FAP24

Government of the People's Republic of Bangladesh

Water Resources Planning Organization

European Commission

Delft Hydraulics

Danish Hydraulic Institute

Hydroland
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RIVER SURVEY PROJECT

Special Report No.18

Sediment rating curves and balances

October 1996

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Acronyms and abbreviations

ADCP	: Acoustic Doppler Current Profiler
BCL	: Bangladesh Consultant Limited
BWDB	: Bangladesh Water Development Board
CBJET	: The China Bangladesh Joint Expert Team
FAO	: Food and Agriculture Organisation
FAP	: Flood Action Plan
FEC	: French Engineering Consortium
GJP	: Ganges-Jamuna-Padma
ISO	: International Standard Organization
LRP	: Land Reclamation Project
MPO	: The Master Plan Organization
NEDECO	: Netherlands Engineering Consultant
RPT	: Rendel Palmer and Tritton
RSP	: The River Survey Project (= FAP24)
SWH	: Surface Water Hydrology (under BWDB)
SWMC	: Surface Water Modelling Centre
UNSF	: United Nations Special Fund
WAPDA	: Water and Power Development Authority
WMO	: World Meterological Organisation

1 Introduction

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

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

The project consisted of three categories of activities:

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

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

The present report was prepared as a monograph within this study programme. Related reports are *RSP Special Report 12: 'Optimization of sediment measurements', RSP Special Report 13: 'Sediment transport predictors', RSP Special Report 19: 'Joint BWDB/RSP measurements, hydrology'*, and *RSP Final Report Annex 3: 'Sediment transport'*.

The study was been carried out and reported by Saleem Mahmood, River Morphologist-FAP24.

The present report was first submitted in December, 1995, as *RSP Study Report 19*. It was reviewed on behalf of WARPO by the PA, prof. J. J. Peters, and by prof. J. U. Chowdhury, BUET. To the extent practical, the comments received have been incorporated in the present edition. Some more far-reaching professional questions raised by the reviewers have been addressed elsewhere in the final reporting of the RSP.

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

2 Background, objectives and approach

2.1 General

The relationship between the discharge and the sediment transport, which is calculated from the samples taken in a transit (transect), can be expressed by an average curve. This curve, generally referred to as a sediment rating curve, is often an exponential function, which can be determined either by a regression analysis or from a graph with the data points (discharge, sediment transport) on a logarithmic scale. These curves are widely used to estimate the sediment concentration or the sediment transport for periods where discharge data are available, but sediment transport data are not.

The reliability of the sediment transport calculated from a rating curve depends upon the quantity and reliability of data used to define that rating curve, and whether the data are representative for the discharges and sediment transports occurring during the period for which sediment transports have to be estimated. Furthermore, a sediment rating curve between S and Q assumes a unique relationship between the average flow velocity in a cross-section and the shear stress at the river bed. This unique relationship exists in a steady uniform flow with a fully developed boundary layer. In these flows, the vertical flow velocity profile is a logarithmic profile or a power-law profile. And this unique relationship requires more or less prismatic cross-sections with only one channel in a cross-section of the river.

However, in an accelerating or decelerating flow, deviations can be expected relative to a sediment transport rating curve. These types of flow occur in bends, near bifurcations and confluences of the channels of a braiding river, and during the rising and receding limbs of the hydrograph. Consequently, the sediment rating curves in the main river system in Bangladesh are regression lines fitted to a strongly elongated cloud of data points. In principle, this can be improved with a sediment transport formula, which gives the sediment transport as a function of the bed shear stress. In 1-dimensional modelling, these sediment transport prediction formulas are used instead of sediment rating curves.

The sediment transport is measured regularly at certain gauging stations along the main river system of Bangladesh by the Bangladesh Water Development Board (BWDB). The sediment transport, which is determined from the sediment measurements in a transect, is analyzed as a function of the discharge only, in order to establish the sediment rating curves (Chapter 3). The coefficients of such a sediment rating curve have to determined separately for each river branch, and the coefficients are often valid for a limited period only, depending on the morphological processes. These sediment rating curves can be used to establish a sediment balance for a river branch or a river network (Chapter 4).

A general tendency for sedimentation or erosion in a river branch can be concluded from a sediment balance. These tendencies are important for an estimation of the long-term morphological development of the entire river delta. There are certain inconsistencies in the sediment transport data measured by BWDB (Chapter 5). 1-dimensional morphological modelling is a useful tool to explore those inconsistencies (Chapter 6).

2.2 Objective

One activity of the River Survey Project (RSP) is a review of all available sediment transport data collected by BWDB from the main gauging stations in the major rivers of Bangladesh, and to examine the reliability of these data. During various studies it was observed that there are inconsistencies in the BWDB sediment transport data. Here, an attempt has been made to verify these data inconsistencies, and to produce suitable sediment rating curves for the stations located on the major river system.

Another aim is to estimate sediment balances between the major stations by means of sediment rating curves, in order to determine the long-term development trend of the river system.

2.3 Approproach

The present study has been divided into different phases, as follows:

Planning phase

An inventory of the sediment gauging stations on the major river system was done. It was found that continuous long-term series of data are available from the following stations:

- Stations on major rivers:
    - Bahadurabad (Jamuna)
    - Hardinge Bridge (Ganges)
    - Baruria (Padma)
- Stations on distributaries:
    - Taraghat (Dhaleswari)
    - Jagir (Kaliganga)
    - Gorai Railway Bridge (Gorai)

The Bhairab Bazar station was not included, as only few data are available, and also, the coarse sediment transport is negligible. The Mawa station is tidal and has therefore been left out in this study. The location of the gauging stations are shown in Figure 2.1.

Based on the data, a sediment balance can be made at Baruria on the Padma River, where the flows are converging from the Jamuna and the Ganges Rivers.

Data collection phase

The sediment transport data have been collected from the Hydrology Department -II, BWDB. Some of the data were available on computer diskettes, and some were taken directly from the field sheets.

Data analysis

A distinction was made between bed material load (grain diameter larger than 63 micron) and wash load (grain diameter smaller than 63 micron). Then, the suspended bed material discharge and the fine (wash load) sediment discharge were computed. The following analyses were carried out:

- Separate rating curves were produced with the following considerations:
    - Sediment rating curves at each station were produced for different periods (each period having a consistent sediment transport)
    - Seasonal effects (dry period, rising flood and falling flood) on sediment transport data were also investigated
- With the use of the sediment rating curve (equation), the daily sediment transport rate was estimated from the mean daily discharge

- The consistency of sediment transport data at each station was investigated
- The daily sediment transport computed from the rating curve was used for estimation of the sediment balance (fine and coarse)
- A 1-D mathematical model was used for a qualitative assessment of the inconsistencies
- The sediment transport measured by RSP was used for comparison

2.4 Observations on the available sediment data

The collection of suspended sediment data started long before the sixties by the Hydrology Directorate of Water and Power Development Authority (WAPDA), at Bahadurabad, Hardinge Bridge, Gorai Railway Bridge and Bhairab Bazar. In the beginning, the results were expressed in Parts Per Million (PPM) and were published by the Hydraulic Research Laboratory. No distinction was made between the coarse and the fine fraction of the suspended sediment. This created a confusion to many authors with respect to the gradation of the samples, and whether these represented coarse or fine or total suspended sediment.

In 1965, it was realized that data on the sediment transport in the main rivers were insufficient, for example for an assessment of the changes in the sediment transport in the main rivers after the completion of any water resources development programme in Bangladesh. The 'Food and Agriculture Organisation-United Nations Special Fund' (FAO-UNSF) Hydrological Survey Team started a sediment transport investigation in 1965 on a more rational footing, using improved techniques at key locations on the rivers in Bangladesh. However, it was confined to suspended sediment transport, as it was practically impossible to organise and operate collection of bed load transport measurements on a regular basis.

No sediment transport measurements were carried out during the Liberation War in 1971. In 1972, regular measurements were resumed. Some data on coarse sediment transport could not be traced, although the measurements were carried out, according to indications in the inventory of fine sediment data of the said periods. The gauging stations which have missing periods of coarse sediment transport data are shown in Table 2.1

Sediment Gauging Station	Missing periods after 1965
Bahadurabad	1971-1975
Hardinge Bridge	1971-1975
Baruria	1971-1975
Mawa	1974, 1975, 1977-1979, 1981 and 1982

Table 2.1: Missing periods of coarse sediment transport data

A possible reason for the missing data is misplacement during moving the Office of the Hydrology II to its present location.

The following stations have no data on fine and coarse sediment transport for certain periods:

- At Baruria station, only data for July is available from the year 1980
- At Mawa station, only data for October is available for the year 1990
- At Bhairab Bazar station, no data is available for 1982

- At Mymensingh station, it appears that the sediment transport measurements were discontinued in 1971 and resumed in 1988. The reason for this long break is not known

- The Taraghat station has a very long series of coarse sediment transport data but no record on fine sediment transport. In 1983, neither data on coarse sediment transport nor on fine sediment transport are available

- At Jagir station, no sediment record is available since the hydrological year 1970-71. Apparently, the importance of the river near Jagir has been reduced due to siltation in the river in such a way that the sediment measurements were stopped

Sediment transport measurements are carried out at all the stations during the monsoon period May to November and, in some years, until December. At Bahadurabad station, the sediment transport is measured for the entire year. FAP3 (BCEOM, 1993) has reported that at Bhairab Bazar, the maximum sediment transport intensities occur probably during the pre-monsoon season, however during the pre-monsoon no sediment transport measurements have been carried out here. The available sediment transport data are summarized in Annex 1.

Please refer to *RSP Special Report 19: 'Joint BWDB/RSP measurements, hydrology'*, and *RSP Final Report Annex 4: 'Sediment transport'* for a discussion of the general quality of the data.

3 Sediment rating curves

3.1 Development of sediment rating curves

Sediment rating curves can be developed with either the sediment concentration, the specific sediment transport, or the sediment transport as a function of the discharge or of the specific discharge for a transect.

Methods commonly used include a visual graphical fit, a group average, and a linear regression of log-transformed data. In a graphical analysis, the sediment transport as a function of the discharge has less scatter in a graph than the sediment concentration as a function of the discharge. Less scatter means that the curve can be fitted more accurately visually (Glysson, 1987). Mathematically, however, the two relationships will produce identical results.

In this report we will discuss the rating curve produced from the relationship between the discharge and the sediment transport measured in a transect. This curve is an exponential function, which is determined from a graph with the data points on a logarithmic scale. The general equation reads as:

$$S = A \cdot Q^B \qquad (3.1)$$

where

S = suspended bed material transport in tons/day
Q = discharge in m^3/s
A and B are coefficients

It is important to note that if a straight line can be fitted through a set of data points, this does not mean necessarily that the line accurately defines the physical relationship between the variables during a long period.

Several factors can have an effect on the shape, slope, and interception of the sediment rating curve, such as: The different seasons, the time lag between the peak with the maximum sediment concentration and the peak with the maximum discharge, and extreme high water events. The seasons can have a significant effect on the sediment yield. A time lag between the peak in the sediment concentration and the discharge peak can also drastically affect the shape of a sediment rating curve.

3.2 Historical review

Sediment rating curves were first made in Bangladesh by the Hydrology Directorate for seven gauging stations for the years 1966 and 1967. These curves were produced in graphs with the log-transformed discharge in cusec (m^3/s) as the ordinate and the log-transformed sediment transport in ton per day as abscissa. The rating curves were fitted to the data points in the graph by visual estimation (FAO-UNSF, Second Hydrological Survey, Dhaka, April 1969) for the gauging stations at Bahadurabad, Goalundo and Gorai Railway Bridge. Those rating curves were not very accurate. Especially, extrapolation of those curves to higher and lower discharges results in inaccurate estimations of the sediment transport. In general, these curves are only representative for the period in which the data were collected.

For the stations at Bhagyakul (Mawa), Paksey (Hardinge Bridge), Kamarkhali (Gorai River), Taraghat, Jagir, and Mymensingh, linear rating curves were determined by visual estimation from the data points plotted in a log-log graph. For the stations at Bhagyakul and Kushtia, the rating curves for 1966 were rather erratic, but showed an improvement in 1967. This is probably because the experience in the field of sediment transport measurements was increased. The rating curves for 1966 and 1967 at both Paksey and Taraghat are rather poor, while those for Kamarkhali, Jagir, and Mymensingh are reasonably satisfactory.

In all the graphs, the discharge was drawn as the ordinate, which can create some confusion in understanding the curves. In general, the possible reasons for outliers were not noted.

Later, for the hydrological years 1968-69 and 1969-70, sediment rating curves for suspended coarse sediment were determined for ten stations, see the report 'Sediment Investigation, Hydrology Directorate (Surface Water), Dhaka, December 1972'. Those stations are: Bahadurabad, Goalundo, Baruria, Hardinge Bridge, Mawa, Gorai Railway Bridge, Kamarkhali (Gorai), Mymensingh, Taraghat, and Jagir. Again, the rating curves were drawn in log-log graphs with the discharge as the ordinate and the sediment transport as the abscissa. The rating curves for those two years did not show a good correlation, except the ones for Bahadurabad station.

In later years, sediment rating curves were assessed in various studies of the major rivers of Bangladesh, mainly the Jamuna and the Ganges Rivers. Often, each study has its own approach for the development of a sediment rating curve, depending on the objectives of the study. In general, rating curves were determined for suspended bed material transport, but in some cases also for the total sediment transport (including wash load), and for the total suspended sediment transport. In the following, the rating curves presented by different studies and authors are summarized.

M. M. Hossain (1992) has defined a sediment rating curve for the Jamuna and the Padma Rivers. He has developed an empirical formula for the prediction of the total sediment load (suspended fine and coarse plus bed load transport). With this formula, the total sediment load was calculated by utilizing hydraulic data for the Ganges River at Hardinge Bridge. His sediment rating curve for the Ganges River is based on data from the period 1980 - 1987 and reads as:

$$S_T = 0.74 \cdot Q^{1.48} \qquad (3.2)$$

where S_T = total sediment load (ton/day)

It is well known that the sources of fine and coarse sediment in the rivers are different. The origin of the fine sediment is the river catchment and bank erosion, while the coarse sediment originates from the bed material. For large wandering rivers with a regularly and strongly variable discharge, mobilization of the fine material from the bed can also from the river bed. The transport of bed material is an important factor for morphological planform changes in a river. The value of about 1.5 (the exponent on Q is roughly 3 times the exponent on the flow velocity) for the exponent of the above equation is very reasonable for a river like the Ganges River.

In the same way, Hossain has also established a sediment rating curve on the total sediment transport for the Jamuna River, based on the data from the period 1980-1987, which reads:

$$S_T = 4.02 \cdot Q^{1.30} \tag{3.3}$$

The study of the China-Bangladesh Joint Expert Team has been reported in 'Flood Control and River Training Project on the Brahmaputra River' (CBJET, 1991). In this report, relationships between the daily sediment transport rate and the daily discharge from the years 1968 to 1980 are shown. They indicate remarkable variations from year to year. In the graphs, the discharges are taken as the ordinate and the suspended sediment transport as the abscissa. In general, the rating curves based on data from the period 1968-1969 read as:

$$S = A \cdot Q^B \tag{3.4}$$

where

A	= a constant	(-)
B	= a constant	(variable)
S	= suspended sediment transport	(variable)
Q	= discharge	(m^3/s)

The value and dimension of the constant A depends on the unit of the suspended sediment transport:

S in tons/day : $A = 4.37 \cdot 10^{-6}\ (m^3/s)^{1-B}$
S in kg/s : $A = 3.77 \cdot 10^{-4}\ (m^3/s)^{1-B}$
S in m^3/s : $A = 1\ (m^3/s)^{1-B}$

The values of the coefficients A and B are given in Table 3.1.

Period	Discharge	A	B
1968-1969		$8.59 \cdot 10^{-3}$	1.48
1980-1981		$9.23 \cdot 10^{-4}$	1.60
1981-1982	Q < 6,000	$1.07 \cdot 10^{-5}$	2.11
1981-1982	Q > 6,000	$7.16 \cdot 10^{-4}$	1.63

Table 3.1: Coefficients of the rating curves for Jamuna according to the CBJET (1991)

In the Report on the Jamuna Bridge Study (RPT/NEDECO/BCL, 1989), a rating curve was made, based on (coarse) suspended bed material data of the period 1968-1970 collected from the Jamuna river at Bahadurabad. This relation reads as:

$S = 4.1 \cdot 10^{-6} \cdot Q^{1.38}$ (3.5)

where S = suspended bed material (m^3/s)

During the same study, the magnitude of the bed load transport in the Jamuna River was estimated by dune tracking measurements during the flood of 1987. It was estimated that the bed load is about 10 % of the suspended bed material load. This 10% is added to the instantaneous discharge and is most likely variable with discharge. Thus, the total sediment load in the Jamuna River can be approximated by:

$S_T = 4.5 \cdot 10^{-6} \cdot Q^{1.38}$ (3.6)

where S_T = the total sediment load (m^3/s)

In the River Training Studies of the Brahmaputra River (Halcrow/DHI, 1993a), rating curves are drawn for the suspended sand transport for the period 1982-1988 and for total (fine and coarse) suspended load for the period 1982-1988. The rating curves read as:

A Total suspended sediment transport (1982-1988)

$S_{ST} = 0.91 \cdot Q^{1.38}$ (3.7)

where S_{ST} = total suspended sediment transport (ton/day)

B Suspended bed material load (1982-1988)

$S = 0.93 \cdot Q^{1.25}$ (3.8)

where S = suspended bed material load (ton/day)

In the FAP4 study (Halcrow/DHI 1993), a suspended bed material rating curve was derived for the Ganges River by regression analyses, which reads as:

$S = 4.33 \cdot 10^{-6} \cdot Q^{2.56}$ (3.9)

where S = suspended bed material load (ton/day)

It has been reported that one single sediment rating curve will not accurately represent the sediment transport under all conditions. For example, when the Ganges River is backed up by high discharges in the Jamuna River, some sediment deposition may be induced in the Ganges, and the sediment transport may be reduced. The exponent found in the above formula is relatively high and indicates a greater increase than expected in sediment transport with an increase in discharge. The high value of the exponent may be due to the constriction at the bridge site.

The rating curve at Hardinge Bridge was consistent with a morphological model which was developed by the Surface Water Modelling Centre (Galappatti, 1993), and which showed strong seasonal changes in bed level. SWMC derived the following equation for a more typical upstream reach of the Ganges river. Further, SWMC verified that using this sediment rating curve, the model calculates a sediment transport at Hardinge Bridge in agreement with the measured sediment transport:

$S = 0.54 \cdot Q^{1.43}$ (3.10)

FAP4 (Halcrow/DHI, 1993) has also developed a rating curve for the Gorai River from the data collected at Gorai Railway Bridge. There are two gauging sites on the Gorai River, namely Gorai Railway Bridge and Kamarkhali. The Railway Bridge site has the longer period of records of the entire discharge entering the river, whereas there may be some over-bank flow during high floods over the left bank before Kamarkhali. The sediment rating curve at Gorai Railway Bridge for the period 1966-1967 reads as:

$$S = 5.10 \cdot Q^{1.23} \tag{3.12}$$

3.3 Analysis of the River Survey Project

The River Survey Project (RSP) has analyzed almost all sediment transport data measured by BWDB during the period 1966-1994. RSP has also collected sediment transport data for the period 1958-1965, but did not analyze those data, because they are extremely scattered and were not separated into a fine and a coarse fraction. In the present study, the sediment data from the following gauging stations were analyzed: Bahadurabad, Hardinge Bridge, Baruria, Goalundo, Taraghat, Jagir, and Gorai Railway Bridge.

During Phase 1, sediment rating curves were produced for the suspended coarse fraction (suspended bed material) and for the fine fraction (wash load) separately (DELFT/DHI, 1993a).

Sediment transport data were divided into two periods, 1966-1970 and 1976-1988. This separation was based on data consistencies, statistical correlation, etc. It was noticed that these two periods exhibit different quantities of sediment transport. The sediment rating curve from 1966-1970 shows a sediment transport which is at least 2 times as high as compared with the rating curve of the period 1976-1988. The exponent 'B' of the sediment rating equation (3.1) varies between 2.5 to 3.0 for the gauging stations Baruria and Hardinge Bridge, which is exceptionally high. In general, the value of B should vary between 1.2 and 1.8 for the rivers in Bangladesh, which is also the case with the Bahadurabad station.

During Phase 2, at each gauging station, a more detailed grouping of sediment periods was made. Additionally, recent sediment transport data (until the hydrological year 1993-1994) were collected for the stations: Bahadurabad, Hardinge Bridge and Baruria. In this elaboration of the rating curve, only suspended bed material transport data were analyzed. Comparatively high or low sediment concentration data (related to sediment plumes) were removed, and may be analyzed separately. Once again, the grouping in sediment transport data was based on the consistency of sediment transport between consecutive years. The coefficients A and B of the sediment rating equation for different periods are shown in Table 3.2 for Bahadurabad, Hardinge Bridge, Baruria, and distributaries.
A further analysis of the sediment transport data at the major stations is described in the following sections.

River	Station	Period	Coefficients $S = A \cdot Q^B$ tons/day A	B
Jamuna	Bahadurabad	1966-1988	0.30	1.38
		1966-1970	0.35	1.42
		1976-1988	0.46	1.32
		1976-1982	0.28	1.39
		1983-1988	1.00	1.21
		1993	0.04	1.46
Ganges	Hardinge Bridge	1966-1993	$5.50 \cdot 10^{-6}$	2.51
		1966-1970	$4.78 \cdot 10^{-6}$	2.56
		1976-1988	$3.30 \cdot 10^{-6}$	2.53
		1976-1982	$6.45 \cdot 10^{-7}$	2.70
		1983-1988	$2.57 \cdot 10^{-4}$	2.10
		1992-1993	$1.54 \cdot 10^{-1}$	1.54
Padma	Baruria	19661993	$2.50 \cdot 10^{-7}$	2.63
		1966-1970	$5.70 \cdot 10^{-8}$	2.85
		1976-1988	$1.00 \cdot 10^{-9}$	3.1
		1976-1982	$1.20 \cdot 10^{-10}$	3.32
		1983-1988	$5.75 \cdot 10^{-7}$	2.51
		1992-1993	$7.08 \cdot 10^{-5}$	2.06
	Goalundo	1966-1969	0.0073	1.77
		1976-1982	0.0062	1.93
Kaliganga	Taraghat	1967-1969	1.77	1.25
		1970-1988	2.03	1.24
Dhaleswari	Jagir	1967-1969	1.15	1.4
Gorai	Gorai Railway Bridge	1966-1970	4.6	1.25

Table 3.2: Coefficients A and B of sediment rating curves of the main river system

The accuracy of the different equation of the rating curves have been calculated by the following discrepancy ratio:

$R \quad = \quad S_{est}/S_{mea}$

where
S_{est} = estimated sediment transport from rating curve

S_{mea} = measured sediment transport

Bahadurabad

The sediment transport data from the period 1966-1994 are plotted in Figure 3.1. The total number of data sets is 554. The data all together look scatter but this scatter is minimum within a bundle of distinct consecutive periods. The data for the period 1989 - 1991 were very scatter and it was reported by the RSP that the observed discharges during that period was wrong. Therefore this period is taken out from the analysis. In Figure 3.1 distinct bundles of sediment data from different periods are identified. A sediment rating curve drawn from all the data points has the value B = 1.37. However, on the one hand, this rating curve overestimates the gauging period 1983-1988, and, particularly, 1993, and, on the other hand, underestimates the period 1966-1970. Apparently, this rating curve mainly represents the period 1976-1982. From Figure 3.1 it is evident that a single rating curve cannot in a good way represent a long series of sediment transport data for the Jamuna river.

Sediment rating curves drawn for different periods are shown in Figure 3.2. This figure shows clearly that each consistent period of sediment transport should have its own sediment rating curve. The visual appearance of all the rating equations are shown in Figure 3.3.

The various regression line (equation for rating curve) were compared against the measured sediment transport. A criteria has been selected for validation of the sediment transport data is the discrepancy ratio i.e deviation of each measured point from the rating curve (regression line). The percentage of observation within closest discrepancy band (0.75-1.25) is 31% for all the data during the period 1966-1993 but this percentage increases sharply when the data are separated into different consecutive periods of consistent sediment transport (see Table 3.3). The ratio is about 20 for all the data and it becomes 2 when data are separated into different periods. In Figure 3.4, the discrepancy ratio is high up to 22 for low to moderate discharges and the ratio is below the range 4-5 for moderate to high discharges. Therefore, the data are more scatter at low to moderate discharges than moderate to high discharges.

Additional observations for this station are:

- Values of the coefficient 'B' of the different rating curves are within the allowable range (1.3-1.8)
- The sediment transport data and the rating curves show a decreasing trend in transport within the period 1966-1994
- The sediment transport is particularly high during the period 1966-1970
- The sediment transport is exceptionally low during the period 1993-1994

Sediment rating curve data period	Discrepancy ratio					Standard deviation	No. of data
	Mean	Percent of data in range					
		0.75-1.25	0.50-1.50	0.25-1.75	0.10-1.90		
1966-1993	1.81	31	59	74	78	2.59	661
1966-1988	1.09	38	72	89	93	0.47	520
1966-1970	1.01	64	87	97	98	0.34	126
1976-1988	1.05	48	81	97	99	0.36	394
1976-1982	1.01	59	93	97	99	0.31	216
1983-1988	0.98	80	99	99	100	0.20	178
1993	0.78	97	100	100	100	0.26	35

Table 3.3: Discrepancy ratio of sediment transport data (BWDB), Jamuna, Bahadurabad.

Hardinge Bridge

The sediment transport data from the period 1966-1994 are plotted in Figure 3.5. The total number of data sets is 385. As compared with the Bahadurabad station, in this figure, the sediment transport data do not cluster into distinct periods. A sediment rating curve drawn from all the data points has the value B = 2.5, reflecting a considerably steeper slope than the Bahadurabad station. This rating curve seems to represent all the data. In Figure 3.6, rating curves are drawn for different periods. Here, the rating curve which was drawn from all the data is significantly under-estimating the transport for the period 1989-1994 for low to moderate discharges. This figure also shows that each consistent period of sediment transport should have its own sediment rating curve. It can be said for this station that a single rating curve cannot represent a long series of sediment transport data. The visual appearance of all the sediment equations are shown in Figure 3.7.

The percentage of data falling within different discrepancy band for Hardinge Bridge gauging station is shown in Table 3.4. The percentage of observation within closest discrepancy band (0.75-1.25) is 21% for all the data during the period 1966-1993 and this percentage did not vary significantly after separating the data into different periods 1966-1970, 1976-1982 and 1983-1988. This indicate that the data are scatter. But for the periods 1989-1991 and 1992-1993, the percentage of observation is high in the closest discrepancy band and thus less scatter in data. In Figure 3.5, the data are scatter even in the bundles of different periods and are concave downward at low discharges. In Figure 3.8, at low discharges the discrepancy ratio is high up to 12 indicating scatter in data but at moderate to high discharges the ratio is below 4. The scatter in sediment transport data is possibly due to the location of the gauging station at Hardinge Bridge which is situated in a artificially constricted reach of the Ganges river.

Additional observations for this station are:

- The sediment transport data are scattered
- The values of the coefficient 'B' are higher than the normal range
- There is a decreasing trend in the sediment transport during the gauging period 1966-1988
- The rating curves for the period 1989-1993 show a higher sediment transport than the previous years

Sediment rating curve data period	Discrepancy ratio					Standard deviation	No. of data
	Mean	Percent of data in range					
		0.75-1.25	0.50-1.50	0.25-1.75	0.10-1.90		
1966-1993	1.57	21	46	70	77	1.79	385
1966-1970	1.38	23	58	76	80	1.26	111
1976-1982	1.45	25	47	63	75	1.29	106
1983-1988	1.50	29	51	74	83	2.60	89
1989-1991	1.15	51	83	91	91	0.80	53
1992-1993	1.06	77	92	100	100	0.24	26

Table 3.4: Discrepancy ratio of sediment transport data (BWDB), Ganges, Hardinge Bridge.

Baruria

All the available sediment transport data from the period 1966-1994 are plotted in Figure 3.9. The total number of data sets is 339. In this figure, unlike the Bahadurabad station, the sediment transport data are very scattered at moderate to higher discharges. A sediment rating curve was drawn from all the data points and the value for the coefficient B is 2.63, which represents a considerably steeper slope as compared with the Bahadurabad station. The data points are very scattered, especially at the lower discharges, where the data points are shaped concavely downward. At a first look, it seems as if one single rating curve may represent all the data. However, this is not the case, as shown in Figure 3.10, where rating curves are drawn for different periods. The rating curve which was drawn from all the data gives a significant over-estimate for the period 1976-1982 and 1989 for low to moderate discharges, and an under-estimate for the period 1966-1970 for high discharges. A careful observation of this figure shows that most of the rating curves are expelling the data points of low discharges. This indicates a transition period between two stages of data points within a single consistent period. Therefore, not only each consistent period of sediment transport should have its own sediment rating curve, but also, within a consistent data period, more than one rating curve is required, i.e. one at higher discharges and another at lower discharges. The visual appearance of all the sediment rating equations are shown in Figure 3.11.

In Figure 3.9, the data are very scatter and are concave downward at low discharges. The percentage of observation within the closest discrepancy band is very low for all the data during the period 1966-1993 (Table 3.5). This percentage did not improve for the same band when the data are separated into different periods. In Figure 3.12, the discrepancy ratio is high up to 16 at low discharges which is the indication of very scatter in data at those discharges. In most cases the ratio is below 5.

The observations at this station can be summarized as follows:

- The sediment transport data are very scattered;
- at lower discharges, the sediment transport is shaped concavely downward;
- the values for the coefficient 'B' of the different rating curves are much higher than the normal range;
- A decreasing trend in sediment transport can be noticed during the gauging period 1966-1989;
- the rating curves for the period 1992-1994 show a higher sediment transport than the previous years.

Sediment rating curve data period	Discrepancy ratio					Standard deviation	No of data
	Mean	Percent of data in range					
		0.75-1.25	0.50-1.50	0.25-1.75	0.10-1.90		
1966-1993	1.70	17	38	49	73	2.72	338
1966-1970	1.30	27	58	76	79	0.89	144
1976-1982	1.10	30	54	73	84	0.80	37
1983-1988	1.10	41	70	94	94	0.62	66
1989-1991	1.02	42	84	95	100	0.37	19
1992-1993	1.67	39	58	86	86	4.05	36

Table 3.5: Discrepancy ratio of sediment transport data (BWDB), Padma, Baruria.

3.4 Comparison with the measurements of the River Survey Project

The RSP has conducted routine sediment and discharge gauging on most of the major rivers and distributaries. All the sediment transport data were analyzed. The sediment transport data were plotted for each station and are shown in the River Survey Data Book (RSP, 1995).

The RSP has used very moderate to high technique instruments. The Acoustic Doppler Current Profiler (ADCP) was used for discharge measurements. Depth Integrated and Point Integrated Samplers were used for suspended sediment measurements. Bed load samplers were used for bed load measurements, but this will not be discussed in the present report.

An analysis of the historical data of BWDB shows a decreasing trend in sediment transport at the major sediment gauging stations, and that the sediment transport data are scattered at Hardinge Bridge and significantly so at Baruria.

A comparison between sediment transport measurements of BWDB and of RSP on the Jamuna is shown in Figures 3.13, 3.14. The RSP gauging transect at Bahadurabad was within a few kilometres of that of BWDB. The Figure 3.13 shows that the measurements of RSP in the years 1993-1995 are higher than those of BWDB in the year 1993-1994. The measurements of RSP in the period 1994-1995 is coinciding with the measurements of BWDB at low discharges. In 1993-1994, the RSP did not separate between the coarse and fine sediment fraction, and therefore, in Figure 3.13, the coarse sediment is taken as 25 percent of the total suspended sediment (which is the average of the percentage found from the sediment transport data measured by the RSP in the year 1994-1995). A comparison of the bathymetry surveys of 1993 at Bahadurabad during the monsoon (August and November) shows that the sediment volume measured from the rating curve of BWDB in the year 1993 is significantly low (Sarker, M.H., 1995). However, the sediment transport measurements by RSP during the same period shows results that are similar to the bathymetry surveys.

A joint measurement of BWDB and RSP was carried out at Bahadurabad in July 1995. Between the two measurements, there was a good agreement in sediment transport in the channels where the flow velocity was relatively low but in the channel where the flow velocities were high (exceeding 2m/s), the difference in sediment transport was significant, the BWDB is measuring less. A comparison was made with the routine gauging sediment samples from RSP and BWDB for the period 1994-1995. The result shows that during monsoon the sediment transport measured by BWDB was up to 10 times less than the sediment transport measured by RSP. In the lean period , BWDB measured the same sediment transport of sand fraction as RSP. This confirmed the result of the joint sediment transport measurements. The most probable explanation of the underestimation of the sediment transport by BWDB during the monsoon period is the large deflection angle of the Binckley silt sampler supporting cable in high flow velocities. This means that the sample was taken in a higher position than the required depth. During joint measurement it was observed that the technique which was recommended by the Food and Agriculture Organization of the United Nation in 1966 for avoiding large deflection angle was not followed (Special Report 19, RSP, July 1996). This means that the underestimation of sediment measurement could be existing for a longer period. Another comparison was made between the BWDB data 1966-1970 and RSP data 1994-1995 and it shows no significant decreasing trend in sediment transport particularly at high discharges (Figure 3.14). In Figure 3.14, the RSP data at low discharges concave downward that may be due to the natural scour hole present in the left channel at Bahadurabad.

The RSP measured sediment transport on the Ganges river at 1 km downstream of Hardinge Bridge, and on the Padma River near the Baruria station. In Figure 3.15, it can be seen that the RSP data for the year 1994 are less scattered in the Ganges river within the discharge range measured by BWDB, and also that the sediment transport is significantly lower than according to BWDB's measurements in 1993. In Figure 3.16, the sediment transport data of the RSP are significantly scattered, like the BWDB data, at the Baruria station.

3.5 Discussion

The River Survey Project has produced sediment rating curves for both fine and coarse suspended sediment transport for the main rivers of Bangladesh (Jamuna, Ganges, and Padma) and of selected distributaries (Gorai, Dhaleswari, and Kaliganga). The sediment transport at Bhairab Bazar on the Upper Meghna River is extremely scattered, and coarse sediment transport is negligible. Therefore, a rating curve could not be produced for that station. Although sediment transport data are available from Mawa station on the Padma river, the data could not be analyzed, as this station is influenced by the tide. The rating curves for fine and coarse sediment which were analyzed during Phase 1 of the RSP, are mentioned in Annex 2.

The sediment rating curve is an exponential function, which is determined from a graph with the data points on a logarithmic scale (equation 2.1). But this exponential function is spurious, because the liquid discharge is multiplied with the sediment concentration to arrive at the sediment discharge. Still, the relation between 'S' and 'Q' in a logarithmic scale is widely used to produce a sediment rating curve.

In this sediment rating equation, the exponent 'B' of the discharge 'Q' is the important factor in determining the extreme sediment transports. In general, for alluvial rivers, the value of B should vary between 1.3 to 1.7. (The value is roughly equivalent to 3 times the exponent of the velocity in a sediment transport equation for estimating sediment transport per unit width). (Please refer to RSP Study Report 13, in preparation, on sediment transport predictors for the rivers in Bangladesh).

As mentioned above, the analysis of RSP shows that the value of B is within the expected range for Bahadurabad, but the value is considerably higher for Hardinge Bridge and Baruria. A comparison has been made between RSP and other studies and is shown in Table 3.6.

The analysis of RSP shows that the sediment transport data at Bahadurabad are less scattered, and that different periods have identical sediment transports. This can be explained by the Bahadurabad site being morphologically well suited for sediment gauging. According to World Meterological Organisation (WMO) (1989), a sediment gauging site should be free from confluence effects, artificially narrowed or trained channels should be avoided, and a uniform cross-section should be preferred. The Bahadurabad station fulfils these requirements to a maximum extent, although the transect is undergoing continuous hydro-morphological changes.

