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RIVER SURVEY PROJECT

**Special
Report
No. 12**

**Optimization
of sediment
measurements**

October 1996



2

Special Report 12
Optimization of Sediment Measurements

October 1996

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Acronyms and Abbreviations

ADCP	: Acoustic Doppler Current Profiler
ASTM	: American Society of Testing Materials
BWDB	: Bangladesh Water Development Board
DB	: Delft Bottle sampler
DGPS	: Differential Global Positioning System
EDI	: Equal Depth Increment
EWI	: Equal Width Increment
H-S	: Helley-Smith sampler
IUCN	: International Union for the Conservation of Nature
Pb	: Pump-bottle
RSP	: River Survey Project (FAP-24)
RSPMU	: River Survey Project Management Unit
SSC	: Suspend Sediment Concentration
SST	: Suspended Sand Transport
UNEP	: United Nations Environmental Programme
WWF	: World Wildlife Fund

1 Introduction

1.1 General

The River Survey Project (RSP, or FAP24) was initiated on June 9, 1992. The Project was executed by the Flood Plan Coordination Organization (FPCO), later merged with Water Resources Planning Organization (WARPO), under the Ministry of Water Resources. Funding was granted by the European Commission (formerly the Commission of the European Communities). Consultant was Delft Hydraulics and Danish Hydraulic Institute (DELFT-DHI Consortium) in association with Osiris, Hydroland and Approtech. The Project is supervised by a Project Management Unit with participation by FPCO/WARPO, a Project Advisor, and a Resident Project Advisor.

The Objective of the Project is to establish a detailed and accurate field database for Flood Action Plan projects, an in general for any planning, impact evaluation, or design activities within national water resources and river engineering activities.

The Project comprises:

- 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 in river hydrology, sediment transport and morphology
- A training component

The scope of the study component was developed in a dialogue with the Client and the Project Advisor, who also undertook supervision and rendered comprehensive professional advice during its execution. The proceedings are reported in a series of *RSP Special Reports*.

The present Special Report 12 describes an optimization study on suspended and near-bed sediment measurements made in Bangladesh rivers. A closely related study on optimization of hydraulic measurements is reported in Special Report 11.

The study was managed and reported by Dr. Dilip K. Barua and Mr. Pieter van Groen with participation by several other members of the RSP study team, especially Mr. Minhaz U. Ahmed and Mr. Krishna C. Dey. Annexure contributions are as follows: B - Mr. Pieter van Groen; C - Mr. Carsten Staub; D - Mr. M.H. Sarker; A and E - Dr. Dilip K. Barua; F - Dr. Dilip K. Barua and Mr. Krishna C. Dey; G - Mr. Maarten vander Wal and Mr. Pieter van Groen.

1.2 Background

Measurements of various sediment transport parameters are important for sedimentological and morphological studies of rivers. Unless such parameters are known, a river behaviour management plan can not be executed. FAO started systematizing hydraulic data collection activities in 1965, and published its findings in 1969 (FAO 1969). Since then, the Bangladesh Water Development Board (BWDB) has been collecting suspended sediment data at approximately 25 transects across different rivers (BWDB, 1972; BWDB, 1982). An instantaneous Binkley sampler is used to measure suspended

sediment at two depths along a measurement vertical. While a large database exists, there are several limitations which require attention and improvement.

- Although weekly measurements are planned, they are often interrupted for various reasons. Specifically, data are missing for high river stages.
- As discussed further in this report, an instantaneous sampler can result in appreciable error of suspended sediment measurements.
- A two-point method, which is usually applied for obtaining suspended sediment transport, can only give an approximate transport.
- Near-bed sediment transport is not estimated.
- Bed-material samples are not taken which is a very important parameter for estimation of sediment transport.

Given this background of sediment measurements, the River Survey Project started its operation in Bangladesh in 1992 as a supporting project for the different Flood Action Plan projects. The survey area includes the main rivers of Bangladesh, the Ganges, the Jamuna, the Upper Meghna, and the Padma, and their major tributaries and distributaries (Figure 1.1).

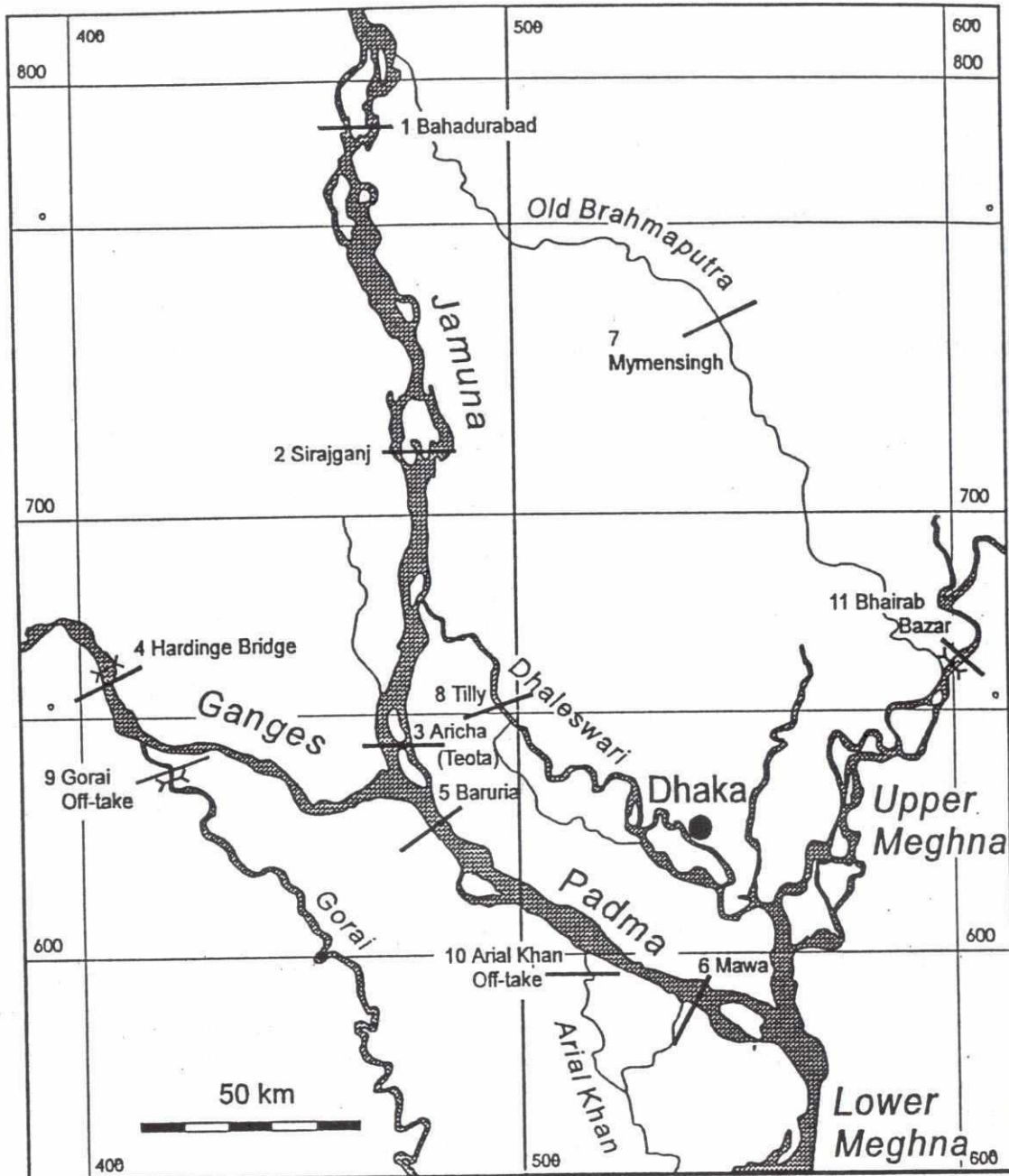


Figure 1.1 The River Survey Project measurement locations in the Ganges, Jamuna and Upper Meghna Rivers in Bangladesh.

Sediment measurements in a network of large alluvial rivers such as in Bangladesh are difficult, expensive, and time-consuming. The difficulty is further aggravated because the standards and guidelines for sediment measurements are not well suited for studies on large alluvial deltaic systems (Peters, 1977). Nevertheless, the measurements are necessary because the known sediment transport predictors have very limited applicability in large sandbed rivers (Lukanda et al., 1992).

Optimization of overall survey techniques is a continuous process where each instrument and method is evaluated to attain an optimal solution. This started with the pre-selection of techniques based on the Technical Specifications of the project and previous work experience of the consortium with the main river systems of Bangladesh (RSP, 1991). The proposed techniques were accepted after adding an alternative method for bed-load sampling (trap sampler) and the first mobilization took place in mid-1992 (RSP, 1992).

In the first phase of the project, the so-called test gauging phase, the performance of pre-selected instruments was evaluated. However, the first test gauging were executed in rather low flows, after a relatively weak monsoon, in the period from October till December 1992 (RSP, 1993a). Therefore, further testing took place in the high flows of the 1993 monsoon (RSP, 1993b). The results of these test gauging and the experience gained in the first phase (also with routine gauging) led to a review of the survey techniques used so far (RSP, 1993c). These techniques were presented and discussed during a field visit of several international experts to our survey vessels, which was part of the programme of the 'International Workshop on the Morphological Behaviour of the Main Rivers in Bangladesh' of November 1993. Based on these discussions, and in close co-operation with the RSPMU, the survey techniques for the second phase of the project were determined. Thereupon, the second mobilization took place in the first half of 1994. These techniques were applied during the second phase of the project from 1994 to 1996.

Present report is focusing on the experience gained during the second phase with the sediment transport measurements.

1.3 Objectives

The objectives of this report are to make a final evaluation of the sediment measuring equipment and methods that were mobilized and used by FAP 24 so that they may be used suitably in Bangladesh rivers. A multi-criterion analysis technique was used to evaluate the equipment and methods for optimization and sustainability. Figure 1.2 shows the applied optimization principle.

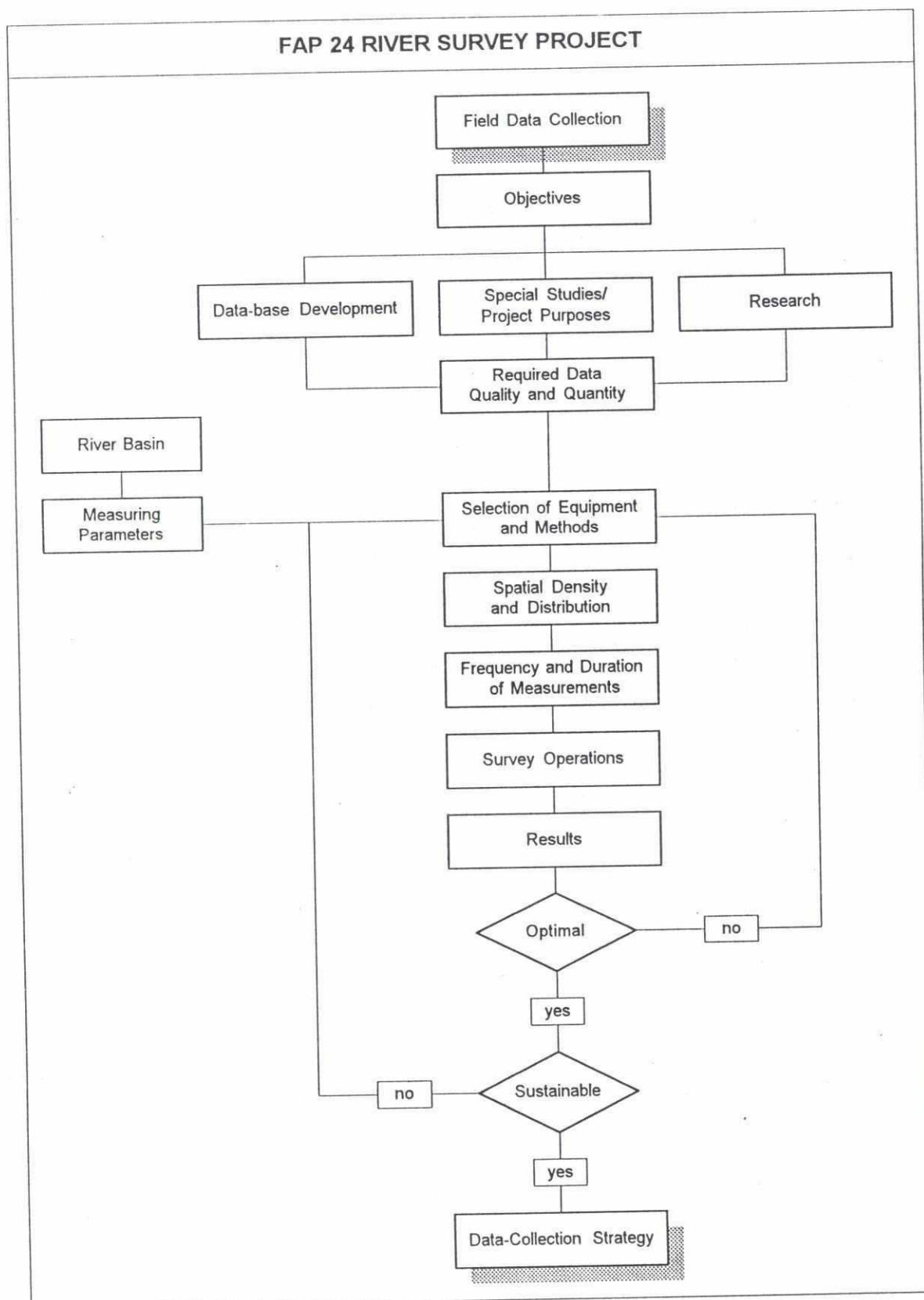


Figure 1.2 Principles of optimization of hydraulic and sediment measurements.

Optimization can be thought of as a series of activities including selection of equipment and methods, a network of measuring stations, a particular frequency of measurements, and a designed survey operation which are evaluated on some criteria, and are adjusted and improved following the evaluation.

In designing a field-data collection plan, the objectives should be clearly distinguished in terms of either database development, project implementation, or research. Each has its definite data requirements and desired accuracy level. We examined the sediment measurements based on the considerations of long-term database development. Special studies and research require accurate data rather than optimization or sustainability considerations. The optimization process is considered under four distinct data collection activities:

- 1 optimization of equipment and methods,
- 2 optimization of spatial density or measurement network,
- 3 optimization of temporal density or frequency of measurements, and
- 4 optimization of survey operations.

To discuss the process, we used and analyzed some routine measurements taken by FAP 24 as well as some specially designed measurements. The special measurements included,

- 1 measurements to determine the bed load transport by means of dune-tracking and trap sampling, and comparisons between both techniques,
- 2 measurements to compare instruments and methods of BWDB and FAP 24,
- 3 time series analyses of near-bed sediment transport using various instruments (e.g. Helley-Smith bed load sampler, pump-bottle sampler and Delft Bottle), and
- 4 special measurements to determine the optimal number of verticals in a transect and the optimal number and distribution of observations in a vertical.

With a discussion on the principle of sediment measurements presented in chapter 2, the available information at the beginning of the River Survey Project is outlined in Chapter 3. This information combined with the experience of the consultants and others during previous projects in Bangladesh was the basis of selection and mobilization of techniques described in Chapter 4. The experience obtained during Phase 1 of the project (1992-1994) is presented in Chapter 5 and resulted in a revised selection of techniques for Phase 2. The experiences during Phase 2 (1994-1996) are presented in detail in Chapter 6. These experiences provided valuable additional information for optimization of sediment measurements on Bangladesh rivers as presented in Chapter 8. Conclusions and recommendations are presented in Chapter 9. Some relevant sediment transport related issues are discussed in Chapter 7. These issues are important for sediment measurements on Bangladesh rivers.

Seven annexures are included at the end of the report covering some specific issues and special measurements. Annexure A describes the principles of sediment measuring instruments based on literature. This Annexure is included in order to provide a common technical background to the users of this report. Annexure B discusses various possibilities of computing total load transport and their limitations. Annexure C discusses the prospects and limitations of Helley-Smith and Delft-Bottle near-bed samplers based on routine measurements. Annexure D relates ADCP backscatter to the suspended sand concentration. The quality of fine sediments in Bangladesh rivers and their importance are discussed in Annexure E. Annexure F shows the bed-load transport estimate based on 1993 dune-tracking in the Jamuna River near Bahadurabad. Finally, Annexure G (G2 to G8) presents the results of the same special near-bed measurements, Annexure G1 gives a brief overview of those measurements.

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2 Principles of Sediment Measurements

Sediment transport is usually conceived of consisting of two modes of transport. A suspended load is transported while suspended in the water column. The suspension of this mode of transport is ensured by turbulence in the water column. A bed load transport occurs along the bed by sliding, rolling, and saltating under the influence of gravity. Saltation is the hopping or jumping of particles over the river bed (van Rijn, 1986; PA's 7th mission report and annex 4 of the final report of the RSP). Figure 2.1 shows the conventional classification of the sediment transport modes.

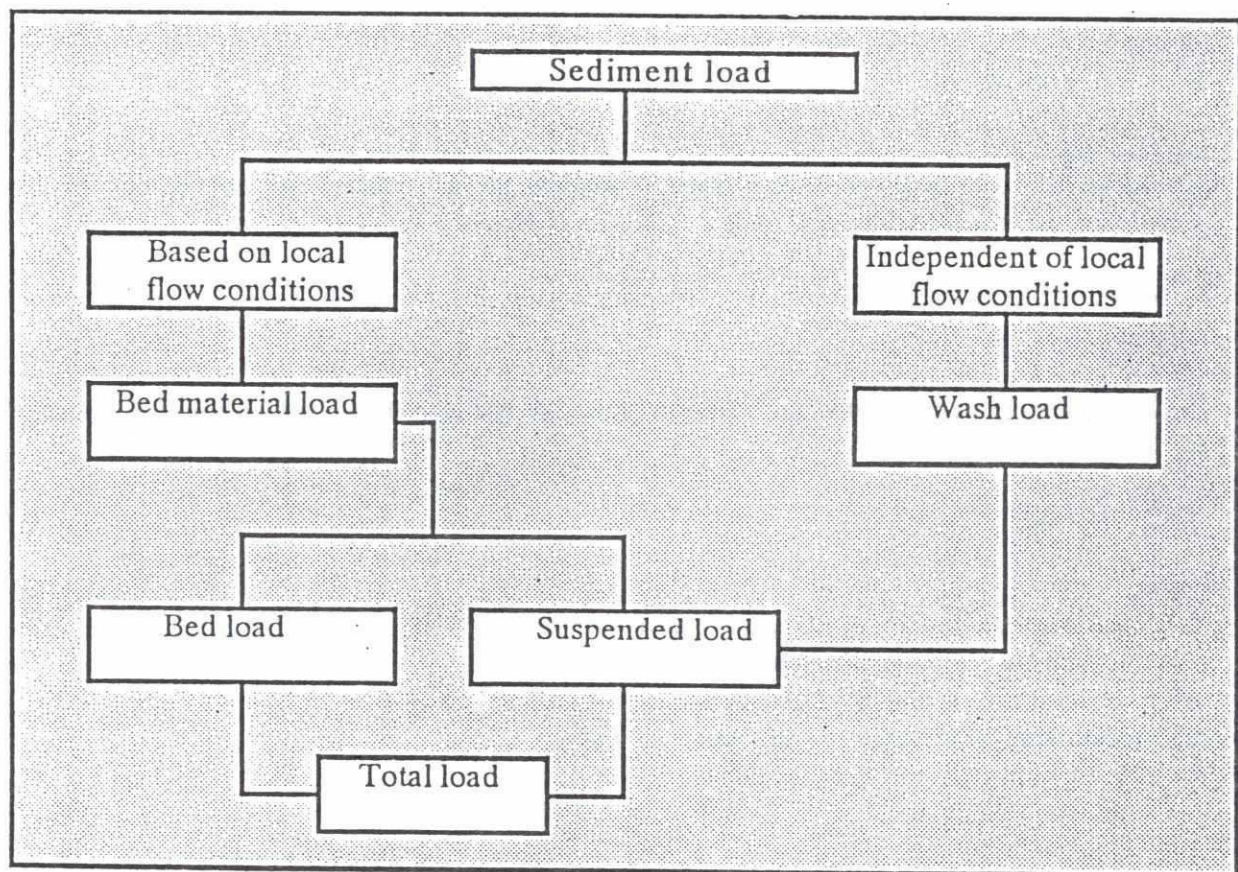


Figure 2.1 Conventional classification of sediment transport mode.

According to the dependence on local flow conditions, sediment transports are classified as "bed-material load" and "wash load." Wash load can form a significant part of the total sediment load.

The principles and instruments used for measurements of these two modes of transport are different. A discussion follows on the principles of measurements of these two modes of transport.

Suspended Sediment Transport

Based on measurements, suspended sediment transport is estimated as,

$$S_t = \sum_{j=1}^m S_v \Delta y \quad (1)$$

where,

S_t = total suspended sediment transport across a channel transect (MS^{-1}),

m = finite number of verticals (-),

Δy = width assigned to each vertical (L),

S_v = transport over the vertical ($ML^{-1}S^{-1}$).

Ideally,

$$S_t \xrightarrow{\text{exact, as } m \rightarrow \infty} \quad (2)$$

But m is finite, and thus the so-called interpolation error is introduced (Van Rijn, 1993). The number of verticals, m , needs to be optimized in order to minimize the interpolation error. In addition, closing errors occur as measurements stop some distance away from the bankline.

It can now be seen how S_v can be estimated by using a point-integrated sampler and a depth-integrated sampler.

For a **point-integrated sampler**, the transport above the bed-load layer over a vertical is estimated as,

$$S_v = \sum_{i=1}^n \langle s_z \rangle \Delta z \quad (3)$$

where,

S_v = total suspended sediment transport over a vertical ($ML^{-1}S^{-1}$),

n = total numbers of points in a vertical (-),

$\langle s_z \rangle$ = local time-averaged suspended sediment transport at z ($ML^{-2}S^{-1}$),

Δz = depth interval assigned to each measuring point (L),

i = counter starting from top of the bed load layer (-),

h = total water depth (L).

Here, again,

$$S_v \xrightarrow{\text{exact, as } n \rightarrow \infty} \quad (4)$$

But n is finite, and thus an interpolation error is introduced again. The number of measuring points, n , need to be optimized so that the interpolation error can be minimized. In addition, there is a closing error as measurements are stopped some distance away from the bed.

The following is a discussion of how the time-integrated transport is determined in a concentration method (determining the velocity and concentration separately). Assuming sediment particle velocity is equal to the fluid velocity, the time-averaged suspended sediment transport at any height z can be written as,

$$\langle S_z \rangle = \langle U_z C_z \rangle = \langle (\langle U_z \rangle + U'_z)(\langle C_z \rangle + C'_z) \rangle = \langle U_z \rangle \langle C_z \rangle + \langle U'_z C'_z \rangle + \langle U_z \rangle C'_z + \langle U'_z \rangle \langle C_z \rangle \quad (5)$$

where,

$\langle S_z \rangle$ = time-averaged suspended sediment transport at z ($\text{ML}^{-2}\text{S}^{-1}$),

U_z = instantaneous velocity at z (LS^{-1}),

C_z = instantaneous suspended sediment concentration at z (ML^{-3}),

$\langle U_z \rangle$ = time-averaged velocity at z (LS^{-1}),

$\langle C_z \rangle$ = time-averaged suspended sediment concentration at z (ML^{-3}),

U'_z = turbulent fluctuation of velocity at z (LS^{-1}),

C'_z = turbulent fluctuation of suspended sediment concentration at z (LS^{-1}),

z = height above bed (L).

The last two terms of equation 5 are zero by definition.

For a depth-integrated sampler,

$$S_v = \bar{C} \bar{U} \Delta h \quad (6)$$

where,

Δh = sampled zone in the water column,

$\bar{C}$ = depth-averaged suspended sediment concentration,

$\bar{U}$ = depth-averaged velocity.

An error is introduced because,

$$S_v = \sum_{i=1}^n U_i C_i \Delta z \neq \bar{U} \bar{C} h \quad (7)$$

Different methods measure different parts of equation 5; however, none of the instruments measure the equation completely which would have been ideal. For example, the direct method of measuring suspended sediment transport, the Delft Bottle, accounts for the complete equation by measuring $\langle U_z C_z \rangle$. Unfortunately, the instrument measures only sediments having sizes larger than about 100 μm (Delft Hydraulics, 1963).

The time-integrated indirect method of measuring suspended sediment transport measures only the mean transport ($\langle U_z \rangle \langle C_z \rangle$). The time-averaged part of the product of turbulent fluctuations which represent diffusive transport is not measured. However, the contribution from diffusive transport is negligibly small. Experiments by Soulsby et al. (1985) and Mulder et al. (1985) show that the diffusive transport is less than about 5% of the mean transport. In developing measuring techniques for bed load in the Yangtze River, Zhian and Gangyan (1992) report that in order to reduce the pulsation error, the measurement duration should be larger than 100 s.

An instantaneous indirect method of suspended sediment transport determination (e.g., a Binckley sampler) measures $\langle U_z \rangle C_z$ at any height, z . The time-averaged velocity component is multiplied with instantaneous suspended sediment concentration. However, BWDB estimates suspended sediment transport as in equation 6 by using the Binckley sampler. Depth-mean velocity and depth-mean suspended sediment concentrations are estimated separately based on measurements at 20% and 80% of total water depth.

Comparison of direct and indirect methods indicates that a direct method measures less than an indirect method; estimates vary from 1% by Soulsby et al. (1985) to 5% by Mulder et al. (1985) to 10% by

Anderson (1975). For Bangladesh conditions, the discrepancy may be even higher since major suspended sediment transport is caused by silt fractions.

The applied averaging time or exposure time for velocity is usually between 50 to 100 s. It is known that the exposure time of point integrating sampling of suspended sediments (which means in fact time integrated sampling at one point) should usually be more than the exposure time of velocity measurements. It should be say 100 to 300 s or more. For instance, Yuqian (1989) mentions 300 s. With this in mind the two instruments of the River Survey Project (which in principle can measure continuous suspended sediments concentration) were set to the following registration interval: 54 s registration interval is used for ADCP backscatter intensity in the profile mode, and a 15 s registration interval is used for MEX turbidity records. Usually these instruments were applied with exposure times of many times the registration interval. To get an impression of the temporal variation of the coarse sediment concentration, some long duration (1 to 2 hours) measurements of the ADCP backscatter intensity were analyzed. Results are presented in the Figures 2.2 and 2.3 and show the increase of the variation in higher flows. Moreover the Figures show that the variability of suspended sediment concentration is higher near the bed than near the surface. Therefore, as for velocity, given the same averaging time, a higher error is made near the bed than near the surface (Nordin et al 1983, Meade et al 1990 and RSP, 1995). Similar conclusions were drawn at other places in the world such as on the Amazon (Richy et al 1986), the Orinoco (Meade et al 1983), the Mississippi (Meade and Stevens 1990), the Zaire (Peters 1981) and also in some irrigation canals in Pakistan (Eyster and Makmood 1976). Figure 2.4 shows the suspended sediment measuring devices used by RSP.

Note on Figs. 2.2 and 2.3

$\langle \bar{c} \rangle$	= time and depth averaged concentration
σ_c	= standard deviation of one time series of concentration at a certain depth
$\sigma_c / \langle \bar{c} \rangle$	= relative standard deviation
d	= depth
u	= time and depth averaged flow velocity

Jamuna River, Bahadurabad Optimization survey, 4-12 Dec 1994

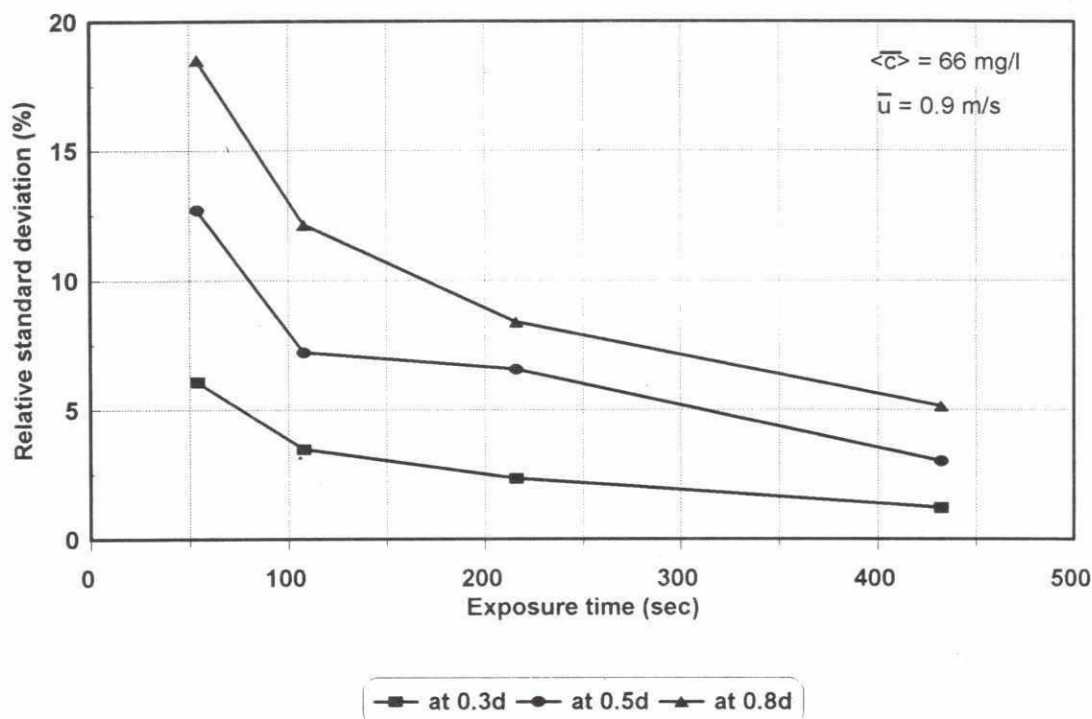


Figure 2.2

Relative standard deviation versus exposure time in low flows on 6 December 1994 based on measurements in the Jamuna River left anabranch near Bahadurabad.

Jamuna River, Bahadurabad Optimization survey, 27 July 1995

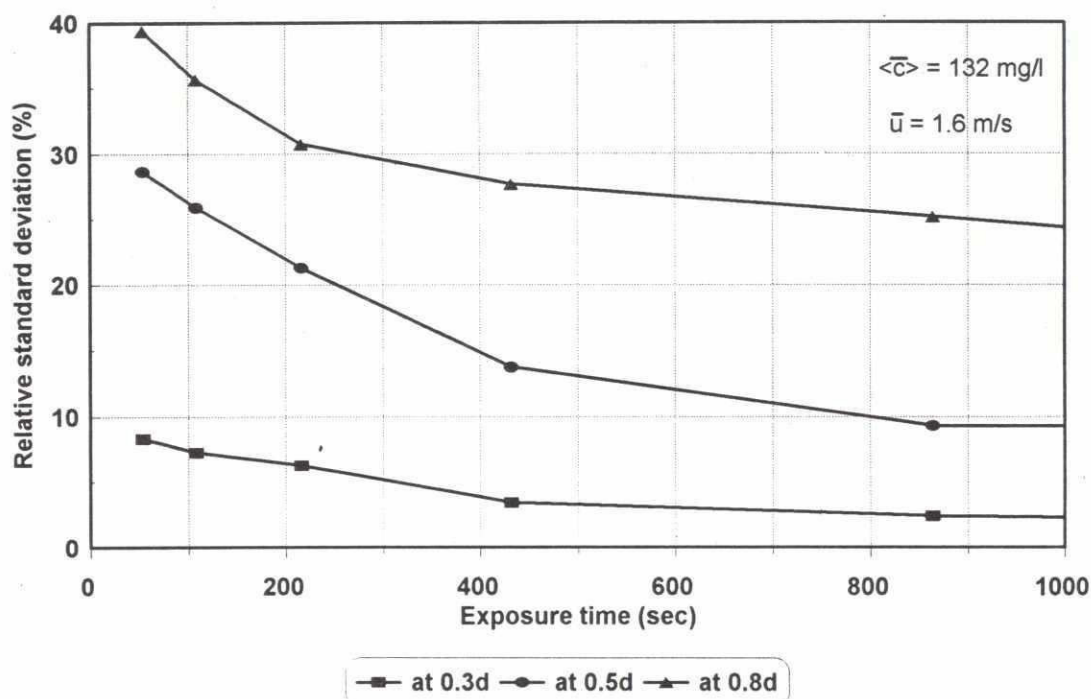


Figure 2.3

Relative standard deviation versus exposure time in higher flows on 27 July 1995 based on measurements in the Jamuna River left anabranch near Bahadurabad.

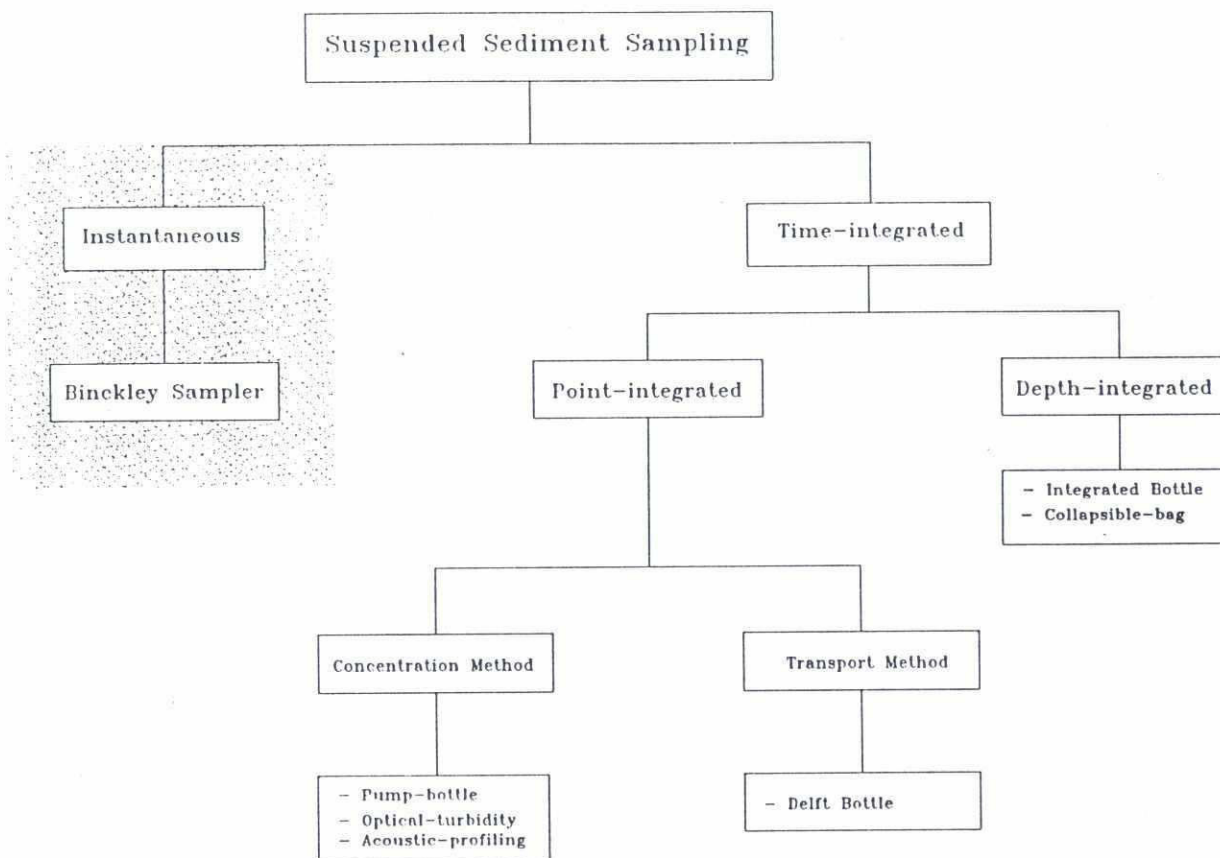


Figure 2.4 Suspended sediment measuring instruments used by RSP. The shaded instantaneous Binckley sampler is used by BWDB.

Bed-load Sediment Transport

Bed-load transport occurs in a thin layer above the bed under the influence of gravity. Investigators differ in their definition of this "thin boundary." For example, Einstein (1950) defined bed-load as transport of sediments occurring above the bed in a layer of 2 particle diameters. Bagnold (1956) defined bed-load as the sediment transport in which the successive contact of particles with the river bed were strictly limited by the effect of gravity. Investigations by Abbot and Francis (1977) indicated that a maximum saltation height of 10 particle diameters can occur. Van Rijn (1984) assumed that the bed-load layer is limited by the saltation of particles which is directly proportional to the transport stage. He assumes that the saltating particles reach half of the bedform height. It should be noted that the description of saltation are mainly based on laboratory observations.

It is impossible to take measurements of bed-load as defined above in fine sand-bed rivers. However, sediments moving near the bed are important for river morphology (Peters and Goldberg, 1989) and they can be measured. Observations in the Zaire River suggest the existence of a moving near-bed layer. It is up to several decimeters thick and its sediment contribute to bed changes. Consequently, measuring sediment transport and sediment concentration is the most difficult part of river surveying. The natural variability of these parameters is large, thus hampering a fair calibration of the available instruments and necessitating a large number of observations to determine a reliable average value. With regard to the height of a measuring point above the river bed, surveyors are facing limited means to determine the exact elevation of this constantly changing bed. Moreover, the stability of any measuring device on the river bed is questionable. Consequently, it has to be accepted that sediment measurements show a larger scatter and have limited accuracy. This is probably the reason that no required accuracy for sediment observations was defined in RSP's Terms of Reference or Technical Specifications.

Another problem is that the so-called bed load samplers like BTMA and Helley-Smith measure much more or much less than the bed-load, depending on the adopted definition of bed-load. To avoid this confusion, the recommendations of the PA were followed (Peters 1994) and the measurements were focused on near-bed transport rather than on bed-load. This was in line with earlier observations done in the Zaire River (Peters and Goldberg, 1989) where it was stated, *'These observations suggest the existence of a layer up to several decimeters thickness, corresponding to that part of the moving sediment contributing to the bed changes (bed load transport and saltation)'*.

From the beginning of the project a certain flexibility with bed-load transport gauging was envisaged (Remarks 19 and 19A of the Reduced Bills of Quantities). There it is stated that different rules could be developed after the test gauging and when experience is gained. This happened and the bed-load gauging of phase I, became the near-bed sediment transport measurements of phase II. Particularly it meant that the measurements were not focusing on the lowest few cm any more, but on the lowest few dm.

For the history of the near bed sediment transport measurements during the River Survey Project please refer to the relevant sections in Chapters 4 and 5.

3 Bangladesh River Characteristics

Bangladesh river characteristics, which are primarily relevant in the context of sediment measurements, are briefly described below. The following characteristics determine sediment measurements, particularly the initial selection of instruments.

- Bangladesh rivers are fine sand-bed rivers. The median sediment diameter varies from 90 μm in the Padma River to 220 μm in the Jamuna River. Consequently, the threshold velocity for sediment mobility is low, approximately 0.2 m/s (Hjulstrom, 1935).
- Due to the low threshold velocity, the rivers are highly mobile with continuous reworking and deformation of their beds and banks. Activity increases during peak river stages in the monsoon months.
- Locally, flow velocities often exceed 3.5 m/s during the peak river stages. Suspended sediment concentration often exceeds 1000 mg/l.
- The seasonality of Bangladesh rivers, with over 6 m of river stage variation between the high and low stages, spreads the hydraulic activity over a wide area.

Many instruments developed in Europe or America were primarily designed to sample a certain river under a particular environmental condition (i.e., specific to a given country). Deploying these instruments to other environments should therefore be made after careful consideration. The purpose of this section is to highlight certain environmental conditions of Bangladesh rivers which are important for the selection of instruments. Particularly relevant in this respect are the climatic conditions and the sedimentary environment of the rivers. The mean January air temperature of Bangladesh varies from 16° C in the north to about 19.5° C in the south (Rashid, 1991). Mean July air temperature varies from 27.5° C in the south to about 29° C in the north. The mean summer relative humidity is high, about 80, as a result of the southwest monsoon. The winter relative humidity, on the other hand, is lower, about 59, due to the northeast monsoon.

3.1 River Morphology and Sediment Measurements

Several sediment transport factors are critical for studying and predicting the morphological behaviour of rivers. Textural properties of bed-material such as bed-material size, standard deviation and sand-silt percentage are important independent variables for sediment transport and morphologic relations. Similarly, total sediment transport, its division into size fractions, and the ratio of suspended-load to bed-load are important. Different physical and mineralogical properties of sediments are also independent variables in many relations. Moreover, most sediment transport relations are not based on theory but are empirically derived; this means that the relations apply only to the cases for which they are derived. The coefficients of these relations have to be determined from observations in the rivers where they will be applied. Therefore, sediment measurements are essential for validating the known transport relations.

For Bangladesh rivers, most of these factors are neither known nor measured. Suspended sediment transport data, however, are available from BWDB.

3.2 Variability of Major Sediment Transport and Morphologic Parameters

Various sediment and morphologic parameters vary widely in space and time in the Bangladesh main rivers. These parameters are useful for preliminary selection, testing, and procurement of hydraulic and sediment measuring instruments. Some of these parameters are known from previous studies (NEDECO, 1967; Coleman, 1969). Some of these earlier findings as well as contemporary information from FAP studies are summarized by FAP 24 in Study Report 3 (RSP, 1994) and by Barua (1994). Table 3.1 shows a summary of these parameters in the rivers covered by the RSP surveys, and their variability, assembled from various sources.

Morphologic Parameters	Ganges	Gorai	Jamuna	Old Brahmaputra	Dhaleswari	Padma	Arial Khan	Upper Meghna
Independent Var.								
Q_{av} (m ³ /s)	11,000	1,400	19,600	500	600	28,000	2,600	4,800
Q_{sl} (mt/a)	196	-	499	7	-	890	-	13
Q_{bl} (mt/a)	-	-	-	-	-	-	-	-
Bed-material Grain Size (d_{50} , μ m)	120	179	220	180	150	90	147	180
Bed-material Std. Dev. (-)	1.40	1.45	1.52	1.80	1.57	1.52	1.57	2.54
Dependent Var.								
Mean Width (m)	5,000	-	11,000	330	256	7,000	-	1,000
Mean Depth (m)	4.5	-	5.0	7.0	9.0	-	-	4.7
Mean Slope (-)	5×10^{-5}	4×10^{-5}	7×10^{-5}	7×10^{-5}	4.5×10^{-5}	4×10^{-5}	-	2×10^{-5}
Form Number (-)	1,111	-	2,200	47	28	-	-	213
Meander Wavelength (m)	29,000	9,200	-	5,500	-	-	4,160	9000
Mean Channel Sinuosity (-)	1.2	1.7	-	1.4	1.5	1.1	1.8	-
Brice Braiding Index (-)	-	-	4 - 6	-	-	-	-	-

Q_{sl} = Mean annual suspended sediment load, Q_{bl} = Mean annual near-bed/bed sediment load.

Table 3.1 Time- and space-averaged various morphologic parameters of the major rivers in Bangladesh obtained from various sources.

The mean annual average discharge varies from 500 m³/s in the old Brahmaputra River to 19,600 m³/s in the Jamuna River. Total annual suspended sediment transport varies from 13 million tons in the Upper Meghna River to 890 million tons in the Padma. No bed-load transport data is available. The median diameter in the fine sand-bed river of Bangladesh varies from 90 μ m in the Padma River to 220 μ m in the Jamuna River with the highest geometric standard deviation occurring in the Upper Meghna River. Other parameters shown as dependant variables indicate the relative sizes, shapes and the morphologic parameters.

Informed by Coleman (1969), Table 3.2 provides some information on bedforms and their dynamics. While they provide a broad overview, an attempt was made to estimate bed-load transport utilizing dune-tracking data which is described in Chapter 5.2 (Details are given in Annexure F).

Bed-forms	Ripples	Megaripples	Dunes	Sand waves
Height, H (m)	< 0.3	0.3 - 1.5	1.5 - 7.6	7.6 - 15.2
Length, L (m)	< 1.5	3.1 - 152.4	42.7 - 487.8	182.9 - 914.6
Ripple Index (H/L)	1:5 - 1:20	1:6 - 1:100	1:30 - 1:60	1:25 - 1:100
Maximum migration (m/day)	-	247.0	158.5	640.2
Average migration (m/day)	3.1	122.0	67.1	204.3
Depth of water (m)	< 30.5	< 30.5	3.1 - 30.5	9.2 - 36.6
Water turbulence pattern	small surface eddies in shallow water	small surface boils in shallow water	large surface boils	large surface boils
Plan view of crestline	linguloid	straight, linguloid and lunate	irregular in shallow water, straight or gently curved in deep water	straight but commonly curved downstream

Table 3.2 Bed-forms in the Jamuna River as reported by Coleman (1969).



4 Pre-selection and Initial Mobilization (1991-92)

4.1 Basic Considerations

Hereafter some international standards for sediment measurements are used, although their applicabilities are limited in large alluvial sand-bed rivers. According to ISO (1977), a suspended sediment sampler should satisfy the following 12 requirements.

- 1 The sampler should be streamlined to minimize disturbances to normal flow velocity.
- 2 The intake velocity should be equal to the ambient velocity.
- 3 The sampler mouth should face into the current, therefore, the sampler should be parallel to the current's direction.
- 4 The sampler mouth should be away from the zone of flow disturbance caused by the sampling structure and gear.
- 5 Sampler filling arrangements should be so smooth that there is no sudden in-rush or gulping of water. In addition, the air escaping from the sampler should not hinder the entry of water.
- 6 For a point-integrated sampler, the collected sample should not be contaminated with samples from any other depth.
- 7 The sampler should be designed in such a way that it is possible to take a sample exactly when and where it is needed.
- 8 The sampler should be portable, yet sufficiently heavy to minimize stream drag and deflection of the cable from the vertical.
- 9 The sampler should require minimum care in maintenance and operation.
- 10 It should be ensured that the sample is removed from the sampler without loss.
- 11 The volume of the sample should be sufficient to obtain sediment concentration and grain size distribution.
- 12 Depth-integrated samplers should be lowered and raised at a uniform rate, equal to a certain fraction of the depth-averaged velocity.

Most of these instrument selection requirements, as well as some additional important considerations, can be grouped into the following ten basic criteria for selecting a suspended load sampler for routine estimation of suspended sediment transport. These ten basic criteria are as follows:

- 1 *Representativity*
- 2 *Minimum sampling and instrumental errors*
- 3 *Reliability*
- 4 *Operation and maintenance*

- 5 *Susceptibility to environmental conditions*
- 6 *Expertise and motivation of the survey crew*
- 7 *Field processing works*
- 8 *Laboratory processing works*
- 9 *Measuring facilities*
- 10 *Cost*

Criterion one, *representativity*, addresses the nature of suspended size populations which are represented by the sampler. For example, certain samplers represent sand populations better, others represent silts better. In fact, this criterion indicates the systematic error of the instrument. Criterion two, *minimum sampling and instrumental errors*, primarily addresses the random errors which occur during sampling and due to sampling-gear configuration. Criterion three, *reliability*, addresses the importance of having reliable instruments. Instruments should have minimum chances of failure, especially during sampling. Similarly, criterion four, emphasizes that the *operation and maintenance* effort of the instrument should be minimal, simple, comprehensible, and affordable. Criterion five, *susceptibility to environmental conditions*, indicates that the instruments need to be less susceptible to environmental and climatic conditions such as temperature and humidity. Criterion six, *expertise and motivation of the survey crew*, addresses that certain instruments require a great amount of expertise and it is important that the crew is motivated to do the strenuous job required by certain samplers. Criteria seven and eight, *field and lab processing works*, are some of the major sources of errors. Therefore, it is understandable that the sampling accuracy increases as the field and lab processing works are minimized. In the selection of instruments, it is also necessary to consider criterion nine, the *measuring facilities*, such as the vessel, anchoring system, booms, winches, etc. Finally, criterion 10, *cost* of the instrument, is also important for selection.

On operational considerations of survey vessels, the experience of the consultants showed that,

- it was difficult to obtain a stable position of the survey vessel.
- the position of any device lowered to the river bed was uncertain with respect to the bed forms, and
- in many cases it appeared impossible to retrieve the anchor.

Given this information, the consultants proposed to execute bed load measurements by means of dune tracking for which no anchoring is necessary, but which requires both an accurate depth measuring device and positioning system (RSP 1991).

In the contracting phase of the project the PA recommended to include at least one alternative measuring method and suggested to add a direct transport measuring device for testing in phase 1. This was agreed and the testing of a trap sampler type of instrument was included in the contract.

4.2 Measuring Facilities

Most of the measuring facilities for hydraulic measurements and navigational requirements are reported in Study Report No. 11 on hydraulic measurements (RSP, 1996a) and in Annexure 1 of the main report

(RSP, 1996b). This report only discusses some measuring facilities for sediment measurements. Most of the facilities on board different vessels were not custom built when the vessels were procured. Therefore, they had to be specially built. The facilities include,

- an aft deck davit to lower and raise the carrier containing the pump nozzle, S4 current meter, and the optical turbidity sensor,
- a starboard side aft deck davit to lower and raise the Helley-Smith trap sampler,
- a portside aft deck davit to lower and raise the bed material samplers,
- two power winches mounted on the aft deck to facilitate lowering and raising of instruments and carriers automatically,
- two manual winches mounted on the davits, and
- the survey boats were equipped with a special steering system, consisting of a steering machine, an auto-pilot and joystick control plus a computerized navigation system to facilitate accurate manoeuvring even in very turbulent high flows. This accuracy was considered to be essential especially during bed-form tracking.

4.3 Sediment Measuring Instruments

In the consultants' technical proposal, a pump sampling method was proposed for determining suspended sediment concentration at various depth-levels (RSP, 1991). The system is combined with velocity registration by an S4 current meter. It was also proposed by the PA during the test gaugings of 1993, that the selection of appropriate locations of the verticals in the cross-section would be assessed using the ADCP backscatter intensity. In the revised inception report, it was recognized that two additional methods, a depth-integrated bottle and a turbidity meter, were needed (RSP, 1992).

Method	Instruments
Suspended Sediment Sampling	- Pump Bottle - Integrated Bottle - Optical turbidity - ADCP back-scatter
Near-bed Sediment sampling	- Dune tracking with echosounder and side-scan sonar - Helley-Smith trap sampler
Bed-material Sampling	- US BM-54 Scoop sampler - Van Veen Grab sampler

Table 4.1 Sediment measuring instruments at the beginning of the River Survey Project in 1992.

5 Experience During Phase I (1992-94)

The first phase of the project officially comprises the first year of the River Survey Project, hence from June 1992 to June 1993. However, essential for phase I were the best gauging in flood (monsoon) conditions to judge the various survey techniques. The floods of 1992 were weak and the waters receded quickly, so by the time the initial mobilization was completed, and the survey system became operational, the rivers were already in mid flow conditions. Thereupon it was decided to do the test gauging in the monsoon of 1993 and the analyses thereafter. Practically it meant that the first phase was extended to December 1993. In the first half of 1994, the second mobilization took place and by mid-1994, the new vessels and equipment for phase II became operational. So experience with the phase I equipment and vessels were gained from September 1992 till May 1994.

In the next sections the experience is summarized with sediment transport measurements. Section 5.1 presents the main findings from suspended sediment measurements while section 5.2 deals with the bed-load measurements. These experiences led to changes in these types of measurements and affected the selected techniques and consequently the second mobilization which is the subject of the last section. The results of phase I measurements were reported in several RSP reports (RSP, 1993a, 1993b, 1994c, 1994b). The dune tracking measurements made in June 1993 is presented in this report (Annexure F).

5.1 Suspended Sediment Measurements

During phase I, a number of alternative suspended sediment measuring devices were used during both special surveys such as test gauging, and routine measurements. These instruments were installed aboard different survey vessels as shown in the following Table.

Equipment	DHA	DHC	DHE
Point-integrated pump bottle system	X	X	X
Depth-integrated bottle	X		
MEX 3 turbidity recorder	X		
300 kHz ADCP	X		

Table 5.1 Suspended sediment measuring devices installed in different vessels during Phase I of the project.

These instruments were used in 1992 in several test gauging. The results hereof have been reported in the 1st Interim Report, vol. II (see RSP, 1993a). Important findings in this period were:

- The point-integrated pump-bottle system worked quite well. The expected interference between power and signal wiring made that pumping with the submerged pump and measuring with the current meter or the turbidity meter could not be done simultaneously.
- As pointed out by the PA, some sediments could settle in the pump-bottle system which made it useful to inverse the pumping direction first and flush old sediments out before starting a measurement.

- Flow induced vibrations of the umbilical were observed (RSP, 1993a, pg 4-6). The vibrations perpendicular to the current were considered unacceptably high. The vibrations could be strongly suppressed by using fairing.
- The initial results of the depth-integrated sampling bottle were very acceptable. Comparison of depth-integrating and point-integrating showed a good agreement (RSP, 1993a, pg 2-30).
- The MEX 3 turbidity meter gave excellent results in the lower and mid flows up to concentrations of 1500 mg/l (RSP, 1993a, pg 4-14). This conforms to the expectations that optical turbidity instruments are suitable to measure fine sediments.
- Special measurements were done with the ADCP system, because loss of bottom track was expected in higher sediment concentrations (tests in December 1992). Although these problems were encountered, not sufficient information on the boundary of the applicability of the ADCP could be collected. Further testing with the ADCP on this issue, preferably with different types of ADCP's was deemed necessary (RSP, 1993a, pg 2-32 and 4-5).
- It was observed that the media grain sizes of the suspended sediments, as measured with the pump bottle were considerably lower than those measured as bed load with the Helley-Smith trap sampler (RSP, 1993c, pg 4-15). This is partly caused by the natural sediment distribution in the vertical (coarse fractions near the bed) and partly by the characteristics (H-S loosing fine sediments).
- The need to distinguish the fine and coarse material in sediment sampling was acknowledged also in view of the different characteristics of some of the samplers (optical systems for fine, acoustic systems for coarse sediments (RSP, 1993a, pg 4-24).

In 1993, the test gauging in high flows were executed as reported in RSP report (1993b). The main findings on the suspended sediment measurements were:

- the pump bottle system worked alright, the fairing suppressed the vibrations of the umbilical sufficiently.
- the ADCP was loosing bottom track, but the mitigating method to determine the ground speed of the vessel not via the bottom track but via the DGPS positioning system would be operated with ease. The software developed in the mean time to apply the off-line corrections using the DGPS signal and to give an on-line warning that the high sediments were spoiling the ADCP positioning were tested and found adequate.
- the MEX showed some scattered results in the higher flows most probably due to the coarser sediments (RSP, 1993c, pg. 2-13).
- the horizontal distribution of the depth-averaged concentrations was plotted against the depth, the flow (u^2/h values) and a sediment rating index. Relations are tricky mainly because of the dynamic processes. It means, for instance, (as was commented on by the PA) that the cross-sections of the channels often show that a channel is composed of several old channels, that the shape of a cross-section is not adjusted to the flow (or the other way around) and that the sediment transport is not adjusted to the flow.

During the international workshop of November 1993, it appeared that the international experts agreed in general with the techniques used so far. However, it was suggested to add a collapsible bag type of depth-integrating sampler to the equipment, especially for the use in the deeper channels. The collapsible bag sampler, already mentioned in the Technical Specifications, has the advantage (in comparison with the bottle type depth-integrated sampling) that no air need to escape from the sampler and bigger containers can be applied. This makes that bottle samplers can be used strictly within appropriate range of water depths (Integrated Bottle, maximum 5 to 7 m), while the collapsible bag can be used till depths of 15 m and more (RSP, 1993c, page 3.2).

5.2 Bed load Measurements

In the beginning of the project two different types of bed load measurements were envisaged:

- Bedform tracking including the use of side-scan sonar.
- Helley-Smith trap sampler.

Already during the first testings in October - November 1992, it appeared that,

- no suitable bedforms were found in the test area and on-trap sampling could be executed (RSP, 1993a, pg 2-21),
- the use of the side scan sonar was very successful in the low and mid-flows. Very clear dune patterns were formed. However, they appeared to be very scarce (RSP, 1993a, pg 4.6).
- the transport as measured with the Helley-Smith appeared to be very scattered. The question was raised is how far this scatter is caused by nature (because of the strong variability of the bed load transport) and/or to what extent the scatter is caused by the way of sampling (scooping of the sampler ?) (RSP, 1993a, pg 4.7). Scooping of the sampler may especially be expected in the high flows when considerable velocity gradients may be expected near the river-bed. So, although the instrument was not yet tested in high flows, some concern was expressed on the applicability of the sampler in flows of say > 2 m/s.
- the Helley-Smith sampler was used during the routine surveys of 1992/93 without problems. During the lowest flows, the catches went down to practically zero at several locations in the river system.

During the high flows of 1993, also the bed load methods were tested on the Jamuna River and the main findings were:

- The system required for dune tracking operated perfectly. The steering system of the survey vessel consisting of a steering machine, an auto-pilot, joystick control and a computerized navigation system made that accurate sailing along the same track is possible, even in very turbulent flow. The navigation system included DGPS positioning, pre-programming of sailing tracks and a left-right indicator. This system and the skill of the crew made bed-form tracking with a high accuracy (repeating tracks with a high uncertainty of a few m), a relatively simple operation.
- The side-scan results appeared to be less useful in the high flows. The maps become hazy due to the high sediment concentration obscuring the recognition of the bedform patterns (RSP, 1993b, pg 8-9).
- The Helley-Smith sampler could be operated easily in the high flows. However, the bed load transports appeared to be very high sometimes. This resulted in two types of problems:
 - the duration of the sampling had to be reduced to 1, sometimes 1/2 minute, which reduces the integration time, resulting in more scatter in the catches.
 - some scooping may occur unnoticed because of the considerable catches.
- The drag of the Helley-Smith sampler is considerable in the high flows. This makes it difficult to determine the moments the sampler touches the river bed and is lifted again. This gives some uncertainties in the determination of the sampling time.

The performance of dune tracking is presented in Annexure F. Summarizing the experience in Phase I, with the bed load measurements, it can be stated that both the selected methods had their disadvantages:

- the dune tracking to determine the total bed load through a river section appeared hardly applicable because,
 - at many locations there were no suitable bedforms at all.
 - in low flows bedforms were hardly propagating, in high flows bedforms disappear as the river is flattening her bed.
 - in most locations with appropriate bedforms, the pattern appeared to be strongly three dimensional, as could be detected with the side-scan. In the Jamuna, for instance, river sections were found with only in one of the major channels locally a 'dune train'.
 - from the beginning of the project, the applicability of the 2D theory to compute bed load from bedform motions was questioned. There are two major problems. Firstly, the above mentioned three-dimensionality. Secondly, the fact that both suspended load and bed load are contributing to the propagation of bedforms and how to distinguish them is not straight forward. (see also Hubbel 1964 and Halcrow, 1993) A special study topic was proposed to tackle this problem (this study topic was not executed after cancellation of the methods of dune tracking). So it had to be concluded that the dune tracking was not the right method to determine bed load transport certainly not a routine basis (RSP, 1993c, pg 2.15). For detailed findings of the dune tracking please see Annexure F.
- Operation of the Helley-Smith becomes critical in high flow conditions. The uncertainties increase with increasing current velocities.

The conclusion hereof was that at least one additional method was required to measure the bed-load, or better, to measure the near-bed transport (see also Chapter 2). Such a method could be the use of the Delft Bottle (in a frame) as recommended by the PA (Peters, 1977). This instrument was used on the Zaire River in flows up to 3 m/s as mentioned by the PA during his presentation in BUET. The method enables to measure point-integrated transport in a vertical.

From the discussions with several international experts it was learned that in many large rivers in the world near-bed sediment transport is not measured as part of routine surveying (in case determination of bulk transport is the main aim). In general, special surveys are executed aiming at the determination of the bed-load/total load ratio per location and for different river stages, as soon as these ratios are known, they are used to compute the bed-load from the measured suspended load (routine surveys).

5.3 Second Mobilization for Phase II (1994)

Based on the experiences gained during phase I of the project, and following the recommendations of the PA the sediment transport survey techniques were modified as follows:

- Suspended load to be measured mainly with the depth-integrated samplers, like the integrated bottle samplers and (after testing, if found appropriate) the collapsible bag. For verification at one vertical per channel, the so-called reference vertical, also pump-bottle samples will be

taken (point-integrating). The backscatter intensity of the ADCP will be used on-line to select the measurement verticals in the main channels and will be stored for eventual further analysis. The MEX 3 will be used to produce time-series of concentration but for special surveys only, not during routine surveys.

- Near-bed sediment transport to be measured with the Helley-Smith trap sampler and an alternative method to be tested as soon as the river stages are sufficiently high, so in the premonsoon of 1994 (RSP, 1993c, pg 3.3). The alternative, being Delft Bottle, to be used also as soon as possible in routine surveys after successful testing.

Measurement types	Selected Techniques for Phase II		
	Routine Measurements		Special measurements
	Main Channel	Minor Channel	Main Channel
Suspended load	Collapsible bag*	Collapsible bag*	Collapsible bag*
	-	Depth-integrated bottle	Depth-integrated bottle
	Pump-bottle	Pump-bottle	Pump-bottle
	-	-	Optical Turbidity
	-	-	Delft Bottle
	Backscatter Intensity	-	Backscatter Intensity
Near-bed Transport	H-S trap sampler	H-S trap sampler	H-S trap sampler
	-	-	Dune tracking
	-	-	Side-scan sonar
	Pump bottle at reference vertical	-	Pump-bottle
	-	-	MEX
	Delft Bottle*	Delft Bottle*	Delft Bottle*
* if found appropriate after testing			

Table 5.2 Selected techniques for phase II

For more details about the second mobilization, also regarding vessels and facilities please refer to the 2^o Interim Report. (RSP, 1995).

6 Experiences During Phase II (1994-96)

After the second mobilization, with the extended fleet and equipment (see Table 5.2), phase II started with the first special measurements at the end of May 1994 and the routine surveys in the monsoon of 1994 from June onwards. Practically, phase II lasted two years, as the project ended in June 1996, according to schedule.

The experiences gained during phase II with the sediment transport measurements are the subject of this chapter. Like in the previous chapters, also here a split is made between suspended load measurements (section 6.1) and near-bed measurements (section 6.2). In order to organize the information, a further split has been made between the experience from the routine surveys and the special measurements. Moreover, an instrument-experience matrix is used to discuss per instruments aspects like calibration, operational ease, performance and reliability, representativity, maintenance including spares and repairs, accuracy, other particulars, special facilities and recommendations. Similarly, per instrument, the main findings regarding the measuring method can be elaborated with aspects like location of stations (network density), measuring frequency, duration of measurements, exposure times, density of measuring points in a cross-section, moving boat vs velocity-area, etc. Along this pattern the following sections have been written.

Based on routine and some special measurements during Phase II of the River Survey Project, experience was gained with the sampling behaviour of different sediment measuring instruments. This was done to determine the optimal survey technique, and to recommend the most sustainable technique. For detailed descriptions of these instruments, please see Annexure A. Comparison of instruments and standard deviations of some individual instruments are presented based on one or two instruments thus, the results should only be treated as indicative.

6.1 Suspended Sediment Measurements

In the following subsections the experience with suspended sediment measurements gained during routine and special surveys respectively has been described.

6.1.1 Results from Routine Measurements

- Instruments

As listed in Table 5.2 the suspended load was measured during the routine surveys with the following instruments :

- i) depth-integrating sampler (collapsible bag* or in the minor channels the depth integrating bottle)
- ii) point-integrating sampler (pump-bottle system in the reference vertical)
- iii) backscatter intensity (on-line with the ADCP to select measurement verticals)
- * after testing (see 6.1.2)

Suspended sediment concentration and transport from some routine measurements were used to evaluate the performance of the instruments and the applied survey method as well.

• Methods

In each routine transect suspended sediment measurements were made by the integrated bottle at several verticals. Based on ADCP backscatter, about 8 to 12 verticals were chosen in large channels (width > 500 m). In smaller channels, four verticals were sampled. In the reference vertical simultaneous measurements were taken by the depth-integrated bottle and the point-integrated pump. In large channels, a 6-point sampling method was followed by the pump-method. The six points were near the surface, at 0.2h, 0.4h, 0.6h, and 0.8h. (h = water depth), and near the bottom (roughly 0.5 m above the bed). 3-point measurements were made at 0.2h, 0.6h, and 0.8h. The DHA vessel was used for measurements in the Jamuna River at Bahadurabad and in the Padma River at Baruria. Either the DHB or a local country boat was used in the Ganges River at Hardinge Bridge.

• Experience with Instruments

- Both the depth-integrating samplers appeared to be reliable, no instrument failure was encountered. As long as, the containers were only partly filled, the samples were accepted. Also a constant transit speed is important for good sampling. To guarantee a constant speed, the power winch was found very useful.
- The transit speed/ambient velocity ratio should be sufficiently low to maintain an appropriate inflow. This can be checked by computing the hydraulic inflow coefficient μ , being the ratio between the inflow velocity and the ambient velocity. The μ value should be closed to 1, but not lower than 0.9 to accept the sample. For the collapsible bag the μ values appeared usually to range from 0.9 to 1.0, see Fig. 6.23, but sometimes larger values were found.
- The unmeasured zone using the different depth-integrating samplers is different due to different configurations. The unmeasured zone is in fact the distance between the intake nozzle and the sampler, when the sampler is resting on the river bed. The unmeasured zone of the integrated bottle sampler was 0.15 m, and of the collapsible bag, as used for the routine measurements, with the bag installed above the sinker weight was about 0.5 m. Especially in low flows when the turbulence is low and the coarser fractions are moving near the river bed only, the magnitude of an unmeasured zone of 0.5 m is considered to be too much. Fortunately, during the low flows, the water-depth is relatively small, so there is more scope for the use of the integrated bottle sampler. However, the above considerations were the reasons to test also another configuration of the collapsible bag, with the bag under the sinker weight which reduced the unmeasured zone to 0.2 m, see further subsection 6.1.2.
- During the peak flows in the monsoon of 1995, considerable instabilities were observed with the collapsible bag (bag above the sinker). The bag was swinging, especially when suspended in the top layer of the flow horizontally perpendicular to the flow direction. Careful analysis, especially comparing the instrument designs for and conditions in the Mississippi with those of the Jamuna, it was found that the instability of the bag on the Jamuna was induced by the shape of the sinker weight. The American sinker weight are carefully shaped and designed for high flows. So an improved shape of the sinker weights for the Jamuna (more fish shaped and stream lined, less cylindrical) is certainly recommended.
- Another point in the design of the collapsible bag is, as mentioned before, the place of the bag in relation with the sinker weight. Some points are: that the sinker weight should affect the flow conditions near the intake nozzle, the bag should not spoil the flow around the sinker weight too much, destroying the smooth streamlines and the effects of fins and tail and the

unmeasured zone should not be too much. This leads to consider an integrated design of the collapsible bag, which means that the bag is installed in the sinker weight. In various countries these type of samplers are in use. As examples the German CUX-samplers (1986) and the Chinese fish-type (Zhian and Huanjin 1990) are shown in the following Figure:

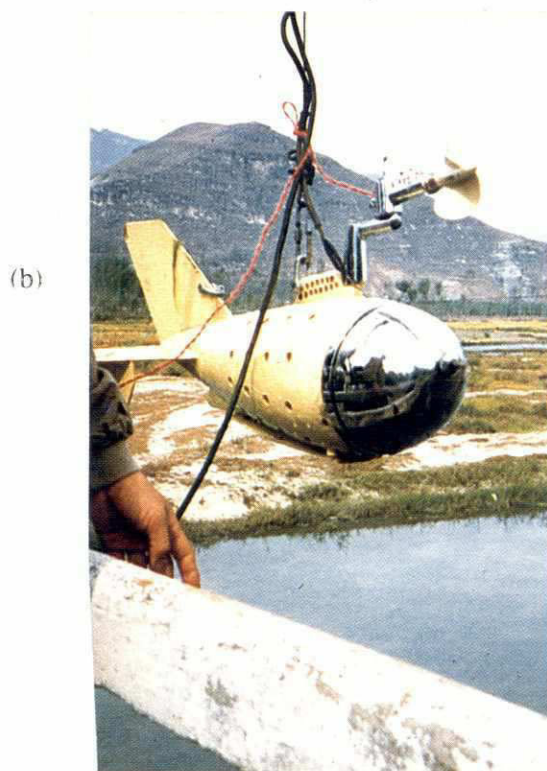
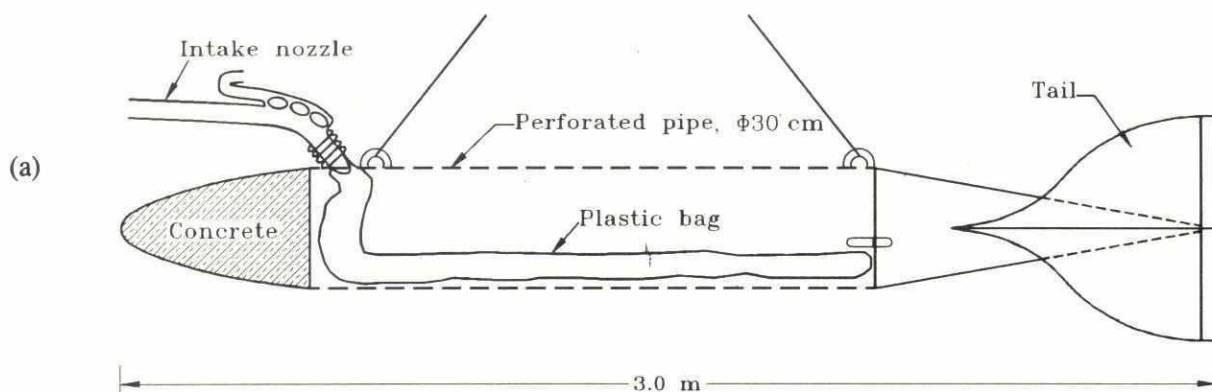


Figure 6.1 Fish-type designs of a collapsible bag sampler. (a) German CUX sampler (250 kg) and (b) Chinese sampler (photographs by J.J. Peters)

- **Intercomparisons**

As pump-bottle measurements improved gradually, amongst others, by using calibration graphs for isokinetic sampling and by applying a splitter to extend the exposure time for smaller samples, the results of these measurements were compared with the other techniques.

