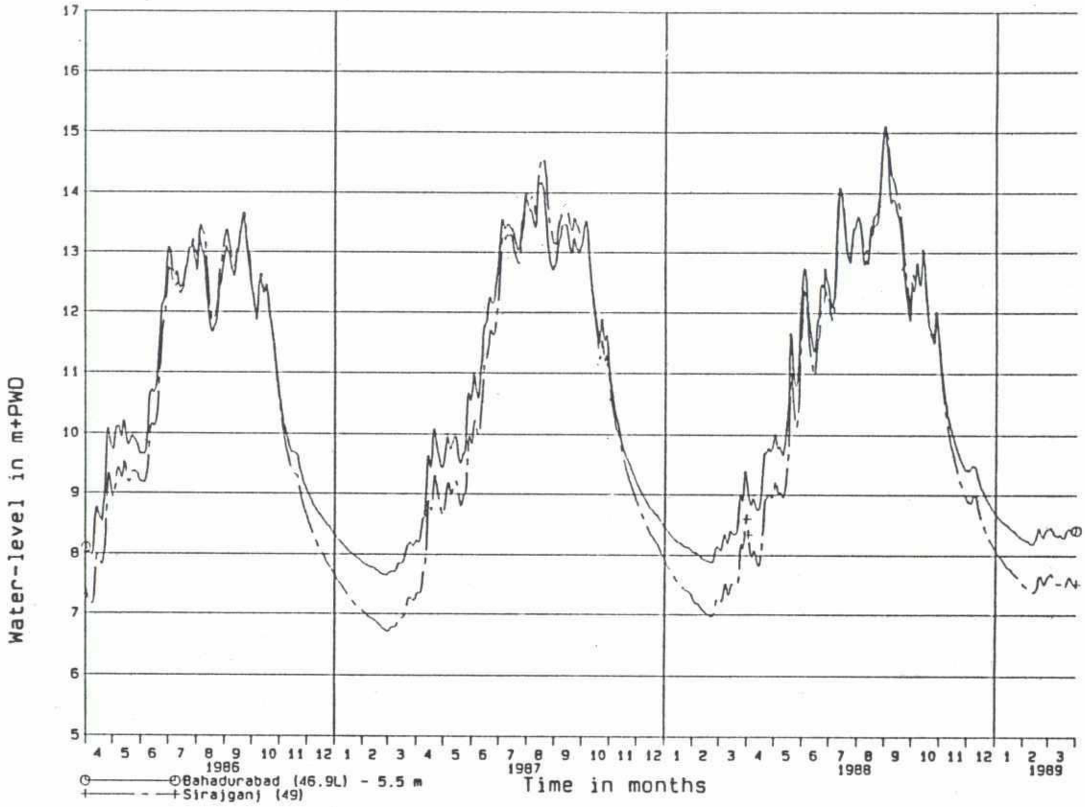

Figure 10.1-c

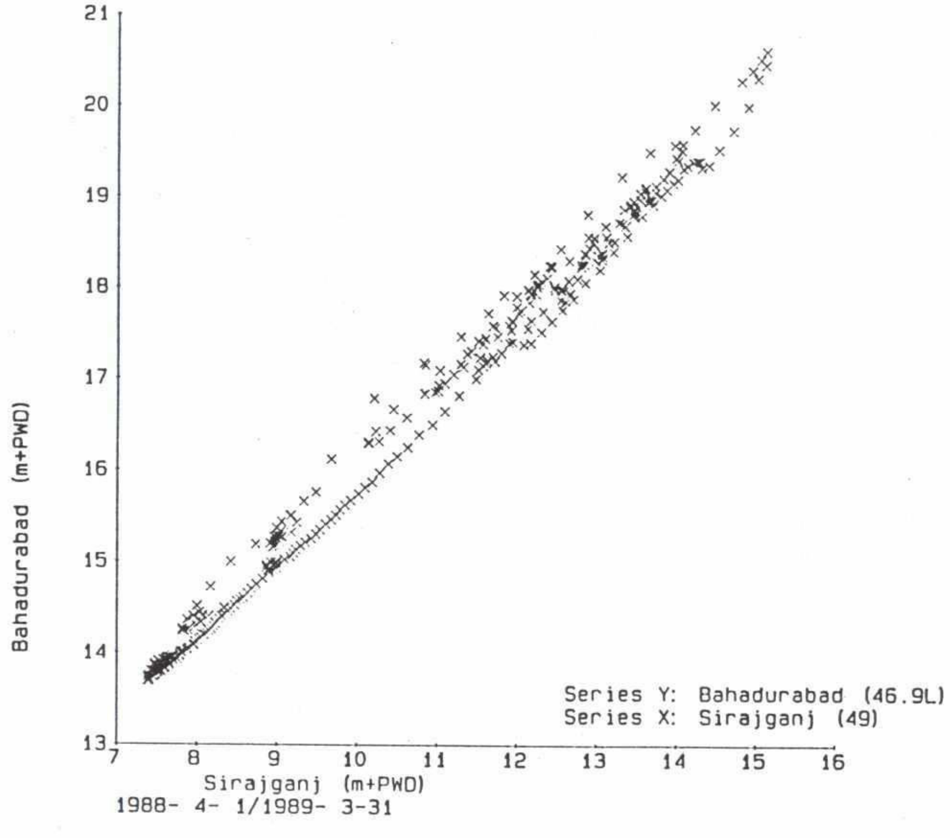

Figure 10.1-d

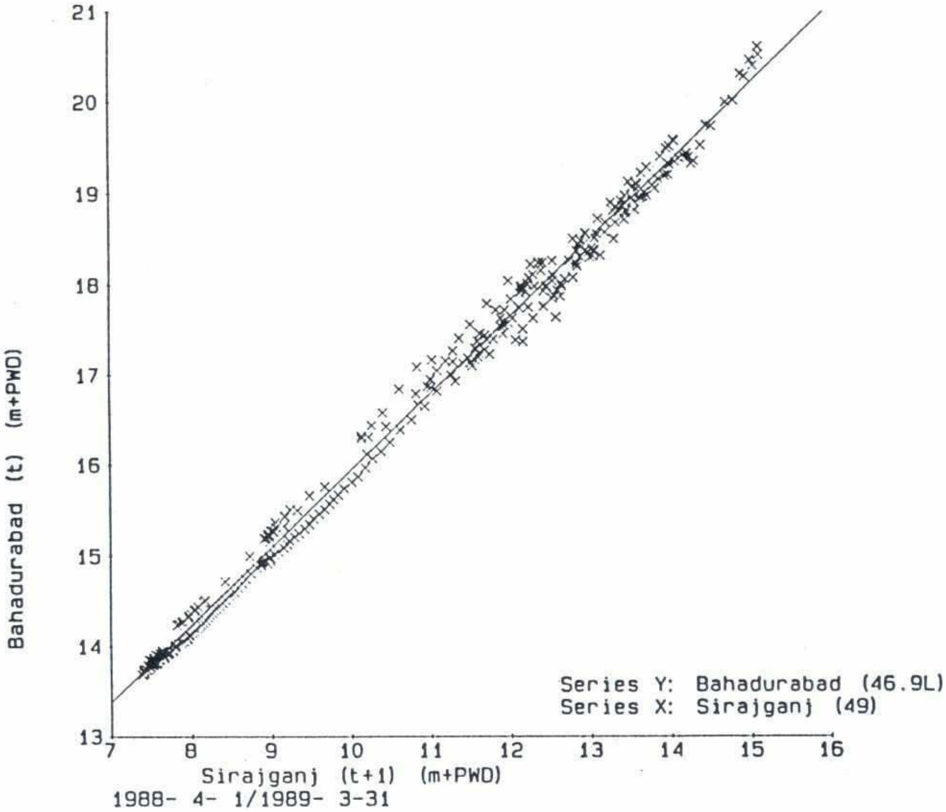

Figure 10.1-e

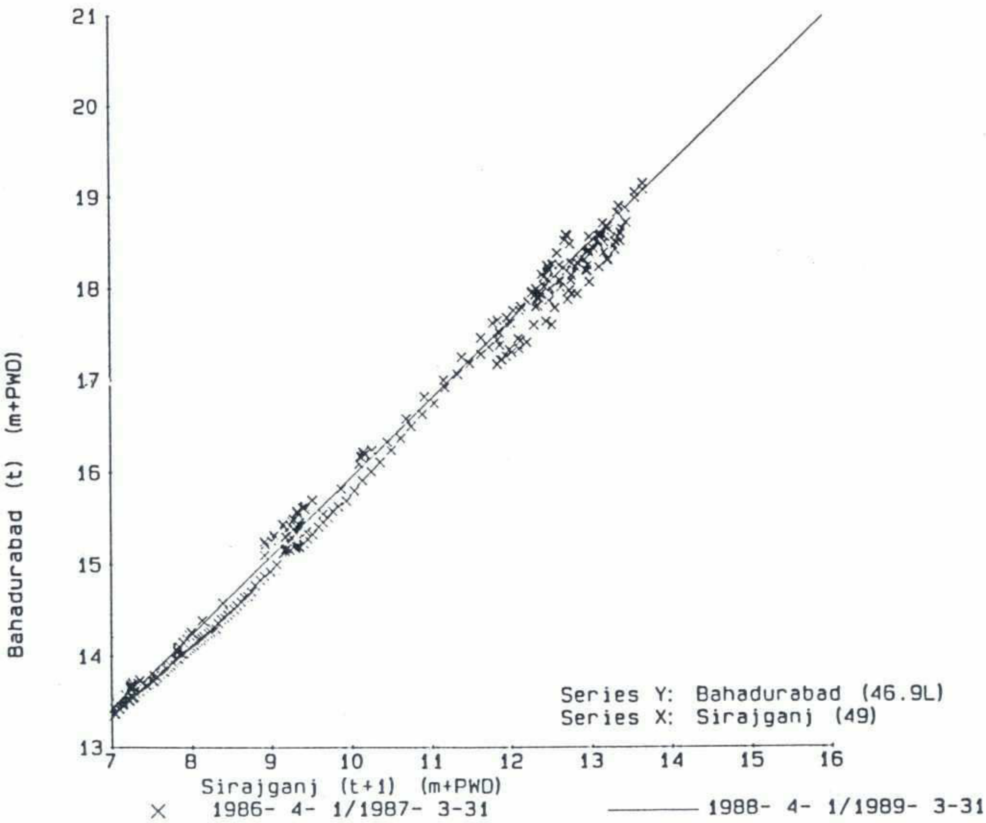

Figure 10.1-f

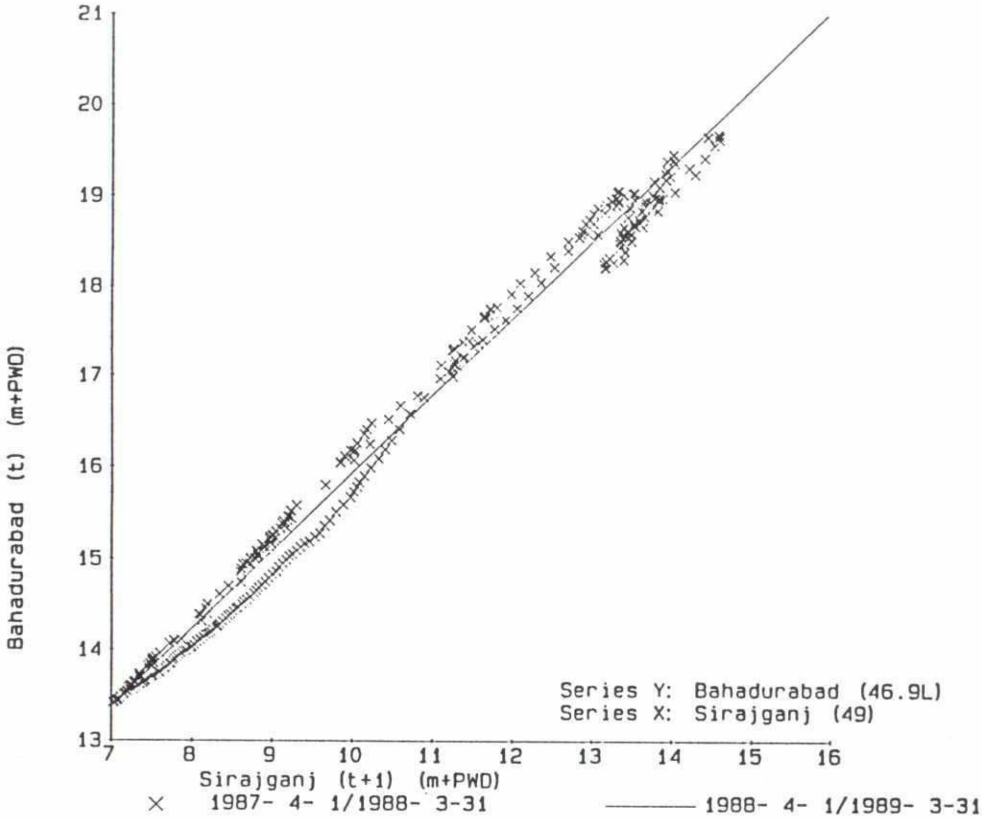

Figure 10.1-g

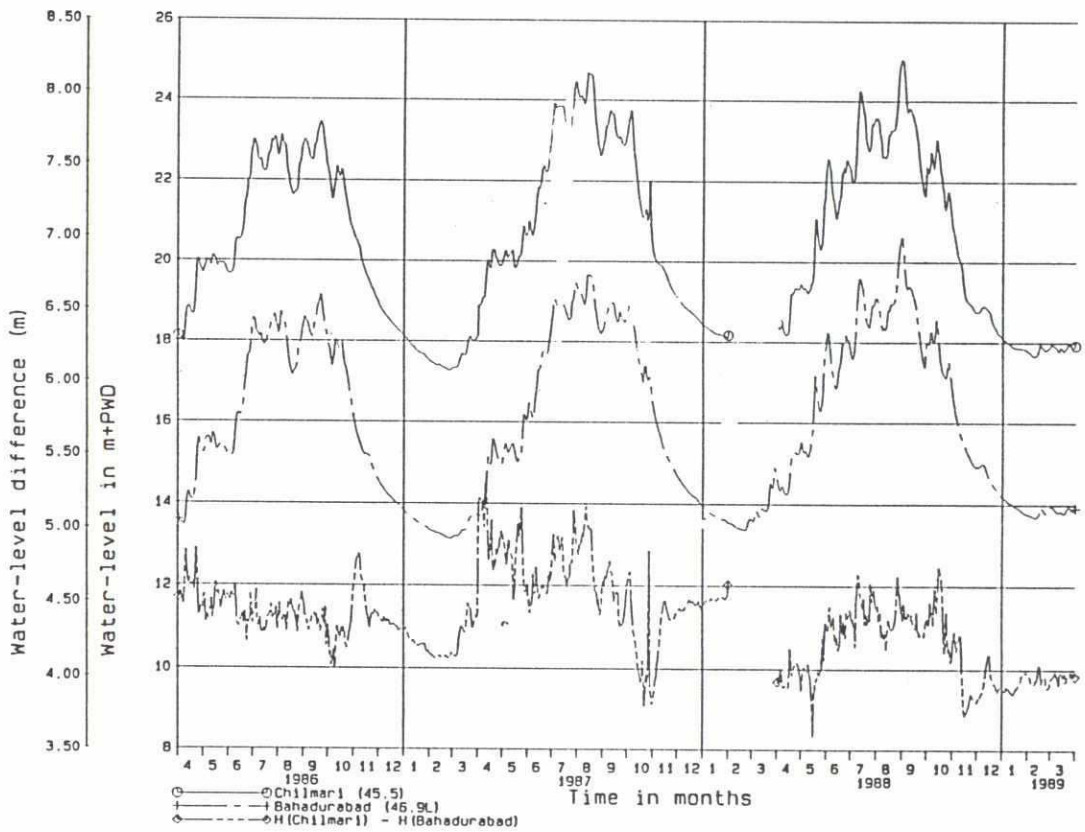

Figure 10.1-h