However, a decreasing trend in the sediment transport is noticed at this station during the period 1966-1994. This could be due to the gradual decrease in the sediment supply from the upstream sources in India (Goswami, 1985). The analysis of the RSP data shows that the sediment transport is significantly higher in 1994, and also in 1993.

The Jamuna Bridge Study shows a higher suspended bed material transport than estimated by RSP and by FAP1 in the Jamuna River at Bahadurabad, see Figure 3.17a. The difference is due to the fact that the RSP has analyzed a longer data series (1966-1970), whereas the outcome of the Jamuna Bridge study was based on data from 1968-1970. In the same figure, FAP1 estimates a sediment transport for the data series collected after 1976 that is similar to the RSP estimate.

It has been mentioned in some studies that the sediment data series collected during the period 1966-1970 is more reliable than those from later years. However, at present, it is difficult to comment on this matter.

The value of the coefficient 'B' derived by the RSP is fairly similar to the values found by FAP4 for the Ganges and Gorai Rivers. In Ganges, the value is considerably above its general range. This difference is probably due to the constriction effect (due to Hardinge Bridge) on the sediment transport mode at the gauging station.

The RSP and FAP4 had developed similar sediment rating curves for the Ganges River at Hardinge Bridge for the data period 1966-1970, see Figure 3.17b. From the point of view of data collection period of sediment data, the analysis does not show any indications that the data from a certain period are not reliable. Each period has its own hydro-morphological conditions, and therefore, the sediment transport can be different. However, with regard to the quality of the data, the sediment transport at the Hardinge Bridge gauging station is scattered, and a single rating curve from these data may estimate a wrong transport. As mentioned earlier, a sediment gauging station should, according to WMO, be free from any artificial constriction which produces a scour hole in its vicinity. At the Hardinge Bridge station, the constriction may be the cause of the scatter and also of the steep rating curve. Further, the analysis shows a decreasing trend in sediment transport, which also appears in the data measured by RSP in the year 1994.

The visual differences between all the mentioned rating curves for the Jamuna River are shown in Figure 3.17a and for the Ganges River in Figure 3.17b.

Hardly any study is available on the sediment rating curve of Padma River at Baruria. During Phase 1 of the RSP, it was found that the data were extremely scattered, and that the value for the coefficient 'B' was very high. Similar observations were made during the further analysis of sediment transport data in Phase 2. Also, at Mawa, the value of B is high. At the confluence, the rivers are in a dynamic state. During a hydrological period, significant morphological changes occur at both the downstream and the upper reaches of the confluence. Moreover, downstream of the confluence, a deep scour area is usually present (which may be compared with the constriction scour) (Klaassen et al., 1988a). These phenomena may cause the scatter in the sediment transport data observed at Baruria. WMO also suggested that a gauging station should be located far away from an upstream confluence.

River	Station	Coefficient 'B'							
		FAP1	FAP4	SWMC	Jamuna	Hossain*	RSP		
Period		82-88			68-70	80-87	66-70	76-82	83-88
Jamuna	Bahadurabad	1.25			1.38	1.30	1.42	1.39	1.21
Ganges	Hardinge Bridge		2.56	1.43		1.48	2.56	2.70	2.10
Gorai	Gorai Railway Bridge		1.23				1.25		

* Total sediment transport

Table 3.6: The coefficient B of sediment rating curves of different studies

3.6 Conclusion

The relation between S and Q in a sediment rating equation is a spurious correlation, and rating curves based on this equation may give biased results. Nevertheless, such relation in a logarithmic scale can be used for the formation of sediment rating curves for estimation of sediment transport, if the liquid discharge is known. Sediment budgets are mainly computed by this relation, and the procedure is widely accepted by the river engineers.

The quality of the sediment transport measurements at Bahadurabad is reliable with respect to the measuring site. According to the data consistencies, the data have been separated into different consecutive periods, each period having a distinct and reliable sediment transport. A decreasing trend in the sediment transport is noticed during the period 1966-1994. The period 1966-1970 had a very high sediment transport. The transport was gradually decreasing in the periods 1976-1982, 1983-1988, and 1993-1994. The reason for this decreasing trend is not known yet. The measurements of RSP in 1994 show a higher sediment transport than those of BWDB in 1993. The joint measurement of RSP and BWDB for the period 1994-1995 and the results show that the sediment measurement by BWDB was 10 times less than the measurement of RSP during monsoon period. Again RSP data for the period 1994-1995 shows quite consistency with the monsoon data of BWDB for the period 1966-1970. The possible explanation of less measurement by BWDB is the deflection of the cable of the Binckley Sampler during monsoon period. Another possibility as mentioned in one study (Galay, 1980), earthquakes in Assam can cause considerable fluctuations in the sediment transport in Brahmaputra River.

At Hardinge Bridge gauging station, the sediment transport data from 1966-1994 are scattered. However, rating curves could be produced, which show a decreasing trend in the sediment transport. The slopes of the rating equations for different periods are considerably steeper than normal. The reason for this is not known. According to WMO, however, a sediment gauging station should be free from any artificial constriction.

At Baruria, the sediment transport data are scattered for the entire period of 1966-1994. An attempt was made to construct rating curves for different consecutive periods. The slopes of the rating equations are unusually steep. 1-D mathematical modelling may give a better understanding of the inconsistencies.

The seasonal variation of the sediment transport at each station should be investigated. Hereby, the sediment transport data collected by RSP may serve as an additional check.

An attempt should be made to review all possible studies available regarding the above mentioned inconsistencies.

4 Sediment balances

4.1 Introduction

A sediment balance of a network of rivers is a check on the reliability on the sediment transport measurements at all gauging stations within that network. A reliable sediment balance of a river reach contributes to the understanding of the main morphological processes, which have created the alluvial delta system by sedimentation and erosion. A sediment balance is the quantitative assessment of the total eroded or deposited volumes between the sediment gauging stations in a river system.

In the present report, the sediment balance of the main river system is considered. This system comprises the Jamuna, the Ganges and the Meghna rivers, together with the main distributaries: Old Brahmaputra River, Dhaleswari River and Gorai River. The sediment balance of the main river system is complicated by phenomena like the sea level rise, the subsidence of the delta, and local tectonic developments. The influence of these phenomena on the sediment balance are not addressed in this report.

This river system carries immense amounts of sediment. However, historical data demonstrate that only a minor seaward growth of the delta has occurred during the last 200 years (Coleman, 1979; Eysink, 1983). This observation has led to the suggestion that most of the sediment discharged into the Bengal Shelf is funnelled down the 'Swatch of No Ground', a large submarine canyon located west of the present river mouth.

Studies of the Bengal Fan suggest that this canyon is cut off from the supply of sediments, and that the sediments carried by the rivers are trapped on the flood plain and on the lower delta plain (Curray and Moore, 1974; Curray et al, 1982; Curray and Emmel, 1985). As the coastal area of Bangladesh is not growing significantly at present, maybe there can exist a balance between sediment deposition on the flood plain and the rate of subsidence. An other possible explanation is that a part of the fine suspended sediment is transported thousands of kilometres into the Bay of Bengal and the Indian Ocean.

Therefore, it is essential to know the sediment balance of the major river system in Bangladesh. Within the scope of the present study, only a part of the major river system was considered for a tentative assessment of the sediment balance. Still, this may contribute to an overall assessment of the deposition (or erosion) of sediments on the flood plain.

In this chapter, reportings by different studies on aspects of the sediment balance for the rivers in Bangladesh are summarized. Subsequently, a tentative balance is computed with the wide range of data.

4.2 Review of existing reports

Coleman (1969) has estimated the total sediment transport in the Jamuna and the Ganges Rivers using sediment transport data from 1958-1962. He reports that the combined daily suspended sediment transport of the three major rivers during the flood season was of the order of 13 million tons: 7

millions tons transported by the Jamuna River, and nearly 6 million tons by the Ganges River, while the Meghna River gives only a small contribution to the combined sediment transport. The annual sediment transport in the Jamuna River is around 600 million tons and in Ganges River around 480 million tons. Therefore, the combined suspended sediment transport is about 1,100 million tons per average year, see Table 4.1. He assumed that most of this sediment transport, about some 1,000 million tons of suspended sediment per average year, is transported to the Bay of Bengal.

Station	Total suspended sediment transport in million tons per year		
	Maximum	Minimum	Mean
Hardinge Bridge	740	260	480
Bahadurabad	700	530	610
Total	1,400	790	1,090

Table 4.1: Summary of sediment transport according to Coleman (1969)

Holeman (1968) assumes that the Ganges River carries approximately 1,600 million tons and the Jamuna River around 800 million tons of sediment annually (average values). The total is thus 2,400 million tons, which is an often quoted value of the total weight of sediment transported annually to the Bay of Bengal. In his report, no details are given how this transport rate has been derived. Probably, the annual erosion of the combined basin of the Jamuna and the Ganges Rivers was the basis for his estimate. However, Hossain (1992) considers these values as unreliable.

MPO (1987a) has developed sediment rating curves both for the sand fraction and the total suspended sediment transport, based on two to five years of suspended sediment transport and discharge data (MPO, Technical Report II, 1987). A total suspended sediment budget has been assessed for the major rivers as shown in Table 4.2. It is noted that no information is given why at Baruria, the sediment rating curve for Mawa and the discharge curve for Baruria were used.

Sl.No.	River (Station)	Total suspended sediment transport in million tons per year
1	Jamuna (Bahadurabad)	390
2	Dhaleswari (Jagir)	40
3	Ganges (Hardinge Bridge)	210
4	Gorai (Gorai Railway Bridge)	30
	Total (1-2+3-4)	**530**
5	Padma (Baruria)	560

Table 4.2: Total suspended sediment balance according to MPO (1987a)

The French Engineering Consortium (FEC) (1989) has estimated the average total annual suspended sediment discharge at selected key locations. The annual sediment transport was calculated from the relationship between yearly discharge and annual suspended sediment transport. The sediment rating curves read as:

Bahadurabad: $S = 0.263 \cdot Q^{2.46}$
Hardinge Bridge: $S = 1.092 \cdot Q^{2.30}$

where S = total suspended sediment transport (tons per year)

The exponent of these sediment rating curves is considerably higher than found for daily measurements by others for the Bahadurabad transit. The yearly discharge is calculated from the Daily Discharge Duration Curve which was used in the Flood Hydrology Study and which was based on data which cover a period of ten years. The estimated sediment balance is shown in Table 4.3.

Sl.No.	River (station)	Total suspended sediment transport in million tons per year
1	Jamuna (Bahadurabad)	430
2	Dhaleswari (Jagir)	45
3	Ganges (Hardinge Bridge)	340
4	Gorai (Gorai Railway Bridge)	50
	Total (1-2+3-4)	**675**
5	Padma (Baruria)	720

Table 4.3: Total annual suspended sediment balance according to FEC

The China Bangladesh Joint Expert Team (1991) has made a sediment balance for the rivers Jamuna, Ganges and Padma at the gauging stations Bahadurabad, Hardinge Bridge and Baruria, respectively. The balance has been made for a period of 24 years, from 1965 to 1988, see Table 4.4. This table indicates that the annual sediment transport at Baruria is significantly less than the sediment transport at Mawa. However, since both stations are on the same river within a short distance, it is expected that this difference should not be significant. The difference is not explained in the report. It is mentioned that Mawa station showed a higher rate of fine sediment transport and therefore, this station was used in the analysis of channel deformation. The data from Baruria served only as a reference. It is mentioned that the sediment transport at Bahadurabad for the period 1975-1985 is much lower as compared with other periods.

Period	Suspended sediment transport in million tons per year				
1965-1988	Bahadurabad (1)	Hardinge Bridge (2)	Baruria	Mawa	Balance (1) + (2)
Average	500	200	320	580	700

Table 4.4: Suspended sediment transport according to CBJET

The annual sediment transport of the Ganges, Jamuna, Padma, Old Brahmaputra, Dhaleswari, and Gorai Rivers was also estimated by BWDB (1972) utilising data from the period 1966-1969, as shown in Tables 4.5, 4.6 and 4.7. In Table 4.5 (1966-1967), the annual average suspended coarse sediment transport in the incoming rivers (Ganges and Jamuna) is around 340 million tons. In the outgoing main river (Padma) at Baruria, it is 260 million tons per year, and at Mawa, it is 180 million tons per year. The difference between Baruria and Mawa is substantial. This can be explained by the considerable sedimentation in the river stretch (including the flood plain) between those stations during those years, in combination with a large amount of sediment transport into the Arial Khan River, a right bank distributary of the Padma River. However, this explanation needs further examination.

The average fine sediment transport in the incoming rivers is 565 million tons per year. In the outgoing river at Baruria, it is 500 million tons per year, and at Mawa, it is 530 million tons per year, see Table 4.6. This table shows an indication of erosion between Baruria and Mawa.

The total suspended sediment balance for 1967-1969 is shown in Table 4.7. This table indicates that the Jamuna River carries a suspended sediment transport which varies from 420 to 575 million tons per year, the average being around 500 million tons per year. The Ganges River, on the average, carries some 450 million tons of suspended sediment annually.

Sl.No.	Name of station	Suspended coarse sediment transport (million tons per year)			
		1966	1967	1968	1969
1	Bahadurabad	256	170	171	186
2	Taraghat	-	5.10	5.40	4.00
3	Jagir	-	1.30	1.00	1.50
4	Paksey (Hardinge Bridge)	210	161	143	151
5	Gorai Railway Bridge	24	24	18	14
	1-2-3+4-5	**442**	**300**	**290**	**318**
6	Goalundo+Baruria	354	254	192	230
7	Bhagyakul (Mawa)	229	193	170	119
8	Kamarkhali	-	15	9	5
9	Mymensingh	4.5	1.5	1.5	1.4

Table 4.5: Suspended coarse sediment balance according to the BWDB (1972)

Sl.No.	Name of station	Suspended fine sediment transport (million tons per year)			
		1966	1967	1968	1969
1	Bahadurabad	-	405	355	235
2	Taraghat	-	19.2	25.6	19.5
3	Jagir	-	4.6	4.6	3.8
4	Paksey (Hardinge Bridge)	-	321	287	282
5	Gorai Railway Bridge	-	49	34	31
	1-2-3+4-5	**-**	**653**	**578**	**463**
6	Goalundo+Baruria	-	576	561	357
7	Bhagyakul (Mawa)	-	612	492	496
8	Kamarkhali	-	35	29	30
9	Mymensingh	-	8	10	6

Table 4.6: Suspended fine sediment balance according to the BWDB (1972)

Sl.No.	Name of station	Total suspended sediment transport (million tons per year)			
		1966	1967	1968	1969
1	Bahadurabad	-	575	526	421
2	Taraghat	-	24.3	31	23.5
3	Jagir	-	6	5.6	5.3
4	Paksey (Hardinge Bridge)	-	482	430	433
5	Gorai Railway Bridge	-	73	52	45
	1-2-3+4-5	**-**	**953**	**868**	**781**
6	Goalundo+Baruria	-	830	753	587
7	Bhagyakul (Mawa)	-	805	662	615

Table 4.7: Total suspended sediment balance according to BWDB (1972)

Hossain (1992) reported that the sediment transport in the Ganges River has an average value of about 480 million tons per year, and that this value shows a slightly decreasing trend. For the Jamuna River, an average value over the last thirty years may be about 650 million tons per year, but a slightly increasing tendency has been found in these sediment transport data. The combined yearly sediment transport through the Ganges and Jamuna River is taken at 1,100 to 1,200 million tons per year on the average. The maximum sediment transport, however, may be as high as 1,500 million tons per year. Hossain has recommended a special sediment transport formula, which is based on the measured data of the Ganges and Jamuna Rivers. The total annual sediment load of the Ganges and Jamuna River were estimated by using his formula, see Table 4.8.

River	Total sediment transport (million tons per year)								
	1980	1981	1982	1983	1984	1985	1986	1987	1988
Ganges	594	-	-	420	423	348	381	-	-
Jamuna	-	-	733	754	747	-	403	815	840

Table 4.8: Total sediment transport according to Hossain (1992)

4.3 Analysis of the River Survey Project

The sediment balances for the coarse and the fine fraction are estimated separately for the incoming rivers of the main river system: Jamuna River at Bahadurabad, and Ganges River at Hardinge bridge, and the outgoing rivers: Gorai River at Gorai Railway Bridge, Padma River at Baruria and at Goalundo, Kaliganga River at Taraghat, and Dhaleswari River at Jagir. The Dhaleswari River at Tilly bifurcates into the Dhaleswari River, which passes along Jagir, and the Kaliganga River, which passes along Taraghat. The Dhaleswari River at Jagir started silting up in the late sixties, and Kaliganga in the late seventies. During flood, the discharge of the Kaliganga River is higher than that of the Dhaleswari. The Padma River at the confluence had two channels in the past, until 1982, one at Goalundo and another at Baruria. After the Goalundo Channel started to silt up due to natural aggradation, this channel was closed by human intervention. The sediment balances (fine and coarse) was calculated for the above mentioned rivers.

During Phase 1 of the RSP, the discharges used for the sediment balance were measured by BWDB and were smoothed in connection with the analysis. The discharges in the Gorai River, the Goalundo Channel and the Dhaleswari River were negligible in comparison to the discharges in the Jamuna, the Ganges and the Padma Rivers. Therefore, the sediment transport in the former group has hardly any effect on the overall sediment balance. Discharge data were available at Goalundo for the period 1966-1982, at Gorai Railway Bridge for the period 1966-1969, and at the remaining stations for the period 1966-1991. Hence, all the coarse and fine sediment data available for the period 1966-1988 were used.

The measured sediment transport data collected within the period 1966-1989 were divided into two groups: One for the period 1966-1970, and another for the period from after the 70-ies and until 1989. This division was based on a possible yearly trend of the sediment transport data in the rivers. In the period 1966-1970, the measured sediment transport seems to be significantly higher than the one in 1971-1989. The data collected in 1966-1970 are relatively consistent, as it can be seen from Table 4.9. The sediment rating curves and the estimated yearly sediment transport for the above mentioned stations with their sediment budget are shown in Annex 3.

The sediment balance for the coarse fraction was determined from data from the two groups of sediment stations. In group one, the sediment stations near Bahadurabad, Hardinge Bridge, Taraghat, Gorai Railway Bridge and Jagir were included. In group two, the sediment stations near Goalundo and Baruria were selected. With BWDB discharge data, the analysis considered two series of data: One series before the 70-ies, and another series after the 70-es. The coarse sediment transport after the 70-ies was around 50 percent higher in group 1 than in group 2, see Table 4.9. Before the 70-ies, a consistency is observed between the two groups of stations. Also, the sediment transport data before the 70-ies were consistent with the findings of the other studies as mentioned earlier.

Sl.No.	Name of the station	Annual average suspended coarse sediment load in million tons (1966-1989)			
			period		period
1	Bahadurabad	202	(66-70)	96	(76-88)
2	Hardinge Bridge	196	(66-70)	91	(76-89)
3	Gorai Railway Bridge	18	(66-70)	18	(66-70)
4	Taraghat	2.85	(67-69)	3.1	(70-88)
5	Jagir	0.77	(67-69)	0.77	(67-69)
	Group 1: Total (1+2-3-4-5)	377		**165**	
6	Goalundo	1.71	(66-69)	6	(76-82)
7	Baruria	366	(68-70)	100	(76-89)
	Group 2: Total (6+7)	368		**106**	

Note: The period of measured sediment data are used is shown within bracket

Table 4.9: Coarse suspended sediment balance according to the RSP

The combined fine and coarse average annual suspended sediment balance for 25 years is shown in Table 4.10 for the measured suspended data collected during the period 1966-1970.

Sl.No	Station	Annual average suspended sediment load in million tons (1966-1989)		
		Coarse (A)	Fine (B)	Total (A+B)
1	Bahadurabad	202	388	590
2	Hardinge Bridge	196	352	548
3	Gorai Railway Bridge	18	29	47
4	Taraghat	2.85	13.7	16.55
5	Jagir	0.77	2.7	3.47
	Group 1: Total (1+2-3-4-5)	**377**	**695**	**1072**
6	Goalundo	1.71	9.1	10.81
7	Baruria	366	520	886
	Group 2: Total (6+7)	**368**	**529**	**897**

Table 4.10: Total suspended sediment balance according to the RSP

The balance shows that the average annual suspended sediment transport is 1070 million tons per year in the rivers of Group 1, and 900 million tons per year in Group 2. The difference of 170 million tons per year between the groups is probably due to sedimentation on the flood plain and to some extent on channel aggradation.

During Phase 2 of the present project, the sensitivity of the sediment balance was investigated by considering different sediment rating curves at one station from different periods. A balance is drawn from the rating curves of different seasons of the hydrological year. Table 4.11 shows such sediment balances, computed by using different rating curves from different consecutive periods.

No.	Sediment data period	Bahadurabad Million ton	Hardinge Bridge Million ton	Baruria Million ton	Gorai + Tara Million ton	Balance Million ton
1	**Sediment rating curve:** Bahadurabad: 1966-1970, 1976-1982, 1983-1988 Hardinge Bridge: 1966-1970, 1976-1988 Baruria: 1966-1970, 1976-1988 **Discharge** MDD for the corresponding period	116	124	143	21	76
2	**Sediment rating curve:** All stations: 1966-1970 **Discharge:** MDD for the periods 1966-1970, 1976-1988	193	204	344	21	32
3	**Sediment rating curve:** All stations: 1976-1988 **Discharge:** MDD for the periods 1966-1970, 1976-1988	91	95	99	21	66
4	Phase 1 of the RSP	202	196	368	22	08

Table 4.11: Coarse sediment balance computed by the RSP

4.4 Results and discussion

As mentioned, RSP has analyzed almost all the available sediment transport data collected by BWDB for the period 1966-1994. Within this period, some years are missing (as no sediment data were collected). RSP (DELFT/DHI, 1993d) has found that the discharge measurements at Bahadurabad were erroneous for the period 1989-1993. Therefore, during Phase 2, the sediment balance has been computed for the hydrological period 1966-1988 for the stations Bahadurabad, Hardinge Bridge and Baruria. In this phase, all the sediment rating curves (Figures 3.2, 3.5, and 3.8) were used in the computation.

The coarse sediment balance shows some tentative storage in the river system. Earlier, in Phase 1, using different sediment rating curves, it was found that the system may be in a dynamic equilibrium. However, the analysis was based on the sediment transport data collected from the Bahadurabad, Hardinge Bridge and Baruria, and it was found that the sediment transport data are scattered at Hardinge Bridge and significantly so at Baruria. Therefore, any estimate on the sediment balance for these stations may give erroneous results.

In Phase 1, it was noticed that the sediment data collected after 1970 show a rapid fall in the coarse sediment transport in the Jamuna and the Ganges Rivers. The reasons for this drop were not known.

It should be noted that no coarse suspended sediment data are available for the major rivers for the period 1970-1976.

Also in Phase 1 of the RSP, the analysis showed that a balance of around 170 million tons of fine sediment per year probably settle on the flood plain and chars. Considering, as an illustration, a floodplain of 300 km length and 20 km width along the Jamuna and the Ganges Rivers between the gauging stations. The balance of 170 million tons can cause a sedimentation of 0.01 m on that floodplain. A sedimentation of about 0.01 m per year is also estimated in other studies.

In the following, a comparison with different studies is described. The sediment balance of such different studies are summarized in Table 4.12.

River	Station	Annual sediment transport in million tons per year							
		Coleman[1]	Holeman[1]	MPO[1]	FEC[1]	CBJET[1]	Hossain[2]	BWDB[1]	RSP
Jamuna	Bahadurabad	607	800	387	431	499	650	507	590
Ganges	Hardinge Bridge	478	1600	212	338	196	480	448	548
Padma	Mawa			563		581		694	
	Baruria				723	317		723	897

(1) Total suspended sediment transport
(2) Total (bed and total suspended) sediment transport

Table 4.12: Comparison of sediment transport according to various authors and studies

The sediment transports determined by Coleman were based on a few data taken during each month for the period 1958-1962. It was reported that before 1966, the sediment samples were collected from the river at different depths by ordinary bottles. The most important factor hereby is that the measurement was carried out at a single vertical located in the deepest part of the river. Therefore, as Coleman stated, the sediment transport data during that period should be used only as a first approximation of the sediment transport in a transit.

The sediment transport presented by Holeman for both the Ganges and Jamuna and Padma Rivers, with a maximum sediment transport in the Padma River of 2,400 million tons per year, are questionable, because this total suspended sediment transport does not comply with the results of other authors or studies, especially with respect to the sediment transport of the Ganges River. This is probably due to the limited amount of sediment data available before 1968. Holeman did not mention the methodology followed in arriving at his estimates, but it appears that they were based on basin erosion. However, the basin erosion is very difficult to calculate. He has also used the high sediment transport values collected from the deepest part of the river, and these values are not representative for the sediment transport passing a transit.

The sediment transport estimated by MPO (1987) is based on the sediment rating curves determined by visual fitting of a curve in a graph, instead of using regression analysis. In general, the extrapolation of such a curve to higher and lower discharges is often inaccurate. Further, the estimation of the sediment transport at Baruria is based on the sediment rating curve at Mawa and the discharge duration curve at Baruria. This is not correct, because the exponents of the sediment rating curves are different for Baruria and Mawa. The data series cover only a rather short period of 2 to 5 years. These remarks explain that the accuracy of these sediment rating curves is probably rather low.

The sediment balance prepared by the French Engineering Consortium is based on the sediment rating curves for the concerned gauging stations and on 10 years of sediment transport data. The calculated sediment transport are somewhat too low, maybe because a period of 10 year sediment data is not sufficiently long. The sediment balance indicates that the combined sediment transport of the Jamuna and Ganges Rivers is 680 million tons per year, while at Baruria, it is 720 million tons per year. This difference in sediment transport is within the range of the assessment of the sediment transport by other studies.

The results of CBJET indicate that the annual sediment transport at Mawa is reasonably close to the combined sediment transport of Jamuna and Ganges Rivers after subtraction of around 100 million tons per year diverted into the distributaries. This means that the rivers upstream of the confluence are, on the average, in a morphologic equilibrium. However, comparing the combined sediment transport of the Jamuna and the Ganges Rivers with the sediment transport at Baruria indicates a considerable sedimentation on the flood plain or an aggradation of the river bed. The difference between the average annual sediment transport at Baruria and Mawa seems to be high, considering soundings of the short reach (of only 60 km) between these stations.

The analysis of BWDB resulted in a reasonably accurate estimation of the sediment transports at several stations, and this analysis was based on a few years of sediment data only. The method to deriving the sediment rating curves was relatively simple. The big difference between the combined sediment transport of the Ganges and the Jamuna Rivers and the measured sediment transport at the Baruria transit indicates an aggradation of the rivers between the respective stations along those rivers. These results appear to be contradictory, as the measurements are mostly conducted during the monsoon period. One can expect more difference in the fine sediment transport than in the coarse sediment transport, because the fine sediments are mainly deposited in the floodplain, while the coarse sediments remain in the river itself during monsoon periods.

A study of the suspended sediment transport in the upstream parts of the Ganges and Jamuna Rivers shows an enormous variation in sediment transport over short time spans, partly because of the considerable variation in the hydrographs. The Brahmaputra River in India shows a sediment storage as high as 70 percent of the incoming sediment transport (Galay, 1980). Sediment slugs in the Ganges River originate from bursting of glacier lakes in the Himalayas, and these slugs have an exceptionally high concentration of sediment for short periods of time. These high sediment loads are deposited upstream, for example on the Kosi alluvial fan. Because of a steady rise of the river bed of the Kosi river on the fan, an avulsion may occur in the near future, which will cause formation of a new river over the alluvial fan, and which may generate massive flooding. The historical alluvial process of deposition over the fan may change during this catastrophic process, and the sediment transport in the Ganges River will increase dramatically. Such an avulsion will modify the preliminary sediment budget for the Ganges system for years.

4.5 Conclusions

In several studies, the long-term tendency of sedimentation or erosion in the main river system was determined by a sediment balance. The analysis of the RSP is the most detailed one, and is based on almost all available sediment data collected during the period 1966-1988. Based on sediment rating curves from different consecutive consistent sediment transport periods, the balance for coarse sediment shows in one instance a tentative minor aggradation, but in other cases that the system is in an equilibrium. However, a study (Galay, 1980) of the suspended sediment transport in the upstream parts of the Ganges and the Jamuna Rivers shows an enormous variation in sediment transport over short time spans, partly because of the considerable variation of hydrographs in the past. The Brahmaputra River in India shows a sediment storage as high as 70 percent of the incoming sediment transport.

The earthquakes in Assam can cause considerable fluctuations of the sediment transport in Brahmaputra River. Therefore, the sediment budget for these rivers will show some long-term variation over the years.

Sediment transport data at Baruria and Hardinge Bridge are scattered. Therefore, for these stations, a computation of the sediment balance might give erroneous results.

During Phase 1 of RSP, and during other studies, it was stated that the analysis of several sediment balances shows that the sediment data collected during 1966-1970 are in general more reliable than the data from later periods. It is difficult to justify this argument, as the analysis shows that all the data periods may be reliable from the measurement point of view, while from the point of view of the gauging stations, there is some doubt about the data from Hardinge Bridge and Baruria. 1-dimensional mathematical morphological modelling can be used to assess the data inconsistencies.

Lastly, the sediment transport measurements should be conducted at a station for a longer continuous period in order to obtain a representative number of samples.

5 Study of inconsistencies

5.1 General

One may think that the reliability of the sediment transport data lies with the accuracy of measurements, such as correct registration of point velocity and corresponding sediment concentration, accurate depth measurement, etc. However, there are other factors which influence the quality of data in a different way: Not so that the registration, sampling or analysis itself is wrong, but that the data do not represent the entire reach of the river. These factors are related to the gauging site. According to WMO, a sediment gauging site should be free from any artificially narrowed channel, an upstream confluence, a river bend etc. etc.

The inconsistencies, which are observed in the sediment transport data of the BWDB, can be summarized as follows:

- Scatter in the sediment transport data presented in linear or log graphs
- Steep rating curves expressed in a log-log graph, i.e. the coefficient 'B' of equation (3.1) is above its normal range: 1.3 - 1.8
- A decreasing trend in sediment transport over the historical period 1966-1994

These inconsistencies can possibly be explained as follows:

a. For scatter and steep rating curve

  - Measuring technique
  - Measuring site (morphology of the gauging station)
  - Seasonal effects

b. For a decreasing trend in sediment transport

  - Measuring technique

- Natural calamities (earthquake, flood etc.)

Only a few theories and studies address these effects. Some are explained below. The following chapter describes 1-dimensional morphological modelling for making a qualitative assessment of the inconsistencies.

5.2 Scatter and steep slope in the rating curve

5.2.1 Measuring technique

At this moment it is difficult to assess the measuring technique and gauging procedure of the past. In the following, some observation are made in order to give an impression on the sediment/discharge gauging which may introduce errors in the measurements.

The ADCP measurements show a significant fluctuation in backscatter (a measure of the sediment concentration) at a point in a vertical in the rivers in Bangladesh. This natural fluctuation in sediment movement has a large influence on the reliability of the observed sediment concentration. The Brinkley sampler is an instantaneous sediment trap-type sampler, which is not able to trap short fluctuations of sediment. A study in China showed that the relative standard error in measured concentration due to this fluctuation in sediment concentration may reach $\pm$ 10 percent (WMO-No 686, 1989).

A joint field survey was made between BWDB and RSP at Bahadurabad in March 1993 (DELFT/DHI, 1994). During sediment gauging with the Brinkley sampler, no extra weight was used to keep the instrument in a vertical position under moderate to strong current. It was observed that at a current velocity of 0.7 m/s, the cable of the sampler was deflected around 10 degrees. No doubt the deflection will be higher under a strong monsoon current, when the sediment transport is intensive, and according to ISO standard, the corresponding discharge variation could be significant. Moreover, the current meter is not equipped with a direction measurement device. The current direction was measured by sextant between surface floats and fixed points on the bank, which can certainly give wrong estimates of the velocity when the flow is skewed in a vertical.

The analysis of the RSP showed that BWDB's discharge measurements at Bahadurabad for medium to high flows are too high (overestimating a peak flood discharge by about 25 per cent) since the major flood in 1988. This can be explained by the large flood having resulted in a local change of the plan forms, channel pattern and cross-section, implying a much more skewed velocity distribution than before the flood. As BWDB's correction for flow direction is based on surface floats, such development can increase the uncertainties during the period 1988-1992 as compared with earlier periods (DELFT/DHI, 1993d). Another analysis of the RSP at Baruria showed that the flow volumes of BWDB before 1971 are estimated 10-15 per cent too low.

5.2.2 Measuring site

Constriction effect

In a study on sediment transport of the Orinoco River, Venezuela (Nordin, et al., 1994), the annual bed-sediment discharge was calculated for two sections, one having a river width of 2660 m and another of 1290 m. It was found that a transport calculation based on the mean overall slope showed that the narrow section transported more sediment than the wide section for all flows. However, when the local water surface slopes were used in the calculations, the sediment rating curves cross at higher discharges, so that during a year, the average continuity of sediment transport is maintained. Figure 5.1 shows that during low flows, the wide section fills relative to the narrow section, and that during high flows, it scours relative to the narrow section.

1-dimensional morphological model studies (Galappatti, 1993) at Hardinge Bridge show that the sediment rating curve at high flows is higher than it needs to be. It was also found that the exponent of the sediment rating curve at that location is very much higher (B = 3.19) than elsewhere in the Ganges river (B = 1.43).

Confluence effect

At the confluence, the typical flow profile will either be a drawdown curve or a backwater curve, depending on whether it is a low flow or flood. This will give rise to either degradation (drawdown curve) or aggradation (backwater curve). Hence, the reaches upstream of a confluence in real rivers are adjusting all the time, but are, at the same time, fluctuating around an average bed level (DELFT/DHI, 1993e). Similarly, it can be shown that downstream of the confluence, aggradation and degradation occur alternatingly. This gives rise to the generation of sand waves which travel downstream. Such a dynamic system at and around a confluence gives rise to a very scattered sediment transport. The system is schematically indicated in Figure 5.2.

Moreover, downstream of the confluence, a deep scour is usually present, often referred to as the confluence scour (Klaassen and Vermeer, 1988a). This has a significant influence on the mode of sediment transport at that location.

5.2.3 Seasonal effect

The season can have a significant effect on the sediment yield. The flow in the river changes with the changes in the hydraulic conditions. A rising flood has different hydraulic parameters than a receding flood, and again as compared with dry season flow. Figure 5.3 shows the difference in sediment yields between a winter and a summer storm for Millers Creek (Glysson, 1987). There is a considerable amount of scatter and even some overlap between the winter and the summer type storm. This figure also explains how a series of lines might describe the changing sediment transport relation at the station better than one single rating curve.

Figure 5.4 shows the typical scatter that can occur at Pigeon Roost Creek (Vanoni, 1977) from a single year of sampling. In the mid portion of the figure, the seasonal effect on the point scatter is also discernible.

The RSP has carried out an extensive analysis of the effect of the seasons (low flow, monsoon, flood, etc.) on the sediment rating curve. The BWDB suspended bed material sediment data for the period 1966-1988 are separated according to different flow conditions. The seasonal sediment transport data for the period 1966-1970 are plotted in Figure 5.5 for Bahadurabad, Hardinge Bridge and Baruria stations. It can be seen that the seasonal effect is insignificant at Bahadurabad but quite significant at Hardinge Bridge and Baruria. At those stations, the sediment transport is very scattered and steep during low (dry period) discharges. The different sediment rating curves from different seasons for the period 1966-1988 are illustrated in Figures 5.6, 5.7, and 5.8 for Bahadurabad, Hardinge Bridge and Baruria. The analysis from the entire period shows that the seasonal effect is insignificant in Jamuna River at Bahadurabad, while at the other stations, the effect is considerable.