-Pump vs Integrated Bottle

Figures 6.2a, 6.2b, and 6.2c show some examples of concentration profiles measured in the monsoon season at Bahadurabad in the Jamuna River. Figure 6.2a shows the comparison of concentration profiles for silt and sand fractions measured on 24 June 1994 in the Jamuna River near Bahadurabad. While there was good agreement for silt fractions, no such agreement existed for sand fractions. As compared to the pump bottle, the integrated bottle overestimated the sand concentration. In Figure 6.2b, the comparison was made based on a measurement on 15 July 1994. Here, underestimation by the integrated bottle occurred both for silt and sand fractions. On 6 August 1994, the agreement in both the fractions appeared reasonable (Figure 6.2c). These were only three examples out of approximately 22 measurements. A summary of all the measurements are presented later.

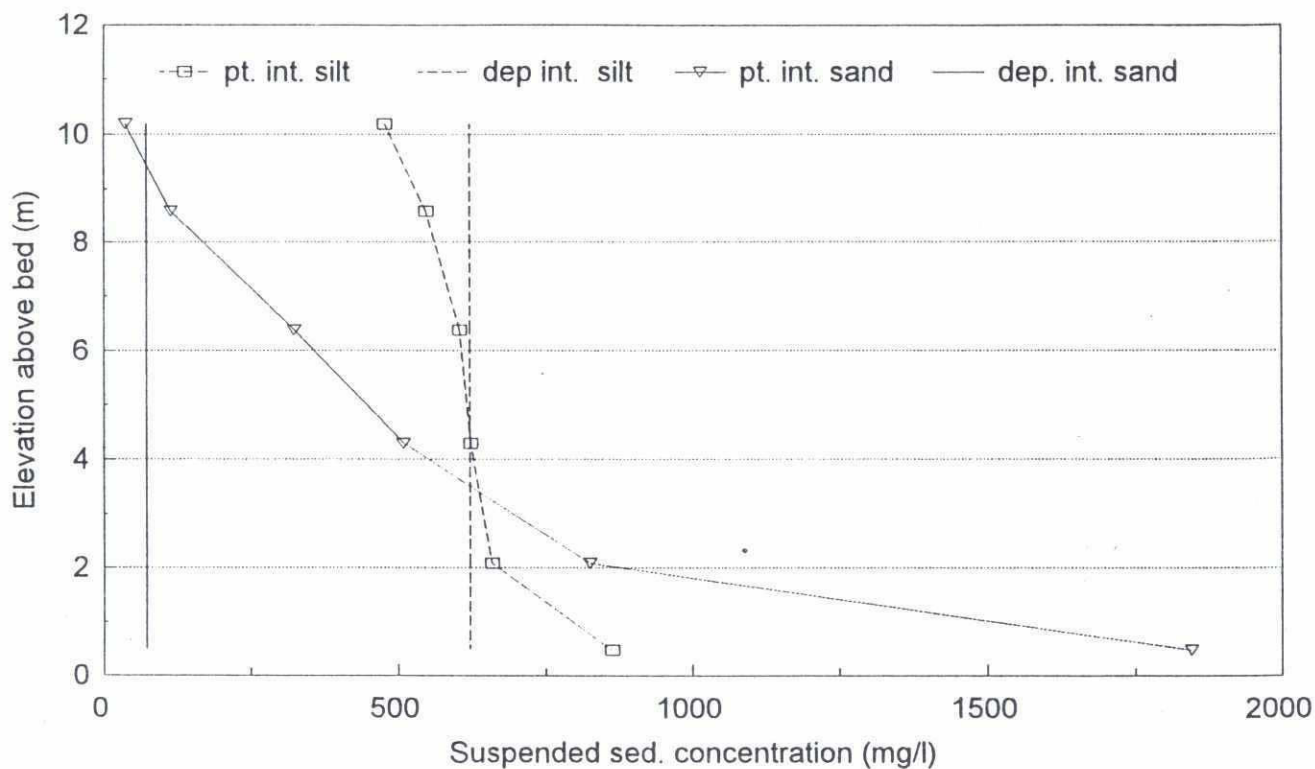


Figure 6.2a Suspended sediment concentration profiles in sand and silt fractions measured in the reference vertical of the Jamuna River left channel near Bahadurabad on 24 June 1994.

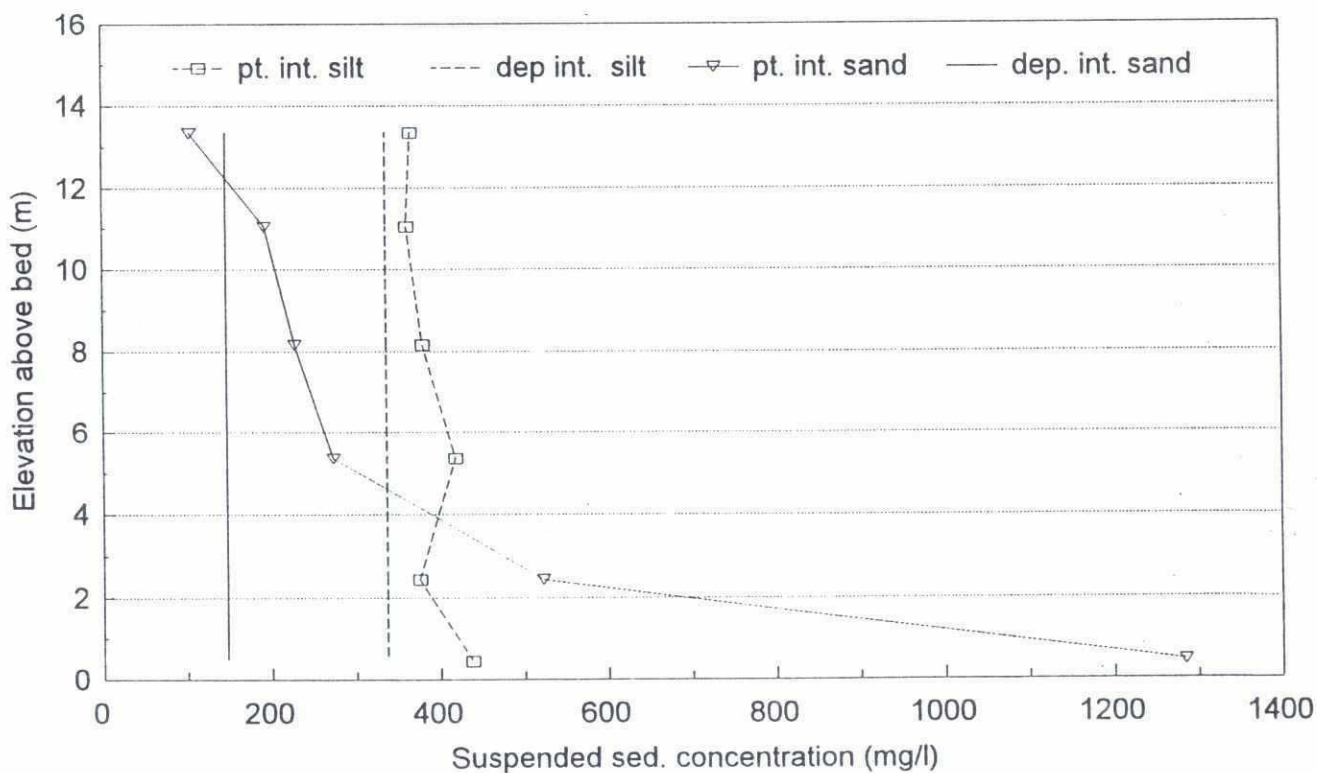


Figure 6.2b Suspended sediment concentration profiles in sand and silt fractions measured in the reference vertical of the Jamuna River left channel near Bahadurabad on 15 July 1994.

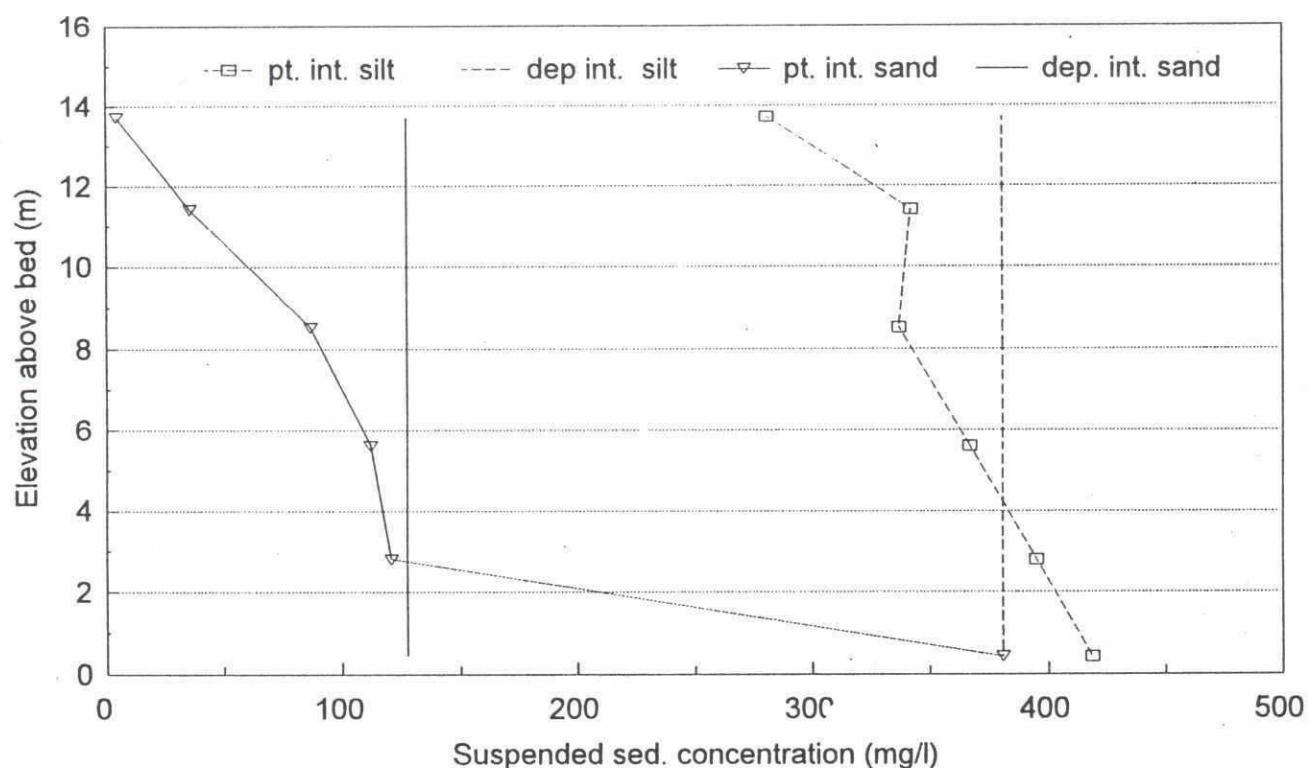


Figure 6.2c Suspended sediment concentration profiles in sand and silt fractions measured in the reference vertical of the Jamuna River left channel near Bahadurabad on 6 August 1994.

Similar exercises were made in the Ganges River at Hardinge Bridge and in the Padma River at Baruria. There were multiple measurements taken at these stations; Figures 6.3 and 6.4 provide some examples. In the example shown in Figure 6.3, based on measurements taken in the Ganges River at Hardinge Bridge on 1 September 1994, the agreement in sand fraction was not good. In the example shown in Figure 6.4, based on measurements taken in the Padma River at Baruria on 29 July 1994, there was poor agreement between the two methods for both sand and silt fractions.

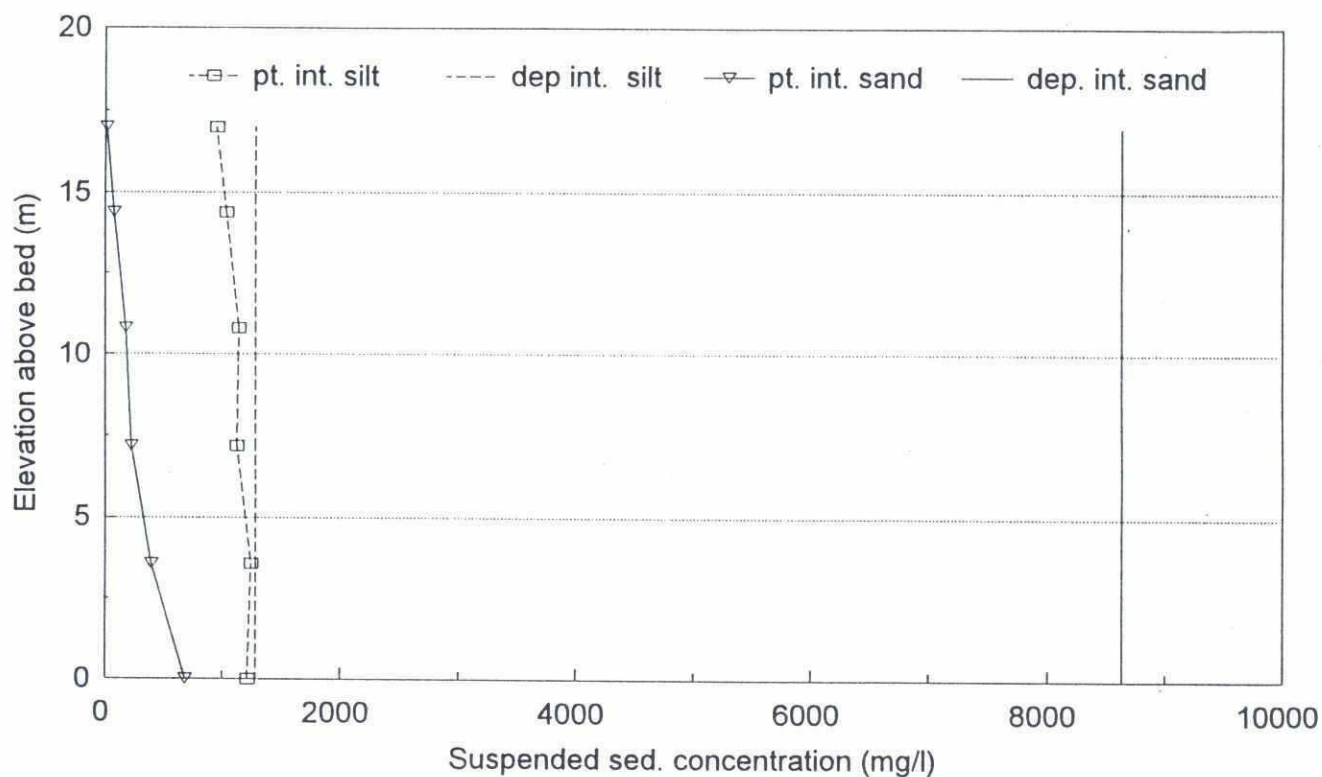


Figure 6.3 Suspended sediment concentration profiles in sand and silt fractions measured in the reference vertical of the Ganges River near Hardinge Bridge on 14 July 1994.

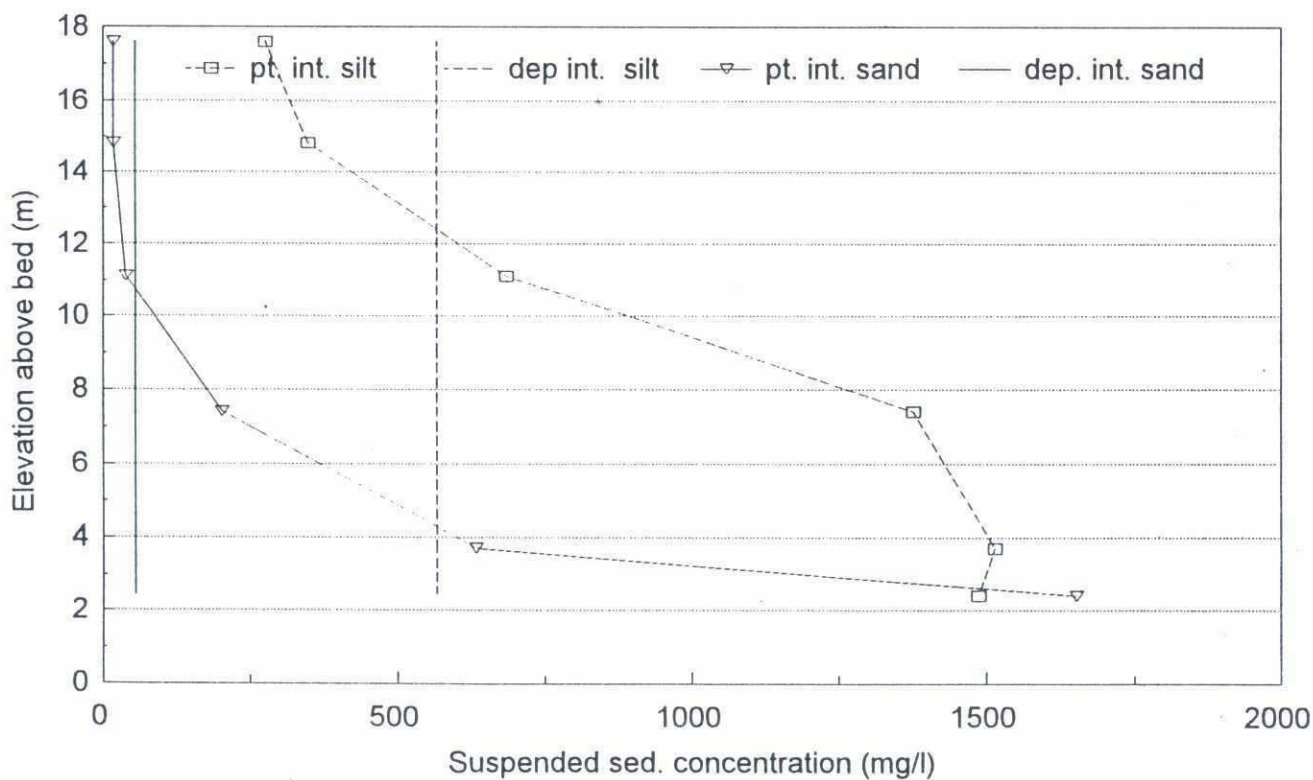


Figure 6.4 Suspended sediment concentration profiles in sand and silt fractions measured in the reference vertical of the Padma River at Baruria on 29 July 1994.

The inter-comparison results between the two instruments are summarized in Figures 6.5 to 6.10. The depth-integrated concentrations from the integrated bottle were compared with the depth-mean concentrations from the pump bottle. As shown in Figures 6.5 to 6.7, there was good agreement between the two methods for silt fractions at all the stations. As shown in Figures 6.8 to 6.10, the same was not true for sand fractions. The pump-method measured more sand-concentrations at Bahadurabad and Baruria but less at Hardinge Bridge.

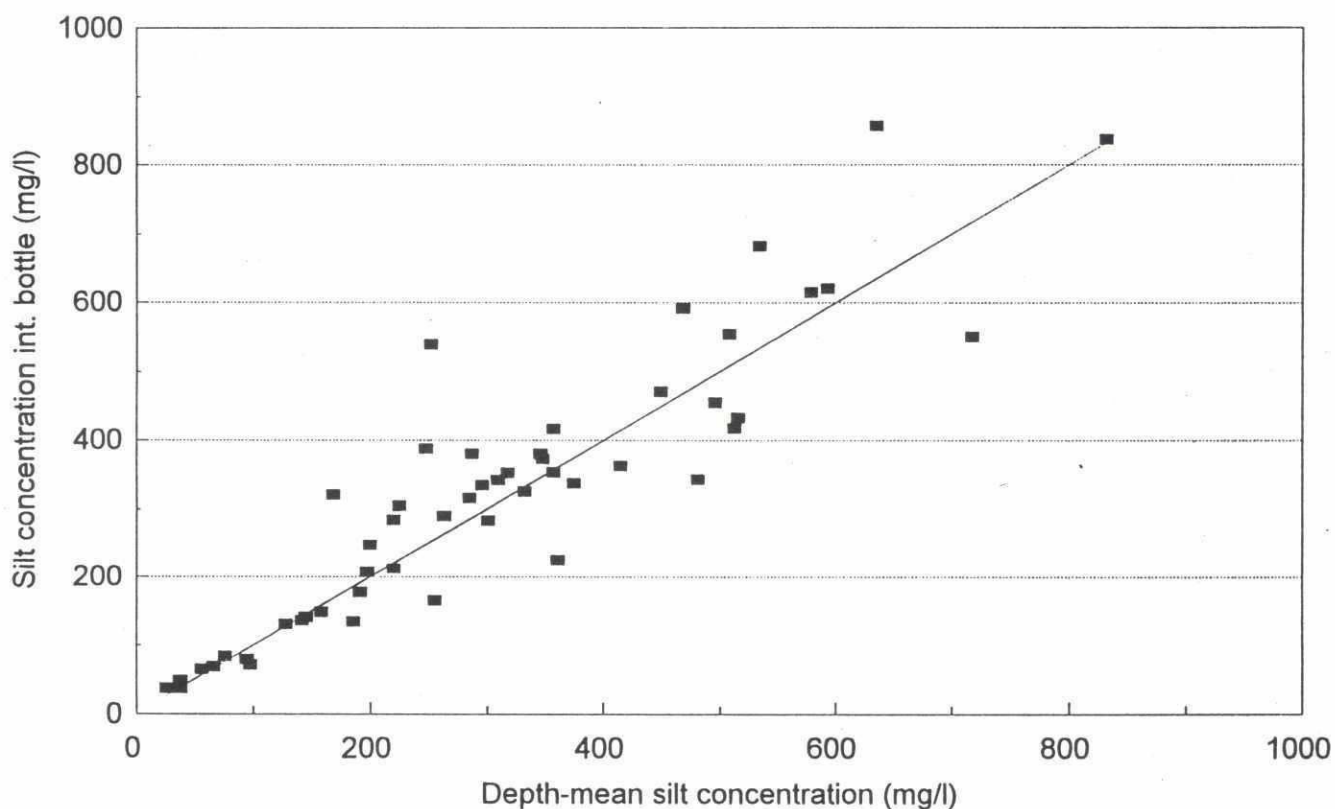


Figure 6.5 Comparison between suspended silt concentrations measured by pump-bottle and integrated-bottle at the reference verticals in the Jamuna River transect near Bahadurabad.

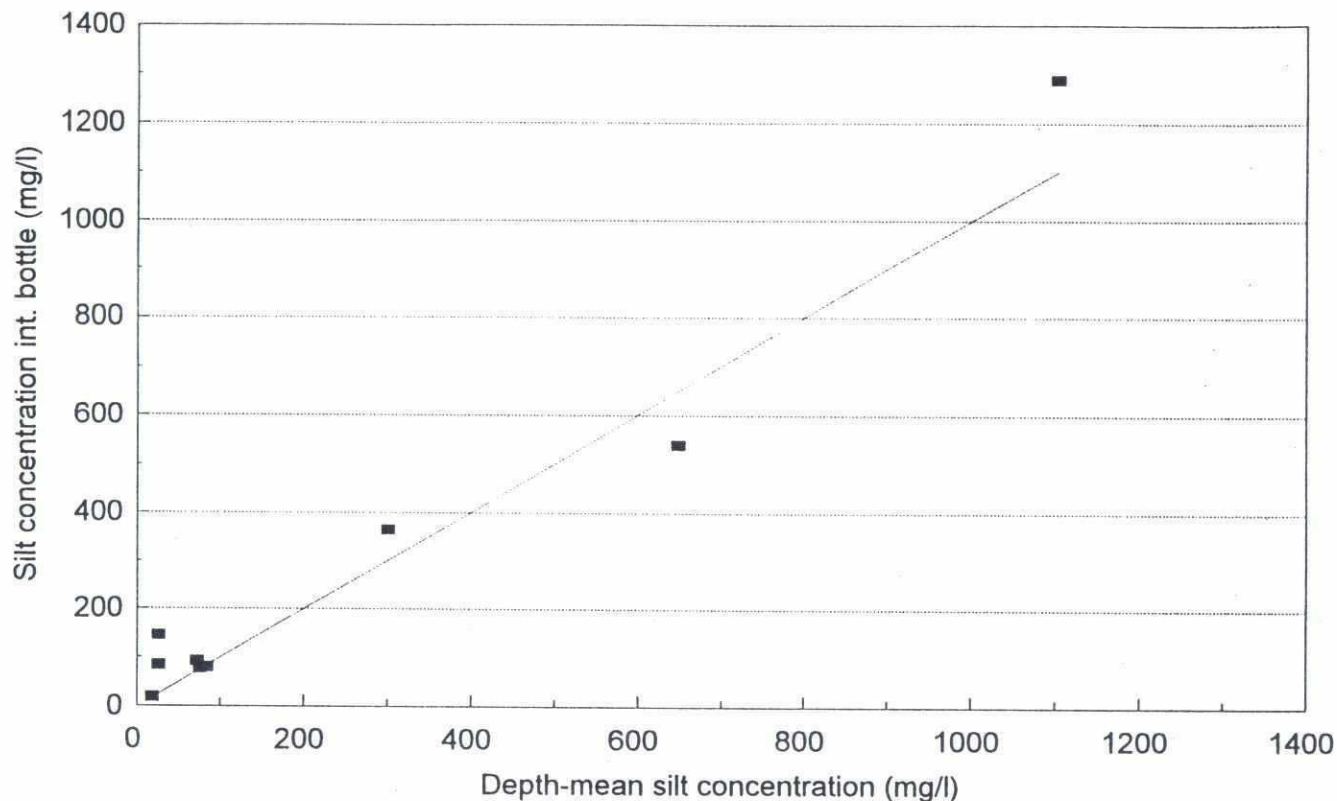


Figure 6.6 Comparison between suspended silt concentrations measured by pump-bottle and integrated-bottle at the reference verticals in the Ganges River transect near Hardinge Bridge.

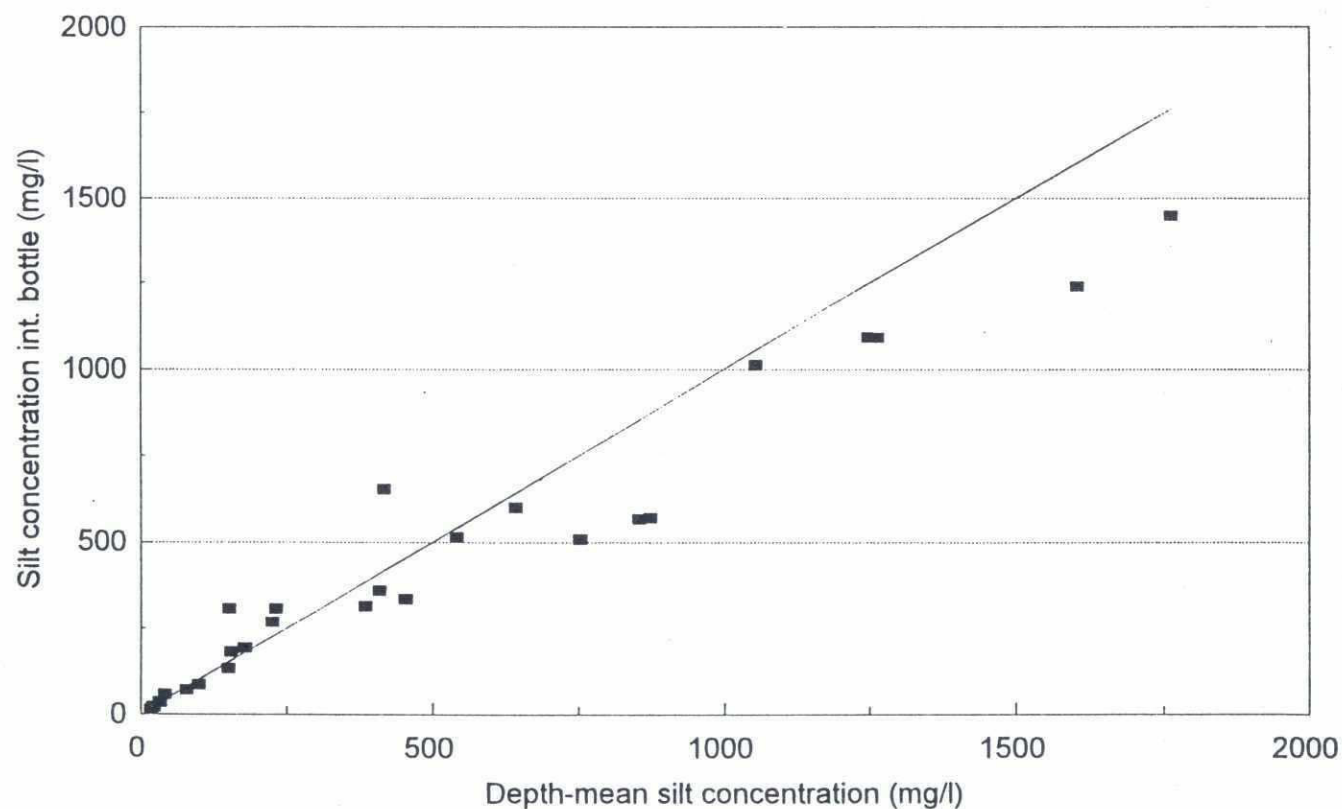


Figure 6.7 Comparison between suspended silt concentrations measured by pump-bottle and integrated-bottle at the reference verticals in the Padma River transect at Baruria.

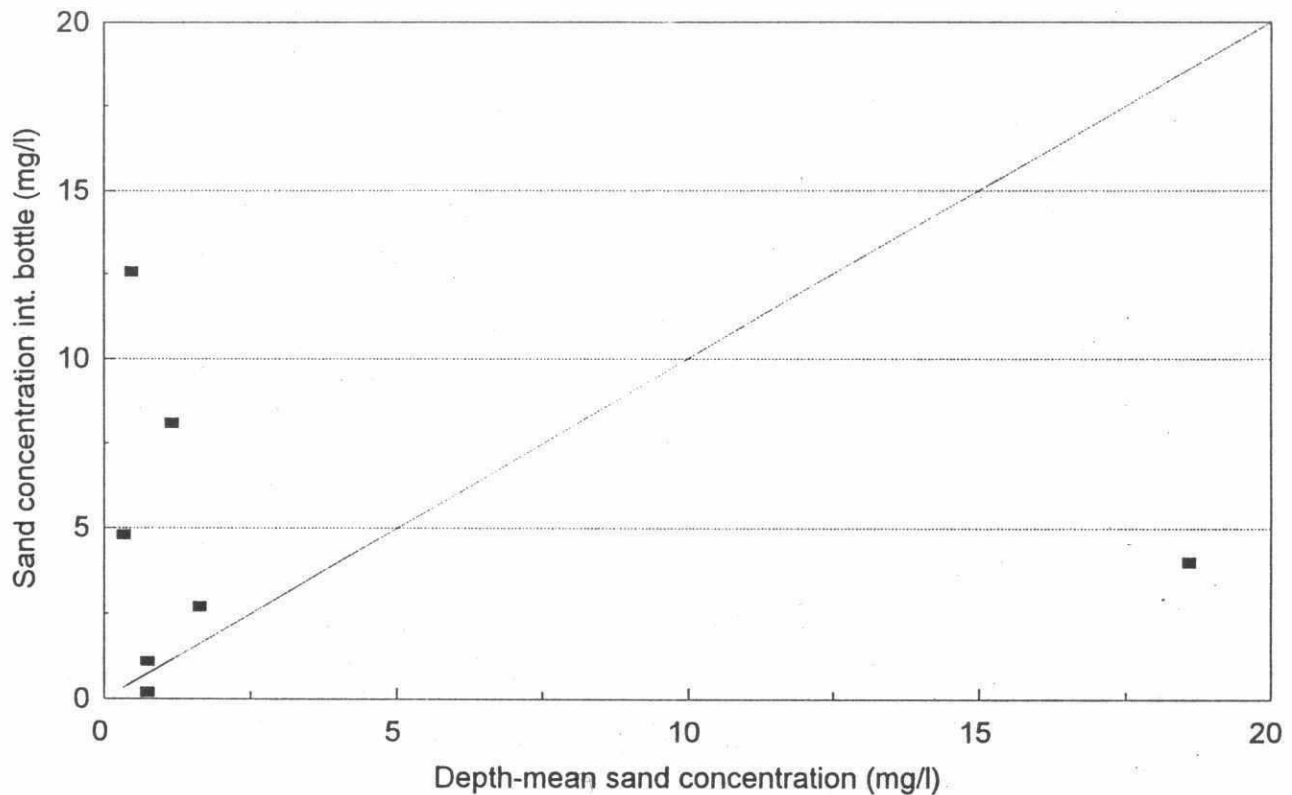


Figure 6.8 Comparison between suspended sand concentrations measured by pump-bottle and integrated-bottle at the reference verticals in the Jamuna River transect near Bahadurabad.

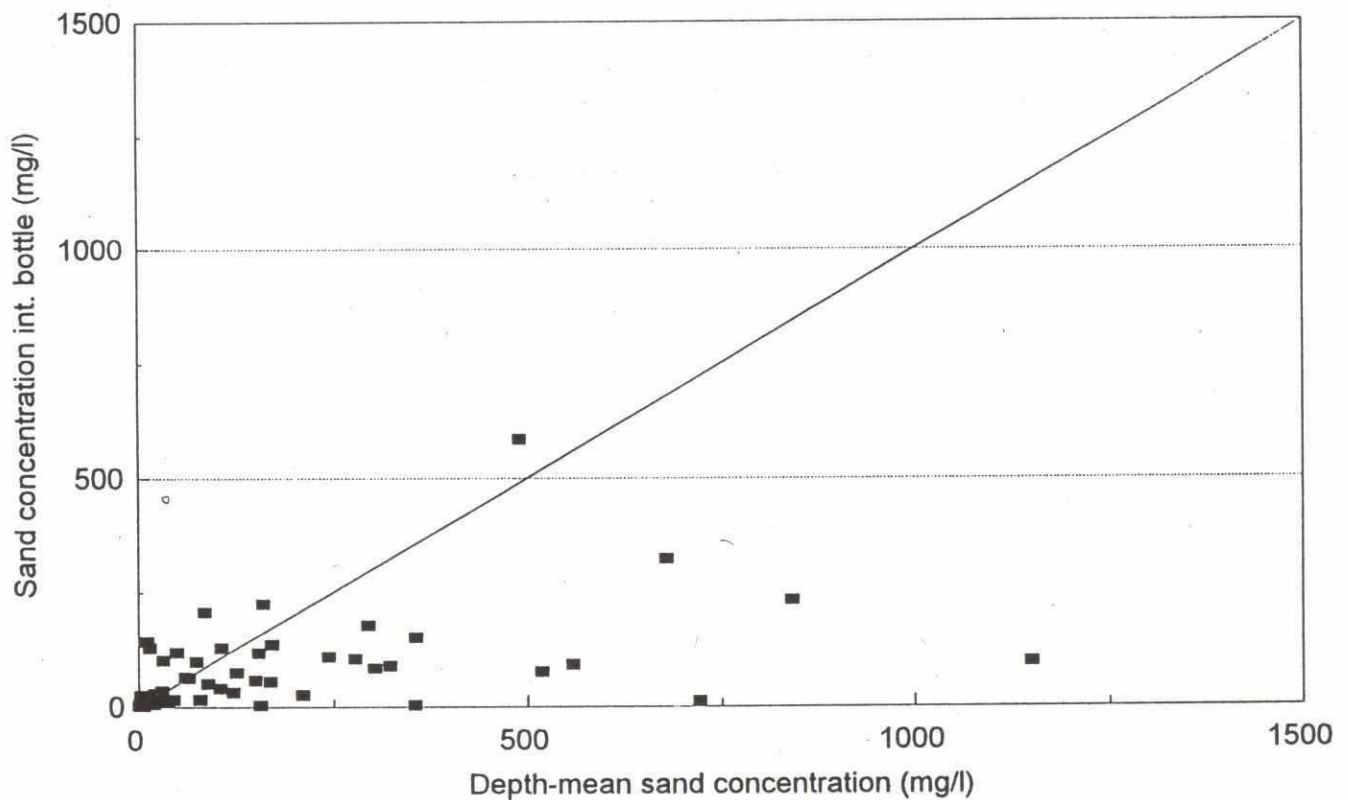


Figure 6.9 Comparison between suspended sand concentrations measured by pump-bottle and integrated-bottle at the reference verticals in the Ganges River transect near Hardinge Bridge.

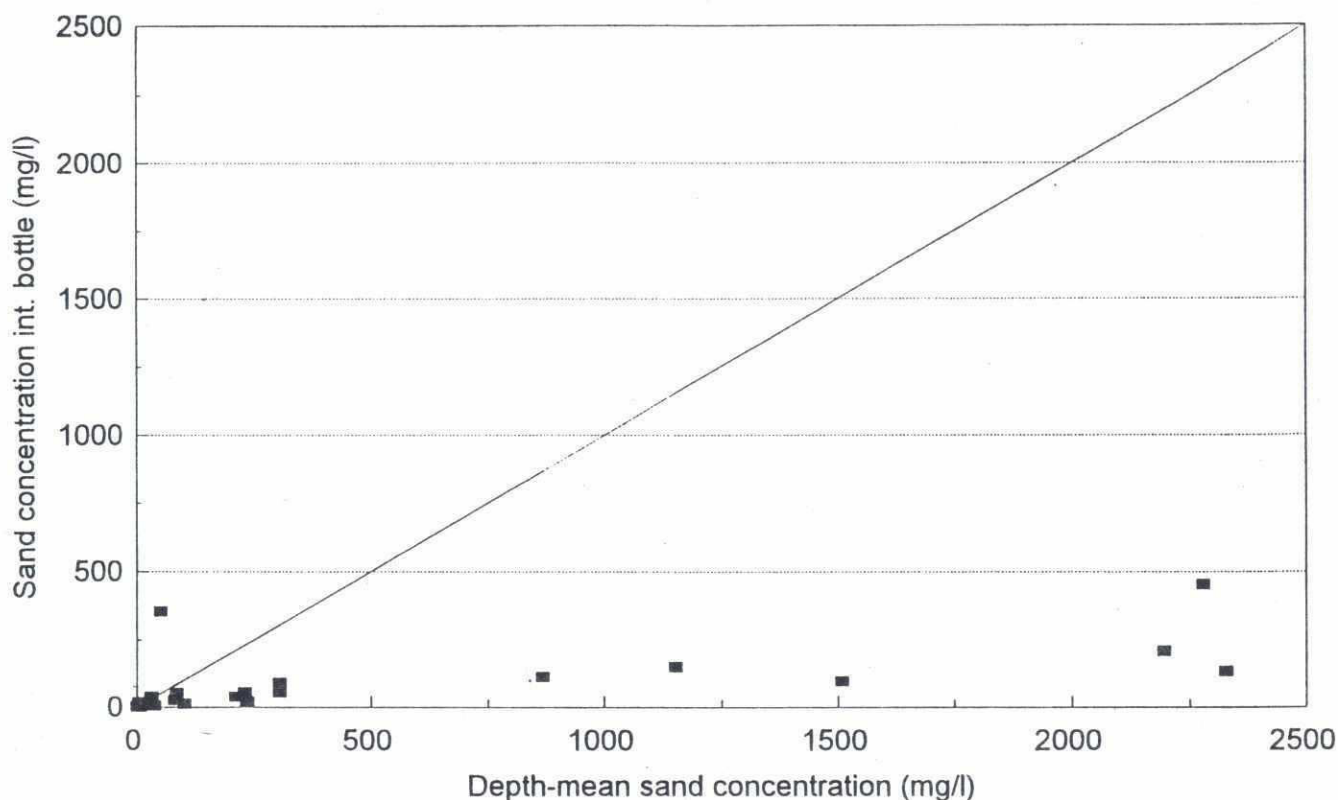


Figure 6.10 Comparison between suspended sand concentrations measured by pump-bottle and integrated-bottle at the reference verticals in the Padma River transect at Baruria.

To quantify the difference between the two methods in sand concentration measurements the following relation was used:

$$\delta_{av} = \frac{1}{N} \sum_{i=1}^n \left[\frac{d_i - p_i}{(d_i + p_i)/2} \right] \times 100$$

where,

δ_{av} = average difference in percentage between the two systems,

d_i = i th number of integrated bottle measurements,

p_i = i th number of depth-mean point-integrated measurements.

The results show the following,

At Bahadurabad, $\delta_{av} = -23\%$, the pump-bottle depth-mean sand concentration was 23% higher than the integrated bottle.

At Baruria, $\delta_{av} = -33\%$, the pump-bottle depth-mean sand concentration was 33% higher than the integrated bottle.

At Hardinge Bridge, $\delta_{av} = 22\%$, the pump-bottle depth-mean sand concentration was 22% lower than the integrated bottle.

It is evident that the Hardinge Bridge measurements behaved differently than the measurements at the other two stations. The reason can be attributed to different rivers and sediments, different survey teams, the use of a different vessel and/or different instruments at Hardinge Bridge. The above results need to be considered with some reservations as the depth-integrated bottle was often used beyond its range (in far too deep waters, see for instance, Figs. 6.2 to 6.4).

-Pump-bottle vs Collapsible-Bag

Similar comparisons were made between the pump-bottle and the collapsible-bag sampler. Eighteen coinciding measurements between the two systems are shown in Figures 6.11 and 6.12. Data were taken from the reference verticals of different transects in the Jamuna River. As with earlier observations, the agreement between the systems for silt fractions was reasonable (Figure 6.11). For sand fractions, however, the differences between the two systems were appreciable (Figure 6.12). On average, collapsible-bag sand concentration was 48.7% lower than the pump-bottle sand concentration. This observation was similar to what was observed between the pump-bottle and the integrated bottle at Bahadurabad and Baruria, though the difference was larger in this case.

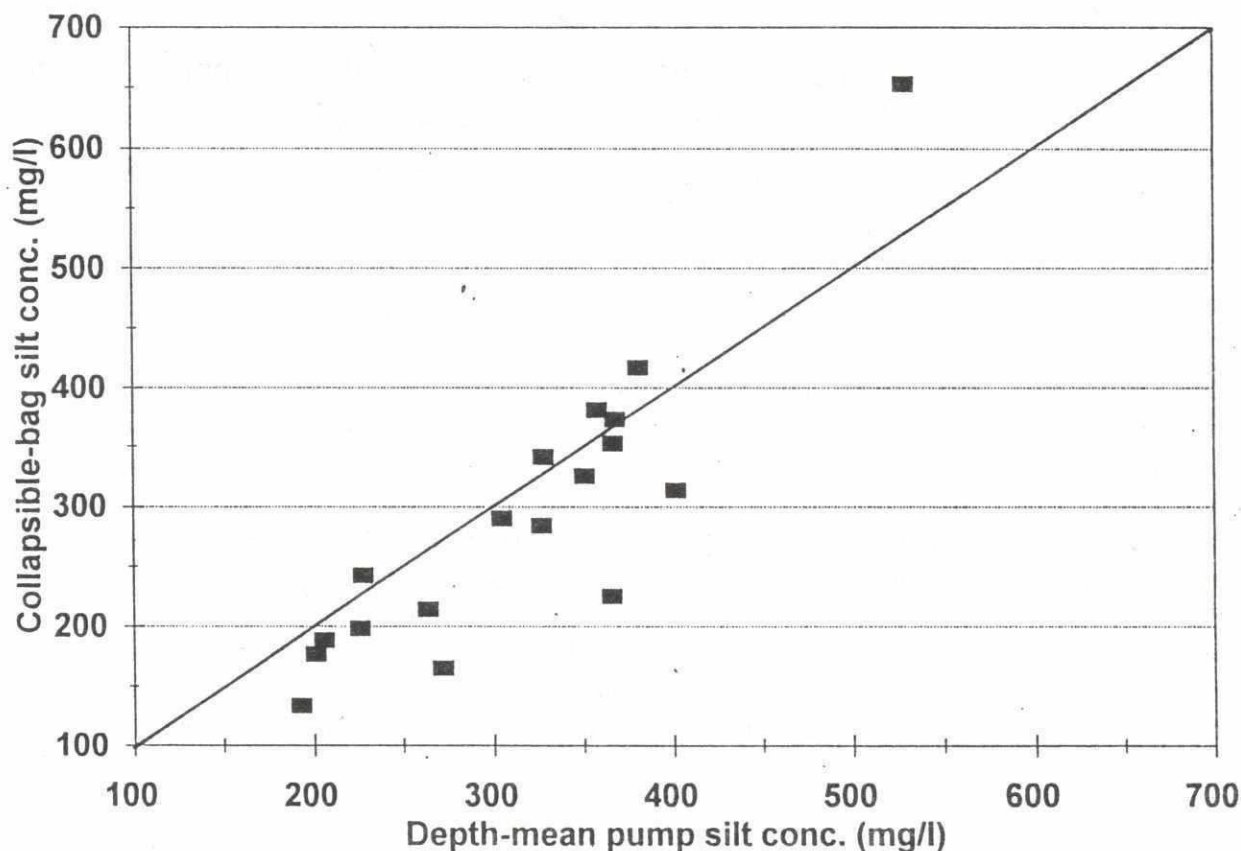


Figure 6.11 Comparison between suspended silt concentrations measured by pump-bottle and collapsible bag at the reference verticals in the Jamuna River transect near Bahadurabad.

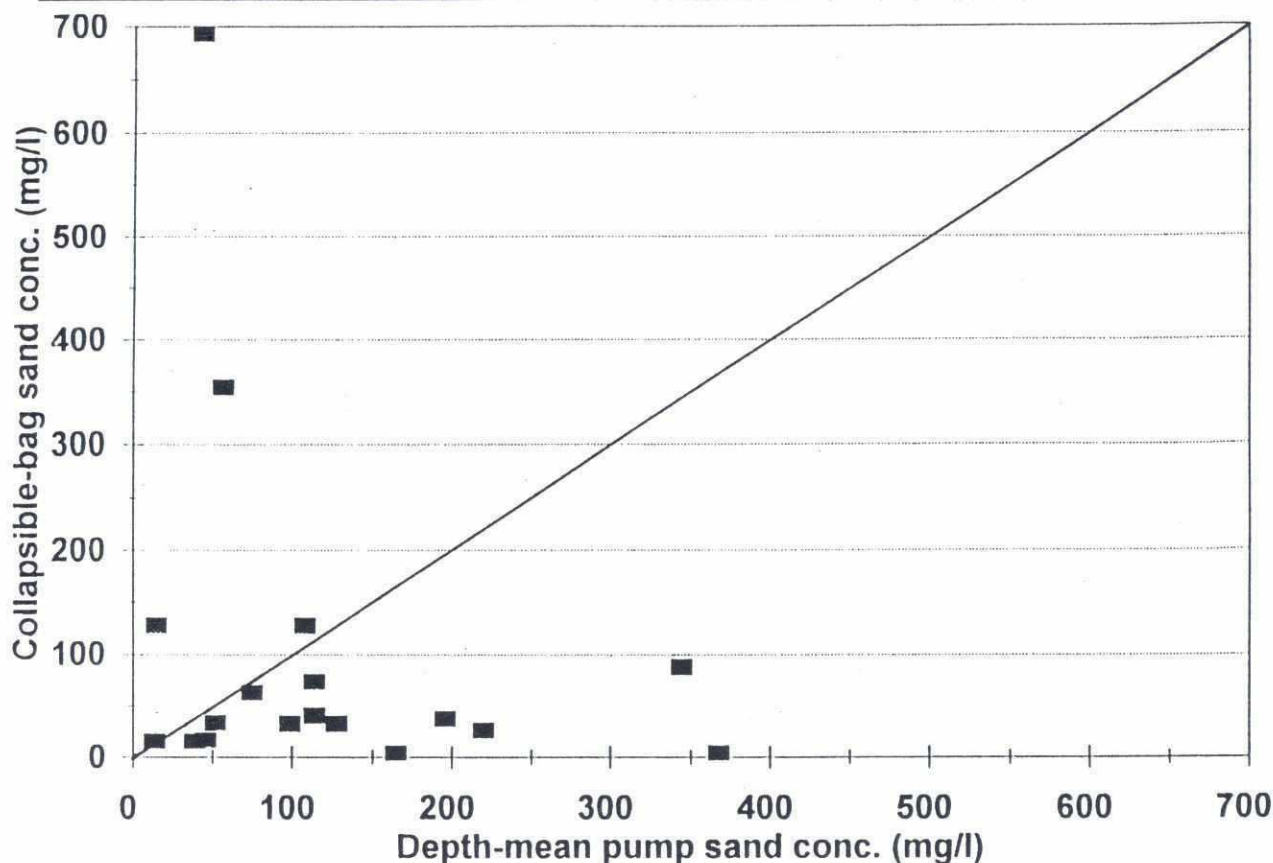


Figure 6.12 Comparison between suspended sand concentrations measured by pump-bottle and collapsible bag at the reference verticals in the Jamuna River transect near Bahadurabad.

-Pump-bottle vs ADCP Backscatter Intensity

In reference verticals of different routine transects, pump-bottle concentration data are available against the 300 kHz ADCP backscatter intensity (dB). The information from 254 data sets from different rivers are assembled in Figure 6.13 to show the relation between the two. Sand and silt fraction relations are shown separately. A wide scatter can be observed and the behaviour of sand fraction is no better than silt fraction. This suggests that sediment from different rivers and different size fractions can not be processed together which is in line with observations in the late 60's and early 70's when the influence of grain size distribution on the backscatter was known already. Further refinements were made at one location, notably Bahadurabad. There, still a wide scatter in the silt fractions were observed. However, reasonable agreements between the two ways of measuring techniques were observed in the sand fraction. Various regression relations for the two techniques were tested, following amongst others, the theoretical approach proposed by Thorne et al (1991) and Weierganag (1995). A regression relation of the following shape yielded acceptable results (Fig. 6.14):

$$\text{dB} = 68 + 0.77 \sqrt{C} \quad (R^2 = 0.79)$$

Another relation reads (Figure 6.15)

$$\text{dB} = 58 + 9.6 \log C \quad (R^2 = 0.8)$$

Where

dB = ADCP backscatter intensity in decibels

C = Pump-bottle concentration of coarse sediments in mg/l.

Details of the derivation are presented in Annexure D.

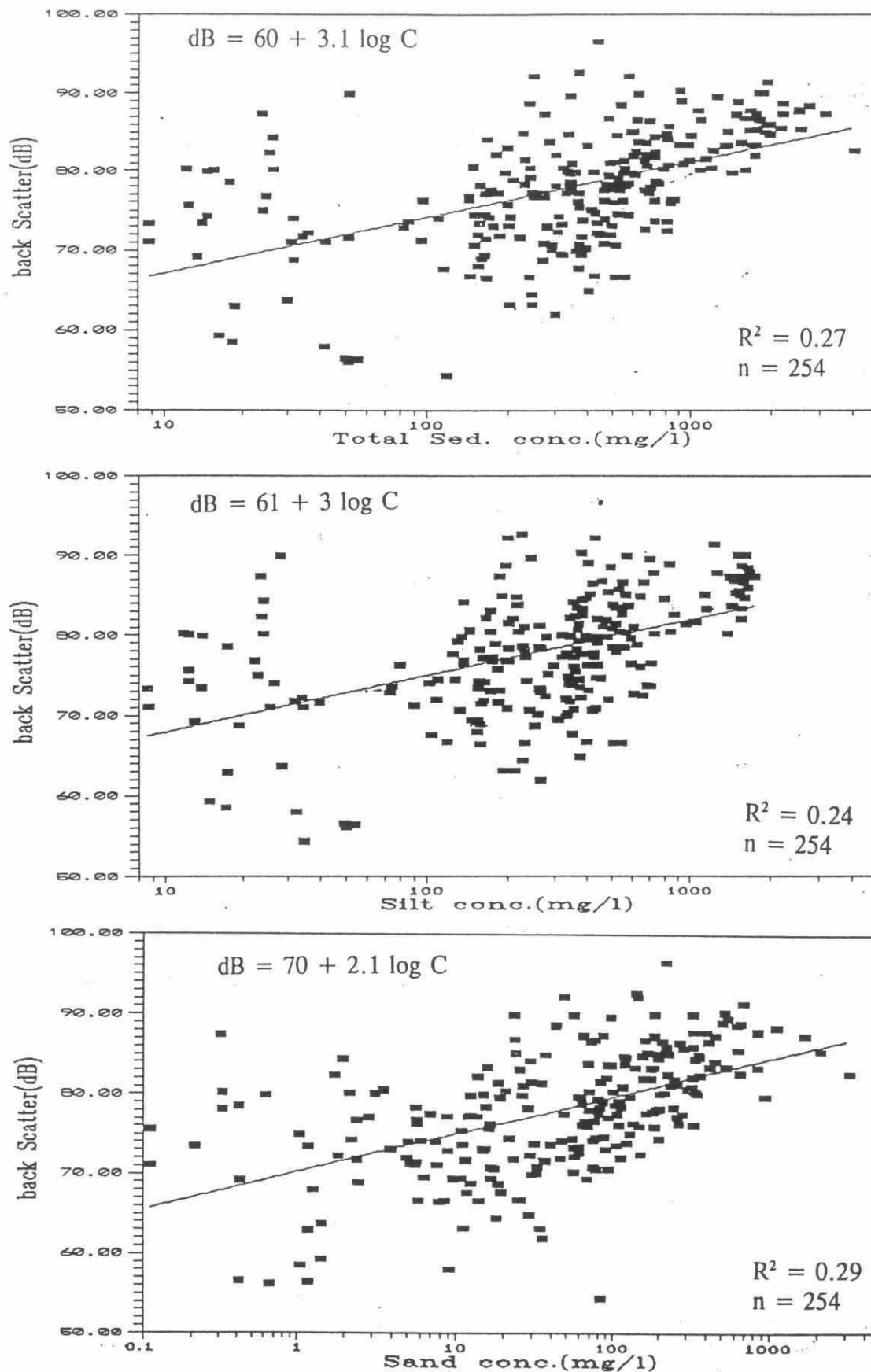


Figure 6.13 Scatter plot of 300 kHz ADCP backscatter and point-integrated pump-bottle concentrations (Total, Silt and Sand) with data from routine measurements in the Jamuna, Ganges, and Padma Rivers.

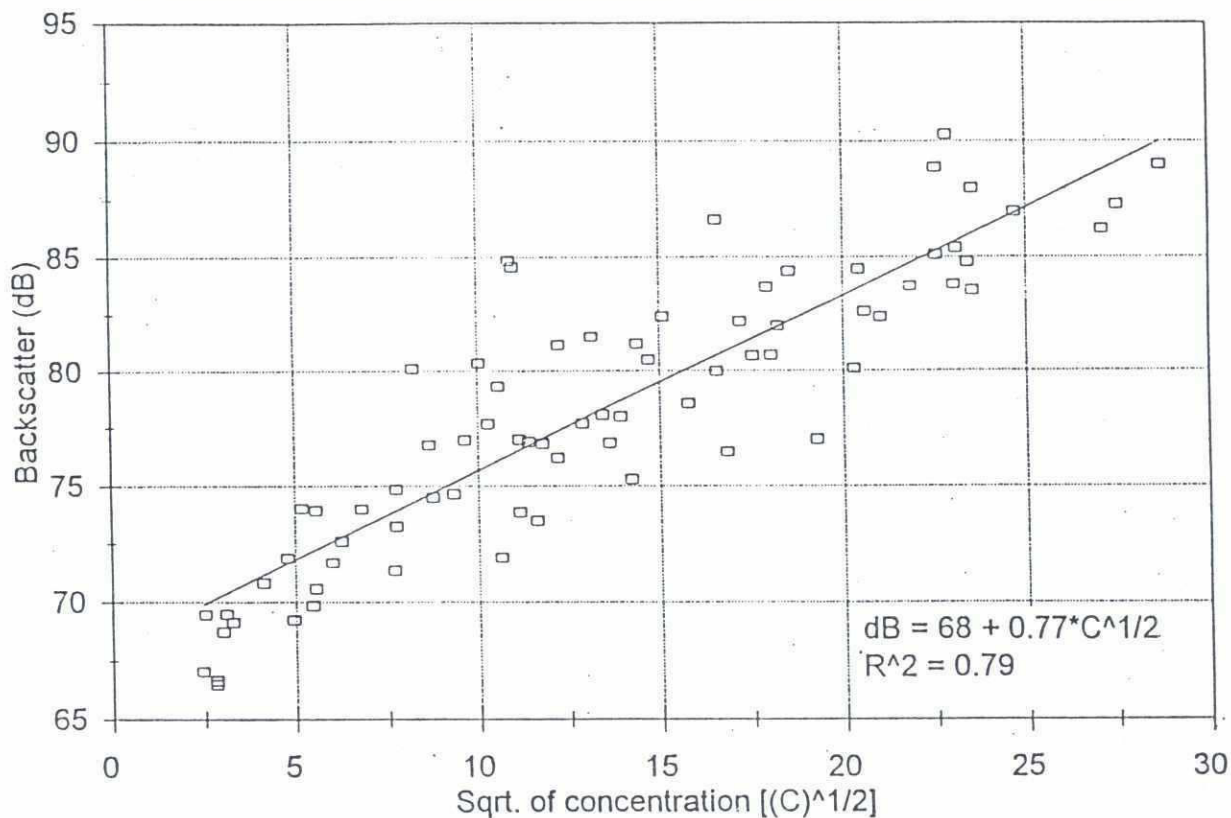


Figure 6.14 Correlation between 300 kHz ADCP backscatter and suspended sand concentration ($\sqrt{C}$) measured by pump-bottle in the Jamuna River near Bahadurabad.

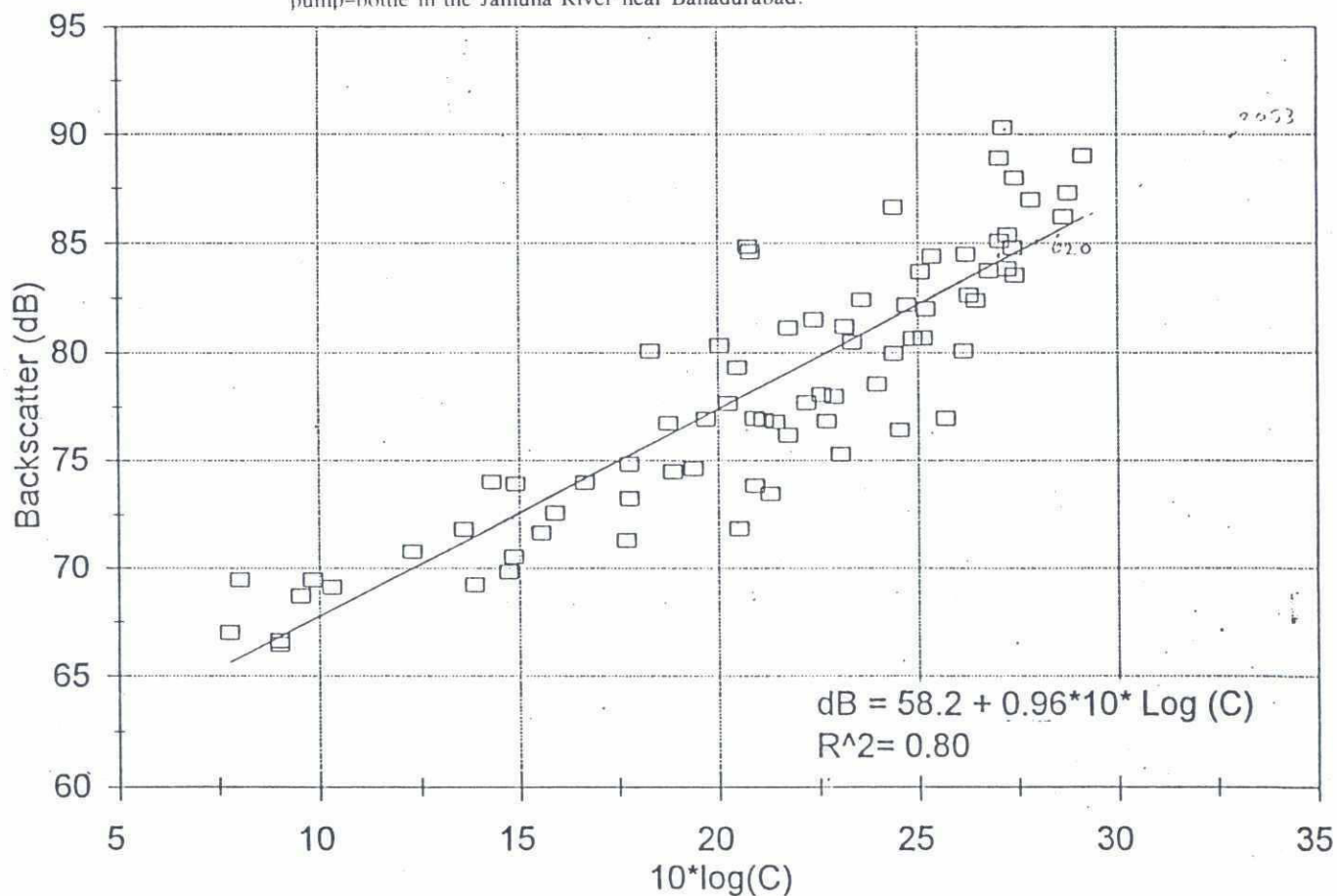


Figure 6.15 Correlation between 300 kHz ADCP backscatter and suspended sand concentration ($10 \log C$) measured by pump-bottle in the Jamuna River near Bahadurabad.

6.1.2 Results from Some Special Measurements

- Instruments**

During the special measurements suspended load was measured by the RSP with:

- i) depth-integrated sampler (collapsible bag)
- ii) point-integrated sampler (pump-bottle system)
- iii) ADCP
- iv) MEX optical turbidity meter
- v) Delft Bottle

During the joint measurements with the BWDB, also their instrument was applied:

- vi) Binckley silt sampler

- Special surveys**

Particulars of special surveys used for this section are presented in the following Table.

Serial Number	Survey Period	Type of survey	Remarks	Flow range (m/s)
1	28-29 May 1994	Study surveys	First tests with DB	1-1.3
2	1-4 August 1994		Near-bed measurements mainly	1.5-2.0
3 *	4-12 December 1994		combined study survey	0.1-1.1
4	1-4 April 1995		pb-DB-MEX	0.7-0.9
5	23-26 May 1995		Plume Surveys	1.5-2.5
6	26-30 July 1995		Density of points	1.8-2.8
7	19-20 July 1995	Joint Measurements	Together with BWDB	-

Table 6.1: Special suspended sediment surveys made in Phase II

- Experience with Instruments**

The experience gained during the routine measurements were confirmed by the special measurements. A few additional aspects were:

- The umbilical of the pump-bottle system was slowly flattening during the project period and it was decided to replace them by another type with more internal strength. The flattening is

- caused by the heavy load of the pump intake carrier. The new umbilicals, with the same outer diameter, behaved well during phase II.
- The umbilical is causing a lot of drag in the high flows. The hydraulic resistance of the umbilical is much higher than the resistance of the carrier. Tests to try to reduce the umbilical diameter were not successful. By the end of the project, a good combination of the inner tube and the pump were found to reduce the outer diameter of 32 mm with about 20%.
 - The collapsible bag version with a bag under the sinker weight was functioning well but also with this version some instabilities occurred.
 - The calibration of the MEX against the pump-bottle showed that with higher flows and more sediments more scatter was found.
 - The Delft Bottle can be used to measure the suspended sand load, both in depth-integrating and point-integrating modes. Good results were obtained.

Accuracies of Certain Instruments

Acceptable accuracies from different instruments are fundamental for making an accurate estimate of sediment transport. However, the accuracy of the instruments is only a part of the overall accuracy of the measurements (including data processing) as elaborated in section 7.1. Only in case of laboratory controlled conditions the accuracy of the instrument may be determined. In the absence of a laboratory, the natural river flow was sampled thus including the unknown natural stochastic processes in the measuring results. The sampling was made by using different instruments at a certain interval at a certain depth. The samples are supposed to be stochastically independent. Assuming that a stochastic model is applicable (see further section 7.1), the accuracies can be expressed by the standard deviations. The differences between the standard deviations are considered to be caused by the survey techniques. Therefore, for some instruments, viz. the Binckley silt sampler, the pump-bottle system and the collapsible bag sampler the results were analysed first per instruments whereafter the differences are discussed.

-Binckley Instantaneous Silt Sampler

A joint measurement was made on 19 July 1995 in the Jamuna River near Bahadurabad. 20 samples were taken at every 3 minutes using the BWDB Binckley sampler at a 60% water depth. These samples were analyzed for sand and silt fractions to determine the relative standard deviation. The results are shown in Figures 6.16 to 6.18. Figure 6.16 shows the relative deviation of silt (and clay) and sand fractions. The relative deviation representing a first moment about the mean is given as,

$$RD_i = \frac{x_i - \langle x \rangle}{\langle x \rangle} \times 100$$

where,

RD_i = relative deviation of the i th sample,

x_i = concentration of the i th sample,

$\langle x \rangle$ = time-mean concentration.



**Binckley, 19 July 1995
at 60% d, Jamuna near Baha**

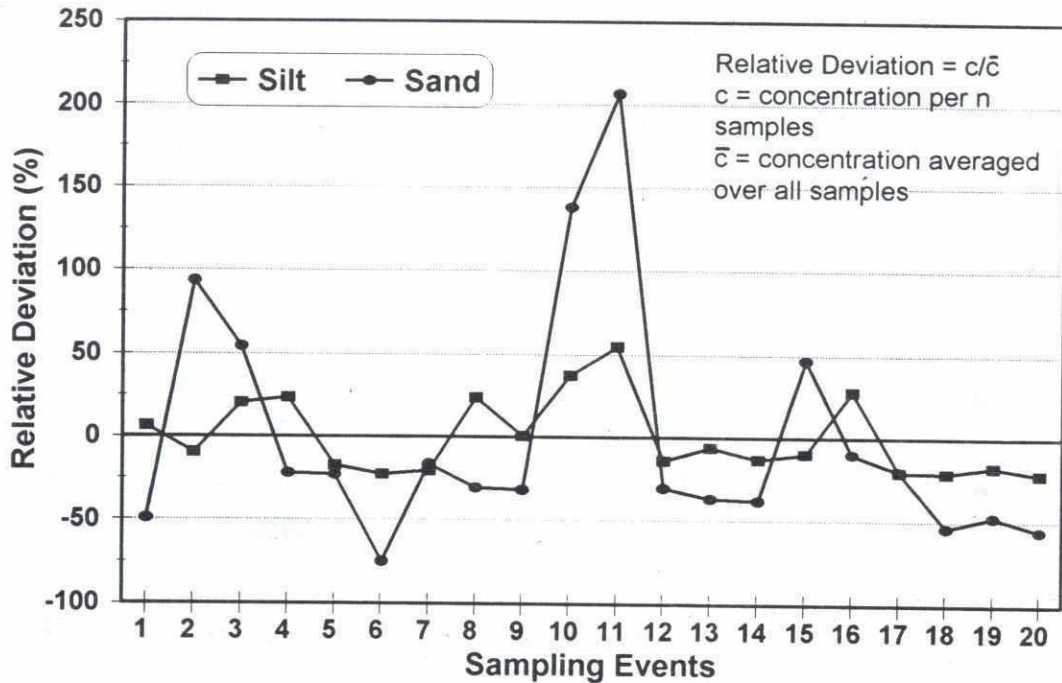


Figure 6.16 Relative deviation of 20 time-series suspended sediment samples in silt and sand fractions taken at 60% water depth by Binckley sampler on board BWDB Catamaran every 3 minutes in the Jamuna River near Bahadurabad on 19 July 1995.

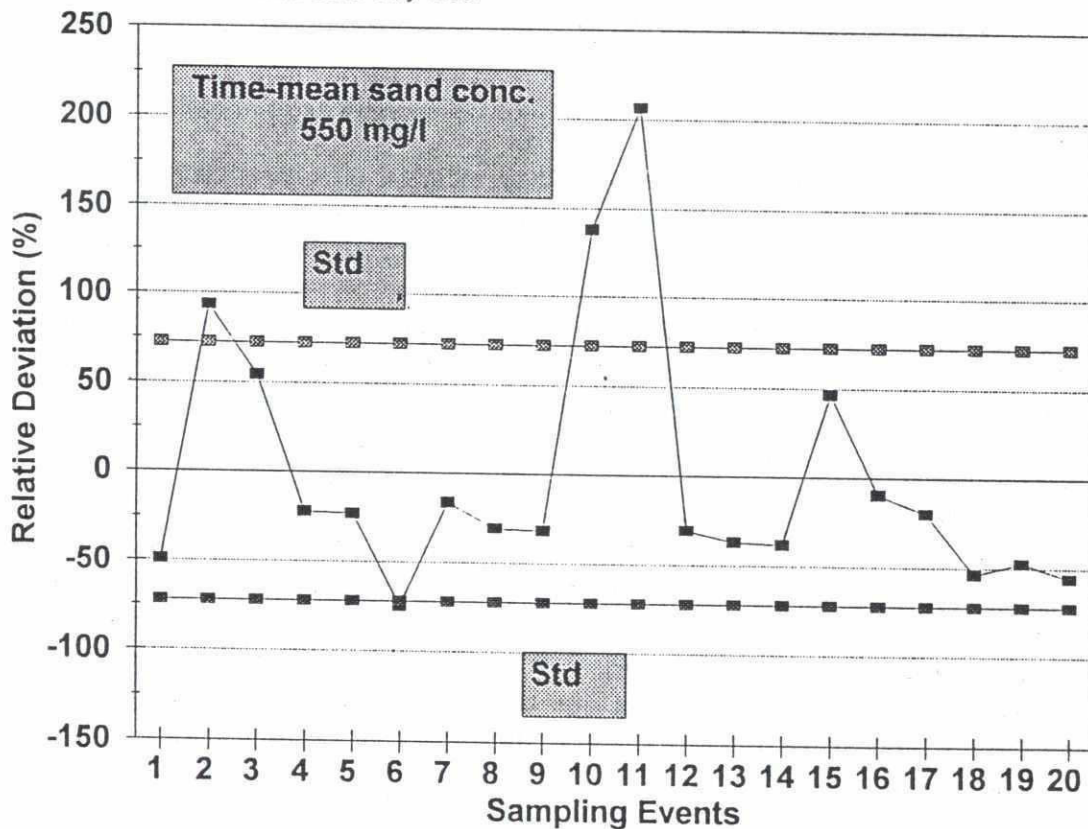


Figure 6.17 Relative deviation of 20 time-series suspended sediment samples in sand fraction taken at 60% water depth by Binckley sampler on board BWDB Catamaran every 3 minutes in the Jamuna River near Bahadurabad on 19 July 1995.