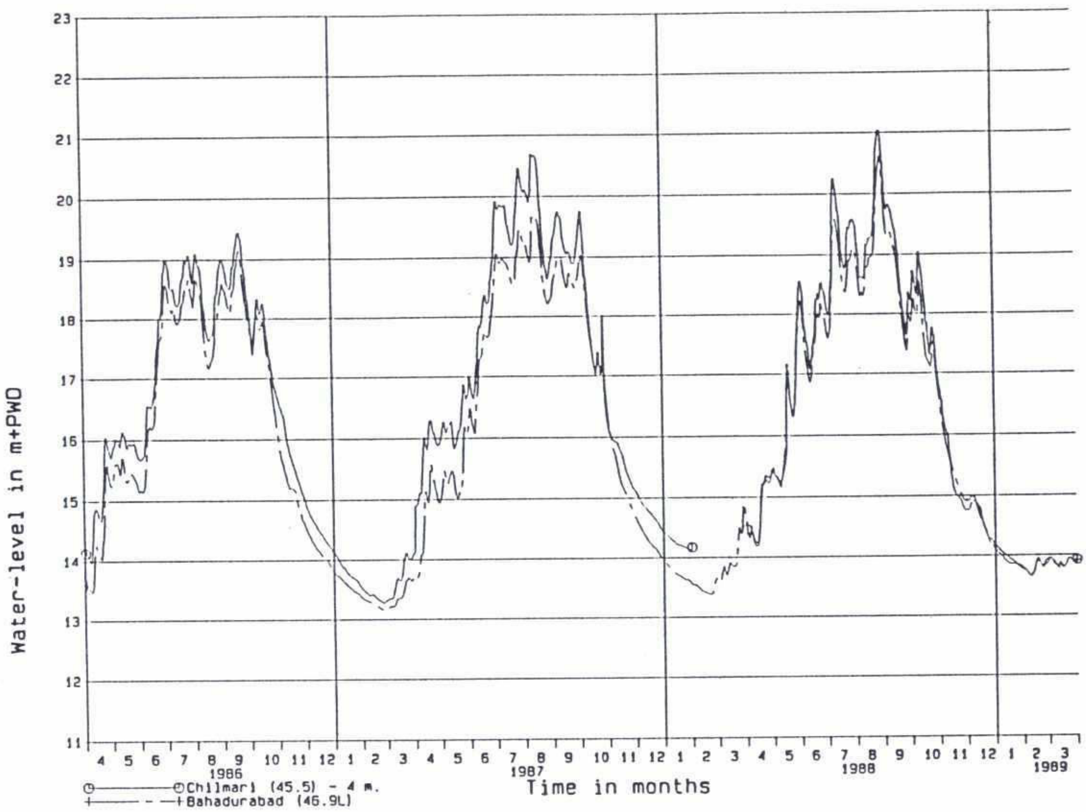

Figure 10.1-i

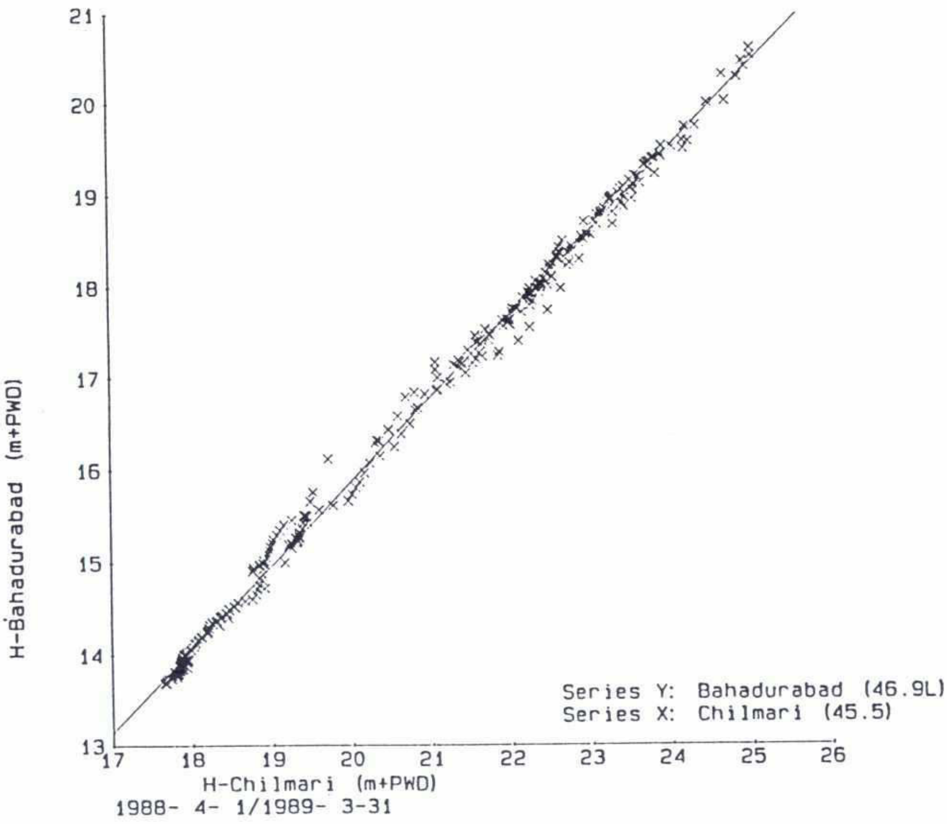

Figure 10.1-j

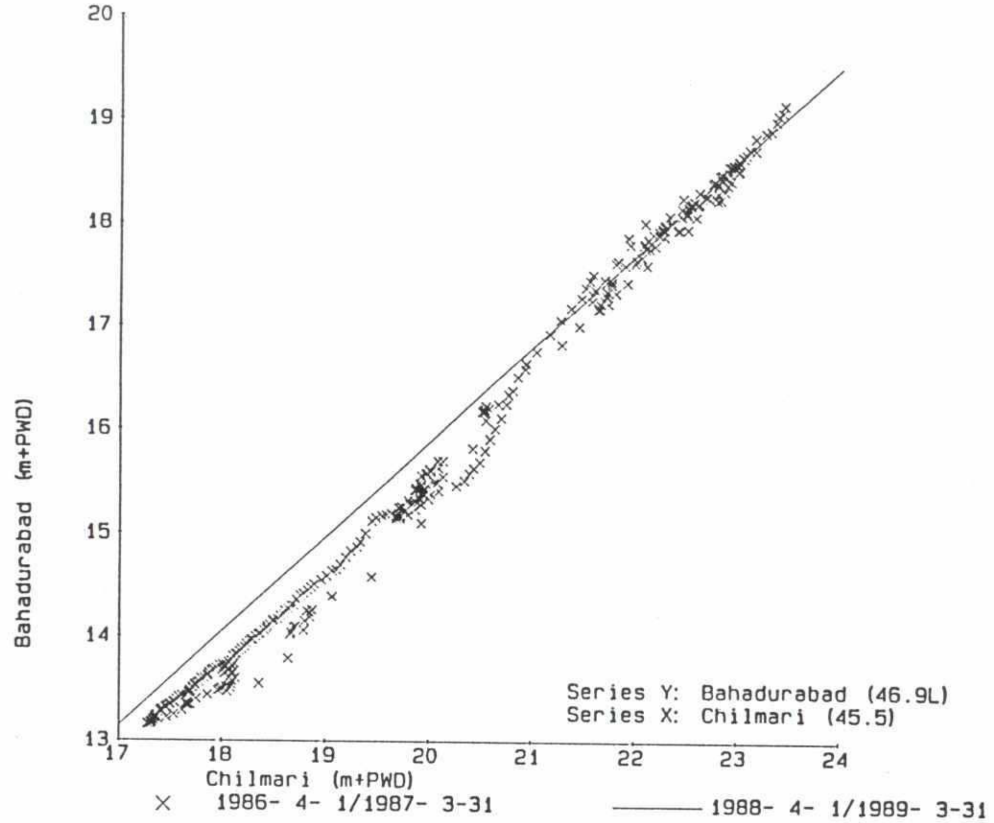

Figure 10.1-k

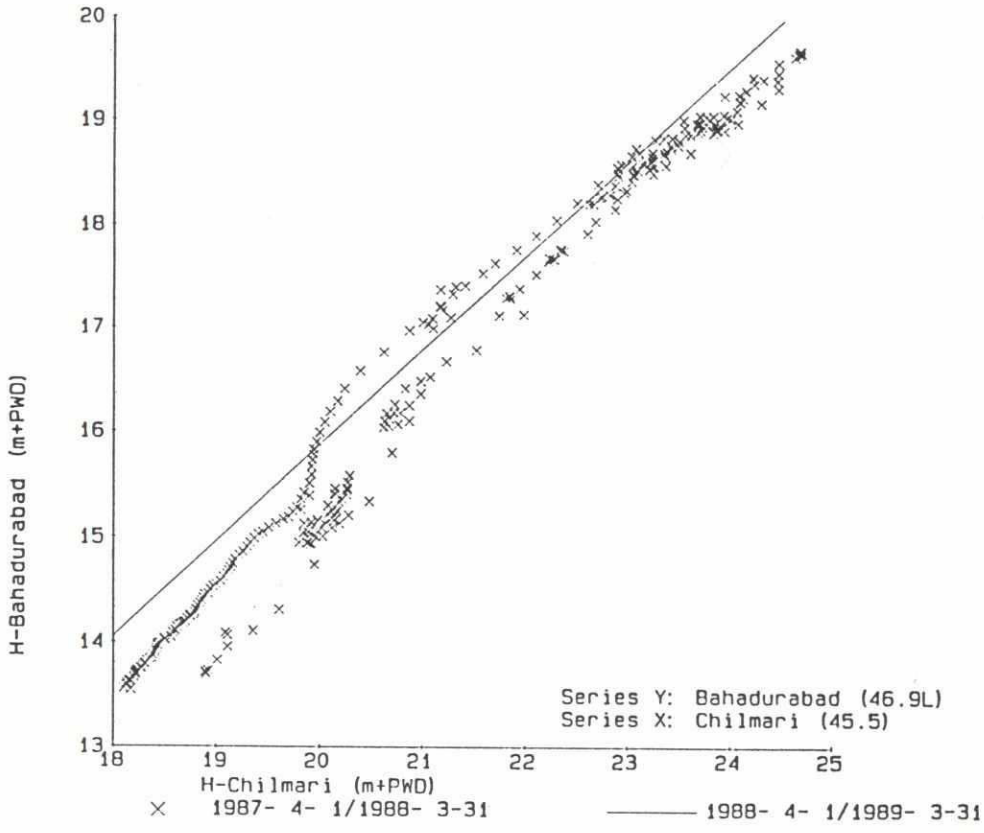

Figure 10.1-l

10.3.2 Stage-discharge relations

The following procedure is recommended.

1 – **For each discharge station:** For all years plot