An annual sediment transport has been calculated with different sediment rating curves including seasonal rating curves from the period 1966-1993 with the discharge of 1987 for the stations Bahadurabad, Hardinge Bridge and Baruria. These are shown in Figures 5.9 - 5.11. From these figures it is evident that each rating curve has individual characteristics. Moreover, it is clear that at Bahadurabad, the annual sediment transport computed from the seasonal rating curve is approximately same as the annual sediment transport computed from the rating curve produced for the whole year. By contrast, at Hardinge Bridge and Baruria, the season has a significant influence on the annual sediment transport. Therefore, the computation of the sediment budget at those stations would be wrong if the annual sediment transport were estimated from all the data in a year, instead of using separate rating curves for different seasons.

Why is the seasonal effect so pronounced at these two stations? It could be due to the constriction and confluence effects. If so, it would be difficult to separate accurately the sediment transport data according to different seasons. This is because the seasonal variation is not dominating the mode of transport, rather than the morphological condition of the river bed. At Bahadurabad, the morphology of the bed is uniform, so the seasonal effect is not noticeable. All these question could be answered by 1-D mathematical modelling. No doubt, different flow conditions would give different modes of transport, but the effect of this may still be insignificant as compared with the other effects mentioned above.

5.2 Decreasing trend in sediment transport

Often, a catastrophic event will significantly change the slope and/or shape of the sediment rating curve (Glysson, 1987). It a apparent from Figure 5.12 that the 1964 flood in Middle Fork Eel River, California, caused a considerable change to the relation between sediment transport and water discharge. Even by 1968, the upper end of the transport curve had not returned to its pre-flood position.

The Himalayas lies in an active seismic zone. The 1959 earthquake in Assam caused whole hillsides to crumble and slide into the Brahmaputra, whose bed level rose by over three meters. The vast amount of debris and sediment altered the regime of the river. While the finer sediment was washed down, the heavier material has been transported slowly, ground and crushed in the process, causing floods. Measurements at Bahadurabad show that the 'dominant low water level in the Jamuna of 11.9 meters in the early fifties had gradually gone up to 13.4 meters, a rise of 1.5 meters, in the sixties. However, since then, a lowering trend can be observed' (Verghese, 1990).

At Pandu, a period of rapid aggradation was observed after the great earthquake of 1950. The period of aggradation was followed by a slower removal. The Brahmaputra River had a much higher rate of sediment transport from 1957-1960 and a moderately high rate during 1966-1969, as against the lowest rate during 1971-1976 (Goswami, 1985). The aggradation of 1.25 m during 1957-1971 in the 145 km reach between Kobo and Bessamara, and the degradation of 21 cm during 1971-1977 in the same reach, seem to indicate removal of only a small fraction of the volume of sediment deposited during 1957-1971. Since the flow in the river did not change appreciably, even during the period of low sediment transport, the reduction in sediment inflow appears to have resulted in a removal of sediment from the bed.

6 1-dimensional mathematical modelling

6.1 Introduction

It is important to be able to explain the inconsistencies that appeared during the analysis of suspended sediment transport data measured by BWDB in the major rivers in 1966-1994. 1-dimensional morphological modelling is one of the main tools available for making predictions of the long-term and medium-term morphological response in an extensive river system. The Ganges-Jamuna-Padma Model (GJP Model) has been developed by RSP to carry out at least qualitative simulations in order to examine the inconsistencies observed in the historical sediment transport data collected from the major rivers in Bangladesh.

The model is based on a schematization of the physical system based on certain restrictive assumptions. However, the results of such model must be interpreted based on a good understanding of the underlying physical processes and also a proper awareness of the assumptions made during schematization.

Although real measured data are used for the simulations, the interpretation of the results is more qualitative then quantitative. Still, there is no doubt that the GJP model can contribute to a deeper understanding of the sediment transport and the morphological phenomena, and provide a clue to the inconsistencies noted during the data analysis.

In the present chapter, the model is applied for an examination of hypotheses and findings of different authors related to the inconsistencies, and a conclusion is drawn in this respect.

6.2 Schematization of river channels

The schematization of the river network of the Ganges-Jamuna-Padma (GJP) Model is shown in Figure 6.1. The principal features of the model are as follows:

1 The schematization of each cross-section is made as a rectangular profile

2 All the lateral inflows and outflows of water from these three rivers are assumed to be negligible and are therefore not included in the model

3 The Engelund-Hansen sediment transport formula was used in the model for simulation of sediment transport

4 A 50 years simulation was achieved by repeating the 1987 boundaries 50 times, in order to reach dynamic condition

The schematization of each cross-section is shown in Figure 6.2. Using symbols shown in that Figure, the following procedure has been applied:

i Divide the cross-section into i segments
ii Compute: $Y = \Sigma B_i(h_i)^{1.5}$
iii Compute the bed level z_b in the schematized cross-section with:
$(H_D - z_b)^{1.5} = [\Sigma B_i (h_i)^{1.5}]/ B$ (with $B = \Sigma B_i$)

A model schematization like this is not suitable for accurate high and low water simulation, as the cross-section flow area is not well represented for very high and very low discharges. For morphological computations, however, this disadvantage is not very important: During low discharge, the sediment transport is very low, and the morphological changes will be small, while the very high discharges (in year 1987) have such a low frequency of occurrence that the temporarily high sediment transport hardly affects the overall river morphology.

The bed roughness is computed from the White and Colebrook equation, where the Chezy coefficient is a measure of the roughness. The bed material grain sizes used in the model are listed in Table 6.1.

Name of river	Gauging station	Length of each branch km	Bed material grain size*						
			No of samples	Collection period	D_{16} mm	D_{35} mm	D_{50} mm	D_{84} mm	D_{90} mm
Jamuna	Bahadurabad	220	56	1993-1994	0.13	0.16	0.22		0.34
Ganges	Hardinge Bridge	220	50	1993-1994	0.1	0.12	0.15	0.18	0.21
Padma	Baruria	220	30	1993-1994	0.1	0.124	0.14	0.185	0.22

* measured by the River Survey Project

Table 6.1: Bed material grain sizes of the major rivers

The upstream boundaries of the Jamuna and Ganges have been extended further upstream using the same schematized cross sections, to delay the propagation of boundary errors into the area of interest during the simulations.

6.3 Applications

The main objective of the modelling is to explore the cause of the inconsistencies in the BWDB sediment transport data.

For this purpose, the following cases have been considered:

1 The constriction of the Ganges river at the location of Hardinge Bridge to a width of 1.6 km from the main river width of 3.8 km

2 The confluence of the Ganges and the Jamuna Rivers and its effect on sediment transport and bed level changes at and around the reaches of the confluences

3 A storage hump at the upstream of the Jamuna river

6.4 Time step for morphological computations

In this model, two time steps are applied. One is for the water movement, which is more or less chosen freely. The numerical scheme for the water movement is implicit, which means that the time step has a minor influence on the stability of the computations. The time step for the water movement was chosen in such a way that discharge variations in time will be well represented.

The second time step is for the morphological process. Due to the explicit numerical scheme for the sediment continuity equation, the time step must be sufficiently small in order to prevent numerical instability of the computations.

The time step for the morphological computations (sediment transport and bed level changes) is determined by the propagation of disturbances in the bed, which takes place with a certain velocity. The celerity is expressed as:

$$C=\frac{\delta s}{\delta u}\frac{u}{h(1-Fr^2)} \tag{6.1}$$

Where

C = the celerity of bed disturbance (m/s)
s = sediment transport per unit width (m^2/s)
u = flow velocity (m/s)
h = water depth (m)
Fr= Froude number ($u/(gh)^{0.5}$) (-)
g = gravitational acceleration (m/s^2)

For normal flow conditions in rivers, Fr << 1, so that equation (6.1) reduces to

$$C=\frac{\delta s}{\delta u}\frac{u}{h} \tag{6.2}$$

The exponent 'n' (Study Report ..) of the Engelund-Hansen prediction formula is 5, which has been calibrated in the model for the constant grain size (D_{50}) and assuming a constant Chezy coefficient (C). Hereby, d_{st}/d_u = 5 s_t/u.

$$s_t=\frac{0.05u^5}{\sqrt{g}C^3\Delta^2D_{50}}=4.0*10^{-6}m^2/s/m \tag{6.3}$$

Where

u = 0.3 m/s minimum water velocity
C = 40 $m^{0.5}/s$ Chezy coefficient
Δ = 1.65
D_{50} = 0.00015 m for Padma river
g = 9.81 m/s^2

Substituting d_{st}/d_u = 5 s_t/u in equation (6.2) gives

$$C=5\frac{S_t}{h}=6.06*10^{-5}m/s \tag{6.4}$$

Where h = 0.33 m = minimum water depth

The time step is being selected from the Courant number

$$C\frac{\Delta t}{\Delta x} \leq 1 \tag{6.5}$$

Where
Δx = 500 m = smallest grid size in the model
$\Delta t \leq \Delta x/c$ = 95 days

In order to determine a suitable morphological time step of the model, an assumed time step was used to perform one morphological time step. The model gave the celerity as output information. So with a known minimum water depth (h) in the schematized river reach, and a known smallest length step, the maximum time step could be calculated by equation 5.5.

The time step calculated in this way was divided by a factor 3, in order to ascertain a Courant number of less than one for all flow conditions, which can occur during a complete simulation. If the time step is too big, instabilities in the bed will occur, and numerical oscillations will grow rapidly, which may even lead to bed levels above the water level.

Therefore, a maximum time step of 30 days was used.

6.5 Study of inconsistencies

6.5.1 Scatter and steep rating curve

Constriction effect on Hardinge Bridge gauging station

As mentioned earlier, it is well possible that the constriction due to the Hardinge Bridge on the Ganges River could be the cause for the scatter observed in the sediment transport data, as well as for the steep sediment rating curve.

In the model, a constriction of 1600 m width and 2000 m length was introduced at the river training length of the bridge. A single width of 3800 m was used for the entire reach of the river.

Two cases were studied: One 'without constriction' and another 'with constriction'. The sediment transports in both cases are illustrated in Figure 6.3 (a and b). In this figure, the sediment transport is scattered in case of a constriction. The power low sediment rating curves are plotted in a logarithmic scale in Figure 6.3c. Within the same range of discharges, the sediment rating curve is steeper at the constricted (B = 3.82) section than at the unconstricted (B = 1.65) section.

A further explanation of the above mentioned figure is made in Figure 6.4 by considering the seasonal (monsoon and dry period) effect on the sediment transport. Here, the data from mid June to mid November 1987 are plotted. In Figure 6.4b, the sediment transport curve at the constriction has its largest slope at low discharges and its smallest slope at the highest discharge, so that the curve is concave downward. However, in Figure 6.4a, the sediment transport curve from the same data period has one mild slope at the unconstricted section. Now, in this figure, the sediment transport data at the unconstricted section from the dry period of the same hydrological year are included, and a curve is plotted which is shown in Figure 6.4c. In the latter figure, the curve has steep slope and is concave downward, as the sediment transport has a large slope at low discharges (< 3000 m^3/s), and a small slope at high discharges. This also explains the scatter in the sediment transport data at the unconstricted section.

This case is typical of sediment transport curves for many streams (Vanoni, 1977). Apparently, at very low water discharges in a natural river, the sediment transport is scattered. By comparing the two sections, it is seen that the sediment transport at the constriction is very low at low discharges (4000-10000 m^3/s), and high at higher discharges ($>$ 30000 m^3/s), in comparison with the sediment transport at the unconstricted section. This can be further explained by Figure 6.5. At low discharges, the velocities are lower at the constriction than at the unconstricted section, and at high discharges, the velocities are higher at the constriction than at the unconstricted section.

The scatter in the sediment transport data at Hardinge Bridge can be explained by Figure 6.6, which shows that a scour hole has developed in the vicinity of the constriction. This scour hole has a tremendous effect on the mode of sediment transport at its location. At low to moderate discharges, the flow is dampened, so that part of the sediments are deposited in the scour hole. At higher discharges, this deposition is washed away, and the sediment transport becomes high. Such exceptionally high and exceptionally low sediment transports give rise to a scatter in the sediment transport.

As mentioned earlier, a segment of a transport curve can be approximated by a power relation in the form of equation 2.1. The exponent 'B' of this equation is the slope of the curve on logarithmic paper, measured in units of logarithmic cycles. When this equation is fitted to segments of a transport curve (like the ones in Figure 6.4b and 6.4c), the exponent 'B' will diminish as the segments are extended to higher and higher ranges of water discharge. This figure shows the typical scatter that can occur from a single year of sampling (one hydrological year). In the mid portion of the figure, the seasonal effect on the point scatter is also discernible. The best fit regression line becomes steeper, when it is drawn from all seasonal data.

Confluence effect on Baruria gauging station

Baruria gauging station is located downstream of the Ganges/Jamuna confluence. At this station, the sediment transport data are very scattered, and the rating curves are steep. For simplicity, a single cross-section for Padma river was used in the model.

The 1-D model results show the typical scatter in the sediment transport data at different sections of the Padma River from the confluence and downstream (Figure 6.7). At the confluence, the scatter is most significant, while further downstream, it is greatly reduced, but the sediment rating curve remains concave downward. Downstream of the confluence, the sediment transport is moderately low and scattered at small discharges, and comparatively high at higher discharges. A sediment rating curve from all these data will have a steep slope, while in reality, there are two slopes: One at the low discharges (which may not be a slope at all, as the data are very scattered), and another at higher discharges.

At the confluence (Figure 6.7a), the higher sediment transport during rising stage is the result of a large supply of sediment from the Jamuna River due to scouring of its bed in the reach near the confluence. The low sediment transport during falling stage is the result of a reduced supply of sediment from the upstream branches.

The reaches upstream of a confluence are continuously adjusting, but are at the same time fluctuating around an average bed level (DELFT/DHI, 1993e), and hence the system is in a dynamic equilibrium. In Figure 6.8, during rising stage, the river bed is degrading, while during falling stage, it is aggrading. This aggrading in the Jamuna is typical of the backwater effect in that river due to the late flood in the Ganges River. It can be seen that downstream of the confluence, an alternating aggradation and degradation occur. This gives rise to the generation of sand waves, which migrate through the downstream reach. These changes of bed levels in different branches near the confluence are the main reason of scatter in the Padma River.

At the confluence, the annual fluctuation of the bed is high, in the order of 1.5 to 2 m (confluence scour). The fluctuation gradually becomes insignificant further downstream (Figure 6.9). Like the constriction scour at Hardinge Bridge, the confluence scour affects the mode of sediment transport in its vicinity. At the start of the monsoon, an enormous scouring takes place, and during the dry period, the bed is partly re-established.

6.5.2 Decreasing trend in sediment transport

As mentioned before, a study on the Brahmaputra River reveals that the earthquake in 1950 had caused a rapid aggradation, followed by a slower degradation at Pandu. Also after that earthquake, there was a period of high sediment transport followed by a decreasing transport in the subsequent period. A few more studies on this aspect exist, as discussed earlier.

An attempt was made to investigate the effect of sediment storage in the 1-dimensional model analysis. A single branch model was developed with the schematized cross-section of Jamuna River. The upstream discharge boundary and the downstream water level boundaries are data measured at Bahadurabad in the year 1987. In order to avoid a large morphological time step in the modelling, and to use the maximum memory of a single branch model, a storage was introduced 50 km upstream of the station from where the sediment transport data were taken. The storage is on the average 25 km long, 1.5 m high and 4000 m wide. The results, 50 km downstream from the end of the storage, indicate that initially, the sediment transport is high, while it gradually decreases in the subsequent years towards the transport in the case without a storage (Figure 6.10).

7 Conclusions and recommendation

The analysis of the RSP is so far the most elaborate detailed analysis of the sediment transport data collected by BWDB during the period 1966-1994.

Analyses presented in *RSP Special Report 19: 'Joint BWDB/RSP measurements hydrology'* and *RSP Final Report Annex 4: 'Sediment transport'* indicate that part of the data systematically under-represent the actual sediment transport (specially, the sand fraction) in the high flow ranges (flow velocity > 2 m/s).

The data collected at Bahadurabad during that period are consistent, except for the period 1989-1993, when the discharge measurements were erroneous. The data at Bahadurabad are less scattered and have a decreasing trend in transport for the period 1966-1994. The rating curve produced from different periods, i.e 1966-1970, 1976-1982, 1982-1988, 1993, etc., are all reasonable and can be accepted for annual sediment transport and budget computation for the respective period. Though Jamuna is a morphologically dynamic river, the gauging transect at and around Bahadurabad can assure reliable sediment transport data.

The sediment transport at Hardinge Bridge are scattered, and the sediment rating curves at that station have steep slopes. The 1-D model results show that the constriction due to Hardinge Bridge is the main cause for these discrepancies in the data. In the vicinity of an artificial constriction in a natural river, the constriction causes a lower sediment transport during low to moderate discharge, and a higher transport during high discharges. This increased transport variation between low and high discharges produces steep rating curves. Moreover, the model shows that the sediment transport is scattered at low to moderate discharges.

The sediment transport data at Baruria are very scattered. The mathematical model results show that the confluence and its reaches are under a continued morphological dynamic adaption. A historical analysis shows that the Jamuna and the Ganges have different hydrological events. The former has an earlier flood than the latter, but also the low discharges are very uneven in the two rivers. At the confluence, these differences cause hydraulic drops in one channel and backwater effects in the other, which create erosion and sedimentation in the respective channels. All these processes give rise to an uneven and scattered sediment transport. Also, the analysis shows that downstream of the confluence, a big (natural) scour area develops, which further contributes to the scatter in the sediment transport. The analysis shows that the confluence effect remains for a very long distance in the downstream channel.

Other results of the 1-D modelling illustrate how a storage caused by natural calamities can be the reason for an initially increased sediment transport, which gradually diminishes through the river system, and with a decreasing tendency in time. This complies with the findings of Goswami (1985).

The sediment budget shows an equilibrium to an insignificant aggradation of the river system in Bangladesh. However, this conclusion is not entirely proven, due to the questionable quality of the sediment transport data from Hardinge Bridge and Baruria.

It was not possible to verify the quality of the sediment transport data with respect to measuring technique, but there is no evidence that not all sediment transport data are reliable (hereby disregarding the significant effect of the measuring site at Hardinge Bridge and Baruria). Hence, it is possible that sediment transport data from the entire period is acceptable. The annual sediment transport should be computed from data from the respective periods. A period such as 1966-1970 should not be used for the computation of sediment transport say for the period of 1982-1988, because the rivers in Bangladesh are yet to reach an equilibrium condition. Any natural calamities will again change the hydro-morphological conditions of the river system.

In order to obtain sediment data with a high quality, the location of a site of a sediment gauging station should be selected carefully according to several criteria explained in this study and in gauging manuals (WMO, 1989). The gauging section should be free from artificially narrowed channels, and should be away from an upstream confluence. At Hardinge Bridge, the contraction scour of the river bed induces a yearly variation in the sediment transport which is not representative for the whole reach of the Ganges River. The sediment transport data from this contraction will not lead to a good estimate of the over-all sediment budget. Therefore, in order to obtain valid data for morphological studies, the location of this gauging station should be changed. Also, upstream of Hardinge Bridge, there is a bend, which again implies that this station is not well suited for sediment gauging. A section downstream of the bridge can provide better data. The exact location should be selected after a detailed investigation.

At Baruria, morphological changes in the river bed are predominant over the year. Satellite images show a significant shifting of the confluence. The confluence with its scour has a significant effect on the sediment transport data at Baruria. Therefore, it is recommended to shift this gauging station to a more stable location further downstream but needs further detail study.

The overall sediment budget for the main river system must be established by computations. It is not clearly known how much sediment goes to the Bay of Bengal through the Meghna Estuary. An improved sediment budget can be obtained with data from new gauging stations on the Arial Khan and Lower Meghna, although the tidal influence on the flow pattern in Lower Meghna river will complicate the measurements.

The amount and the quality of the available data on sediment transport in the Jamuna-Ganges system should be further extended and improved in the future. Many factors influence the reliability of the sediment sampling, and one important factor is the size of the sample. Obviously, the size of a sediment sample taken during the monsoon flood should be studied carefully. Therefore, a more profound and comprehensive study of the sediment budget of the main river system including the main distributaries is recommended for future work.

Such a future, more detailed analysis of the sediment balance can provide a more accurate determination of long-term trends and variations, also such developments that are caused by extreme phenomena, such as for example earthquakes, avulsions, bursts of glacier lakes in the upstream rivers, or by climatic changes and the sea level rise.

The sediment plumes were not considered in the present overall analysis, but should be analyzed separately, as they may have a significant influence on the sediment balance.

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Vol. IB: Main Report on River Training/AFPM
Vol. II: Annex 1: River training and morphological response
Annex 2: River Morphology
Vol. VII: Annex 15: Special scour study
prepared for FPCO, financed by KfW (Germany) and CFD (France)

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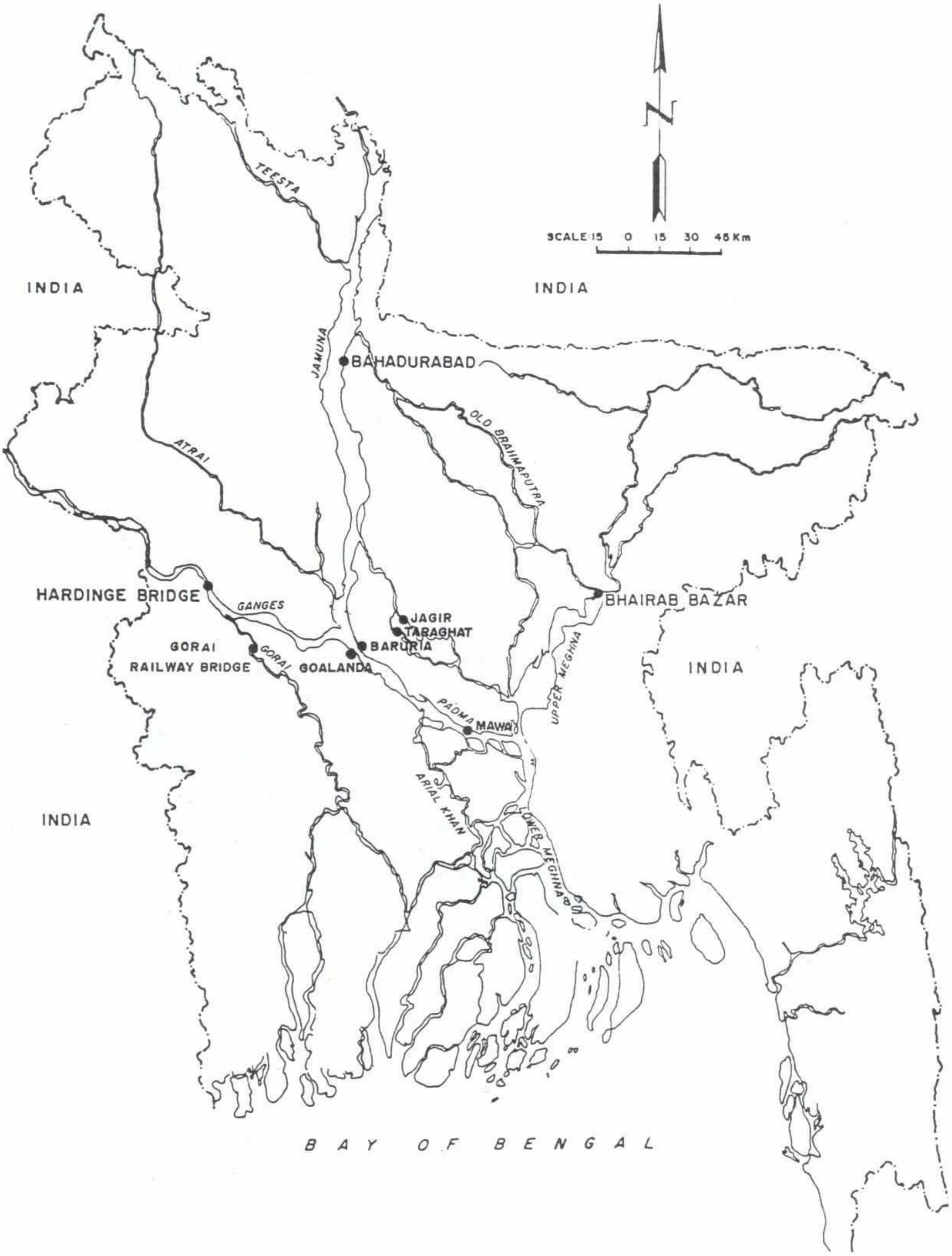