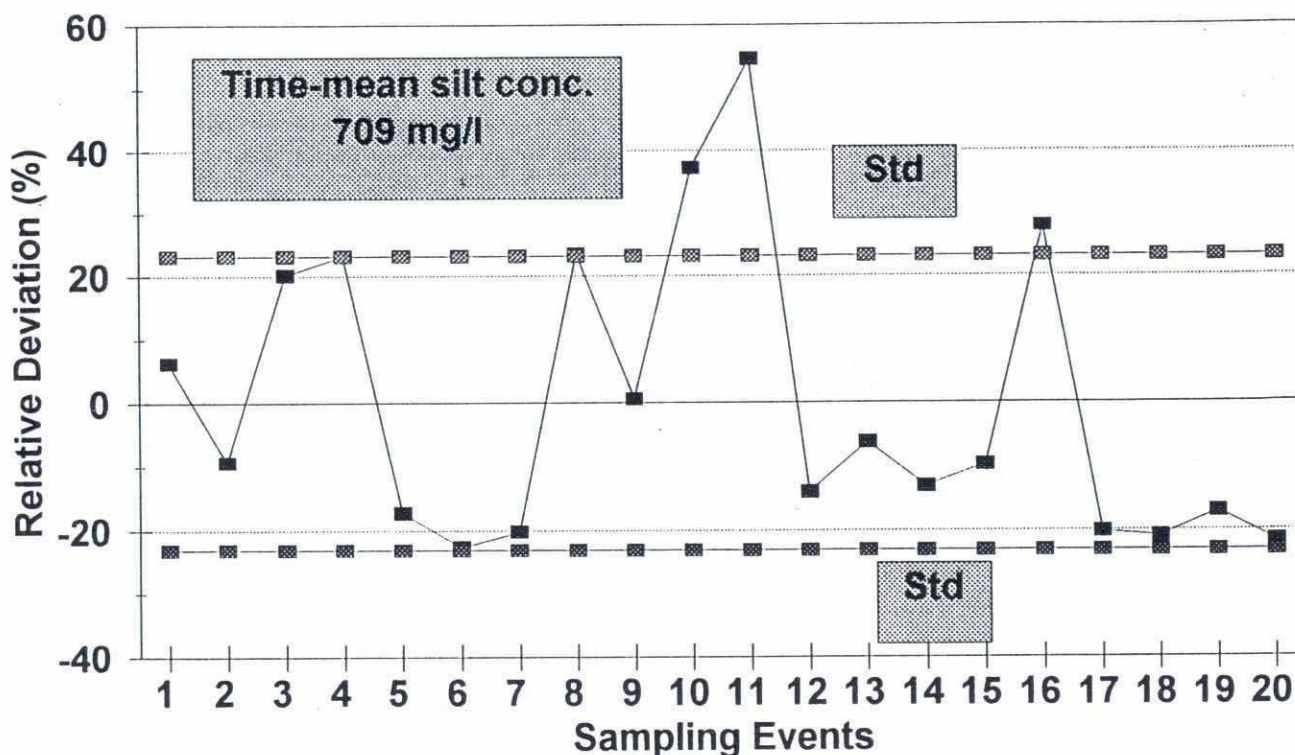


Figure 6.18 Relative deviation of 20 time-series suspended sediment samples in silt fraction taken at 60% water depth by Binckley sampler on board BWDB Catamaran every 3 minutes in the Jamuna River near Bahadurabad on 19 July 1995.

The time-mean concentrations for silt and sand fractions were 709 mg/l and 550 mg/l respectively. As can be expected, the relative deviation for silt fraction was less than that for sand fraction. Figure 6.17 shows the relative deviation and standard deviation (at 67% confidence level) for the sand fraction. The relative standard deviation represents a second moment about the mean. The standard deviation was found to be about $\pm 72\%$. Figure 6.18 shows that the standard deviation for silt fraction was $\pm 23\%$. These analyses show that to attain an uncertainty level of $\pm 20\%$ in the sand fraction, at least 13 or more samples should be taken by the Binckley silt sampler.

-Pump-Bottle Sampler

On 20 July 1995, a pump sampling exercise was made in the Jamuna River near Bahadurabad. 21 samples were taken every 3 minutes at 60% water depth using an integration time of 100 s. The pump-bottle samples were analyzed similar to the Binckley sampler; the results are shown in Figures 6.19 to 6.21. In Figure 6.19, the relative deviations of the silt and sand fractions are shown. Figure 6.20 shows that a relative standard deviation of $\pm 14\%$ can be made for the sand fraction. Figure 6.21 shows that this error was reduced to $\pm 4\%$ for the silt fraction. In terms of relative deviations and standard deviations, the performance of the pump sampler was better than the Binckley silt sampler.

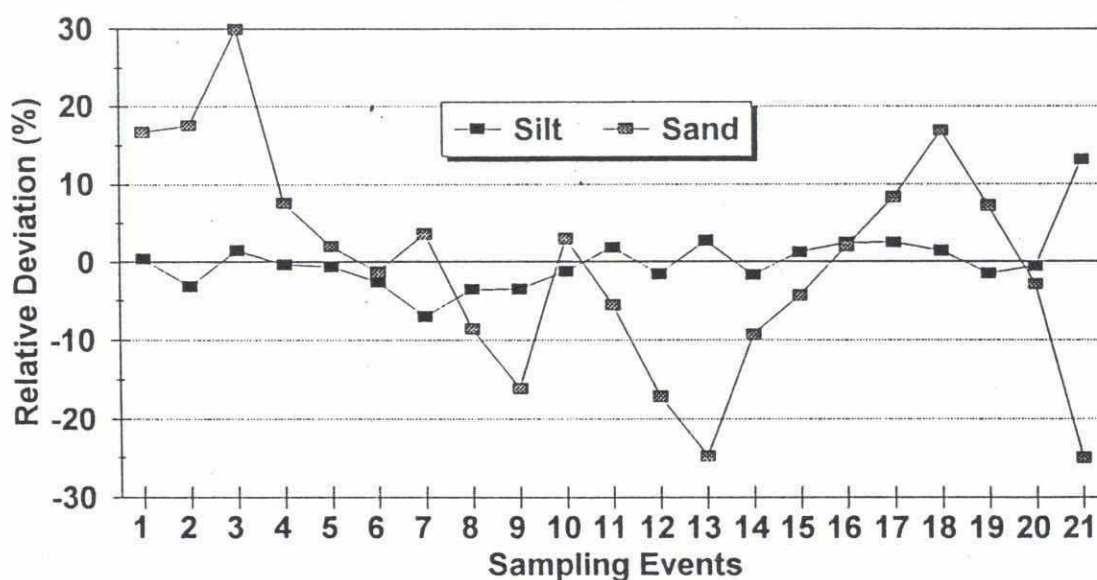


Figure 6.19 Relative deviation of 21 time-series suspended sediment samples in silt and sand fractions taken at 60% water depth by pump-bottle sampler on board DHA vessel every 3 minutes in the Jamuna River near Bahadurabad on 20 July 1995.

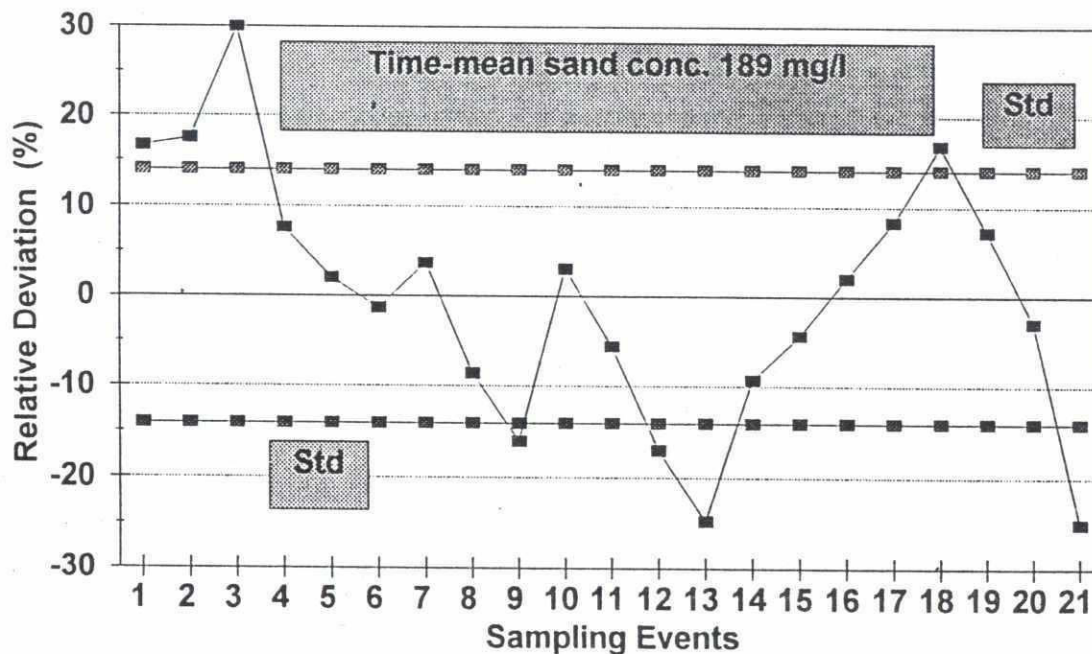


Figure 6.20 Relative deviation of 21 time-series suspended sediment samples in sand fraction taken at 60% water depth by pump-bottle sampler on board DHA vessel every 3 minutes in the Jamuna River near Bahadurabad on 20 July 1995.

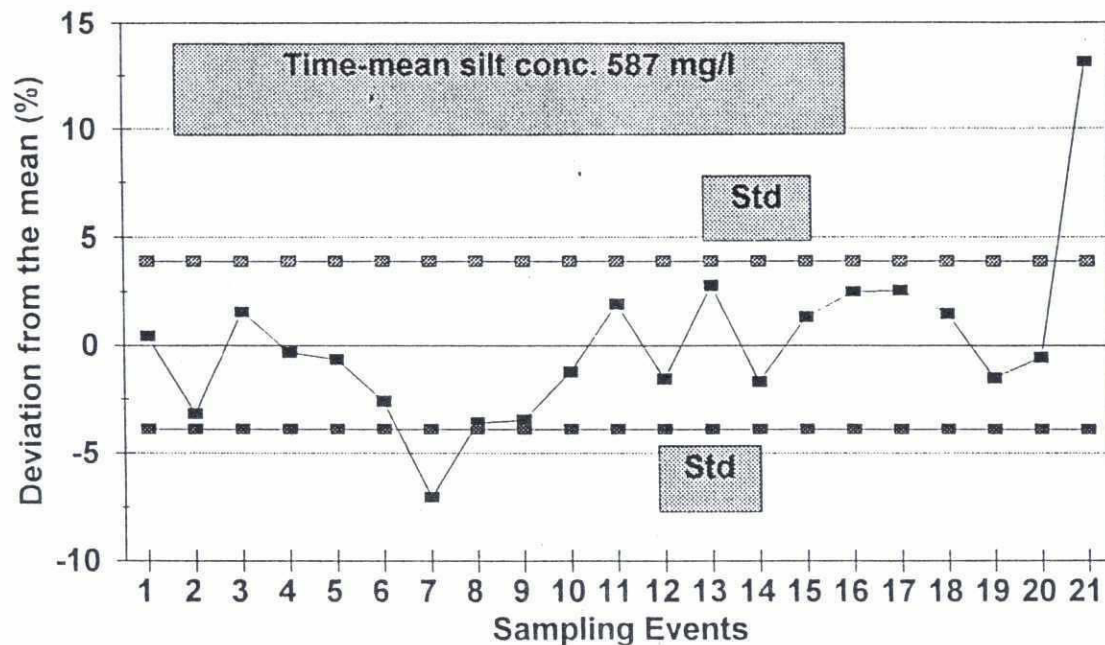


Figure 6.21 Relative deviation of 21 time-series suspended sediment samples in silt fraction taken at 60% water depth by pump-bottle sampler on board DHA vessel every 3 minutes in the Jamuna River near Bahadurabad on 20 July 1995.

-Collapsible-Bag Sampler

Figure 6.22 shows the relative standard deviation of 13 time-series samples collected by the collapsible bag sampler in the Jamuna River near Bahadurabad on 2 April 1995. These samples were not systematically collected like the pump and the Binckley sampler. Given this information, the relative standard deviation in this case was estimated at $\pm 19\%$. Figure 6.23 shows the influence of the hydraulic coefficient. Except in the first two samples, the hydraulic coefficients were low, and they were nearly uniform. Therefore, the influence of the hydraulic coefficients were negligible in these cases.

Collps-bag, 2 April 1995 Jamuna River at Baha

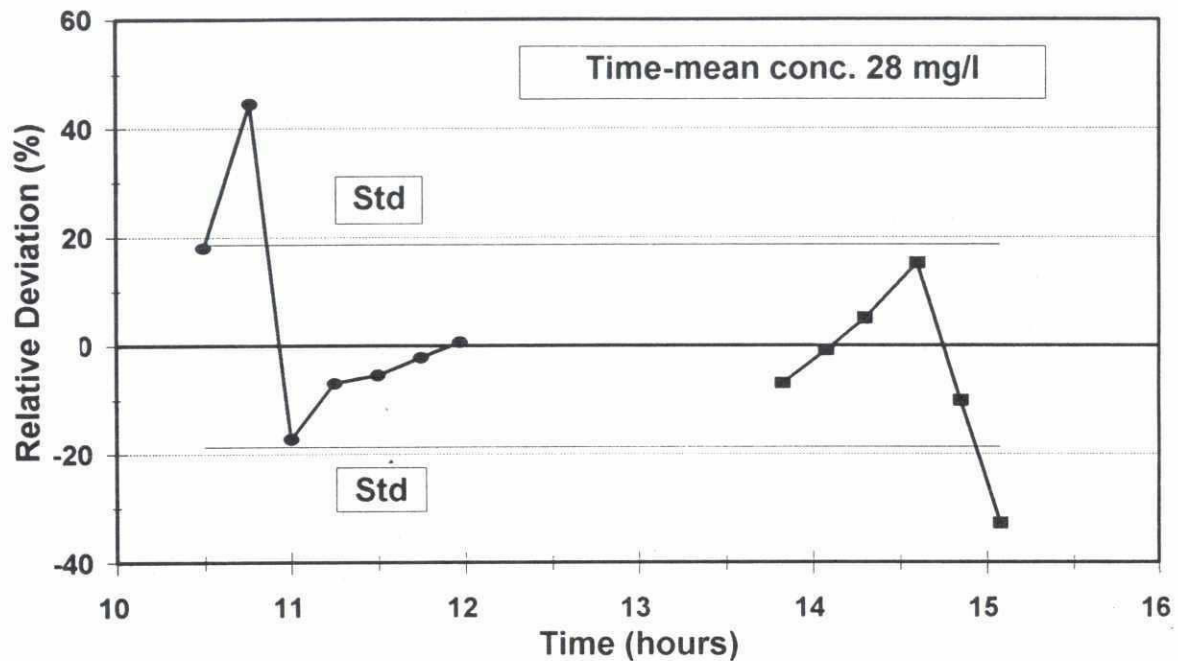


Figure 6.22 Relative deviation of 13 time-series suspended sediment samples in sand fraction taken at mid-depth by collapsible-bag sampler on board DHA vessel every 3 minutes in the Jamuna River near Bahadurabad on 2 April 1995.

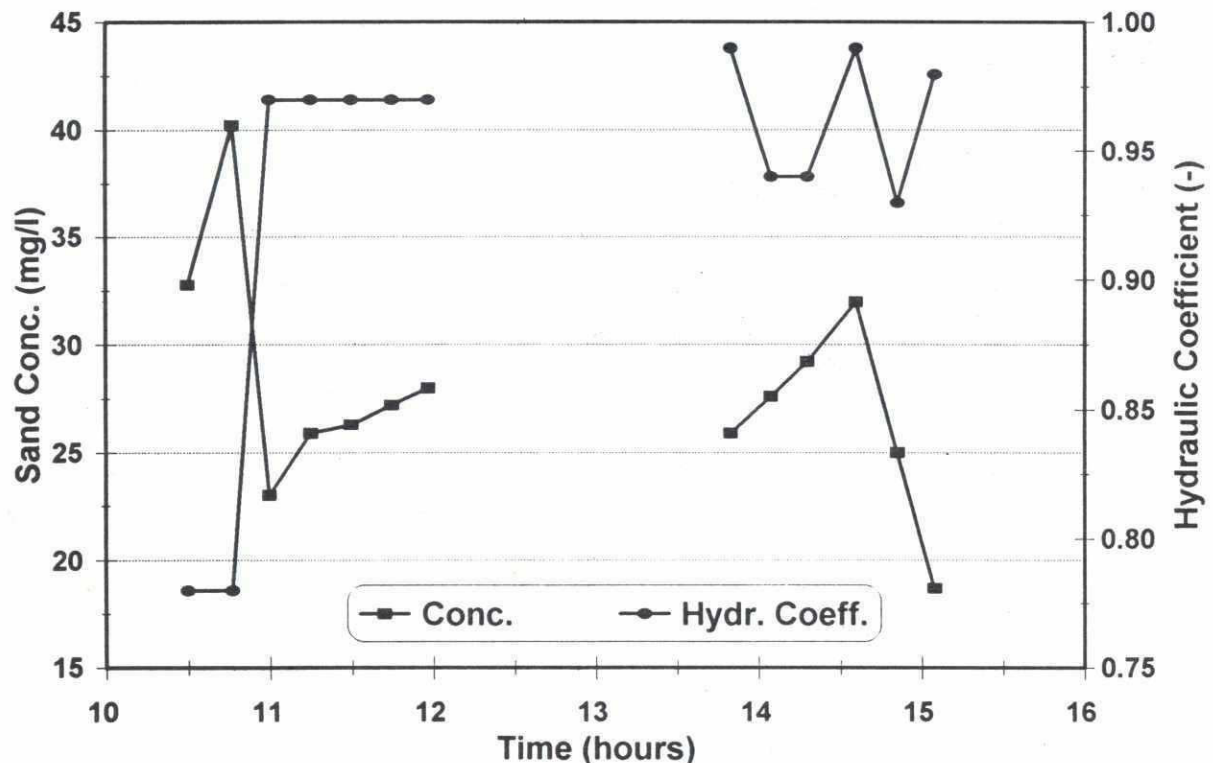


Figure 6.23 Suspended sand concentration and hydraulic coefficient of 13 time-series suspended sediment samples in sand fraction taken at mid-depth by collapsible-bag sampler on board DHA vessel every 3 minutes in the Jamuna River near Bahadurabad on 2 April 1995.

-Delft Bottle

Figure 6.24 shows the relative standard deviation for a set of 12 measurements taken by a big-size straight nozzle Delft Bottle on 2 April 1995 in the Jamuna River near Bahadurabad. The overall (instrumental and natural) variation was indicated by the relative standard deviation. The relative standard deviation in this case was $\pm 10\%$. The example shows that the performance of Delft Bottle is better than the other samplers.

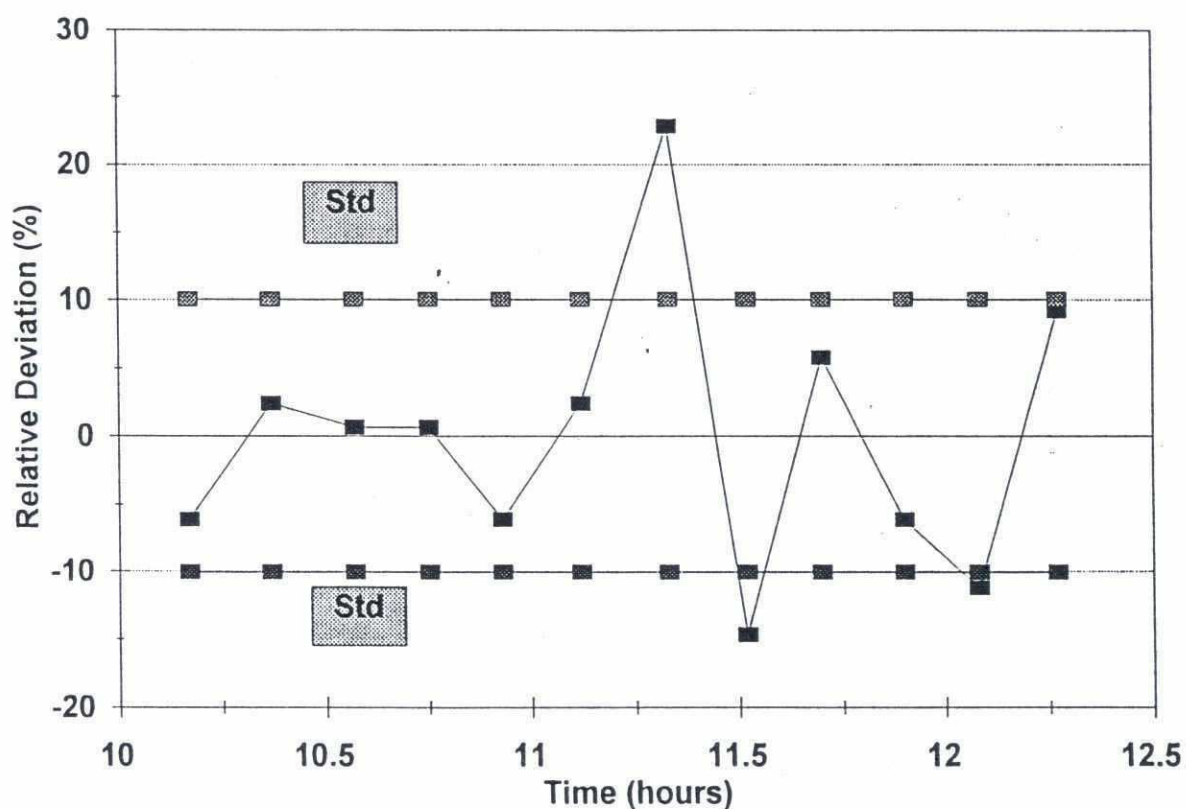


Figure 6.24 Relative standard deviation in suspended sand concentration of 12 time-series suspended sediment samples in sand fraction taken at mid-depth by Delft Bottle on board DHA vessel every 3 minutes in the Jamuna River near Bahadurabad on 2 April 1995.

•Inter-Comparison of Instruments

-Point-Integrated vs Delft Bottle

Figures 6.25 to 6.28 show the qualitative differences in sampling by a Delft Bottle and a pump-bottle. The results are based on measurements in the Jamuna River near Bahadurabad in August 1994. Delft Bottle measurements were taken at 0.35 m on a sleigh and pump-bottle measurements were taken at 0.5 m above the bed to compare the different sized fractions. The samples were collected at nearly the same time. The local transports at 0.5-1.0 mm, 0.25-0.5 mm, 0.125-0.25 mm, 0.063-0.125 mm, and < 0.063 mm size fractions were compared. Theoretically, a positive gradient towards the bed should be present for all size fractions if they are sampled correctly. Figure 6.25 shows that a positive gradient was indeed present for fraction sizes between 0.125-1.0 mm. Such gradients were absent for finer fractions; this indicates that these sizes were not correctly represented by the Delft Bottle. However, Figures 6.26 to 6.28 show that the Delft Bottle probably represented some finer particles, up to 0.063-0.125 mm. Figure 6.25 shows that the 0.063-0.125 mm sized particles were also affected. In all the cases, the dominant transport occurred in particles sized 0.125-0.25 mm. Figure 6.25 shows a higher transport situation than the others. It seems logical to conclude that in low transport rates, fractions of all sizes, except particles < 0.063 mm, were represented in the Delft Bottle. In high transport rates, however, the particles < 0.125 mm were also affected.

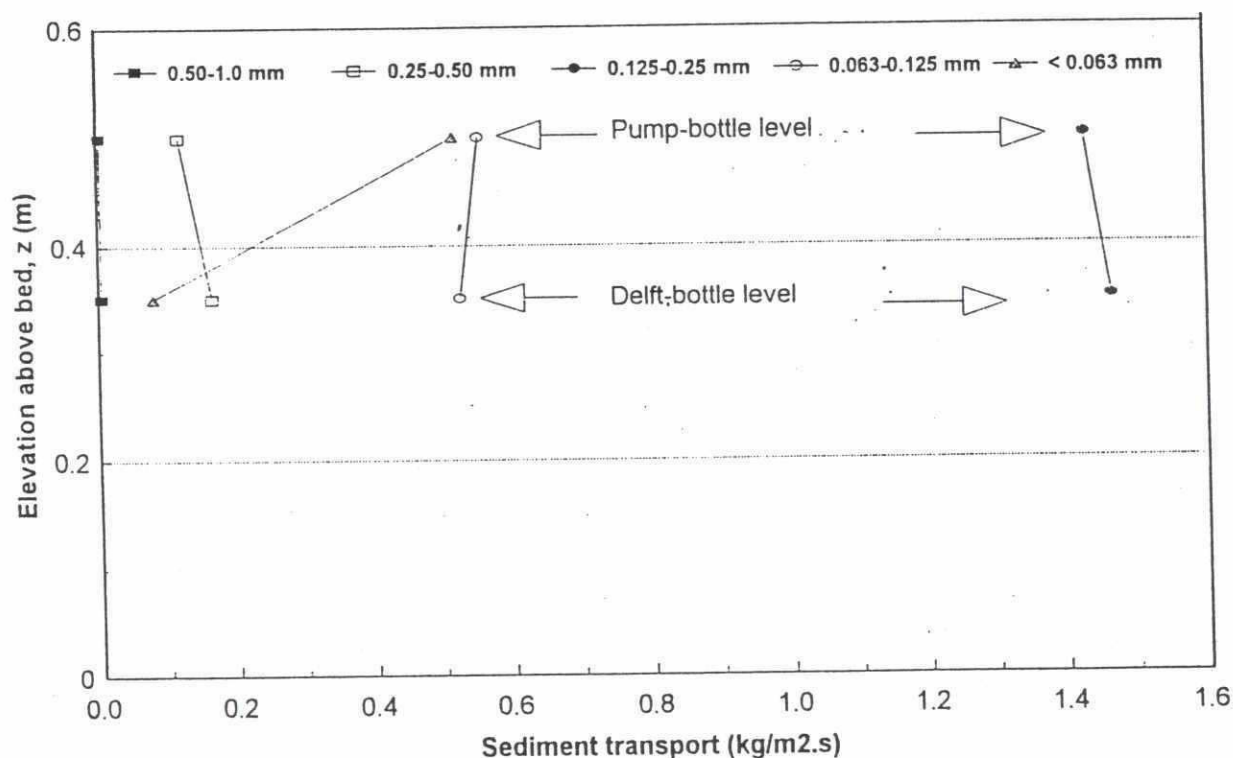


Figure 6.25 Comparison of local suspended sediment transport in various size fractions between the pump-bottle measured at 0.5 above bed and Delft Bottle measured at 0.35 m above bed based on measurements on 4 August 1994 at a dune crest in the Jamuna River left channel near Bahadurabad.

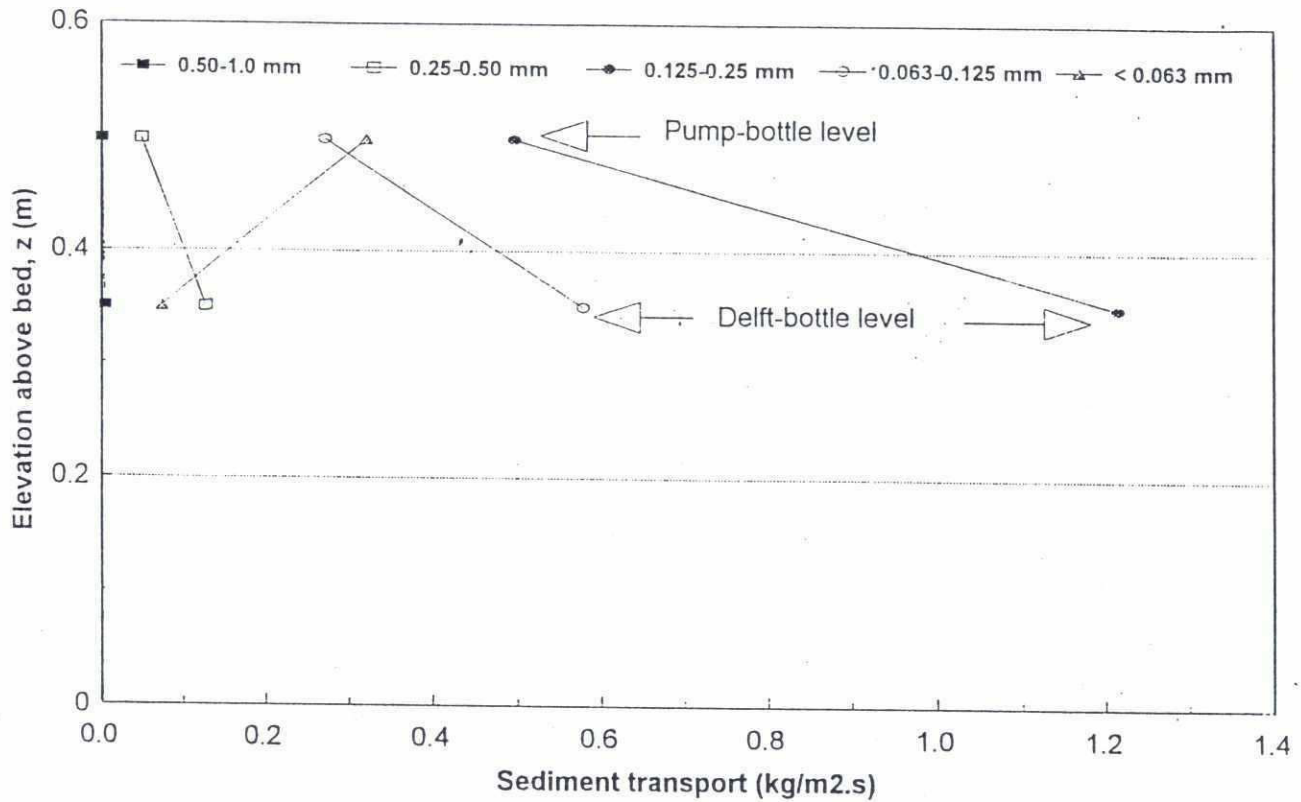


Figure 6.26 Comparison of local suspended sediment transport in various sizes of fractions between the pump-bottle measured at 0.5 above bed and Delft Bottle measured at 0.35 m above bed based on measurements on 3 August 1994 at a dune stoss-side in the Jamuna River left channel near Bahadurabad.

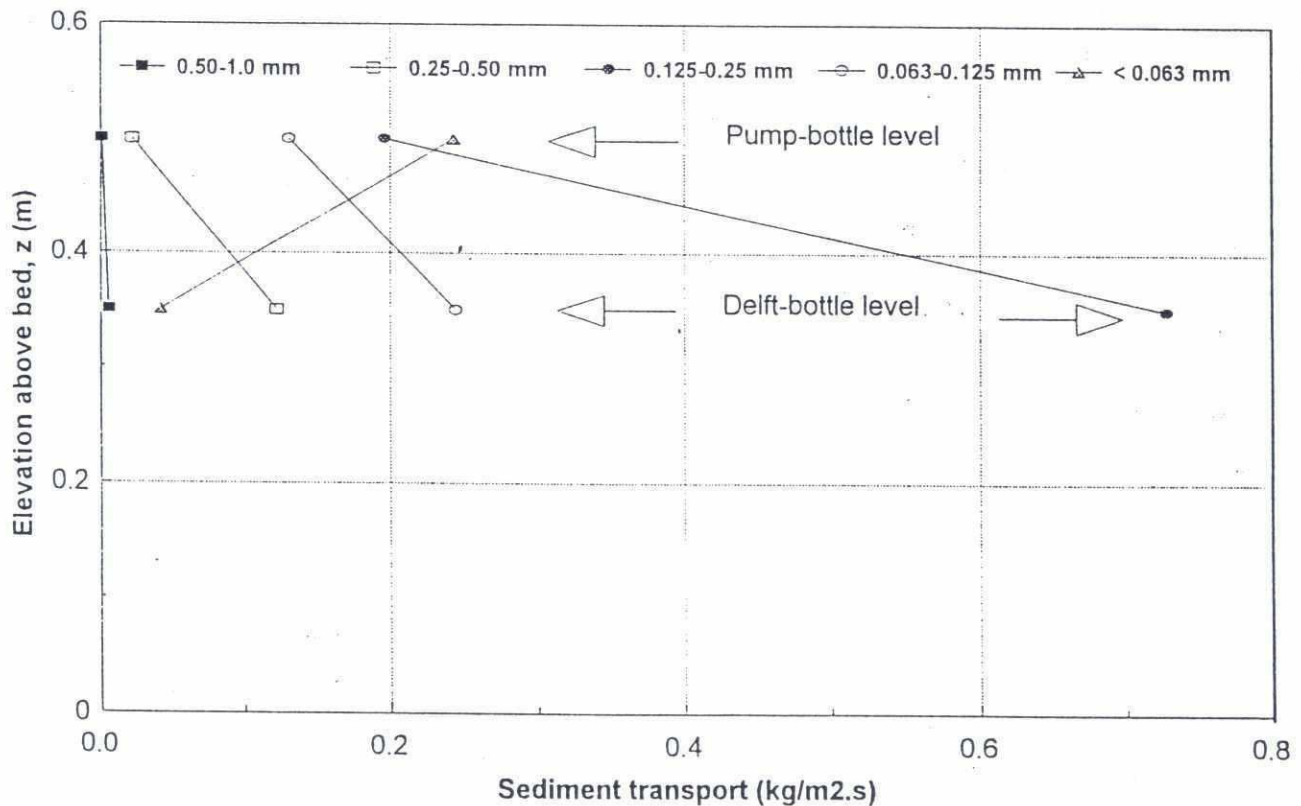


Figure 6.27 Comparison of local suspended sediment transport in various sizes of fractions between the pump-bottle measured at 0.5 above bed and Delft Bottle measured at 0.35 m above bed based on measurements on 3 August 1994 at a dune trough in the Jamuna River left channel near Bahadurabad.

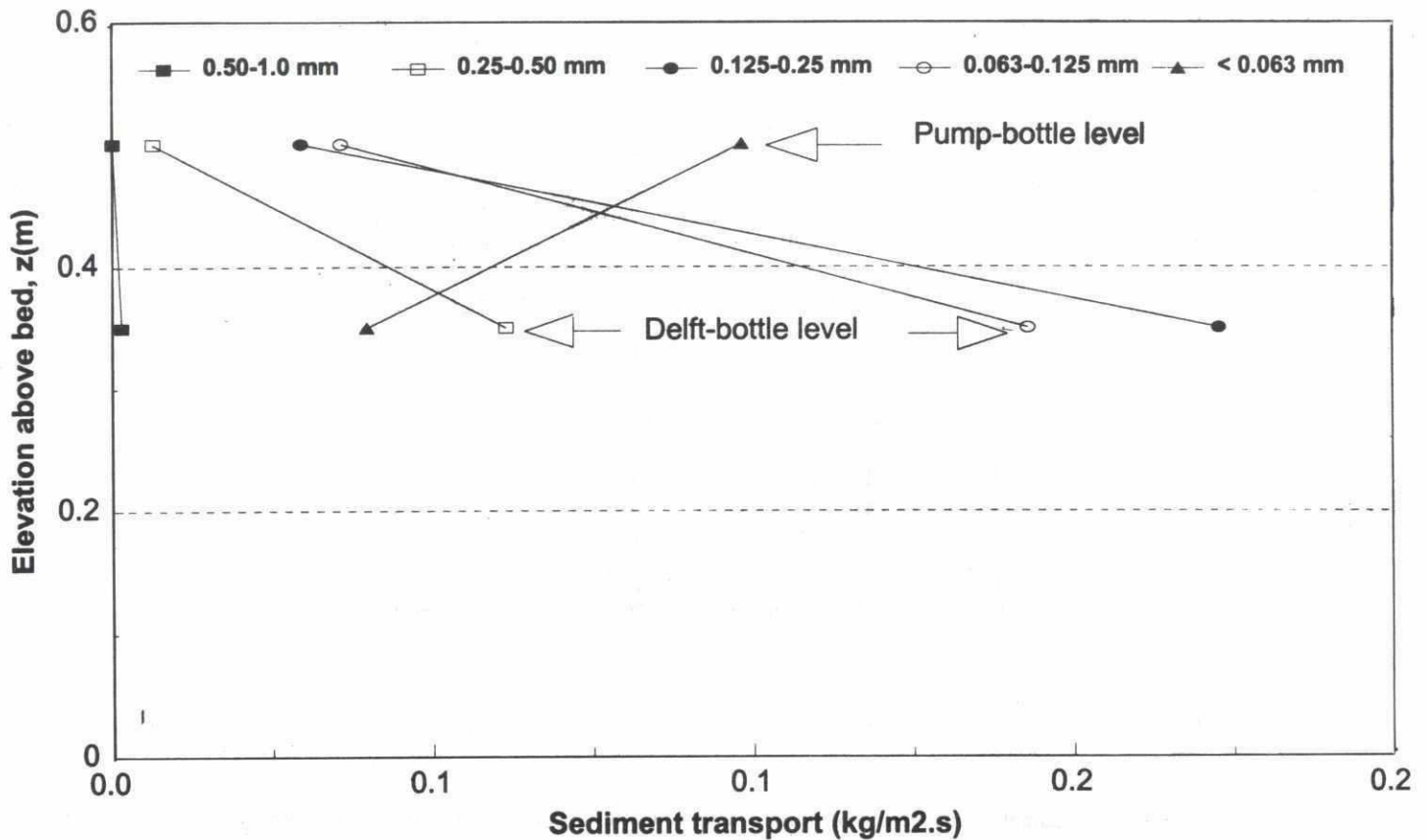


Figure 6.28 Comparison of local suspended sediment transport in various sizes of fractions between the pump-bottle measured at 0.5 above bed and Delft Bottle measured at 0.35 m above bed based on measurements on 3 August 1994 at a relatively flat-bed in the Jamuna River right channel near Bahadurabad.

-Pump-bottle vs Collapsible Bag

Some concentration profiles are shown in Figures 6.29 to 6.33 for comparison of the pump-bottle and the collapsible-bag. The results were similar to the routine measurements comparison. On all occasions, the agreement in silt fractions was good. For sand fractions, there were no good agreements, except in Figures 6.29 and 6.30, see also annexure G8.

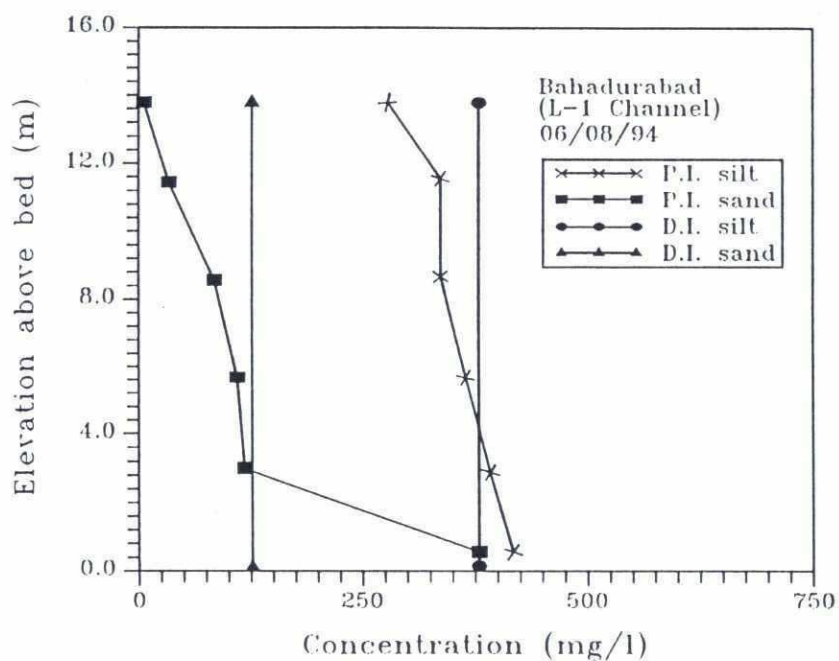


Figure 6.29

Examples of concentration profiles in sand and silt fractions measured by pump-bottle and Collapsible-bag sampler in the Jamuna River left channel near Bahadurabad on 6 August 1994.

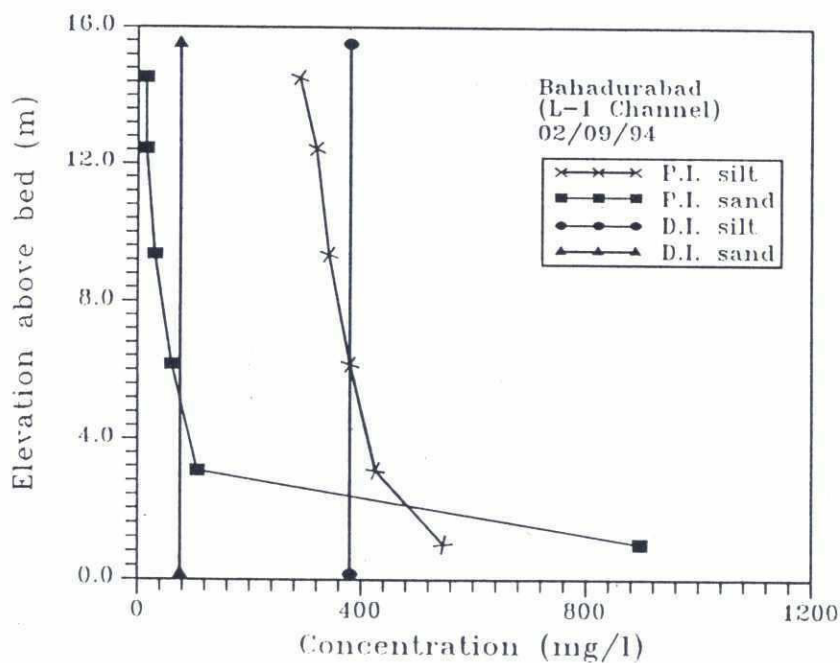


Figure 6.30

Examples of concentration profiles in sand and silt fractions measured by pump-bottle and collapsible-bag sampler in the Jamuna River left channel near Bahadurabad on 2 September 1994.

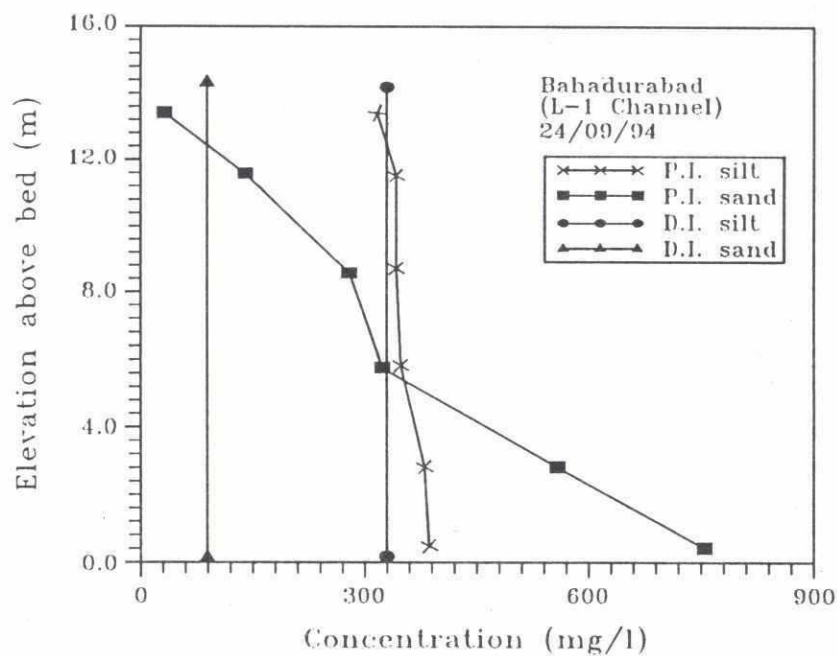


Figure 6.31

Examples of concentration profiles in sand and silt fractions measured by Pump-bottle and collapsible-bag sampler in the Jamuna River left channel near Bahadurabad on 24 September 1994.

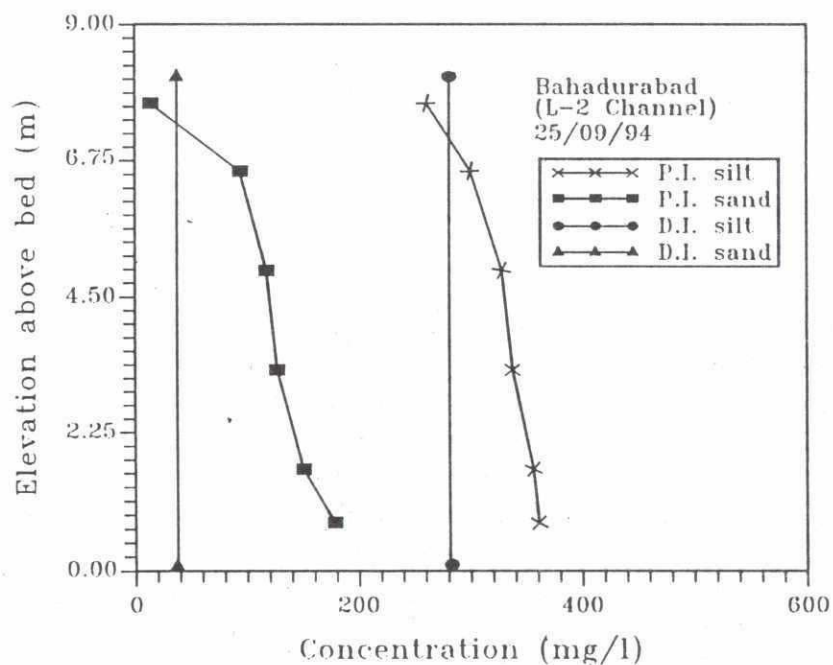


Figure 6.32

Examples of concentration profiles in sand and silt fractions measured by pump-bottle and collapsible-bag sampler in the Jamuna River left channel near Bahadurabad on 25 September 1994.

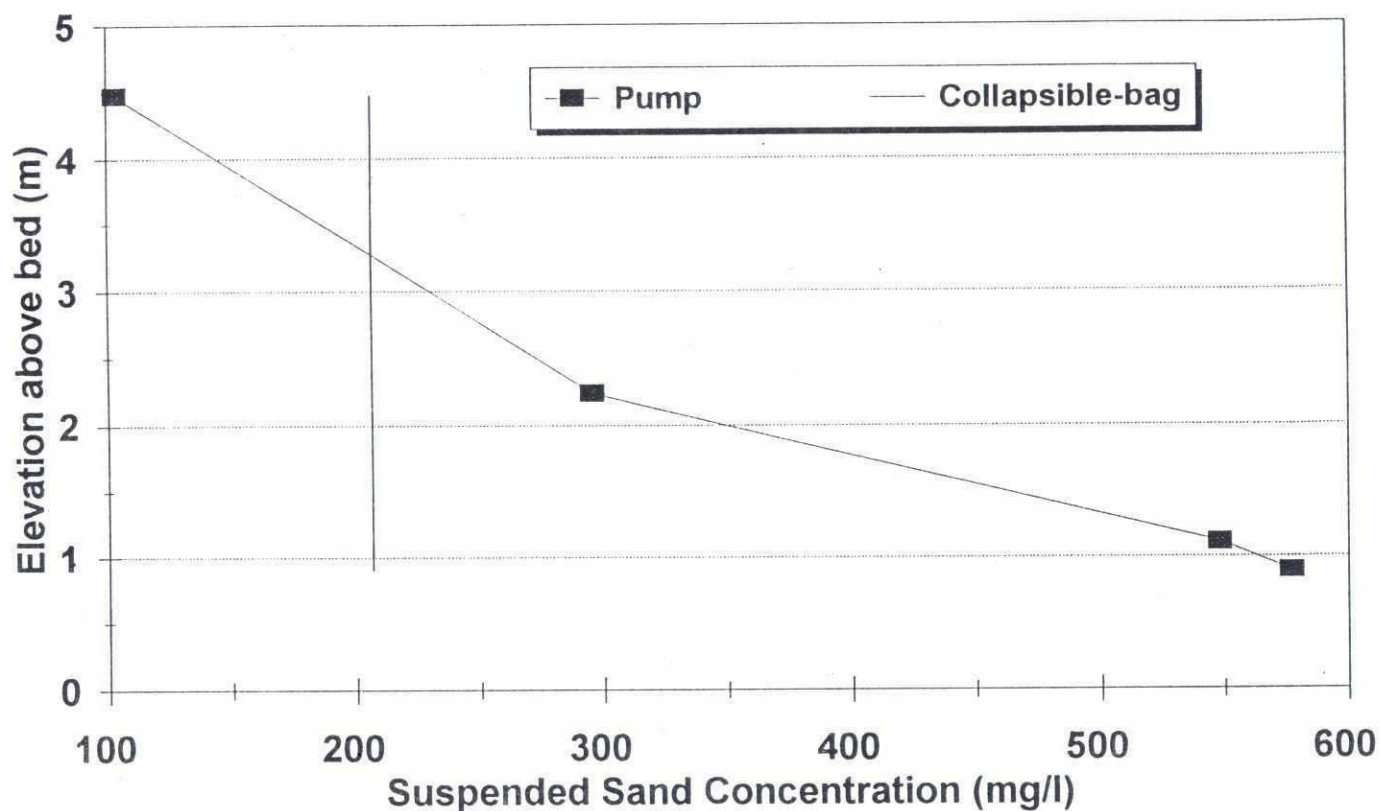


Figure 6.33 Examples of concentration profiles in sand fraction measured by pump-bottle and collapsible-bag sampler in the Jamuna River left channel near Bahadurabad on 18 August 1994.

-Pump-bottle vs MEX-3 Turbidity

Some calibration exercises of the MEX-3 turbidity meter were made by FAP 24 in the past; the results were reported in the First Interim Report (RSP, 1993a) and in the Selection of Survey Techniques (RSP, 1993b). The turbidity was compared with the suspended sediment concentration. While a good agreement was reported in the First Interim Report, the results from test gauging exercise were erratic. In the low concentration ranges, there was a reasonably good agreement. To determine the accuracy of the MEX-3 turbidity sensor, a special experiment was done first by using Jamuna River silt and later in combination with sands; the results are shown in Figure 6.34. The Figure shows that the sensor works perfectly well in silt ranges, however, it does not function very well with the addition of sand, especially in high concentration ranges. Figure 6.35 presents the results of another field measurement which support the conclusion reached earlier. These results are in agreement with what is known from literature.

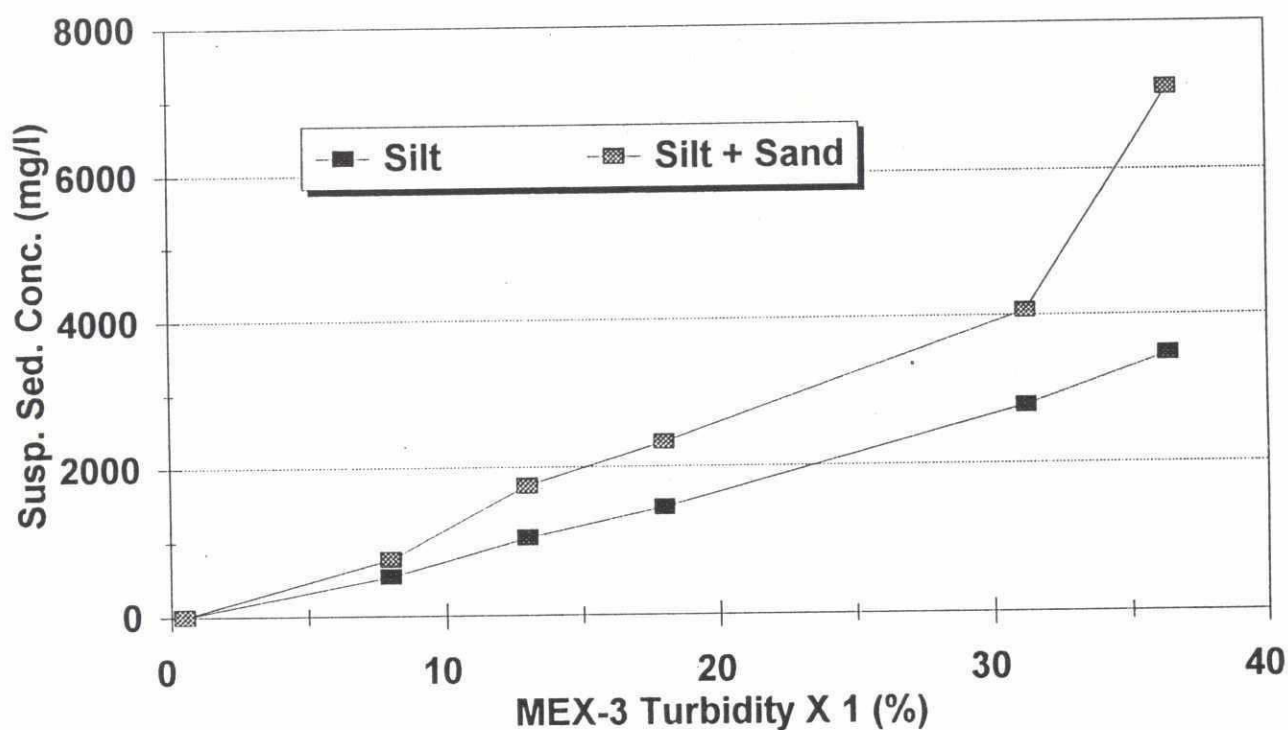


Figure 6.34 Pump-bottle suspended sediment concentration with MEX-3 turbidity.

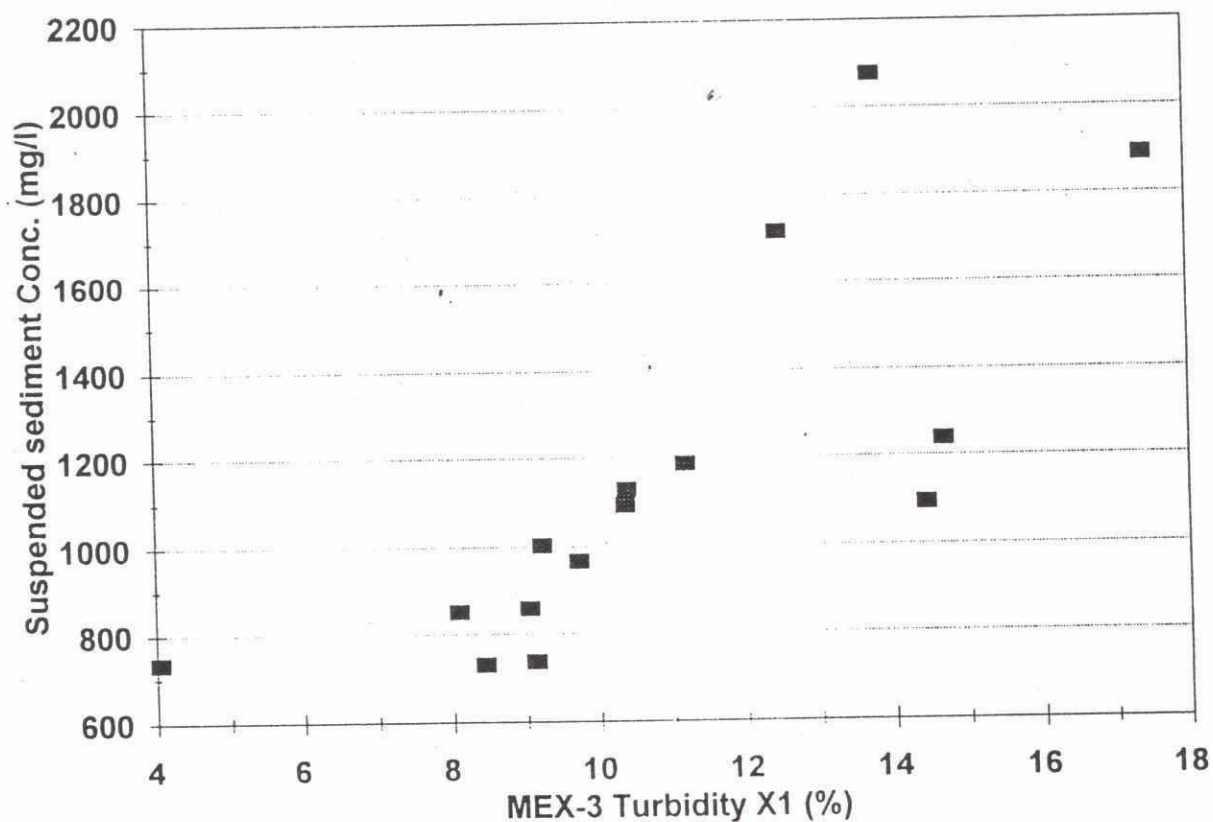


Figure 6.35 Pump-bottle suspended sediment concentration with MEX-3 turbidity measured on board DHA vessel.

-ADCP vs DB and pb

Annexure D discusses the use of ADCP dB for estimation of suspended sediment concentration based on measurements at Bahadurabad. This section reports some comparison of ADCP dB with DB and pb. Figure 6.36 shows the measurement location during sediment plume survey in May 1995. During these measurements, among others, the Delft Bottle suspended sediment transport was compared with transports derived from the ADCP backscatter intensity (for details of these measurements, please see Annexure G7). In Figure 6.37, some examples are presented for verticals 4 and 7. In the two cases presented, the ADCP shows respectively a higher and the same transport. The increase of the near bed transport is not 'observed' by the ADCP.

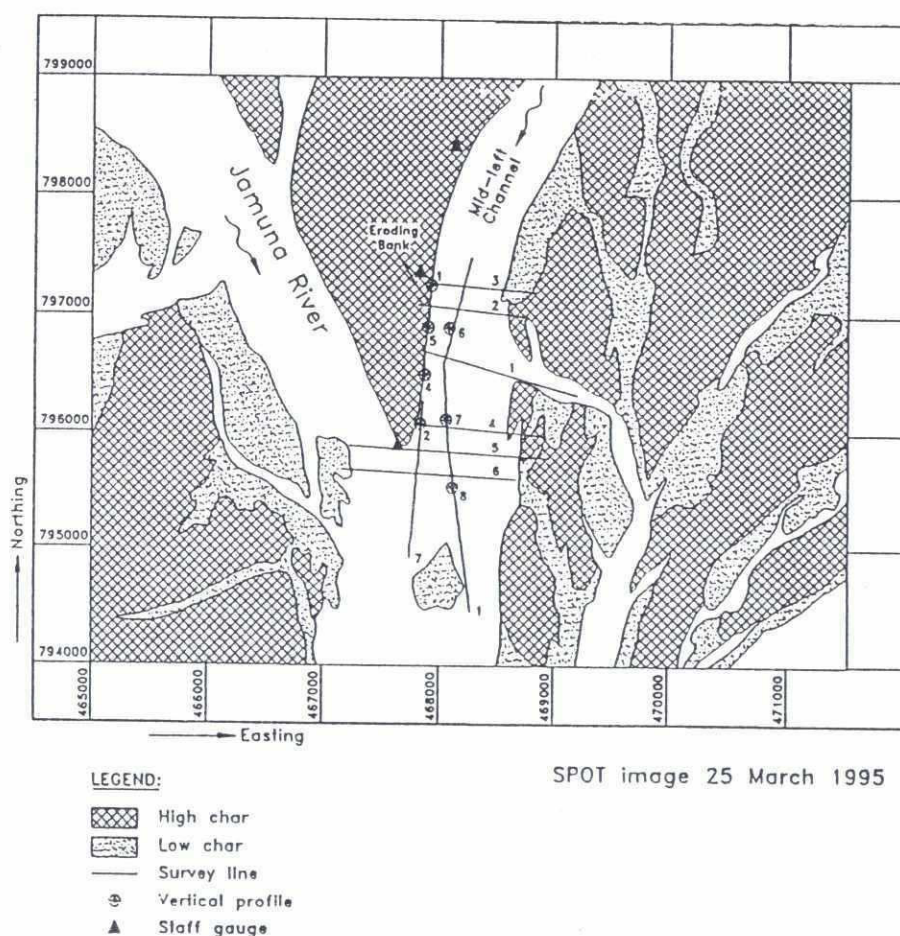


Figure 6.36 Measurement location during May 1995 sediment plume survey in the Jamuna River near Bahadurabad.

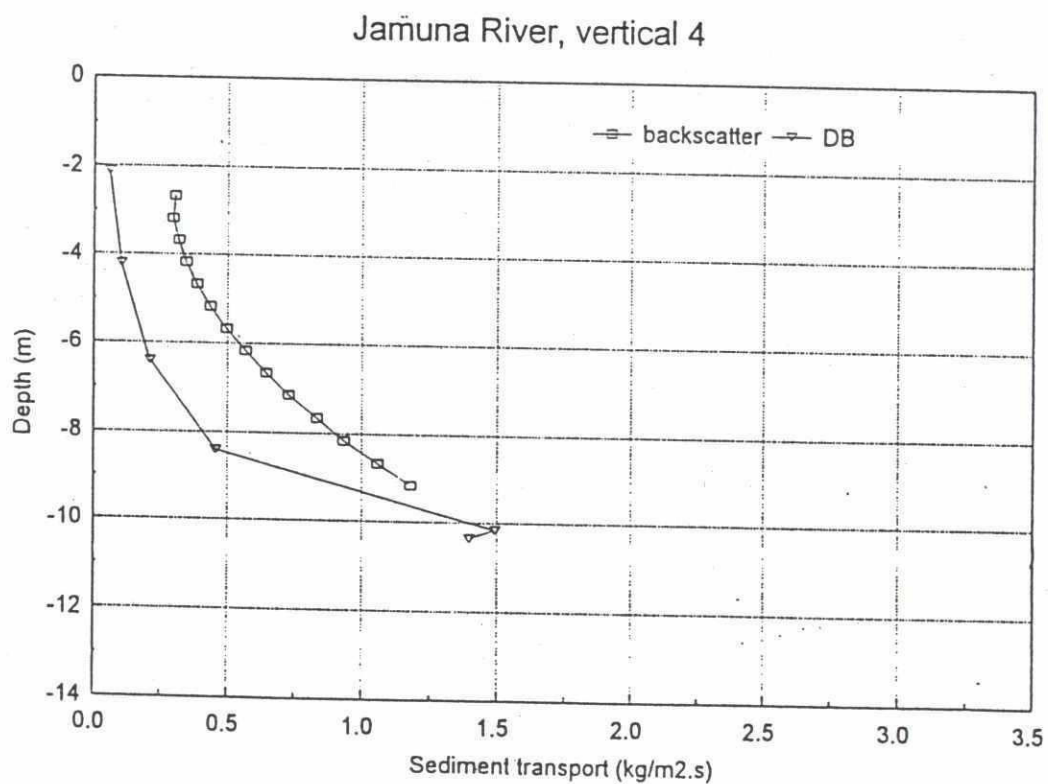
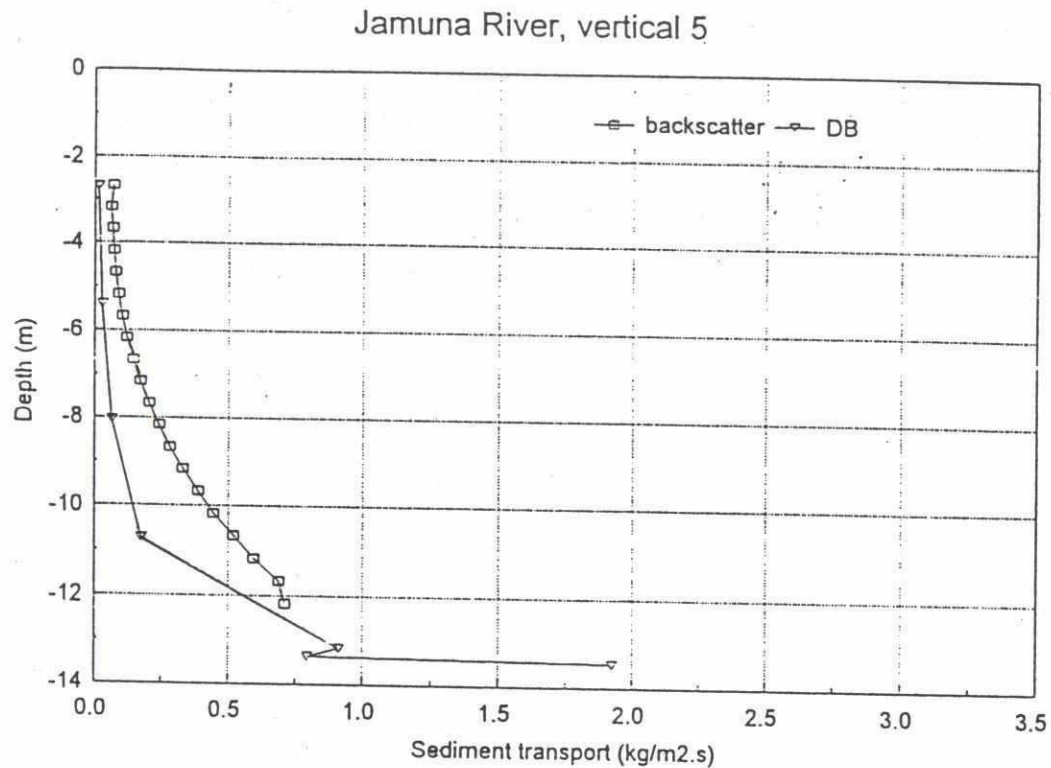
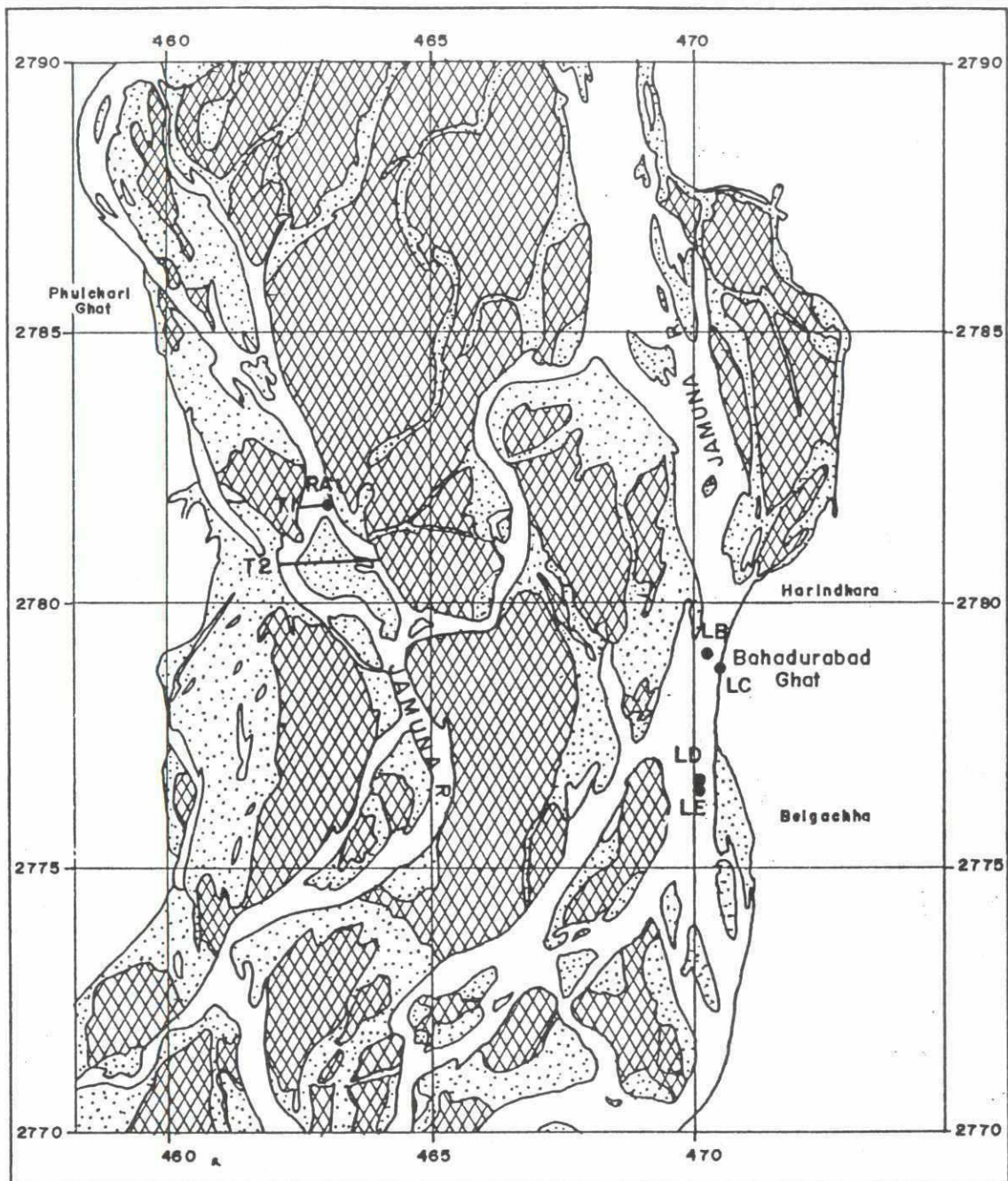


Figure 6.37 Sand transport measurements in verticals 5 and 4 during May 1995 in the Jamuna River near Bahadurabad.

Some more results are presented based on measurements in July 1995. Details of this measurements are presented in Annexure G8 and in the next section only some examples are given. Figure 6.38 shows the location of measurements. Figures 6.39 to 6.41 show some examples of concentration profiles by ADCP and pump bottle. While in some cases a good agreement can be seen (Figure 6.39), in others a weak agreement is noticeable. A special limitation of ADCP is that it can not measure the near-bed region. The ADCP shows a much more regular profile than the pump-bottle. Partly this can be explained by the sampling time. During sampling with the pump-bottle (duration per point 100 seconds) the ADCP was switched on. This means that the ADCP vertical represents an average over say 1.5 hours.

**LEGEND:**

- T1 ——— MULTI-VERTICAL TRANSECTS.
 [Cross-hatched box] HIGH LAND
 [Dotted box] LOW CHAR
 ● RA
 ● LB
 ● LC
 ● LD
 ● LE ——— MULTI-POINT MEASUREMENT VERTICALS.



2500 m 0 2.5 km

Map based on SPOT
image of March 1995.

Figure 6.38

Locations of multi-point measurement verticals and multi-vertical transects in the Jamuna River near Bahadurabad for measurements during 26 - 30 July 1995.