year-by-year the available Q/H-measurements on linear plot and log-log plot (i.e. two plots for each year). In order to obtain plots of an appropriate scale, in particular the log-log plots, it is necessary to adjust the scales by trial and error, i.e. the selected values of Hmin, Hmax, Qmin, Qmax. These are of course selected according to the range of H and Q for the actual stations. But on the log-log plot HYMOS automatically assumes Hmin and Qmin to be either 0.01, 0.1, 1.0, 10, 100 etc, so select the highest of these values which are still less than the minimum observed H and Q.
Important: ***For each station use the same scale for all years.***

Examples of scale applied for various stations in Bangladesh:

Station	Min Q	Max Q	Step Q	Min H	Max H	Step H
46.9 BAH	1001	100.000	10.000	10.01	21.0	1.0
90.0 HAB	101	100.000	10.000	1.0	16.0	1.0
91.9L BAR	1001	150.000	10.000	0.1	10.0	1.0
93.5L MAW	1001	150.000	10.000	0.1	10.0	1.0
273. BBZ	1001	24.000	2.000	0.1	10.0	1.0
99.0 GRB	0.1	10.000	1.000	1.0	15.0	1.0

2 – **For each station/year: On the linear plot:**

- Draw manually the approximate rating curve through the Q/H-points.
- Mark which points are non-reliable (i.e. far away from the curve).
- Compare the approximate rating curve for each year with the curve for the year before and after so as to determine if the same or similar rating curves can be used for successive years, or if major changes have occurred (e.g. after big floods).
- Note on the plot for each year the maximum observed mean daily water level that year, so as to assess the importance of extrapolation.
- Determine the need for extra points for extrapolation of rating curve, e.g. by using a high Q/H point measured the year before or after if the rating curves seem similar.