Figure 2.1: Location of gauging stations

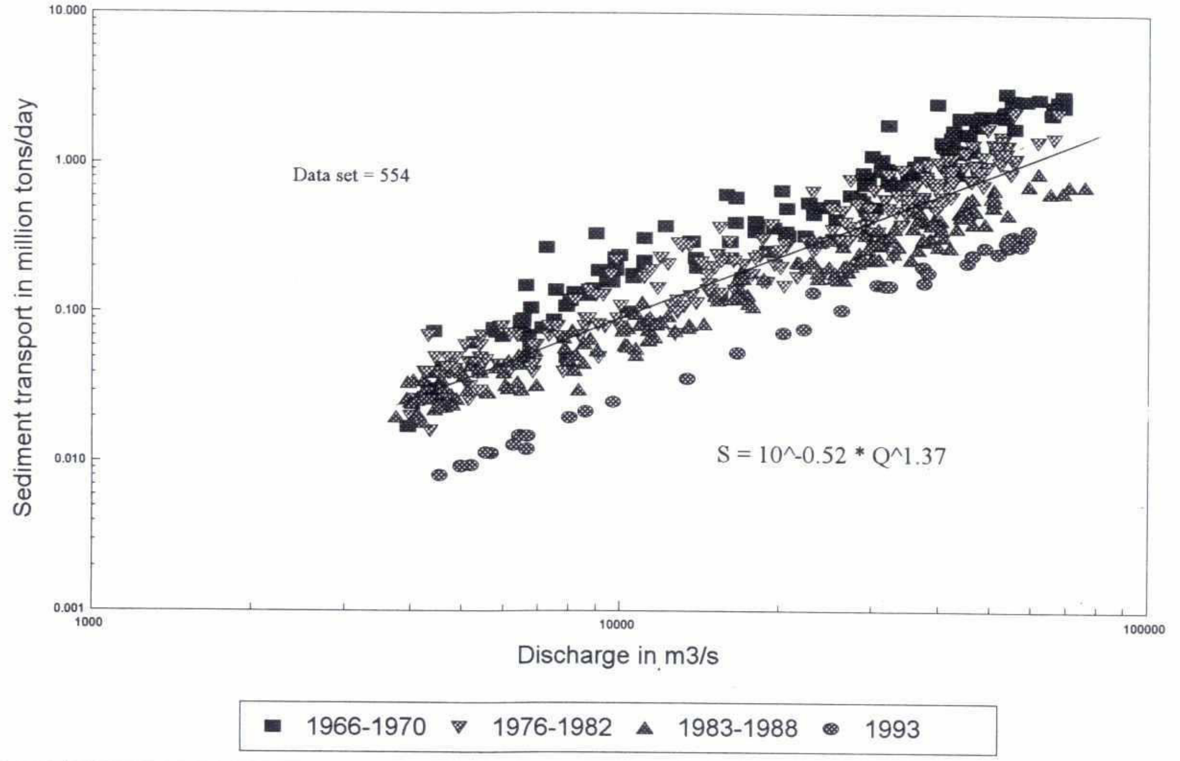


Figure 3.1: Sediment transport data, Bahadurabad, 1966-1994

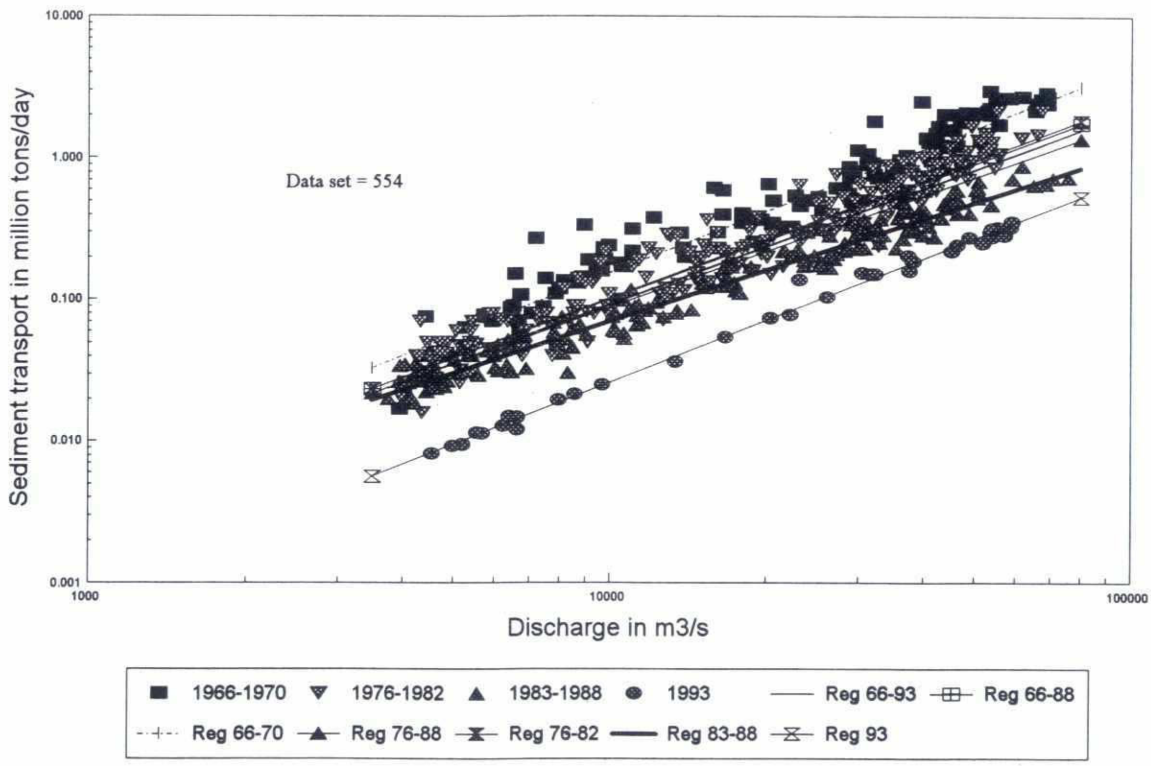


Figure 3.2: Sediment rating curves, Bahadurabad

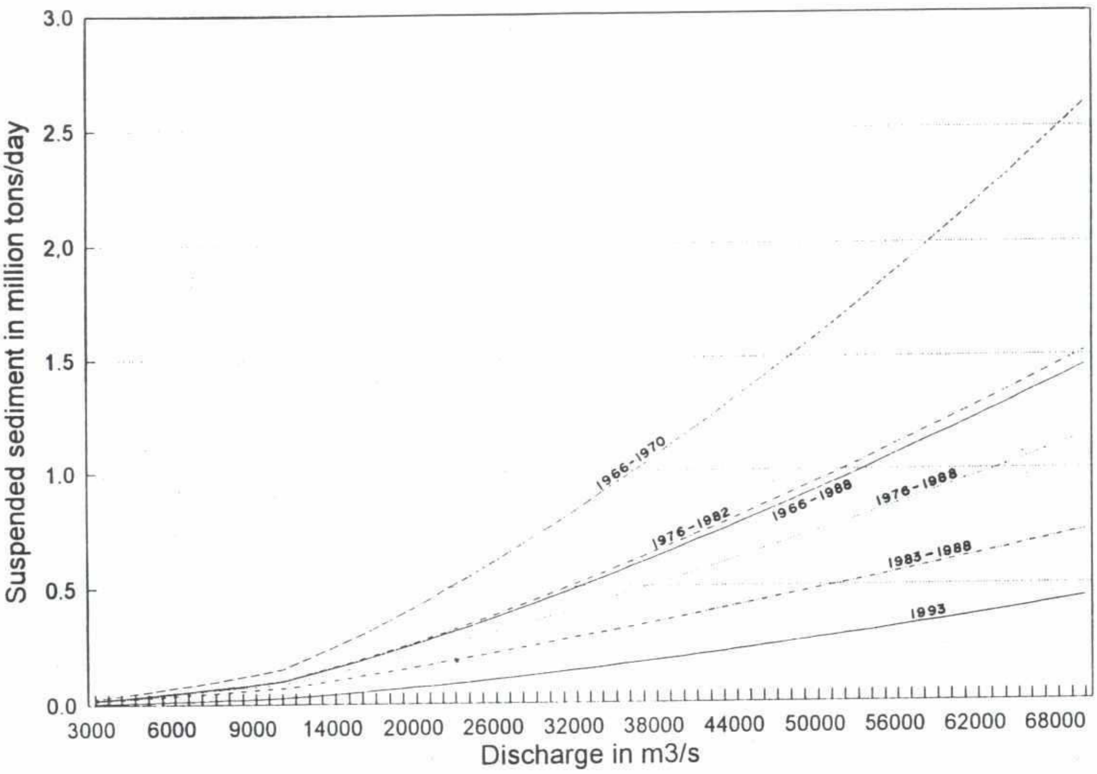


Figure 3.3: Sediment rating equations (visual appearance), Bahadurabad

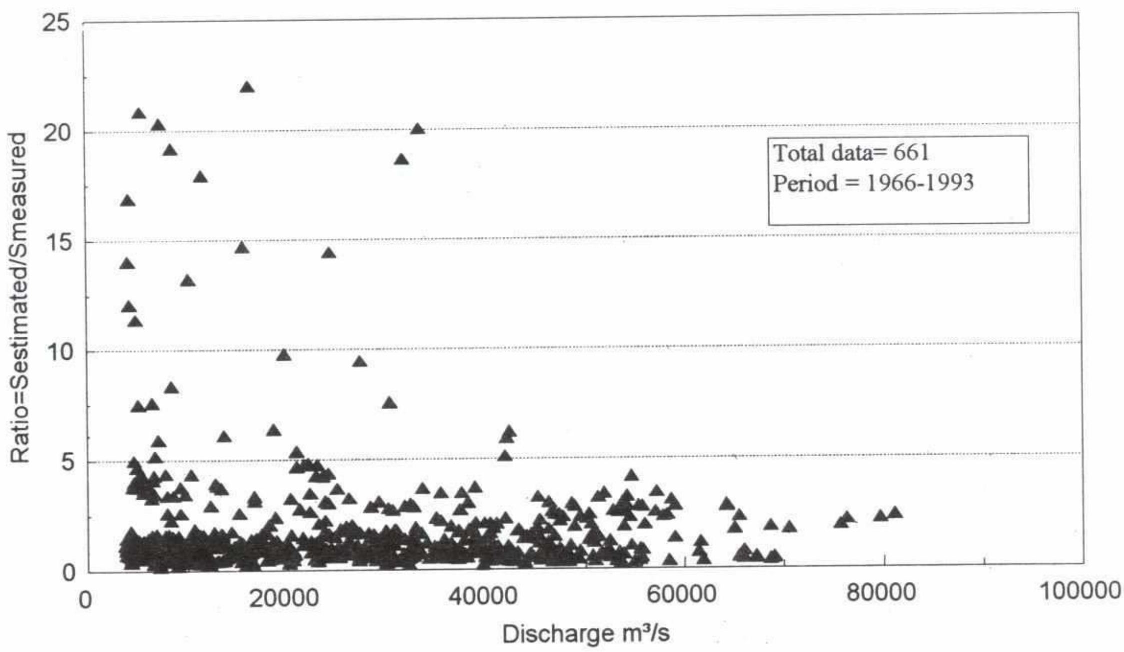


Figure 3.4: Discrepancy ratio of sediment transport data (BWDB), Bahadurabad

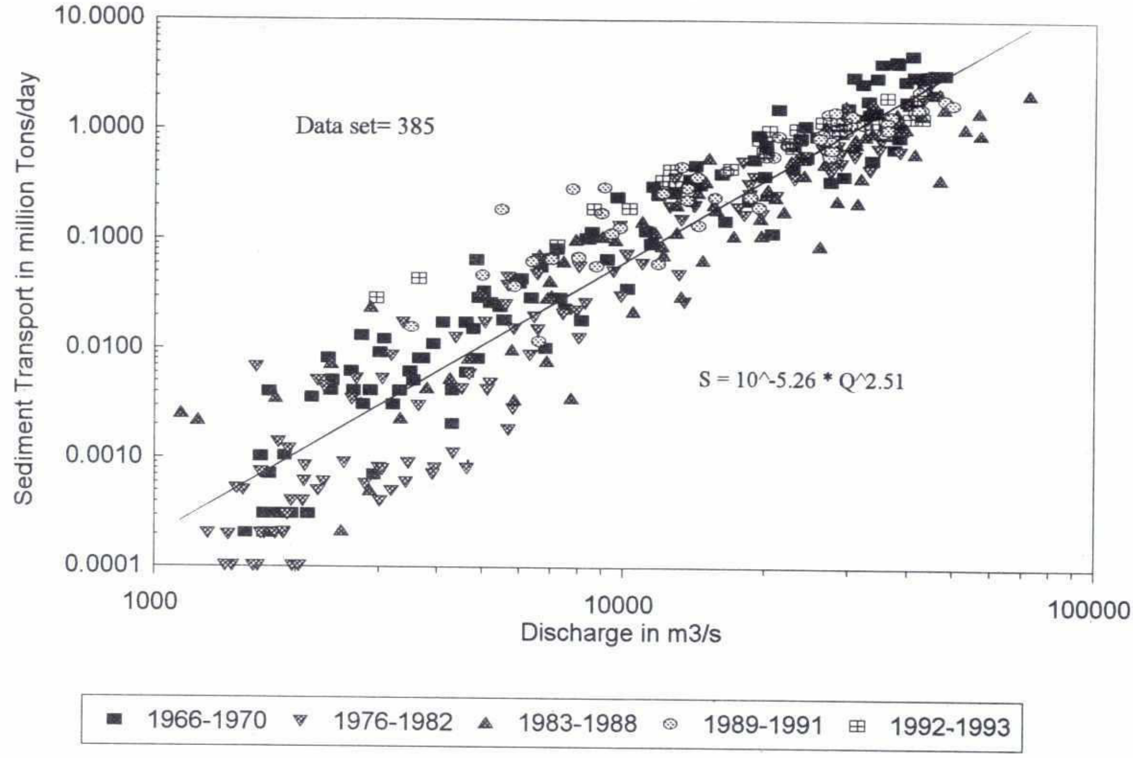


Figure 3.5: Sediment transport data, Hardinge Bridge, 1966-1994

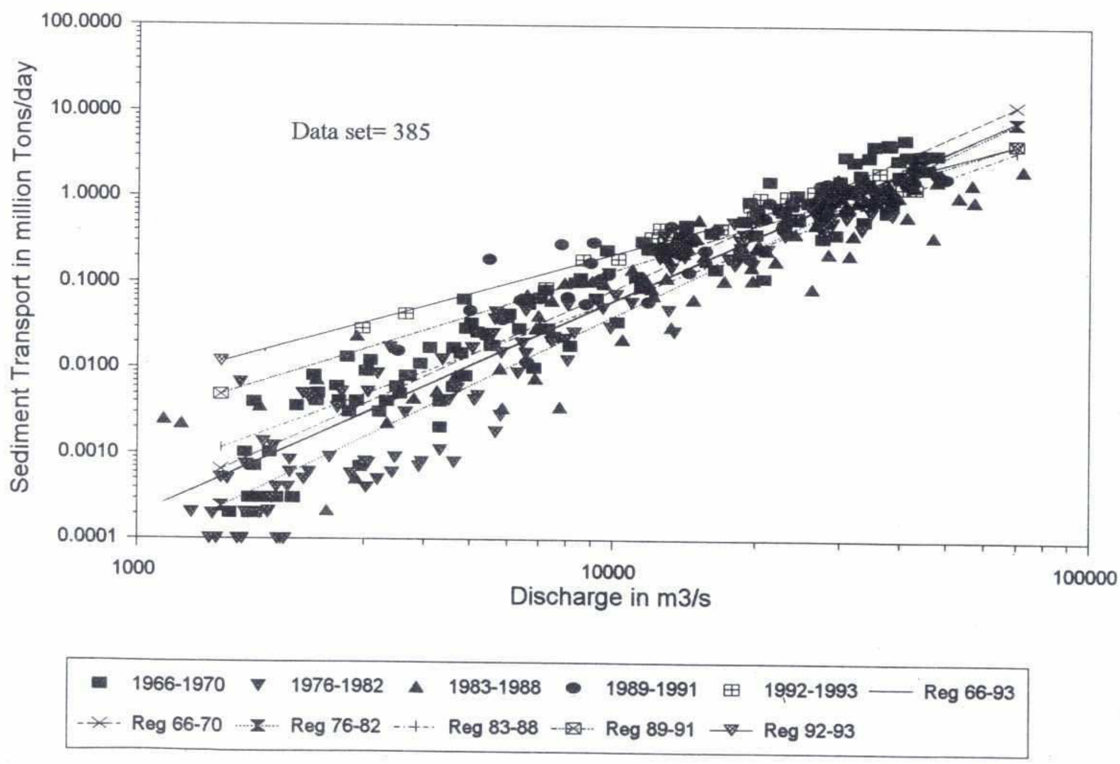


Figure 3.6: Sediment rating curves, Hardinge Bridge

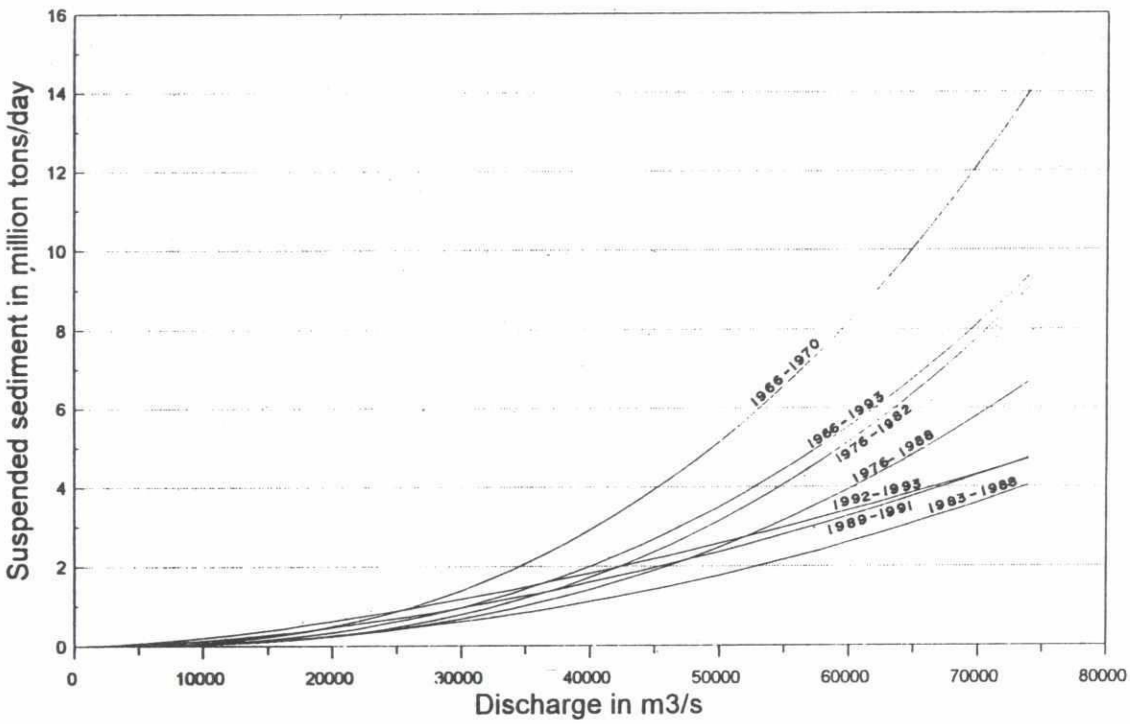


Figure 3.7: Sediment rating equations (visual appearance), Hardinge Bridge

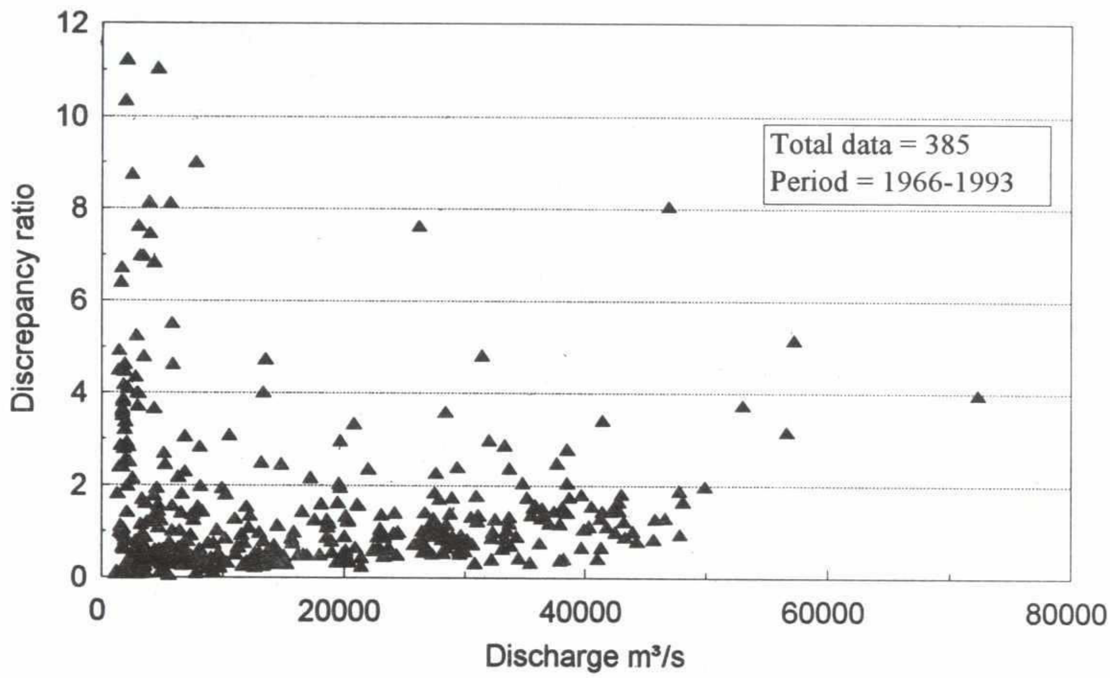


Figure 3.8: Discrepancy ratio of sediment transport data (BWDB), Hardinge Bridge

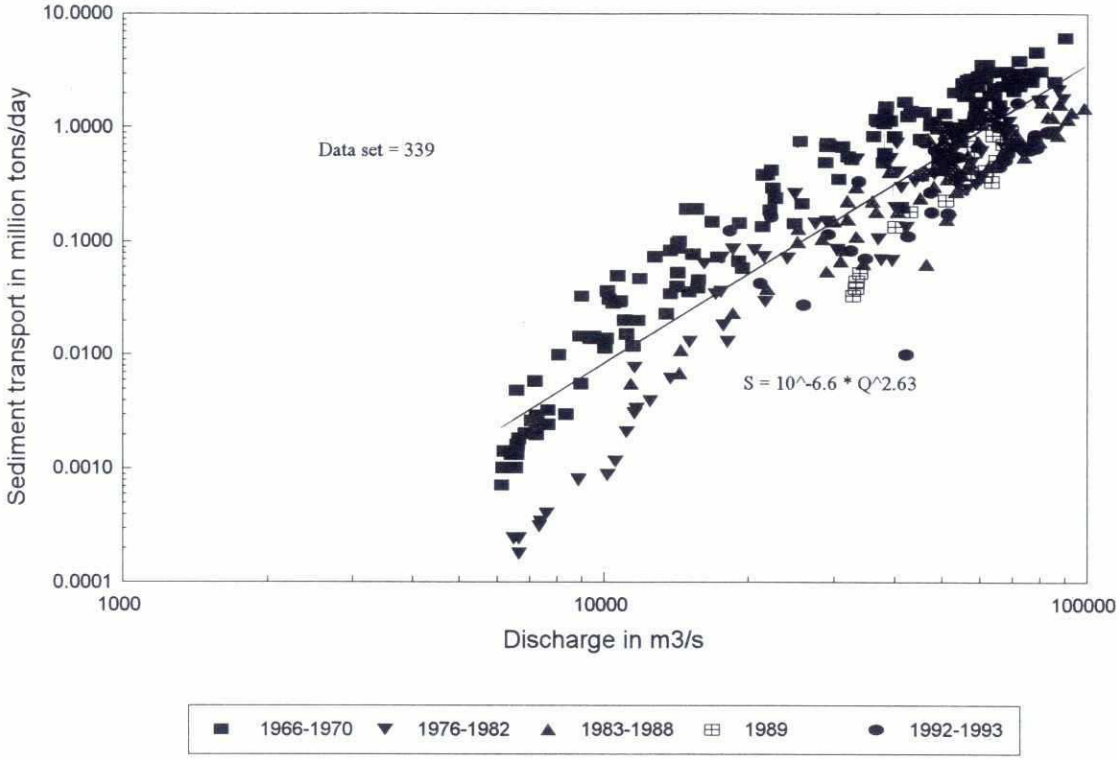


Figure 3.9: Sediment transport data, Baruria, 1966-1994

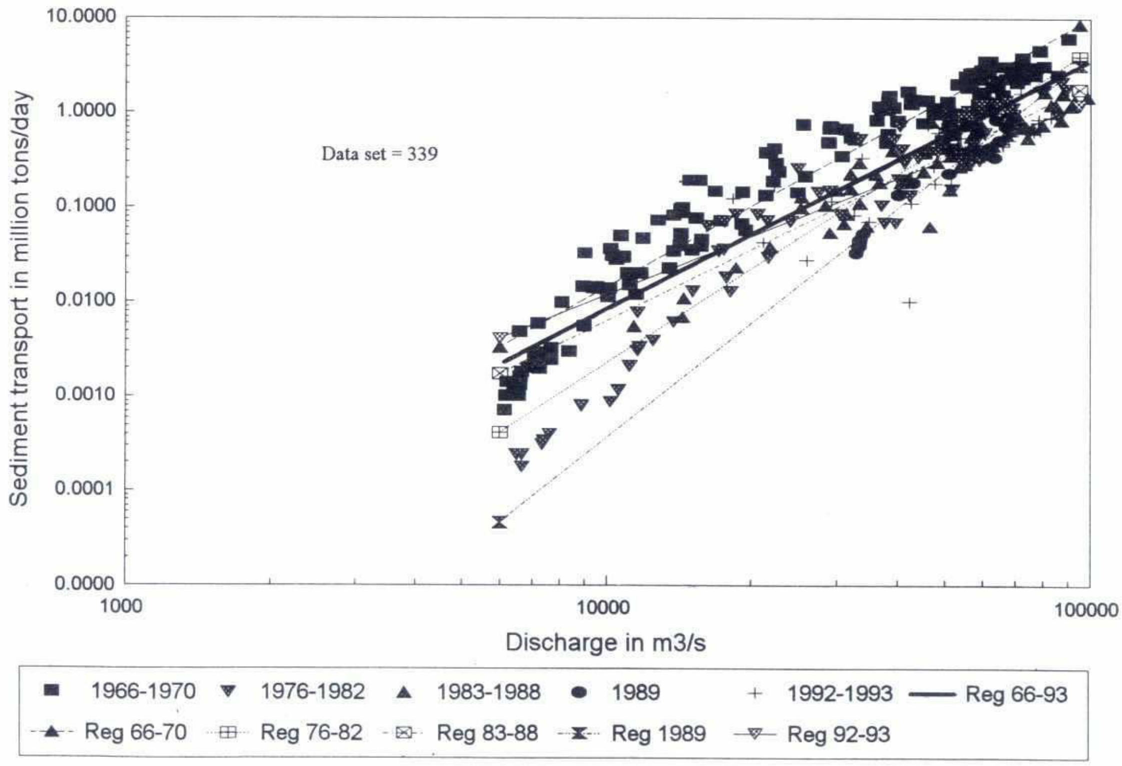


Figure 3.10: Sediment rating curves, Baruria

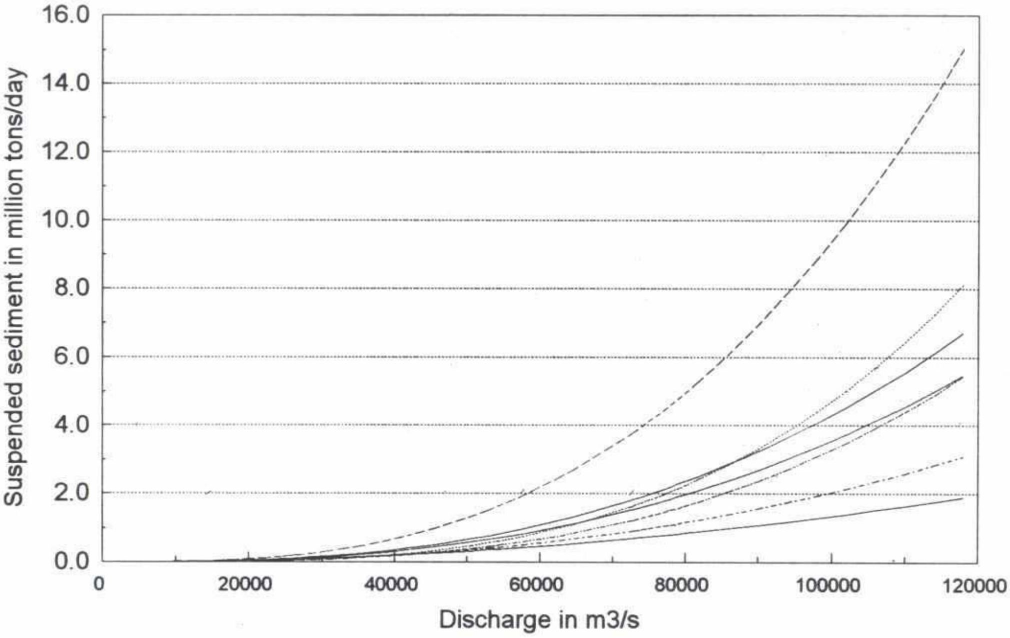


Figure 3.11: Sediment rating equations (visual appearance), Baruria

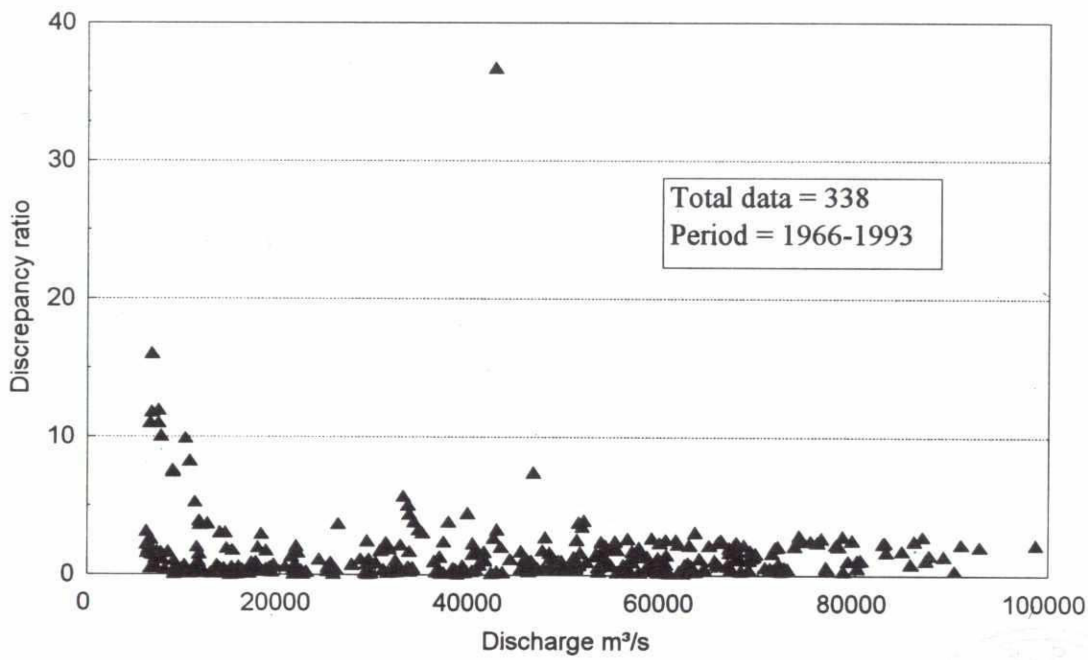


Figure 3.12: Discrepancy ratio of sediment transport data (BWDB), Baruria

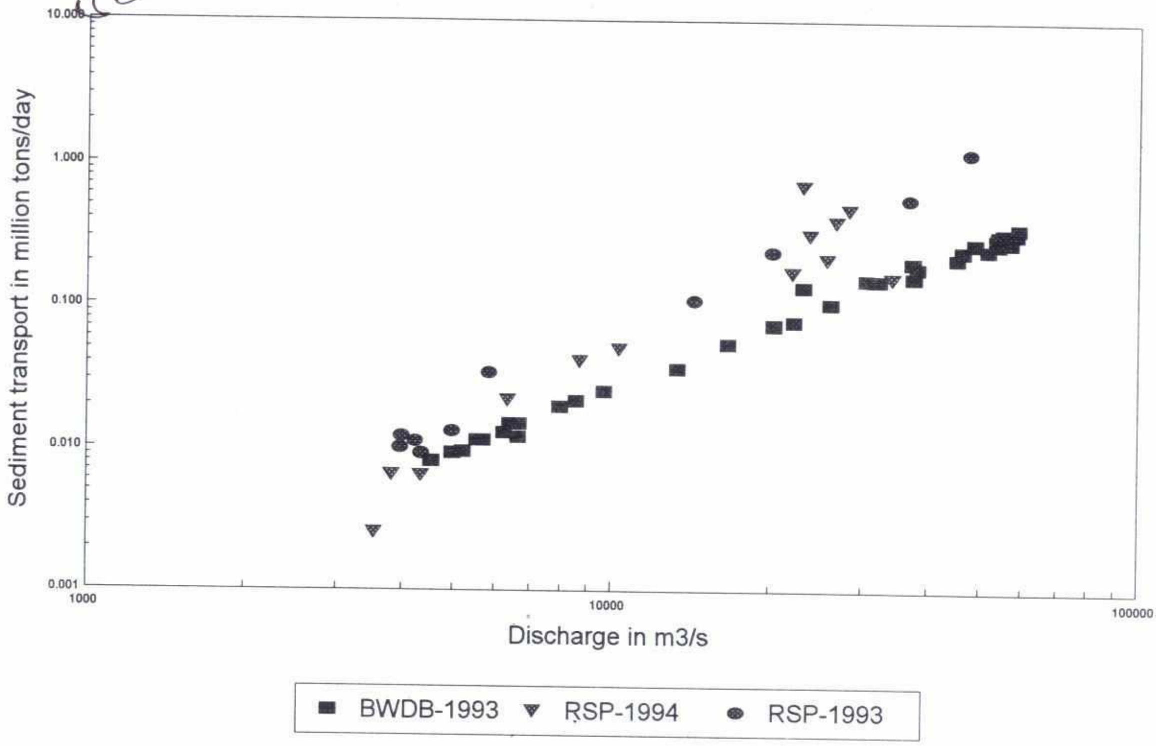


Figure 3.13: BWDB and RSP sediment transport measurements, Jamuna

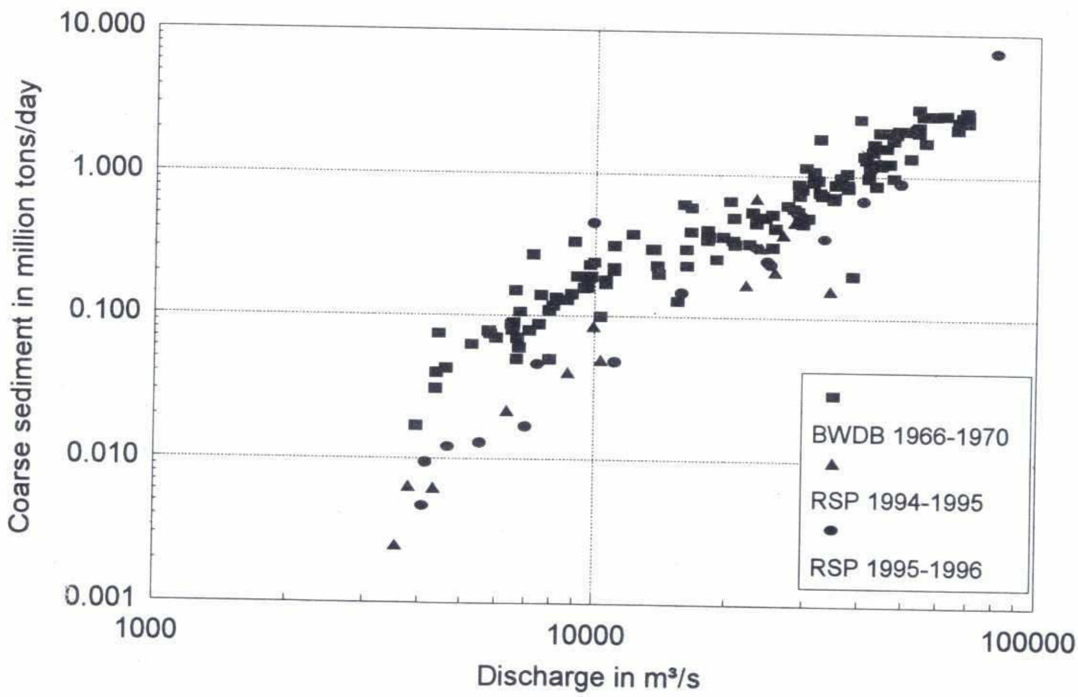


Figure 3.14: Comparison of sediment transport data of BWDB and RSP

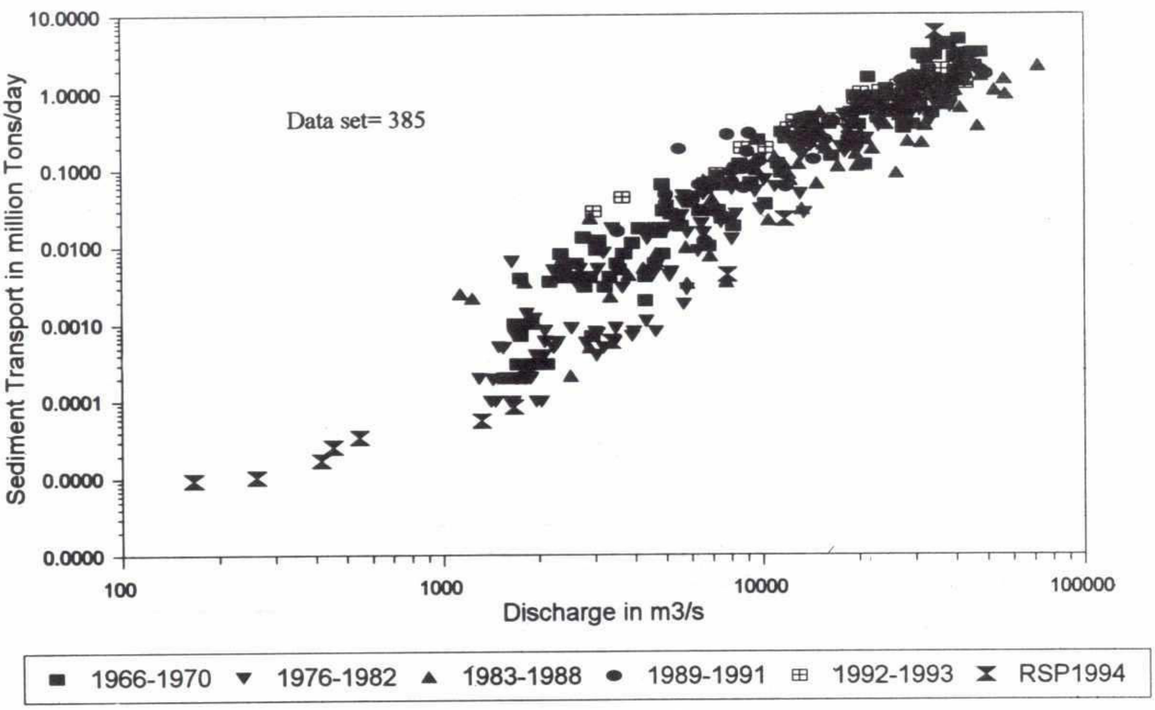


Figure 3.15: BWDB and RSP sediment transport measurements, Ganges

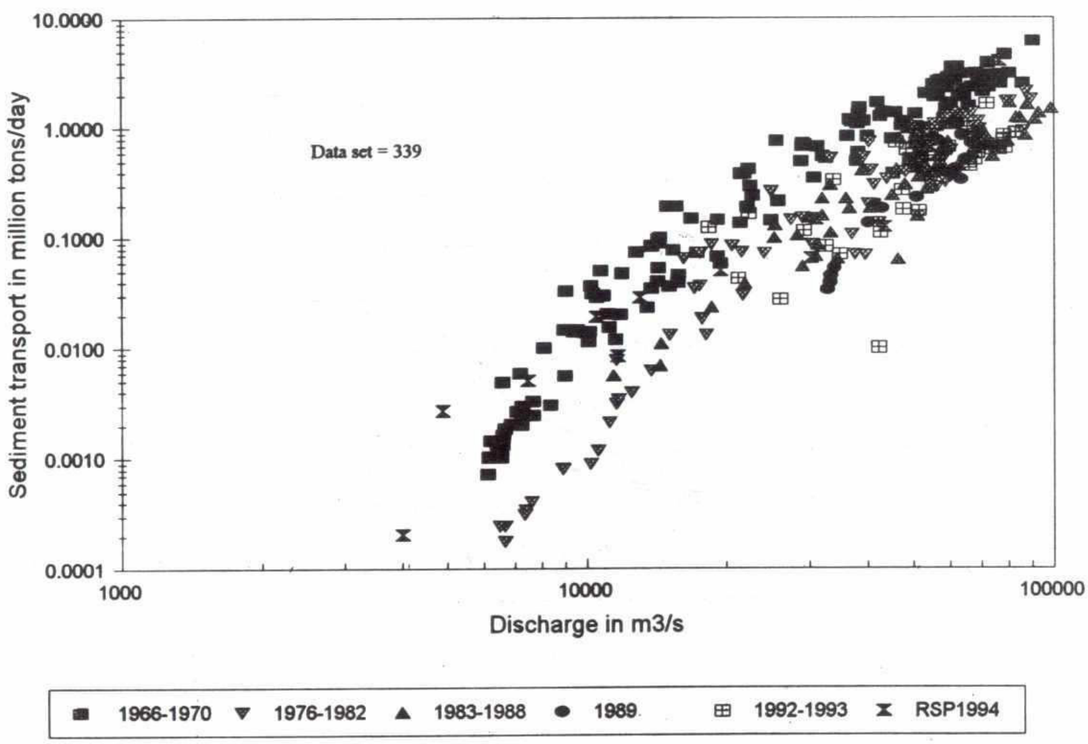
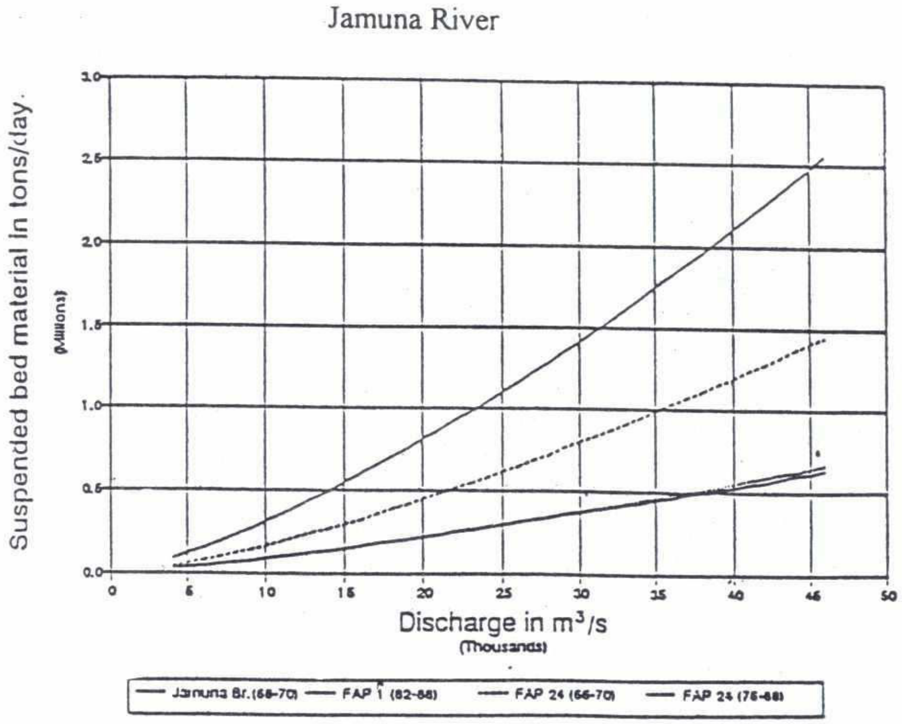


Figure 3.16: BWDB and RSP sediment transport measurements, Padma



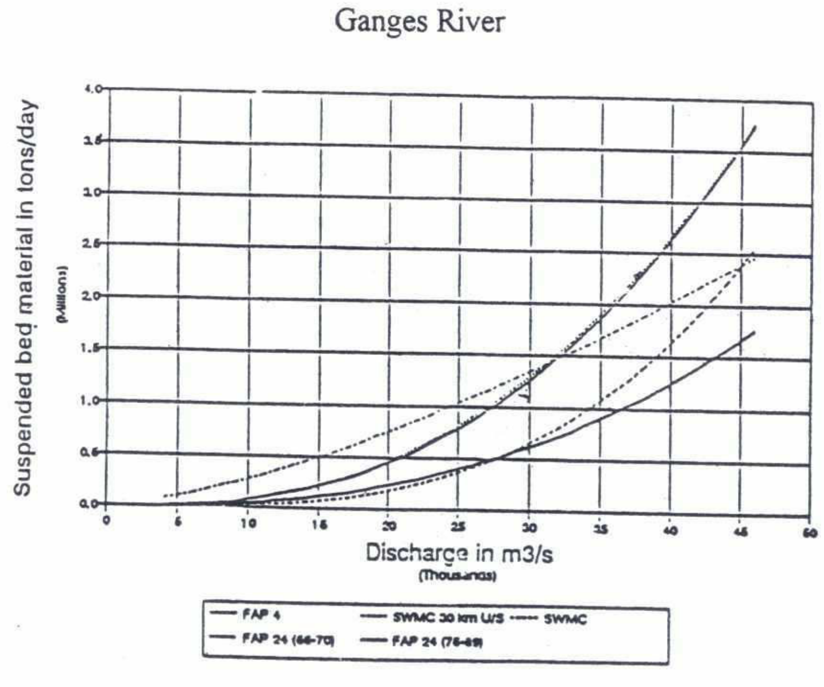


Figure 3.17: Rating curves from different studies, Jamuna and Ganges

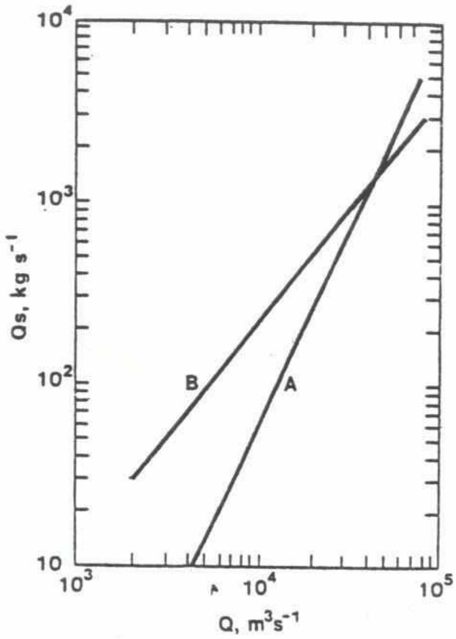


Figure 5.1: Sediment transport relations for wide sections (A) and narrow sections (B), near Musinacio