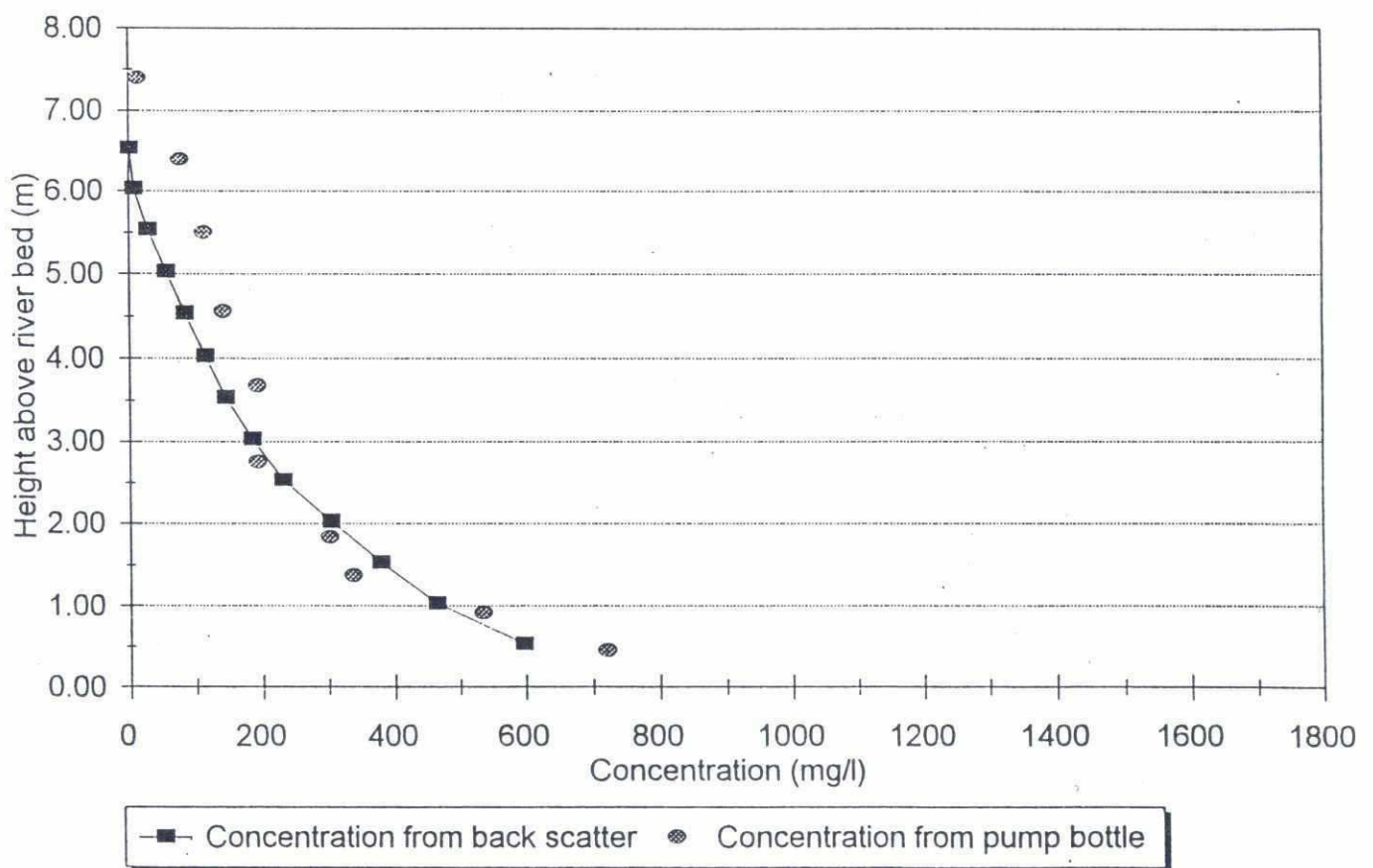
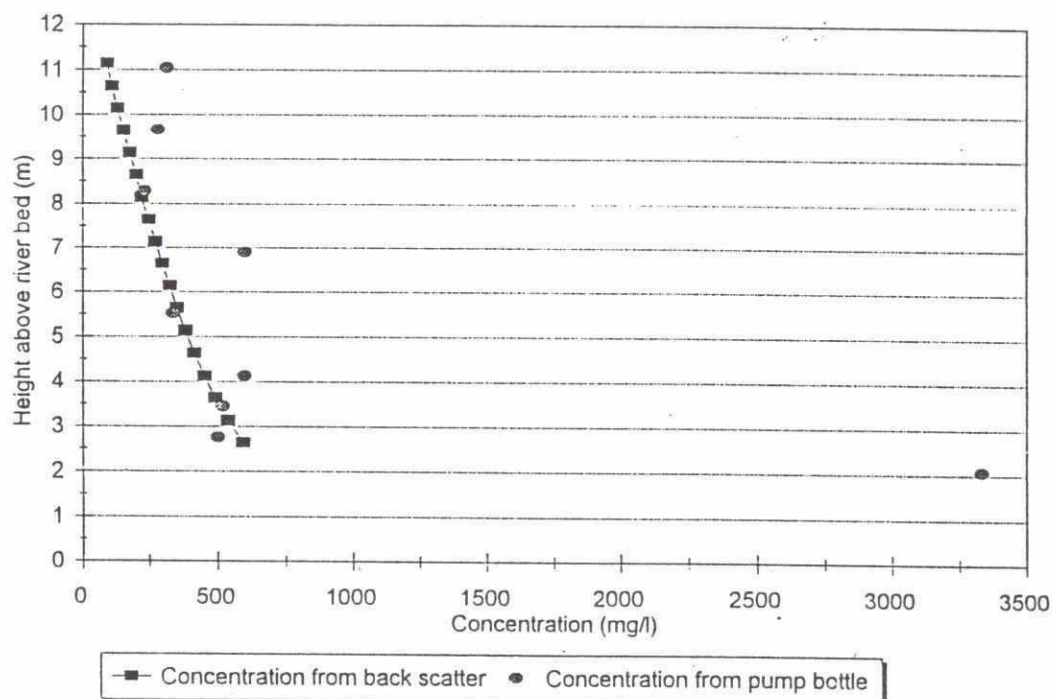


Figure 6.39 ADCP and pump-bottle concentrations at vertical RA based on measurements on 27 July 1995

Jamuna River, Bahadurabad, Vertical LB
Left Channel, 29.07.95



Jamuna River, Bahadurabad, Vertical LC
Left Channel, 29.07.95

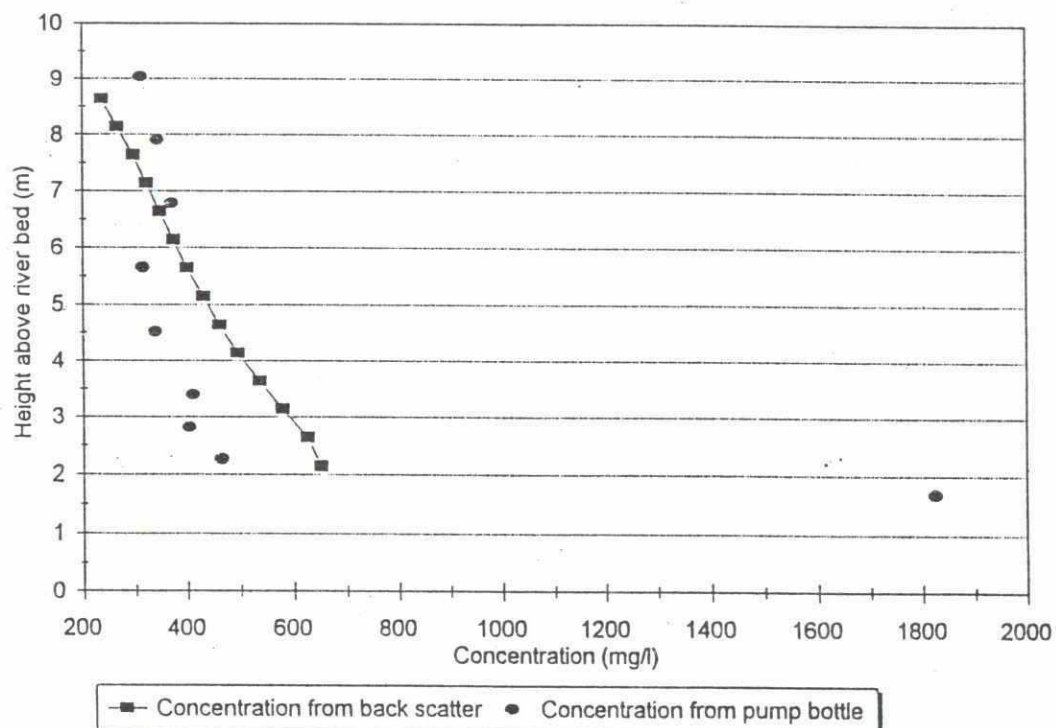


Figure 6.40 ADCP and pump-bottle concentration at verticals LB and LC based on measurements on 29 July 1995

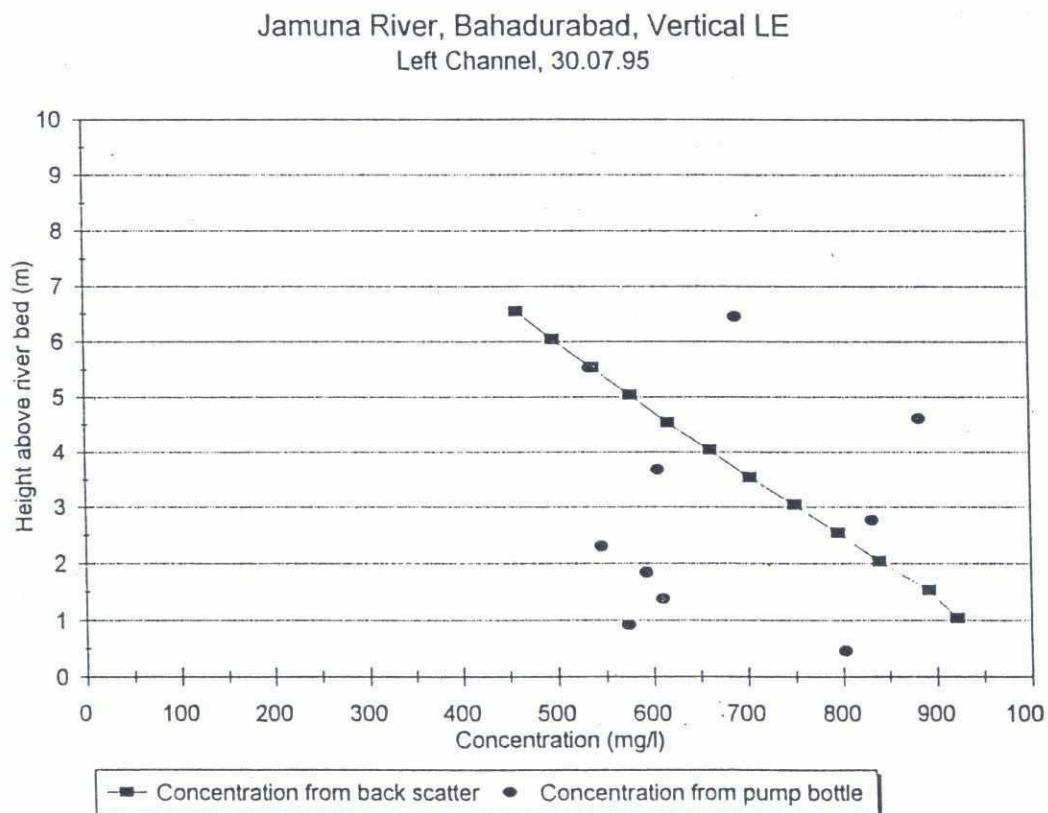
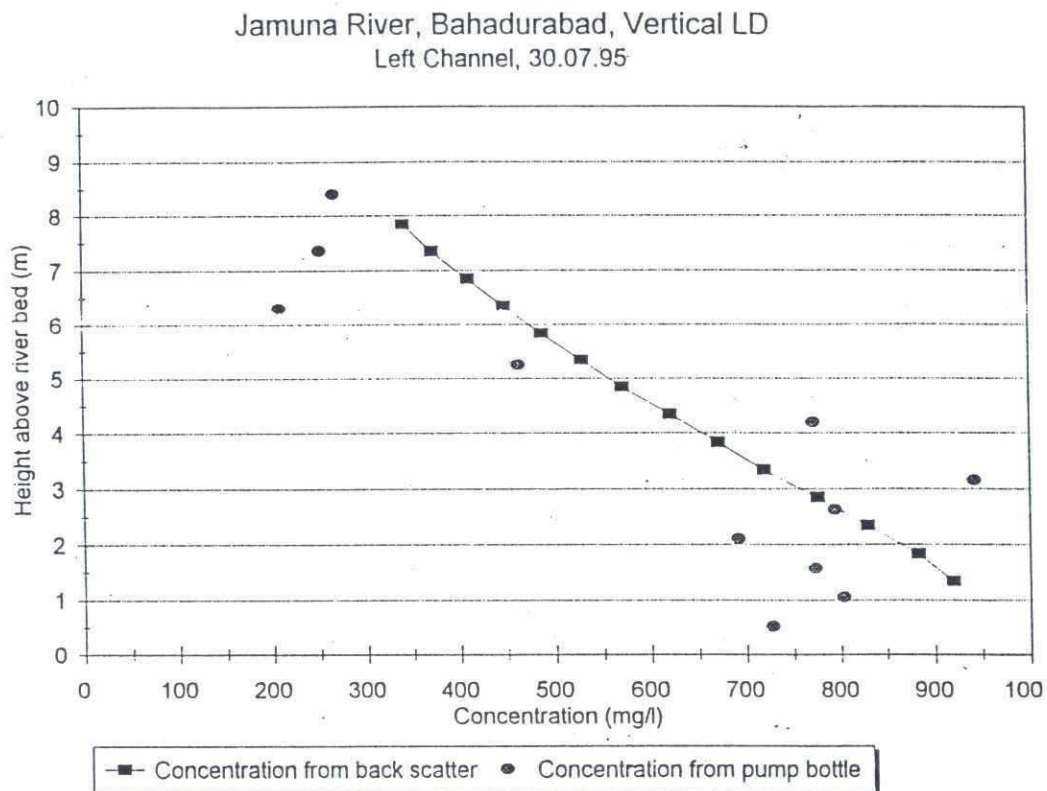


Figure 6.41 ADCP and pump-bottle concentration at verticals LD and LE based on measurements on 30 July 1995

Spatial Distribution of Measurements

Nature can never be measured in enough detail; there are always limitations in the measurements and interpolation is always necessary. A representativity is perfect only when the sampling population is equal to the actual natural population, and this is never the case. This is particularly relevant when choosing the suitable number of points in a vertical and the suitable number of verticals in a transect. Based on some special measurements we attempted to address these issues.

Special field measurements were taken in the Jamuna River near the Bahadurabad discharge measurement transect from 26 to 30 July 1995. The measurements were taken in the left and right channels of the Jamuna River (Figure 6.38) during high river stages (Fig. 6.42).

The measurements were done in the right channel along the transects T1 and T2. In transect T1 a detailed measurements in vertical RA was executed. Thereafter detailed measurements were done in 4 verticals in the left channel. The measurements in the transects were used to analyze the number of verticals in a cross-section versus the accuracy of the total suspended sediment load. The detailed measurements in the vertical were used to analyze the number of measuring points in a vertical versus the accuracy of the suspended sediment load per unit of width.

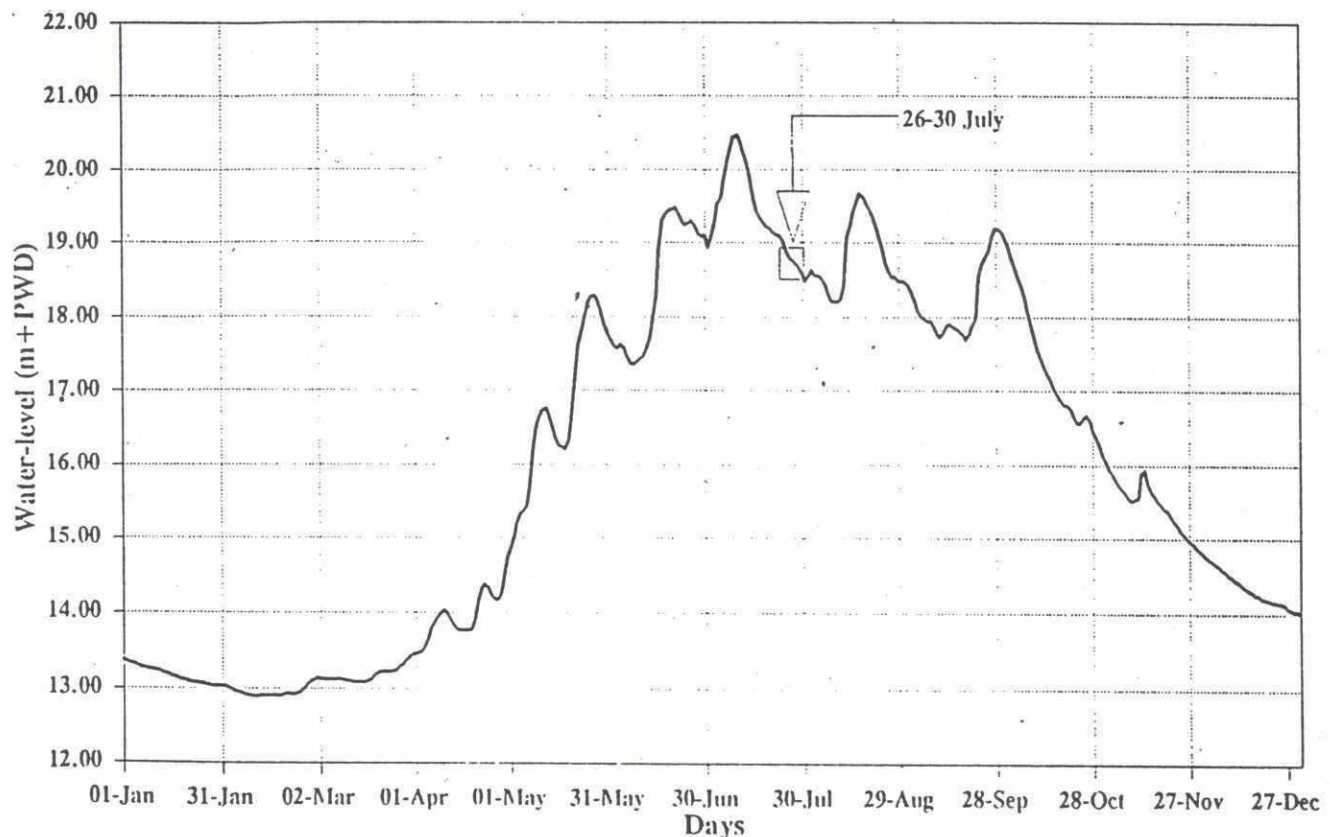


Figure 6.42 Water-level hydrograph of the Jamuna River near Bahadurabad showing the measurement dates in July 1995.

Optimal Number of Measuring Points in a Vertical

Figure 6.43 shows the suspended sand concentration at anchor station RA.

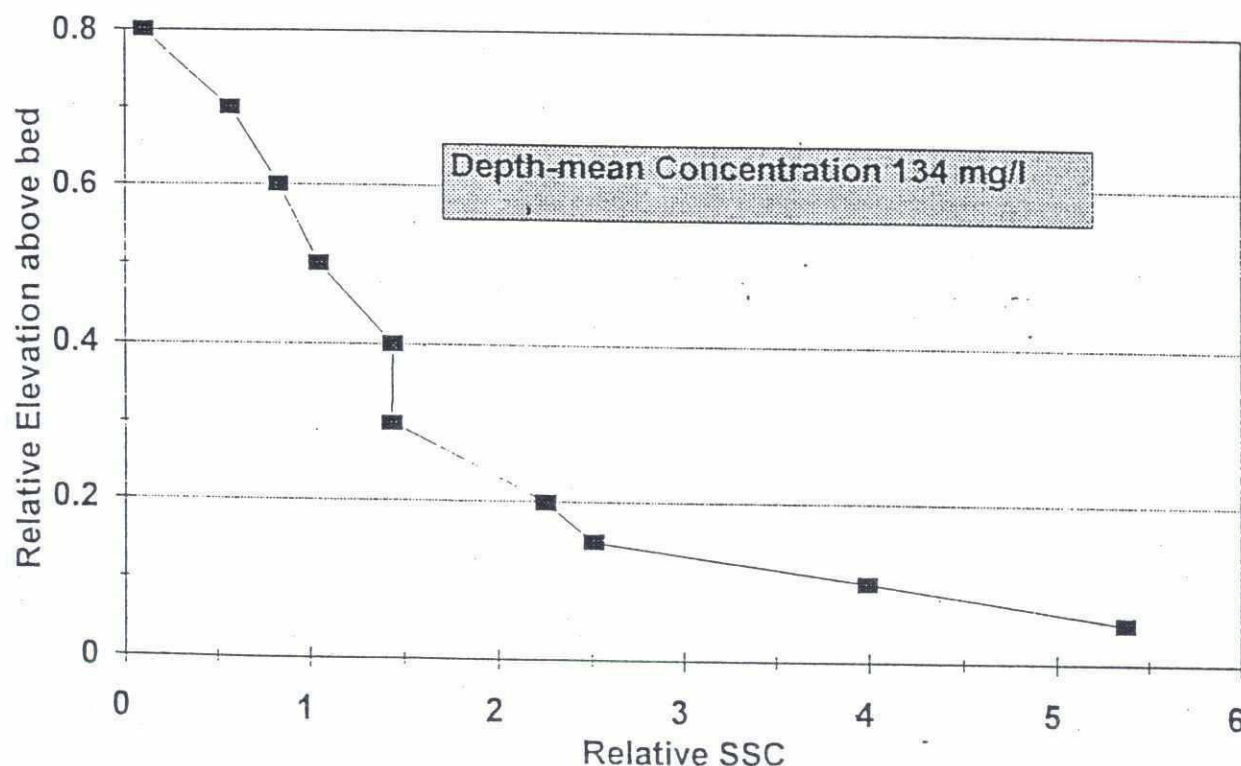


Figure 6.43 Suspended sand concentration measured by pump-bottle on board DHA vessel on 27 July 1995 at vertical RA in the Jamuna River right channel near Bahadurabad.

Relative suspended sand concentration (SSC), with respect to the depth-mean concentration, is plotted against relative elevation above the bed, with respect to the total depth (Fig 6.43). The depth-mean concentration at the station was 134 mg/l. Specific sand transports were computed per vertical using different point measurements as shown in Table 6.2.

1 point =	0.5h
2 points =	0.2h, 0.8h
3 points =	0.2h, 0.6h, 0.8h
4 points =	0.2h, 0.4h, 0.6h, 0.8h
5 points =	0.2h, 0.4h, 0.5h, 0.6h, 0.8h
6 points =	0.2h, 0.3h, 0.4h, 0.6h, 0.7h, 0.8h
7 points =	0.2h, 0.3h, 0.4h, 0.5h, 0.6h, 0.7h, 0.8h
8 points =	0.2h, 0.3h, 0.4h, 0.5h, 0.6h, 0.7h, 0.8h, 0.9h
9 points =	0.2h, 0.3h, 0.4h, 0.5h, 0.6h, 0.7h, 0.75h, 0.8h, 0.9h
10 points =	0.2h, 0.3h, 0.4h, 0.5h, 0.6h, 0.7h, 0.75h, 0.8h, 0.85h, 0.9h
11 points =	0.2h, 0.3h, 0.4h, 0.5h, 0.6h, 0.7h, 0.75h, 0.8h, 0.85h, 0.9h, 0.95h

Table 6.2 Distribution followed for computation of suspended sand transport per unit width.

The Simpson Rule was used for computation,

$$q_s = \sum_{i=1}^n C_i U_i \Delta z$$

Figure 6.44 shows the results of computation as percent deviation in suspended sand transport (SST).

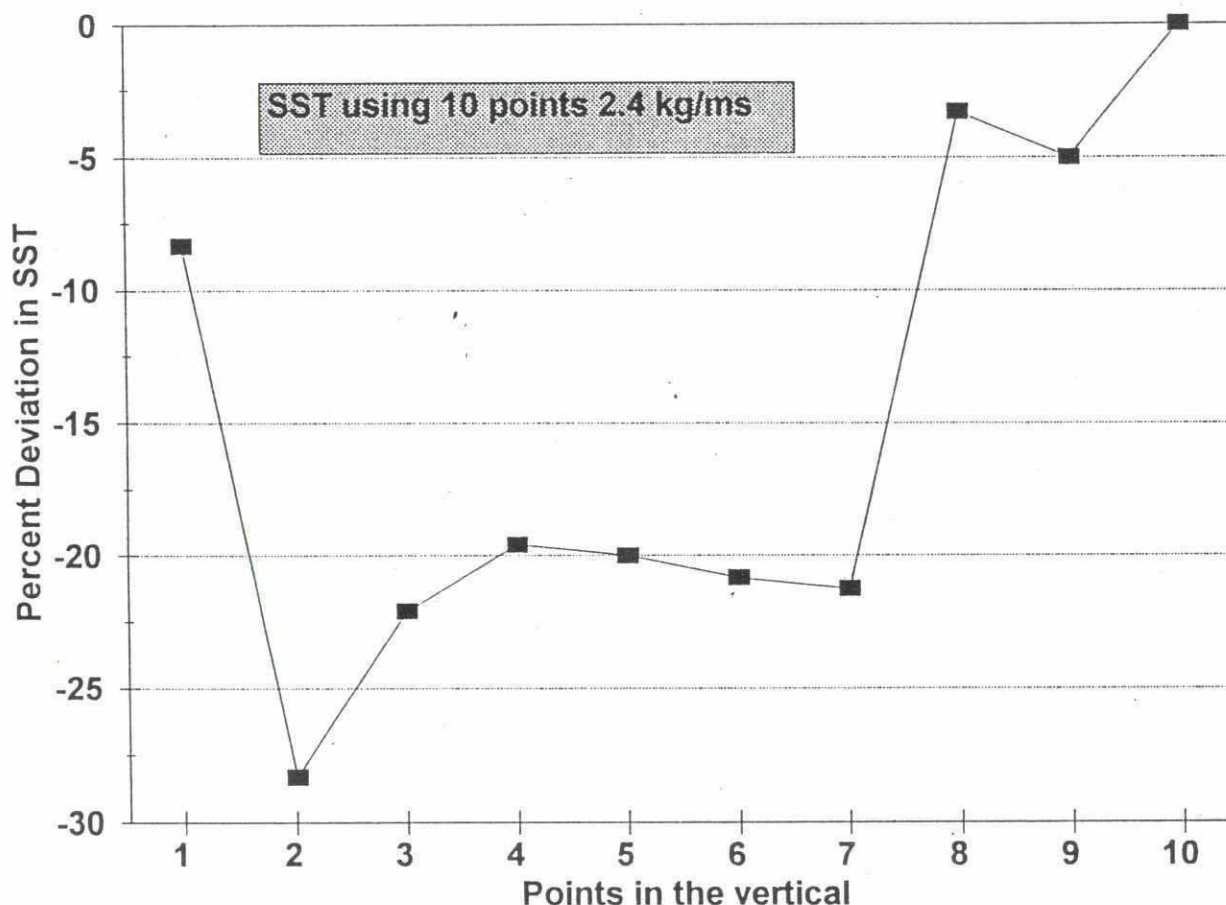


Figure 6.44 Percent deviation in SST from the 10-point transport at vertical RA measured on 27 July 1995 in the Jamuna River right channel near Bahadurabad.

Assuming the 10-point measurement as the representative transport for the vertical, the percent deviation is found as,

$$\delta = \frac{q_{si} - q_{sm}}{q_{sm}} \times 100$$

where,

q_{si} = transport used at point i ,

q_{sm} = transport used at the maximum number of points.

When less numbers of points in a vertical were used, the transport was underestimated by as much as 30%. Depending on the concentration profile (Figure 6.42), the mid-point (0.5h) measurement can yield a closer estimate, as happened in this case. Comparisons were made with methods known from the literature. The following methods were compared with the 10-point estimate: the Straub method

(Straub, 1936), the mid-point method, the Chinese 2- and 3-point methods (Chinese Ministry of Water Conservancy, 1975), and the River Survey Project methods. Brief descriptions of some of these methods are given.

A 2-point method was developed by Straub (1936) based on sediment investigations in the Missouri River system. The mean concentration is computed as,

$$\bar{C} = \frac{3}{8}C_{0.8h} + \frac{5}{8}C_{0.2h}$$

In contrast, the Chinese 2-point method uses unit coefficients with measurements at the same points.

$$q_s = \frac{h}{2}[C_{.2h}U_{.2h} + C_{.8h}U_{.8h}]$$

The Chinese 3-point method is based on measurements at three points,

$$q_s = \frac{h}{3}[C_{.2h}U_{.2h} + C_{.6h}U_{.6h} + C_{.8h}U_{.8h}]$$

The River Survey Project (RSP) used the Simpson rule to estimate the transport based on measurements at the surface, 0.2h, 0.4h, 0.6h, 0.8h, and at 0.5 m above the bed. Figure 6.45 shows that the performance of the RSP method was very close to the representative 10-point method. In this case, the performance of the Straub method was better than the Chinese methods.

Similar measurements and comparisons are shown for station LB in Figures 6.46 to 6.48. As with station RA, the transport was underestimated when less numbers of points in a vertical were used. Here, again, the RSP method was closer to the representative 9-point estimate. The Straub and Chinese methods performed frustratingly poor (Figure 6.48). Figures 6.49 to 6.51 show the results of similar comparisons at station LC where similar comparisons were made.

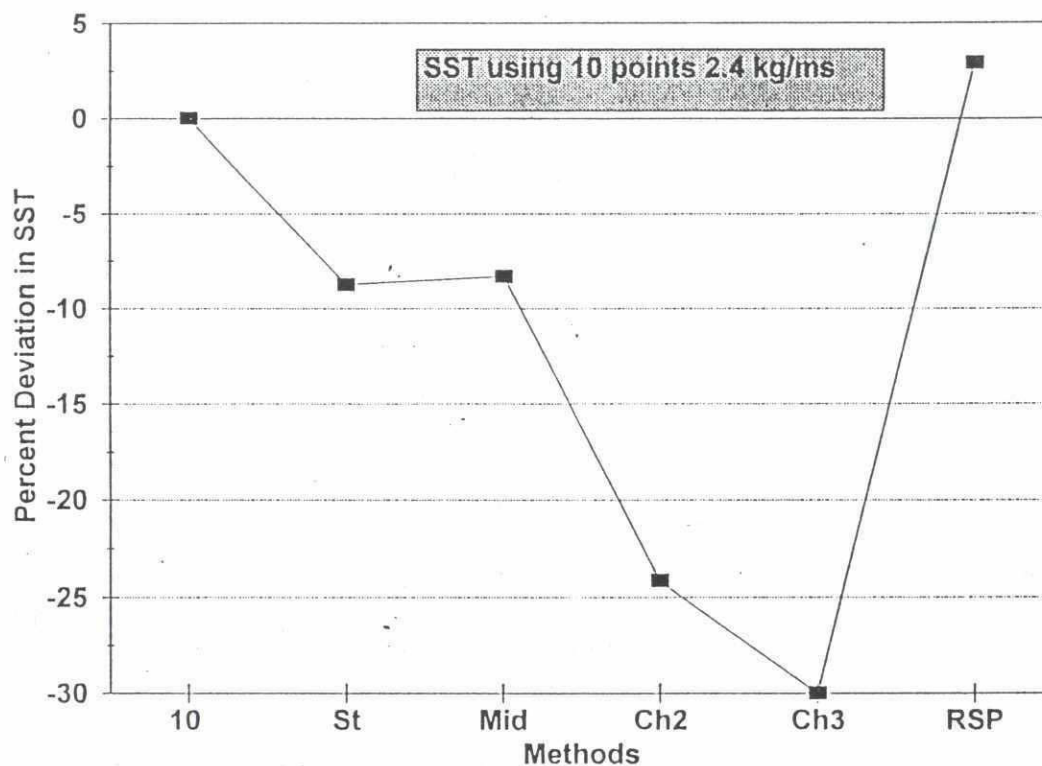


Figure 6.45 Percent deviation in SST estimated by using different methods from the 10-point transport at vertical RA measured on 27 July 1995 in the Jamuna River right channel near Bahadurabad.

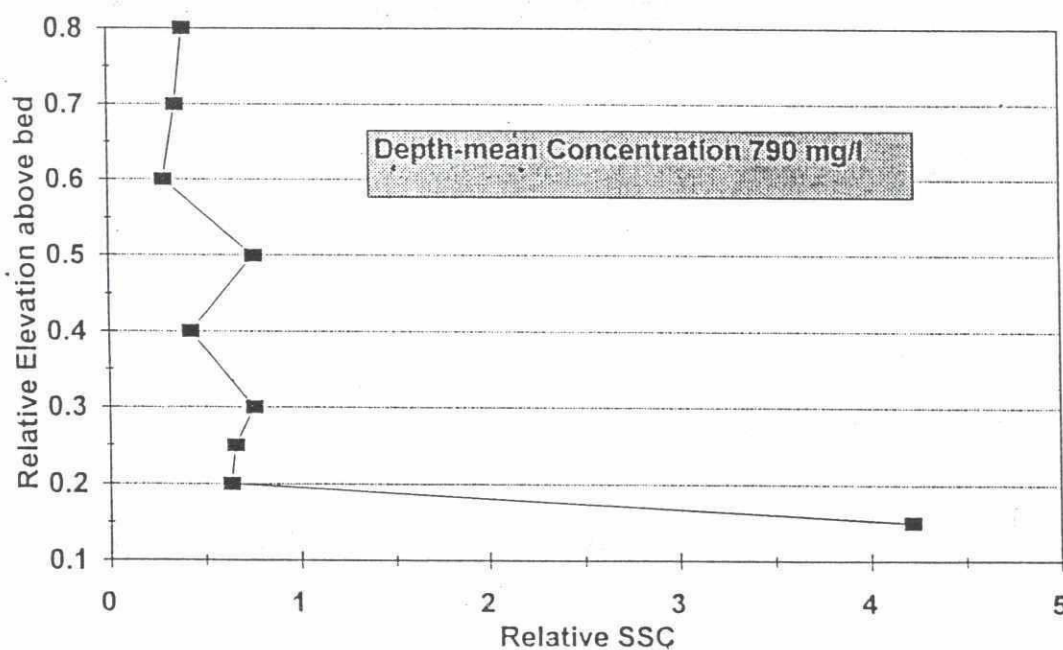


Figure 6.46 Suspended sand concentration measured by pump-bottle on board DHA vessel on 29 July 1995 at vertical LB in the Jamuna River right channel near Bahadurabad.

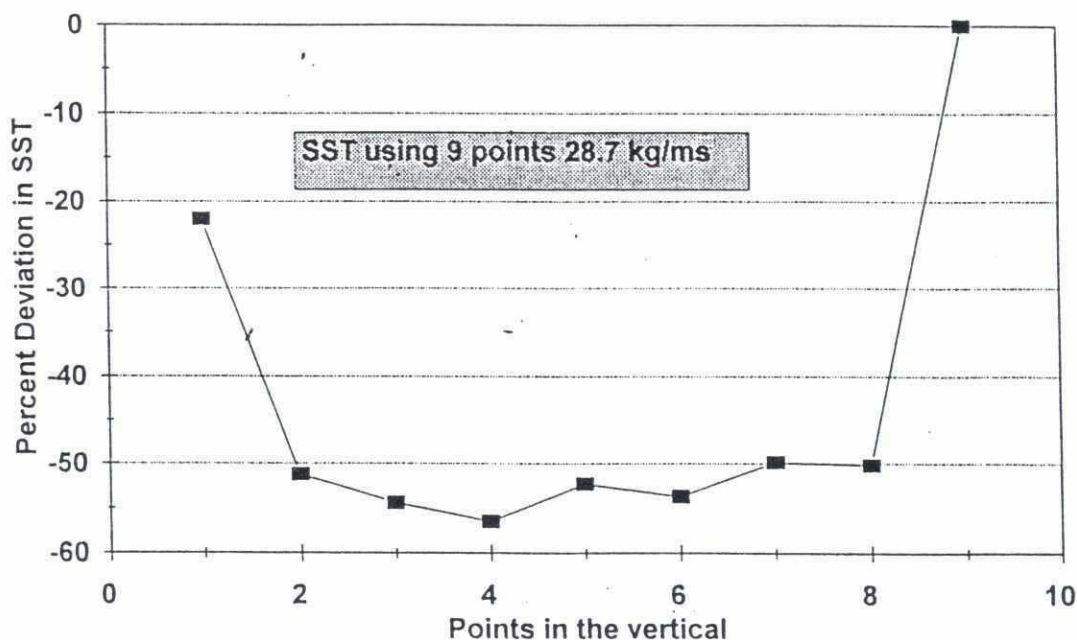


Figure 6.47 Percent deviation in SST from the 10-point transport at vertical LB measured on 29 July 1995 in the Jamuna River right channel near Bahadurabad.

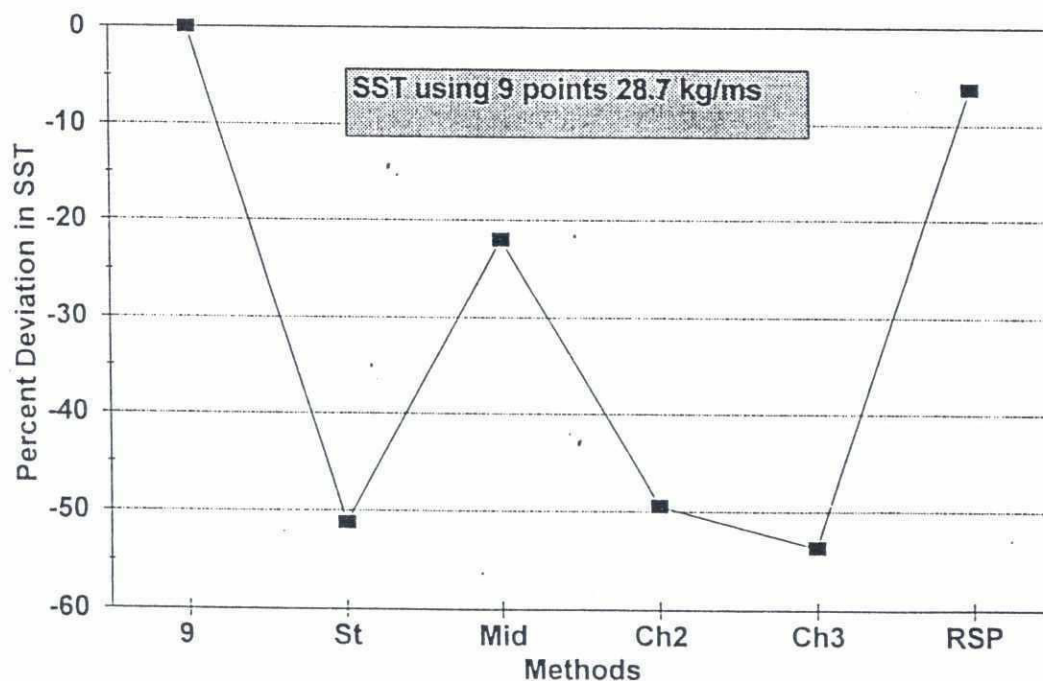


Figure 6.48 Percent deviation in SST estimated by using different methods from the 10-point transport at vertical LB measured on 29 July 1995 in the Jamuna River right channel near Bahadurabad.

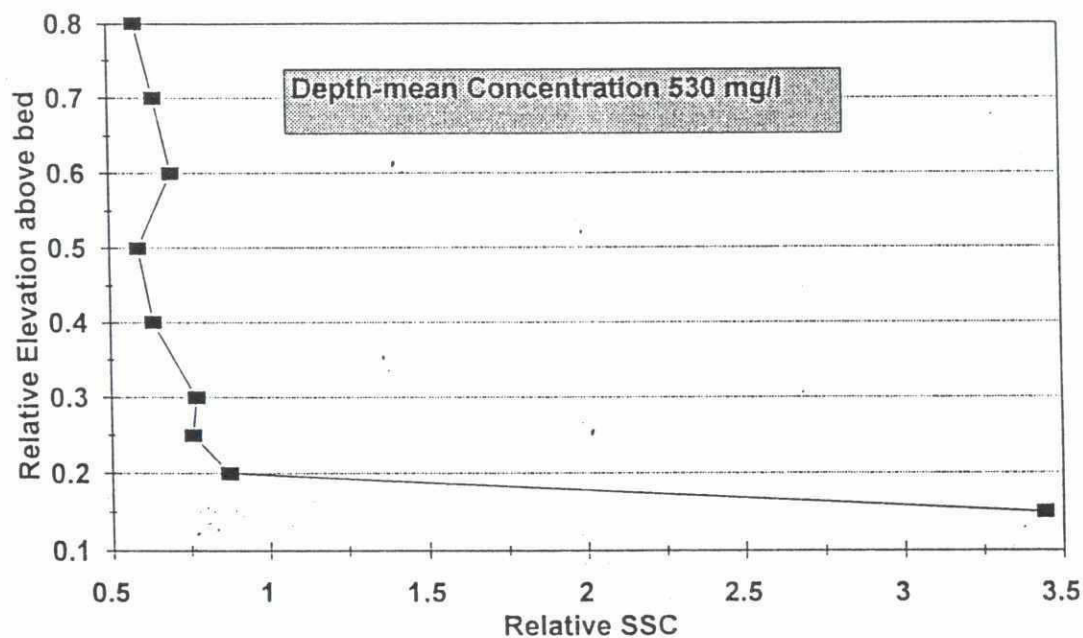


Figure 6.49 Suspended sand concentration measured by pump-bottle on board DHA vessel on 29 July 1995 at vertical LC in the Jamuna River right channel near Bahadurabad.

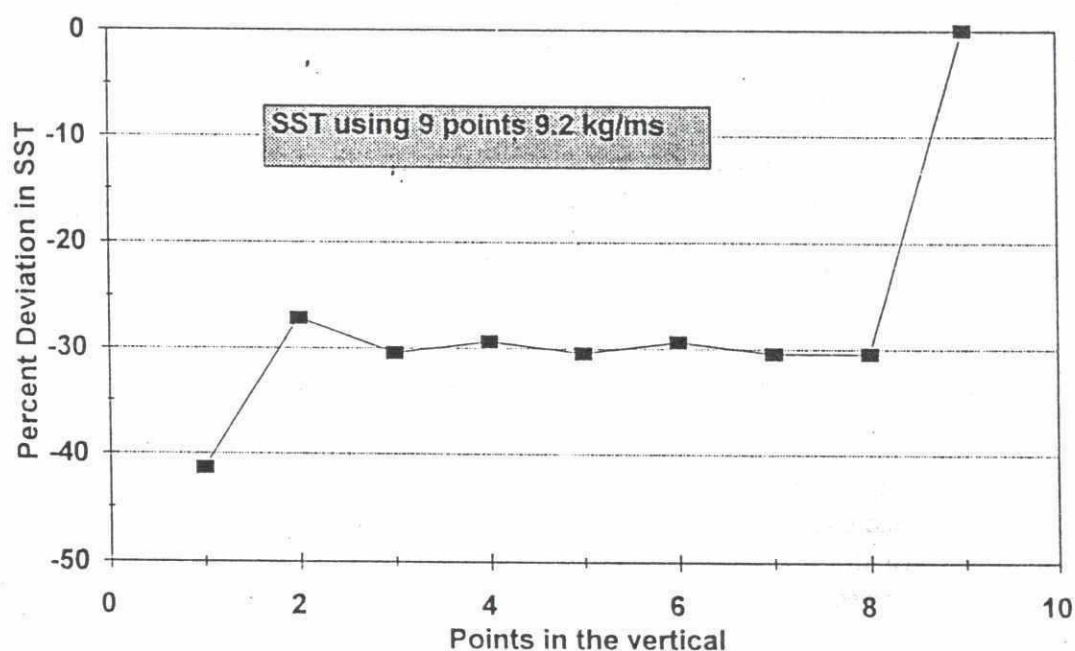


Figure 6.50 Percent deviation in SST from the 10-point transport at vertical LC measured on 29 July 1995 in the Jamuna River right channel near Bahadurabad.

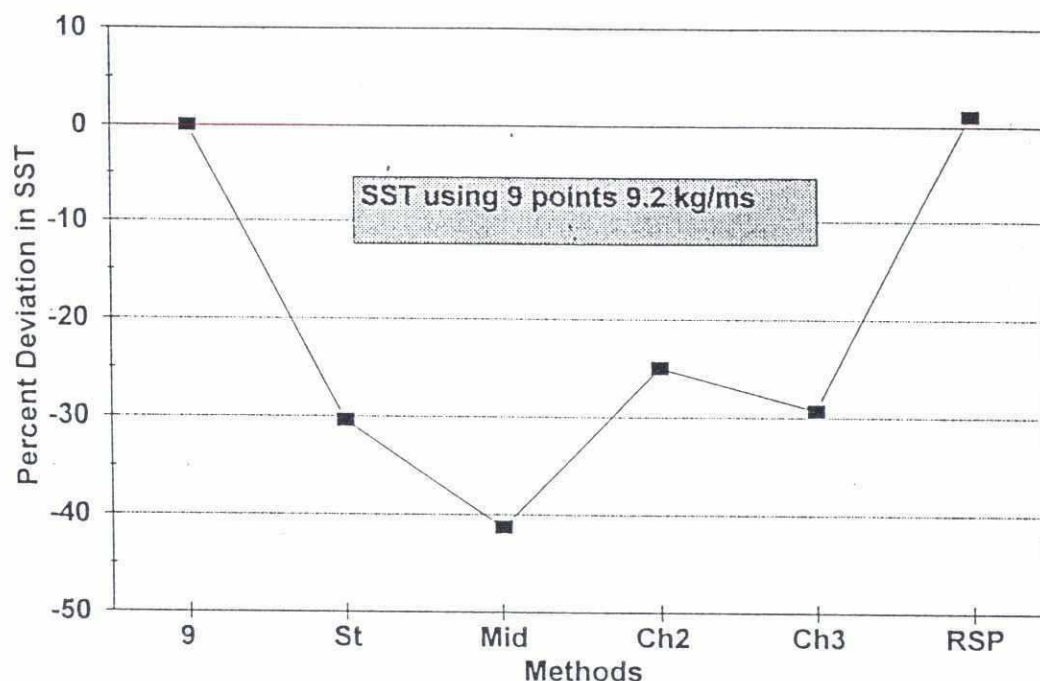


Figure 6.51 Percent deviation in SST estimated by using different methods from the 10-point transport at vertical LC measured on 29 July 1995 in the Jamuna River right channel near Bahadurabad.

These few measurements indicate that a multi-point method should be followed for an accurate estimate of suspended sediment transport. Some simple theoretical analyses were done to investigate the reasons why the multi-point method gives such good results. Specifically, the measured suspended sediment profile was fitted with the Rouse profile (Rouse, 1937). It may be mentioned that the Rouse profile is applicable under steady state conditions when the downward settling of sediment particles is balanced against L upward vertical turbulent flux. In large alluvial rivers, the situation is likely to deviate from this assumption. Therefore, the analysis should be considered as an engineering approach only.

$$\frac{C_z}{C_a} = \left[\frac{h-z}{z} \cdot \frac{a}{h-a} \right]^Z$$

C_z = Suspended sand concentration at any height z ,

C_a = Suspended sand concentration at reference height, obtained from the Delft Bottle measurements taken at 5 cm above the bed,

a = Assumed the lowest Delft Bottle measurements at 5 cm above the bed,

Z = Rouse suspension number,

$$Z = \frac{W_s}{\kappa \beta U_*}$$

W_s = Settling velocity, estimated by using the Rubey equation (Rubey, 1933),

$$W_s = \frac{\sqrt{\frac{2}{3}g(s-1)D^3 + 36v^2 - 6v}}{D}$$

The equation is applicable for particles of a certain shape and with a diameter less than 1 mm; this is the case for Bangladesh rivers, except for flakes. The equation was used for particles with 0.22 mm median diameter at the Jamuna River near Bahadurabad.

The bed-shear stress velocity, U_* , is estimated from the Chezy equation for steady uniform flow, replacing the depth and slope product with the bed-shear stress velocity,

$$U_* = \frac{\bar{U}}{C}\sqrt{g}$$

where,

s = specific density (ρ_s/ρ),

D = particle diameter,

C = Chezy roughness coefficient,

$\bar{U}$ = Depth-mean velocity obtained from measured ADCP profile.

The Delft Bottle sand concentration was obtained by dividing the transport with the local ambient velocity (assuming isokinetic conditions). Since this velocity was not measured, the velocity was estimated by using a power function (Van Rijn, 1993),

$$U = U_1 \left(\frac{z}{z_1} \right)^{0.25}$$

where,

U = velocity at any point between the lowest measuring point and the bed,

U_1 = velocity at the lowest measuring point z_1 above the bed by ADCP.

By varying the Chezy coefficient, a different U_* and Rouse number were obtained which were used to fit the measured sand concentration profile. Figures 6.52 to 6.55 show the concentration profiles best fitted to the measured profiles in the routine transects of the left channel of the Jamuna River near Bahadurabad. These profiles represent different stages of the river. These four fitted profiles show that the Rouse number varied from 0.48 to 0.99 in these measurements. Lin Binwen's (1982) examined the relation between the relative measuring errors and the suspension number, see also Yuqian (1989), for different measuring methods. For our range of suspension numbers (0.48-0.99), the relative error for 1-, 2-, or 3-point methods exceeded 15%. This examination indicated that as suspension numbers increase, the 1-, 2-, or 3-point methods do not work because the errors become larger. For example, with a suspension number of 0.99, the relative error exceeds 50%.

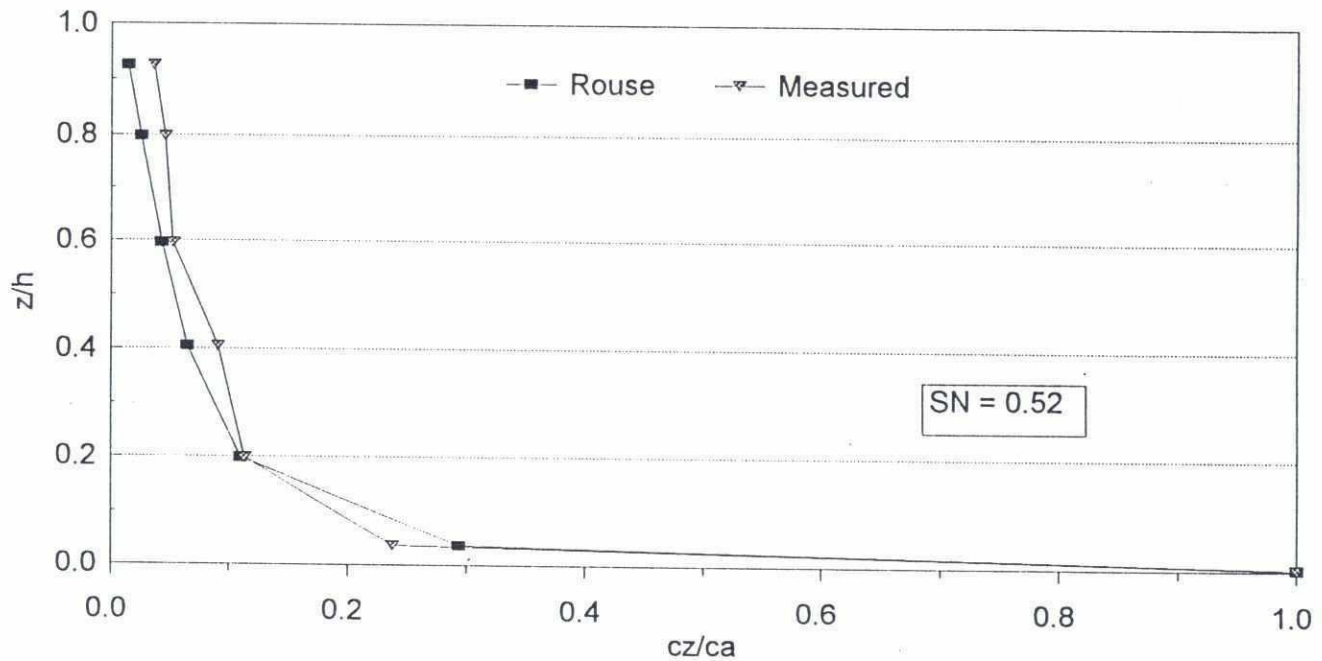


Figure 6.52 Concentration profile from pump-bottle and Delft Bottle with the fitted Rouse profile in the Jamuna River left channel near Bahadurabad measured on 10 June 1995.

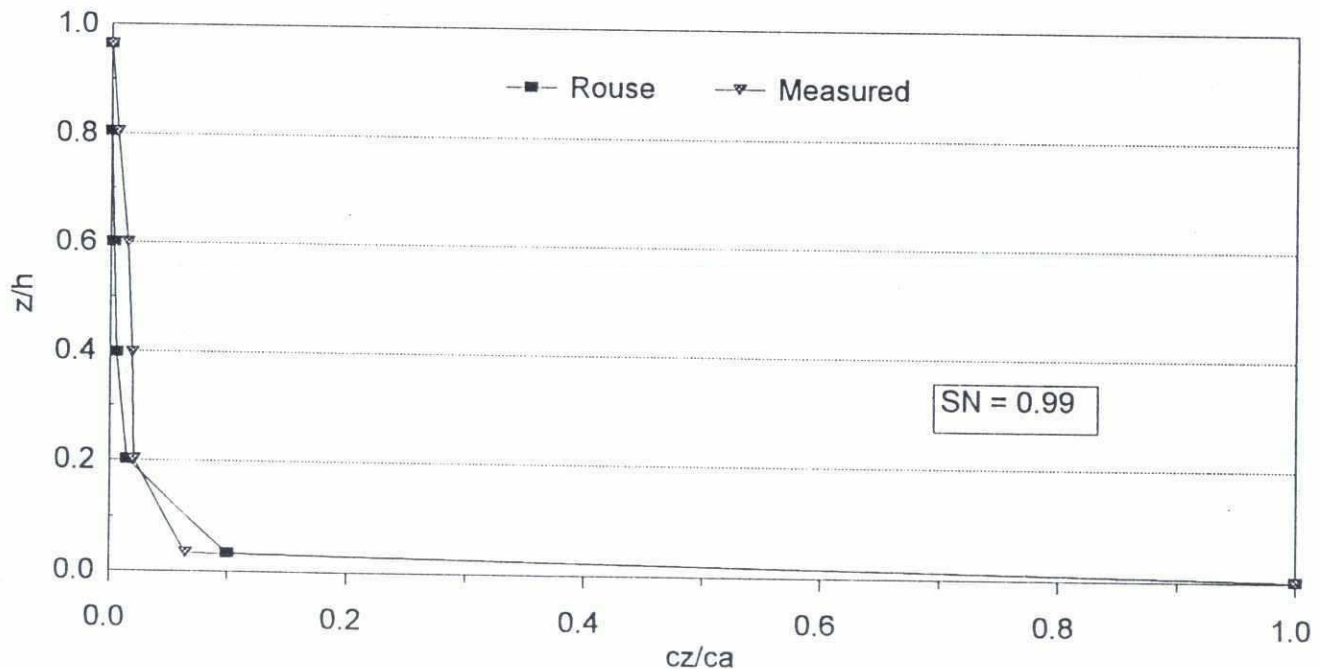


Figure 6.53 Concentration profile from pump-bottle and Delft Bottle with the fitted Rouse profile in the Jamuna River left channel near Bahadurabad measured on 6 August 1994.

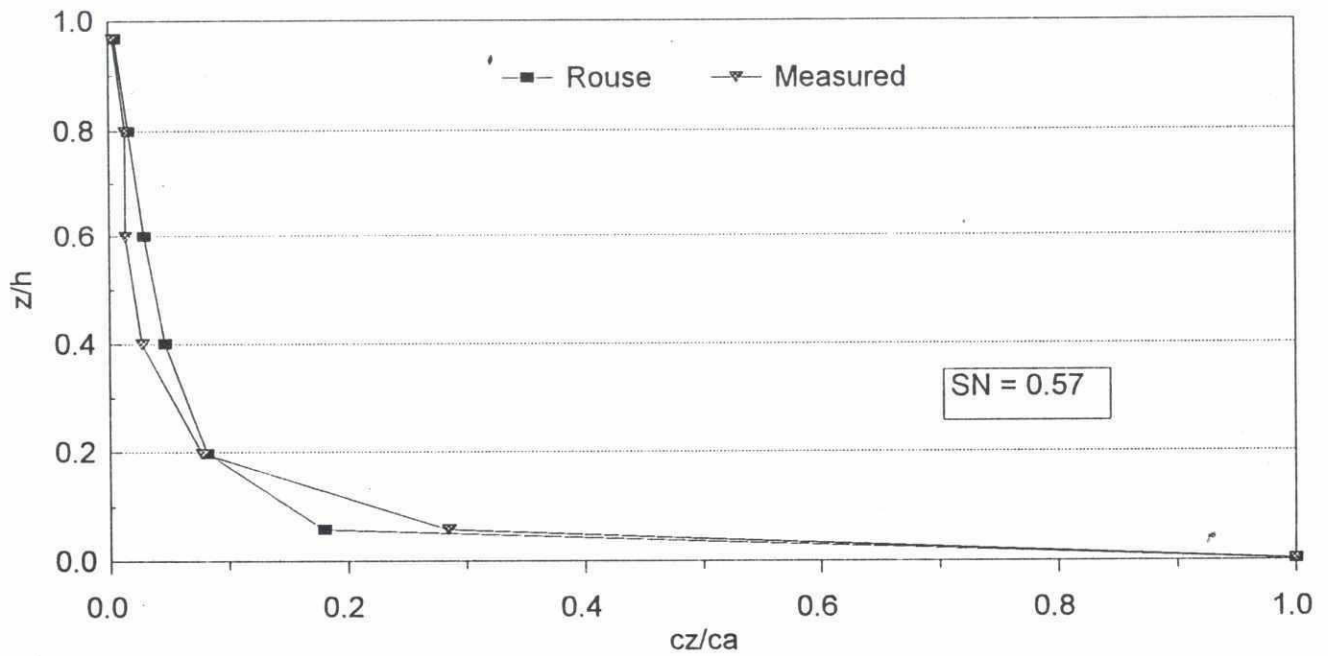


Figure 6.54 Concentration profile from pump-bottle and Delft Bottle with the fitted Rouse profile in the Jamuna River left channel near Bahadurabad measured on 8 October 1994.

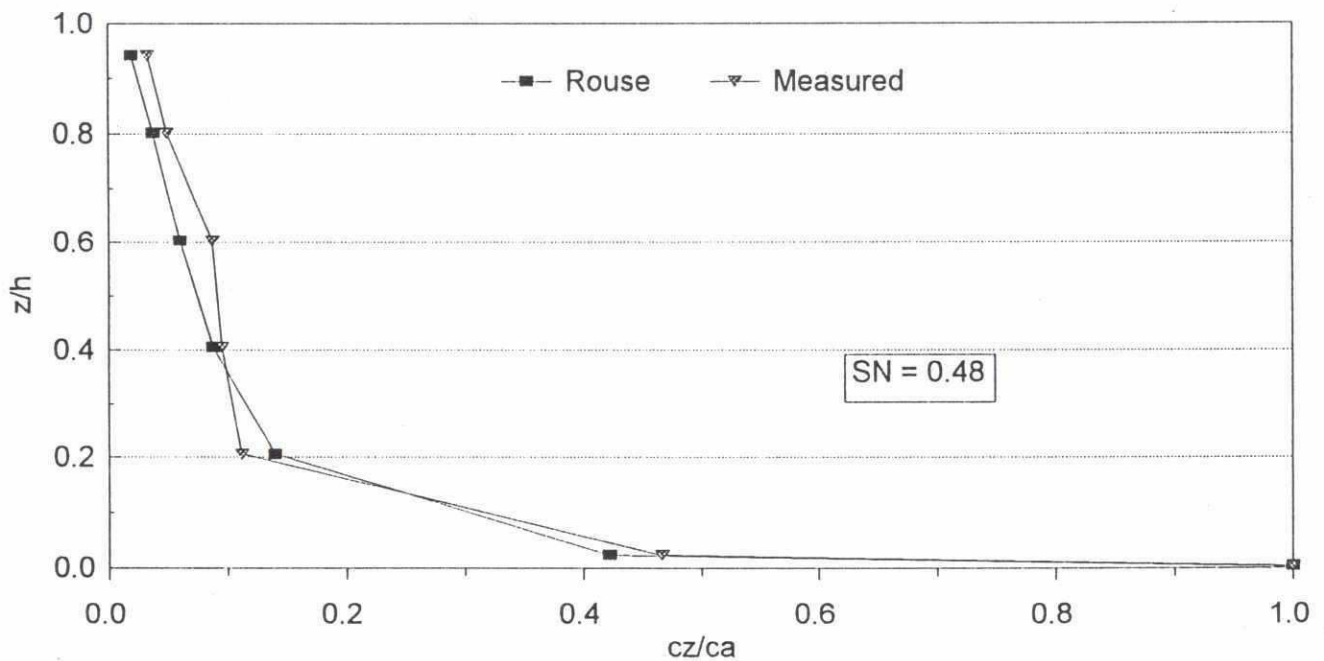


Figure 6.55 Concentration profile from pump-bottle and Delft Bottle with the fitted Rouse profile in the Jamuna River left channel near Bahadurabad measured on 8 November 1994.

Optimal Numbers of Measuring Verticals in a Transect

The Inter-agency Committee on Water Resources (1963) suggested the following measurement locations to estimate suspended sediment transport.

- single vertical at midstream,
- single vertical at thalweg or point of greatest depth,
- verticals at 1/4, 1/2, and 3/4 width,
- verticals at 1/6, 1/2, and 5/6 width,
- four or more verticals at mid-points of equal-width-increments (EWI),
- verticals at the centroid of equal-discharge-increments (EDI) across the stream.

ASTM (1987) recommended only the last two measurement locations. While all these suggestions are applicable for narrow rivers, the question is what distribution should be applied in Bangladesh rivers and how the measurement locations affect the sediment transport estimate.

To illustrate this a special measurement was made in the Jamuna River right channel on 27 July 1995. Detailed reporting on the effect of such a distribution is presented in Special Report No. 11 and in Annexure G8 of this report. Figure 6.56 shows transect T1 with 14 measurement verticals. In each vertical the suspended concentration was obtained by making measurements with collapsible bag samplers (see Annexure A for discussion). Three methods of vertical distribution were followed to estimate the transport. Table 6.3 shows the distribution using equal-width-increment distribution, suspended sand concentration distribution, and Froude number factor u^2/h distribution. The u^2/h distribution was adopted from Guy and Norman (1976). The suspended sand concentration distribution and the u^2/h distribution has been measured. The combination of verticals are chosen such that they best fit the distribution.

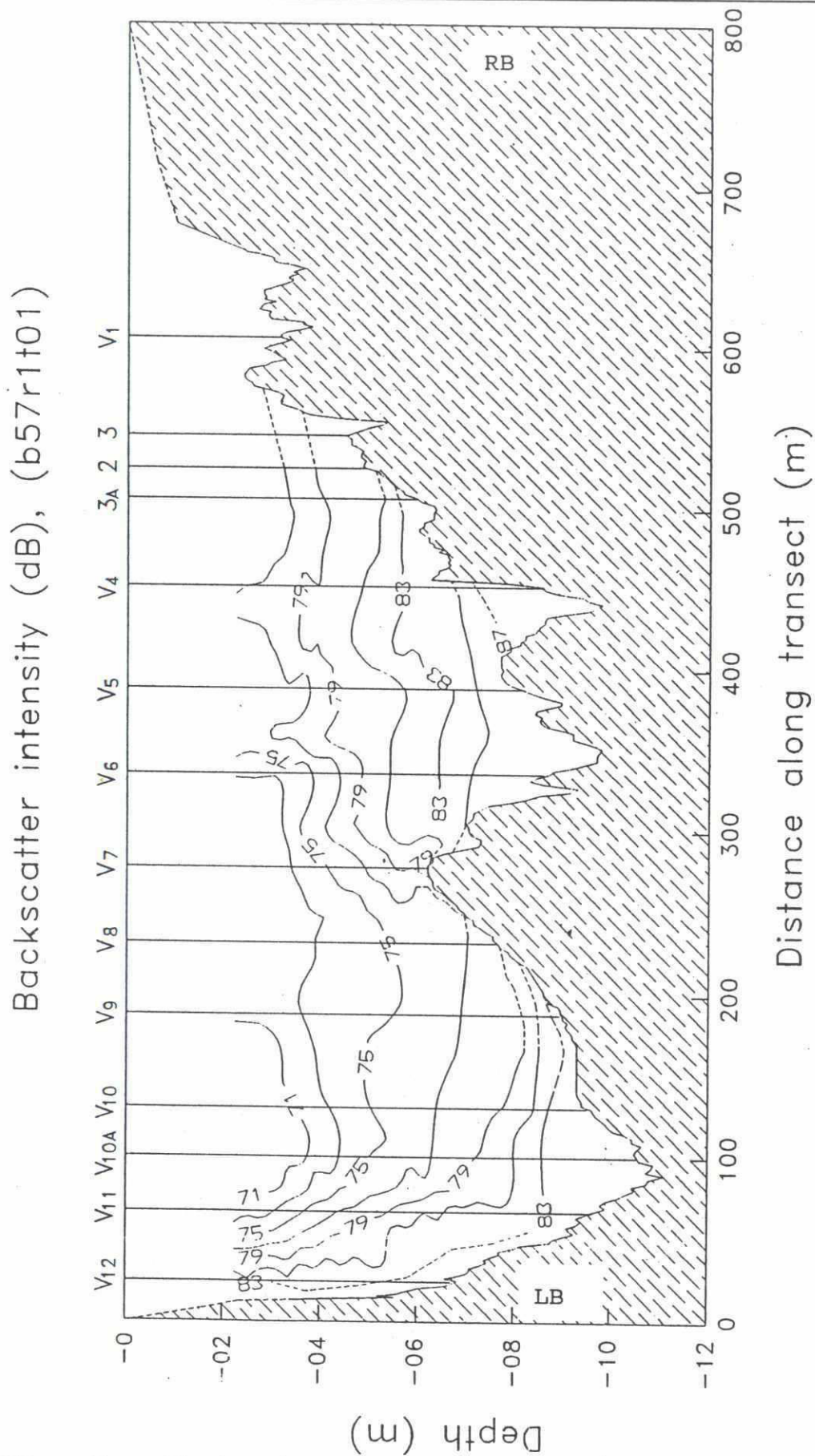


Figure 6.56

Transect T1 and several measurement verticals in the Jamuna River right channel near Bahadurabad measured on 27 July 1995.

Number of verticals	Arbitrary equal width increment distribution	Suspended sand concentration Distribution	U ² /h Distribution
2	10A, 6	7, 1	8, 2
3	10A, 6, 5	7, 1, 6	8, 2, 11
4	10A, 6, 5, 10	7, 1, 6, 2	8, 2, 11, 5
5	10A, 6, 5, 10, 4	7, 1, 6, 2, 3	8, 2, 11, 5, 7
6	10A, 6, 5, 10, 4, 11	7, 1, 6, 2, 3, 8	8, 2, 11, 5, 7, 10A
7	10A, 6, 5, 10, 4, 11, 9	7, 1, 6, 2, 3, 8, 12	8, 2, 11, 5, 7, 10A, 10
8	10A, 6, 5, 10, 4, 11, 9, 7	7, 1, 6, 2, 3, 8, 12, 9	8, 2, 11, 5, 7, 10A, 10, 6
9	10A, 6, 5, 10, 4, 11, 9, 7, 8	7, 1, 6, 2, 3, 8, 12, 9, 10	8, 2, 11, 5, 7, 10A, 10, 6, 3A
10	10A, 6, 5, 10, 4, 11, 9, 7, 8, 3A	7, 1, 6, 2, 3, 8, 12, 9, 10, 4	8, 2, 11, 5, 7, 10A, 10, 6, 3A, 1
11	10A, 6, 5, 10, 4, 11, 9, 7, 8, 3A, 12	7, 1, 6, 2, 3, 8, 12, 9, 10, 4, 10A	8, 2, 11, 5, 7, 10A, 10, 6, 3A, 1, 3
12	10A, 6, 5, 10, 4, 11, 9, 7, 8, 3A, 12, 2	7, 1, 6, 2, 3, 8, 12, 9, 10, 4, 10A, 3A	8, 2, 11, 5, 7, 10A, 10, 6, 3A, 1, 3, 12
13	10A, 6, 5, 10, 4, 11, 9, 7, 8, 3A, 12, 2, 3	7, 1, 6, 2, 3, 8, 12, 9, 10, 4, 10A, 3A, 5	8, 2, 11, 5, 7, 10A, 10, 6, 3A, 1, 3, 12, 4
14	10A, 6, 5, 10, 4, 11, 9, 7, 8, 3A, 12, 2, 3, 1	7, 1, 6, 2, 3, 8, 12, 9, 10, 4, 10A, 3A, 5, 11	8, 2, 11, 5, 7, 10A, 10, 6, 3A, 1, 3, 12, 4, 9

Table 6.3 Distribution of verticals according to different methods for estimating suspended sand transport.

Figures 6.57 and 6.58 show the suspended sand concentration distribution and u²/h distribution respectively. The results of the analyses are presented in Figures 6.59 to 6.61. On the y-axis of each graph the percent deviation in suspended sand transport (SST) was plotted against the verticals. The percent deviation was computed as,

$$\Delta = \left(\frac{q_{si} - q_{s14}}{q_{s14}} \right) \times 100$$

where,

q_{si} = suspended sand transport (SST) considering i numbers of verticals,

q_{s14} = suspended sand transport (SST) considering 14 verticals.