3 – **For each station/year: On the log-log plot:**

- Determine the approximate location of break points and number of segments (maximum three segments in HYMOS).
- Determine approximate values of Ho for each segment using the next guidelines:
- If the Q/H-points for a segment plot as a straight line: Ho approximately equal to the selected Hmin on the H-axis.
- If the Q/H-points for a segment plot as a curve bending upward: Ho > selected Hmin.
- If bending downward: Ho < selected Hmin.
- Usually the Ho-value is higher for upper segments than for lower segments.

4 - Fitting rating curves with HYMOS

With the preliminary results of Activity 2 and 3 for each year in mind, start the fitting of the appropriate rating curve for each year by HYMOS using the "Standard Procedure". The aim is to fit the best possible rating curve through the observed Q/H-points each year using the Power function option $Q = c\,(H + a)^b = c\,(H - Ho)^b$, i.e. to fit the best possible parameters a (= −Ho), b and c for each segment and to determine the most appropriate break points between segments.

In the following some guidelines and hints for rating curve analysis with HYMOS are given. The following steps should be done for each year of rating curve analyses.

4.1 If it appears from Activity 2 above that the same rating curve can be used for two successive years, for which a HYMOS-rating curve has already been developed for the first year, then check it by plotting the Q/H-points for the actual year together with the already developed rating curve for the other similar year (using the option "Validation of rating curves" in main menu). If it fits nicely, then store the same parameters/break points in the rating curve data base for the actual year and go to 4.5. If it does not fit well, go to 4.2 below.

4.2 Using the option "Adjust" Q-H data use flag O to "delete" non-reliable Q-H points from the following analyses.

4.3 First use the option "a not fixed".

- Fill in the number of segments.
- Fill in the lower and upper limits for each segment (use an overlap around estimated break point(s)).
- Calculate and plot rating curve on the screen.
- Based on the linear plot, get a first impression of the fit of each segment and adequacy of estimated break points.
- On log-log plot: The points of the lowest segment should have a unbiased fit to the straight line. If not, the calculated value of a for the lowest segment is not correct.
- If required for obtaining reasonable extrapolations, include extra high Q/H-points from other years.
- In option "Error Analysis" the calculated break points and parameters a, b, and c for each segment are listed. Evaluate the estimated a-values and exponents b. The values of b should usually be in the range of 1.5-3.0. If b is too high the Ho value should be higher (i.e. a = −Ho smaller). Use the experience from other years from the same station as a guideline to assess reasonable a-values.

4.4 Then use the option "a fixed"

- Fix a value for each segment and calculate and plot the rating curve again.
- On the linear plot: Evaluate the fit of the rating curve for all segments, in particular the upper segment used for extrapolations.
- If necessary for obtaining good extrapolation, include high Q/H points from other years as extra points.
- On the log-log plot: Check that the points of the lowest segment fit unbiased to the straight line.

- On linear plot: If the fit is not satisfactory, modify location of break point(s) to obtain a better fit.
- If required, modify a-values again and repeat the exercises 4.4 above again until the best possible fit for each segment is obtained, in particular for the upper segment used for extrapolation.

4.5 When a good fit is obtained for all segments, store the obtained parameters for that year.

4.6 Using option "Validation of rating curves" in Main menu :

Plot on printer of

- Parameters.
- Linear plot + log-log plot of "final" rating curve together with the Q/H-points.

4.7 Compare the resulting rating curves for successive years and check the similarity of the curves, in particular with respect to extrapolations. If necessary modify the upper segment curves (used for extrapolations) for the individual years so that they become more similar/consistent.

For stations along the same river reach, with relatively little in- or outflow, stage-relation curves (adjusted for travel time) are advised to be used to transfer the flow measurements at one site to the other to investigate the consistency of the established stage-discharge relation.

10.3.3 Discharge data

Historical series

After the transformation of stages into discharges using for the time being the rating curve the average daily discharges should be aggregated to monthly values. Based on these monthly series water balance checks are to be made to investigate the consistency of the discharge series.

Data of the current year

Water balance checks as decribed above should be executed monthly to allow for immediate measures in case of anomalies. For the stage-discharge transformation the rating curve of the last year can be used. This check is to be repeated at the end of the year using the rating curve established for the measurements of that particular year.

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