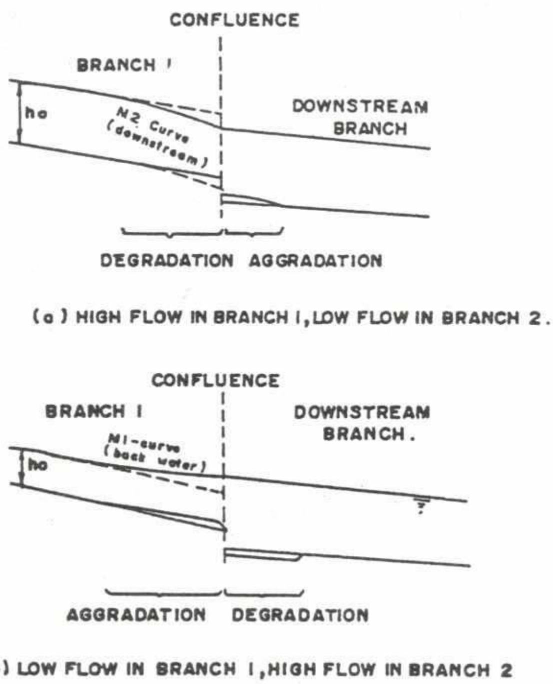


Figure 5.2: Dynamic equilibrium around a confluence

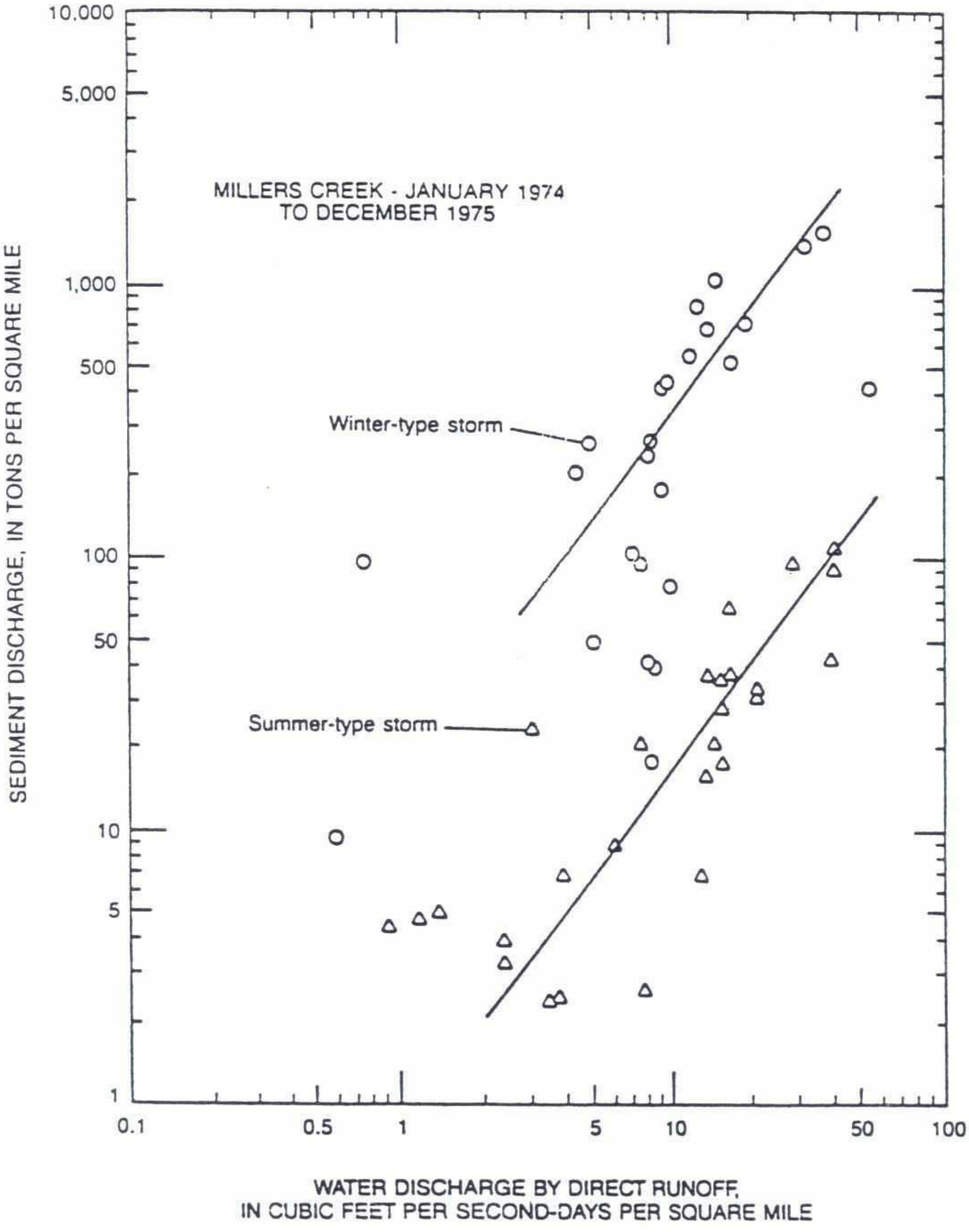


Figure 5.3: Sediment yield, Millers Creek (Glysson, 1987)

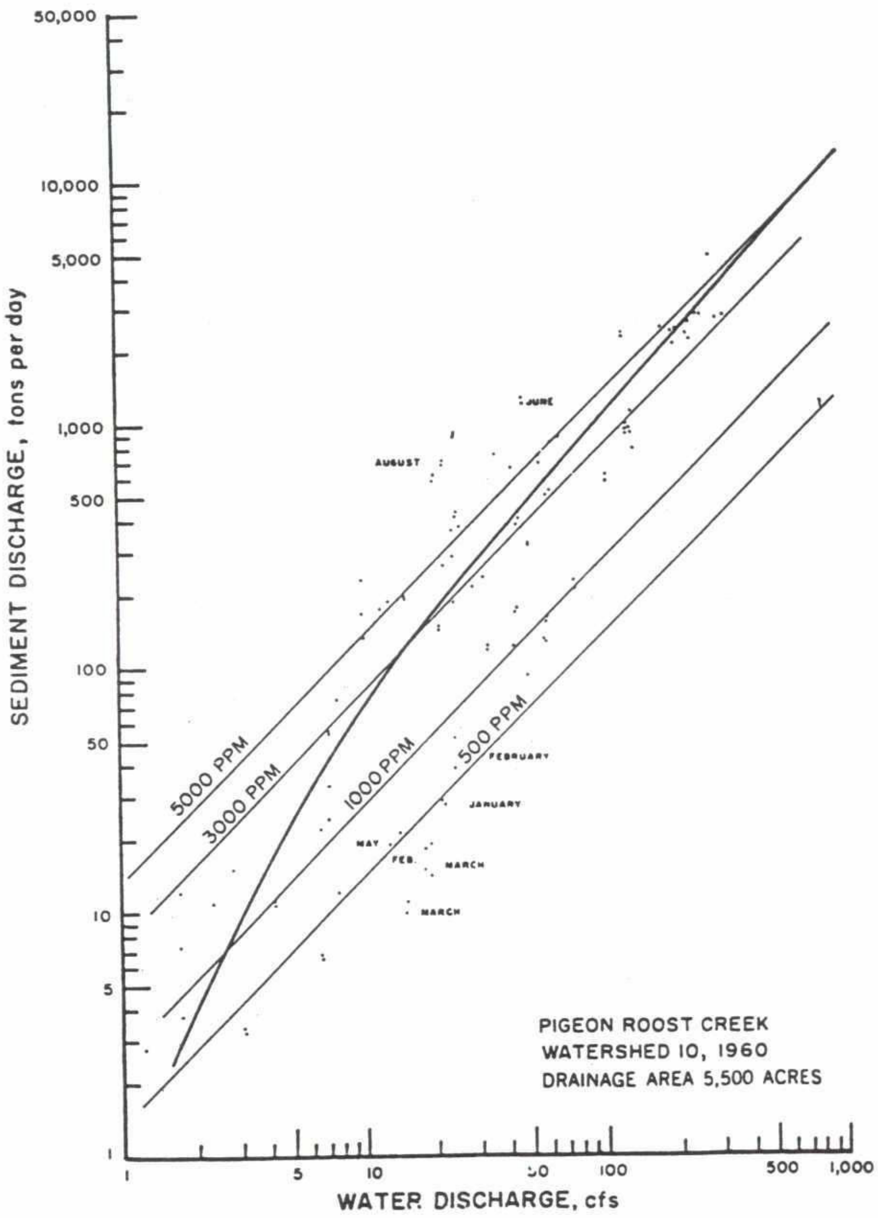


Figure 5.4: Suspended sediment transport, mixed cover watershed in Mississippi

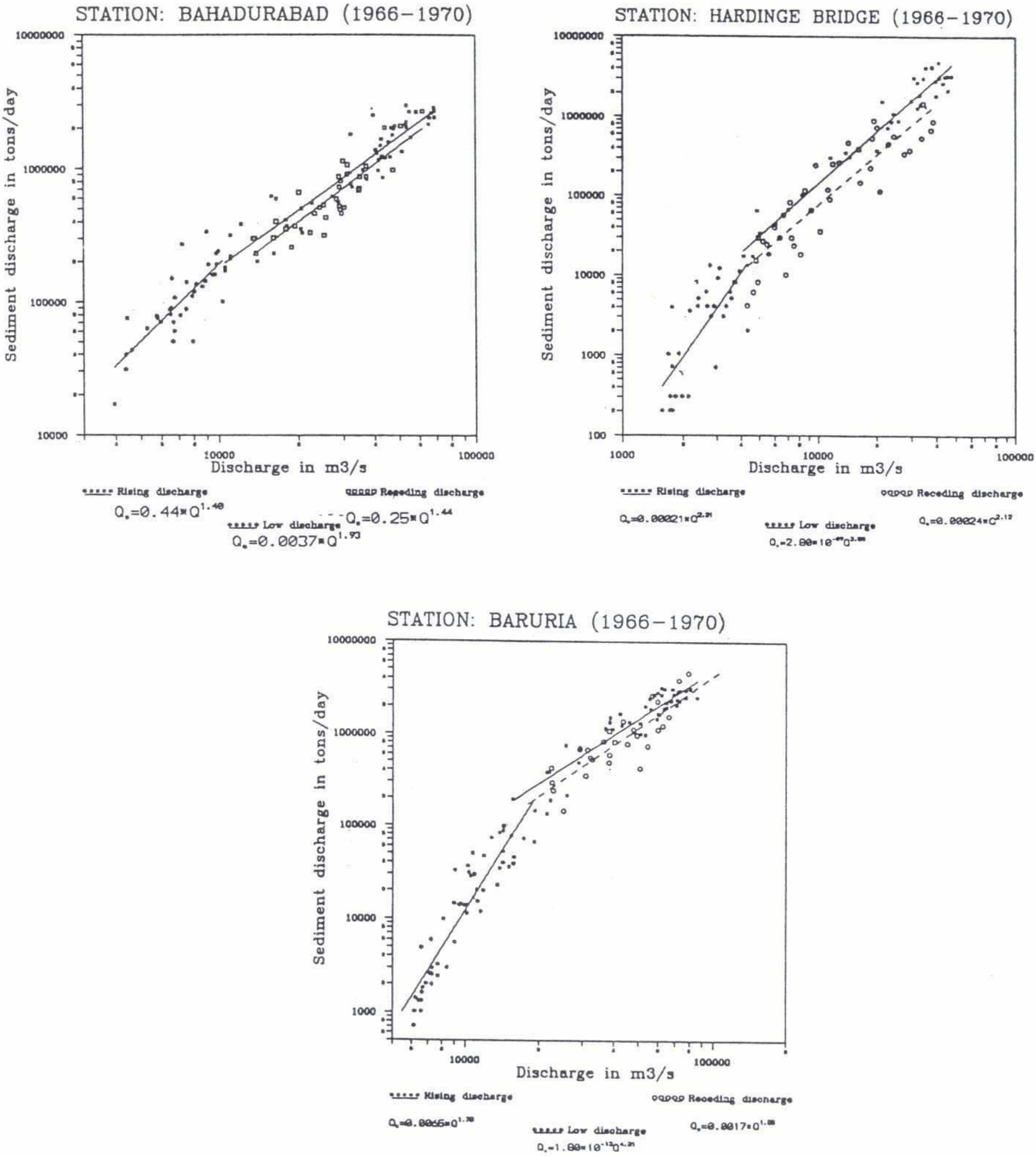


Figure 5.5: Seasonal variation of sediment transport

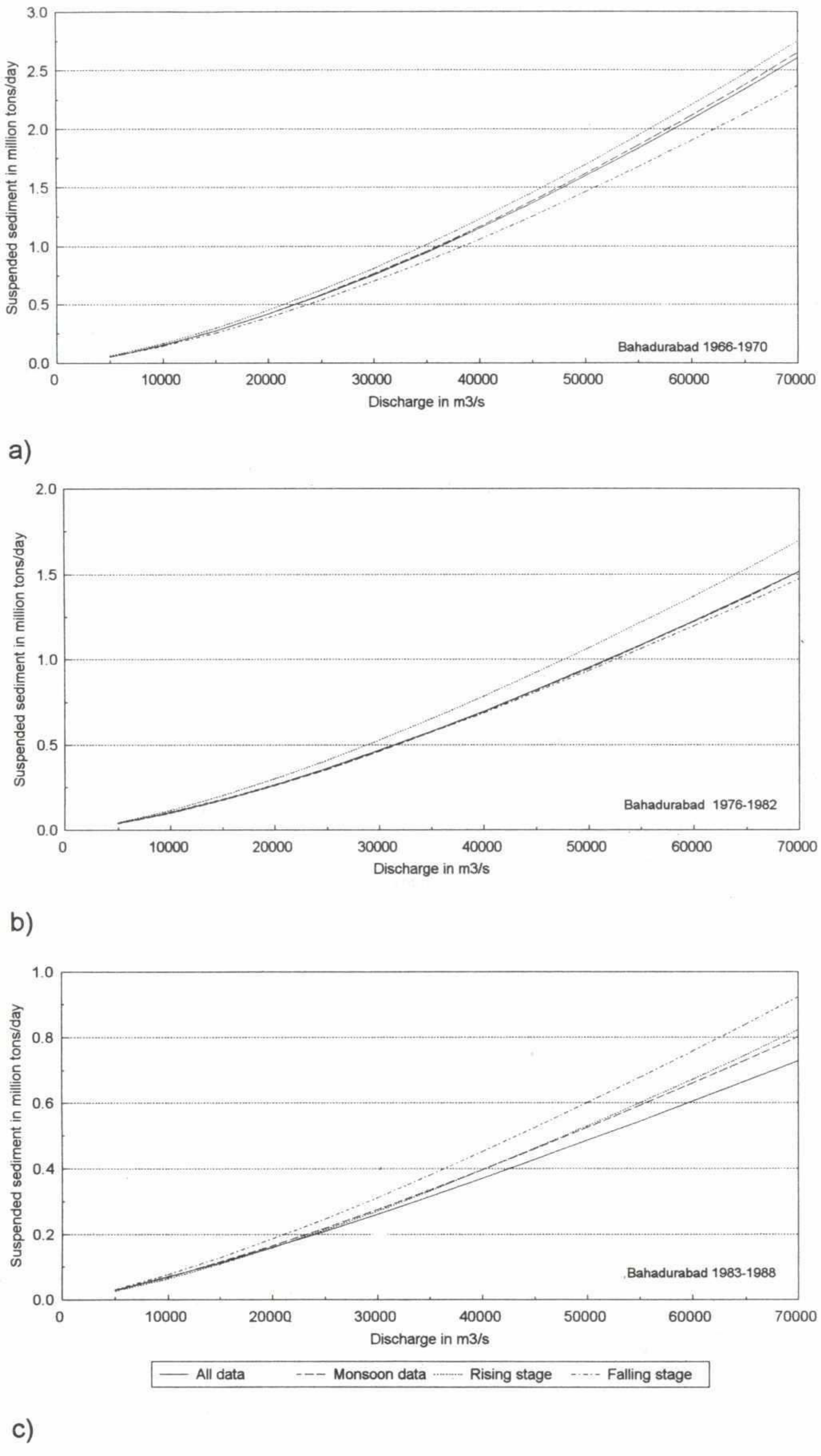


Figure 5.6: Seasonal variation of sediment transport, Bahadurabad

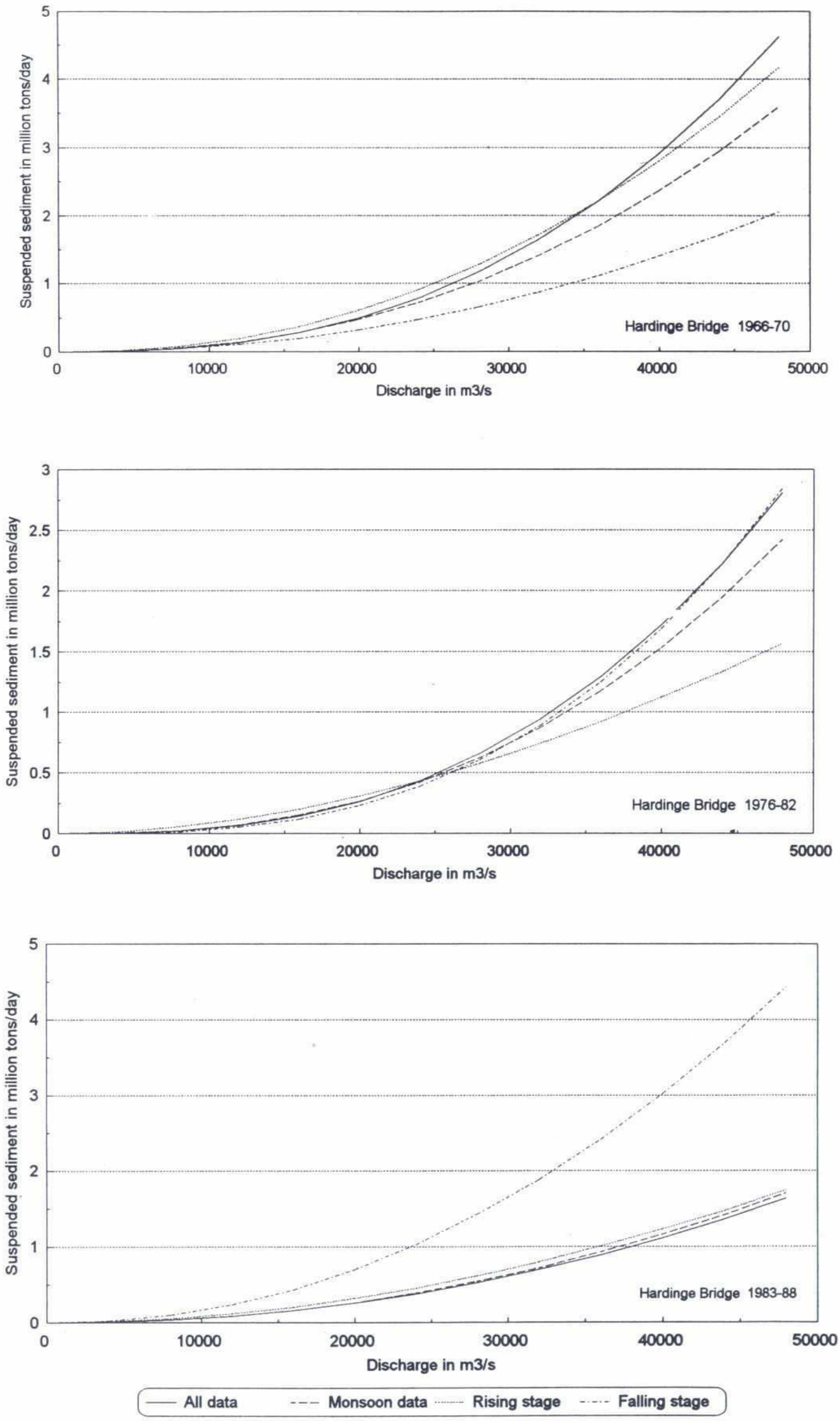


Figure 5.7: Seasonal variation of sediment transport, Hardinge Bridge

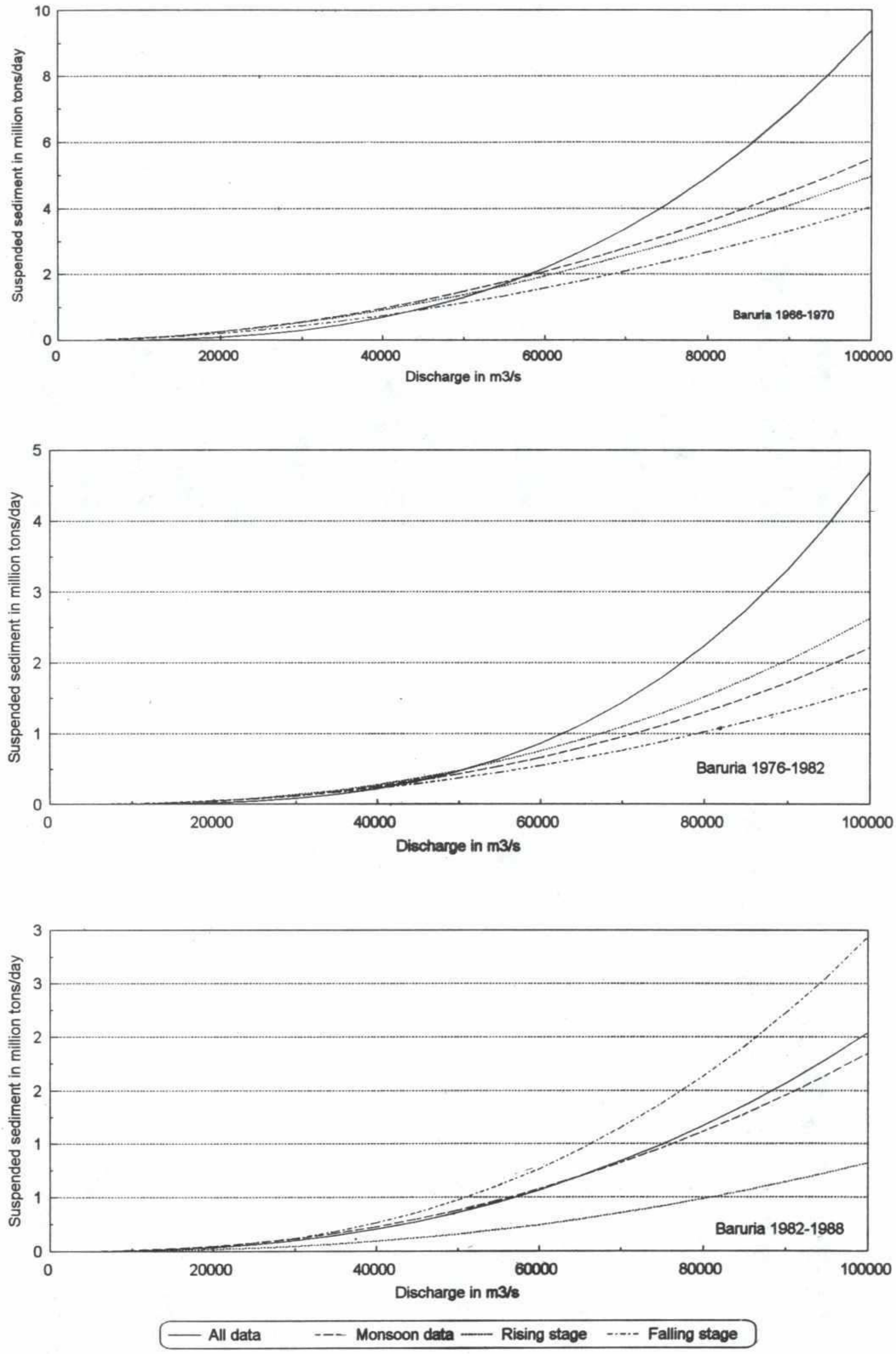


Figure 5.8: Seasonal sediment rating curves, Baruria

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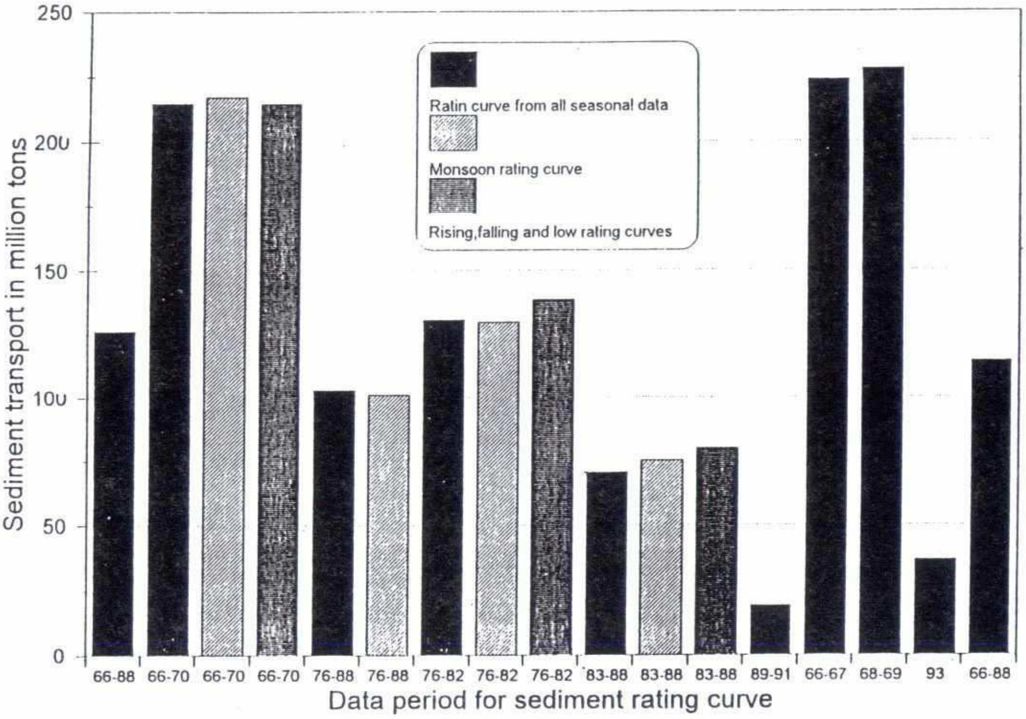


Figure 5.9: Annual sediment transport calculated for the 1987 discharge, Bahadurabad

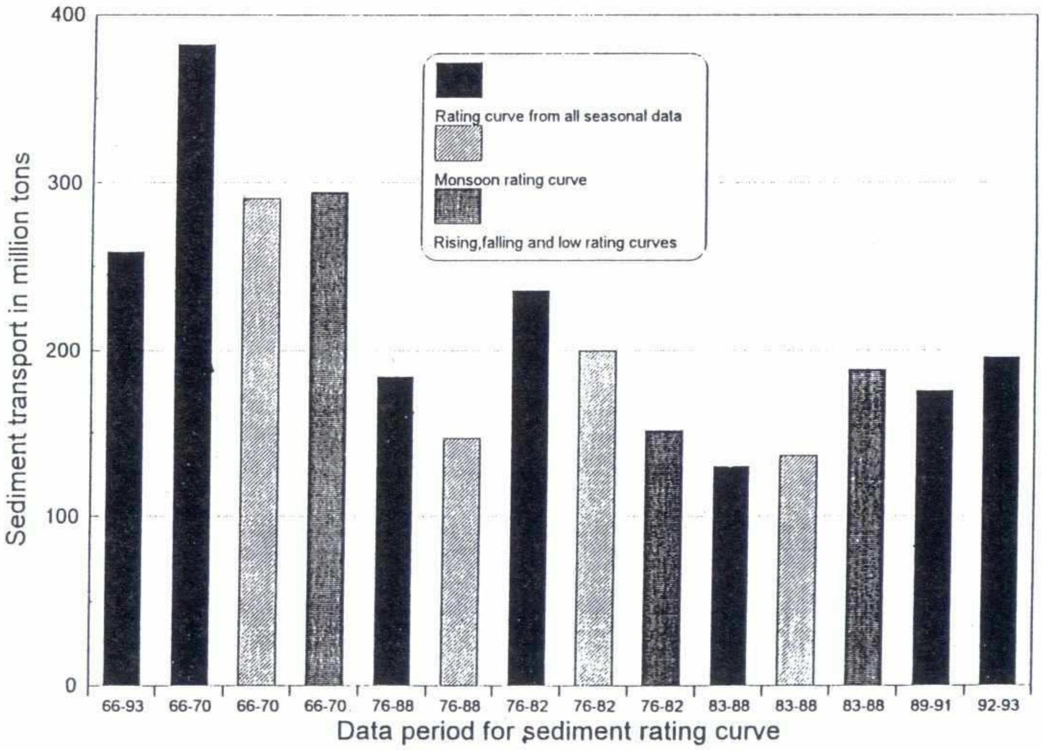


Figure 5.10: Annual sediment transport calculated for the 1987 discharge, Hardinge Bridge

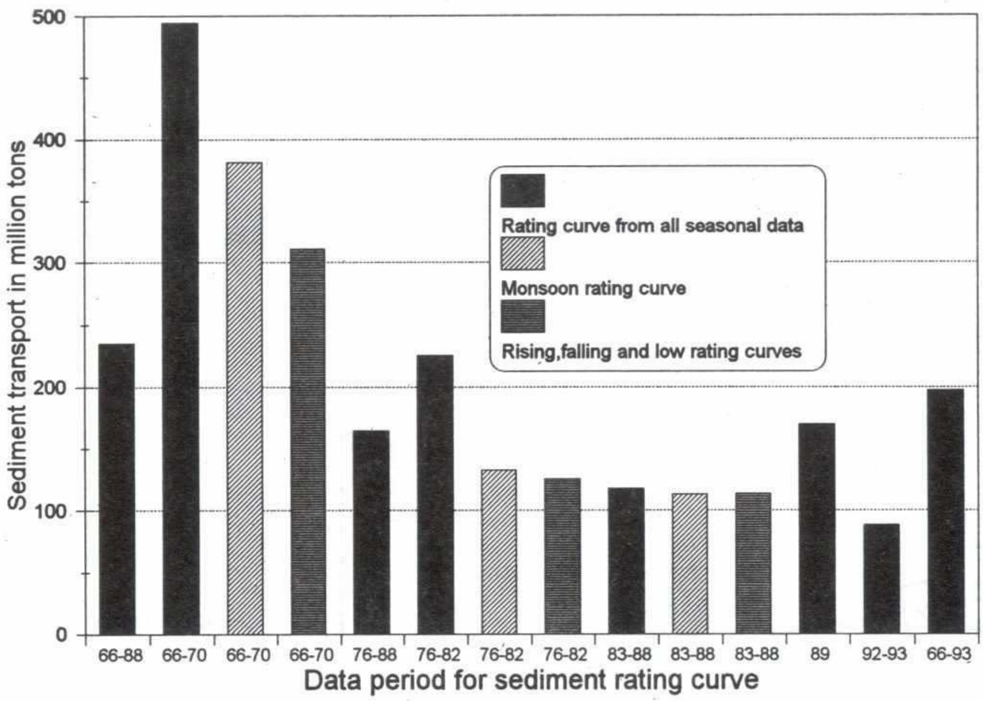


Figure 5.11: Annual sediment transport calculated for the 1987 discharge, Baruria

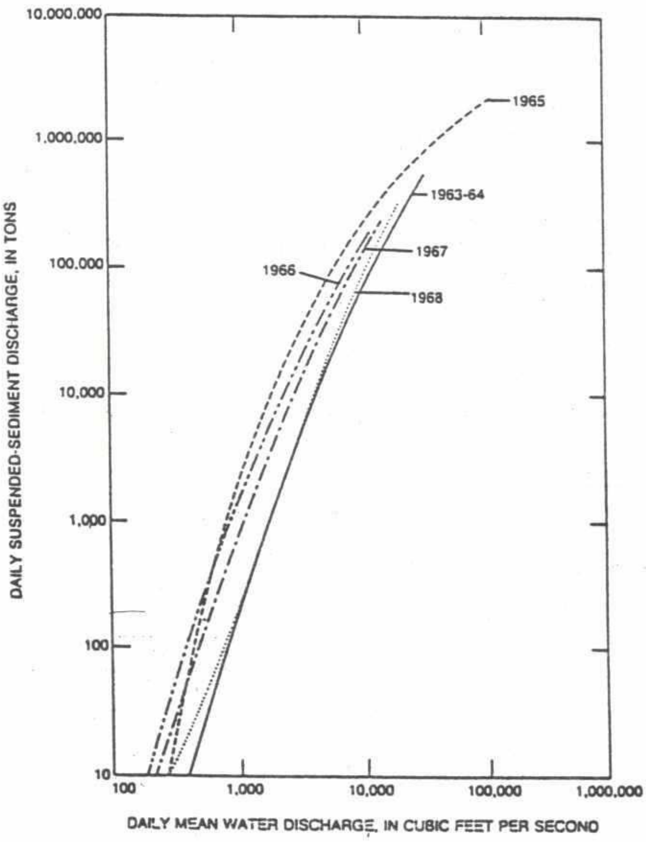


Figure 5.12: Effect of a flood on the sediment rating curve (example, Middle Fork Eel River, California, 1964)