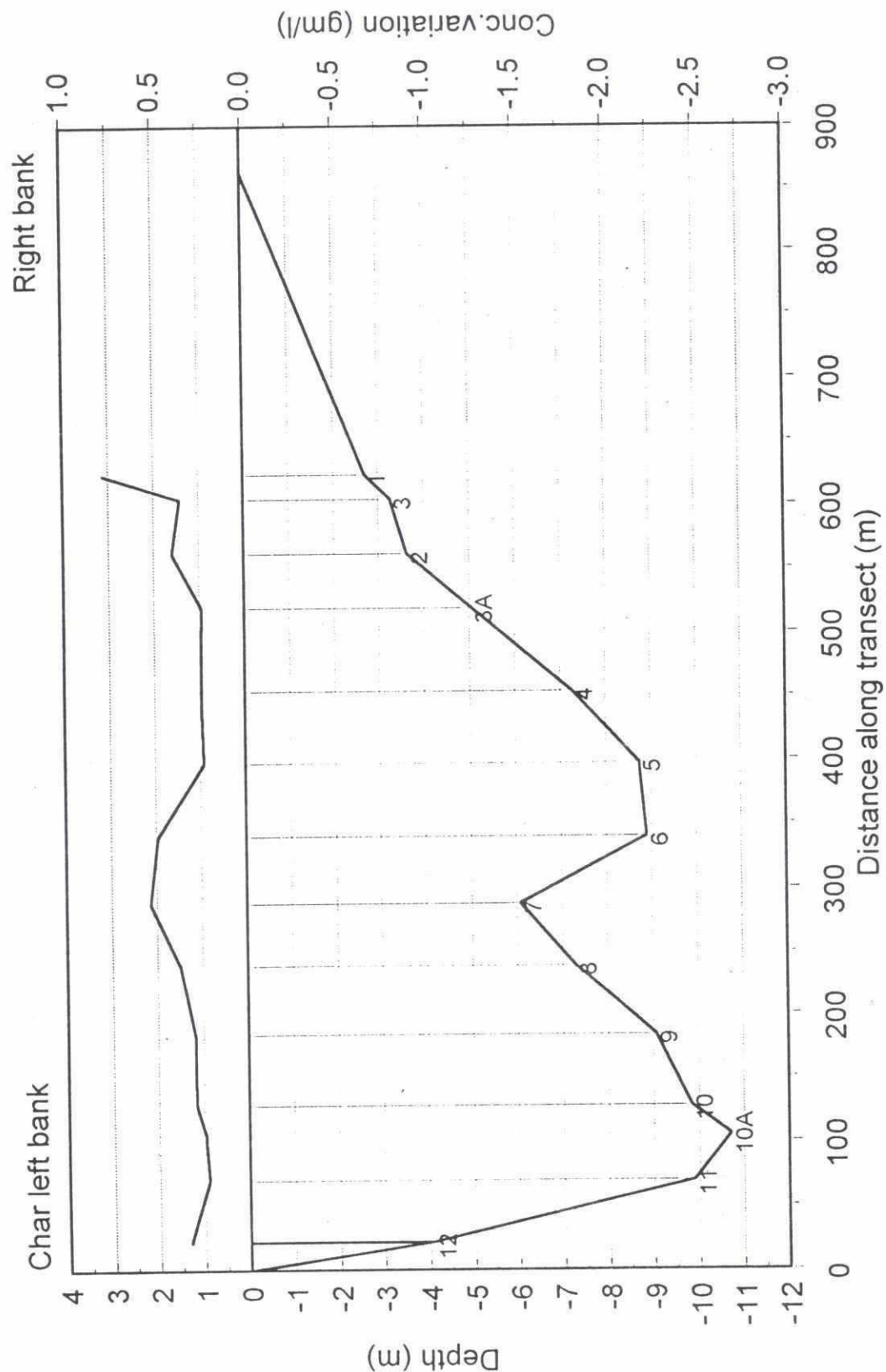


Figure 6.57 Transect T1 and suspended sand concentration distribution in the Jamuna River right channel near Bahadurabad measured on 27 July 1995

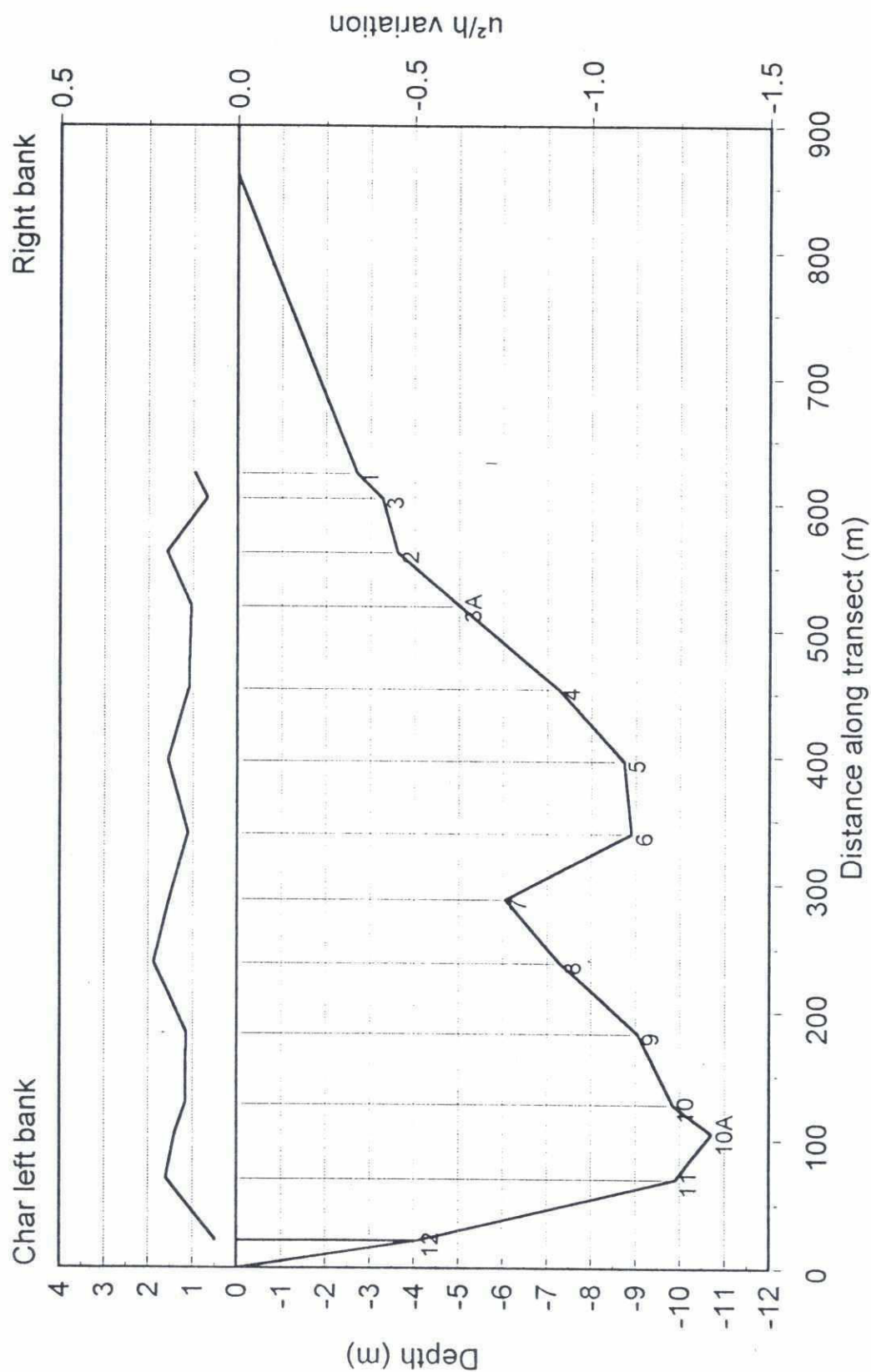


Figure 6.58 Transect T1 and u^2/h distribution in the Jamuna River right channel near Bahadurabad measured on 27 July 1995

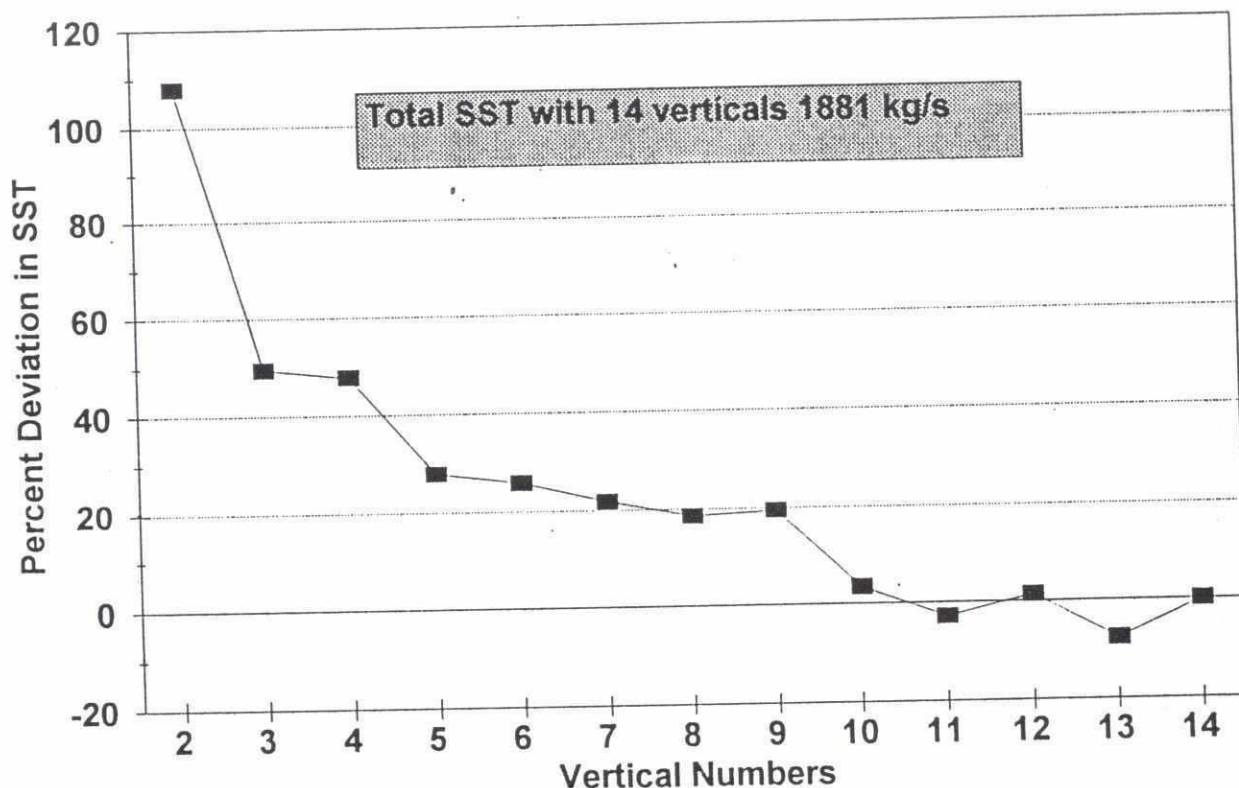


Figure 6.59

Percent deviation in SST at transect T1 in the Jamuna River right using different combinations of verticals according to equal width-increment method from the 14-vertical SST based on measurement on 27 July 1995

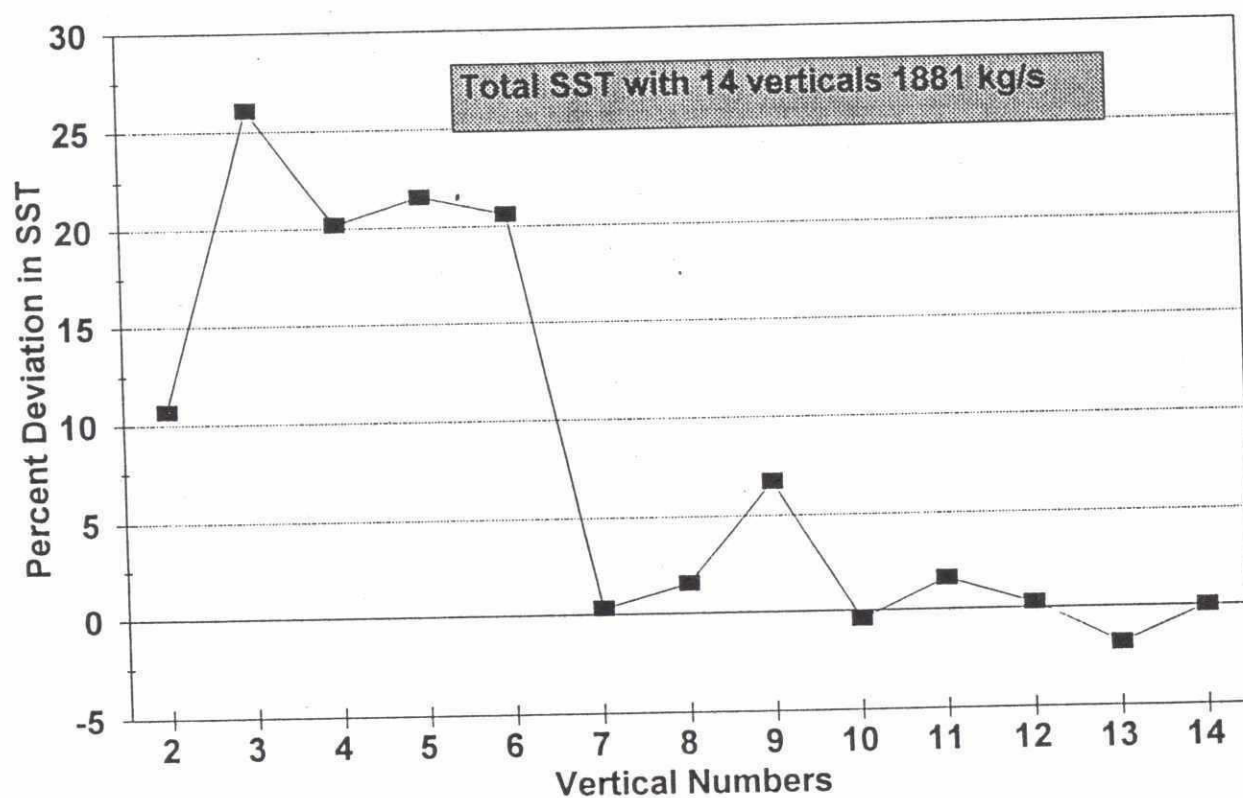


Figure 6.60

Percent deviation in SST using different combinations of verticals according to concentration distribution from the 14-vertical SST based on measurements of 27 July 1995.

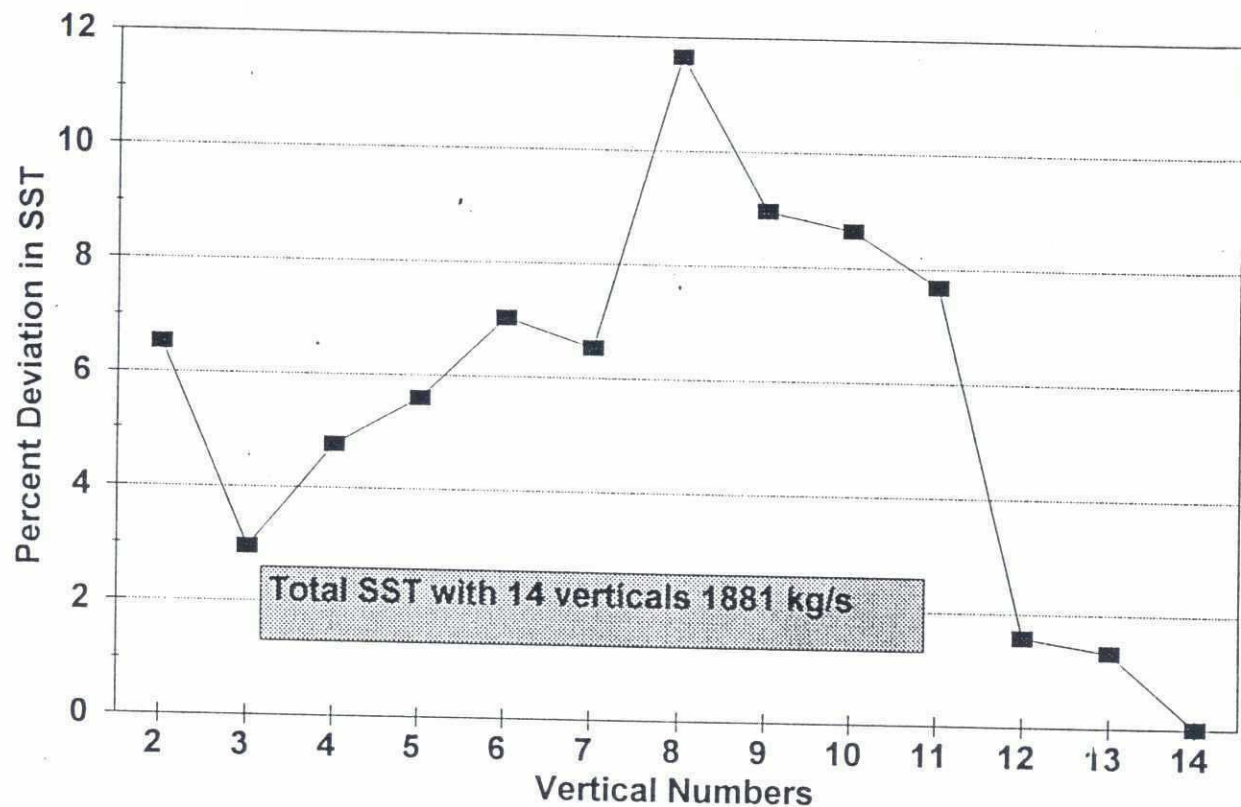


Figure 6.61 Percent deviation in SST using different combinations of verticals according to u^2/h distribution from the 14-vertical SST based on measurements of 27 July 1995.

Figure 6.59 shows that in the case of equal-width-increment distributions starting with measurements at the deepest locations, the Δ -value decreases rapidly as the numbers of verticals are increased. In this case, to limit the transport estimate within 20%, at least 7 verticals should be sampled. If the concentration distribution is followed as in Figure 6.60, the percent deviation decreases. Here it can be seen that the deviation can be reduced to about 5% if 7 or more verticals are sampled. Figure 6.61 shows the percent deviation based on u^2/h distribution. In this example, the percent deviation is less than the other methods. Therefore, we suggest that either concentration distribution or u^2/h distribution should be followed to limit the errors to an acceptable value. Since these two factors are not known *a priori*, a reconnaissance survey should be made to determine the concentration or u^2/h distribution. FAP24 obtains the concentration distribution through a reconnaissance survey using ADCP backscatter.

6.2 Near-bed Sediment Measurements

During both the routine measurements and the special surveys, experience was gained with the near-bed sediment measurements described in the following subsections (6.2.1 and 6.2.2, respectively). Near bed sediment transport is the mixture of bed load and suspended load in the lowest part of the sediment vertical. In the near bed layer a considerable increase of transport and variability of the transport takes place. The thickness of the near bed transport layer is dependent on the flow conditions. Measurements in the Jamuna River indicated that often a thickness of few dm is appropriate. However, more investigations on the subject are recommended.

6.2.1 Results from Routine Measurements

- **Instruments**

As listed in Table 5.2, the routine near-bed measurements were done with the following instruments:

- i) Helley-Smith (H-S) trap sampler (Helley and Smith, 1971) was used in every vertical where also depth-integrated sediment sampling was done.
- ii) After initial testing of the Delft Bottle (DB) in May 1994, the analyses showed consistent results and it was decided to use DB also in the routine surveys, for the time being additional to the H-S to get a good database for comparison.

The catches of both the instruments were used to analyze the grain size distribution and to compute the transport per unit of cross-sectional area ($\text{kg/m}^2\text{s}$), called the sediment flux.

- **Methods**

In each measurement vertical where suspended load was determined, the H-S trap sampler was used two-times (in view of the considerable scatter observed earlier, see 5.2). The duration of sampling was often 2 minutes, but in case of heavy transport, the duration had to be shortened to one minute. In the lean season, the sampling time was extended to 5 minutes and more, in order to get a measurable catch.

The DB in general was used in 2 points, at 0.05 m and at 0.15 m above the river bed. Sometimes, in the reference vertical also at 0.25 and 0.35 m above the river bed was measured. During the special measurements, nearly always these four points in the vertical were measured, see next subsection). As discussed before, initially, the DB was used in addition to the H-S, (in the second half of 1994). Based on the results (see Annexure C), it was decided to replace the H-S sampling by the DB sampling, especially in the high flows (monsoon, 1995). To improve the coverage, a second DB was procured. From the smaller vessels, however, the H-S had to be used.

- **Experience with Instruments**

As learned in the first phase, the H-S sampler is difficult to judge in the high flows because of possible scooping and problems with the determination of the sampling time. On the other hand, the instrument is very useful in the mid-flow ranges (1 to 2 m/s), as coarse transport concentrates then in the lowest cm of the vertical where only the H-S sampler can be used.

- The DB in the frame could be operated with ease. A number of small improvements, suggested by the PA, were realized.
- The bottom plates of the standard frame of the Delft Bottle were too small in the fine sands of the Jamuna. Therefore, the recommendation of the RSPMU was followed to enlarge the plates by welding 'skins' under the plates.
- the vertical position of the intake nozzle appeared not very rigid, which is specially required when measuring at 0.05 m above the riverbed. Uncertainties of a few cm are then not acceptable. Therefore, fixation of the bottle to the hanging bar was improved by increasing the width of the bar. Both the connection between the bottle and the bar and the connection between the bar and the frame became better and more stable.
- In the high flows, the drag of the DB was also considerable and it took a lot of experience to determine the sampling period like the H-S.
- The scatter of the transport according to the Delft Bottle at 0.05 m above the river-bed appeared to be considerably more than the scatter at 0.15 m above the river bed.
- **Intercomparisons**

For the comparison between the H-S and the DB during routine surveys, reference is made to the Annexure C). In this Annexure, the data from the routine measurements of August to November 1994 at Bahadurabad was used. Some important conclusion are:

- The analyses show that, in general, the Helley-Smith sampler underestimated near-bed transport rates. This conclusion was reached by comparing the Helley-Smith transport rates with the Delft Bottle transport rates at 5 cm and 15 cm above the bed. Figure 6.62 shows the comparison between the Helley-Smith flux and the Delft Bottle flux at 5 cm above the bed; the underestimation was clearly noticeable. The primary reason for the underestimation is that the Helley-Smith sampler has a mesh size of 0.25 mm, through which finer particles (which are dominant in Bangladesh rivers) escape. For coarser fractions, however, the reason for the underestimation is not as obvious. Figure 6.63, for example, clearly shows that the Helley-Smith sampler measuring higher transport rates for fractions sized 0.125-0.25 mm. The transport estimates for the 0.25-0.50 mm size fractions were not so obvious. Out of 7 samples analyzed, 5 samples indicated that the Helley-Smith sampler overestimated the transport rate for fractions sized 0.25-0.5 mm. This is understandable, since the Helley-Smith measured more to the bed than the Delft Bottle at 5 cm above the bed. Figure 6.64 shows that as the finer particles escape the Helley-Smith sampler, the median grain size of the sampler becomes more than the Delft Bottle sampler.
- The correlation between the sediment flux and the depth averaged flow velocity of the direct transport sampler is much better than the correlation of the depth integrated sampler (Figure 6.65). The depth-integrated transports, have a weak correlation; this is because they took measurements also at higher levels in the water column.
- The near-bed transport in an arbitrarily defined layer of about 20 cm above the bed (see also Section 6.2) which represents some 15 to 25% of the total sediment load. For the higher transport rates, 'these ratios' tend to decrease (Figure 6.66). Since it moves near the bed, its contribution to bed deformation and river morphology is very important, thus it should be measured (Peters 1994). Conventional suspended sediment samplers can not reach that close to the bed.

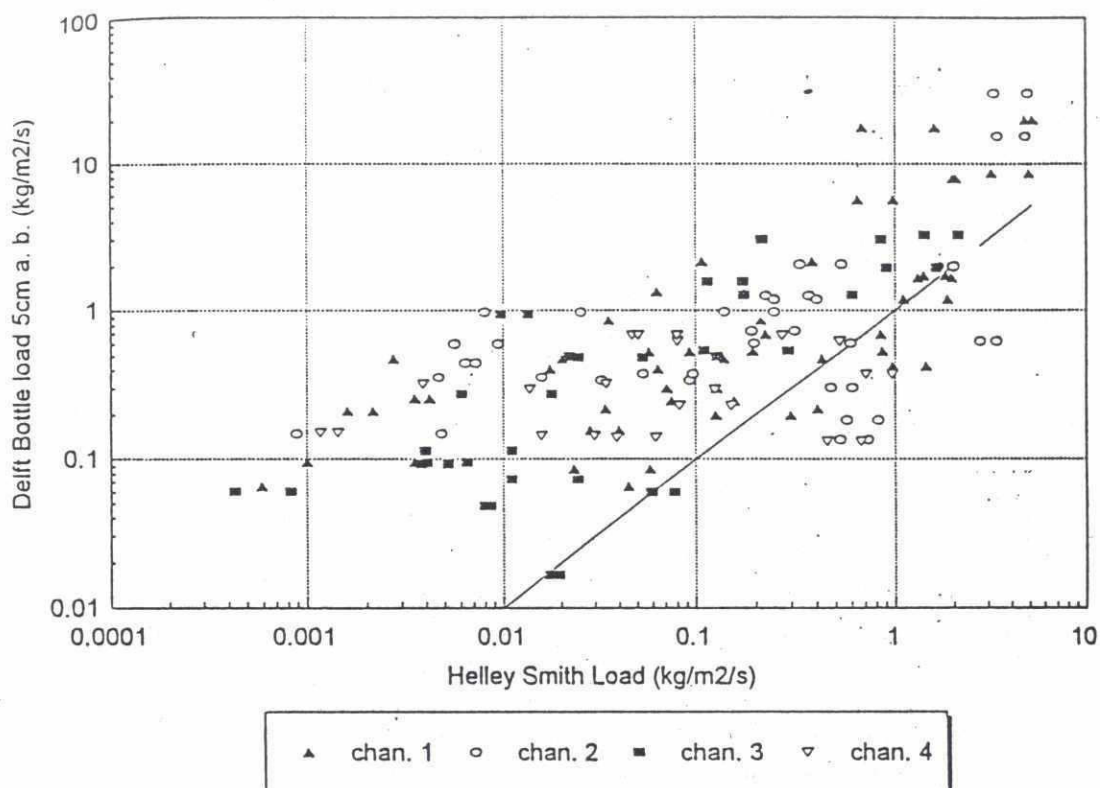


Figure 6.62 Comparison of sand transport measurements at 5 cm above bed with Helley-Smith transport in the Jamuna River at Bahadurabad on August to November 1994.

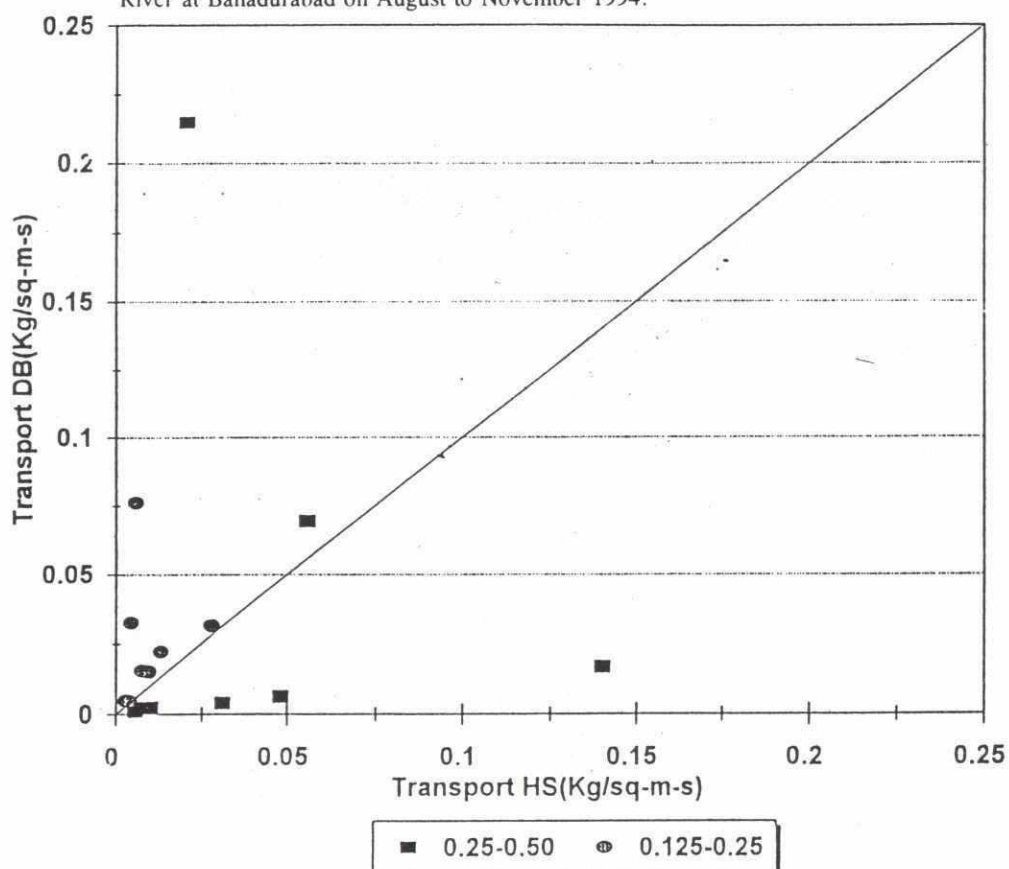


Figure 6.63 Comparison of sand transport measurements at 5 cm above bed with Helley-Smith transport in two sizes of fractions measured in the Jamuna River near Bahadurabad in March 1995.

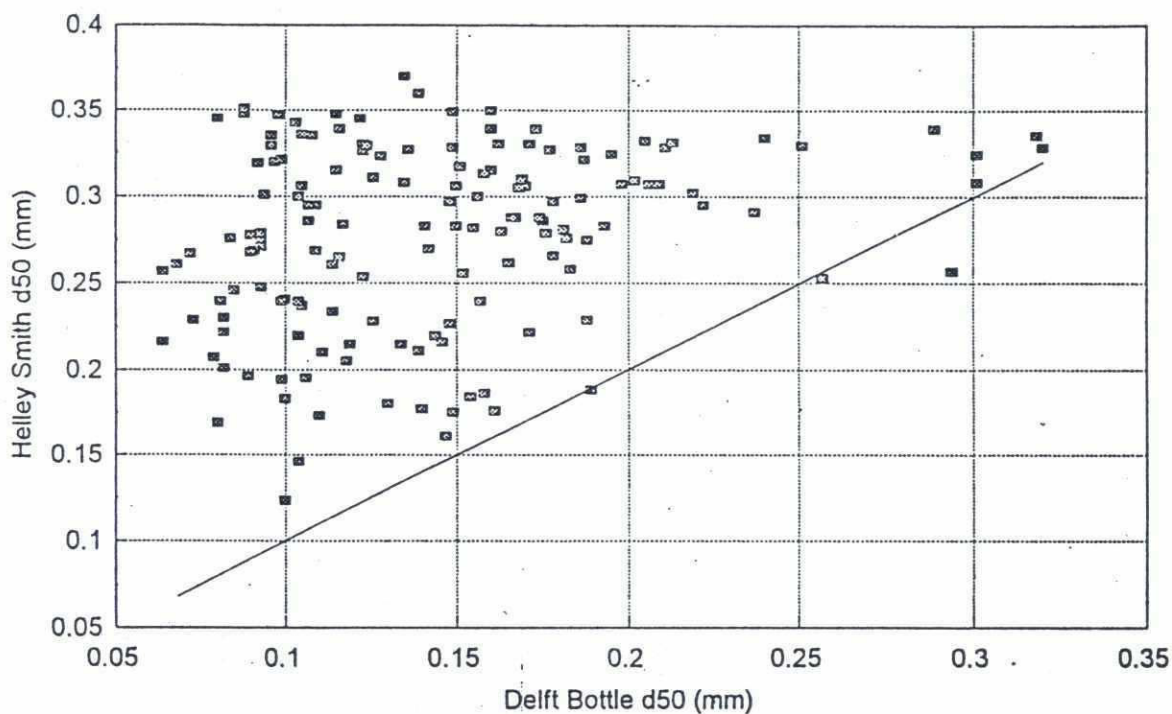


Figure 6.64 Median grain diameter of Helley-Smith samples compared with the same of the Delft Bottle samples based on measurements of August to November 1994 in the Jamuna River at Bahadurabad.

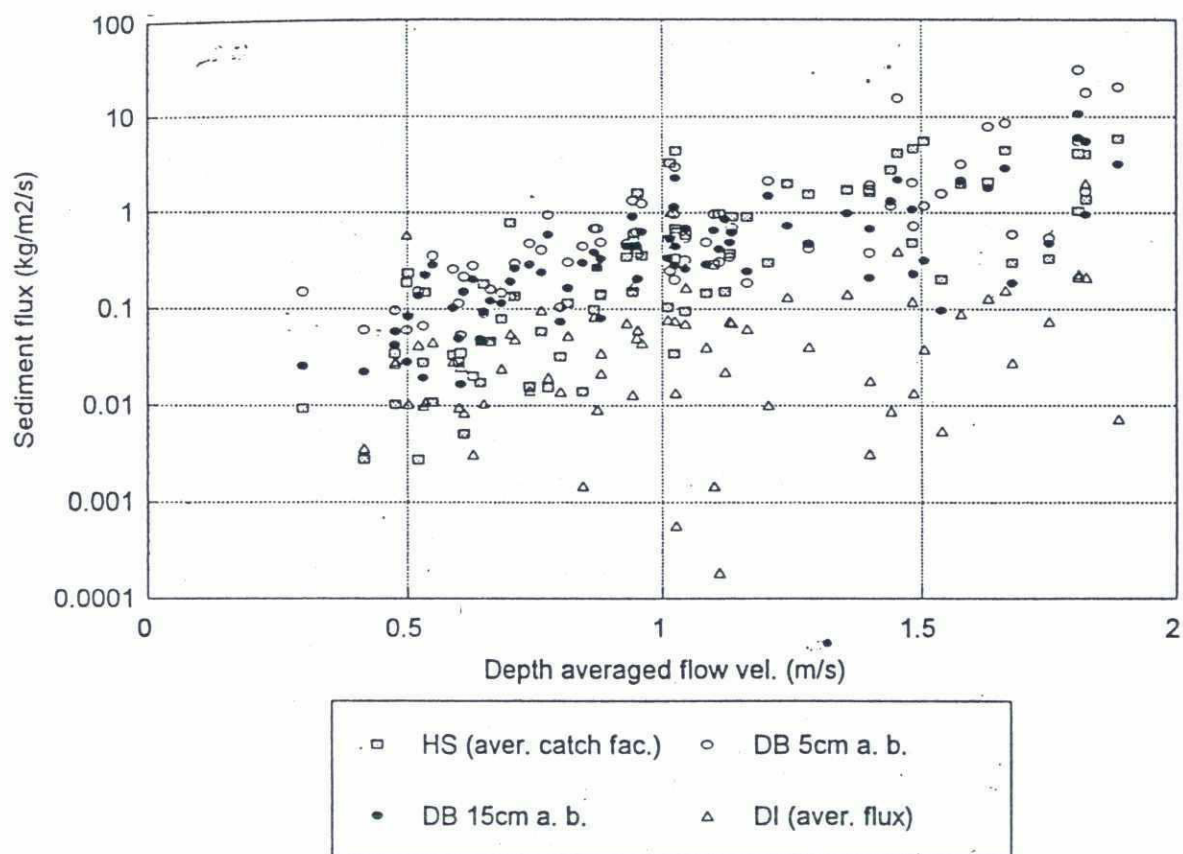


Figure 6.65 Scatter plot of sand transport flux using various samplers with depth-averaged velocity based on measurements of August to November 1994 in the Jamuna River at Bahadurabad.

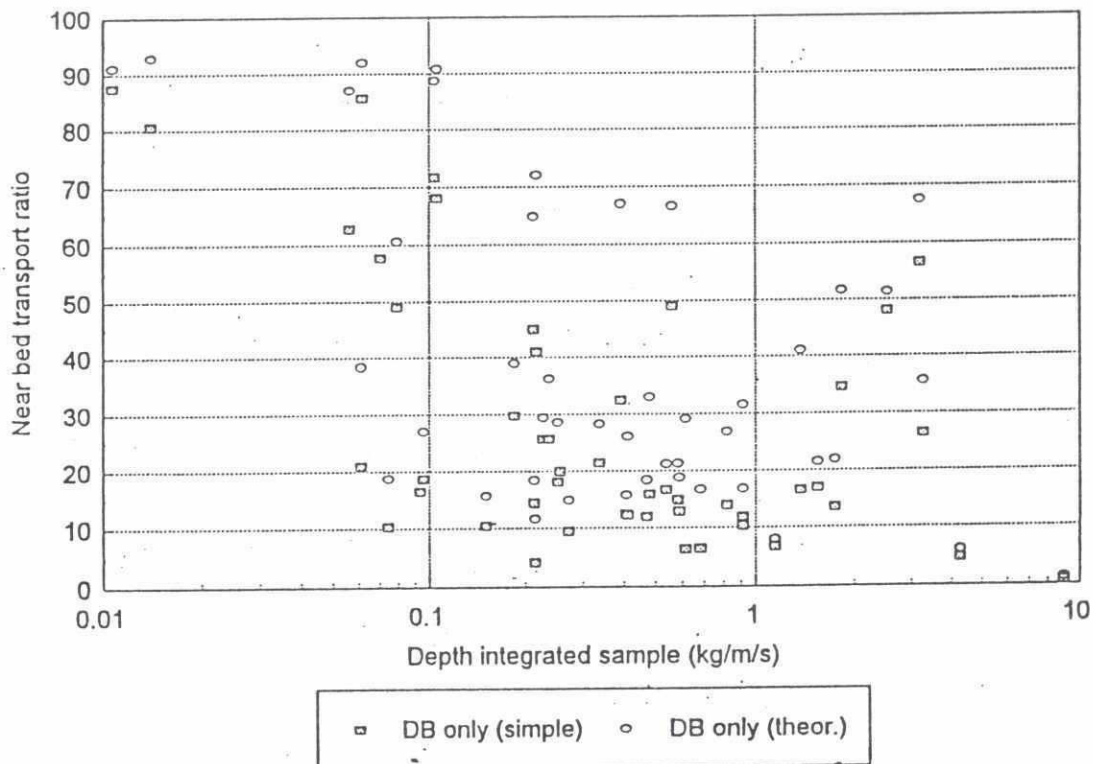


Figure 6.66 Sand transport in the near-bed zone as a ratio of the total sand transport estimated from Delft Bottle measurements using two different methods based on measurements of August to November 1994 in the Jamuna River at Bahadurabad.

6.2.2 Results from Some Special Measurements

• Instruments

During the second phase of the project, several special measurements were executed to study the measuring techniques needed to measure the near-bed processes in an appropriate way. These techniques were:

- i) H-S trap sampler
- ii) DB in a frame
- iii) Dune tracking including the use of the side-scan sonar
- iv) Pump-bottle system, and
- v) MEX turbidity

During the special surveys the H-S and the DB samplers were used most frequently for further testing as these were the techniques for routine surveys. The dune-tracking was not done to test the method, but mainly to make a bed-form inventory and to study the changing bedforms as a function of time. The pump-bottle system was slightly modified by installing a bottom plate under the carrier by which the intake nozzle and the main sensor position was 0.25 m above the river-bed when the carrier was placed on the river-bed. This made it possible to compare the Delft Bottle with the pump-bottle and the MEX at this position.

• Special Surveys

Particulars of special measurements on near-bed transport are presented in the following Table.

Serial No.	Survey Dates	Survey types	Flow ranges (m/s)
1	28-29 May 1994	First tests with DB	1-1.3
2	1-4 August 1994	Pump-bottle and DB over the dune profile	1.5-2.0
3	4-12 December 1994	Near-bed	-
4	1-4 April 1995	pb-DB-MEX	0.7 - 0.9
5	27-30 May 1995	near bed transport	1.6-2.9
6	22-26 May 1995	plume survey	1.5-2.5
7	26-30 July 1995	Spatial density of measurements	1.8 - 2.8

Table 6.4 Special near-bed transport measurements at Bahadurabad during phase II

Detailed reporting on these measurements are made in Annexures G2 to G8. Only a summary is presented here.

• Experience with instruments

- As observed earlier the H-S is losing the finer parts of the sediments which are passing the 250 μm mesh width of the sampling bag. Practically, all the fractions $< 125 \mu\text{m}$ are lost but a considerable part of the 125 - 250 μm fraction is caught.
- In low flows the H-S sampler can be handled with ease. There has been no scooping and the sampling period was long and could be determined accurately. However there is hardly any transport of coarse sediments when the flow is lower than say 1 m/s. When only a few grains are moving and if a few are missed, the error is high. But the low transports are not significant on overall considerations. From these considerations and earlier observations during the high flows, the H-S is preferred in the mid-flow ranges.
- The representativity of the DB in the frame is questionable, when the sampler is used on an irregular river bed. After each measurement, the sampler has to be lifted to take the sample out and then lowered again. The question is whether the sampler comes back to the same position on the river-bed. From the irregularities on the river-bed, it is known that local bed slopes (e.g. at the lee-side of a dune), are sometimes in the order of 45 degrees, which means depth variations of meters when the inaccuracy of the horizontal positioning is a few meters (extreme situation), often the DB is used 2, 3 or 4 times in one measurement vertical and near-bed transports are plotted then nicely at 0.05, 0.15, 0.25 and 0.35 m above the river-bed. It is noted that especially on deep water (say 15 m) and high currents ($> 2 \text{ m/s}$), it is clear that positioning of the instrument within a few meters is hardly possible. The only way to avoid these problems is by attempting to select an appropriate area within a relatively flat river bed.

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This type of uncertainties is obviously not specific for the DB. They are valid for other samplers as well.

- The losses through the DB are in broadlines nearly everything below 63 μm and part of the 63 - 125 μm fraction.

- **Testing the DB on Sleigh**

The first special measurements were dedicated to the Delft Bottle as this was the new introduced instrument for the near-bed measurements. In this context, two measurements need to be mentioned:

- i) the special survey of May 1994
- ii) the special measurements of August 1994.

The main results of these surveys are summarized hereafter

- May 1994: The first testing of the DB was very successful. Results were presented by the PA in his seventh mission report and by the RSP (see Annexure G2 of the present report). The Delft Bottle measurements were found consistent over the vertical. Comparison of the sediment sizes of the DB and H-S samples confirmed that DB was losing finer fractions.
- August 1994: In August 1994, some special sediment transport measurements were made with the Delft Bottle on a sleigh over the dune profile. Measurements were made on the crest, stoss, and lee side of the dune in the left channel of the Jamuna River near Bahadurabad. Detailed results are provided in G3. One measurement was taken in a flat bed situation in the right channel of the river. Figure 6.67 shows the measurement verticals over a dune profile in the left channel of the Jamuna River near Bahadurabad. Local transports were computed by different sizes of fractions at 5 cm, 15 cm, 25 cm and 35 cm above the bed. Figures 6.68 to 6.72 show the results of these measurements. In all the cases, the dominant size fraction for transport was 0.125-0.25 mm. In most cases, the next dominant fraction size near to the bed (i.e., 5 cm above the bed) was 0.25-0.5 mm. As indicated earlier, the fractions sized < 0.125 mm were not well-represented by the Delft Bottle.

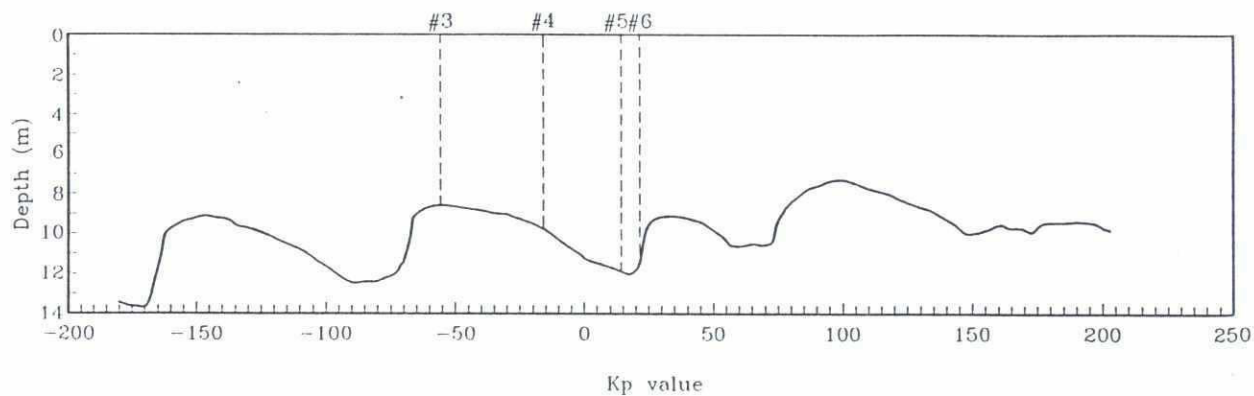


Figure 6.67 Dune profile in the Jamuna River left channel near Bahadurabad over which near-bed sediment measurements were made in different verticals on 1-4 August 1994.

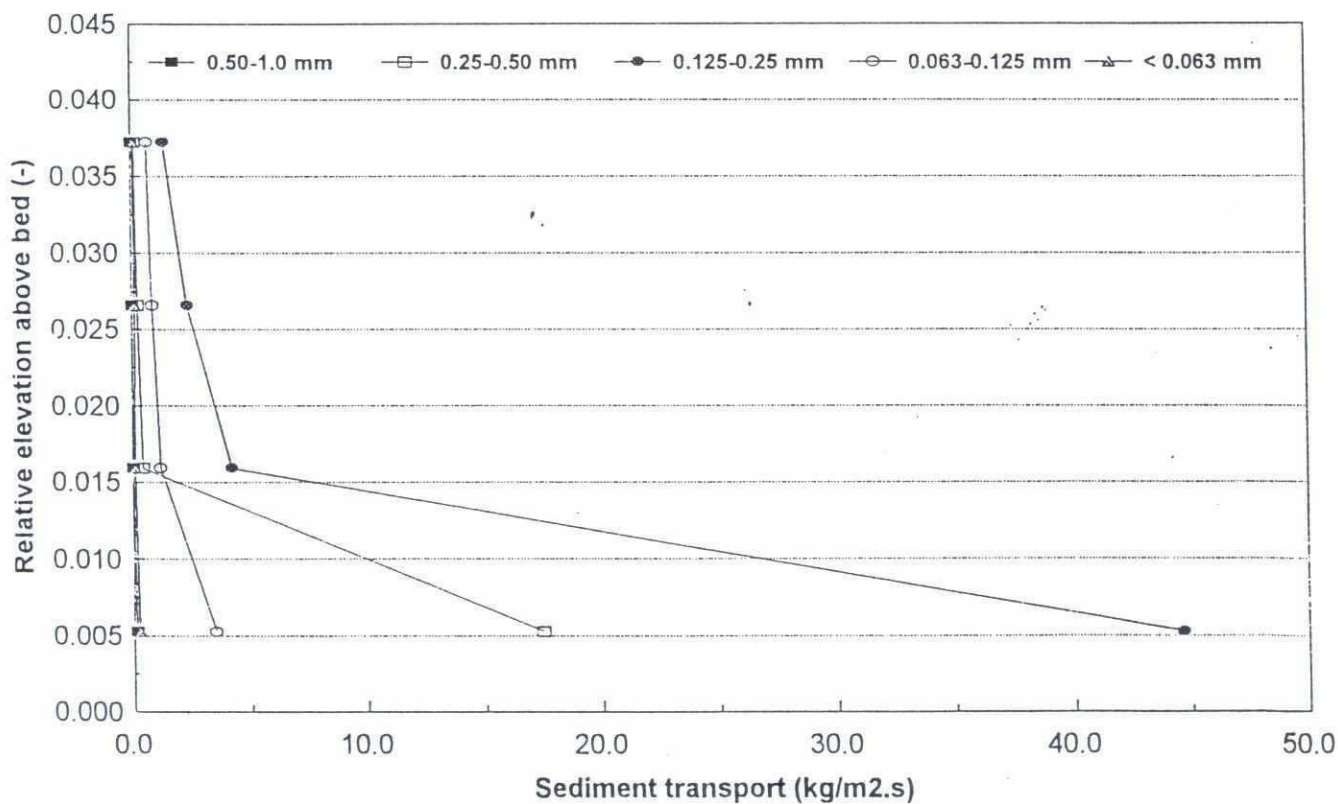


Figure 6.68 Near-bed Delft Bottle sand transport according to different sizes of fractions in the Jamuna River left channel near Bahadurabad at the dune crest on 3 August 1994.

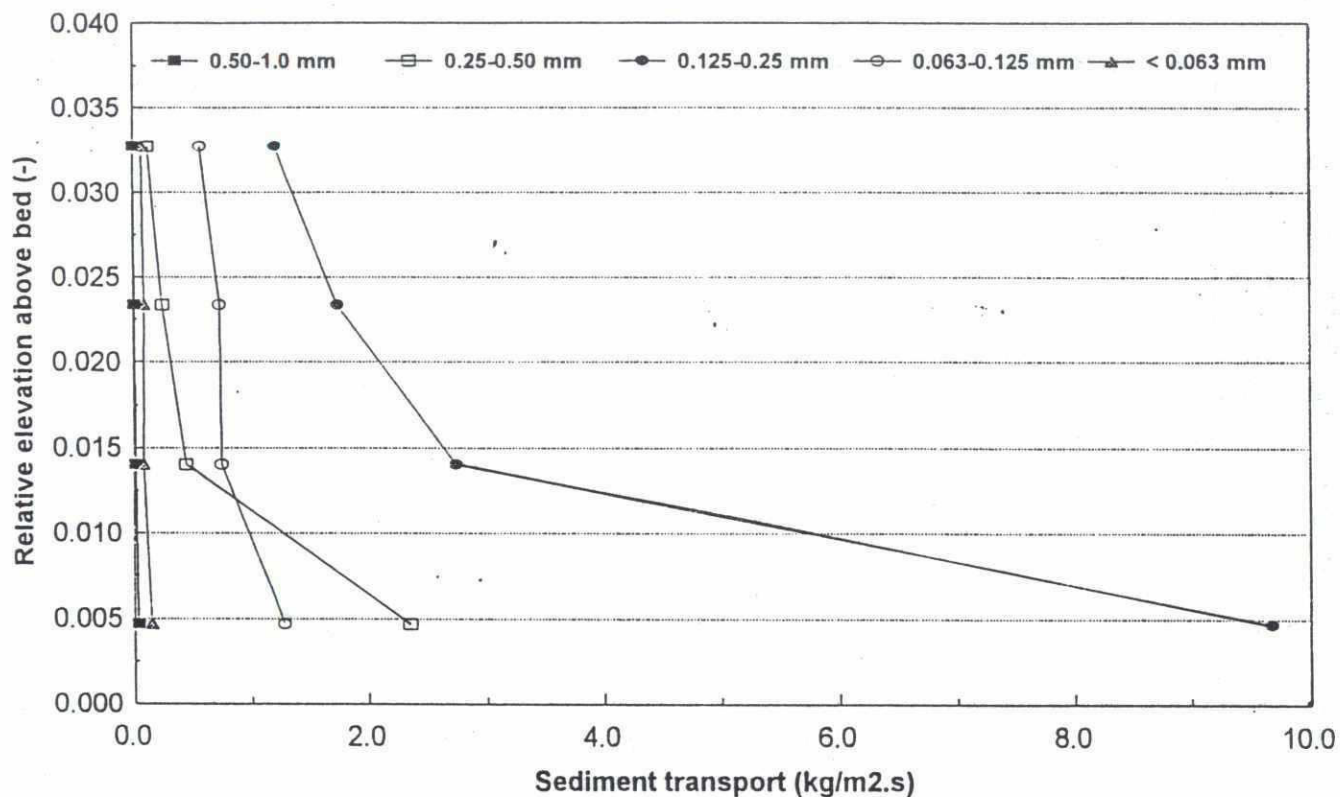


Figure 6.69 Near-bed Delft Bottle sand transport according to different size fractions in the Jamuna River left channel near Bahadurabad at the dune stoss-side on 3 August 1994.

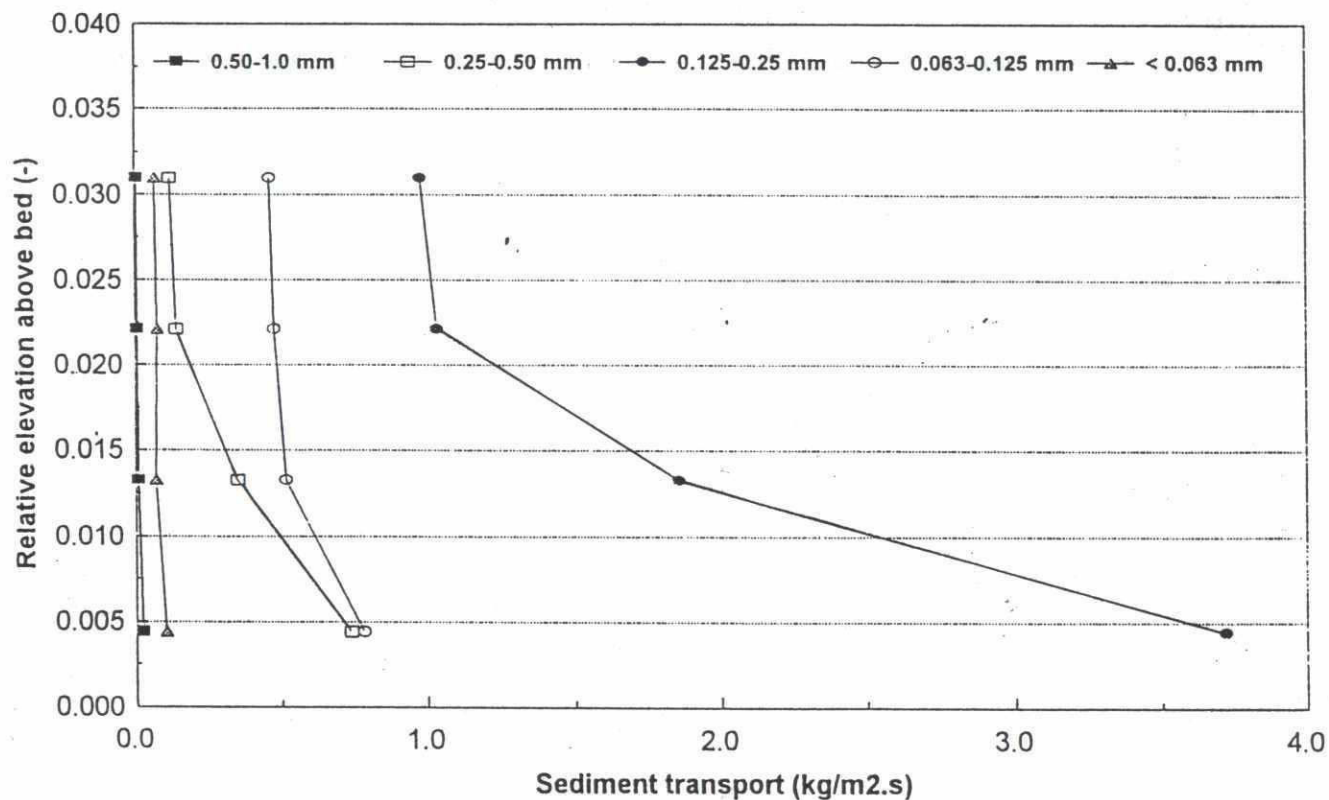


Figure 6.70 Near-bed Delft Bottle sand transport according to different sizes of fractions in the Jamuna River left channel near Bahadurabad at the dune trough on 3 August 1994.

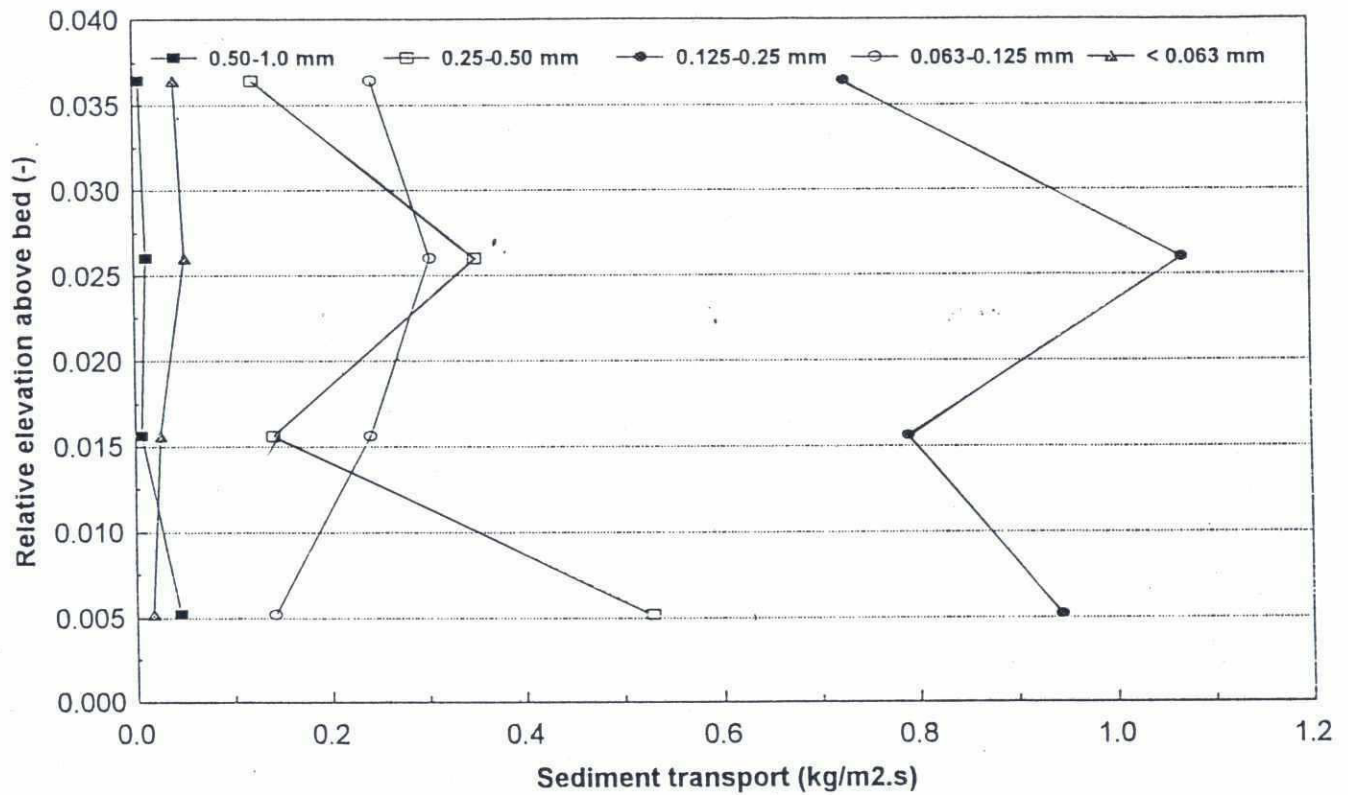


Figure 6.71 Near-bed Delft Bottle sand transport according to different sizes of fractions in the Jamuna River left channel near Bahadurabad at the dune lee side on 3 August 1994.

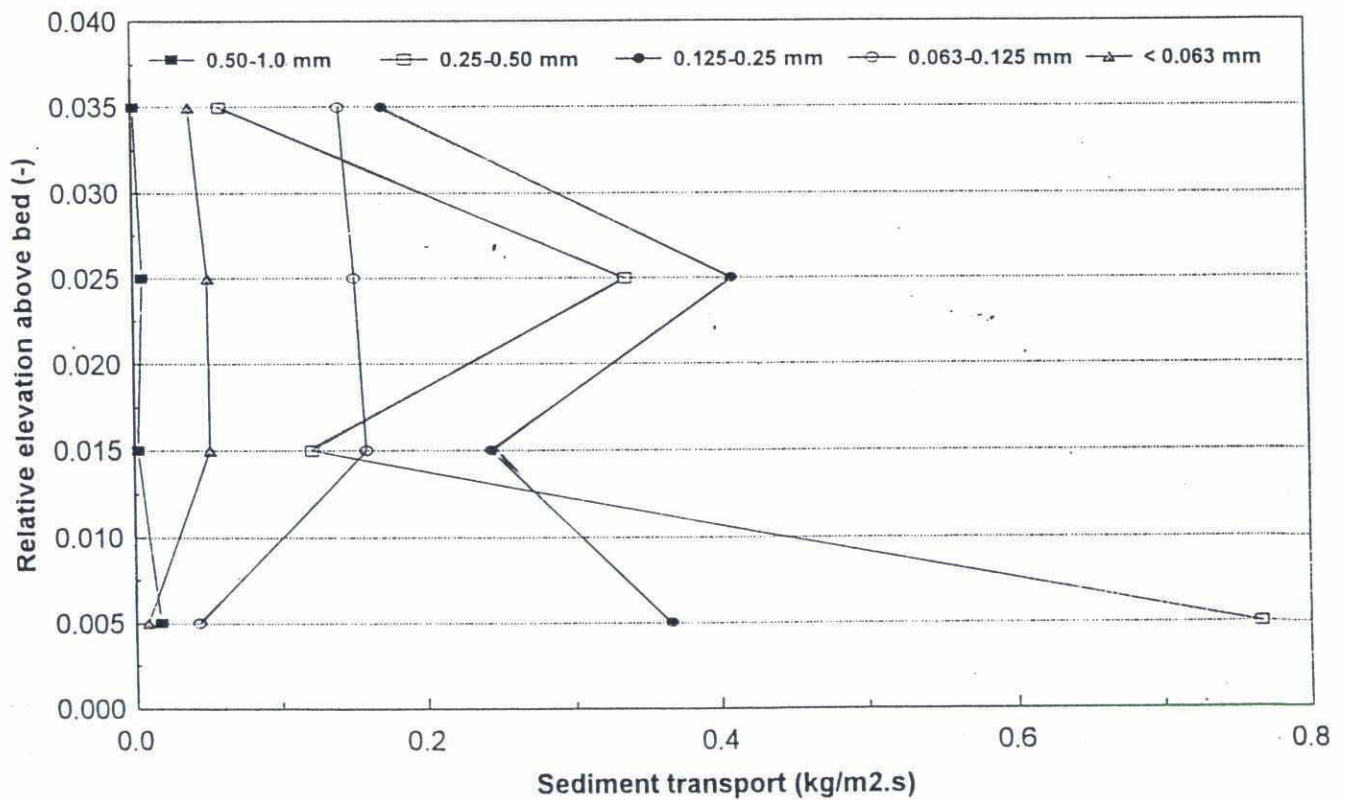


Figure 6.72 Near-bed Delft Bottle sand transport according to different sizes of fractions at a relatively flat-bed situation in the right channel of the Jamuna River near Bahadurabad on 4 August 1994.

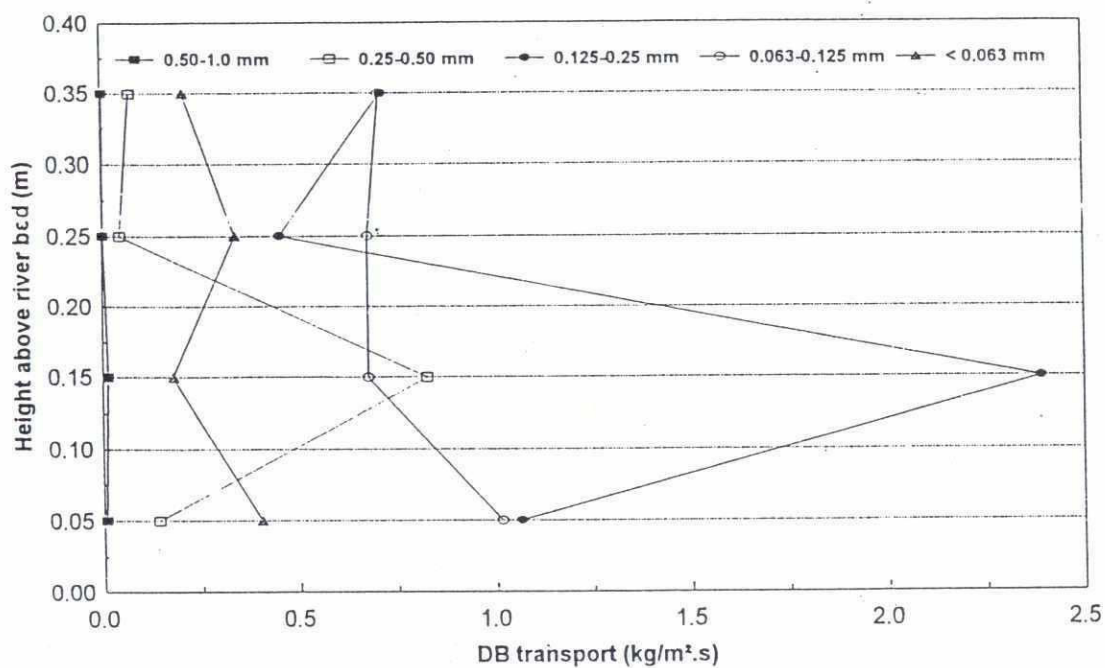
The measurements indicate that very high transport took place at the crest of the dune at vertical 3 (Figure 6.68), followed by stoss side transport at vertical 4 (Figure 6.69), and then transport at the trough at vertical 5 (Figure 6.70). At all three of these locations, the local transport over the vertical was very regular. At the lee side of the dune (Figure 6.71) and surprisingly also at the flat bed (Figure 6.72), the transports over the vertical were very erratic. A smooth increase of transport towards the bed was absent in these cases. This exercise indicates the difficulty in interpolating or extrapolating near-bed transports. Since a large variation of transports takes place over a bed-form, considerable overestimation or underestimation is possible. For example, when the measurements over a dune crest are used to interpolate transports between measuring verticals, overestimation can occur. The contrary may happen when the lee side or flat-bed measurements are used.

Moreover, the Figures (especially Figs. 6.68 to 6.72) show that the transport from 0.35 m to 0.15 m is increasing gradually and only in the lowest measuring point, the transport increases sometimes tremendously. This is a regular shape of the transport vertical as was confirmed many times during the other special measurements.