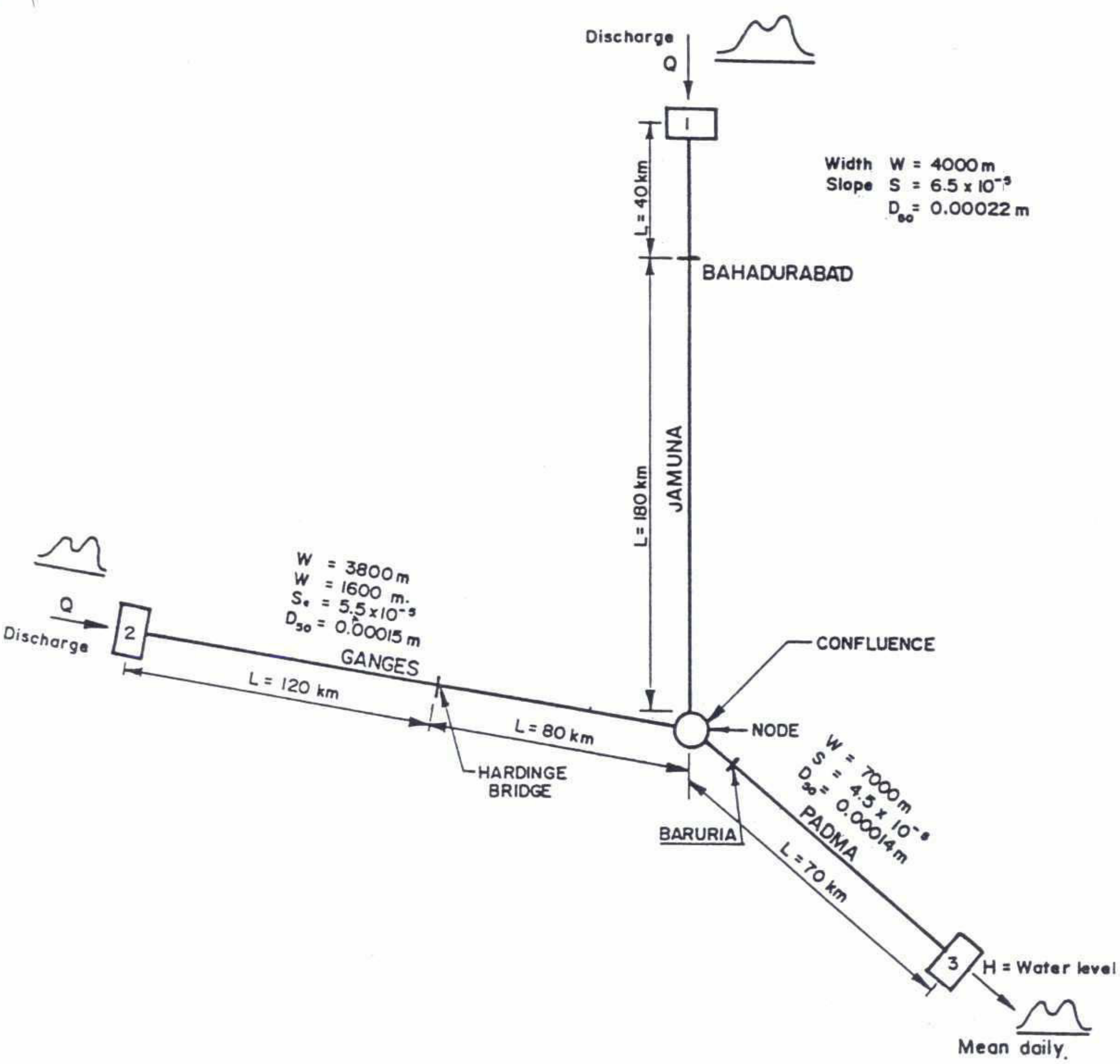


Figure 6.1: Network schematization of the GJP Model

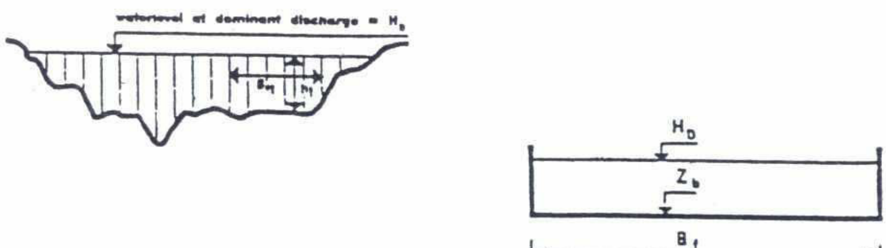
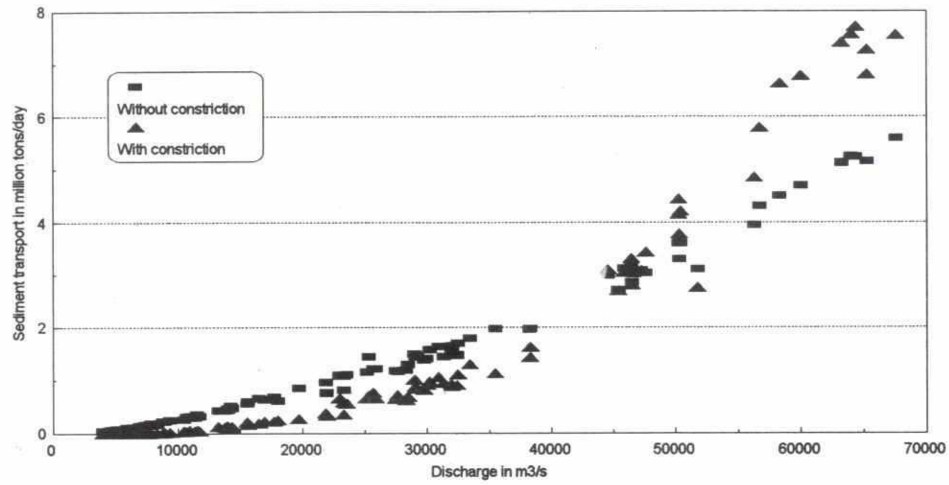
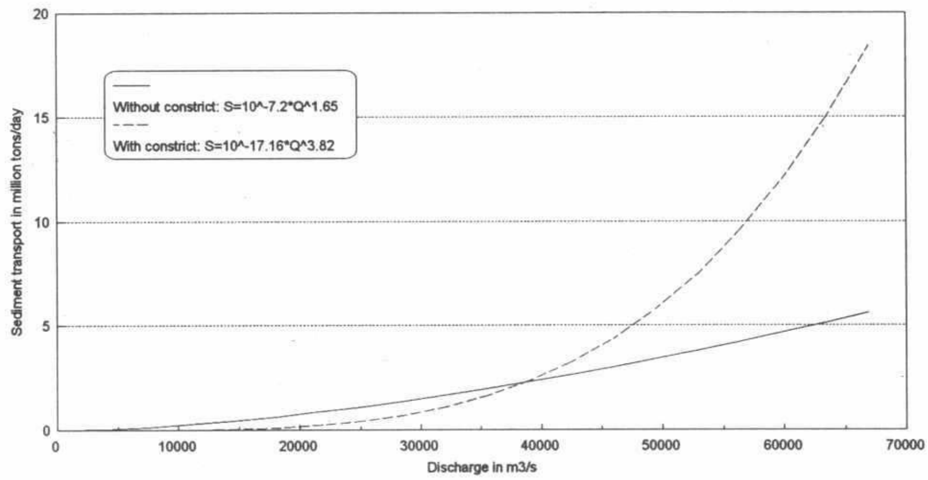


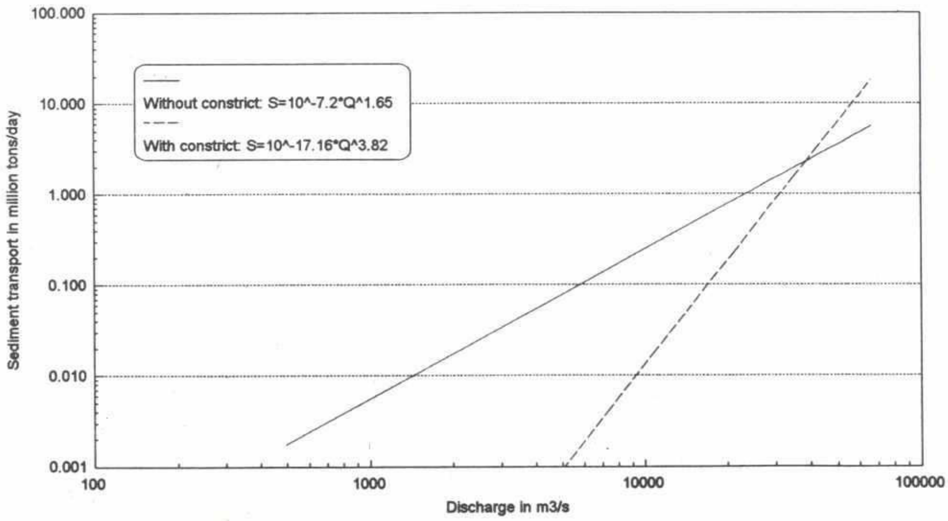
Figure 6.2: Cross-section schematization of the GJP Model



a)

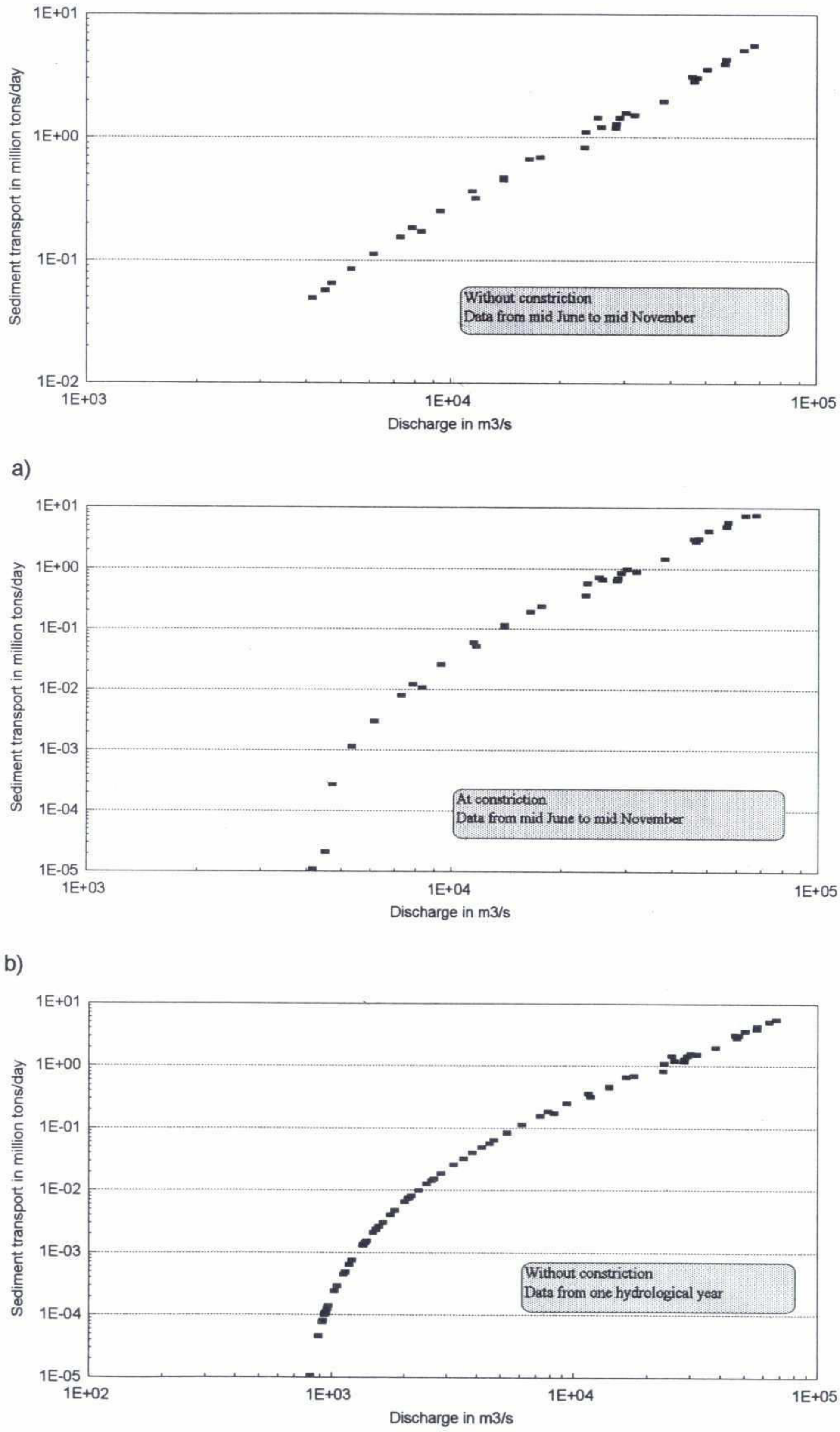


b)



c)

Figure 6.3: Calculated sediment transport, Ganges, without and with constriction



a)

b)

c)

Figure 6.4: Seasonal variation of calculated sediment transport, Ganges

TD

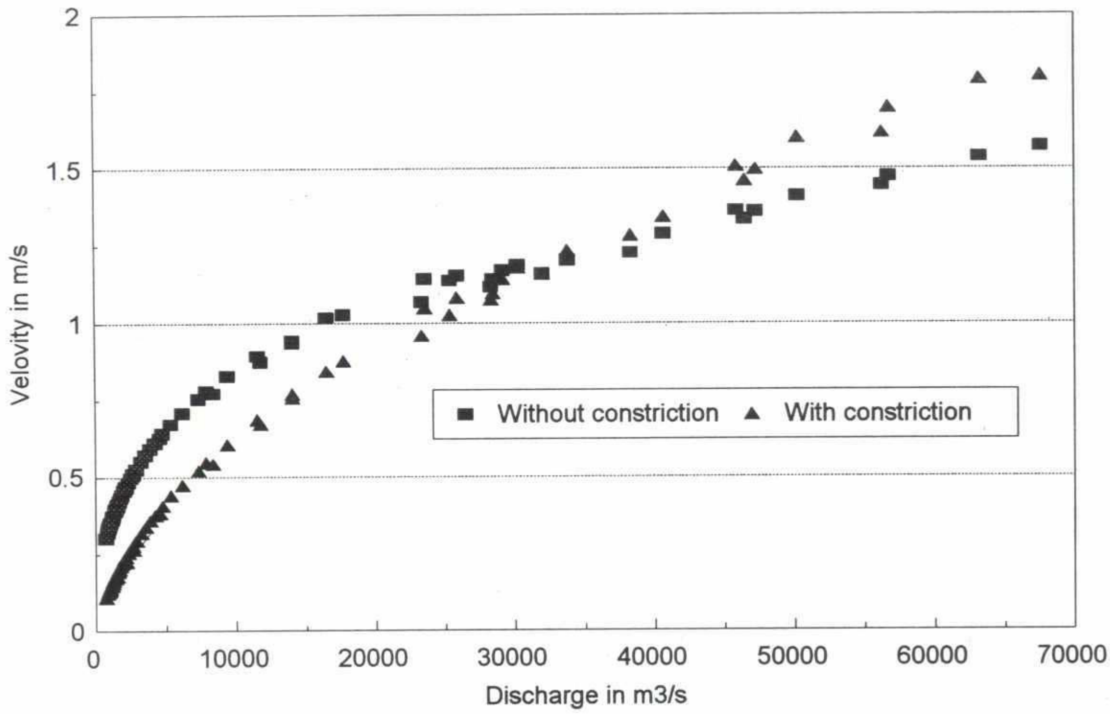


Figure 6.5: Effect of constriction on flow

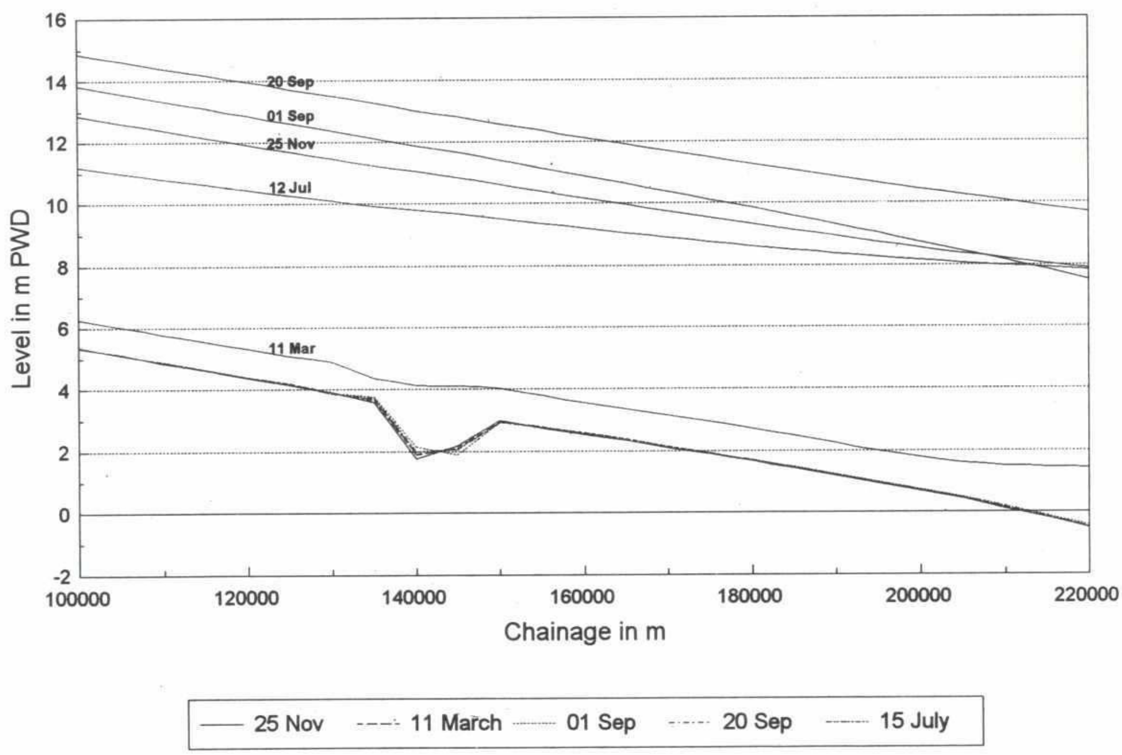


Figure 6.6: Bed and water levels variation, Ganges

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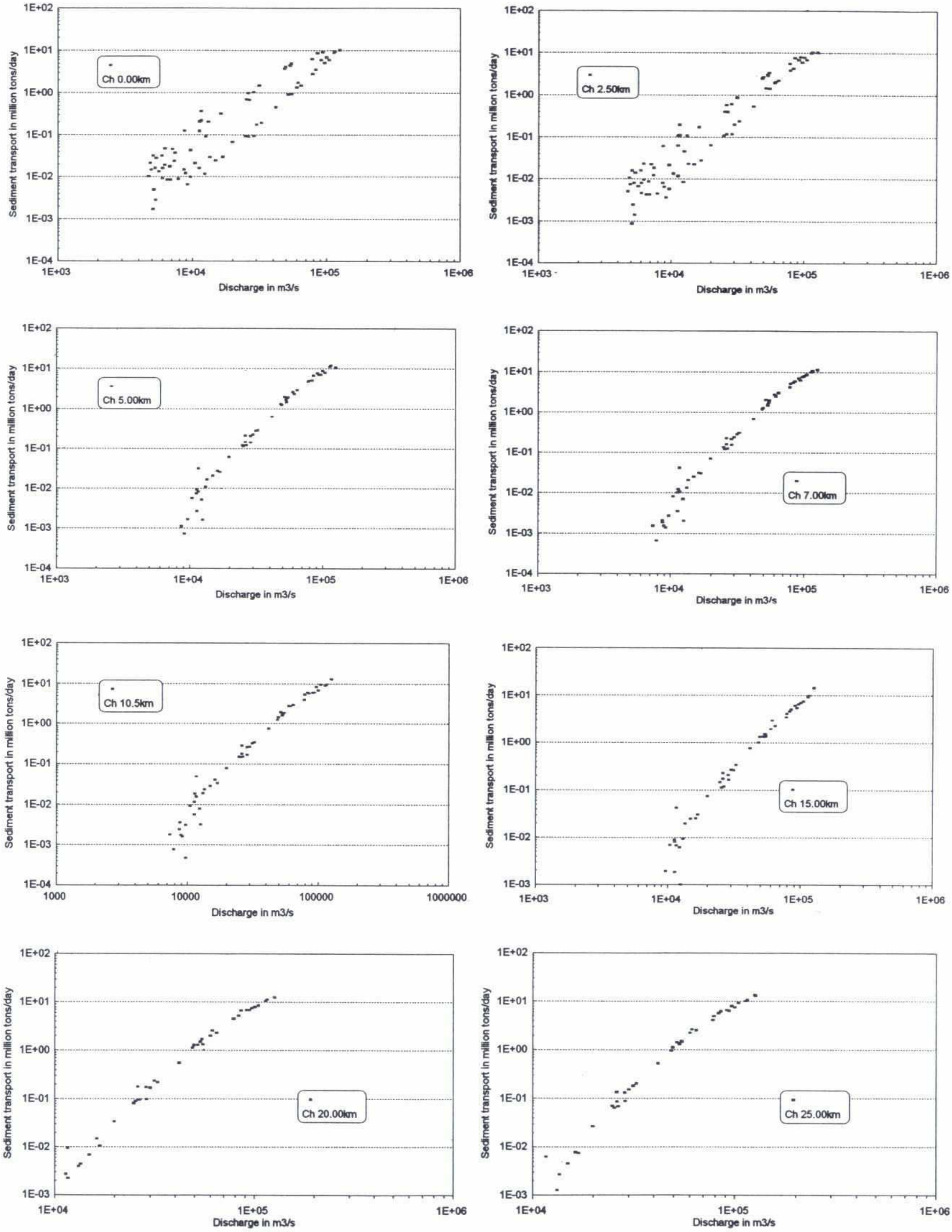

Figure 6.7: Calculated sediment transport, Lower Padma

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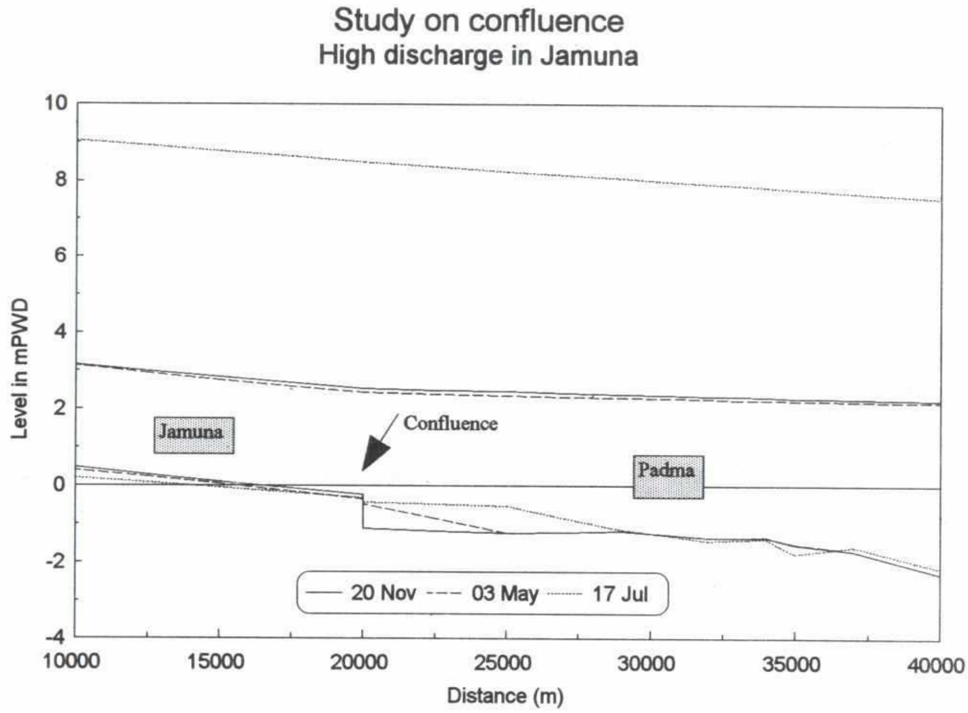

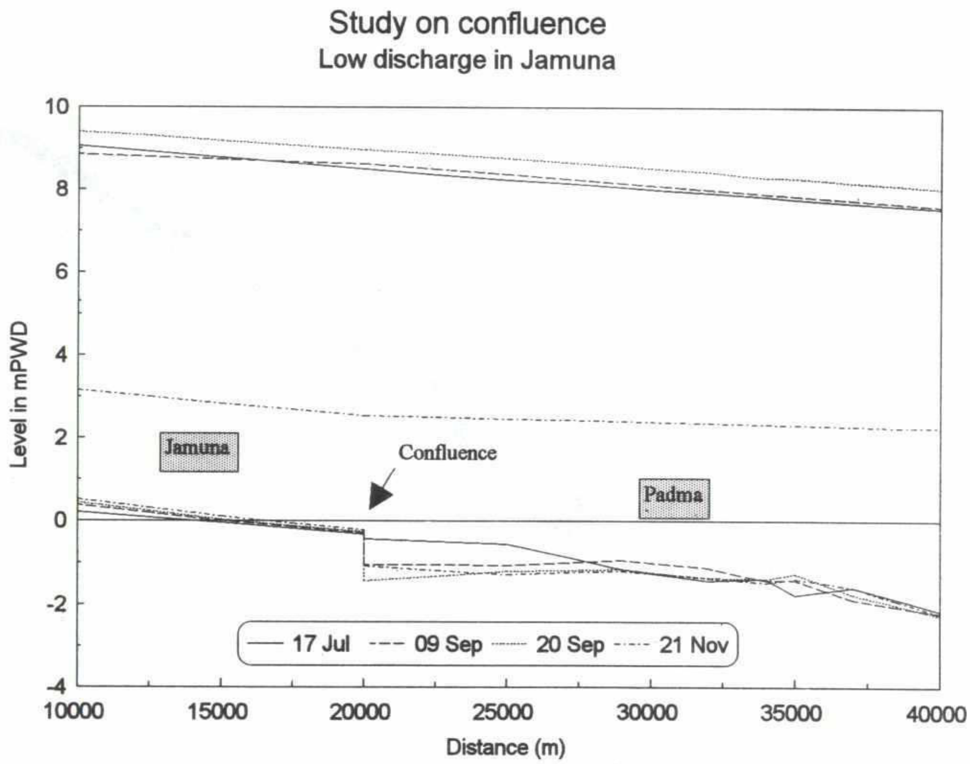

Figure 6.8: Dynamic equilibrium around the confluence of the Jamuna - Ganges river system

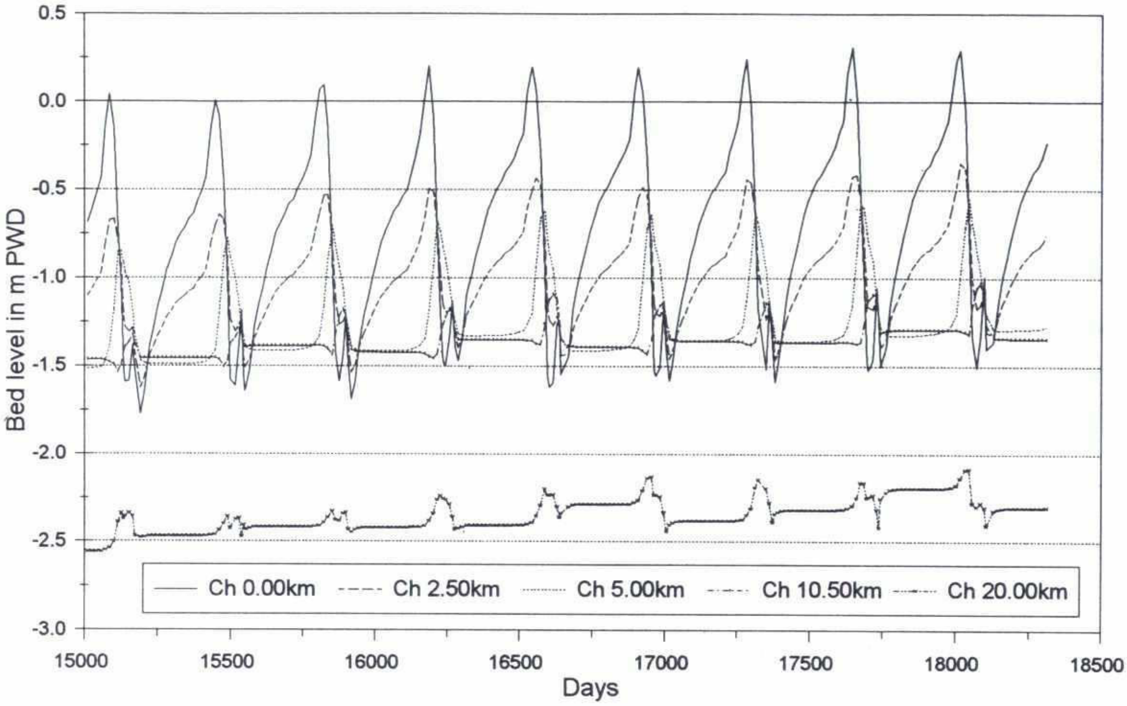

Figure 6.9: Bed level changes, Padma

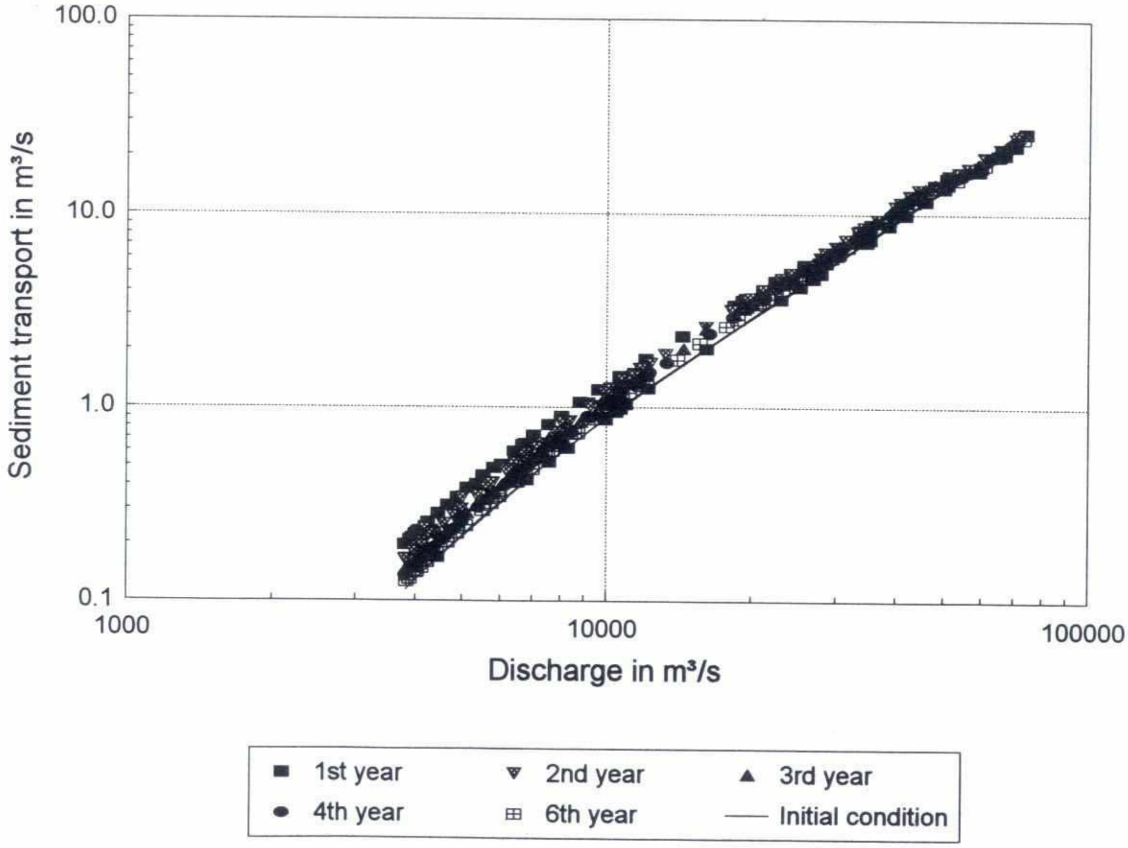

Figure 6.10: Effect of storage on sediment transport

Annex 1

Inventory of Available Suspended Sediment Data

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Tables

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1 Introduction

An inventory of the available data from suspended sediment measurements has been prepared for the sediment gauging stations along the main river system. These stations are the ones near Bahadurabad, Hardinge Bridge, Baruria and Goalundo, Mawa, Mymensingh, Taraghat, Jagir, Gorai Railway Bridge, and Bhairab Bazar.

Characteristics of the stations are mentioned in the following, and the data inventory is presented in Tables 1.5 to 1.14.

In those tables, the following codes are used:

C = coarse
F = fine
T = total
Fm = monthly fine sediment transport

The number of measuring days is given in brackets.

2 Bahadurabad

The station Bahadurabad transit, no. 46.9L, is located on the Jamuna River at approximately 25°09.3' N and 89°40.5' E. The sampling of suspended sediment transport started in 1956. The present location of the Bahadurabad transit was established in 1963. Since 1972, regular measurements of suspended sediment transport have been made both in the monsoon and in the lean period. However, during the period 1972-1975, only information on fine suspended sediment measurements could be traced. The available suspended sediment data at Bahadurabad are shown in Table 1.5. The data measured after 1966 were computerized recently by the SWH-II.

Hydrological period	Description
1966-1969	Coarse and fine (monthly discharge) sediment
1972-1975	Fine sediment
1976-1988	Coarse and fine sediment
1989-1994	Coarse sediment only

Table 1.1 Suspended sediment records at Bahadurabad

3 Hardinge Bridge

The main sediment gauging station along the Ganges River is located at approximately 23°04.1' N and 89°02.3' E. This station has number 89.9L and was established in 1934. The Paksey station (89.9L) close to the Hardinge Bridge was established in 1963 and was abolished in the same year. The sediment sampling is carried out approximately 500 m upstream of Hardinge Bridge and the water level is measured at a pier of that bridge. Weekly measurements of the sediment transport between April-November were started in 1966 by the Hydrology Directorate under the guidance of the FAO-SF Hydrological Survey Project. During 1972-1983, only the fine sediment transport was measured, and the data were published by the Hydraulic Research Laboratory. Recently, SWH-II has computerised the available suspended sediment data, see Table 1.2.

Hydrological period	Description
1966-1969	Coarse and fine (monthly discharge) sediment
1972-1983	Fine sediment
1984-1988	Coarse and fine sediment
1989-1994	Coarse sediment only

Table 1.2 Suspended sediment records at Hardinge Bridge

4 Baruria and Goalundo

The stations Goalundo (91.9R) on the right bank and Baruria (91.9L) on the left were together called Goalundo Station and were located downstream of the confluence of the Jamuna and Ganges Rivers. Both stations were established in 1963. The station Baruria is located at approximately 23°47.9' N and 89°47.2' E. The channel near Goalundo station was fed by the Ganges River. This channel gradually silted up in 1982 and so, the measurements were stopped.

Collection of samples on a regular basis started in 1966. The sediment samples were collected between April and November for the period 1966-1968, and for the entire Hydrological Year of 1969. All the data are computerized by SWH-II. The available suspended sediment data from the station are summarized in Table 1.3.

Hydrological period	Description
1968-1969	Coarse and fine (monthly discharge) sediment
1972-1975	Fine sediment
1976-1982	Coarse sediment only
1983-1986	Coarse and fine sediment
1987-1994	Coarse sediment only

Table 1.3 Suspended sediment records at Baruria

9+

5 Mawa

The Mawa gauging station lies downstream of Goalundo on the Padma river at approximately 23°30.5' N and 90°11.25' E. This station has number 93.5L and was established in 1965. In the past, sediment sampling was carried out at Bhagyakul, but those data were presented as if they were collected at Mawa. This site was selected because the channel width at the measurement transit is extremely narrow, as compared with both the upstream and downstream reaches. Since 1986/1987, the sediment sampling has been carried out at Mawa, as the narrow section has moved downwards to this place. Regular measurements of sediment transport between April-November were started in 1966 by the Hydrology Directorate under the guidance of the FAO-SF Hydrological Survey Project.

During 1974-1982, fine sediment transport data were measured. Recently, SWH-II has computerised the available suspended sediment data, measured at that station, see Table 1.4.

Hydrological Period	Description
1968-1969	Coarse and fine (monthly discharge) sediment
1972-1982	Fine sediment only
1976-1980	Coarse sediment only
1983-1993	Coarse sediment only

Table 1.4 Suspended sediment records at Mawa

6 Mymensingh

The Mymensingh sediment transport gauging station is located on the Old Brahmaputra River, which was the old course of the mighty Brahmaputra River before the avulsion. It has been informed that during the sixties, the offtake of the Old Brahmaputra was entirely cut off from the main channel in the low flow season. In the flood season, part of the flow of the Jamuna River is diverted through this course. The approximate coordinates of this station (228.3) are 24°45' N and 90°25.5' E. The station was established in 1940.

Regular measurements of the sediment transport between April-November were started by Hydrology Directorate in 1966 under the guidance of the FAO-SF Hydrological Survey Project. It was reported that the measurements were interrupted from 1970 and until 1988. In 1989, the measurements started again for the months July-October. Data until October 1991 were computerized by Hydrology Directorate.

7 Taraghat

The Dhaleswari River is a distributary of the Jamuna River, the takeoff located near Porabari. Downstream of this off-take, the Dhaleswari River bifurcates into Kaliganga and Dhaleswari Rivers. The Taraghat station has number 137a and is located at the Kaliganga River about 15-20 m upstream of the Dhaka-Aricha Highway Bridge. The approximate coordinates of this station are 23°47.7'N and 89°57.7'E. After establishment in 1963, regular sediment sampling started in 1967. This station has a long series of suspended coarse sediment data, available with SWH, and computerized until October 1993.