July 1995: On 26-30 July 1995 measurements were made in the Jamuna River left and right channels near Bahadurabad. Figure 6.38 shows the measurement locations and suspended sediment transport optimization is reported in sub-section 6.1.2. Annexure G8 describes the measurement results in detail. Some DB results are shown in Figures 6.73 to 6.77. The Delft Bottle transports per size fraction are shown in Figure 6.73 for vertical RA. As with other observations, the dominant transport occurs in the 0.125 - 0.25 mm size fraction. For different locations in the left channel, the transport and the grain size are consistent over the vertical (Figures 6.74 to 6.77)



Jamuna River, Bahadurabad, Vertical RA
27.07.95, Time : 15:56-16:12



Jamuna River, Bahadurabad, Vertical RA
27.07.95, Time : 16:17-16:30

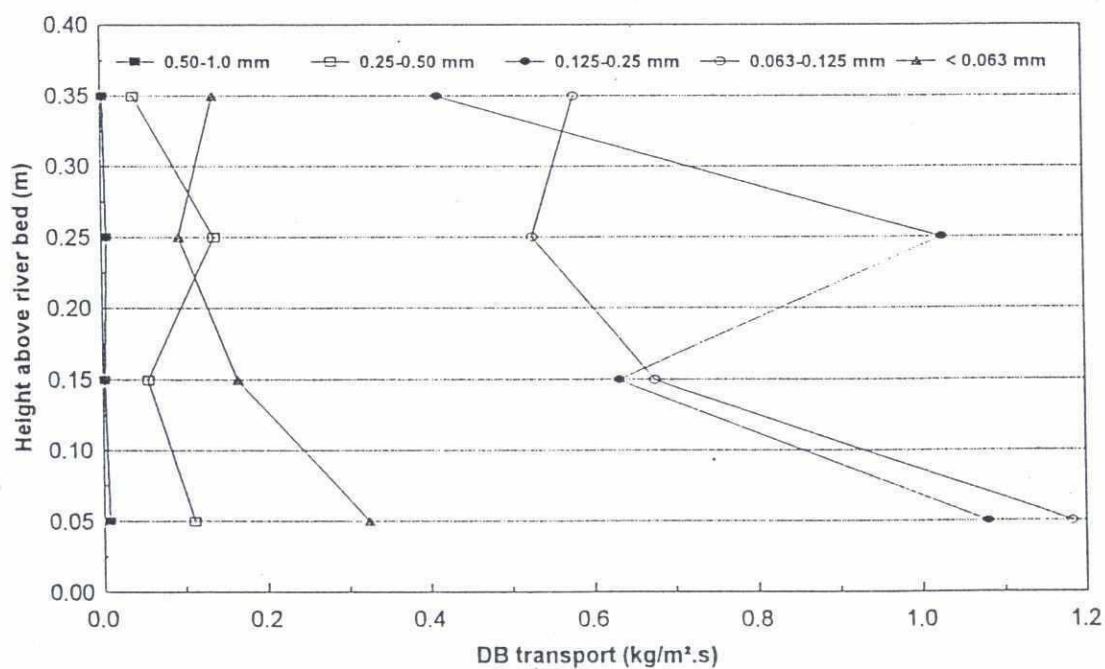


Figure 6.73 Near-bed transport by Delft-Bottle in the vertical RA on the Jamuna River right channel near Bahadurabad on 27 July 1995

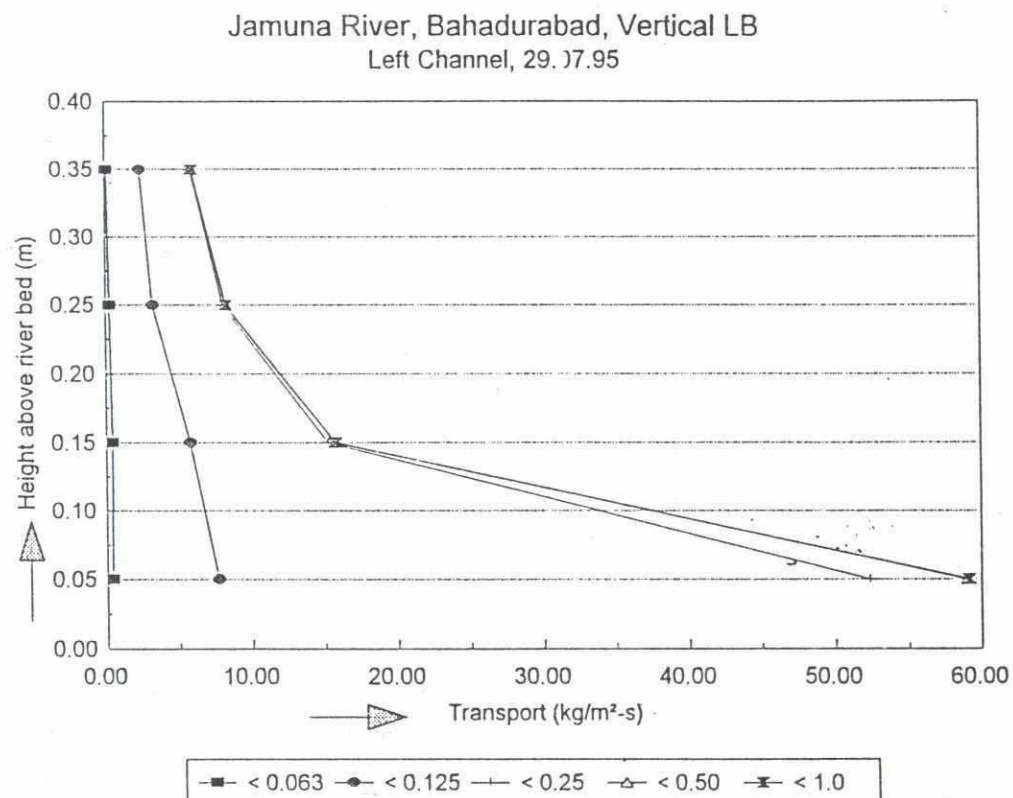
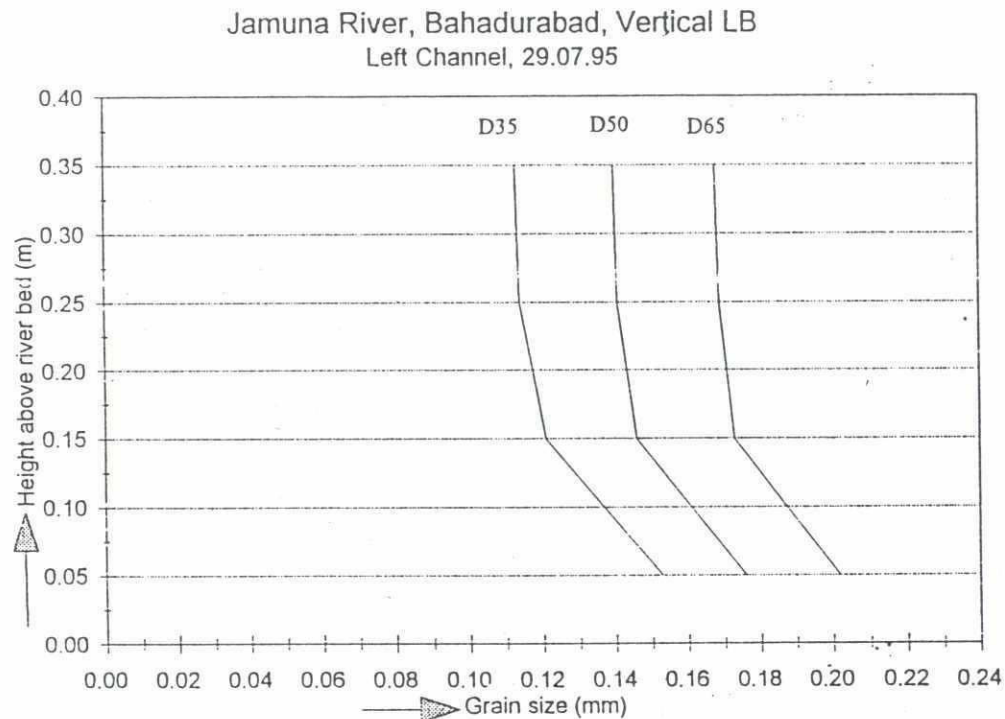
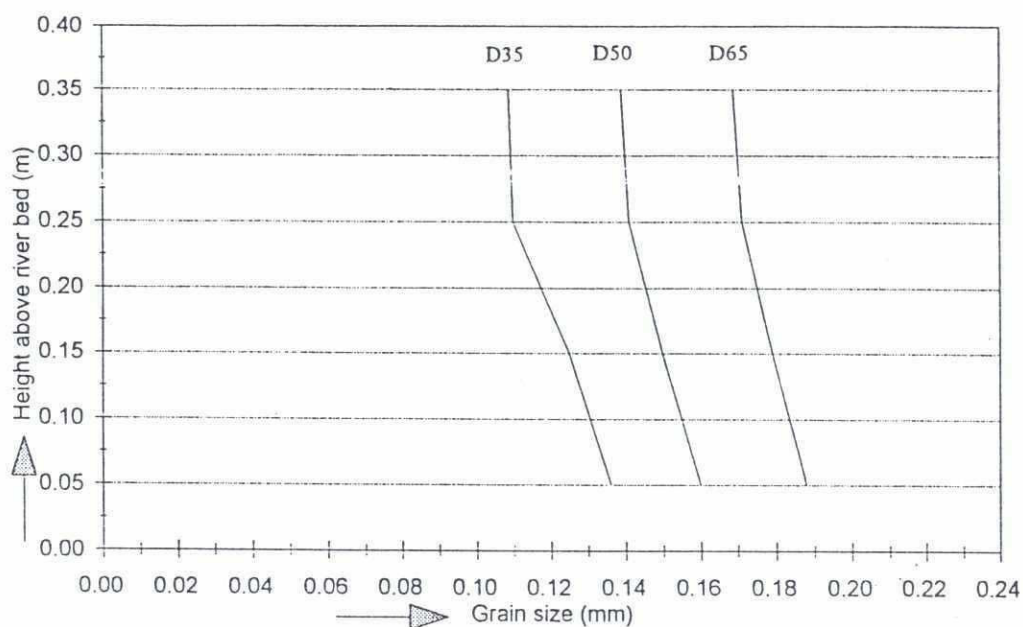


Figure 6.74 Near-bed grain sizes and transport in the vertical LB on the Jamuna River left channel near Bahadurabad on 29 July 1995

Jamuna River, Bahadurabad, Vertical LC
Left Channel, 29.07.95



Jamuna River, Bahadurabad, Vertical LC
Left Channel, 29.07.95

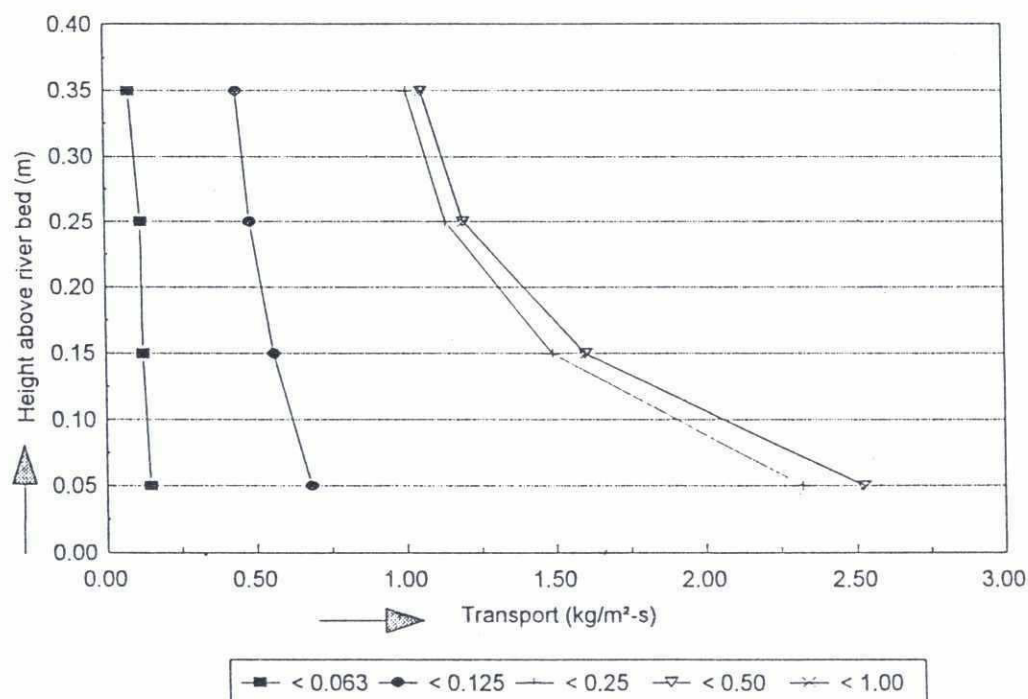


Figure 6.75 Near-bed grain sizes and transport in the vertical LC on the Jamuna River left channel near Bahadurabad on 29 July 1995.

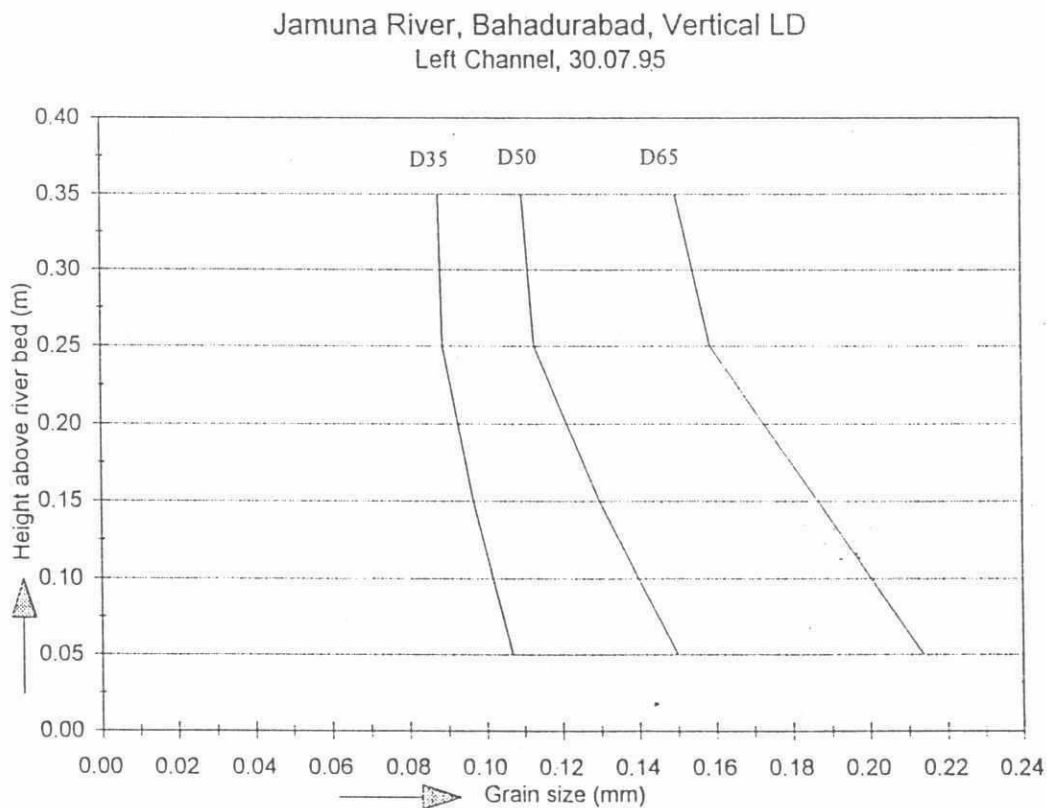
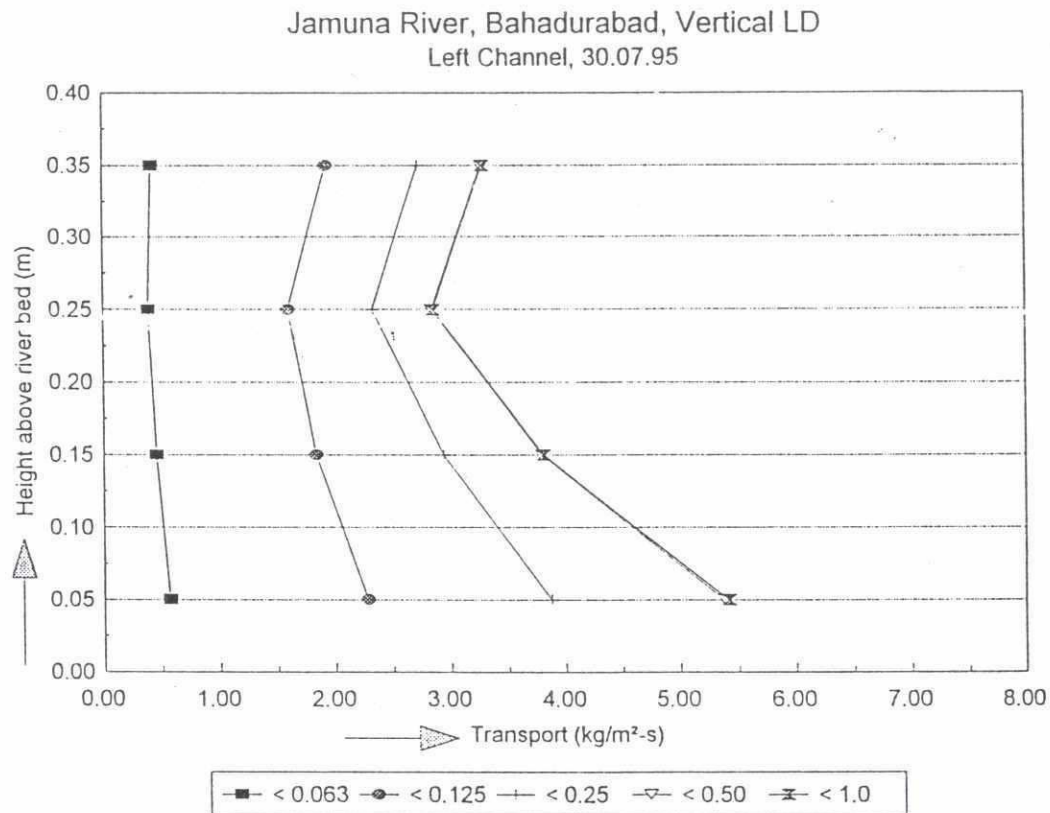


Figure 6.76 Near-bed grain sizes and transport in the vertical LD on the Jamuna River left channel near Bahadurabad on 30 July 1995.

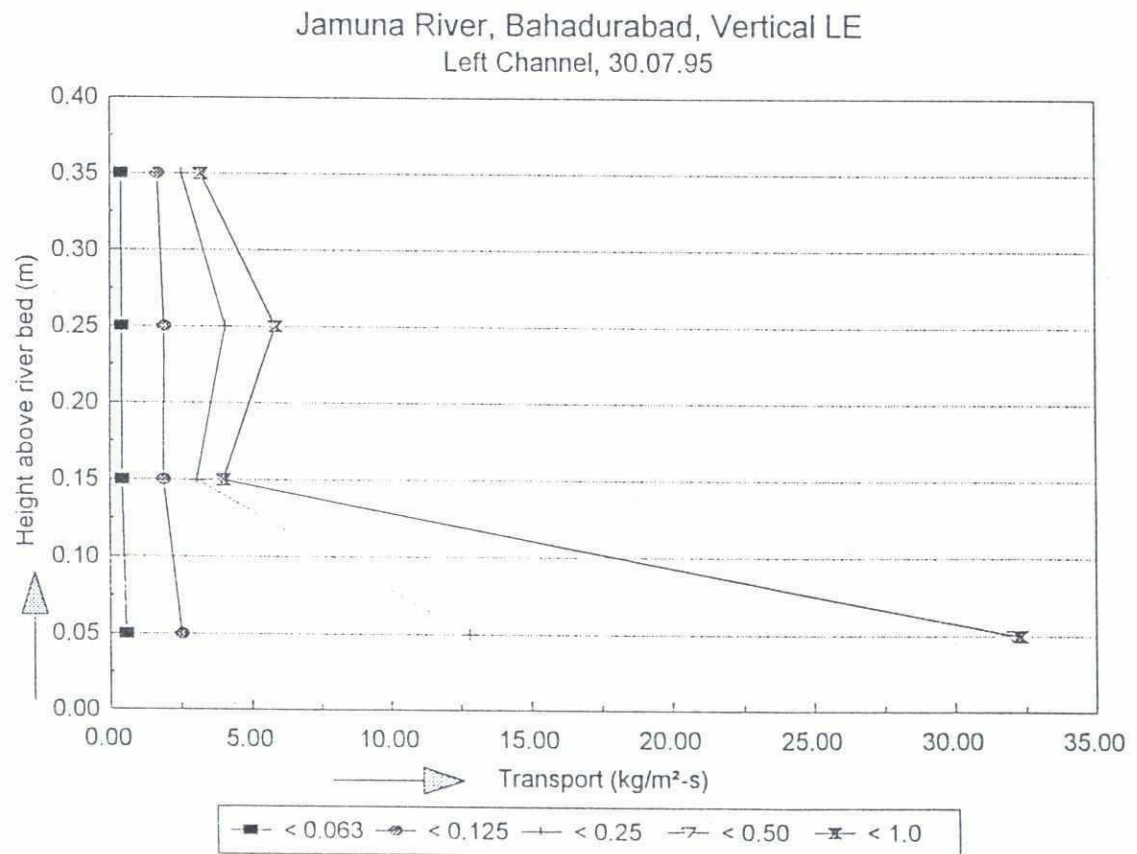
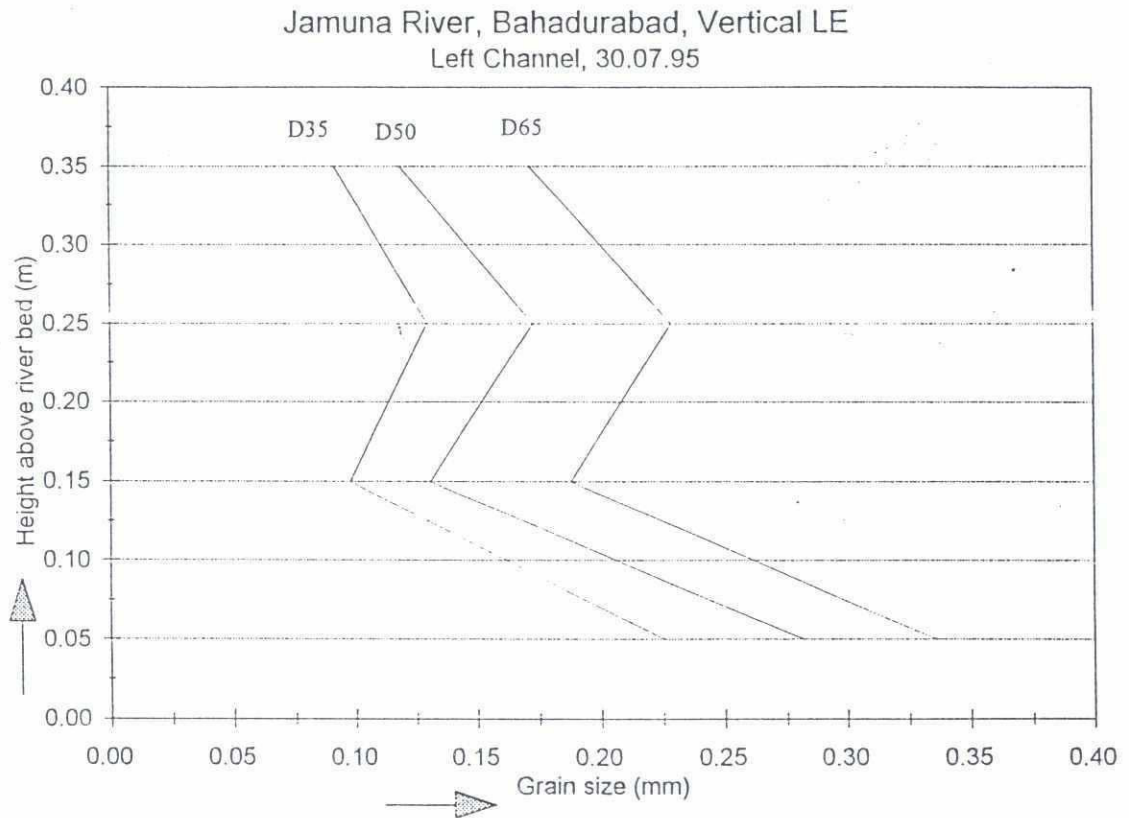


Figure 6.77 Near-bed grain sizes and transport in the vertical LE on the Jamuna River left channel near Bahadurabad on 30 July 1995.

- **Intercomparisons**

H-S versus DB

The main intercomparison of the near-bed measuring results from different instruments were between the H-S sampler and the DB.

- In April 1995, in low flow conditions, these comparisons were made (Annexure G5). The main conclusions were:
 - The variability of the transport is increasing towards the river-bed, see Figure 6.78. The H-S results were consequently more scattered than the DB catches.
 - The transport is increasing towards the river-bed, see also Fig. 6.78. The average transport of the H-S is smaller than the average catches of the DB. The DB transport between 0.35 and 0.15 m is rather constant, while only in the lowest point, a sudden increase can be observed.
 - The grain sizes are increasing towards the river-bed (see Fig. 6.78). This is a very consistent pattern, which can be observed many times (using one type of sampler). When using different types of samplers, the different loss of the different samplers play an important role (see Fig. 6.79). From the Figure, it can be seen that the grain-sizes of the DB catches at 0.05 m above the river-bed are much finer than those of the H-S.

In May 1995, the time-series measurements of the DB and H-S were made in strong flows (1.5 - 2.5 m/s) (annexure G6). Important conclusions were:

- H-S transport was much lower than the DB.
- Variation of the H-S was considerable, but with a few (say 3 or 4) samples, a reasonable estimate is possible.
- Also, in these flows, the transports as measured with the DB are consistent. The pattern shows again that only in the last say dm, the transport increases considerably (Fig. 6.80) Also the consistent increase of the grain sizes towards the river-bed was noticed from the same Figure.

P-b versus DB

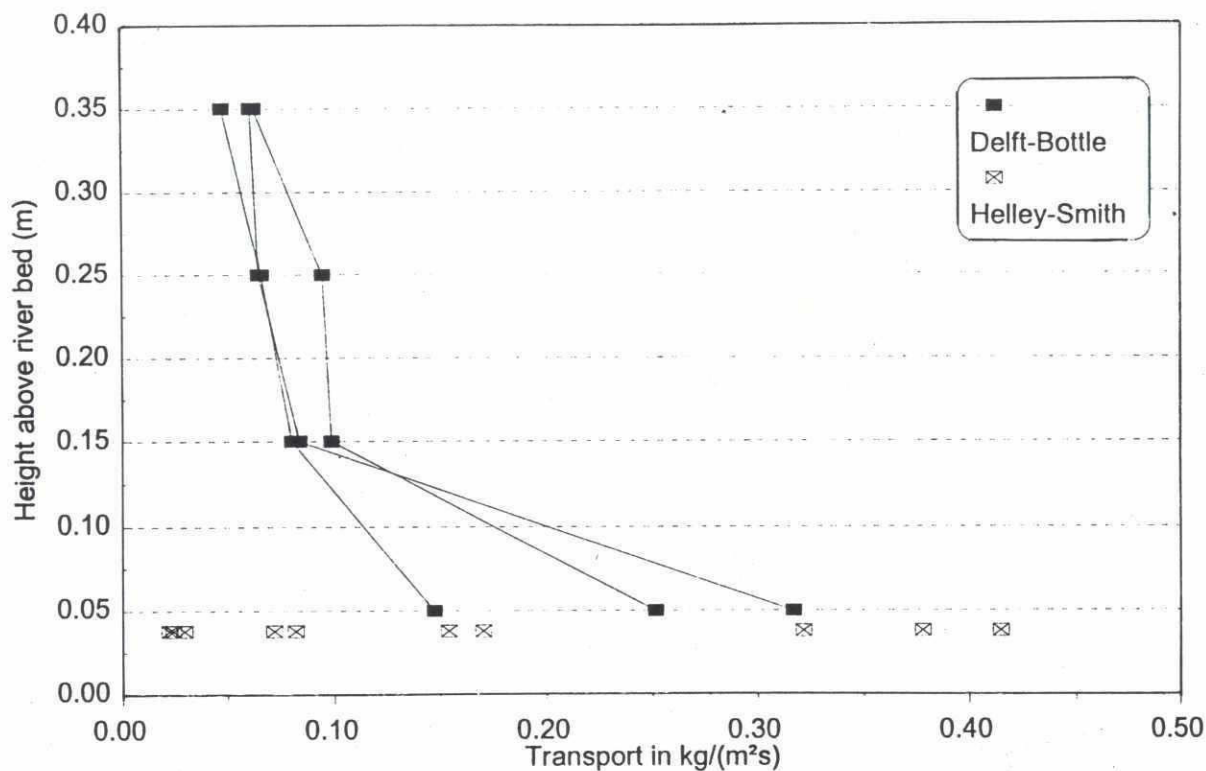
Another intercomparison took place comparing the pump-bottle with the Delft Bottle in the near bed transport range. This was for instance done in the surveys of August 1994 (annexure G3), April 1995 (annexure G5), May 1995 (annexure G6) and July 1995 (annexure G8). Some results have been summarized hereafter.

The measurements of 3,4 August 1994 need to be mentioned here, see 6.1.2, although reported under suspended load measurement. The pump-bottle was lowered 0.5 m above the river bed.

while the DB was positioned in the frame at 0.35 m above the river bed. The main results here show the losses of the DB in the lower fraction, Figs. 6.25-6.28.

- In April 1995, also pump-bottle measurements were done, with the carrier on the river bed which means that the intake nozzle was 25 cm above the river bed. So at this position the measurements with the pump-bottle and the Delft bottle are comparable. A few bulk samples (of 25 litre) with the pump-bottle were taken to enable grain size analyses.
- Comparison of the grain sizes of the pb vs DB25 reveals that the pb is catching more of the finer fractions as the DB is loosing this part (Fig. 6.79). From the different sieving curves it was found that in these conditions the DB was missing 80 % of the finer fraction, which is half of the total (according to the pb) at this level.
- The measurements of May 1995 contain the same comparison, see annexure G1. The main conclusions are:
 - The transport of the DB varies more than according to the pb, although the MEX indicates a constant transport over the measuring period. The possible reason for this is the position of the DB. These pb remained on the same spot, while the DB had to be lifted after each sample and to be replaced afterwards.
- During the July 1995 measurements (annexure G8) detailed verticals were measured with many (about 10) points in the vertical measured with the pb and the lowest 4 points with the DB, a smooth transition between suspended and near bed and between pb and DB can be observed, Fig. G8.16.

Jamuna River, Bahadurabad 3 April 1995



Jamuna River, Bahadurabad 3 April 1995

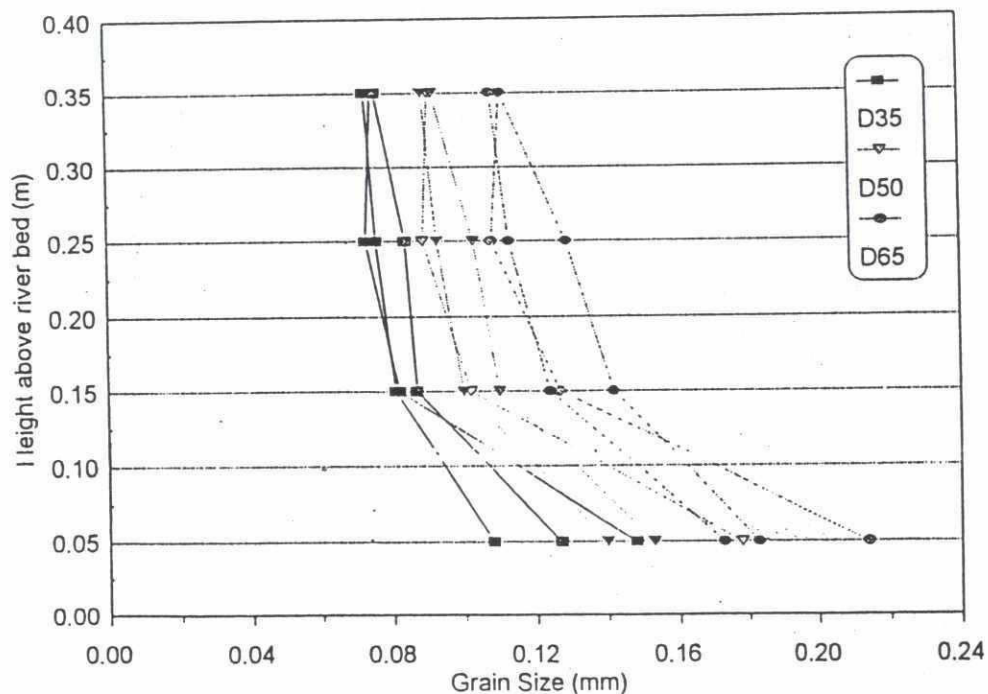
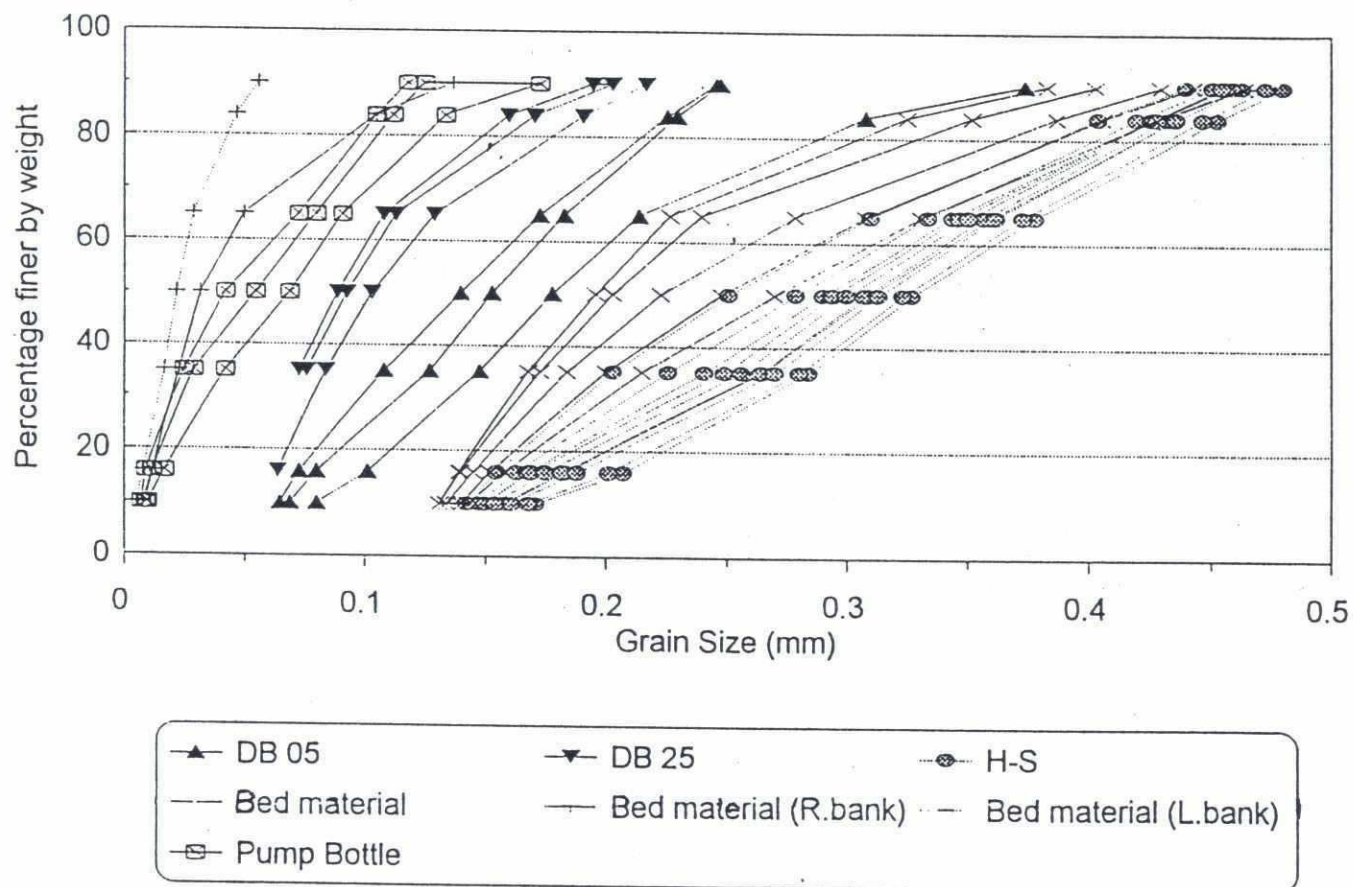


Figure 6.78 Near-bed sediment transport and grain sizes measured by Delft Bottle on 3 April 1995 in the Jamuna River left channel near Bahadurabad.



Note: All samples, except the bed material ones, were taken in vertical 1 (left channel; water depth 6.6 m; distance from bank 225 m)

Figure 6.79 Grain size distribution of Delft-Bottle, Helley-Smith and bed-material samples collected on 3 April 1995 in the Jamuna River left channel near Bahadurabad

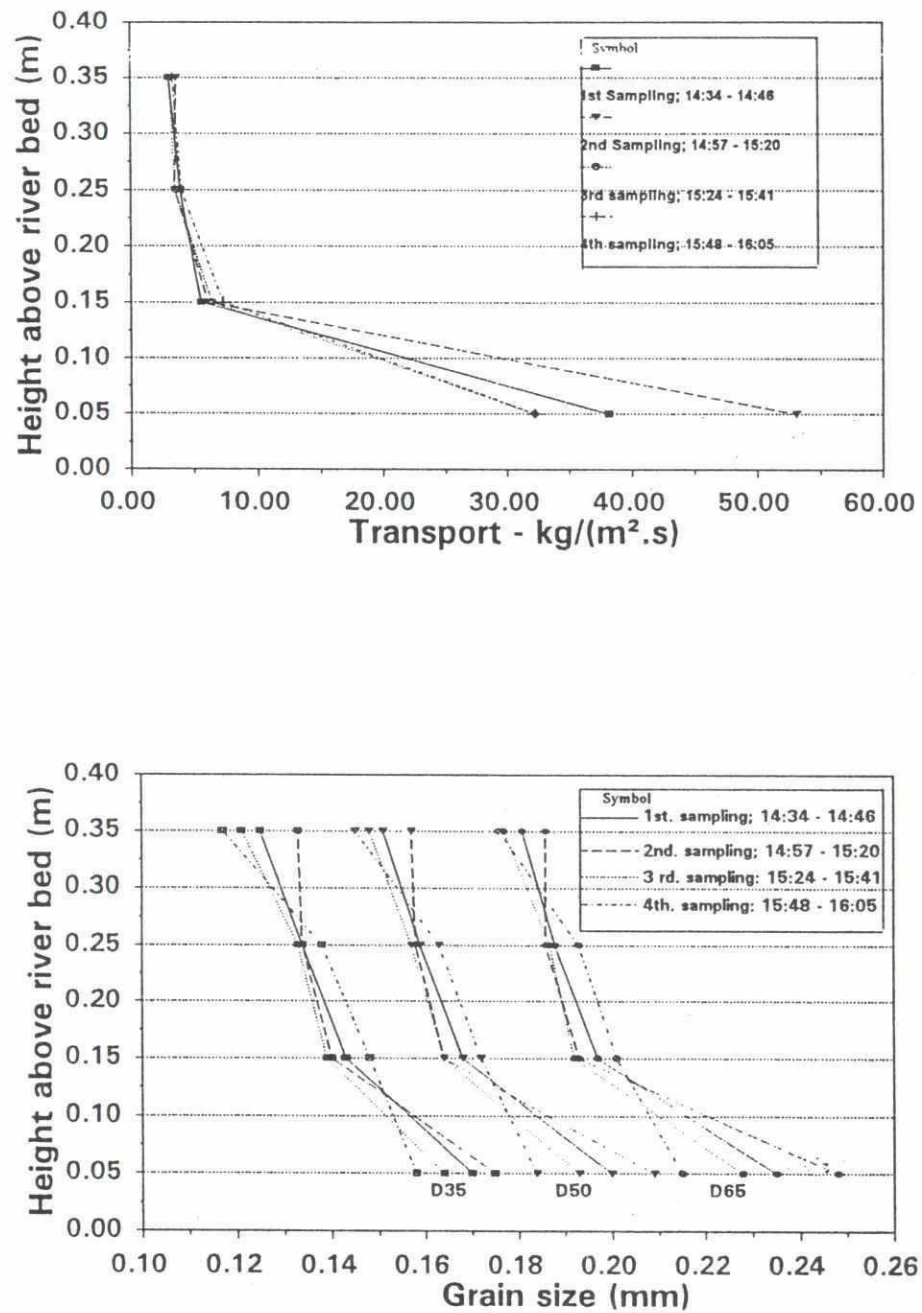


Figure 6.80 Near-bed transport and grain sizes by Delft-Bottle on 27 May 1995 in the Jamuna River left channel near Bahadurabad

7 Important Sediment Transport Issues for Bangladesh Rivers

This chapter highlights some of the sediment transport related issues which have measurement implications. A complete treatment of these issues could not be made in the context of RSP project. Nevertheless, these issues are very important for Bangladesh rivers and should be considered in the future.

7.1 Accuracy Considerations

When suspended sediment data (either concentration or transport) goes to a user, it has undergone two distinct and separate processes, the measuring processes and the laboratory processes. Therefore, any error can be a combination of errors from both of these processes. The sources of errors are as follows:

- *Instrumental,*
- *Sampling,*
- *Field processing,*
- *Lab processing.*

The errors from these sources can be of two types, systematic and stochastic or random. While instrumental errors are primarily systematic, the other errors can be both systematic and stochastic or random.

Some typical systematic instrumental errors are:

- *Optical method representing primarily silt,*
- *Acoustical method representing primarily sand,*
- *Delft Bottle representing primarily particles greater than 0.1 mm.*

Some sampling errors are:

- *Different relative sampling rate (intake velocity/ambient flow velocity),*
- *Contamination of samples during transit,*
- *Vibration and flow disturbance at the nozzle entrance,*
- *Lowering of the sampler at the incorrect depth with point-integrating case,*
- *Partial depth-integration.*
- *Inadequate exposure time.*

Some field recording and processing errors are due to:

- *Splitting of the sample,*
- *Loss during sample removal,*
- *Wrong field recording.*

Some errors due to lab processing are due to:

- *Splitting into size fractions,*
- *Measuring water volume and weighing of samples and filter paper,*

- *Obtaining sieve diameter.*
- *Obtaining Stoke's diameter.*
- *Wrong lab recording.*

A main problem is encountered when analyzing the stochastic 'error' from measuring results in a river. The variation of a registration is caused by the natural variability of the signal (e.g. of the concentrations) which is partly measured (depending on the exposure time) and other sampling inaccuracies. Other related questions are, in how far the registration consists of stochastic independent samples, and whether a stochastic model (and what model) is applicable. The PA noted that possibly the near surface variation is more symmetrical whereas near river bed skewed distributions may be expected. Another aspect is related with the objective of the measurements (e.g. are averaged or instantaneous values desired?). This should be kept in mind when applying an engineering approach in which errors are expressed in terms of standard deviations.

Errors range from 0 to 100% or higher. A 100% error means that the value of the standard deviation is as high as the mean value. Random errors can be minimized by improving the measuring facilities and the operational skills of the survey crew. Studies by Van Rijn (1986) indicate that pump-systems have the lowest overall errors and the instantaneous trap samplers have the highest, when used for suspended sediment sampling.

One of the major sources of sampling error is the non-isokinetic sampling. Isokinetic sampling means that the relative sampling rate (intake velocity/ ambient velocity) is unified. The error from this source can be systematic or random. USGS studies (1978) indicate that there are errors in concentration estimates at different relative sampling rates. These studies also show that the relative sampling rate should remain between 0.8 and 1.2, so that the error remains within $\pm 5\%$. Above or below that sampling rate, the errors become unacceptably high. Studies by Nelson and Benedict (1950) show that the grain sizes of suspended sediment have a strong influence on the accuracy of sampling; the influence is appreciable for particles greater than about 0.06 mm. When the hydraulic coefficient is less than 1, over-sampling occurs; the converse happens when the hydraulic coefficient is greater than 1. When intake velocity is greater than ambient velocity, less sediments than are actually present are sampled. This happens because of the converging flow lines which can not be followed by sediment particles having higher density than water.

The operation and accuracy of different samplers can be discussed by considering different functional relationships. The functional relationship of different mechanical samplers can be written as follows.

A Delft Bottle sediment catch is a function of,

$$M = f [c(v), v, 1/\Omega, \tau].$$

A pump bottle concentration is a function of,

$$V = f [c(v), 1/\Omega, \tau].$$

A depth-integrated concentration is a function of,

$$V = f [c(v), 1/\Omega, t, \Delta h, \tau].$$

An instantaneous sediment concentration is a function of,

$$V = f [c(v)].$$

In all these cases.

M = mass of sediment trapped inside the Delft Bottle,

Ω = hydraulic coefficient (intake velocity/ambient velocity),

c = sediment concentration,

d = grain size diameter,

v = flow velocity,

t = transit speed,

Δh = covered water depth,

τ = integration period,

V = water-sediment mixture.

Among the independent variables, $c(v)$ and v represent the sedimentary and hydraulic environment of the river in a particular space and time. Other listed independent variables, such as Ω , τ , Δh , and t , were introduced for accurate sampling of the environment; however, they were also the sources of systematic and random errors. Therefore, a sampler was designed and operated to minimize the errors from these sources.

The electronic sensors of sediment concentration measurements were similarly dependent on different factors. An optical record can be summarized in the following functional relationship,

$$I = f [I_o, 1/L, 1/C, d].$$

where,

I = received optical intensity,

I_o = transmitted optical intensity,

L = distance between the source and the receiver,

C = sediment concentration,

d = grain size.

The discussion in Annexure A on the optical turbidity measuring principle indicates that one calibration curve can not describe the whole range. A different calibration curve is obtained each time a different measurement is made in a different space and time.

An ADCP backscatter signal can be simplistically written as a function of,

$$E = f [S, B, 1/L, 1/\chi].$$

where,

E = echo amplitude,

S = transmitted power,

B = scatterer strength,

L = distance between source and receiver,

χ = absorption coefficient.

The most notable reason for presently not using these two types of sensors in natural rivers is their sensitivity to grain sizes. Since the grain-size distribution of natural rivers varies extensively in time and space, it is often very difficult to develop a single calibration curve which can be used.

This section concludes with a discussion of the indications of the influence of sampling errors on overall accuracy of the sediment transport computation. Recommendation of a particular suspended sediment measuring strategy depends on the sampling purpose. The discussion heretofore was based on the consideration that the sampling was for routine surveys. A routine survey should not be considered as purpose-less because basically all routine surveys are used for calibrating sediment transport equations. An example of the typical computational error is given here according to Van Rijn

and Schaafsma (1986). This consideration is made for the total load equation of Engelund-Hansen (1967).

$$S = \epsilon \frac{u^2 b (hi)^{1.5}}{\Delta^2 g^{0.5} D_{50}}$$

where,

S = total load transport [$L^3 T^{-1}$],

u = cross-section averaged velocity [LT^{-1}],

b = width [L],

h = water depth [L],

i = water surface slope [-],

$\Delta = (\rho_s - \rho)/\rho$ = relative density,

g = acceleration due to gravity [LT^{-2}],

D_{50} = median particle size of bed material [L],

ϵ = coefficient (0.05, proposed by Engelund and Hansen, 1967).

Assuming that the basic variables are stochastically independent, the relative error of the α coefficient can be expressed as,

$$\left(\frac{\sigma_\alpha}{\alpha} \right)^2 = \left(\frac{\sigma_s}{S} \right)^2 + 4 \left(\frac{\sigma_u}{u} \right)^2 + \frac{9}{4} \left(\frac{\sigma_h}{h} \right)^2 + \frac{9}{4} \left(\frac{\sigma_i}{i} \right)^2 + \left(\frac{\sigma_b}{b} \right)^2 + \left(\frac{\sigma_{D_{50}}}{D_{50}} \right)^2$$

Typical relative errors are,

$$\sigma_u/u = 0.1,$$

$$\sigma_h/h = 0.05,$$

$$\sigma_b/b = 0.05,$$

$$\sigma_{D_{50}}/D_{50} = 0.1,$$

$$\sigma_i/i = 0.15 - 0.25.$$

The relative errors of Δ and g were not significant. Using these values, the typical errors are shown in Figure 7.1 (after van Rijn, 1990). The Figure indicates the relatively insignificant influence of sampling errors on the overall accuracy of total sediment transport computation.

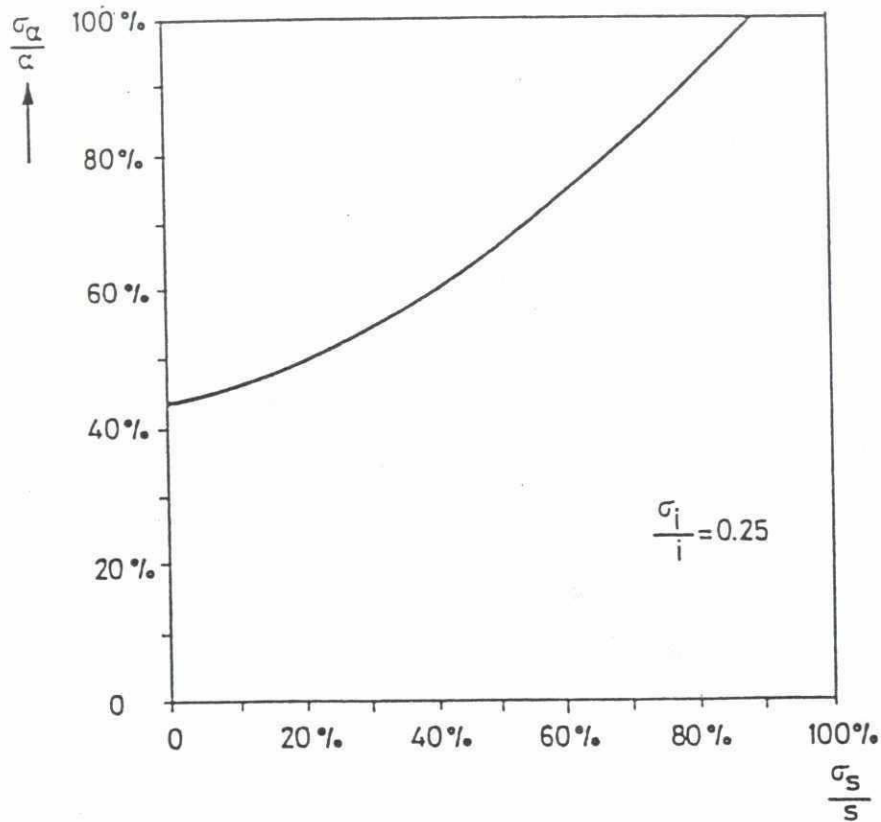


Figure 7.1 Total load computation error as a function of sampling error (after Van Rijn, 1990).

The measured suspended sediment transport, however, can be highly dependent on errors made in the determination of sediment concentration. Suspended sediment transport can be expressed as,

$$S = \sum_{j=1}^m \sum_{i=1}^n u_i c_i h_i b_j,$$

The relative error relation of the equation can be expressed as,

$$\left(\frac{\sigma_s}{s}\right)^2 = \left(\frac{\sigma_u}{u}\right)^2 + \left(\frac{\sigma_h}{h}\right)^2 + \left(\frac{\sigma_b}{b}\right)^2 + \left(\frac{\sigma_c}{c}\right)^2$$

Figure 7.2 was constructed assuming a relative velocity error of 0.1, a relative depth error of 0.05, and a relative width error of 0.05. Errors increased almost linearly, with the minimum error occurring at 12%.

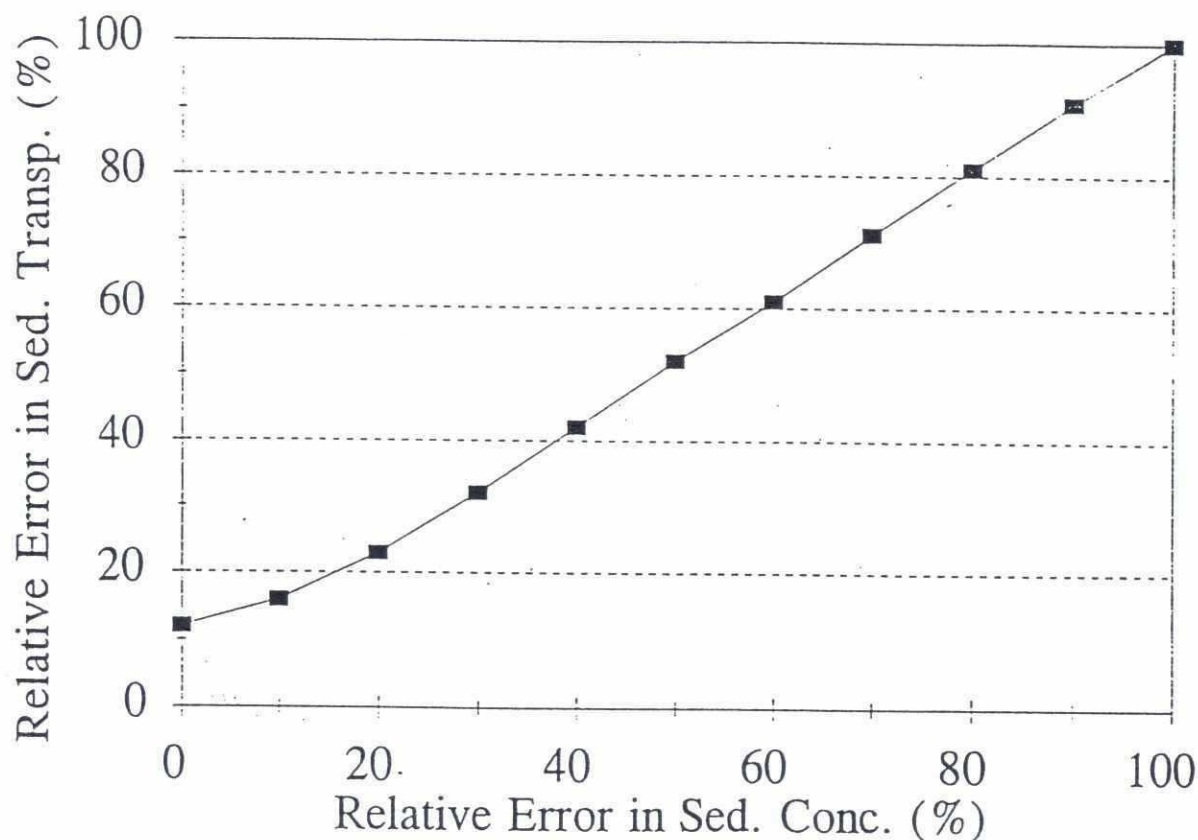


Figure 7.2 Relative error in suspended sediment transport estimation as a function of the relative error in sediment transport measurements.

7.2 Silt-Clay Transport and their Importance for Bangladesh Rivers

Annexure E, based primarily on Barua's (1995) paper, addresses the issue of silt-clay transport and their importance for Bangladesh rivers. The hydraulic behaviour and the quantity of silt transport ($< 63 \mu\text{m}$) make silt-clay transport important for Bangladesh rivers. Conventionally, they are known as wash load; this implies that their contribution is supply-rate limited. This appears not to be case for Bangladesh rivers (Barua, 1995). The following observations were made about their hydraulic behaviour:

- Vertical distribution of suspended silt in concentration profiles provided a gradient towards the bed suggesting that their origin was partly located in the river bed.
- Suspended silts were not uniformly distributed over the river width; rather they were found to be higher in high energy environments (with higher velocity), thus indicating their river-bed source.

- Silt transport rating curves $Q_s = mQ^n$, showed that the n-values varied from 0.6 to 1.8 indicating their direct relationship with discharge (RSP, 1994).

Similar observations indicated that their sources were the river bed and bank. The sand-silt percentage of 33 bed-material samples collected along the Ganges River showed that on average 25% of the bed-material consisted of silt. Thorne et al. (1993) reported that 40% of the bank-material consisted of silt. They also found that the median diameter of the surface suspended sediment was about 21 μm which is far less than 63 μm .

In addition, the quantity of depth-integrated suspended silt concentration was 400 to 600% higher than the corresponding sand concentration. Figures 7.3 and 7.4 show the annual variation of sand and silt concentration in the Jamuna River at Bahadurabad and in the Padma River at Baruria. These Figures show the large differences between the fraction sizes in the suspended sediment concentration. The Figures also show that the silt concentration increases with the river stages.

The bulk of the suspended sediment transport comprising silt had significant consequences for the morphology of Bangladesh rivers. They are summarized as follows:

- The selective deposition of fine sediments in relatively sheltered areas of the deformed bed and bank introduced heterogeneity in the hydraulic boundary complicating the morphological response of the rivers. (Peters 1994)
- Silt-clay fractions, with their relatively high resistance to entrainment (as compared to fine sands), influence the river meander relations. Schumm (1968) demonstrated that meander wavelengths were inversely proportional to the silt-clay percentage.
- In addition, higher concentrations of suspended sediment reduce the von Karman constant, κ (Einstein and Chien, 1955) and particle Fall velocity (McNown and Lin, 1952). Investigations by Hushild et al. (1961) indicated that the maximum effect on fall velocity was well within about 10%.

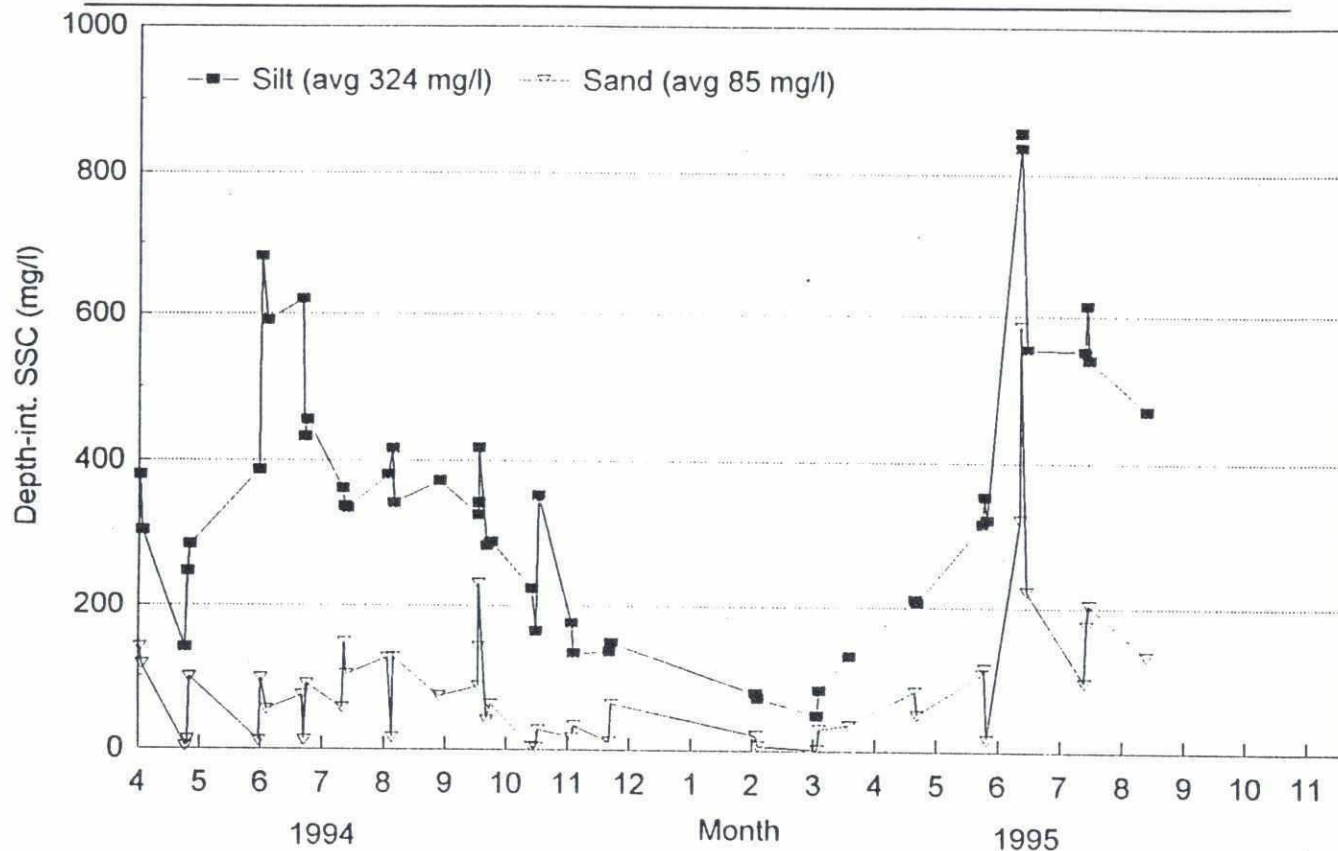


Figure 7.3 Depth-integrated silt and sand concentration in 1994-95 in the reference verticals of the Jamuna River at Bahadurabad.

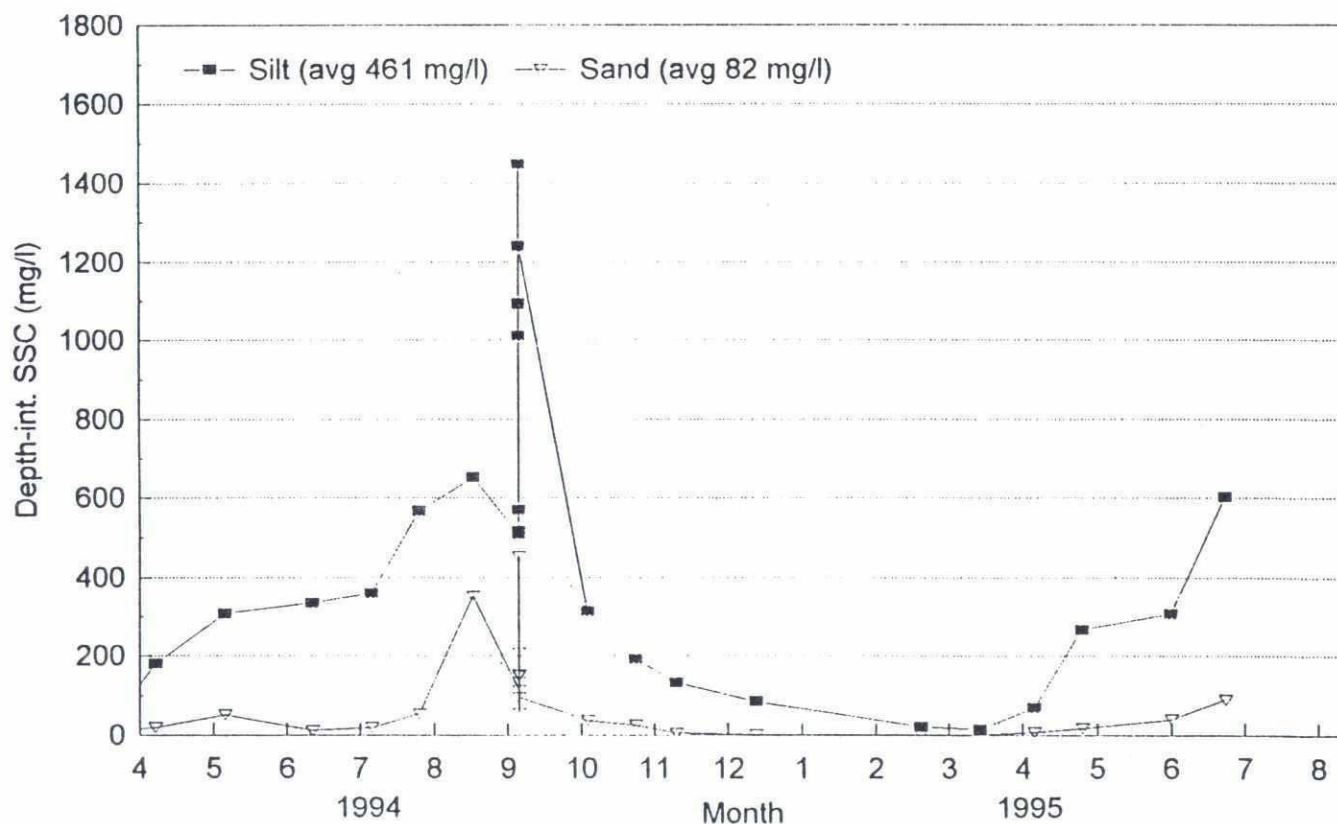


Figure 7.4 Depth-integrated silt and sand concentration in 1994-95 in the reference verticals of the Padma River at Baruria.

7.3 Ratio of Near-Bed Transport to Total Transport

Discussions in Chapter 6 indicated that the near-bed sediment load was approximately 15 to 25% of the total load. This was based on an arbitrary definition of a 20-cm near-bed layer. Delft Bottle measurements at 5 cm and 15 cm above the bed were used for this purpose. As mentioned earlier, it was difficult to measure bed-load in the theoretically defined bed-load layer. In addition, the distinction between bed load and suspended load was often not obvious (Peters and Goldberg, 1989). This raises the question of whether transport of fine sands occurs significantly in bed-load mode and if so where and when. These questions are relevant for at least two reasons. First, it is related to the threshold velocity for bed-material erosion which is very small (0.2 m/s) for all size fractions (see Hjulsstrom diagram, Annexure E). Second, the mobility number, defined as a ratio of U_* and W_s (Dyer, 1986), was in most cases above a critical value determining the mode of transport. This critical value varies from about 0.56 (McCave, 1971), to 0.8 (Bagnold, 1966), to 1.0 (Middleton, 1976). Figure 7.5 was constructed to see the influence of the mobility number.

The mobility is shown against the depth-mean velocity for different sized fractions: 0.1875 mm (0.125 - 0.25 mm), 0.375 mm (0.25 - 0.5 mm), and 0.75 mm (0.5 - 1.0 mm). The bed-shear velocity is computed from the depth-mean velocity as,

$$U_* = \frac{\bar{U}}{C} \sqrt{g}$$

A constant C , (Chezy roughness coefficient), of $45 \text{ m}^{1/2}/\text{s}$, was used to roughly simulate the low-stage flows. The Rubey relation was used to compute particle settling velocity W (Rubey, 1933, see Chapter 6). Figure 7.5 shows that the dominant size fraction, 0.125 - 0.25 (see Chapter 6), went immediately into suspension mode of transport (with a mobility number of 0.8) as the threshold was exceeded. The coarser fraction sizes went into suspension at later stages, but with a depth-mean velocity above 1.0 m/s, all sized fractions were transported as a suspension population.

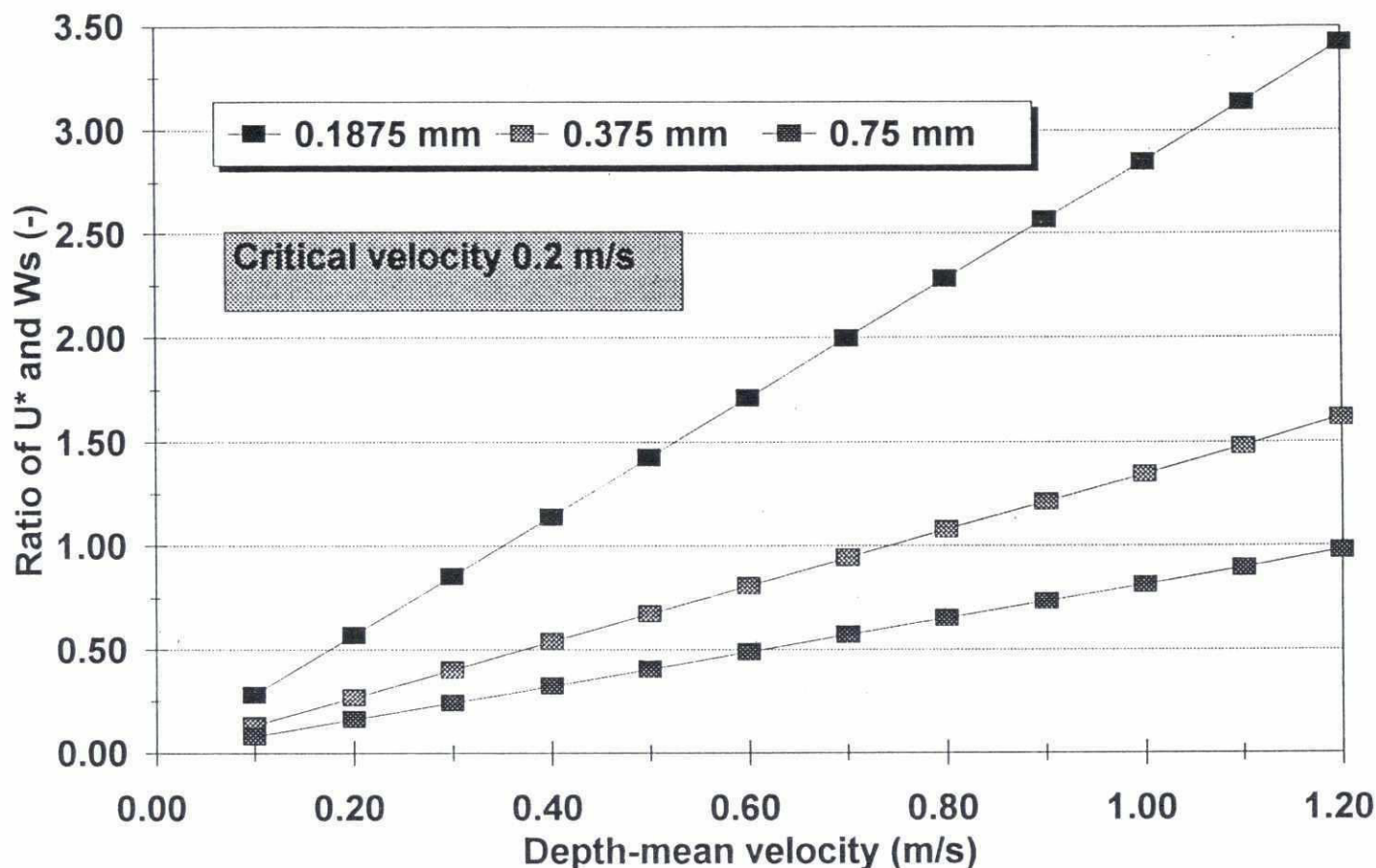


Figure 7.5 Ratio of mobility number (U^*/W_s) as a function of depth-mean velocity for different size fractions (for a Chezy roughness coefficient of $45 \text{ m}^{1/2}/\text{s}$).

7.4 Physical Properties and Transport Relations

Sediment transport behaviour and relations are dependent on the physical properties of the materials they transport. Among others, these physical properties include, grain size distribution, density, and shape factor. Effect of grain size distribution is very significant; therefore, this parameter is invariably measured in all sediment-related field investigations. For density and shape factor, the representative values of quartz are used because this mineral is most abundant in natural rivers. A characteristic density ρ_s of 2650 kg/m^3 and the Corey shape factor of 0.7 are used.

The River Survey Project investigated the physical properties of sediments (RSP, 1996c). The Project showed that the average density of sediments was about 2750 kg/m^3 , approximately 3.8% higher than the quartz particles. This finding was explained by the presence of a significant portion of heavy minerals in the river sediments. Similarly, sand and silt-sized mica flakes were found in significant portions in the Bangladesh rivers. The Corey shape factor of these flakes was less than 0.7.

To determine how these values affected the fall velocities of particles, some simple estimates were made. Figure 7.6 shows the fall velocity ratio (fall velocity of the particular density/fall velocity with a density of 2650 kg/m^3).

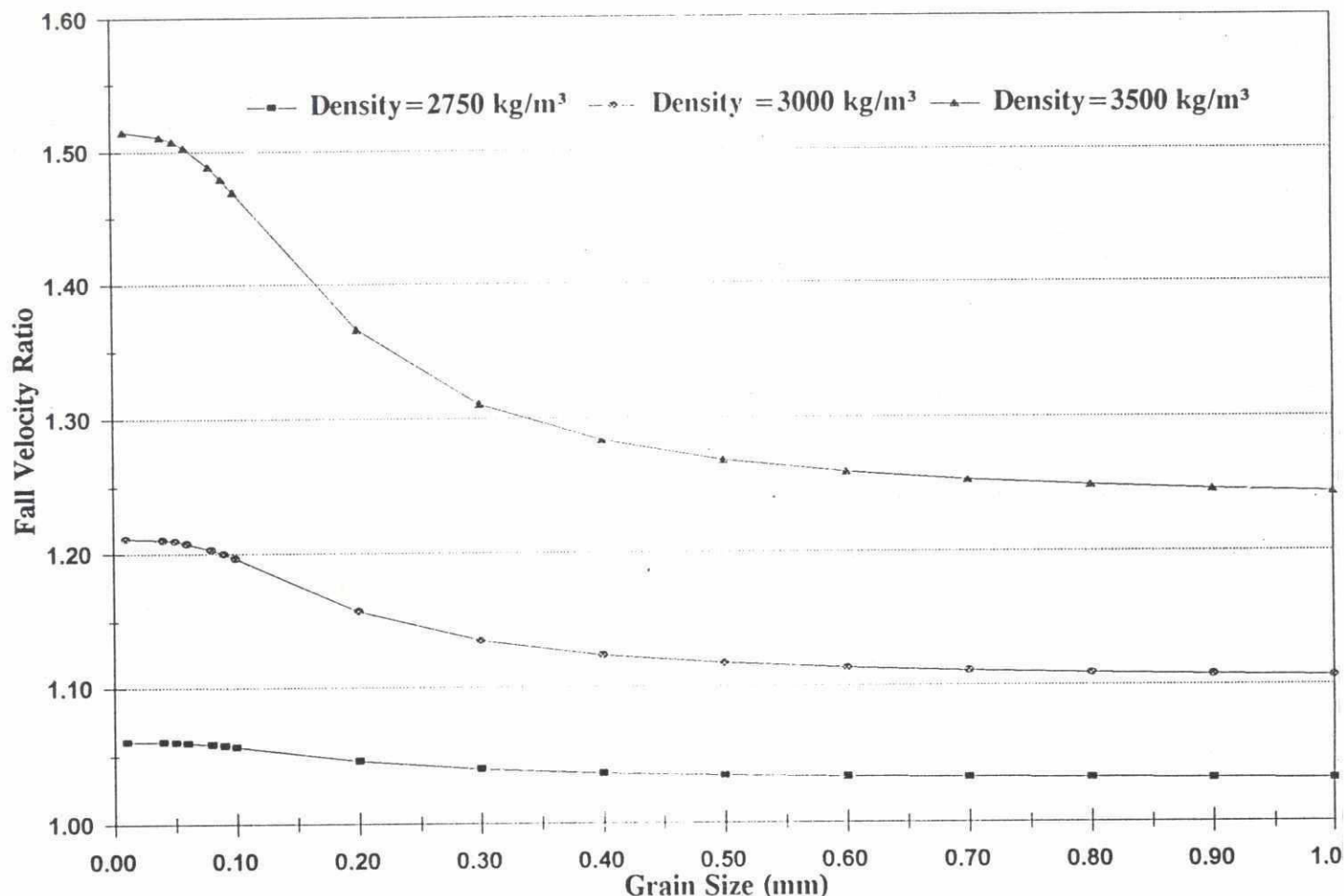


Figure 7.6 Fall velocity ratio (W_s with a particular density/ W_s with 2650 kg/m³) as a function of grain size.