8 Jagir

The Jagir sediment transport gauging station is also located on a branch of the Dhaleswari River. The river has been silting up since the start of the sediment collection. The station with number 68.5 is located approximately 200 m upstream of the Dhaleswari Bridge on the Dhaka-Aricha Highway at 23°5' N and 90°01.6' E. It was established in 1963, and regular sediment sampling started in 1967.

This station is now closed, but since when it is not known. However, it was checked with Hydrology II that no data are available after 1970.

9 Gorai Railway Bridge

This station downstream of the Gorai Railway Bridge has number 99 and is located at approximately at 23°52' N and 89°10.5' E.

It was established in 1946. The sediment sampling started prior to 1960 and results are published in the form of PPM by the Hydraulic Research Laboratory. Regular sampling using a Binkley Sampler started in 1966 under the supervision of the FAO-UNSF Team. Long series of data from 1970-1987 could not be traced in the SWH-II. Suspended coarse sediment data are available for 1988.

10 Bhairab Bazar

The sediment gauging station at Bhairab Bazar is located on the Upper Meghna River at the upstream side of the railway bridge. This station has number 273 and it was established in 1949. The sediment sampling started prior to 1960 and the results were published in the form of PPM by the Hydraulic Research Laboratory. Regular sampling started in 1972 after a long interruption from 1963 to 1971. Computerized data are available with SWH for the period 1972-1988, except for the years 1976, 1977 and 1978. Here, the suspended sediment consists of fine sediment only, and the distribution is very uneven.

HYDROLOGICAL YEAR	RIVER : JAMUNA STATION : BAHADURABAD (46.9L)											
	Number of days in a month											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1957-58					T(1)	T(2)	T(3)					
1958-59						T(1)	T(2)			T(1)		T(1)
1959-60						T(1)	T(1)	T(1)				
1960-61	T(1)	T(1)	T(2)			T(1)	T(1)				T(1)	
1961-62	T(2)	T(2)	T(2)	T(1)	T(2)	T(1)	T(1)	T(1)				
1962-63			T(1)				T(2)	T(1)	T(1)	T(2)		
1963-64	T(2)	T(1)		T(1)	T(2)	T(1)	T(3)		T(2)	T(1)		T(1)
1964-65									T(1)		T(2)	T(1)
1965-66									T(1)			
1966-67				F(1) C(3)	F(3) C(4)	F(2) C(3)	F(2) C(4)	F(3) C(6)	F(2) C(4)	F(1) C(4)	F(1) C(2)	
1967-68				C(4)Fm	C(5)Fm	C(4)Fm	C(5)Fm	C(5)Fm	C(4)Fm	C(5)Fm	C(4)Fm	
1968-69				C(5)Fm	C(4)Fm	C(4)Fm	C(5)Fm	C(4)Fm	C(5)Fm	C(4)Fm	C(4)Fm	
1969-70	C(2)Fm	C(2) Fm	C(2) Fm	C(2)Fm	C(2)Fm	C(2)Fm	C(3)Fm	C(2)Fm	C(2)Fm	C(2)Fm	C(2)Fm	C(3)Fm
1970-71	F(3)	F(1)										
1971-72												
1972-73	F(2)	F(2)	F(3)		F(2)	F(2)	F(2)	F(2)			F(2)	F(2)
1973-74				F(2)	F(1)	F(2)	F(2)	F(1)	F(1)			F(2)
1974-75	F(2)	F(1)	F(1)									F(2)
1975-76	F(1) C(2)	F(2)	F(3)	F(3)		F(2)	F(3)	F(1)	F(1)	F(2)	F(2)	F(2)
1976-77	C(1)	C(4)	C(5)	F(1) C(3)	F(2) C(4)	F(3) C(5)	F(2) C(4)	F(2) C(5)	F(2) C(3)	F(2) C(4)	F(3) C(5)	F(2) C(4)
1977-78	C(2) F(1)	C(2) F(1)	C(2) F(1)	C(4)	C(5)	C(3)	C(4)	C(5)	C(4)	C(5)	C(2)	C(2)
1978-79	C(2)	C(2)	C(3)	C(2) F(1)	C(1) F(1)	C(4) F(2)	C(5) F(3)	C(4) F(2)	C(4) F(2)	C(5) F(2)	C(2) F(1)	C(2) F(1)
1979-80	C(2) F(1)	C(2) F(1)	C(2) F(1)	C(3)	C(2)	C(4)	C(5)	C(4)	C(4)	C(5)	C(1)	C(1)
1980-81	C(2) F(1)	C(2) F(1)	C(2) F(1)		C(2) F(1)	C(2) F(1)	C(2) F(1)		C(4) F(2)	C(4) F(2)	C(2) F(1)	C(2) F(1)
1981-82	C(2) F(1)	F(1)		C(4) F(1)	C(3) F(1)	C(2) F(2)	C(2) F(2)	C(3) F(2)	C(2) F(1)	C(2) F(1)	C(2) F(1)	C(2)
1982-83	F(1)	F(1)	F(1)		F(1)		F(1)	F(2)	F(1)	F(2)	F(1)	F(1)
1983-84	F(1) C(1)	F(1) C(1)	F(1) C(1)	F(1)	F(1)	F(1)	F(2)	F(2)	F(2)	F(3)	F(1)	F(1)
1984-85	F(1) C(1)	F(1) C(1)	F(1) C(1)	F(1) C(1)	F(1) C(1)	F(2) C(2)	F(2) C(2)	F(2) C(2)	F(2) C(2)	F(3) C(3)	F(1) C(1)	F(1) C(1)
1985-86	F(1) C(1)	F(1) C(1)	F(1) C(1)	F(1) C(1)	F(1) C(1)	F(2) C(2)	F(2) C(2)	F(2) C(2)	F(2) C(2)	F(2) C(2)	F(1) C(1)	F(1) C(1)
1986-87	F(1) C(2)	F(1) C(2)	F(1) C(3)	F(1) C(1)	F(2) C(2)	F(2) C(2)	F(2) C(2)	F(2) C(2)	F(3) C(3)	F(2) C(2)	F(2) C(2)	F(1) C(1)
1987-88	F(1) C(2)	F(1) C(2)	F(1) C(2)									
1988-89				F(1) C(2)	F(1) C(2)	F(2) C(3)	F(1) C(3)	C(4)				
1989-90	C(2)	C(2)	C(1)				C(2)	C(3)	C(4)	C(5)	C(2)	C(3)
1990-91	C(2)	C(1)	C(2)	C(2)	C(2)	C(2)	C(3)	C(3)	C(4)	C(2)	C(2)	C(1)
1991-92	C(2)	C(2)	C(3)		C(1)	C(3)	C(2)	C(4)	C(5)	C(4)	C(2)	C(2)
1992-93	C(2)	C(2)	C(4)	C(2)	C(2)	C(5)	C(5)	C(1)	C(2)	C(3)	C(22)	
1993-94				C(2)	C(2)	C(3)	C(4)	C(5)	C(4)	C(4)	C(2)	C(2)

Table 1.5 Available suspended sediment records at Bahadurabad

HYDRO LOGICAL YEAR	RIVER : GANGES STATION : HARDINGE BRIDGE (90) Number of days in a month											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1958-59												
1959-60												
1960-61												
1961-62												
1962-63												
1963-64												
1964-65												
1965-66												
1966-67				C(1)	C(1)	C(1)		C(4)	C(5)	C(4)	C(5)	
1967-68					C(1)	C(2)Fm	C(4)Fm	C(5)Fm	C(5)Fm	C(4)Fm	C(5)Fm	
1968-69				C(1)Fm	Fm	C(2)Fm	C(5)Fm	C(3)Fm	C(4)Fm	C(5)Fm	C(4)Fm	
1969-70	C(5)Fm	C(4)Fm	C(4)Fm	C(4)Fm	C(4)Fm	C(4)Fm	C(5)Fm	C(4)Fm	C(4)Fm	C(5)Fm	C(3)Fm	C(4)Fm
1970-71	F(4)	F(3)										
1971-72												
1972-73												
1973-74	F(5)	F(2)					F(1)	F(3)	F(2)	F(3)	F(3)	F(4)
1974-75							F(3)		F(1)	F(3)		
1975-76	F(3)									F(1)	F(4)	F(3)
1976-77												
1977-78	F(4)	F(4)	F(5)									
1978-79				F(4)	F(5)	F(4)	F(4)	F(1)	F(3)	F(4)	F(5)	F(3)
1979-80	F(2)		F(2)									
1980-81	F(3)			F(4)	F(2)	C(3) F(3)	CF(3)		F(4)	F(7)	F(2)	F(2)
1981-82						F(4)	F(5)	F(3)	F(1)		F(2)	F(1)
1982-83									F(5)	F(4)	C(3) F(3)	C(1) F(1)
1983-84							F(4)	F(3)	F(2)	F(4)	F(4)	F(1)
1984-85						C(2) F(4)	C(4) F(4)	C(4) F(4)		C(5) F(5)	C(4) F(4)	C(2) F(2)
1985-86							CF(4)	C(4) F(4)	C(4) F(4)	C(3) F(3)	C(4) F(4)	C(2) F(2)
1986-87							C(5) F(5)	C(3) F(3)	C(5) F(5)	C(4) F(4)	C(3) F(3)	
1987-88						C(5) F(5)	C(4) F(4)					
1988-89							C(2) F(2)	C(4) F(3)	C(3) F(3)	C(4) F(4)		
1989-90					C(1)	C(5)	C(4)	C(5)				
1990-91					C(1)	C(5)	C(4)	C(4)	C(5)	C(2)		
1991-92					C(1)	C(5)	C(4)	C(3)	C(4)			
1992-93						C(4)	C(4)	C(5)	C(4)			
1993-94								C(5)	C(4)	C(4)		

Table 1.6 Available suspended sediment records at Hardinge Bridge

HYDRO LOGICAL YEAR	RIVER : PADMA STATION : BARURIA (91.9L)											
	Number of days in a month											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1968-69				C(1)Fm	C(5)Fm	C(4)Fm	C(6)Fm	C(4)Fm	C(4)Fm	C(5)Fm	C(4)Fm	
1969-70	C(5)Fm	C(4)Fm	C(4)Fm	C(4)Fm	C(5)Fm	C(4)Fm	C(5)Fm	C(5)Fm	C(4)Fm	C(5)Fm	C(4)Fm	C(4)Fm
1970-71												
1971-72												
1972-73	F(3)	F(2)	F(4)				F(2)	F(2)	F(2)	F(4)	F(2)	F(3)
1973-74	F(4)	F(4)	F(4)	F(2)	F(2)	F(4)	F(1)	F(4)	F(2)	F(3)	F(4)	F(3)
1974-75	F(3)	F(4)	F(3)	F(2)		F(4)	F(1)			F(1)	F(3)	F(4)
1975-76			F(3)	F(2) T(2)								
1976-77	C(4)	C(2)								C(3) C(3)	C(4) C(4)	C(5) C(5)
1977-78	F(2)	F(2)	F(2)	C(1)	C(4)	C(4)	C(4)	C(2)	C(4)	C(4)		
1978-79				F(2)	F(2)	C(2)	C(1) F(1)	C(1) F(1)	C(4)	C(1) F(3)	F(2)	F(2)
1979-80						C(2)	C(3)	C(2)				
1980-81							C(4)					
1981-82						C(2)	C(4)	C(3)	C(4)	C(1)		
1982-73	F(1)					C(2)	C(5)	C(3)	C(3)	C(2)	C(1)	C(2)
1983-84	F(2)	F(3)	F(2)		C(2) F(2)	C(5) F(5)	C(2) F(2)	C(1) F(1)	C(2) F(3)	C(4) F(4)	C(2) F(2)	C(1) F(1)
1984-85	F(2)	F(2)	F(2)	F(2)	F(2)	F(4)	C(1) F(4)	C(5) F(5)	C(3) F(4)	C(4) F(4)	C(2) F(2)	F(2)
1985-86	F(2)	F(2)	F(2)	F(2)	F(2)	C(4) F(4)	C(4) F(5)					
1986-87				F(2)	F(3)	C(1) F(4)	C(5) F(5)	C(2) F(4)	F(3)	C(3) F(5)	F(4)	F(2)
1987-88						C(2)	C(3)	C(4)	C(5)			
1988-89								C(4)	C(5)	C(4)		
1989-90						C(4)	C(5)	C(5)	C(4)	C(4)		
1990-91						C(4)	C(3)	C(4)	C(4)	C(5)	C(1)	
1991-92						C(4)	C(4)	C(5)	C(4)	C(5)		
1992-93							C(1)	C(4)	C(4)	C(5)		
1992-94						C(4)	C(5)	C(4)	C(4)	C(2)	C(2)	

Table 1.7 Available suspended sediment records at Baruria

HYDRO-LOGICAL YEAR	RIVER : PADMA STATION : GOALANDO (91.9R)											
	Number of days in a month											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1960-61												
1961-62												
1962-63												
1963-64												
1964-65												
1965-66												
1966-67				C(2) F(1)	C(5) F(2)	C(4) F(2)	C(4) F(2)	C(7) F(3)	C(4) F(2)	C(4) F(2)	C(4) F(2)	
1967-68					C(3)Fm	C(4)Fm	C(4)Fm	C(5)Fm	C(4)Fm	C(4)Fm	C(5)Fm	
1968-69				Fm	Fm	Fm	C(5)Fm	C(4)Fm	C(4)Fm	C(5)Fm	C(3)Fm	
1969-70							C(5)	C(5)Fm	C(4)Fm	C(5)Fm	C(4)Fm	C(1)Fm
1970-71												
1971-72												
1972-73												
1973-74												
1974-75												
1975-76												
1976-77										C(1)		
1977-78							C(4) F(4)	C(5) F(5)	C(4) F(4)	F(4)		
1978-79						C(1) F(1)	F(4)	C(1) F(4)	F(4)	F(4)		
1979-80							F(4)	F(4)	F(3)	F(4)		
1880-81							C(2)					
1981-82							C(5) F(5)	C(4) F(4)	C(5) F(5)	F(4)		
1882-83							C(1) F(2)	C(5) F(4)	C(5) F(3)	C(1)		

Table 1.8 Available suspended sediment records at Goalundo

HYDRO-LOGICAL YEAR	RIVER : PADMA STATION : MAWA (93.5L)											
	Number of days in a month											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1966-67				C(1) F(1)	C(4) F(2)	C(4) F(2)	C(5) F(2)	C(2)	C(6) F(5)	C(6)	C(3)	
1968-69				Fm	Fm	C(4)Fm	C(4)Fm	C(5)Fm	C(4)Fm	C(4)Fm	C(5)Fm	
1970-71				Fm	C(1)Fm	C(4)Fm	C(4)Fm	C(5)Fm	C(4)Fm	C(5)Fm	C(4)Fm	C(1)Fm
1971-72												
1972-73												
1973-74												
1974-75		F(2)	F(1)									
1975-76				F(1)								
1976-77	F(4)	F(4)	F(4)					C(2)	C(2)	C(4)	C(4)	C(1)
1977-78	F(4)	F(2)	F(3)	F(4)	F(4)	F(5)	F(4)	F(4)	F(5)	F(4)	F(5)	F(4)
1978-79				F(2)	F(2)	F(3)	F(1)	F(2)				
1979-80					F(3)	F(4)	F(5)	F(4)	F(4)	F(5)	F(1)	F(1)
1980-81						C(3)	C(2)	C(5)	C(3)	C(4)	C(1)	
1981-82						F(4)	F(4)	F(4)	F(4)	F(4)	F(2)	
1982-83						F(4)	F(1)	F(1)	F(4)	F(4)	F(1)	
1983-84						C(4)	C(3)	C(3)	C(1)	C(1)	C(1)	
1984-85						C(1)	C(2)	C(3)	C(1)	C(4)	C(1)	
1985-86									C(2)	C(4)	C(2)	C(2)
1986-87							C(1)	C(3)	C(4)	C(5)	C(2)	C(1)
1987-88							C(2)	C(4)	C(10)	C(6)		
1988-89						C(1)	C(4)	C(2)	C(2)			
1989-90						C(1)	C(4)	C(5)	C(3)			
1990-91										C(4)		
1991-92						C(6)	C(5)	C(4)				
1992-93						C(3)	C(4)	C(4)	C(4)	C(4)		
1993-94							C(3)	C(4)	C(4)	C(4)		

Table 1.9 Available suspended sediment records at Mawa

HYDRO-LOGICAL YEAR	RIVER : MEGHNA-UPPER STATION : BHAIRAB BAZAR (273)											
	Number of days in a month											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1959-60												
1960-61							T(1)		T(1)			
1961-62		T(1)				T(1)	T(2)	T(2)	T(1)		T(1)	
1962-63				T(1)	T(1)	T(1)	T(1)	T(1)	T(1)			T(1)
1963-64	T(1)								T(1)	T(2)	T(2)	
1964-65												
1965-66												
1966-67												
1967-68												
1968-69												
1970-71												
1971-72												
1972-73							F(4)	F(1)	F(4)	F(5)		
1973-74					F(1)	F(3)	F(4)	F(2)	F(3)			
1974-75							F(2)	T(3)	F(1)			
1975-76					F(1)						F(3)	F(2)
1976-77												
1977-78												
1978-79					F(1)	F(1)	F(5)	F(4)	F(5)	F(4)	F(1)	
1979-80												
1980-81					F(3)	F(4)	F(4)	F(4)	F(4)	F(4)	F(2)	
1981-82							F(1)	F(2)				
1982-83												
1983-84							F(2)	F(2)	F(2)	F(1)		
1984-85					F(1)	F(1)	F(1)	F(2)	F(1)	F(1)	F(1)	
1985-86						F(1)	F(1)	F(2)	F(1)	F(1)		
1986-87						F(1)	F(2)	F(2)	F(4)	F(4)	F(3)	
1987-88						F(4)	F(5)	F(4)	F(4)	F(5)	F(2)	
1988-89					F(1)	F(5)	F(4)	F(4)	F(5)	F(4)	F(2)	

Table 1.10 Available suspended sediment records at Bhairab Bazar

HYDRO-LOGICAL YEAR	RIVER : OLD BRAHMAPUTRA STATION : MYMENSINGH (228.5)											
	Number of days in a month											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1960-61												
1961-62												
1962-63												
1963-64												
1964-65												
1965-66												
1966-67					C(5) F(1)	C(4) F(2)	C(5) F(2)	C(6) F(3)	C(4) F(2)	C(5) F(1)	C(2) F(1)	
1967-68				C(4)	C(5)Fm	C(4)Fm	C(4)Fm	C(5)Fm	C(4)Fm	C(5)Fm	C(4)Fm	
1968-69				C(2)	C(4)	C(4)	C(5)	C(4)	C(5)	C(1)		
1979-70					C(1)	C(4)	C(5)	C(4)	C(4)	C(5)	C(2)	
1970-71												
1971-72												
1972-73												
1973-74												
1974-75												
1975-76												
1976-77												
1977-78												
1978-79												
1979-80												
1980-81												
1981-82												
1982-83												
1983-84												
1984-85												
1985-86												
1986-87												
1987-88												
1988-89								C(4)	C(3)	C(2)		
1989-90							C(1)	C(4)	C(4)	C(1)		
1990-91								C(3)	C(3)	C(2)		
1991-92					C(1)	C(5)	C(4)	C(4)	C(4)	C(4)		

Table 1.11 Available suspended sediment records at Mymensingh

HYDRO-LOGICAL YEAR	RIVER : KALIGONGA STATION : TARAGHAT (137A)											
	Number of days in a month											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1964-65												
1965-66												
1966-67												
1967-68						C(5)Fm	C(4)Fm	C(5)Fm	C(4)Fm	C(4)Fm	C(5)	
1968-69				C(2)	C(5)	C(4)	C(5)	C(4)	C(5)	C(5)	C(3)	
1969-70	C(2)	C(2)	C(2)	C(2)	C(4)	C(4)	C(5)	C(4)	C(5)	C(4)	C(2)	C(3)
1970-71				C(1)	C(1)	C(3)	C(4)	C(4)	C(2)	C(4)	C(2)	
1971-72												
1972-73					C(4)	C(5)	C(4)	C(5)	C(3)			
1973-74							C(7)	C(4)	C(4)	C(5)	C(1)	
1974-75						C(3)	C(5)	C(2)	C(3)	C(3)		
1975-76								C(1)	C(3)	C(2)	C(1)	C(1)
1976-77	C(1)	C(1)					C(1)	C(3)	C(3)	C(1)		
1977-78				C(1)	C(5)	C(4)	C(4)	C(3)				
1978-79						C(1)	C(2)	C(3)	C(2)	C(2)		
1989-80							C(1)	C(2)	C(1)	C(2)		
1980-81							C(3)	C(2)	C(2)	C(2)		
1981-82							C(1)	C(2)	C(2)	C(1)		
1982-83								C(2)	C(2)	C(2)	C(1)	
1983-84												
1984-85						C(1)	C(3)	C(2)				
1985-86						C(1)	C(2)	C(1)	C(2)			
1986-87							C(1)	C(3)	C(5)	C(3)		
1987-88							C(1)	C(4)	C(5)	C(4)		
1988-89								C(4)	C(4)	C(3)		
1989-90						C(1)	C(4)	C(5)	C(4)	C(2)		
1990-91									C(1)	C(4)		
1991-92						C(2)	C(5)	C(4)	C(4)	C(4)		
1992-93							C(3)		C(3)	C(2)		
1993-94								C(5)	C(4)	C(4)		

Table 1.12 Available suspended sediment records at Taraghat

HYDRO-LOGICAL YEAR	RIVER : DHALESWARI STATION NAME : JAGIR											
	Number of days in a month											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1967-68					Fm	C(2)Fm	C(5)Fm	C(4)Fm	C(5)Fm	C(4)Fm	Fm	
1968-69						C(5)	C(4)	C(5)	C(4)	C(4)		C(1)
1969-70					C(1)	C(4)	C(4)	C(5)	C(4)	C(3)		

Table 1.13 Available suspended sediment records at Jagir

HYDRO-LOGICAL YEAR	RIVER : GORAI STATION : GORAI RAILWAY BRIDGE (99)											
	Number of days in a month											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1960-61												
1961-62												
1962-63												
1963-64												
1964-65												
1965-66												
1966-67						C(1)	C(1)	C(4)	C(4)	C(4)	C(4)	
1967-68				C(4)	C(5)	C(3)Fm	C(5)Fm	C(4)Fm	C(4)Fm	C(5)Fm	C(4)Fm	
1968-69				C(4)	C(4)	C(4)Fm	C(5)Fm	C(4)Fm	C(4)Fm	C(4)Fm	C(4)Fm	
1969-70	C(4)Fm	C(4)Fm	C(5)	C(1)	C(4)	C(3)Fm	C(4)Fm	C(4)Fm	C(5)Fm	C(4)Fm	C(4)Fm	C(5)Fm
1970-71												
1971-72												
1972-73												
1973-74												
1974-75												
1975-76												
1976-77												
1977-78												
1978-79												
1979-80												
1980-81												
1981-82												
1982-83												
1983-84												
1984-85												
1985-86												
1986-87												
1987-88												
1988-89												
1989-90									C(4)	C(4)		
1990-91							C(5)	C(5)	C(4)	C(5)	C(2)	
1991-92							C(5)	C(4)	C(5)	C(5)		
1992-93							C(3)	C(4)	C(5)	C(4)		

Table 1.14 Available suspended sediment records at Gorai Railway Bridge

Annex 2

Sediment Rating Curves

Contents

Figures

Tables

1 General

The analysis of sediment transport in Phase 1 of the RSP was a tentative exercise in order to obtain a preliminary idea on the amount and fate of the sediment carried by the rivers.
The consistency of the measured data was checked by regression analysis, whereby the outliers were removed on the basis of a statistical confidence test. The data were split into two groups of continuous series, namely the periods of 1966-1970 and 1976-1988. Sediment rating curves including and excluding outliers were produced for the stations Bahadurabad, Hardinge Bridge, Goalundo, Baruria, Gorai Railway Bridge, Jagir and Taraghat for these two periods.

In Phase 2 of the project, a more elaborate analysis was made, and new data from the RSP surveys were included.

The present Annex describes the statistical analysis applied for removing outliers, and the produced sediment rating curves are shown.

2 Statistical analysis

The first step is the calculation of the logarithm of the discharge (m^3/s) and the sediment transport data (tons/day) at each station. It may be assumed that these log-values are normally distributed. The T-test method is used to remove outliers from the data series of each station within a reasonable confidence limit and then, the value of the correlation parameter R^2 is checked.

The values of R^2 and the number of data removed with and without statistical analysis for each station are shown in Table 2.1 for suspended coarse sediment transport and in Table 2.2 for suspended fine sediment transport. The analysis shows that the data are quite consistent in the log-transformed axis. The value of R^2 for each station indicates that the measured data are well correlated after removal of a few outliers.

3 Sediment rating curves

The sediment rating curves are the exponential curves fitted to the log-transformed data. These curves have been made separately for the coarse and the fine sediment for two distinct periods: 1966-1970 and 1971-1989. results are shown in Figures 2.1 and 2.2.

Name of station	Data series (year)	Original data		After removing outliers		
		R^2	No of obs.	Confidence limit	R^2	No of obs.
Bahadurabad	1976-78	0.79	411	95%	0.90	397
Bahadurabad	1966-70	0.90	127	95%	0.91	126
Hardinge Bridge	1966-70	0.80	120	95%	0.90	117
Hardinge Bridge	1976-89	0.80	230	95%	0.88	219
Baruria	1968-70	0.93	86	-	-	-
Baruria	1976-89	0.83	202	-	-	-
Taraghat	1967-69	0.81	90	-	-	-
Taraghat	1970-88	0.48	174	80%	0.66	158
Goalundo	1966-69	0.74	108	95%	0.85	103
Goalundo	1976-82	0.62	43	95%	0.73	42
Gorai Railway Bridge	1966-70	0.83	131	99%	0.91	122
Jagir	1967-69	0.56	61	90%	0.68	59

Table 2.1 Statistical analysis of coarse sediment transport data

Name of station	Data series (year)	Original data		After removing outliers		
		R^2	No of obs.	Confidence limit	R^2	No of obs.
Bahadurabad	1966-70	0.89	43	-	-	-
Hardinge Bridge	1967-70	0.87	26	90%	0.96	25
Baruria	1968-70	0.88	20	-	-	-
Taraghat	1967-69	0.92	22	-	-	-
Goalundo	1966-69	0.43	30	80%	0.71	26
Gorai Railway Bridge	1967-70	0.86	20	-	-	-
Jagir	1967-69	0.68	18	95%	0.89	17

Table 2.2: Statistical analysis of fine sediment transport data

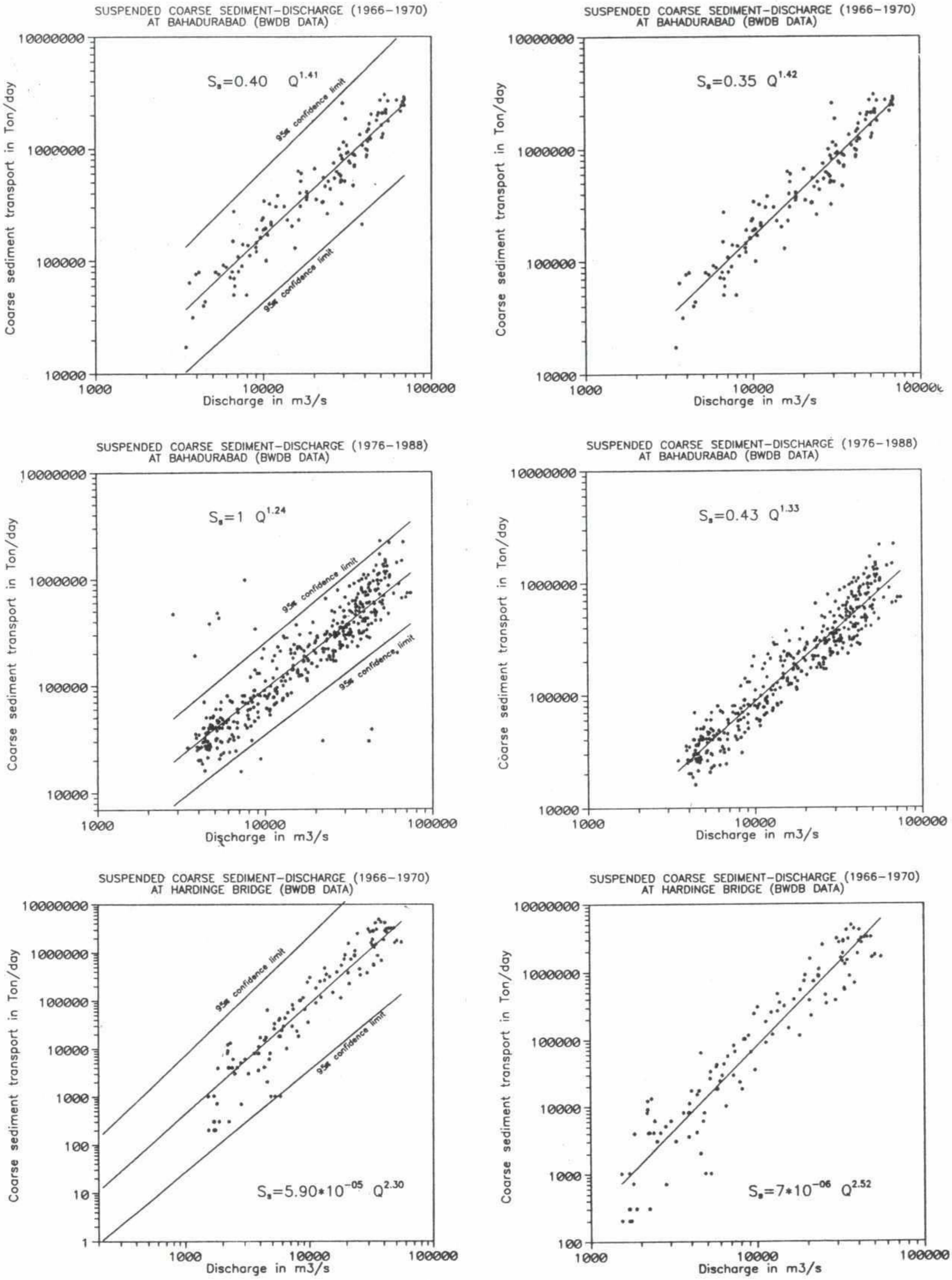

Figure 2.1: Coarse sediment rating curves

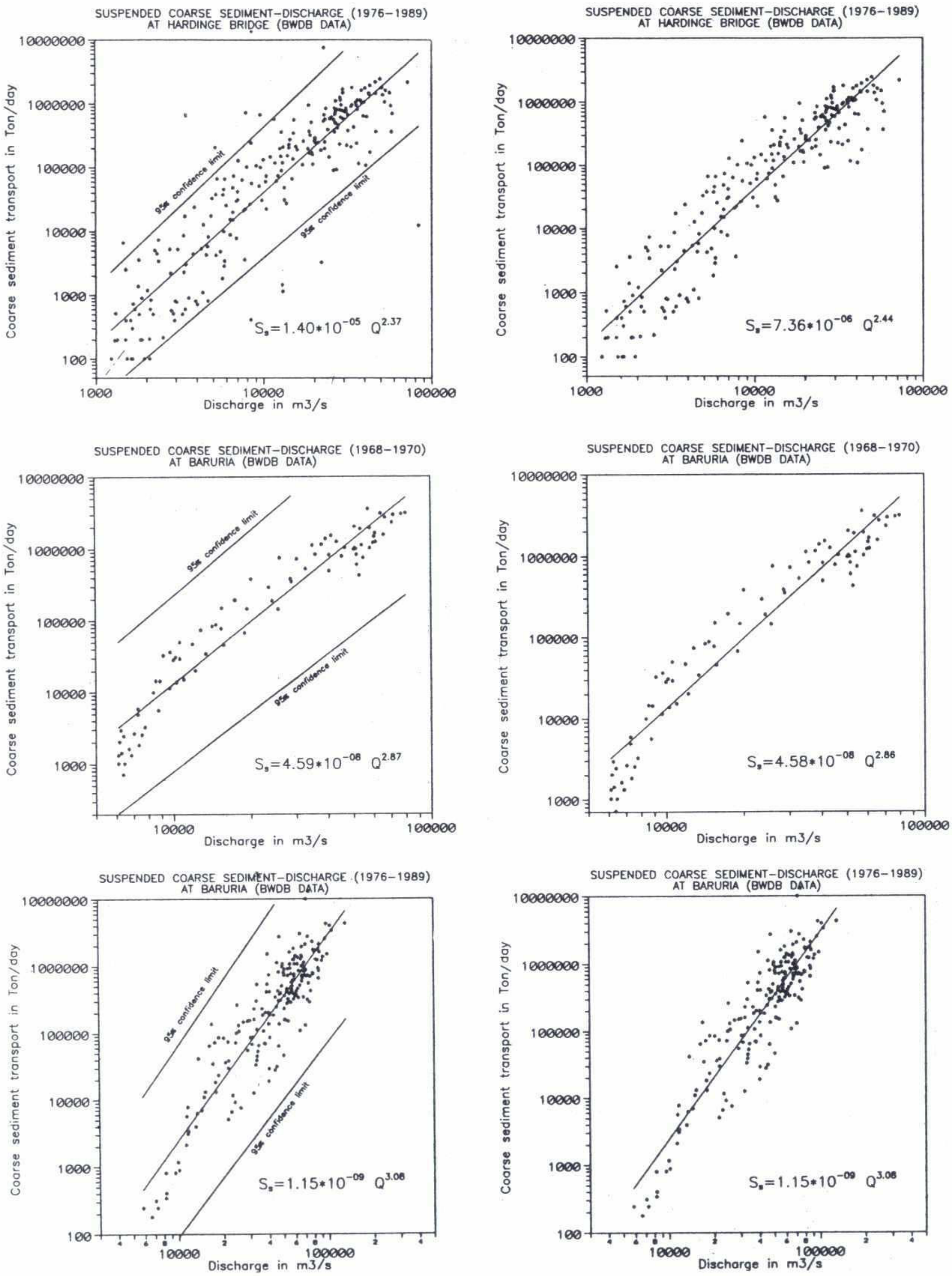

Figure 2.2: Coarse sediment rating curves

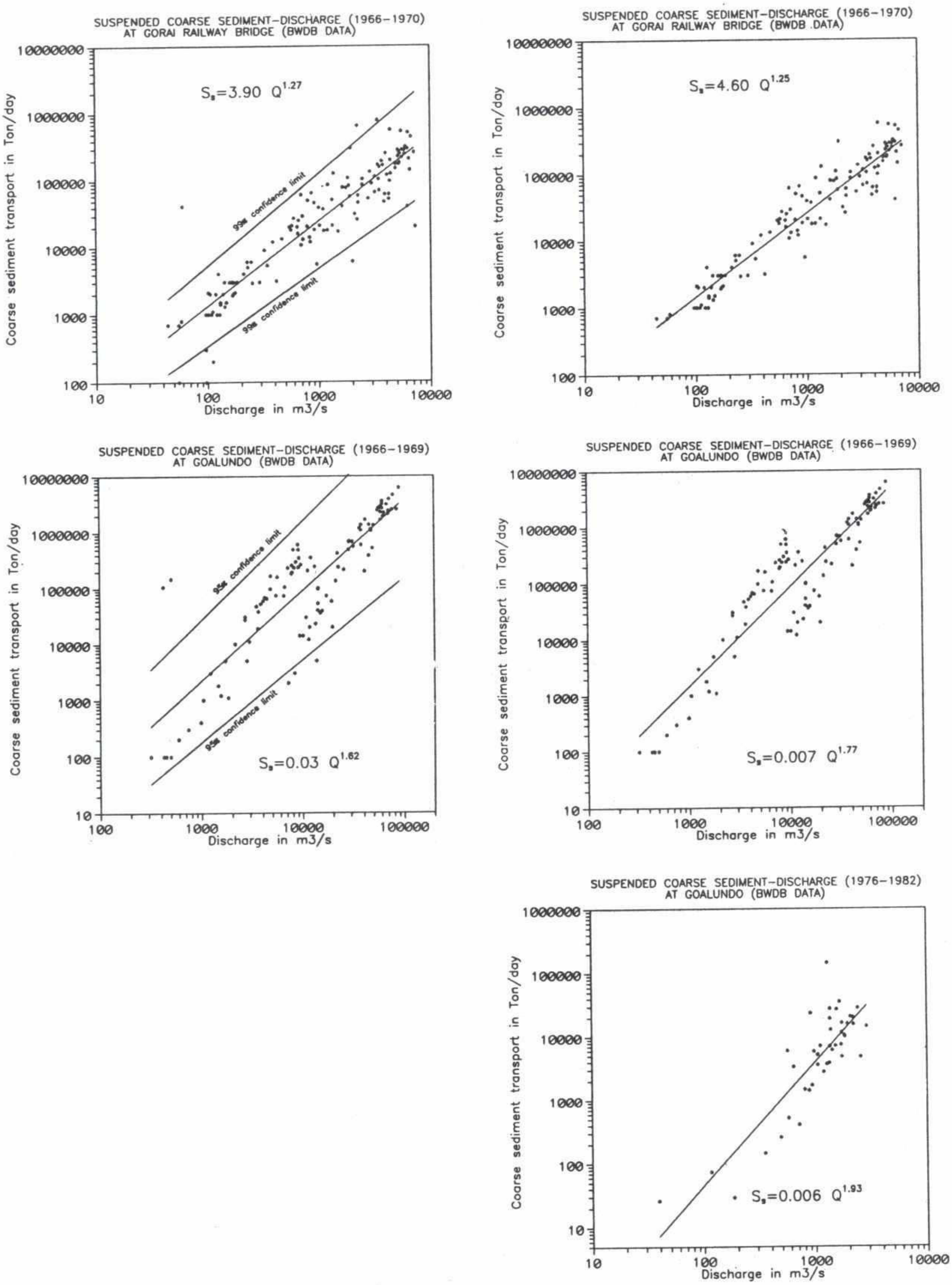

Figure 2.3: Coarse sediment rating curves

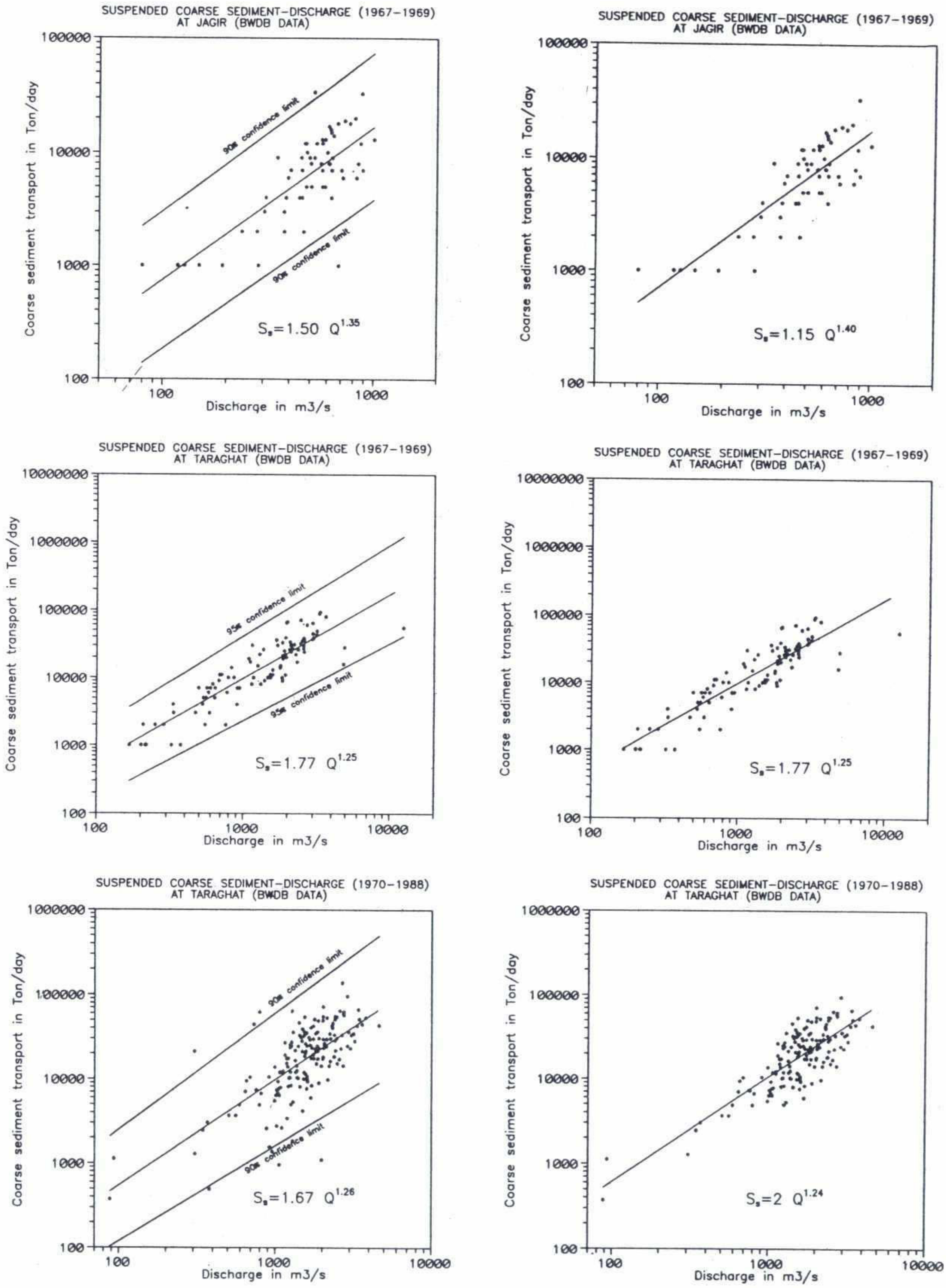

Figure 2.4: Coarse sediment rating curves

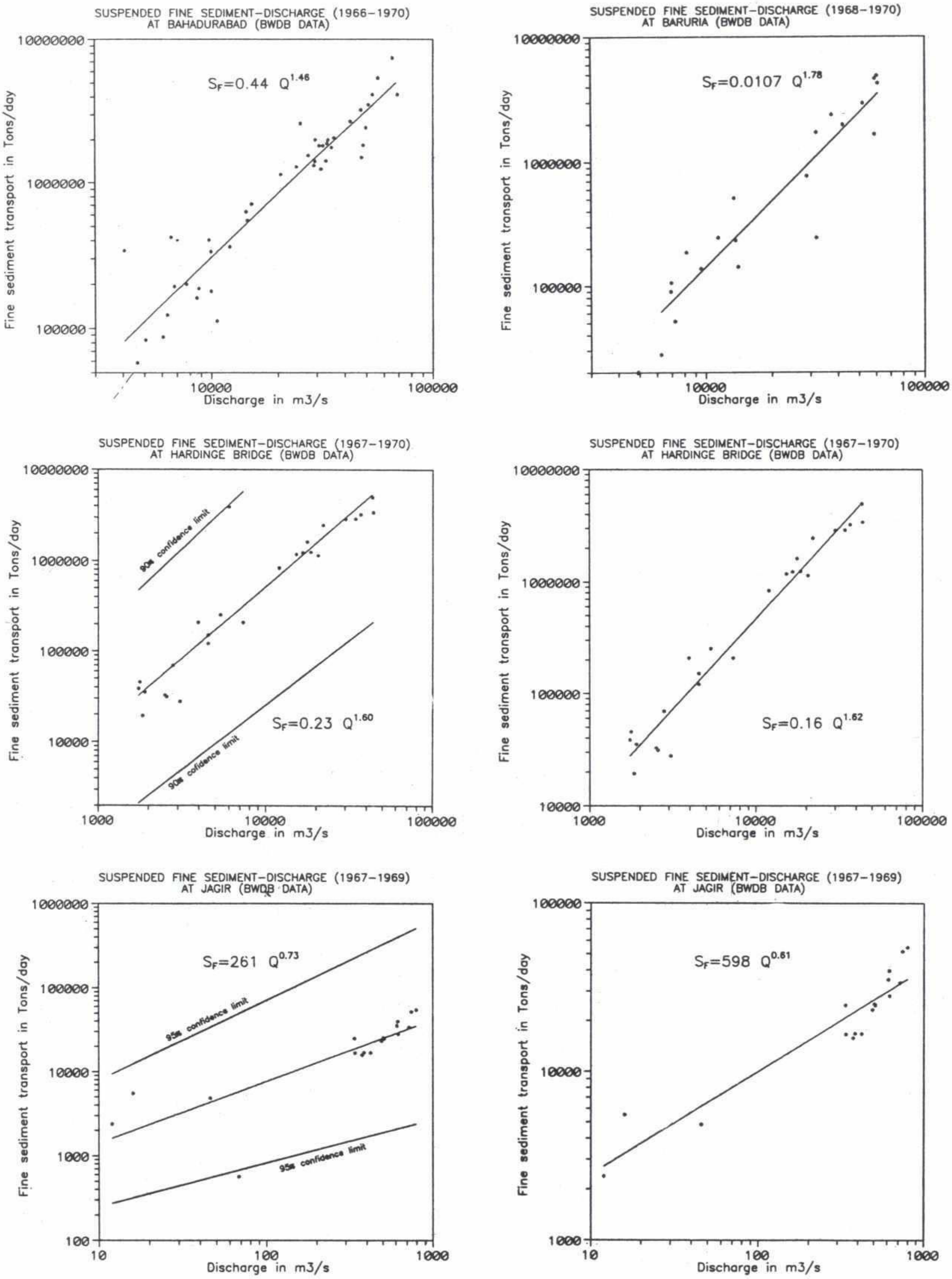

Figure 2.5: Fine sediment rating curves

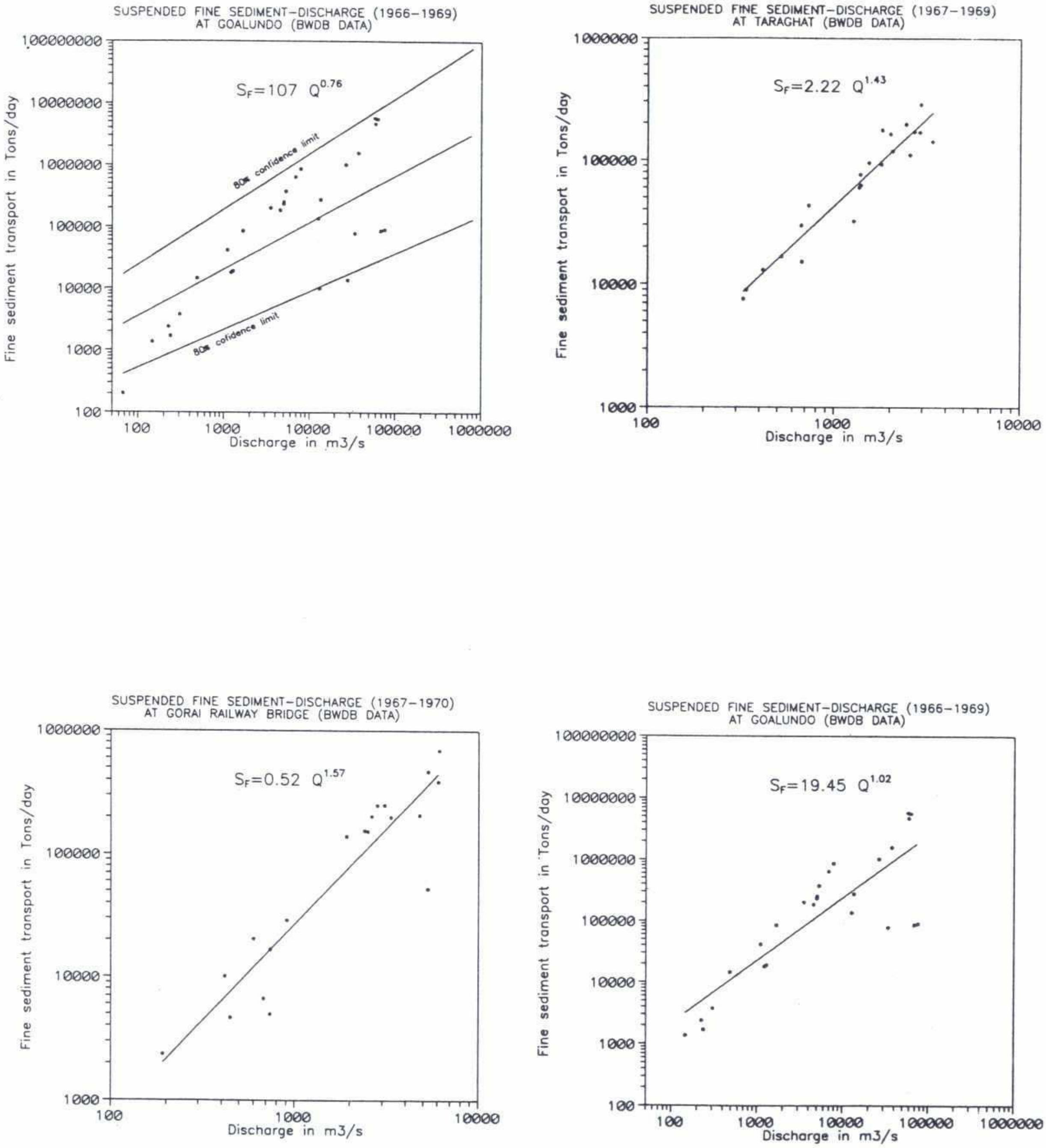

Figure 2.6: Fine sediment rating curves

Annex 3

Sediment Balances

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Figures

Tables

1 Sediment balances

During Phase 1 of the RSP, sediment balances were estimated between two groups of stations. Group I comprised Bahadurabad, Hardinge Bridge, Taraghat, Gorai Railway Bridge and Jagir, and Group II comprised Goalundo and Baruria.

The daily sediment discharge was calculated with the use of sediment rating curves and Mean Daily Discharge. On this basis, the annual sediment transport was computed. Balances were made with both the RSP and the BWDB discharge data. The coarse and fine sediment balances were computed with the 1966-1970 sediment rating curve for the hydrological period 1966-1988. Results are shown in Figures 3.1 and 3.2, respectively.

The balances for the period 1966-1991 are shown in Tables 3.1, 3.2, 3.3 and 3.4. Table 3.1 indicates that in Group I, the coarse suspended sediment balance with the sediment data series after the 70-ies exhibits a sediment flow that is approximately 2 times as large as compared with Group II. By contrast, in Table A3.4 it is seen that the data series from before the 70-ies are consistent between these two groups, with some exceptional cases, like the years 1974 and 1988. These exceptions can be explained: In 1974 and 1988, the flood volumes were very high, and there could well have been a severe erosion between Bahadurabad-Hardinge Bridge and Baruria. The sediment balance computed with data from 1966-1970 shows more than double the amount than the balance made by data measured after 1970.

At one early stage of the study, it was understood that the sediment data after the 70-ies are less reliable than the ones before the 70-ies. Therefore, sediment balances were made with the data series collected before the 70-ies using RSP discharge data. The coarse sediment balance with BWDB data is shown in Table 3.2, and with the RSP data in Table 3.3. The fine sediment balance is shown in Table 3.4.

The fine sediment balance as estimated with RSP discharge data indicates that the sediment transport is some 20-25% higher in Group I than in Group II. The reason for this difference could be over-bank spilling between Bahadurabad and Baruria, and between Hardinge Bridge and Baruria.

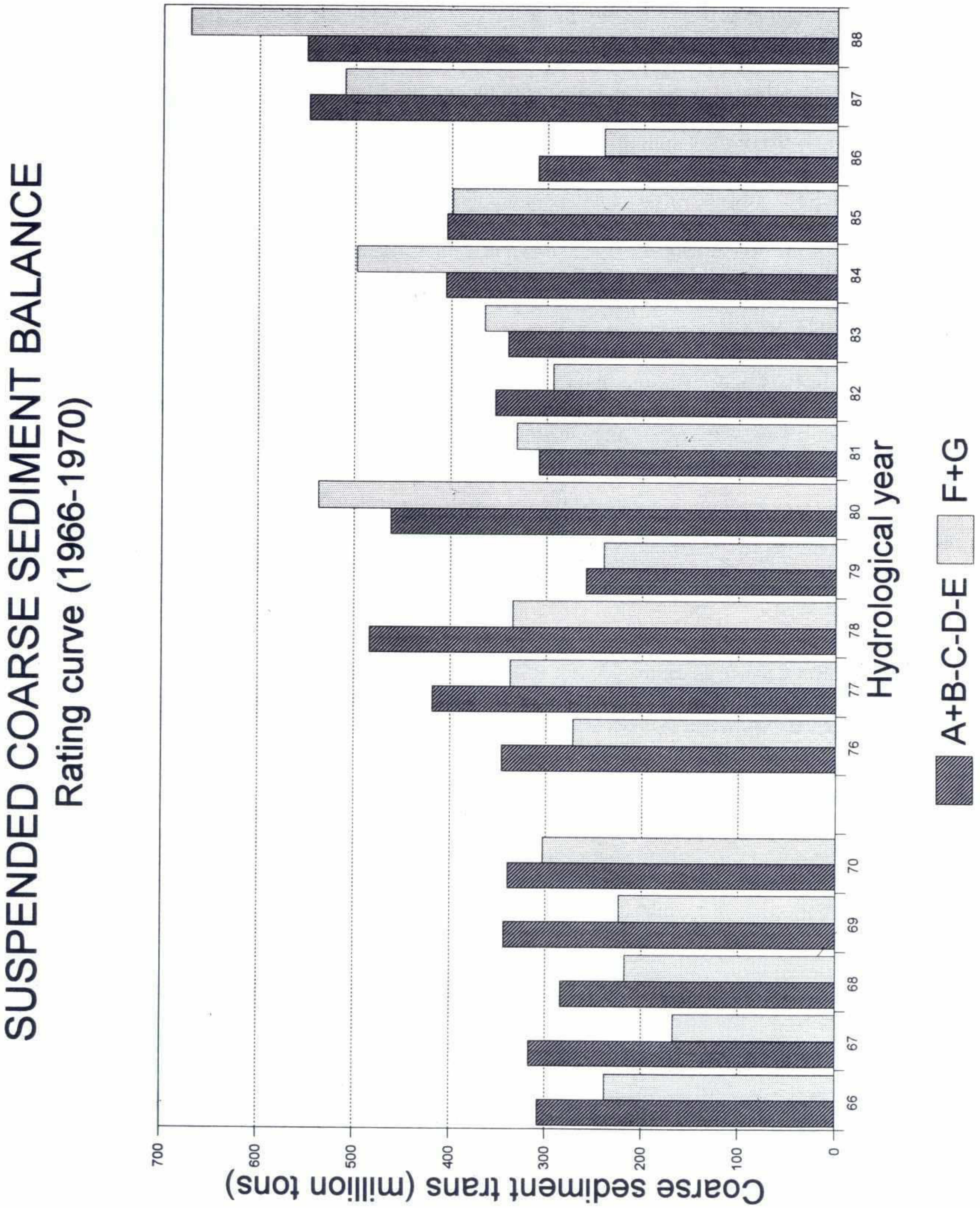

Figure 3.1: Coarse sediment balance

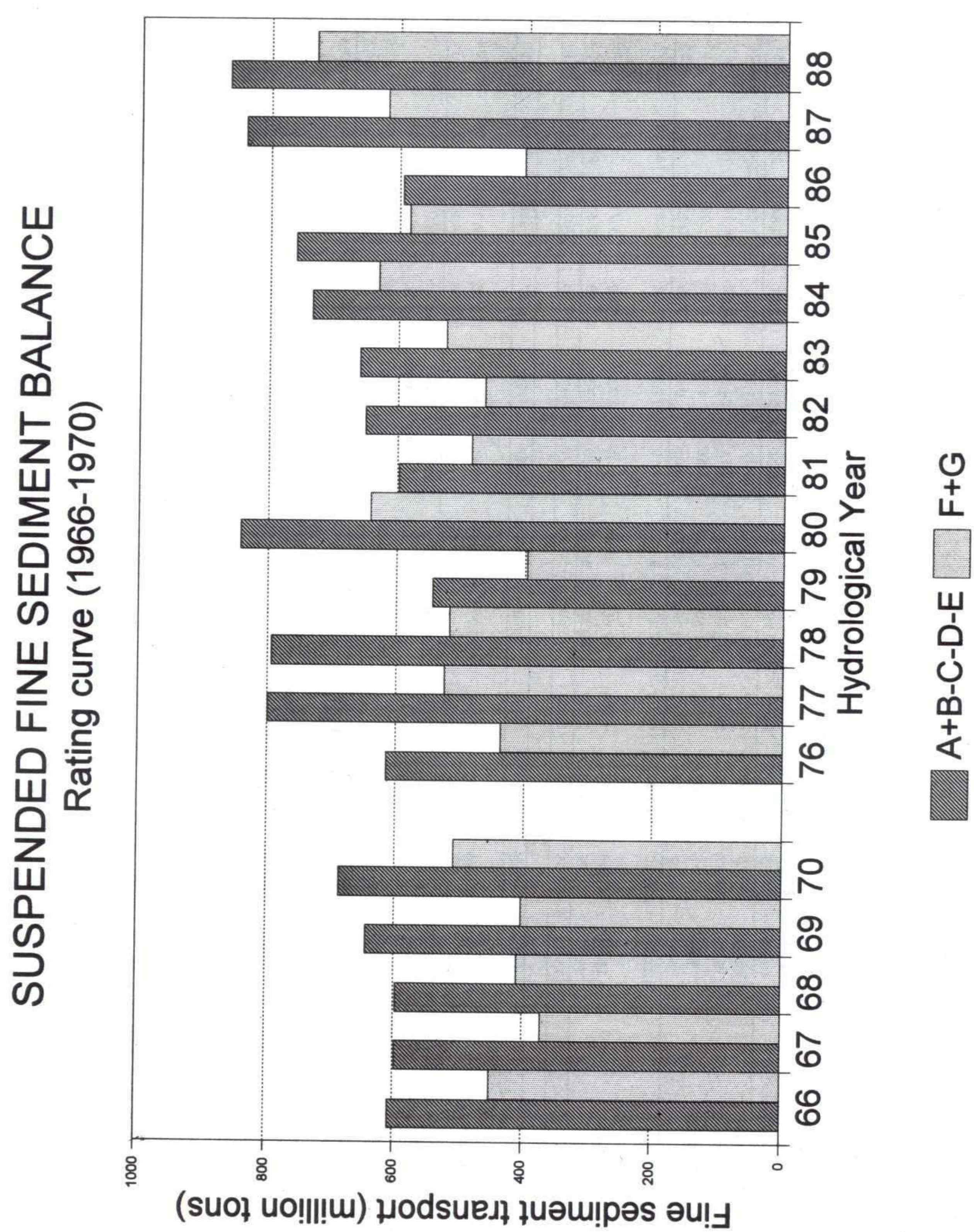

Figure 3.2: Fine sediment balance

	1966	1967	1968	1969	1970	1972	1973	1974	1975	1976	1977	1978	
A Bahadurabad 76-88	112.58	84.10	83.68	77.27	102.07	77.70	81.53	106.96	81.76	77.2'	111.45	81.27	
B Hardinge 76-89	43.50	76.65	61.87	96.30	66.99	32.83	108.94	94.79	118.57	93.84	92.85	155.51	
Sub_total (A+B)	156.08	160.75	145.55	173.57	169.06	110.53	190.47	201.75	200.33	171.05	204.30	236.78	
C Goral RB 66-70	15.02	19.47	17.30	19.69	15.50	14.49	28.11	24.58	20.27	15.58	18.82	21.17	
D Taraghat 70-88	4.81	4.31	5.02	4.67	4.80	3.29	4.56	4.17	2.36	1.93		2.05	
E Jagir 67-69	8.91	1.17	1.26	0.93	0.79	0.37	0.61	0.68	0.28	0.23		0.35	
Total (A+B-C-D-E)	127.34	135.80	121.97	148.28	147.97	92.38	157.19	172.32	177.42	153.31	185.48	213.21	
F Goalundo 76-82	12.94	16.66	14.98	10.64	9.85	3.56	8.09	7.15	3.40	1.71	1.14	0.86	
G Baruria 76-89	62.23	41.39	55.76	57.77	80.58	50.35	103.69	177.38	120.48	72.61	90.60	89.95	
Total (F+G)	75.17	58.05	70.74	68.41	90.43	53.91	111.78	184.53	123.88	74.32	91.74	90.81	

	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991
A Bahadurabad 76-88	97.38	86.89	75.83	79.00	83.77	98.66	89.12	68.44	103.55	118.11	127.03	135.34	156.75
B Hardinge 76-89	29.91	139.07	79.20	93.66	85.71	99.53	111,24	86.01	158.53	144.27	41.23	107.72	64.72
Sub_total (A+B)	127.29	225.96	155.03	172.66	169.48	198.19	200.36	154.45	262.08	262.38	168.26	243.06	221.47
C Goral RB 66-70	10.48	19.04	17.80	14.73	17.38	16.58	18.75	13.55	17.70	16.43	13.46		
D Taraghat 70-88	1.90	2.60	2.15		2.21	2.78	2.56	1.83	2.99	3.08	1.97	2.28	2.27
E Jagir 67-69	0.28	0.27	0.24	0.23	0.15	0.23	0.09	0.08	0.14	0.22	0.09	0.10	
Total (A+B-C-D-E)	114.63	204.05	134.84	157.70	149.74	178.60	178.96	138.99	241.25	242.65	152.74	240.68	219.20
F Goalundo 76-82	0.36	1.85	0.67	0.51									
G Baruria 76-89	64.96	154.94	91.88	80.07	101.74	142.06	110.09	64.68	147.25	198.69	86.15	122.77	138.87
Total (F+G)	65.32	156.79	92.55	80.58	101.74	142.06	110.09	64.68	147.25	198.69	86.15	122.77	138.87

Table C.1: Coarse sediment balance (Sediment data series 1976-1988)

Table 3.1: Coarse sediment balance (Sediment data series 1976-1988)

	1966	1967	1968	1969	1970	1972	1973	1974	1975	1976	1977	1978	
A Bahadurabad 66-70	244.64	178.93	177.62	163.23	219.56	164.26	173.41	232.79	172.57	162.73	240.11	171.71	
B Hardinge BR 66-70	90.85	162.54	129.65	204.93	140.40	67.31	231.22	201.66	252.57	200.98	197.04	335.55	
Sub-total (A+B)	335.49	341.47	307.27	368.16	359.96	231.57	404.63	434.45	425.14	363.71	437.15	507.26	
C Goral RB 66-70	15.02	19.47	17.30	19.69	15.50	14.49	28.11	24.58	20.27	15.58	18.82	21.17	
D Taraghat 67-69	4.48	4.01	4.68	4.34	4.48	3.06	4.25	3.89	2.19	1.79		1.91	
E Jagir 67-69	8.91	1.17	1.26	0.93	0.79	0.37	0.61	0.68	0.28	0.23		0.35	
Total (A+B-C-D-E)	307.08	316.82	284.03	343.20	339.19	213.65	371.66	405.30	402.40	346.11	418.33	483.83	
F Goalundo 66-69	3.64	4.59	4.21	2.99	2.86	1.12	2.41	2.08	1.07	0.54	0.39	0.30	
G Baruria 68-70	233.93	161.94	212.73	220.23	300.26	193.80	380.08	618.80	434.96	270.66	336.47	334.24	
Total (F+G)	237.57	166.53	216.94	223.22	303.12	194.92	382.49	620.88	436.03	271.20	336.86	334.54	

	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991
A Bahadurabad 66-70	208.70	184.12	160.32	167.12	177.23	212.33	189.74	142.31	223.41	256.47	275.86	294.78	348.28
B Hardinge BR 66-70	61.81	299.57	167.54	201.30	182.42	212.38	235.95	182.15	345.40	313.84	84.80	229.12	137.39
Sub-total (A+B)	270.51	483.69	327.86	368.42	359.65	424.71	425.69	324.46	568.81	570.31	360.66	523.90	485.67
C Goral RB 66-70	10.48	19.04	17.80	14.73	17.38	16.58	18.75	13.55	17.70	16.43	13.46		
D Taraghat 67-69	1.76	2.41	2.00		2.05	2.59	2.38	1.69	2.78	2.86	1.82	2.11	2.11
E Jagir 67-69	0.28	0.27	0.24	0.23	0.15	0.23	0.09	0.08	0.14	0.22	0.09	0.10	
Total (A+B-C-D-E)	257.99	461.97	307.82	353.46	340.07	405.31	404.47	309.14	548.19	550.80	345.29	521.69	483.56
F Goalundo 66-69	0.13	0.60	0.24	0.18									
G Baruria 68-70	239.81	536.13	330.59	293.01	364.90	497.82	398.82	240.89	511.40	671.44	318.48	440.46	489.61
Total (F+G)	239.94	536.73	330.83	293.19	364.90	497.82	398.82	240.89	511.40	671.44	318.48	440.46	489.61

Table C.2: Coarse sediment balance (Sediment data series 1966-1970)

Table 3.2: Coarse sediment balance (Sediment data series 1966-1970)

	1966	1967	1968	1969	1970	1972	1973	1974	1975	1976	1977	1978	
A Bahadurabad 66-70	237.18	176.16	191.80	165.48	225.37	179.50	170.82	247.19	175.15	164.21	242.01	179.28	
B Hardinge BR 66-70	89.28	168.43	128.24	215.91	137.98	76.81	255.69	233.10	262.20	191.45	194.01	309.12	
Sub-total (A+B)	326.46	344.59	320.04	381.39	363.35	256.31	426.51	480.29	437.35	355.66	436.02	488.40	
C Goral RB 66-70	15.02	19.47	17.30	19.69	15.50	14.49	28.11	24.58	20.27	15.58	18.82	21.17	
D Taraghat 67-69	4.48	4.01	4.68	4.34	4.48	3.06	4.25	3.89	2.19	1.79		1.91	
E Jagir 67-69	8.91	1.17	1.26	0.93	0.79	0.37	0.61	0.68	0.28	0.23		0.35	
Total (A+B-C-D-E)	298.05	319.94	296.80	356.43	342.58	238.39	393.54	451.14	414.61	338.06	417.20	464.97	
F Goalundo 66-69	3.64	4.59	4.21	2.99	2.86	1.12	2.41	2.08	1.07	0.54	0.39	0.30	
G Baruria 66-70	262.13	184.66	222.47	221.39	312.36	191.84	379.75	666.40	411.73	267.57	336.47	334.24	
Total (F+G)	265.77	189.25	226.68	224.38	315.22	192.96	382.16	668.48	412.80	268.11	336.86	334.54	

	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991
A Bahadurabad 66-70	208.70	212.66	166.32	182.21	181.68	211.90	192.14	144.19	222.62	242.70	220.25	252.54	251.46
B Hardinge BR 66-70	65.22	317.67	167.54	201.30	197.21	208.45	234.26	181.41	313.65	312.42	93.45	224.43	135.91
Sub-total (A+B)	273.92	530.33	333.86	383.51	378.89	420.35	426.40	325.60	536.27	555.12	313.70	476.97	387.37
C Goral RB 66-70	10.48	19.04	17.80	14.73	17.38	16.58	18.75	13.55	17.70	16.43	13.46		
D Taraghat 67-69	1.76	2.41	2.00		2.05	2.59	2.38	1.69	2.78	2.86	1.82	2.11	2.11
E Jagir 67-69	0.28	0.27	0.24	0.23	0.15	0.23	0.09	0.08	0.14	0.22	0.09	0.10	
Total (A+B-C-D-E)	261.40	508.61	313.82	368.55	359.31	400.95	405.18	310.28	515.65	535.61	298.33	474.76	385.26
F Goalundo 66-69	0.13	0.60	0.24	0.18									
G Baruria 66-70	241.63	536.13	340.71	293.81	360.68	499.02	401.83	239.61	509.65	683.01	316.76	445.85	494.77
Total (F+G)	241.76	536.73	340.95	293.99	360.68	499.02	401.83	239.61	509.65	683.01	316.76	445.85	494.77

Table C.3: Coarse sediment balance (FAP 24 generated discharge data for the sediment data series 1966-1970)

Table 3.3: Coarse sediment balance (RSP generated discharge data for the sediment data series 1966-1970)

	1966	1967	1968	1969	1970	1972	1973	1974	1975	1976	1977	1978	
A Bahadurabad 66-70	458.548	337.619	368.427	316.609	434.784	344.535	327.892	480.059	334.840	313.687	467.012	343.290	
B Hardinge BR 67-70	208.432	316.949	284.231	385.950	302.761	211.168	463.171	398.711	455.911	335.475	361.690	495.577	
Sub-total (A+B)	666.980	654.568	652.658	702.559	737.545	555.703	791.063	878.770	790.751	649.162	828.702	838.867	
C Goral RB 67-70	22.662	32.221	27.342	32.732	23.674	22.031	49.026	42.873	33.420	24.468	29.795	34.264	
D Taraghat 67-69	22.349	19.430	23.164	21.346	22.446	14.612	21.641	19.555	10.104	7.983		8.735	
E Jagir 67-69	13.970	4.880	4.807	3.718	3.661	2.021	3.082	3.159	2.026	1.584		2.329	
Total (A+B-C-D-E)	607.999	598.037	597.345	644.763	687.764	517.039	717.314	813.183	745.201	615.127	798.907	793.539	
F Goalundo 66-69	16.483	18.324	18.570	13.651	14.128	8.038	13.271	10.955	7.499	4.362	3.948	3.502	
G Baruria 66-70	432.879	353.048	391.139	389.584	493.916	369.135	551.578	740.657	564.009	432.939	520.740	512.680	
Total (F+G)	449.362	371.372	409.709	403.235	508.044	377.173	564.849	751.612	571.508	437.301	524.688	516.182	
	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991
A Bahadurabad 66-70	401.668	409.673	318.587	349.836	348.081	408.524	368.795	274.143	429.594	469.813	424.057	488.427	486.498
B Hardinge BR 67-70	165.932	478.359	320.516	327.562	351.149	366.722	433.695	350.365	453.994	437.696	238.080	404.103	261.615
Sub-total (A+B)	567.600	888.032	639.103	677.398	699.230	775.246	802.490	624.508	883.588	907.509	662.137	892.530	748.113
C Goral RB 67-70	14.633	31.863	29.673	24.077	28.102	26.184	30.297	20.455	30.107	28.302	20.705		
D Taraghat 67-69	8.010	11.322	9.423		9.325	12.247	10.976	7.503	13.438	13.919	8.065	9.435	9.538
E Jagir 67-69	1.757	1.537	1.732	1.832	1.438	1.971	1.260	1.155	1.425	1.718	1.191	1.349	1.325
Total (A+B-C-D-E)	543.200	843.310	598.275	651.489	660.365	734.844	759.957	595.395	838.618	863.570	632.176	881.746	737.250
F Goalundo 66-69	2.007	4.885	2.911	2.489									
G Baruria 66-70	394.996	637.075	481.178	462.248	525.336	631.151	584.187	406.325	618.707	729.920	514.646	624.957	637.633
Total (F+G)	397.003	641.960	484.089	464.737	525.336	631.151	584.187	406.325	618.707	729.920	514.646	624.957	637.633

Table C.4: Fine sediment balance (sediment data series 1966-1970)

Table 3.4: Fine sediment balance (sediment data series 1966-1970)