The Rubey relation (Rubey, 1933) was used to compute the fall velocity (see Chapter 6). When the density was 2750 kg/m³, the fall velocity increased by about 4 to 6%. The influence was greater in the Stoke's region than in other fractions. The influence was more significant for heavy minerals with densities of 3000 to 3500 kg/m³.

Figure 7.7 shows the effect of shape factor on the fall velocity. When there was a shape factor lower than 0.7, as was the case with mica flakes, the fall velocity decreased by more than 10%. The opposite happened with the higher shape factors.

Similarly, influence on other factors using particle density and shape factor were observed. For example, Shield's entrainment function was reduced as a result of higher particle density and Van Rijn's particle parameter was increased.

Instead of this theoretical approach an experimental approach is possible as was pointed out by the PA.

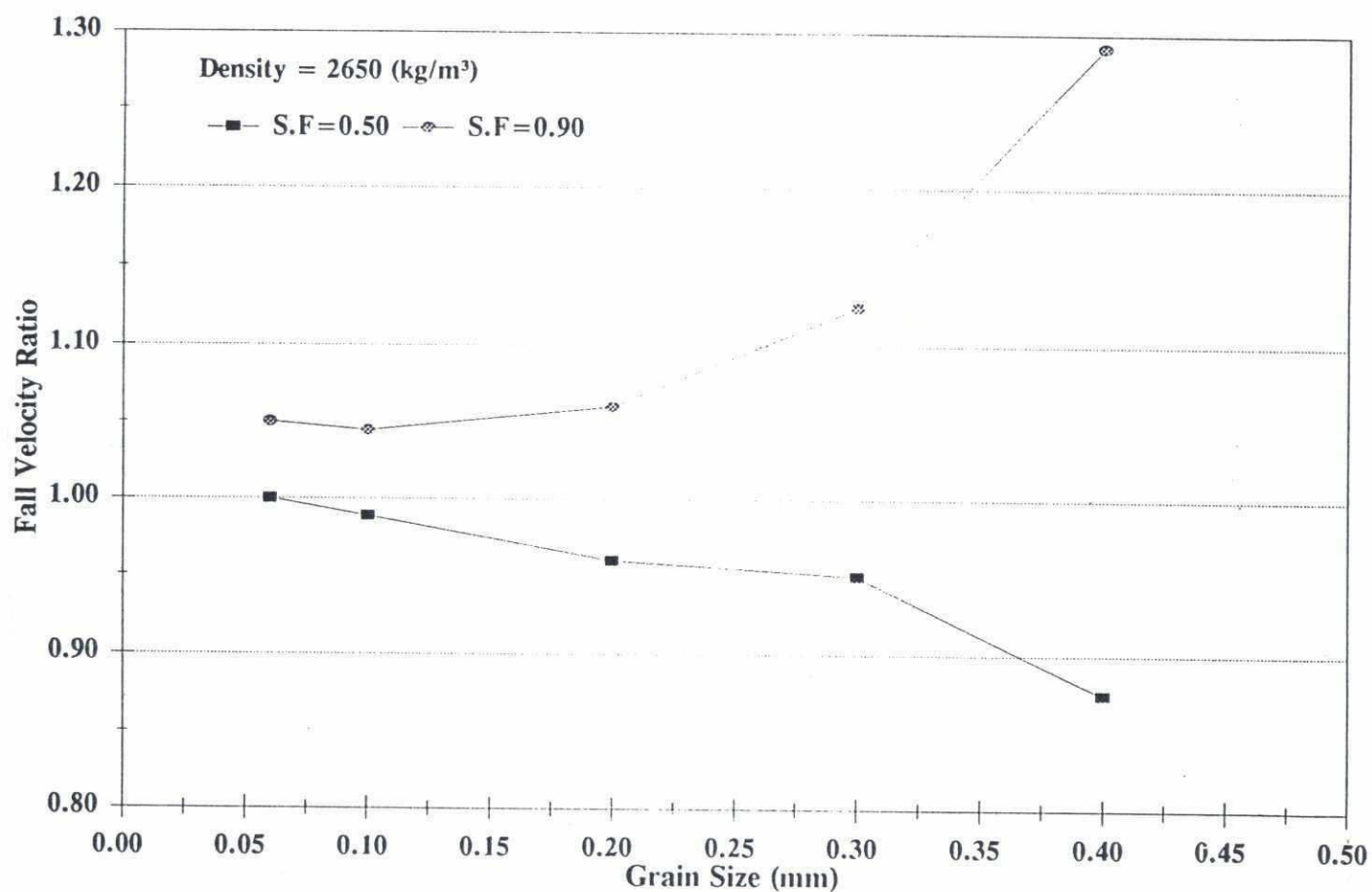


Figure 7.7 Fall velocity ratio (W_s with a particular shape factor/ W_s with 0.7 shape factor) with 2650 kg/m³ as a function of grain size.

8 Optimization of Sediment Measurements

8.1 Principles of Optimization

Optimization is a process of attaining the most favourable solution such that the results meet the quantified objectives. It is a well-established scientific process using rigorous numerical techniques (e.g., Fletcher, 1987) and practical heuristic approaches (e.g., Delft Hydraulics, 1990). Depending on the objectives, time, and resources employed, one chooses between a rigorous numeric or practical heuristic approach. Figure 1.2 shows the optimization principle in the form of a flow-chart. Basically, it consists of a series of activities that are evaluated on optimization criteria, and, if necessary, repeated at an advanced level, thus forming a loop. Further, an external loop can be imposed to examine the activities on the basis of sustainability criteria. Ultimately, this leads to the data collection strategy of an institution or a country. Therefore, it is suggested that being optimal is a necessary pre-condition of being sustainable. The quality and quantity of data collection can be defined on the basis of three basic objectives which have their own requirements.

- 1 Routine measurements for the purpose of long-term data-base development which may be less detailed in space and time and may require less accuracy,
- 2 Data for special studies or project requirements should fulfil their objectives in quality and quantity,
- 3 Data required for research purposes should often be very detailed in space and time and represent a higher quality.

Once the required objectives are defined in terms of data quality and quantity, the variability and ranges of measuring parameters of the rivers should be recognized before starting the selection of equipment and method. Based on the above considerations, the activities can be pursued in the following four distinct disciplines.

- 1 Selection of equipment and method,
- 2 Determining spatial density and distribution of measuring stations,
- 3 Determining the frequency and temporal distribution of measurements, and
- 4 Actual survey operations.

Each of these activities should be evaluated after a certain time on some optimization criteria. Our analyses were based on a multi-criteria format. Six basic criteria were identified that can be applied to attain an optimal solution: (1) cost, (2) required accuracy, (3) operational ease, (4) measurement duration, (5) maintenance of equipment, and (6) representativity of parameters being measured (see Table 8.1). When considering cost, a certain equipment or method should have the lowest procurement, operation, and maintenance costs. When considering accuracy, a certain equipment or method should provide the highest accuracy. In addition, the equipment and methods should be easy to operate, take less measurement time, have less maintenance, and represent the hydraulic parameters well.

OPTIMIZATION CRITERIA
1. Investment, operation, and maintenance costs
2. Required accuracy according to the objectives
3. Operational ease
4. Measurement duration
5. Maintenance
6. Representativity of parameters being measured

Table 8.1 Optimization criteria for sediment measurements.

Each instrument and method was evaluated and ranked according to how well it fulfilled the optimization criteria (Table 8.1). It is important to determine whether each criterion should get equal weight or should some be weighted higher than others. We contend that cost and accuracy should be weighted higher than the other criteria. Detailed application of the proposed method is discussed later in this chapter.

8.2 Network Optimization

Sediment measurements in natural rivers are comprised of two components, discharge-stage and sediment transport.

Figure 8.1 shows the network optimization principle for hydraulic and sediment measurements. Before general optimization criteria can be applied, the measurements should yield some satisfactory diagnostic relationships (e.g., stage-discharge relationship) or sediment rating curves, and later the results of the network should yield reasonable water balance or sediment balance results.

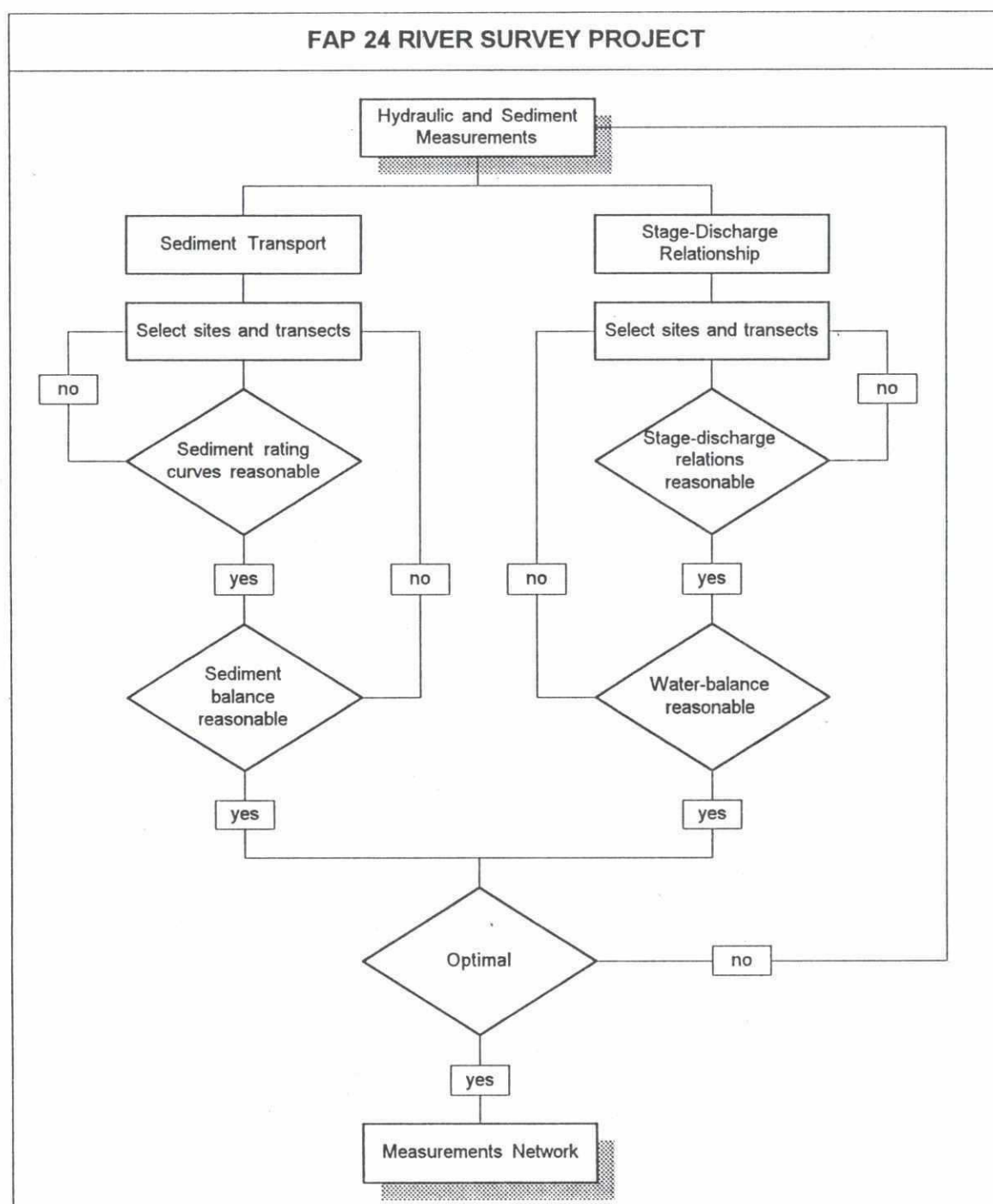


Figure 8.1 Optimization principle of hydraulic and sediment measurements network.

In Bangladesh, there are about 300 water-level stations and 80 discharge measurement stations; 25 of these stations are covered with sediment measurements (BWDB, 1982). Since 1965, data have been systematically collected in these stations following FAO initiatives (FAO, 1969). Table 8.2 shows 11 measuring stations in the main rivers of Bangladesh which are covered by FAP 24. Of these, 8 are primary stations and 3 are secondary stations. BWDB does not cover stations at Aricha, Sirajganj and Arial Khan. As proposed in Figure 8.1, a network optimization consists of three initial steps which are necessary before a final selection can be made. Depending on the purpose (as discussed earlier), the steps are.

- 1 The initial selection of a measuring site or transect should be as close as possible to the conditions prescribed by WMO (1994),
- 2 The measurements should yield good stage-discharge relations or good sediment rating curves,
- 3 The time-integration of results obtained from measurements in the network should yield a reasonable water-balance or sediment-balance picture.

A measuring transect is chosen, as much as possible, according to the WMO (1994) suggestions to avoid converging and diverging flow lines. The guidelines are summarized as follows:

- Straight channel reach, channel length > 5 times the channel width,
- Uniform bed topography, no scour holes or shoals,
- No converging or diverging flow lines, no vortices, no backward flow, and no deadwater zones,
- Transect normal to the main flow direction,
- Sufficiently deep with respect to the sampling device,
- Clear of obstacles such as trees, bridges, piers, etc.

Measurements from the various chosen sites should yield acceptable stage-discharge relations or sediment rating curves. If the results are not satisfactory, site selection procedure should be repeated until a satisfactory result is obtained. Using the data, a water-balance or sediment balance for the gauging network should be computed. If the balances are acceptable then they should be screened against several optimization criteria. If not, the activities should be repeated. In this way, three loops are suggested.

The 1987 flood year data were used to evaluate the stations with respect to their different relations (see Figure 8.1). Using BWDB observations, stage-discharge relationships were established at Bahadurabad in the Jamuna River, at Hardinge Bridge in the Ganges River, and at Baruria in the Padma River. Accumulated volumes for 1987 were $387 \times 10^9 \text{ m}^3$ through the Ganges River at Hardinge Bridge, $688 \times 10^9 \text{ m}^3$ through the Jamuna River at Bahadurabad, and $966 \times 10^9 \text{ m}^3$ through the Padma River at Baruria. The water-balance indicated that about 11% of the Padma discharge was shared by different distributaries, specifically the Old Brahmaputra, Dhaleswari, and Gorai Rivers. The exercise showed a reasonable water-balance considering the unaccounted tributaries and distributaries, and the uncertainty ranges for these factors.

A similar exercise with BWDB suspended sand transport data had give unrealistic results. Sand-transport rating curves were established using 1987 BWDB data with 24, 21, and 14 data points for Bahadurabad, Hardinge Bridge, and Baruria stations respectively. Using these rating curves, the sand transport were 55 million tons through Jamuna River at Bahadurabad, 29 million tons through the

Ganges River at Hardinge Bridge, and 95 million tons through the Padma River at Baruria. The total transport through the Ganges and the Jamuna Rivers was 84 million tons, 11 million tons lower than the transport at Baruria. The results showed a degradation of the system which appeared to be unrealistic. This unrealistic finding suggests that the BWDB sediment gauging techniques need evaluation and improvement. Note that these values represent sand transport (excluding silt), therefore they are about an order less than the values given in Table 3.1.

Each station chosen by FAP 24 (see Table 8.2) is discussed with respect to their status and importance in the overall sediment transport estimation of Bangladesh.

Bahadurabad: Bahadurabad is a primary discharge and sediment transport measuring station on the Brahmaputra-Jamuna River in Bangladesh. It is an important station for estimating the country's water resources, especially in relation to cross-country flow. In the river's multiple channels, which change in planform very rapidly, it is very difficult to take accurate measurements; extra care must be taken to handle the changing situations. This station is covered both by FAP 24 and BWDB.

Sirajganj: Sirajganj is a secondary network station for discharge and sediment measurements. Water and sediment balance measurements are taken on the Jamuna River. The present morphological situation of the river at Sirajganj is a better site for measurements. The station is not covered by BWDB.

Aricha: Aricha is a secondary network station for discharge and sediment measurements. The station is not suitable for gauging due to its proximity to the Ganges-Jamuna confluence. The station is not covered by BWDB.

Mymensingh: Mymensingh is a primary measurement network on one of the major distributaries of the Jamuna and the Old Brahmaputra Rivers where discharge and sediment transport measurements are made. The present river course, abandoned two centuries ago by the present Jamuna River flow, has an important role in the sedimentology and river behaviour of the northeast and north-central regions. The transect taken near the Mymensingh Railway Bridge is an ideal measurement network station (relative to the other stations). It is covered both by FAP 24 and BWDB.

Tilly: Tilly is a discharge and sediment measuring station on the Dhaleswari River and forms a primary measurement network station. It is one of the major distributaries of the Jamuna River, responsible for draining and supplying water to the north-central region.

Hardinge Bridge: Hardinge Bridge is a primary discharge measuring station on the Ganges River. It is an important primary station which monitors the cross-country flow through the Ganges River. The station is located in a constricted river bend, thus it is not an ideal location for stream-gauging. Relocation of the measuring site may be considered.

Kushtia Railway Bridge: Kushtia Railway Bridge is a primary network station on the Gorai River, a right-bank distributary of the Ganges River. The river is important for draining and supplying fresh water to the south-western region.

Baruria: Baruria is a primary measurement station located on the Padma River. This station is also not ideal because of stream-gauging considerations. It is effected by the confluence of the Ganges and the Jamuna Rivers and the river bend at the transect. Relocation of the measuring site may be considered.

Mawa: Mawa is a lower reach stream gauging station on the Padma River which has a seasonal tidal effect. This station has secondary status and is important only to check Baruria flow and tidal effect on sedimentation and river morphology.

Arial Khan Offtake: Arial Khan is a right bank distributary of the Padma River. The station located at the offtake is seasonally tidal and has primary status. It is important for estimating water resources in the southwestern region and for monitoring delta development.

Bhairab Bazaar Railway Bridge: Bhairab Bazaar is a primary discharge gauging station on the Upper Meghna River. The station is seasonally tidal. It is an important station for estimating water resources of the northeast region and sedimentological behaviour of the Upper Meghna River.

River System	River	Station	Network status	Remarks
Brahmaputra-Jamuna	Jamuna	Bahadurabad	Primary	Important for assessing the sedimentological behaviour of the river but difficult for gauging.
	Jamuna	Sirajganj	Secondary	Present condition is good for gauging.
	Jamuna	Aricha	Secondary	Too close to the Ganges-Jamuna confluence
	Old Brahmaputra	Mymensingh	Primary	Important for assessing sedimentological behaviour of the river.
	Dhaleswari	Tilly	Primary	Important for assessing sedimentological behaviour of the river.
Ganges	Ganges	Hardinge Bridge	Primary	Important for assessing sedimentological behaviour of the river but may need relocation.
	Gorai	Kushtia R.B.	Primary	Important for assessing sedimentological behaviour of the river and monitoring delta development.
Padma	Padma	Baruria	Primary	Important for checking water-balance and sediment balance.
	Padma	Mawa	Secondary	Seasonally tidal
	Arial Khan	Offtake	Primary	Seasonally tidal and important for assessing sedimentological behaviour and monitoring delta dev.
Meghna	Upper Meghna	Bharirab Bazaar R.B.	Primary	Seasonally tidal and important for assessing sedimentological behaviour of the river.

Table 8.2 Hydraulic and measurements network in the main rivers of Bangladesh. WR – water resources, NE – northeastern region, NC – north-central region, SW – southwestern region.

8.3 Optimization of the Frequency of Measurements

Optimization of the frequency of measurements involves determining at what distribution and how many times a year the measurements should be made. Prior to these determinations, it is necessary to optimize the measuring technique. DVWK (1991) suggested that approximately 250 to 300 measurements should be taken each year to obtain a good overview of sediment measurements.

The question of how often measurement should be taken each year is an important one which needs an answer and optimization. The answer depends on the variability of the measuring parameters. The seasonality of rivers makes this an important issue for Bangladesh rivers. Figure 8.2 presents a proposal for the optimization process of the frequency of measurements.

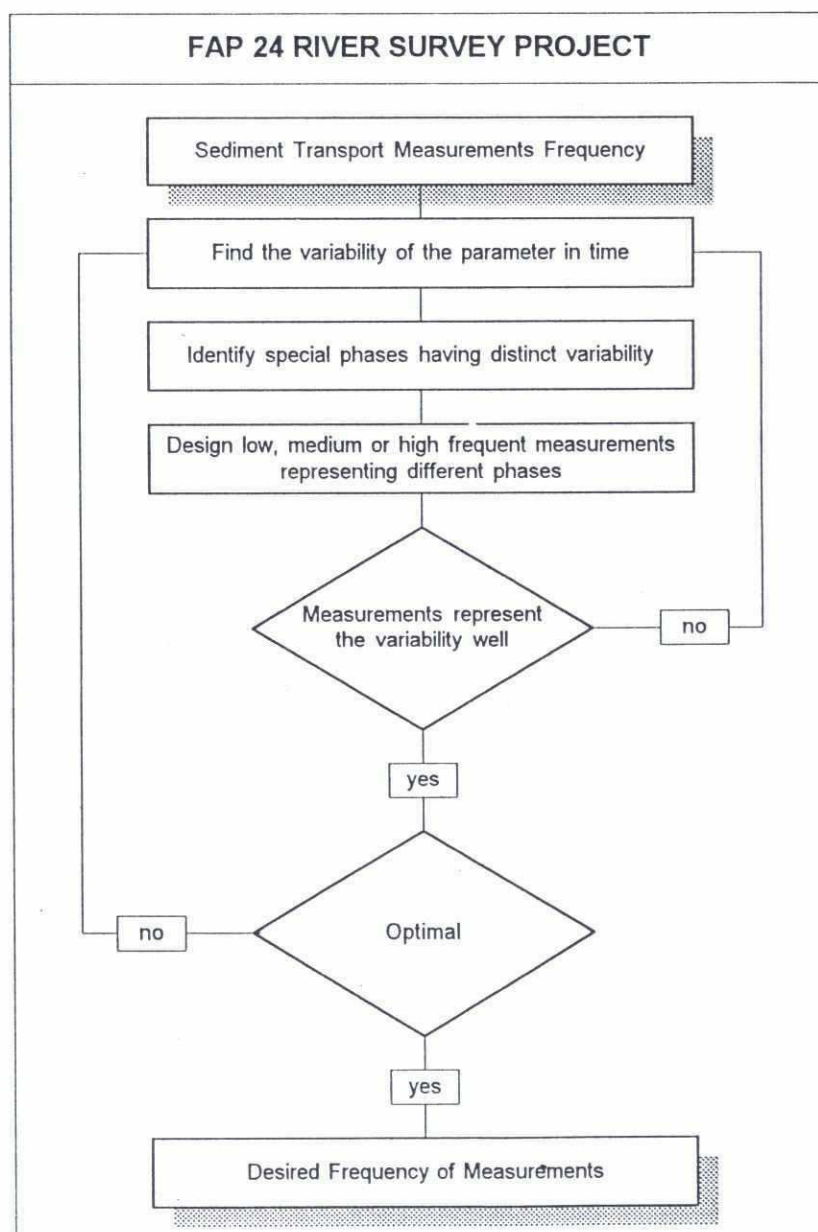


Figure 8.2 Optimization principle of sediment transport measurements frequency.

The essential feature of the optimization process is to identify the discontinuity and distinctiveness of the variability of the parameter being measured and schematize different segments to avoid unnecessary measurements. It is also important to see which part of the segment is important for a certain purpose. The proposal suggests two loops, examining the measurements on natural variability and screening them against some optimization criteria. Technical Specification and the Bill of Quantities described a definite frequency of measurements. In the flood-stage period from June to October weekly measurements were suggested. For the rest of the season, fortnightly measurements were proposed. This frequency would result in approximately 36 data sets being collected each year. During actual survey execution, however, measurements would be taken less frequently because of various constraints. This chapter attempts to identify distinct phases of the hydrograph which can be schematized for different frequencies of measurements. This is necessary because stage-discharge relations and sediment rating curves were found to be dependent on the phases of the hydrograph (Khan and Barua, 1995).

Water-level and discharge hydrographs of major stations show some distinct phases which represent the annual hydrograph. At first, these phases were distinguished as tidal or non-tidal. Most of the measuring stations were non-tidal, except the Padma River station at Mawa, the Upper Meghna River station at Bhairab Bazar and the Arial Khan Offtake (see also the Technical Specifications and Bill of Quantities). The variability of non-tidal and tidal stations are summarized in Tables 8.3 and 8.4 respectively. Table 8.3 shows the variability status of non-tidal rivers (in this case the Jamuna River at Bahadurabad) where various phases of the hydrograph were identified. The rising limb of the hydrograph from March to June was identified as consisting of a slow rising part from March to May and a rapid rising part in June. The overall peak river stage from July to September was identified as consisting of varying peaks in July and August and a very slow falling stage in September. Similarly, the falling river stage was identified as consisting of a rapid falling limb in October and a slow falling limb in November and December. January and February were a flat low river stage.

Following these distinct phases of seasonal variability, measurement frequencies were suggested (see Table 8.2). For the flat low river stage, fortnightly low-frequency measurements were suggested because very little hydraulic or morphological action takes place during this stage. For slow rising and falling stages, weekly medium-frequency measurements were suggested. For rapid stages or the peak stage, bi-weekly (every 4 days) measurements were suggested by the PA. In this way, there will be 60 to 70 measurements from each station which are sufficient to develop or update a stage-discharge relationship or a sediment rating curve. It is important to note that this scheme is only applicable to routine measurements required for long-term data-base development. For any other purpose (e.g., for special studies or research), a different scheme should be designed which supports the given objectives.

When years of data indicate that the stage-discharge relations or sediment rating curves are stable or unchanging, further optimization can be made which will probably result in a lower frequency of measurements. A careful watch should be made of episodic events such as an unusual flood or an earthquake. The variability of the Bangladesh rivers, either in rapid planform changes or in bed-form developments, indicates that a continuous update of rating relations will be necessary.

It is learnt that presently BWDB makes fortnightly measurements in the tidal stations from December to April. Hourly measurements are made for 17 hours.

Presently BWDB makes weekly measurements from June to October and bi-weekly measurements during rest of the year.

Phases	Variability Status	Months	Measuring Frequency
1	Slow rising	March-May	Medium (weekly)
2	Rapid rising	June	High (bi-weekly)
3	Varying peak	July-August	High (bi-weekly)
4	Very slow falling	September	High (bi-weekly)
5	Rapid falling	October	High (bi-weekly)
6	Slow falling	November-December	Medium (weekly)
7	Flat low	January-February	Low (fortnightly)

Table 8.3 Optimal routine sediment measurement frequency for non-tidal stations in the Bangladesh rivers obtained by considering the Jamuna River hydrograph at Bahadurabad.

For seasonally tidal stations, such as Mawa and Bhairab Bazar, a different measurement scheme should be followed (see Table 8.4). In these stations, tidal variability was noticeable from December to April. Thus, the scheme suggested for these stations incorporates weekly spring and neap tidal measurements from December to April. Tidal measurements should be taken hourly for a full tidal cycle (preferably 26 hours). The PA pointed out that establishing a rating relation for such stations is difficult because the residual flows should be related to both the river stage and the spring-neap tidal phases.

Phases	Variability Status	Months	Measuring Frequency
1	Non-tidal slow rising	May	Medium (weekly)
2	Non-tidal rapid rising	June	High (bi-weekly)
3	Non-tidal varying peak	July-August	High (bi-weekly)
4	Non-tidal very slow falling	September	High (bi-weekly)
5	Non-tidal rapid falling	October	High (bi-weekly)
6	Non-tidal slow falling	November	Medium (weekly)
7	Tidal	December-April	Spring-neap weekly tidal

Table 8.4 Optimal routine sediment measurements frequency for tidal stations at Mawa, Bhairab Bazar, and Arial Khan Offtake.

8.4 Optimization of Sediment Measuring Techniques

8.4.1 Suspended Sediment

Table 8.5 shows various advantages and disadvantages of suspended sediment measuring devices, as reported by FAP 24. The Binckley silt sampler was used for comparison only since it is used by BWDB. The errors (e.g., relative standard deviation in percentage) are given from the literature (e.g. Van Rijn and Schaafsma, 1986; Nordin, 1994). As can be seen from the Table, Bi-weekly sampler has the highest error ranges compared to the others. This can be improved by taking repeated samples as suggested earlier.

Sampling Device	Advantages	Disadvantages
Delft Bottle	- Sturdy and reliable. - Moderately easy to operate and nearly maintenance free. - Not sensitive to damage by heat and humidity.	- Represents particles > 0.1 mm only. - Errors are usually in the range of 50%. - Some crew expertise is needed to measure volume, adjust nozzles, and rear openings.
Pump-Bottle	- Represents all particle sizes in iso-kinetic conditions. - Moderately easy to operate.	- Vulnerable to pump and hose break-down and pump-speed modulation. - Pump hose may clog with high concentration. - Crew expertise is needed to adjust the pump-speed to the ambient flow. - Errors are usually in the range of 20%
Acoustic - ADCP backscatter	- Very easy to operate. - Concentration profile can be obtained in a relatively short time. - Has great potential use for future applications. - No field processing is required.	- Represents primarily sand. - Vulnerable to electronic and software failure. - Vulnerable to heat and humidity. - Crew expertise is needed for hardware and software use. - Calibration is at the developing stage. - Error 50%
Optical - MEX 3	- Very easy to operate. - Has great potential use for monitoring of suspended silt. - No field processing is required.	- Represents primarily silt. - Vulnerable to electronic and software failure. - Crew expertise is needed for hardware and software use. - Error 50%.
Integrated Bottle	- Sturdy and reliable. - Easy and nearly maintenance free. - Represents all particle sizes in iso-kinetic conditions.	- Often its application is limited by high water-depth. - Crew expertise is needed to ensure a uniform lowering and raising rate of the bottle. - Error 10- 100%
Collapsible Bag	- Represents all particle sizes in iso-kinetic conditions. - Moderately easy and nearly maintenance free.	- Teflon bag may leak. - Crew expertise is needed to ensure a uniform lowering and raising rate of the bottle. - Error 10% - 100%
Binckley Silt Sampler	- Easy to operate and nearly maintenance free.	- Represents instantaneous suspension status. - Vulnerable to leakage. - Error in the range of 100%.

Table 8.5 Advantages and disadvantages of various suspended sediment measuring devices. The quoted errors are taken from literature (Van Rijn and Schaafsma, 1986; Nordin, 1994).

Following the optimization principle as outlined in section 8.1, Table 8.6 shows the results of the multi-criteria optimization analyses of suspended sediment measuring instruments.

Instruments	Cost x 2	Accuracy x 2	Operation x 1	Duration x 1	Maintenance x 1	Represent. x 1	Total
TIME-INTEGRATED:							
<i>Point-integrated:</i>							
Direct:							
Delft Bottle	8	12	2	1	7	3	33
Indirect:							
Pump	4	14	1	3	1	7	30
Acoustic	2	4	7	7	3	2	25
Optical	6	6	6	6	2	1	27
<i>Depth-integrated:</i>							
Indirect:							
Integrated Bottle	12	8	5	5	6	5	41
Collapsible Bag	10	10	4	4	4	6	38
INSTANTANEOUS:							
Indirect:							
Binckley Sampler	14	2	3	2	5	4	30

Table 8.6 Multi-criterion optimization analyses of the suspended sediment measuring devices.

The experience of the consultant was used to screen each instrument on the various criteria. Each instrument was ranked according to its performance on the various optimization criteria. The Binckley sampler was included because it has been used by BWDB. The integrated-bottle was the most optimal option (see Annexure A for details); the collapsible bag was the next most optimal option.

8.4.2 Near-Bed Sediment

During the RSP activities, a continuous optimization procedure for near-bed measurements took place.

- Before the start of the project the Consultant proposed dune tracking to measure bed load
- In the contracting phase the PA recommended trap sampling as an alternative for the dune tracking
- In the first phase of the project, attempts were made to measure bed load by dune tracking but mostly the Helley-Smith sampler was used.
- The Delft Bottle on a frame was introduced by the PA for Phase 2 when during Phase 1 it was found that dune tracking was not always possible (due to the absence of dunes or too rapidly deforming dunes).
- During Phase 2 it was found that the DB added valuable information on sediment transport close to the river bed; some limitations were encountered, especially concerning the position of the instrument with respect to the bedforms, however the same problem holds for the H-S.
- Near-bed pump sampling was introduced at the end of 1994 to facilitate measuring up to 10 minutes at the same location.
- Promising results supported the development of a Jamuna sampler which would finally facilitate pump sampling at a fixed location and at various elevations above the river bed. The initial Jamuna sampler was tested in December 1995 and February 1996.

In order to define an optimal technique to measure near-bed sediment transport in the Bangladesh rivers, the advantages and disadvantage of all the various techniques applied are presented.

Technique or device	Advantages	Disadvantages
Dune Tracking	- No mooring problems.	- Dunes not always present. - Rapid change of dune shape. - Three-dimensional effects. - Contribution of bed load. Transport on dune migration uncertain.
Helley-Smith Sampler	- Easy handling. - Direct measurement of near-bed load.	- Location with respect to bed forms unknown and necessity to lift the instrument for each observation. - Short observation time. - Large scatter in results. - Reduced efficiency for fine sediment.
Delft Bottle	- Rather easy handling. - Direct measurement of near-bed load. - Various sampling heights above the river bed possible.	- Location with respect to bed forms unknown and necessity to lift the instrument for each observation. - Short observation time. - Calibrated up to a flow velocity of 2 m/s. - Limited efficiency for the fraction 63 - 125 microns. - Risk for losing sediment while retrieving the instrument.
Pump Sampler	- Rather easy handling (but more arrangements required). - High efficiency for fine sediment. - Continuous measurement possible without lifting the instrument. - Constant (but unknown) position with respect to bed forms.	- Location with respect to bed forms unknown. - Long sampling period only possible when large volume sample containers are available (unless a sample splitter is applied). - Sampling only possible at 0.25 m above the river bed.
Jamuna sampler	See pump sampler - Sampling possible in a range from 0.05 to 0.45 m above the river bed. - Flow velocity at intake nozzle known	- Location with respect to bed forms unknown - Long sampling period only possible when large volume sample containers are available (unless a sample splitter is applied)

Table 8.7 Advantages and disadvantages of near-bed sediment techniques tested within RSP.

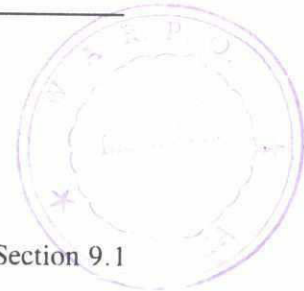
It is important to note that the Jamuna sampler was in its initial stage of development and testing. In this stage one nozzle and one EMF were mounted at a fixed level. After successful testing as a following step, a remote control device is considered for shifting the nozzle and current meter over the range of 0.05 to 0.45 m above the river bed.

Similar optimization analyses with near-bed sediment measuring devices are shown in Table 8.8.

Instruments	Cost x 2	Accuracy x 2	Operation x 1	Duration x 1	Maintenance x 1	Represent. x 1	Total
Direct:							
Delft Bottle	4	4	2	2	2	2	16
Helley-Smith	6	2	2	2	2	1	15
Indirect:							
Pump (Jamuna Sampler)	2	6	1	2	1	3	15

Table 8.8 Multi-criterion optimization analyses of the near-bed sediment measuring devices.

The Delft Bottle, Helley-Smith sampler, and the Jamuna (pump) sampler were all included in the analyses. Dune tracking was not considered because the method was eliminated at the beginning of the project. The pump sampler was also not considered because of its limitations (see Table 8.7). The Jamuna sampler, which is virtually a pump sampler on a specially designed carrier, has a greater appeal for future applications; therefore, the multi-criteria technique was applied for the sampler. The scores of the three measuring techniques were very similar, however, the Delft Bottle had a slightly higher score.



9 Conclusions and Recommendations

9.1 Accuracy of Sediment Measuring Instruments and Methods

Analyses presented in Chapters 6, 7, and 8 allow us to draw some tentative conclusions. Section 9.1 presents the conclusions from Chapter 8.

The following tentative conclusions were outlined for suspended and near-bed sediment measurements.

Suspended sediment

- Based on some time series/duration measurements a number of registrations were made from which the relative standard deviation was computed. The results were as follows
 - The Binckley silt sampler had relative standard deviations ranging from $\pm 23\%$ for silt to $\pm 72\%$ for sand.
 - A pump-bottle sampler, as used by FAP 24's DHA vessel, had relative standard deviations ranging from $\pm 4\%$ for silt to $\pm 14\%$ for sand.
 - The collapsible bag sampler, as used by FAP 24's DHA vessel, had relative standard deviations of about $\pm 19\%$ for sand.
 - The Delft Bottle representing primarily sand had a relative standard deviation of about $\pm 10\%$.
- The silt concentrations measured by both the integrated-bottle and pump-bottle were in good agreement.
- The integrated-bottle underestimated the sand concentration by about 23 to 33% compared to the pump-bottle as applied in the DHA vessel. The pump-bottle of the DHA vessel was about 22% lower than the integrated-bottle.
- The depth-integrated collapsible bag underestimated the sand concentration by about 49%.
- The Delft Bottle did not correctly represent particles less than about 0.125 mm.
- The MEX-3 turbidity sensor worked well to measure and monitor silt-concentration.
- With local calibration, the ADCP-backscatter represented the sand-concentration reasonably well.
- For accurate estimation of suspended sediment transport in a vertical, multi-point measurements should be used. FAP 24's 6-point method gave better results than the Straub or Chinese methods.
- For locating the sediment measuring verticals, a U^2/h or concentration distribution gives good results.

The results of Figures 6.38 to 6.46 are summarized in Table 9.1 with optimal numbers of suspended sediment measuring points in a vertical.

Method	Vertical RA	Vertical LB	Vertical LC
9 or 10 multi-point	0%	0%	0%
Mid-point	-8%	-22%	-41%
Straub 2-point	-9%	-51%	-30%
Chinese 2-point	-24%	-50%	-25%
Chinese 3-point	-30%	-54%	-29%
RSP 6-point	+3%	-6%	+1%

Table 9.1 Comparison of different methods of computing suspended sediment transport per vertical.

Bed load near-bed sediment transport

- Helley-Smith samplers underestimated the near-bed transport, especially in finer fractions (< 0.25 mm). This conclusion was reached by comparing the sampler with the Delft Bottle. The sampler was found to give attractive results in mid-flow ranges.
- Delft Bottle measurements show a consistent and smooth transition between the suspended and near-bed mode. The transport variation between the 0.35 m and 0.15 m is small, and only the lowest 0.05 m above the bed shows the highest variation. Some deviation from this observation was observed in places with excessive scouring (for example, the transport verticals in the plume survey, Annexure G7). The near-bed transport phenomena indicate that in routine gauging, the near-bed transport is appropriately represented by measurements at 0.05 m and 0.15 m above the river-bed.
- Near-bed transport, defined as occurring within 20 cm above the bed, was about 15 to 25% of the total transport.
- A large variation in near-bed transport occurred over the bed-form. Measurements at the dune crest were much higher than at the trough.
- The Delft Bottle is preferable for the near-bed measurements, a pump-bottle system may be a good alternative.
The variability of the transport along the vertical is highest in the near-bed region.
- The grain-sizes increase consistently towards the river-bed.

9.2 Optimal Sediment Measurements

The arguments shown in favour of different optimization exercises, as elaborated in Chapter 8, are summarized as follows.

Primary stations (see Table 8.2) should get priority in data collection. Some stations, such as Hardinge Bridge and Baruria, however, may need relocation from hydrometric and sedimentic considerations. Bahadurabad is a difficult gauging station. A suitable station would preferably be upstream from where it is presently located. However, any relocation has the repercussion of changing the long data-base which exists with BWDB.

The frequency of measurements on a seasonal time-scale should be determined according to the variability of the discharge. For non-tidal stations, 7 seasonal phases can be recognized. Bi-weekly, weekly, or fortnightly measurements should be taken as shown in Table 8.3. In the tidal stations, similar measurements should be taken as shown in Table 8.4. It is uncertain why measurements should be taken more frequently as is often done by BWDB in some stations. Once some stable relations are established, the frequency of measurements can be reduced further.

In terms of survey instruments, the integrated bottle is the most optimal option. Near-bed sediment measurements can be optimally taken by Delft Bottle.

Only multi-point measurements can give accurate results. The River Survey Project 6-point method was an accurate optimal option.

For selection of the location of suspended sediment measuring verticals, a width-wise concentration distribution or u^2/h distribution can be followed.

The silt-clay transport forms a major portion of the suspended sediment transport. Its hydraulic behaviour suggests that it contributes to the river morphology.

Some simple analyses indicate that in most hydraulic conditions, the river-borne sediments are transported as a suspension population with the largest sand transport occurring in the near-bed region. The near-bed transport in an arbitrarily defined layer of 20 cm thick was about 15% to 25% of the total transport.

The physical and mineralogical properties observed in the Bangladesh rivers influence the transport relations which are usually computed based on the properties of quartz. Their influence, however, was found to be negligible.

9.3 Sustainable Sediment Measurements

A sustainable survey technique means that the technique used can be continued into the future as desired by a certain institution in a certain environment. This definition is derived from IUCN, UNEP, and WWF's (1991) broader definition of sustainability as "a characteristic of a process or state that can be maintained indefinitely." However, any instrument or method should be re-evaluated after a certain time because the ranking applied against each criteria may change depending on the country's societal and technological development. The technique can be continued if it satisfies the following six

requirements (see Table 9.2): (1) when the investment is affordable by the concerned institution, (2) when the concerned institution has the capability to operate the technique and maintain the equipment applied, (3) when the technique has the technological compatibility with the country where it will be applied, (4) if the technique gives optimal results, (5) if the investment is justified by the expected results and return, and (6) if the technique is environmentally suitable. Among these six criteria, the institutional capability and justification of results against the incurred expenditure should be given double weight. This is because equipment and methods can not be sustained or even introduced until the institutional capability is developed. Sustainability raises important questions about training, human resources development, and capacity building. If the investment and O & M costs can not be justified by the survey results, a technique can not be sustained. A good and acceptable result can be sold which contributes to the institution's capability to recover the expenses incurred.

SUSTAINABILITY CRITERIA
1. Affordability of investment and O & M costs
2. Institutional capability in O & M
3. Technological compatibility
4. Optimal technique and survey results
5. Justification of results against the incurred expenses
6. Suitability of the technique on environmental considerations

Table 9.2 Sustainability criteria for sediment measurements.

Tables 9.3 and 9.4 show the multi-criteria sustainability analyses of different instruments. Table 9.3 shows the sustainability analyses of the suspended sediment measuring devices. Most of the measuring devices had close scores, except for the Acoustic and the Optical methods whose wide-scale application depends on further research and development. The Binckley sampler, which is used by BWDB, had a slightly higher score than the other measuring devices. This is primarily because BWDB, which is the prime organization in Bangladesh for such data collection, is institutionally most capable of handling the instrument. However, other instruments which received a similar score should also be considered.

Table 9.4 shows the sustainability analyses of near-bed sediment measuring instruments. According to the ranking of each instrument against the selected criteria, the Delft Bottle appears to be the most sustainable near-bed measuring device, followed by the Helley-Smith sampler. Near-bed sediment load and bed-load are very difficult to measure accurately, thus it is important to determine whether near-bed measurements should be taken routinely. So it is crucial to consider or review the objectives of the measurements, assess the accuracy and judge whether it is justified to spend time, money, and effort for such measurements. Some countries, such as the United States, have abandoned measuring near-bed sediment load on a routine basis (U.S. Inter-Agency Committee on Water Resources, 1963). Such countries, however, have determined the range of the ratios of near-bed sediment load to the suspended sediment load for varying flow conditions.

Instruments	Afforded.x 1	Instt. Cap.x 2	Tec.Com x 1	Optimal x 1	Just.Results x 2	Env. Suitab. x 1	Total
TIME-INTEGRATED:							
<i>Point-integrated:</i>							
Direct:							
Delft Bottle	4	10	4	5	12	7	42
Indirect:							
Pump	2	10	5	3	14	7	41
Acoustic	1	6	3	4	4	6	24
Optical	3	6	3	3	4	6	25
Depth-integrated:							
Indirect:							
Integrated Bottle	6	8	6	7	8	7	42
Collapsible Bag	5	8	6	6	10	7	42
INSTANTANEOUS:							
Indirect:							
Binckley Sampler	7	14	7	4	4	7	43

Table 9.3 Multi-criterion sustainability analyses of the suspended sediment measuring devices.

Instruments	Afforded.x 1	Instt. Cap.x 2	Tec.Com x 1	Optimal x 1	Just.Results x 2	Env. Suitab. x 1	Total
Direct:							
Delft Bottle	2	6	3	3	4	2	20
Helley-Smith	3	6	3	2	2	2	18
Indirect:							
Pump	1	4	2	1	6	2	16
(Jamuna Sampler)							

Table 9.4 Multi-criterion sustainability analyses of the near-bed sediment measuring devices.

9.4 Recommendations

FAP 24's recommendations for sediment transport measurements are summarized as follows. Some of the recommendations are common, as in Special Report 11 (RSP, 1996b).

- 1 The human factor is an important consideration for any field measurements. A sophisticated and high-tech survey can fail if the equipment and method are not operated properly. Therefore, human resources development through training should be a fundamental step towards having a sustainable survey.
- 2 A survey vessel, with its facilities for handling the survey operations, is a basic requirement which determines the failure or success of sediment measurements. Therefore, careful consideration should be given when selecting the vessel.
- 3 Utmost care should be given to measuring sediment transport parameters accurately in the primary gauging stations. Relocation of certain stations may be considered, see also 9.2.
- 4 Different phases of the hydrograph show that it is necessary for suspended sediment measurements to be taken either bi-weekly, weekly, or fortnightly. Near-bed sediment measurements should be taken similarly unless a suitable relation is established with total sediment transport for all hydraulic conditions.
- 5 For an accurate sampling of suspended sediment, a sufficient recording length is required to obtain appropriate time averaged values. This means that either a time integrated sampler should be used, applying sufficient exposure time, or an instantaneous sampler should be used for obtaining a series of repeated measurements. This implies that the Binckley instantaneous sampler currently in use with BWDB should preferably be used for time series to improve the accuracy or be replaced. A depth-integrated sampler such as a collapsible-bag can be used when details of concentration distribution over the vertical are not required. For obtaining such details, a pump-method is the best alternative. Use of Delft-bottle as a transport method, either as point-integrated or depth-integrated is attractive but its losses of finer fractions should be quantified.
- 6 Some exercises carried out during the low-flow and the high-flow seasons, show that with an exposure time of 100 s which was followed by FAP24, a relative error of 4 to 36% is made. With 300 s of exposure time, as often suggested in literature, the error reduces to 2 to 30%. Based on this, a 100 s exposure time (integration time) appears to be reasonable choice for a time-integrated sampler.
- 7 As accurate sampling of near-bed sediment is difficult and expensive, such sampling should be made to establish if possible a suitable relationship with the total or suspended sediment transport. If such a relationship does not exist it should be investigated whether a shift in location improves the situation. For routine estimates, near-bed sampling is not recommended.
- 8 For special near bed sediment measurement the Delft Bottle or pump sampling is recommended. For the bed load sampling a trap sampler like BTMA or H-S is useful especially in the mid flow range.

- 9 When a multi-point suspended sediment sampling is made over a vertical, at least 6-points over the vertical should be sampled with at least 1-point near to the bed (0.5 m above the bed). The Straub or Chinese methods appear to give unacceptable large errors.
- 10 For selecting the numbers and locations of suspended sediment sampling verticals, a u^2/h or a suspended sediment distribution over the river width should be used. The verticals have to be placed in such a way that the schematised concentration profile over the verticals fits best with the concentration distribution over the channel width. To effectively follow this method, a reconnaissance survey should be made beforehand.
- 11 When large bedforms are present, it is not conspicuous where to locate a near-bed sampling vertical. In such cases, a mid-point location on the stoss-face may provide reasonable average results. Such methods have been applied (Zaire, Jamuna) but not on routine basis as they are time consuming.



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Annexure A
Sediment Measuring Instruments

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1 Introduction

In conjunction with sediment transport measurements in Bangladesh rivers, the River Survey Project mobilized and used several instruments. Brief descriptions of the different sediment measuring instruments are presented in this Annexure to provide a common background to the users of this report. Limitations and accuracies of the samplers with respect to their applicability in Bangladesh are described in the main report. Details of the principles discussed can be obtained in different sediment transport manuals such as (WMO, 1981); Van Rijn, 1986, 1993). Principles of the sediment measuring instruments are discussed in the main report (Chapter 2).

2 Concentration Method of Suspended Sediment Measurements

2.1 Instantaneous Sampling

An instantaneous suspended sediment sampler is a trapping device. The most primitive such method involves taking a bucket of water from the surface. The Binckley sampler is an instantaneous silt sampler. It is an horizontal cylindrical sampler having a uniform bore. It is lowered in the water in open conditions and is closed by pulling a wire when it reaches the desired water depth. Figure A.1 shows such a sampler used by the Bangladesh Water Development Board (BWDB). Van Rijn (1986) showed that when taking a single sample, the error can be as high as 100%. This sampler is not used by the River Survey Project. Discussion of this sampler is included here, because the sampler has been in use with the BWDB since 1956. It is still being used.

2.2 Time-integrated Sampling

Time-integrated samplers have been widely adopted all over the world (Peters, 1981; Yuqian, 1989). The intake velocity of a time-integrated sampler is adjusted by pressure equalization in the sampling container. Usually 300 s or more time is considered for averaging (Yuqian, 1989). Samplers with an intake nozzle and pump, those that use the optical or acoustic methods, and depth-integrated samplers are all time-integrated sampling devices that are used by the River Survey Project.

2.2.1 Point-integrated Sampling

Pump Method

In the pump sampling method a water-sediment mixture is pumped through an intake nozzle. Figure A.2 shows the intake nozzle of the pump system, the S4 current meter, turbidity sensor, and the submersible pump. The sampler is set up on board the FAP 24 DHA vessel.

The field activities begin with assurance of pumping at a rate such that the intake velocity is equal to the ambient velocity. To install appropriate pumping conditions a special monograph was used (see Figure A.3) Examination of Figure A.4 would reveal that unless the hydraulic coefficient is close to unity, errors are made in estimating suspended sediment concentration. The second field activity of the pump method is splitting the pumped sample on-board the vessel deck. This is necessary because pumping for a long period (i.e, 300 s) may involve collection of a large sample which can not be

contained. Therefore, splitting ensures a hydraulic separation of a large sample into smaller container volumes.

Sampling error by a pump system can occur when,

- a hydraulic coefficient is greater or smaller than unity,
- sorting of sediments takes place inside the hose or umbilical chord and
- sorting of sediments takes place during splitting of the sample.

Optical Method

An optical method records turbidity of a sample either using the absorptiometric (light attenuation) or nephelometric (light scatter) principles or a combination of these methods. While the former is more applicable for finer particles, the latter is for coarser particles. Absorptimeters generally obey the Beer-Lambert Law which states that the intensity of light I , transmitted through a sample of concentration c and thickness L is given by:

$$I = I_0 \exp[-\beta cL] \dots \dots \dots (1)$$

where, I_0 is the initial intensity of transmitted light and β is the extinction coefficient of light.

Nephelometers work on the principle of the Tyndall effect which is the effect of light being laterally diffused or scattered. The intensity of scattered light I , at an angle θ is related to the incident beam of intensity I_0 by the Rayleigh formula.

$$I = I_0 \frac{\gamma N V^2}{\lambda^4} \sin^2 \theta \dots \dots \dots (2)$$

where,

N = Number of particles causing scatter in the illuminated volume,

V = Volume of particles,

λ = Wave length of light, and

γ = Constant.

The optical turbidity meter deployed by FAP 24 is called the MEX-3 Suspended Solids Meter. The MEX-3 uses 4-Beam™ sensors (BTG, ..). Two infrared emitting diodes and two photodetectors are molded into the sensor (Fig. A.5). The diodes emit light in infrared frequencies which then pass through the water-sediment mixture, are attenuated, and are received by the photodetectors. Each photodetector receives 2 signals. The output comes from the 4 signals received by 2 detectors. Use of 4 signals eliminates the errors due to contamination and wear of components.

The principle of a photoelectric turbidity meter such as MEX 3 works on the light attenuation principle as in equation 1, but with dependence on particle size.

$$I = I_0 \exp[-kL \frac{c}{d}] \dots \dots \dots (3)$$

where,

I = intensity of light,

I_0 = intensity of light before transmission,

k = extinction coefficient,

L = distance between light source and detector,

c = sediment concentration (g/l),
d = particle size.

The extinction coefficient varies with grain size but approaches a constant value when particle size exceeds 0.02 mm. The above equation shows that a unique relationship between photodensity (I/I_0) and sediment concentration is possible only when the grain size distribution is constant. MEX-3 gives the photodensity output as a percentage. Figure A.6 shows that photodensity is dependent on the sediment concentration and sediment grain size. The data for Figure A.6 were obtained from experiments on the Yellow River.

The great advantage of an optical turbidity meter is its quick result and avoidance of lab procedures. However, it is most suitable for silt particles ($< 50 \mu\text{m}$) (van Rijn, 1990). The upper concentration limit of an optical sensor is 30,000 mg/l.

Figure A.2 shows the MEX turbidity sensor as they are used on board the FAP 24 DHA vessel.

ADCP Back-scatter Method

The detector radiation (R) by an acoustic system is related to the sediment concentration (c) as,

$$R = \kappa c e^{-\zeta c} \dots \dots \dots (4)$$

where,

κ and ζ are calibration constants depending on instrument characteristics, fluid properties, sediment particle properties, water depth and travel distance.

An Acoustic Doppler Current Profiler (ADCP) records the signal strength of returning echoes by measuring echo amplitude (RD Instruments, 1989).

$$E = \psi + S + B - 20 \log L - 2\chi L \dots \dots \dots (5)$$

where,

E = echo amplitude in decibels (dB),
S = source level of transmitted power (dB),
 ψ = a constant,
B = water mass volume backscattering strength (dB),
L = distance from the transducer to the depth cell (m),
 χ = absorption coefficient (dB/m).

The constant ψ is included because the measurement is relative rather than absolute. The term $2\chi L$ accounts for absorption and the term $20 \log L$ accounts for beam spreading. Absorption reduces the strength of echoes as a result of physical and chemical processes. The absorption coefficient increases with an increase in the acoustic frequency of the ADCP. The beam spreading effect is purely a geometric cause for echo attenuation as a function of depth range. The scatterers affecting backscattering strength (dB) are zooplankton, suspended sediments, and detritus. Therefore, this function is strongly dependent on sediment size. In a sedimentary environment with a uniform sediment distribution, the system may work extremely well compared to an environment with rather non-uniform distribution. Recent advances in the use of acoustic back-scatter signals for estimating suspended sediment concentration can be found in Thorne et al (1991) and Thorne et al (1994).

Use of the device for obtaining suspended sand concentration in the Jamuna River at Bahadurabad is discussed in Annexure D.

2.2.2 Depth-integrated Sampling

A depth-integrated sampler is lowered into the stream bed and raised again to the surface at a uniform transit rate. The device samples continuously during both periods of slow-speed transit. The transit rate is usually suggested as 40% of ambient velocity. There are several varieties of depth-integrated sampling devices. The sampling devices used by FAP 24 include an integrated-bottle type sampler and a collapsible-bag sampler.

Integrated-bottle

The bottle sampler has an intake nozzle that points towards the flow and an air exhaust that points away from the flow. Water enters through the nozzle at hydrostatic pressure and fills the bottle to the level of the exhaust tube entrance. This limits the volume that can be collected by the sampler. The standard sampler with a bottle volume of 1 liter can be effectively used only in depths under 4.5 m (Yuqian, 1989). However, this depth limitation can be increased by using instruments with a larger bottle. The ambient depth-averaged velocity of the vertical must be equal to the average intake velocity through the nozzle. The volume of samples at each point will then be proportional to the local velocity. Figure A.7 shows a 1 liter depth-integrated bottle as implemented by FAP 24. Since there is no opening or closing device on the intake nozzle, the sampler continues sampling while in the water.

The measuring errors of the device are due to:

- non-uniform lowering and hoisting rates,
- a transit rate that is too high or low such that the hydraulic coefficient is not equal to unity
- when a higher depth is covered such that the capacity of the bottle is exceeded.

Collapsible-bag

The collapsible bag implemented by FAP 24 was described by Nordin (1994). The sampling system has the following parts: (1) sampler frames to hold 3-liter or 8-liter plastic bottle, (2) perforated 3-liter and 8-liter plastic bottles, (3) streamlined plastic caps that screw on the bottles and nozzles, (4) lightweight plastic bags, (5) streamlined sounding weights and (6) hanger bars. Figures A.8 and A.9 show the typical set-up of a 8-liter collapsible bag on board the DHA vessel. In Figure A.8 the sounding weight is fitted below the collapsible bag and in Figure A.9 the bottle is fitted below the sounding weight. It may be mentioned that China adopted the sampler with a different design (Anex3-1) and replaced a plastic bag with a rubber-bag (Yuqian, 1989; Zhian and Huanlin, 1990). For discussion on the other types of collapsible bag samplers, please refer to the main text section 6.1.

The uniform transit rate is usually set as less than 40% of ambient flow velocity. However, Nordin (1993) reported using transit rates less than 20% of ambient velocities in large rivers such as the Mississippi and the Amazon. Figure A.10 shows the sample volumes collected at different sized nozzles

in different flow depths. The advantage of a collapsible bag is that it does not have a depth-limitation (depending on the plastic bottle size). However, the sampler is susceptible to plastic bag leakage.

3 Suspended Sand or Near-bed Sand Transport Measurements by a Delft Bottle

A Delft Bottle is a point-integrating or depth-integrating flow through sampler that utilizes the transport method. It can be used either as a suspended load sampler or as a near-bed sediment load sampler (usually on a frame). For a description of near-bed transport please refer to the main text Chapter 2 under 'Bedload sediment transport'. At a certain time (2 - 5 min.), a water-sediment mixture enters through the nozzle and flows out from the back of the sampler leaving behind the suspended sediments coarser than approximately 100 μm . The pressure difference between the entry point at the nozzle and at the rear exit drives the flow through the nozzle. The cross-sectional area of the nozzle equals the area of the rear openings. Therefore, once the bottle is filled the flow is continuous. Inside the chamber, flow is reduced because of the large chamber area. The flow reduction is responsible for settling of sediments coarser than approximately 100 μm . Nozzle sizes of the Delft Bottle are usually classified as big or small. A big-sized nozzle (internal diameter 0.22 m) is used for flow velocities less than approximately 1.0 m/s. When using big nozzles four rear openings are kept open. A small nozzle (internal diameter 15.5 mm) is used for flow velocities higher than approximately 1.0 m/s. When using small nozzles two bottom rear openings are kept open. A straight nozzle is used in suspended sediment sampling and a bent nozzle is used in near-bed sediment sampling. Figure A.11 shows a Delft Bottle on a frame with a small bent nozzle as implemented in the River Survey Project for near-bed sampling. Figure A.12 shows elutriation of the Delft Bottle sample. The local average sediment transport ($\text{kgm}^{-2}\text{s}^{-1}$) of a Delft Bottle is computed as,

$$S = \frac{\alpha(1-p)\rho_s V_s}{AT} = \frac{\alpha G_s}{AT} \dots\dots\dots(6)$$

where,

α = calibration factor (see the chart),

p = porosity factor (~ 0.4),

ρ_s = density of sediment (kgm^{-3}),

V_s = volume of sediment sample (m^3),

A = cross-sectional area of the nozzle (m^2),

T = sampling period (s),

G_s = dry sediment mass (kg).

Figure A.13 shows the calibration factor (α) of a Delft Bottle sampler for different sized nozzles in different sedimentary environments (after Van Rijn, 1986). It shows that the calibration factor is higher for finer sediments and lower for coarser sediments. Also it increases as the velocity increases.

The usual errors introduced by the sampler are:

- incorrect intake velocity compared to the ambient velocity causing a hydraulic coefficient different than 1,
- loss of sand due to the difference between the total sand volume entering the nozzle and the part that is settling inside the bottle causing the coefficient of loss,
- inefficiency of the sampler to collect sediments less than approximately 100 μm .

- additional sampling during raising and lowering of the instrument during point-integrating sampling,
- sediment losses during removal of the sand catch from the Delft Bottle.

The calibration factor is a ratio of the loss coefficient and the hydraulic coefficient. The hydraulic coefficient of a straight-nozzle Delft Bottle is usually less than 1.1 in lower flow velocities (< 1 m/s). In greater flow velocities (> 1 m/s), the coefficient becomes a constant of about 1.1 (Delft Hydraulics, 1963). The loss coefficient is greater than 1 for all velocity ranges and is higher for finer sediments (Delft Hydraulics, 1963). Calibration factor shown in Figure A.13 are applied to take care of the errors.

Field experiments with the Delft Bottle and other samplers in the Danube River (Dijkman and Milisic, 1982) indicated that the Delft Bottle sampler gives systematically lower transport than USP-61 and Pump-filter samplers in the fine fraction ranges (70 - 150 μm). An integration time of approximately 600 - 900 s was applied for sampling. The experiment concluded that transport with particles less than 140 μm can not be measured accurately. For further comparison of the Delft-bottle with the USP 61, please refer to Beverage and Williams (1989).

4 Near-Bed Sand Transport Measurements by a Helley-Smith Trap Sampler

A Helley-Smith trap sampler (Helley and Smith, 1971) was designed for estimating bed load transport in coarse sand bed rivers or in gravel bed rivers. It is an adapted version of the BTMA (Bedload Transport Meter Arnhem) sampler (Delft Hydraulics, 1958, 1966, 1969; and Hubbel et al, 1985). In fine sand bed rivers as are present in Bangladesh the Helley-Smith sampler can best measure the near bed transport. Figure A.14 shows a Helley-Smith trap sampler with sand-catch. Samples are trapped in 250 μm mesh polyester for a period of about 2 min.

$$q_{nb} = \frac{\gamma m}{bt} \quad (7)$$

where,

q_{nb} = near-bed sediment transport ($\text{kgm}^{-1}\text{s}^{-1}$)

γ = 0.5 for particles with d_{50} between 0.25 mm to 0.50 mm.

= 1.0 for particles with d_{50} between 0.50 and 16 mm.

m = dry mass of the sediment catch

b = width of the intake opening (0.0762 m)

t = sampling period (~ 2 min.)

The BTMA was applied in large sand-bed rivers such as the Zaire (Peters and Goldberg, 1989).

5 Bed-load Transport Measurements by Dune Tracking

An accurate measurement of sediment transport in large alluvial rivers is extremely difficult (U.S. Inter-agency Committee on Water Resources, 1963; WMO, 1981). Among the two modes of transport: suspended load and bed-load, the latter is almost impossible to measure. The bed-load transport occurring in contact with the bed under the influence of gravity is confined within a 'thin layer' near the bed. The thickness of this 'thin layer' has been shown to vary from 2 particle diameters by Einstein (1950) to the maximum saltation height measuring up to 10 particle diameters by Abbot and Francis (1977). For fine sand-bed rivers, the layer comprises only a few millimetres which is practically difficult to sample by any conventional device. Despite such difficulty, it is necessary to have a reasonable estimate of bed-load transport which is very important for river-bed morphology. One approach is to estimate indirectly with the help of tracking the bedforms at a suitable time-interval (Hubbel, 1964; Simons et al, 1965; Fredsoe, 1979; Engel and Lau, 1980). Bed load transport by dune tracking (dunes or megaripples) can be estimated simplistically by a relation proposed by Engel and Lau (1980) for steady uniform flow.

$$q_b = \alpha_s(1-p)\rho_s v \Delta \quad (8)$$

where,

q_b = bed load transport ($\text{kgm}^{-1}\text{s}^{-1}$)

α_s = shape factor (0.5 ~ 0.6)

p = porosity factor (~0.4)

ρ_s = density of sediment (~ 2650 kg/m^3)

v = average migration velocity of the dune (m/s)

Δ = average dune height (m)

For application of the method and the many problems encountered to apply the method in the Jamuna River please refer to Section 5.2 and Annexure F. One of these problems is that not only the bed load but also part of the suspended load is responsible for the propagation of bedforms as was outlined already by Hubbel in 1964, see Fig A.15. For this reason an approach to tackle this problem was discussed in the 1991 proposal of the consortium. However, it is questionable whether such an approach will give appropriate results on the Jamuna. As dune tracking was not selected as a suitable method for routine bed load measurements, the problem has not been tackled.

6 Bed-Material Sampling

Bed-material can be sampled by using a grab sampler, scoop sampler, or a dredge sampler. FAP 24 used a Van Veen grab sampler (Fig. A.16), a US BM-54 scoop sampler (Fig. A.17) and a drag (dredge type) sampler (Fig. A.18). The drag bed-material sampler was fabricated in accordance with the RWS (1954) design and was suggested by J.J. Peters.



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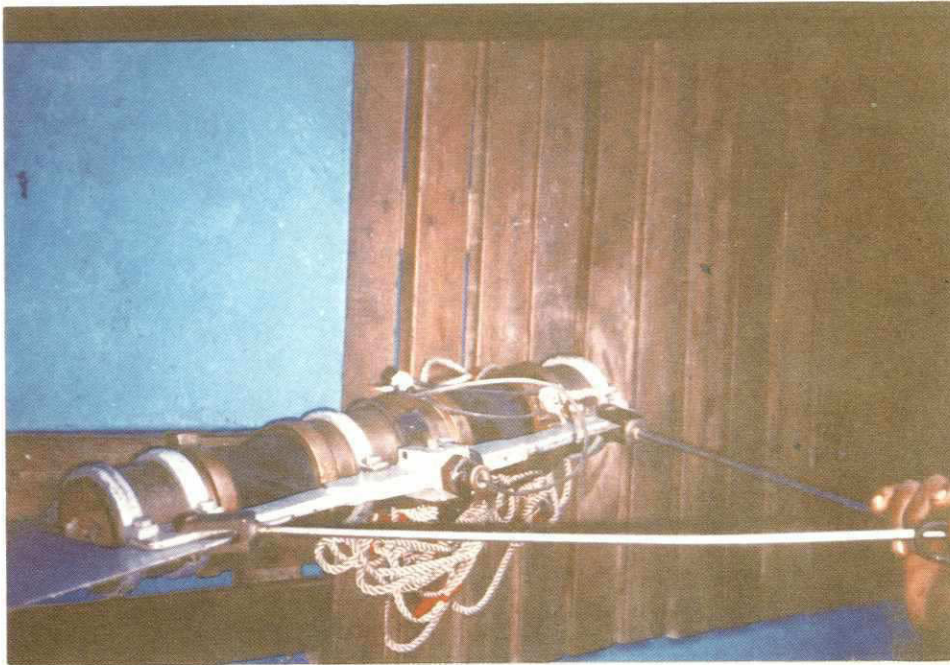


Figure A.1 Photograph of a Binckley Silt Sampler used by Bangladesh Water Development Board.

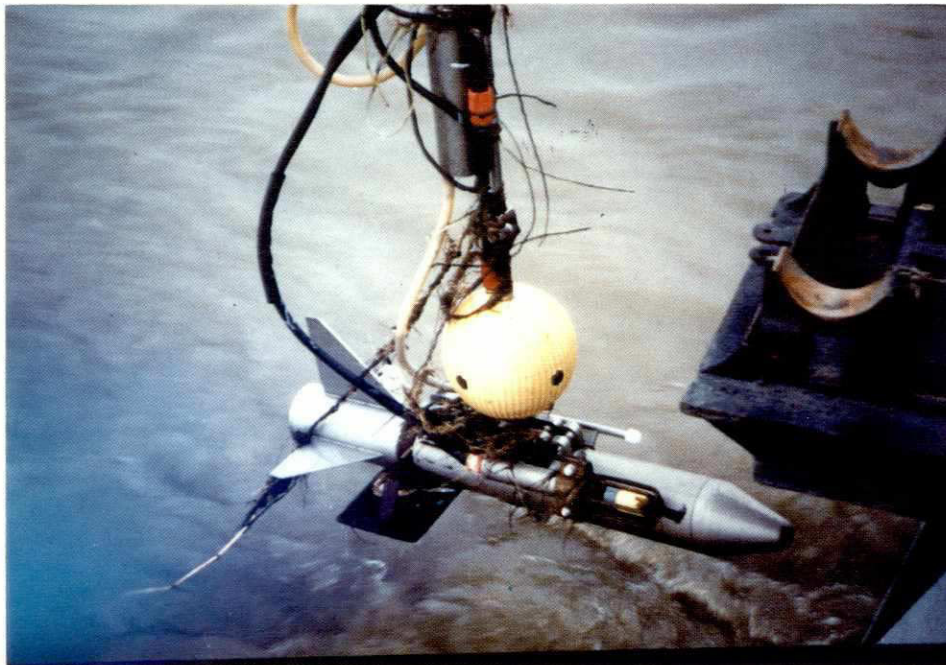


Figure A.2 The intake nozzle of the pump-system fitted in a fish, with a MEX-3 turbidity sensor, a S4 current meter, and a submersible pump on board DHA vessel of the River Survey Project.

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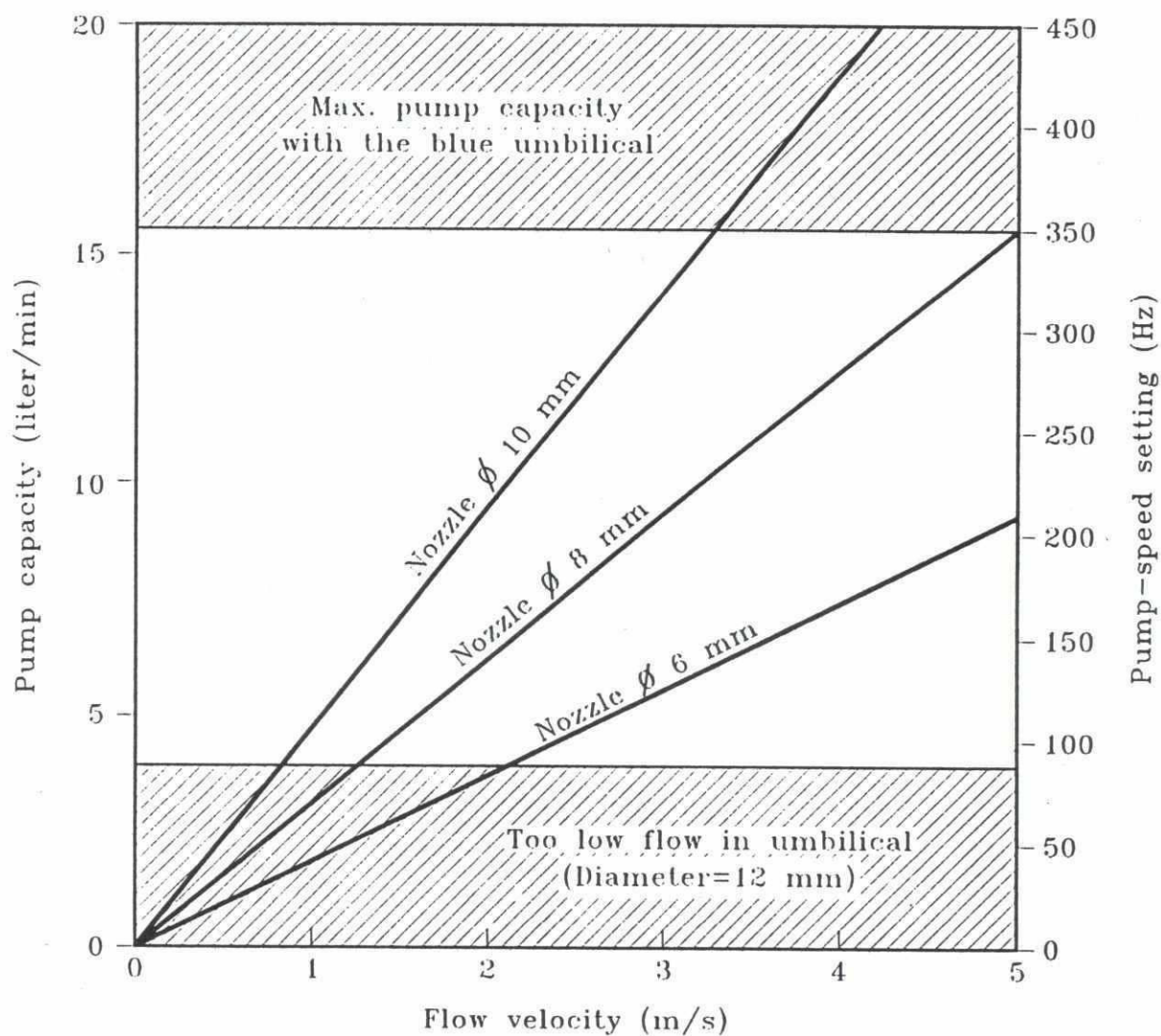


Figure A.3 For iso-kinetic pumping, pump-speed (on board DHA and DHB vessels) as a function of ambient flow velocity.

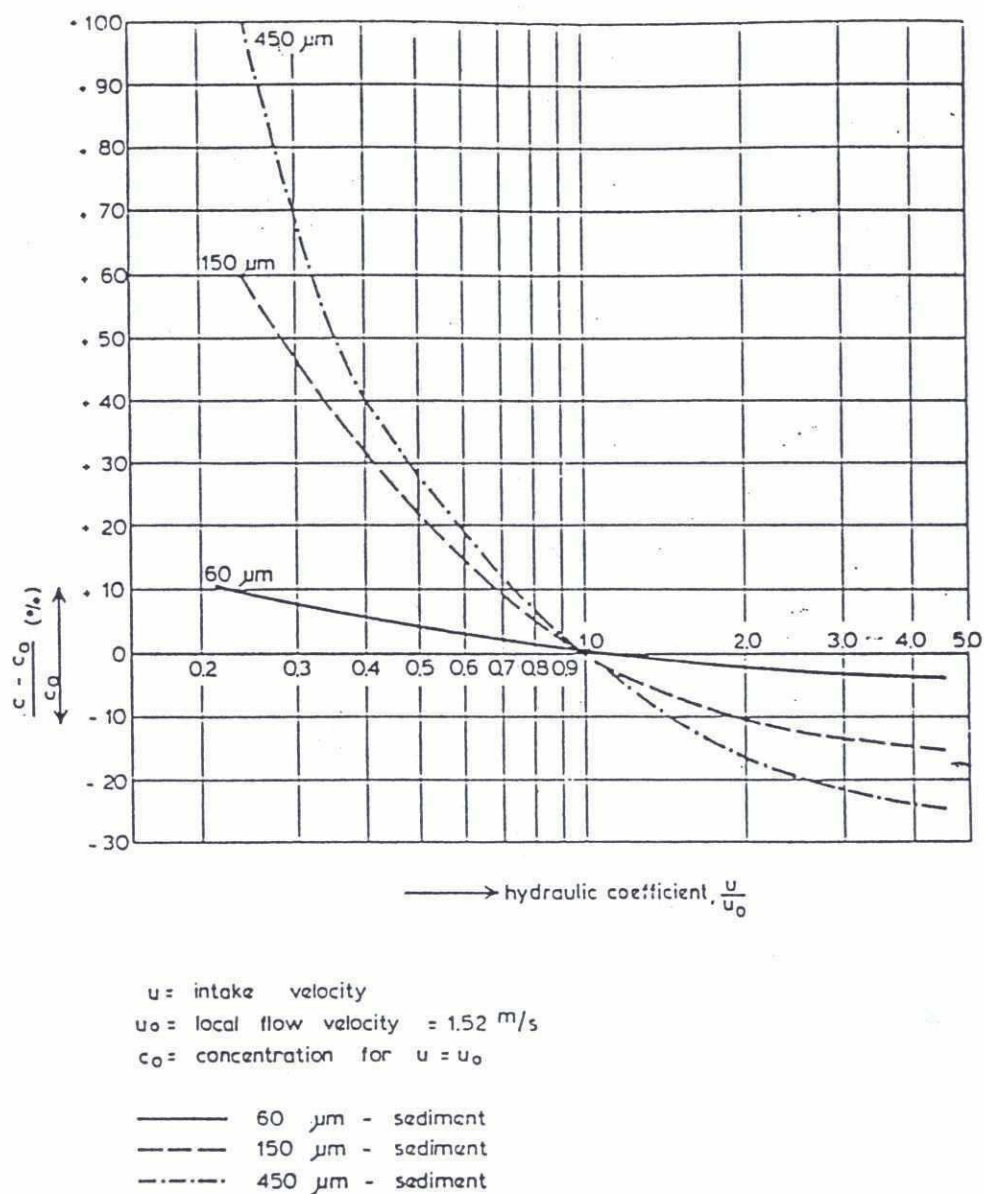


Figure A.4 Sampling errors of sediment concentration at different hydraulic coefficients (after Nelson and Benedict, 1950).

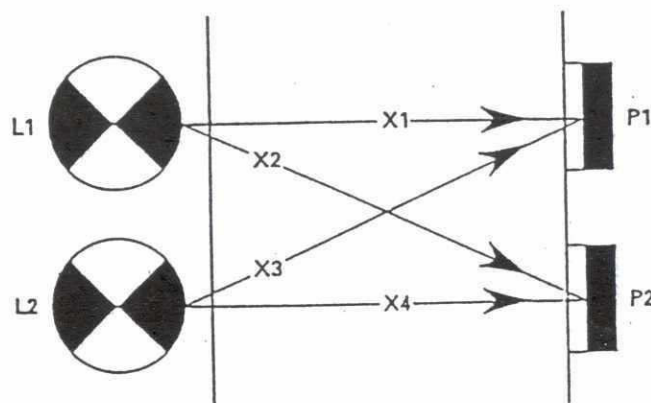


Figure A.5 The light measuring principle of a MEX-3 turbidity sensor.

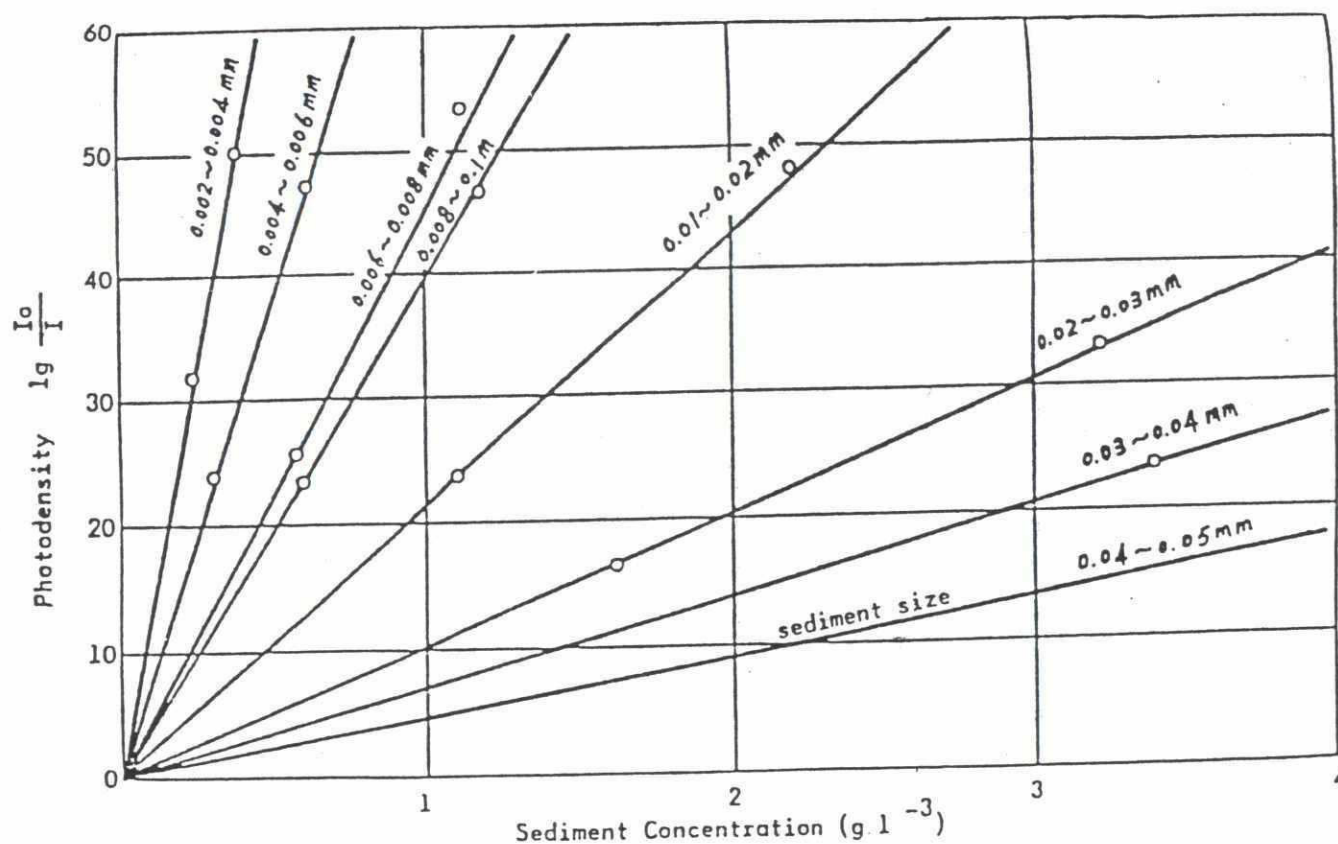


Figure A.6 Dependence of photodensity to sediment concentration and grain size of sediment particles.

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Figure A.7 Photograph of an integrated bottle implemented by the River Survey Project.

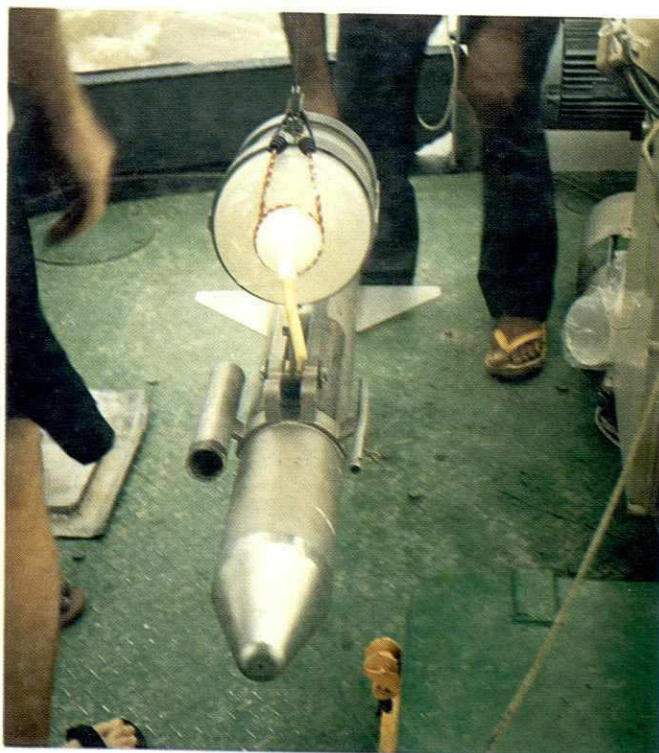


Figure A.8 An 8-liter collapsible bag sampler with a tube fitted to the nozzle and a sounding weight fitted below the bottle on board DHA vessel of the River Survey Project.



Figure A.9 Photograph of a collapsible bag fitted underneath the sounding weight.

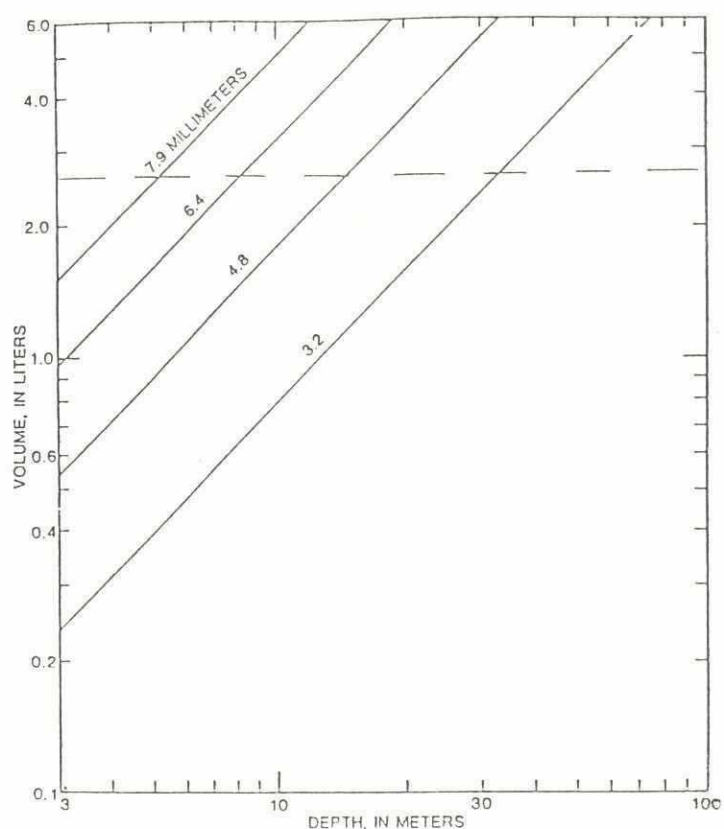


Figure A.10 Sample volume of a collapsible bag sampler as a function of water-depth and nozzle size (after Nordin, 1994).

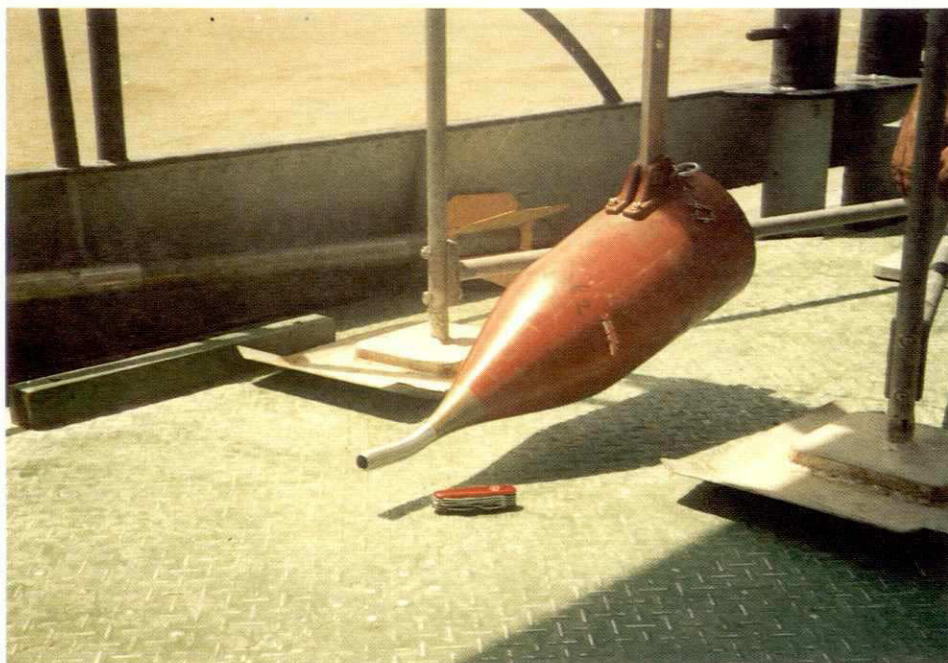


Figure A.11 Photograph of a Delft Bottle on a frame for near-bed sand transport measurements.



Figure A.12 Photograph of elutriation of Delft Bottle sand catch on board DHA vessel.

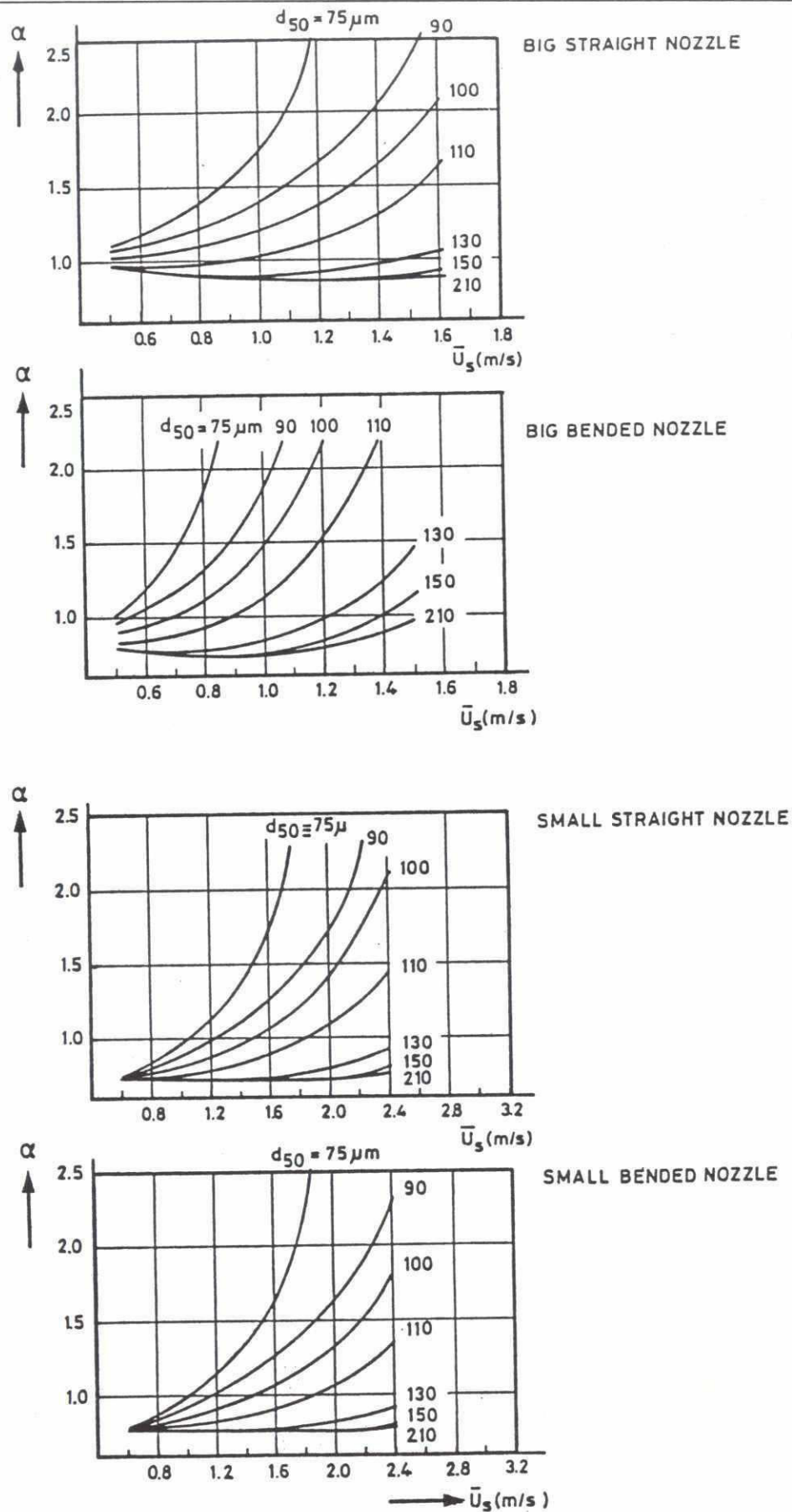


Figure A.13 Calibration factor of Delft Bottle samplers for small and big size straight and bent nozzle sizes (after Van Rijn, 1986).



Figure A.14 Photograph showing the sand catch by a Helley-Smith trap sampler on board the DHA vessel.

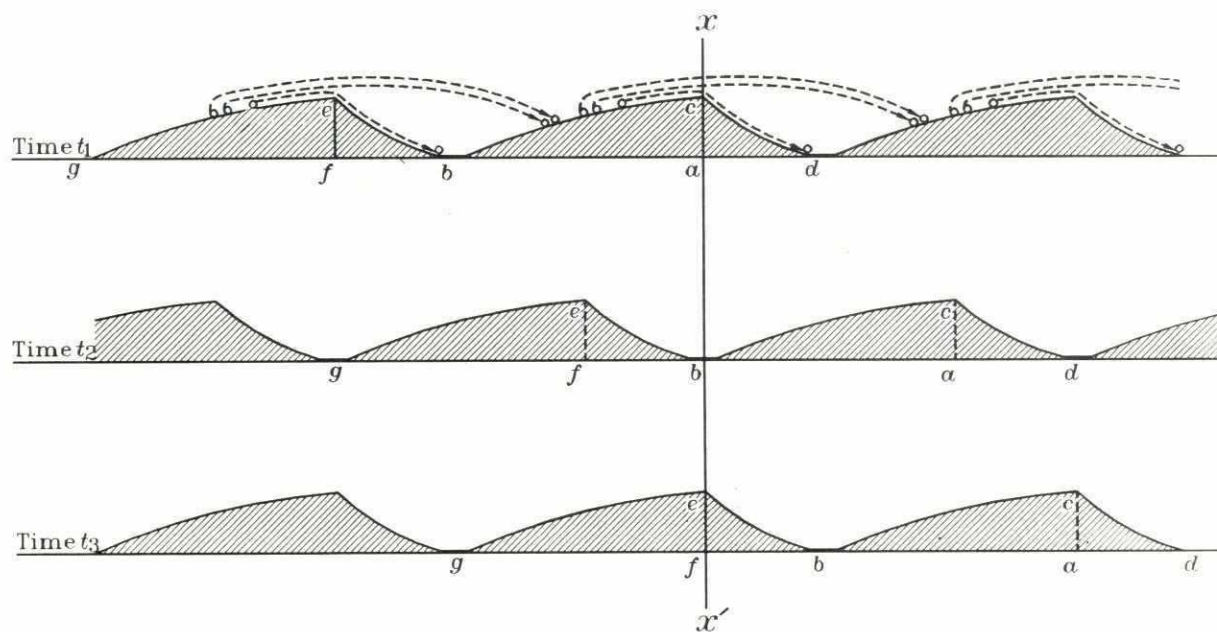


Figure A.15 Idealized diagram of dune movement if only one of every three particles eroded from a dune is deposited on the downstream side of the same dune and the other two pass on to the next dune.

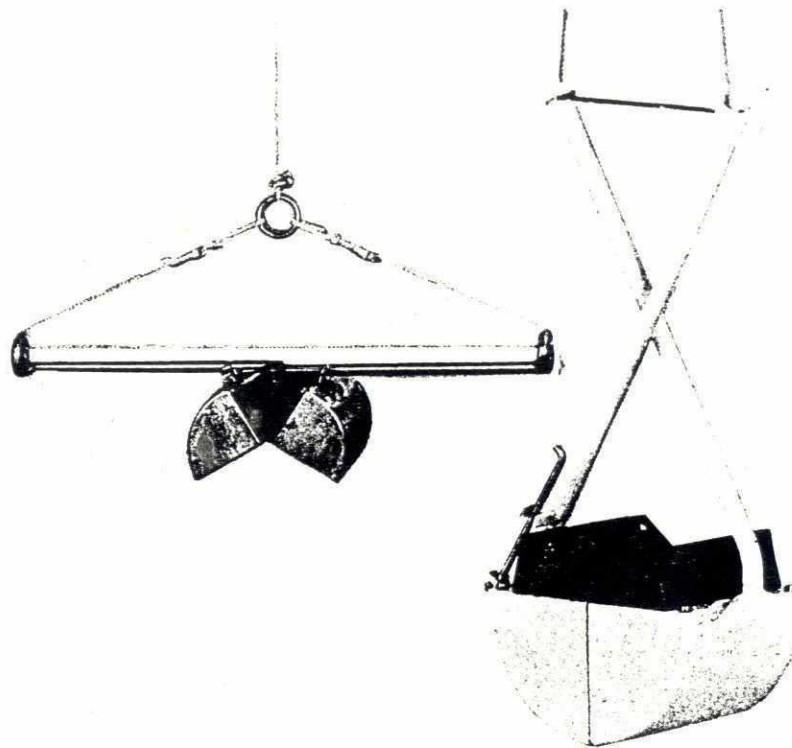


Figure A.16 Van Veen grab sampler.

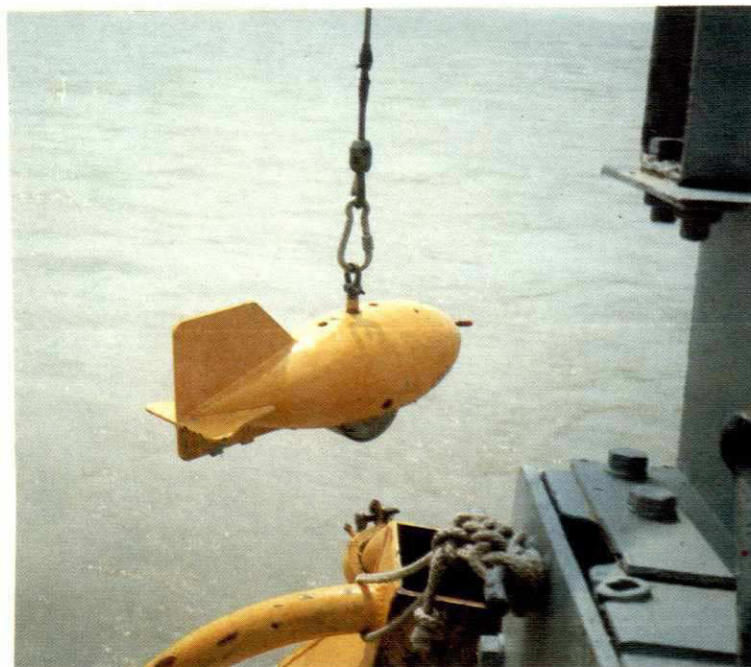
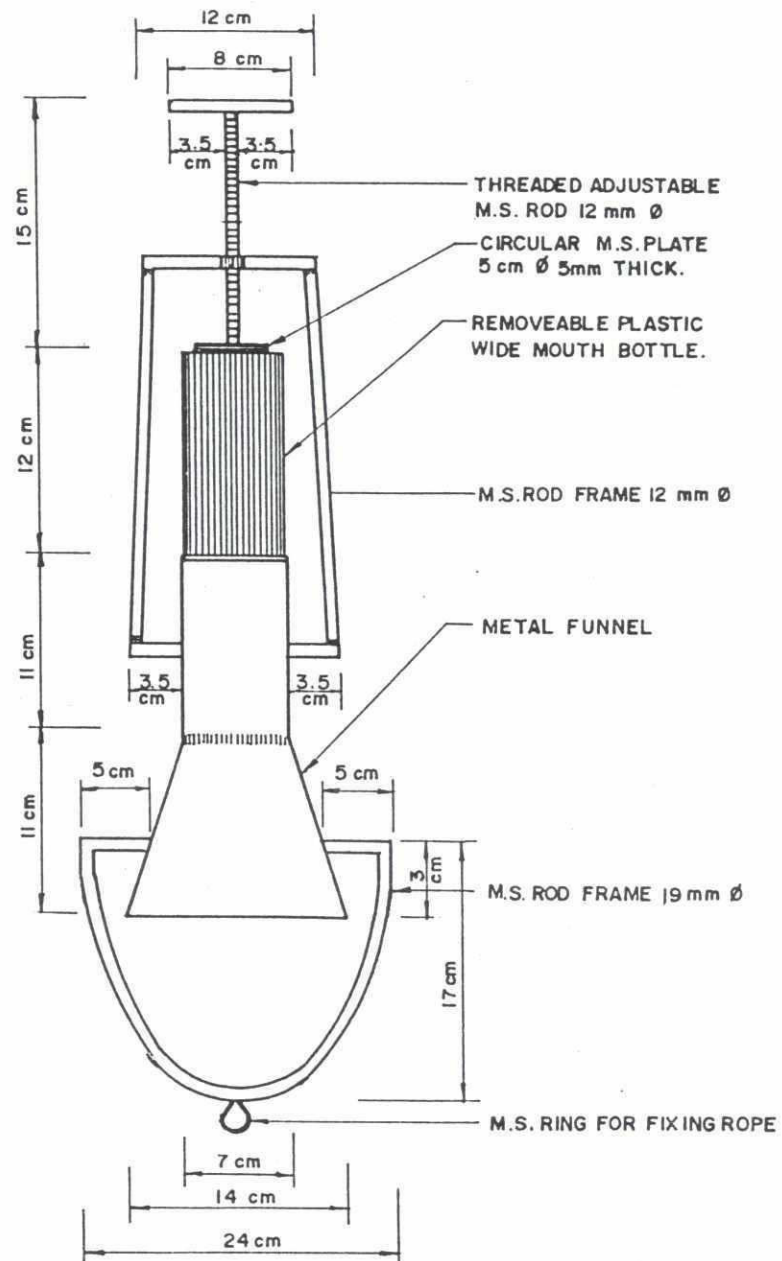


Figure A.17 Photograph of US BM-54 bed-material sampler on board DHA vessel.



Drag bed-material sampler fabricated in Bangladesh by FAP24

Figure A.18 Drag bed-material sampler fabricated in Bangladesh by FAP24 (after PIANC, 1953).

Annexure B
Total Sediment Transport Computation



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1 Introduction

In the River Survey Project sediment transport was measured in various ways using different combinations of samplers. It was necessary to determine how to calculate the sediment transport at different widths and if possible distinguish between fine and coarse material transport.

In this Annexure different sediment transport computation possibilities are discussed. Basic principles of sediment transport computation are discussed in Sections 3 and 4. In Section 5 some estimates are presented using these methods.

2 Combination of Samplers

In this project the following combinations of samplers were used (Table B.1).

Combination Category	Main Channels			Sec. Channels
	bulk previously	bulk recently	ref. verticals	small boat
DI	+	+	+	-
PI	-	-	+	+
DB	-	+	+	-
HS	+	-	+	+

Table B.1 Combination of samplers

where,

DI= depth integrating sampler either a bottle or collapsible bag type. The unmeasured near bed zone varies from 0.2 to 0.5 m depending on the sampler configuration. The corresponding velocity can be measured using an ADCP, S4 propeller, or current meter.

PI= point integrating sampling which was done using a pump bottle system in the River Survey Project. Velocity measurements were usually taken using S4.

DB= Delft Bottle. Usually used in a frame 5 and 15 cm above the river bed; in the reference vertical also used 25 and 35 cm above the bed.

HS= Helley-Smith bed load sampler

When using two or more samplers in a measuring vertical, it is necessary to determine how to calculate sediment transport for the different combinations. This problem is tackled generally in Section 3 with a discussion of the principles of sediment transport computation and more specifically in Section 4 with a discussion of the different combinations of samplers.

3 Principles

The principle of sediment transport computation at different widths is indicated in Figure B.1

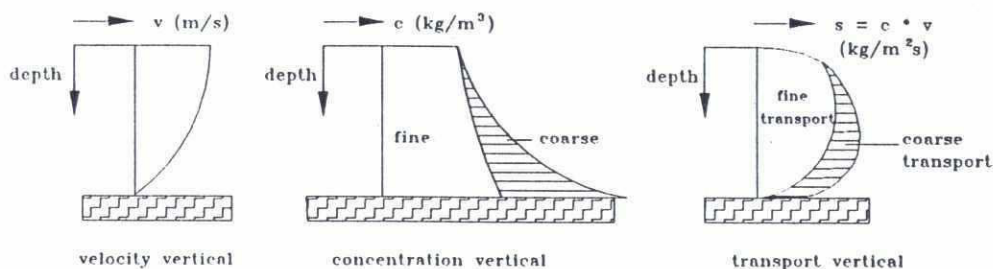


Figure B.1 Ideal computation principle of total load transport over a vertical.

The sediment transport (fine, coarse, and total) by width (s in kg/ms) is determined by integration over the transport vertical.

The full profile is not measured so interpolation and extrapolation techniques have to be used to measure the velocity. The velocity is assumed to be constant from the surface to the measured level (Fig. B.2). For the unmeasured near-bed region a power function is assumed (Van Rijn, 1993).

$$U = U_1 \left(\frac{z}{z_1} \right)^{0.25}$$

where,

U = Velocity at any level in the unmeasured zone, z .

U_1 = Velocity at the lowest measured point, z_1 in the vertical.

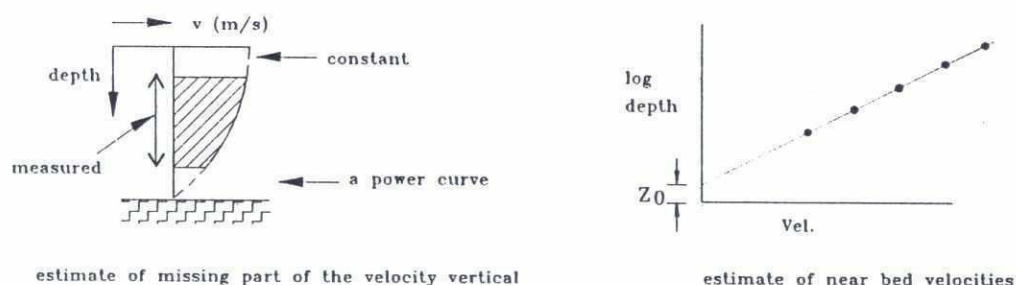


Figure B.2 Extrapolation of velocity curve and obtaining zero velocity level (z_0). (Remark: The application of this theory for large alluvial rivers is questionable (Peters, 1994). Accurate near-bed velocity profiling could solve the problem. However, for this purpose, a frame with some current meter in the vertical is required which was not available in the project)

Calculating the sediment concentration and transport is more complicated because the different samplers do not measure the same parameters. The DI and PI categories measure the concentration while DB and HS are transport meters. The DI and PI categories are usually split the fine and coarse fractions.

However, the DB does not sample much sediment finer than 0.1 mm and the HS does not sample much sediments finer than 0.25 mm.

Another set of problems arises because the sampling sometimes overlaps, while in other combinations a clear unmeasured zone exists.

4 Analyses per Combination

In the following section the possible analyses for the different combinations of samplers are discussed.

4.1 Integrated-bottle with Helley-Smith

There are several problems when using this combination which are illustrated in Figure B.3. The vertical is divided into three parts. The upper part (1) is covered by the DI sampler and the lower part (3) by the Helley-Smith sampler. The middle depth (2) is the zone that is not sampled.

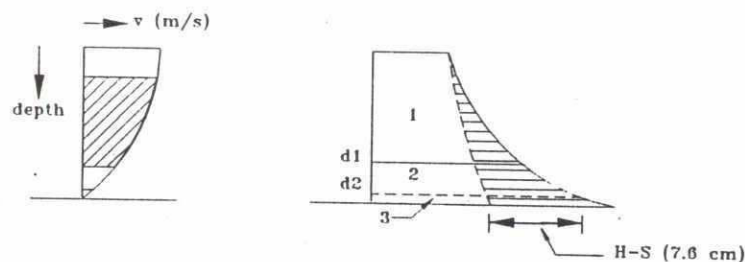


Figure B.3 Combination of Integrated-Bottle with the Helley-Smith sampler.

When using the DI, the depth-averaged values for fine, coarse, and total sediments are determined. Also, the average v_1 value over the corresponding depth (d_1) can be determined. The transport for the upper part is:

$$s_1 = v_1 * c_1 * d_1$$

In the lower part the transport is,

$$s_3 = \alpha s(\text{HS})$$

where, α (> 1) is a correction factor for H-S which does not sample the finer sediments

A value for c_3 can be calculated from s_3 and v_3 (depth-averaged velocity over part 3 of the vertical estimated by using a power function). A curve through c_1 and c_3 should provide the values for c_2 after which $s_2 = v_2 * c_2 * (d_2 - d_1)$

$$s = s_1 + s_2 + s_3$$

The two major problems envisaged are:

The transport measurements are better than the DB/HS combination as the DB is only losing the fine sediments and a part of the 0.063 - 0.125 fraction.

The problems to be solved include:

- 1) assessing what sediment sizes the DB does not sample
- 2) determining a concentration or a transport curve for the lower part of the vertical

Simple calculations include:

$$s_{\text{fine}} = c_{\text{fine}} * \bar{v} * d$$

$$s_{\text{coarse}} = c_{\text{coarse}} * \bar{v} * d + (DB_{05} + DB_{15}) * 0.1$$

4.3 Point-Integrated with Helley-Smith

The principle of computation for this combination is basically the same as that discussed in Section 4.1. However, the point-integrated values in the measured zone are integrated by using the Simpson Rule (one example). Also, the lowest measuring point in the vertical is used for estimation of the unmeasured zone.

5 Some Estimates of Total Sediment Transport

Estimates using the various methods discussed in Section 4 are shown in Tables B.2 and B.3 .

In Table B.2, the estimates are shown by vertical. It shows that the PI-DB method is higher than the other methods. Between the DI-HS and the PI-HS combinations, there is no systematic difference.

Verticals in Channels	DI - HS (kg/ms)	DI-DB (kg/ms)	PI - HS (kg/ms)
L1	3.0	4.4	2.3
L2	1.7	-	3.1
L3	0.9	-	0.1

Table B.2 Estimates of total sediment transport by vertical using various combinations based on measurements in the Jamuna River transect near Bahadurabad from 6 to 9 August 1994. The α value is assumed to be 1.

These kind of comparisons can be extended using the vast amount of data in the database of FAP24 on the reference verticals. However, the differences are mainly caused by the different instruments and the variability of the sediment transport. Therefore, not much can be concluded regarding the concentration method.

In Table B.3, estimates for the DI-HS combinations according to Section 4.1 and FAP24 method (RSP, 1996) are compared.

Channels	DI-HS (kg/s)	PSD24 (kg/s)
L1	7569.0	7438.7
L2	471.0	419.7
L3	502.0	506.3

Table B.3 Estimates of total sediment transport per transect using various combinations based on measurements in the Jamuna River transect near Bahadurabad from 6 to 9 August 1994.

It can be seen that the differences between the straight-forward method (Section 4.1) and the more refined one used for the PSD24 data-base (based on the mid-section method and using more elaborate estimates for the bank sections) are small.

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Annexure C

**Near-Bed Sand Transport Measurements by
Delft Bottle and Helley-Smith Samplers**

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- Figure C.16 Estimated vs. measured Helley-Smith flux. One grain size applied for suspended sediment ($d_{50}=0.22$ mm). Bed load not included.
- Figure C.17 Estimated vs. measured Helley-Smith flux. Measured grain size from Delft Bottle applied for suspended sediment. Bed load not included.
- Figure C.18 Estimated vs. measured Helley-Smith flux. Measured grain size from Delft Bottle applied for suspended sediment. Correction for reduced catch of Helley-Smith sampler applied. Bed load not included.
- Figure C.19 Estimated vs. measured Helley-Smith flux. One grain size applied for suspended sediment ($d_{50}=0.22$ mm). Bed load included (calculated by van Rijn formula).
- Figure C.20 Estimated vs. measured Helley-Smith flux. Measured grain size from Delft Bottle applied for suspended sediment. Bed load included (calculated by van Rijn formula).
- Figure C.21 Estimated vs. measured Helley-Smith flux. Measured grain size from Delft Bottle applied for suspended sediment. Correction for reduced catch of Helley-Smith sampler applied. Bed load included (calculated by van Rijn formula).
- Figure C.22 Bed material transport in the near-bed zone as a ratio of the total bed material transport, estimated from Delft Bottle measurements by two different methods.
- Figure C.23 Correlation of sediment flux with depth average flow velocity for Helley-Smith, Delft Bottle, and depth integrating sampler (catch factor applied for Helley-Smith).
- Figure C.24 Comparison of sediment flux measured by Delft Bottle at two levels with the flux measured by Helley-Smith sampler (corrected for estimated loss of fines).

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- Figure C.25 Comparison of near-bed transport determined in the 'old' way by Helley-Smith and in the new way from Delft Bottle samples (simple and integrated method).
- Figure C.26 Comparison of near-bed transport rates estimated by simple method and by theoretically based method.

1 Introduction

Until recently, the Helley-Smith sampler (Helley and Smith, 1971) was the only instrument used by FAP 24 for measuring the near-bed sediment transport in routine transect measurements. The results of these measurements were used together with the suspended sediment concentrations measured by the depth-integrated bottle sampler and the velocity measurements to calculate sediment transport rates. The results were reported in Survey Bulletins as bed load, suspended bed material load, wash load, and the sum of all as total transport. The Helley-Smith measurements were interpreted simply as bed load. The results were also reported in PSD24 in the *.sed* file in the same categories; instead of using the term bed load, the more neutral term Helley-Smith load was used.

Starting with the 1995 monsoon, Delft Bottle measurements at 5 and 15 cm above the river bed have replaced the Helley-Smith samples, except when the applied survey vessel was not equipped to take such measurements. Furthermore, both Helley-Smith and Delft Bottle samples have been collected at the reference vertical.

Prior to the decision to replace Helley-Smith measurements with Delft Bottle measurements, the Delft Bottle was tested in a number of routine and study surveys. In a transition period from August to November 1994, both types of measurements were taken routinely at Bahadurabad.

2 Objectives

- To evaluate the importance of near-bed sediment transport as compared to the total transport.
- To compare the results obtained by the Helley-Smith sampler and the Delft Bottle sampler.
- To recommend a method for using Delft Bottle measurements instead of Helley-Smith measurements in sediment transport calculations.

3 Measurements Analyzed

Only the results of routine measurements at Bahadurabad from August to November 1994 were included in the present analysis. Figure C.1 shows the sampling locations in the Jamuna River at Bahadurabad. The results of the near-bed measurements are all in the *.bdl* files of PSD24 (see Table C.1). Primarily, it was these measurements that were analyzed; however, other sediment transport measurements were also included. The analysis dealt with the transport of bed material only; i. e., wash load was not included.

The reasons for choosing these measurements for initial analyses were:

- They represented routine measurements. A main objective was to determine a processing procedure which is suitable primarily for routine measurements.

- The number of measurements was sufficient to clearly indicate correlations, trends, etc., if there were any.
- The measurements were all from the same transect (although from different channels), thereby reducing the number of independent variables.

The importance of an accurate description of the near bed sediment transport was closely related to how large a fraction of the total bed material load it comprised. Section 7 deals with this aspect by using comparisons made between sediment transport determined from the different types of instruments. The near-bed instruments measured the sediment flux directly; i. e., concentration times velocity in units (for example) of $\text{kg/m}^2/\text{s}$. The depth integration and pump bottle samplers measured concentrations in units of kg/m^3 . Thus, the latter require flow velocity data for determining the sediment flux.

Survey dates	File name	Channel	Vertical numbers	Pump sample vertical no.
7 Aug. 94	b4861t05	1	1,3,4,5,6,7,8,9,10	8
1-3 Sep. 94	b4911t07	2	9,10,11	10
3 Sep. 94	b4911t08	2	1,2,3,4,5,6,7,8	-
4 Sep. 94	b4941t04	3	1,2,3,4	-
5 Sep. 94	b4951t08	4	1,2,3,4,5,6,7,8	-
23 Sep. 94	b4911t02	1	1,2,3,4,5,6,7,11	7
25 Sep. 94	b49p1t03	2	1,2,3,4	1
28 Sep. 94	b49r1t03	3	1,2,4,5,6	5
28 Sep. 94	b49r1t08	4	7,8,9	-
19 Oct. 94	b4a1t02	1	2,3,4,5,6,7,8	6
20 Oct. 94	b4ak1t05	2	1,2,3,4	4
21-22 Oct. 94	b4al1t08	3	1,2,3,4,5	3
7 Nov. 94	b4b71t04	3	2,3,4	3
8 Nov. 94	b4b81t03	1	1,2,3,4	3

Table C.1: Stationary vertical data of the Jamuna River at Bahadurabad included in the analysis.

4 Accuracy of Sediment Transport Measurements

The high variability which was usually found in the field measurements of sediment transport may be associated with the variability of the natural phenomena involved, as well as with a number of other factors related to the accuracy of the instrument, measurement procedures, etc. It was particularly difficult, especially for the Helley-Smith sampler which rested on the bed during sampling, to make accurate near-bed measurements of sediment transport. Neither of the two instruments are able to catch the silt fraction. With respect to the sand fraction, the sampling efficiencies related to the instrument and measuring procedures may seriously affect the result (Hubbel, 1964). The Helley-Smith and the Delft Bottle samplers are shown in Figures C.2 and C.3.

The sampling efficiencies which were primarily associated with the Helley-Smith sampler were as follows:

- Blocking of the flow through the bag by sediment particles reduced the flow through the mouth of the sampler and thereby the inflow of sediment. This may have resulted in an underestimation of transport.
- The relatively large mesh size of the sampler bag allowed a large fraction of the finer material (also including sand fraction) to pass through without being collected. This may have also resulted in an underestimation of transport.

The sampling efficiencies which were primarily associated with sampling operations were as follows:

- The sampler often had difficulty catching the very near-bed sediment transport (lower millimeters). The instrument was an obstruction to the flow, therefore local scouring quickly formed a gap under the mouth of the sampler. The gap may have already been there from the beginning due to the unevenness of the bed. Some of the transport bypassed the sampler, and the transport very near the bed was not represented in the sample. This may have resulted in an underestimation of transport.
- When the instrument settled on the river bed this caused a cloud of sediment to be stirred from the bed. Part of this may be caught by the sampler. This may have caused an overestimation of the transport.
- The sampler may have drifted somewhat downstream during lowering to the bed. When it was later lifted off at an oblique angle, it was pulled along the bed with continuous or intermittent contact with the bed. During this process, it picked up samples directly from the bed which had no relation with the sediment transport. This may have resulted in an overestimation of sediment transport.

Of the above limitations, the instrument related ones were more systematic; they all tended to underestimate the transport rates. Thus, if Helley-Smith samples are collected carefully and correctly they will clearly underestimate the actual sediment transport in the near-bed layer from where they have been taken.

Although the Delft Bottle suffers largely from the same measuring limitations as mentioned above for the Helley-Smith sampler, it is to a far less extent. Section 5 shows that the Delft Bottle catches far more

of the finer material than the Helley-Smith sampler. In addition, the Delft Bottle was used a small distance above the bed, and not on the bed like the Helley-Smith, thus its measurements were more reliable.

The accuracy of the sediment transport measurements higher up in the water column (i.e., the depth integrating sampler and velocity profiles at reference verticals supported by pump bottle samples) was relevant for evaluating how large a fraction of the total transport was taking place near the bed (see section 7). Sometimes the results of the depth integrating sampler deviated significantly from those obtained from the pump bottle samples; usually, the depth integrating sampler indicated a lower transport. The most prominent possible limitations of these instruments were related to the measuring procedure. (For detailed discussion on the subject, please refer to the main report).

- The depth integrating sampler filled up at the larger depths before the sampling was completed. When a full bottle sample was obtained the results may have been incorrect; they may have underestimated or overestimated the concentrations depending on where in the water column the bottle filled up.
- The pump bottle samples needed to be taken with a suitable intake flow velocity. In particular, intake velocities which were too low resulted in overestimation of the concentration and thereby of the transport.

5 Comparisons of Near-Bed Measurements

Figures C.4 and C.5 show simple comparisons of Helley-Smith and Delft Bottle measurements at 5 and 15 cm above the bed respectively. Different markers were used for the 4 different channels. To illustrate differences between the channels more clearly, the results from the different channels were plotted separately in Figures C.4a to C.4d and C.5a to C.5d. The plots show the following:

- There was considerable scatter for all the measurements (which was not unexpected); however, there was more scatter for the Helley-Smith than for the Delft Bottle measurements.
- Generally, the Delft Bottle measured **higher** transport rates (approximately factor 3). This was surprising considering that the Helley-Smith measured closer to the bed. One explanation is that the Helley-Smith did not catch the finer part of the bed material load.
- The difference between the Helley-Smith and Delft Bottle measurements was relatively higher at low transport rates. This characteristic was indeed to be expected as a consequence of the Helley-Smith catching less of the finer part of the bed material load than the Delft Bottle.
- Differences between the four different channels did not seem significant. Therefore, results from all four channels were analyzed together in the following section.

In Figure C.6, the Delft Bottle measurements at the two levels were simply averaged and divided by 3. These measurements were compared with Helley-Smith to determine if a factor 3 could be applied between the two samplers.

The Helley-Smith sampler lost a larger fraction of the moving sediment than the Delft Bottle. This is clearly illustrated in Figure C.7 where the grain diameter of the Helley-Smith samples appear to be consistently higher than for the Delft Bottle samples. Figure C.8 shows that the grain diameters of the sediment in motion was increasing with flow velocity.

The above comparisons were very crude. Large scatter was to be expected because the measurements were taken at different flow conditions. Figure C.9 shows the test of the dependence of the measured sediment flux on the flow speed. The depth-averaged velocity at each vertical was calculated from the S4 velocity profiles in the .ase files of PSD24. This plot shows the following:

- Both the Helley-Smith and the Delft Bottle measurements tended to increase with flow velocity, although the latter increased less steeply.
- The scatter of Delft Bottle measurements (as mentioned above) was far less than for the Helley-Smith measurements.

6 Use of Theory

Both instruments measured the sediment flux averaged over the area of their inlet openings. The flux, f , is defined as sediment concentration times velocity,

$$f = C \cdot u \quad (1)$$

Near the bed, both the concentration and velocity varied strongly with the height above the bed. This makes the theoretical expression of the sediment flux rather sensitive with which to work.

Although some sediment transport formulae describe bed load and suspended load separately, the bed load is not a well defined contribution to the total transport. An interpretation of Helley-Smith transport as bed load does not take into account that bed load may be confined within millimeters from the bed at low flow and within decimeters at high flow. The Helley-Smith sampler measures within 3 inches (i. e., up to 7.6 cm from the bed). To begin with, consider only the suspended sediment.

Descriptions for both u and C near the bed are required:

- The classical Rouse distribution (Rouse, 1937) for the concentration profile (including the β factor),
- Logarithmic velocity profile.

The logarithmic profile can be applied in different ways. In continuation of the test of the sensitivity of measurements to flow conditions shown in Figure C.9 using the depth averaged velocity, Figures C.10 and C.11 instead apply different calculated friction velocities. In Figure C.10 the friction velocity based on skin friction, U_r' , is shown on the x-axis (the roughness was set to $k_N = 2.5 \cdot d_{50}$ and $z_0 = k_N/30$ with $d_{50} = 0.22$ mm), and in Figure C.11 the friction velocity estimated from the steepness of the velocity profile was used on the x-axis. For the latter a few profiles were excluded because the

velocity measurements did not fit a logarithmic profile. The latter method gave considerably higher friction velocities.

The logarithmic profile is described by:

$$u = \frac{U_f}{\kappa} \cdot \ln(z/z_0) \quad (2)$$

where,

U_f = friction velocity,

κ = von Karman's constant (=0.4),

z_0 = reference level

The skin friction velocity, U_f , was calculated by:

$$U_f = \frac{\kappa \cdot V}{\ln(h/z_0) - 1 + (z_0/h)} \quad (3)$$

where,

V = depth averaged velocity,

h = water depth.

The friction velocity in Figure C.10 was calculated from measured velocity profiles as:

$$U_f = \kappa \frac{du}{d(\ln z)} \quad (4)$$

Figure C.10 confirms the findings in Figure C.9. Figure C.11 shows a less clear picture of the dependence of flux measurements on flow velocity. Based on this, the use of skin friction velocity is preferred to using a friction velocity determined from the gradient of the velocity profile.

The purpose of making near-bed measurements is to be able to estimate the near-bed sediment transport. This can be done, however, in more or less simplified ways. First, it is necessary to define the near-bed zone. The correct way, from a physical point of view, would be to distinguish between the different modes of transport and to define a transition based on this distinction. With such a definition, the thickness of the near-bed transport layer would be non-constant and vary with the flow. In the following analysis, the near-bed transport is simply the transport which is taking place within the lower 20 cm above the river bed. A fairly good description of the near-bed transport is obtained with the use of the Delft Bottle at 5 and 15 cm above the bed.

The following two approaches were used to determine how the near-bed transport based on these measurements:

- A simple description by which the measurements at 5 and 15 cm above the bed were taken to represent the transport in two 10 cm layers (see Figure C.12).
- The more complex, and maybe more correct, integration method by which the existing theory for transport of suspended sediment was used and adapted to the measurements to obtain an estimate of the near-bed transport. The method is described below and in the Appendix.

According to the above theory, the suspended sediment flux at a level, z , above the bed is:

$$f = \frac{C_a \cdot U_f}{\kappa} \cdot \left(\frac{a}{h-a}\right)^z \cdot \ln(z/z_0) \cdot \left(\frac{h-z}{z}\right)^z \quad (5)$$

where,

C_a = reference concentration,

a = the level at which it occurs

The Rouse number, Z , is given as:

$$Z = \frac{w_s}{\beta \cdot \kappa \cdot U_f} \quad (6)$$

where,

w_s = the fall velocity of the sediment, and

$$\beta = 1 + 2 \left(\frac{w_s}{U_f}\right)^2 \quad 0.1 < \frac{w_s}{U_f} < 0.7 \quad (7)$$

The theoretical sediment flux profile given as the product of equations (2) and (5) can be used by fitting it to a certain measurement. Subsequently, this fitted profile may be integrated to give, for example, the transport between the bed and 20 cm above the bed.

The sediment flux measured by the Delft Bottle a certain distance above the bed were determined as:

$$f_{DB} = \frac{1}{z_2 - z_1} \cdot \int_{z_1}^{z_2} f \, dz = \frac{C_a \cdot U_f \cdot z_0}{\kappa \cdot (z_2 - z_1)} \cdot \left(\frac{a}{h-a}\right)^z \cdot F_{DB} \quad (8)$$

where,

$z_2 - z_1$ = the depth interval represented in the Delft Bottle sample.

Correspondingly, the near-bed sediment transport, defined as the transport up to 20 cm above the bed, was determined by the following relation:

$$q_{NB} = \int_{z_0}^{0.2m} f dz = \frac{C_a \cdot U_f \cdot z_0}{K} \cdot \left(\frac{a}{h-a}\right)^z \cdot F_{NB} \quad (9)$$

The functions F_{DB} and F_{NB} are determined by

$$F_{DB} = \frac{1}{z_0} \cdot \int_{z_1}^{z_2} \ln\left(\frac{z}{z_0}\right) \cdot \left(\frac{h-z}{z}\right)^z dz \quad (10)$$

$$F_{NB} = \frac{1}{z_0} \cdot \int_{z_1}^{0.2m} \ln\left(\frac{z}{z_0}\right) \cdot \left(\frac{h-z}{z}\right)^z dz \quad (11)$$

The near-bed transport can thus be estimated by using theory in combination with measurements. If the flux measured by Delft Bottle is f_{DB} , then the near-bed transport is estimated as,

$$q_{NB} = \frac{F_{NB}}{F_{DB}} \cdot \frac{z_2 - z_1}{0.2m} \cdot f_{DB} \quad (12)$$

It is important to note that neither the reference concentration, nor the level where it occurs, enters into this relation. The method outlined above was used in the following analyses.

Figure C.13 shows a comparison of the two levels of Delft Bottle measurements. The tendency for higher transport rates to be near the bed rather than higher up agrees well with the theory. The fact that this seems more pronounced for the higher transport rates, however, appears to contradict the theory-based expectation, at least if the suspended material was assumed to have the same size independently of the flow condition. Figure C.14 shows that the ratio between the Delft Bottle measurements at 15 and 5 cm above the bed were calculated and shown together with the measured ratio. In the calculation with one size, the sediment size was measured to be, $d_{50}=0.22$ mm; this is a typical size for Bahadurabad. Figure C.15 shows a corresponding analysis, where the d_{50} was actually measured for each Delft Bottle sediment sample. The relation between measured and calculated ratios improved considerably, although there was still a systematic difference. Based on this, the actual measured grain size of the suspended sediment sample was preferred in calculations of near-bed suspended sediment transport.

Figures C.16 to C.18 show a set of comparisons of measured and estimated Helley-Smith measurements using the above procedure, with the exception that bed load was neglected. The Delft Bottle at 5 cm above the bed was used as the base measurement, and no artificial factors were applied to improve the fit. In all cases, the skin friction velocity was used. In Figure C.16 one grain size, 0.22 mm, was used. In Figure C.17, the measured d_{50} was used. In Figure C.18, a catch factor was used to reduce the estimated Helley-Smith measurements. The catch factor corrects for the fact that the Helley-Smith sampler loses a larger fraction of the moving sediment than the Delft Bottle does. This is clearly

illustrated in Figure C.7 where the grain diameter of the Helley-Smith sample appears to be consistently higher than for the Delft Bottle sample. Figure C.8 shows that the grain diameters of the sediment in motion was increasing with flow velocity. The catch factors were determined by comparing grain size distribution curves for Delft Bottle and Helley-Smith samples.

Figures C.19 to C.21 show comparisons corresponding to the ones in Figures C.16 to C.18, except that now the bed load was included (van Rijn formula). The bed load was included as a contribution to the flux within 7.6 cm from the bed (unit $\text{kg/m}^2/\text{s}$).

At this stage in the study, there has been no systematic attempt to adjust the various parameters to get the best fit. The above two sets of comparisons clearly show the effects of some selections.

7 Importance of the Near-Bed Transport

The near-bed transport may be particularly important in relation to certain morphological developments, even when it constitutes a relatively minor portion of the total bed material load. Nevertheless, it is relevant to know how large a fraction of the total transport it constitutes before deciding how detailed a description of this portion of the transport to adopt in converting measurements to transport rates.

The sediment transport outside the near-bed zone was estimated from the depth integrating sampler in combination with velocity measurements. The results are in PSD24. Figure C.22 shows the bed material transport in the near-bed zone as a ratio of the total bed material transport. The two different methods of estimating the near-bed transport described above were used.

In spite of the considerable scatter of the results, the following observations were made from this plot:

- The near-bed transport constituted a higher ratio of the total transport for low transport conditions.
- The simple method indicated a somewhat lower fraction of transport in the near-bed zone than the integration method. A crude average ratio of near-bed transport (excluding the very low transport situations) was approximately 15% as predicted by the simple method, and approximately 20 to 25% as predicted by the complex method.
- It seems that both the average ratio and the scatter increased towards the high transport conditions. More data are required to substantiate this observation for high transport conditions.

The Helley-Smith measurements were not included in the above estimate of the ratio of near-bed transport. The Helley-Smith samples, on average, indicated a somewhat lower sediment flux than the Delft Bottle measurements, even after correction for estimated loss of fines (see Figure C.24). If the Helley-Smith results were taken into account, the estimated ratio of near-bed transport would be slightly reduced. The Helley-Smith samples were omitted because they were believed to be less reliable than the Delft Bottle samples, and they did not add to the reliability of the estimated ratio.

The scatter in the plot of near-bed transport ratio in Figure C.22 may be caused to a large extent by the variability in measurements by the depth integrating sampler rather than near-bed measurements.

Figure C.23 indicates that this may be the case. It shows that near-bed sediment fluxes measured by Delft Bottle, as well as by the Helley-Smith sampler, had a far more pronounced correlation with local flow conditions in the plot represented by the depth-averaged velocity. Transport rates determined by the depth integrating sampler were converted to average fluxes by dividing by the depth.

It was concluded that the near-bed transport was a considerable fraction of the total bed material transport, and therefore requires detailed consideration in the way that it is included in the calculation of transport rates.

8 Conclusions

The recommended method to determine near-bed sediment transport (see section 9) was based on the following main conclusions:

- The use of the Helley-Smith sampler, as it has been used thus far, considerably underestimated the transport rate (see Figure C. 25). This is partly due to the loss of the finer material in the Helley-Smith sample. Consequently, it is concluded that whenever Delft Bottle measurements are available, the Helley-Smith should not be used to estimate the near-bed transport.
- The near-bed transport was considerable; on average, it was 15 to 25% of the total transport, depending on the calculation method applied, see Fig. C 22. Because of this relatively high ratio it is important to measure not only the suspended load higher above the bed, but to determine also the near-bed sediment transport.
- The near-bed transport, as measured by both Helley-Smith and Delft Bottle, were clearly correlated with the flow velocity. This correlation was much weaker for the suspended transport at higher levels measured by the depth-integration sampler.
- A good correlation of near-bed transport with flow was found when the flow was represented by the depth average velocity, see Fig. C 9 or the skin friction velocity, see Fig. C 10, but not when a friction velocity derived from the gradient of the flow profile was used, see Fig. C 11. Therefore, a skin friction type velocity is preferred when determining the suspended sediment profile.
- No reasons were found to weight the Delft Bottle samples at two different levels differently when calculating the near-bed transport.
- A better agreement with the measured sediment flux gradient was obtained when the actual grain size measured in Delft Bottle samples was used rather than a typical bed material size.
- It was observed that the predicted near-bed sediment flux gradient was consistently higher than the measured near-bed sediment flux gradient. This indicates that the integration method will tend to overestimate the near-bed transport. On the other hand, the simple method is expected to underestimate it.

9 Recommendations

The integration method is recommended for determining near-bed transport rates from Delft Bottle measurements (see sections 6 and 7).

Since two Delft Bottle measurements will always be available, the methodology can be as follows:

1. The particle fall velocity for the d_{50} found in each Delft Bottle measurement should be determined by available formulas or by a settling method.
2. The skin friction velocity, U_f , is determined by equation (3).
3. The Rouse parameter is determined by equations (6) and (7).
4. F_{DB} for both measurements and F_{NB} should be calculated using the actual intake height of the Delft Bottle (two different types are used) in equations (10) and (11).
5. The near-bed transport, q_{NB} should be determined for each Delft Bottle measurement using equation (12).
6. For each pair of measurements, the average of the two near-bed transport rates should be taken to be the best estimate of the near-bed transport.

The parameters for the above calculations are:

- Temperature or viscosity of water,
- Specific density of sediment,
- Grain diameter of sediment being transported,
- Flow velocity,
- Water depth,
- Velocity profile reference level (or roughness).

The selections that have been made concerns:

- Which grain size to select for the material being transported,
- Which method to apply in calculating the near-bed velocity and bed shear (friction velocity),
- How much weight to put on measurements at each of the two levels.

Although the theoretically based method may be more correct in many instances, it is recommended that the simple method be used by FAP 24 (PSD24 as well as bulletins) for processing. The reasons for this recommendation are as follows:

- a. It is easy to explain to any user of the data how the near-bed transport was calculated. Users can then review the analysis of the alternative methods and do their own based on the measurements.
- b. The measurements indicate a less steep sediment flux profile than the theory can explain, at least without making it more complex (i.e., to include grading etc.). Thus, the theory based method

will tend to overestimate the transport while the simple method will underestimate it. On average, the former method predicts 2 to 3 times higher near-bed transport rates than the simple method.

10 Further Analyses

When evaluating near-bed measurement techniques and processing methods, more measurements should be analyzed in a similar way, especially measurements at other locations and measurements where the Delft Bottle was used at a larger number of levels above the bed. Near-bed measurements need to be evaluated together with measurements at higher levels above the bed.

The sensitivity of the calculation procedure to the choice of parameters is important and should be analyzed further. In particular, the fact that measured flux gradients are not predicted very well by theory requires further investigation.

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Appendix:**Numerical Integration to Calculate Near-Bed Suspended Sediment Transport**

Coordinate stretching is required near the bed to calculate the two integrals eqs. (10) and (11). Since the procedure is the same, only one is considered:

$$F_{DB} = \frac{1}{z_0} \int_{z_1}^{z_2} \ln\left(\frac{z}{z_0}\right) \cdot \left(\frac{h-z}{z}\right)^z dz \quad (A1)$$

or

$$F_{DB} = \int_{\eta_1}^{\eta_2} \eta e^{\eta} \left(\frac{h}{z_0} e^{-\eta} - 1\right)^z d\eta \quad (A2)$$

where

$$\eta = \ln\left(\frac{z}{z_0}\right) \quad (A3)$$

With

$$g(\eta) = \eta e^{\eta} \left(\frac{h}{z_0} e^{-\eta} - 1\right)^z \quad (A4)$$

then

$$F_{DB} = \int_{\eta_1}^{\eta_2} g(\eta) d\eta \quad (A5)$$

Numerical integration:

$$F_{DB} = \frac{1}{2} \Delta\eta \sum_{i=0}^{n-1} [g(\eta_i) + g(\eta_{i+1})] \quad (A6)$$

where

$$\Delta\eta = \frac{(\eta_2 - \eta_1)}{n} \quad \eta_i = \eta_1 + i \Delta\eta \quad (A7)$$

List of Symbols

a	Reference level for sediment concentration
C	Sediment concentration
C_a	Reference concentration at distance 'a' above bed
DB	Delft Bottle (subscript)
f	Sediment flux, unit: $\text{kg}/\text{m}^2/\text{s}$
F	Integral related to suspended sediment profile (non-dimensional)
h	Water depth
HS	Helley-Smith (subscript)
n	Integer number
NB	Near-bed (subscript)
q	Specific sediment transport, unit: kg/m
u	Flow velocity
U_f	Friction velocity
U_f'	Skin friction velocity
V	Depth averaged velocity
w_s	Particle fall velocity in water
z	Vertical coordinate, distance above bed
z_0	Reference level for velocity profile, level of zero velocity
Z	Rouse parameter, equation (6)
β	Suspended sediment parameter, equation (7)
η	Non-dimensional transformed vertical coordinate
κ	von Karman constant (0.4)

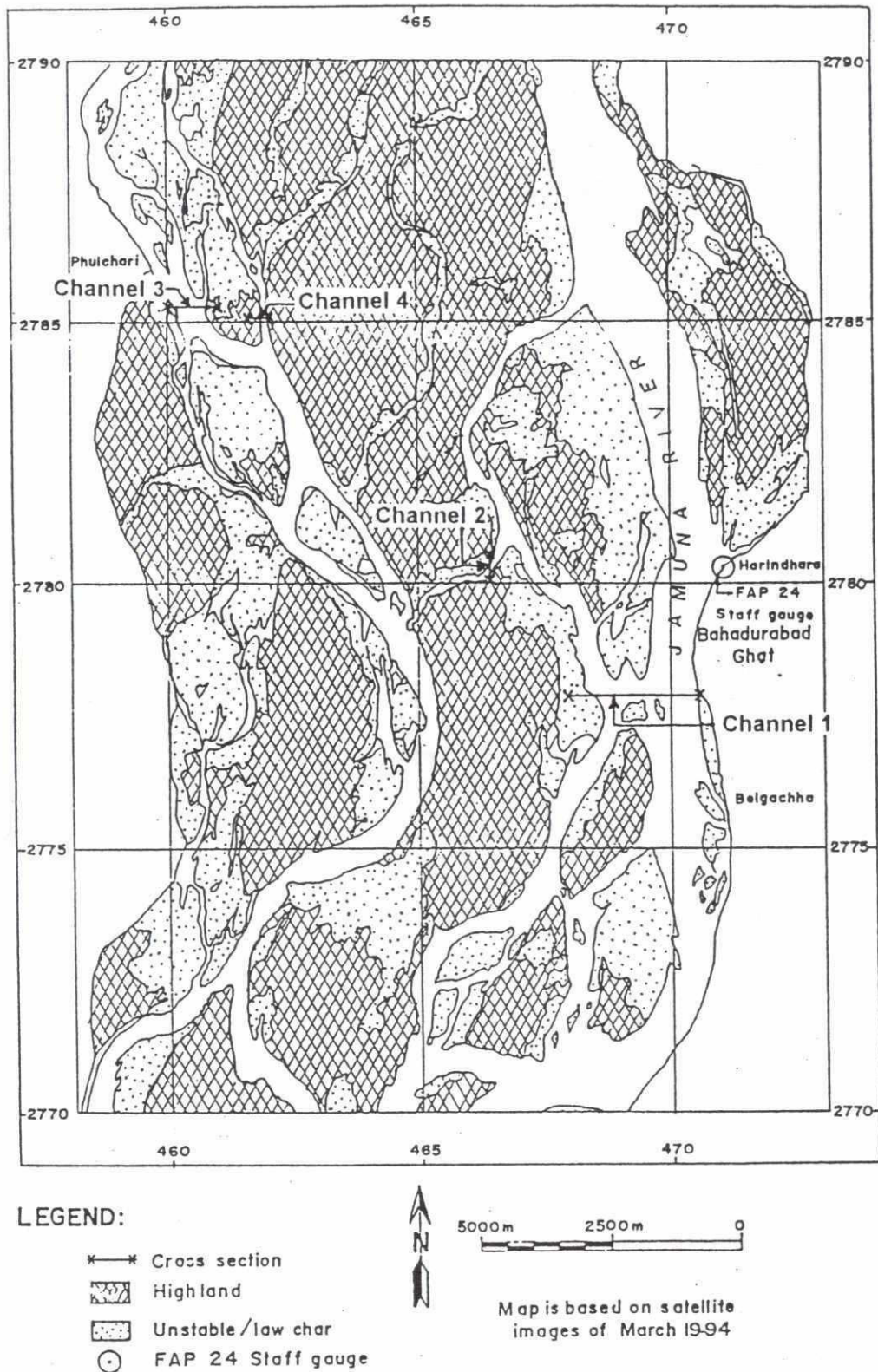


Figure C.1 Measurement transects in the Jamuna River at Bahadurabad.

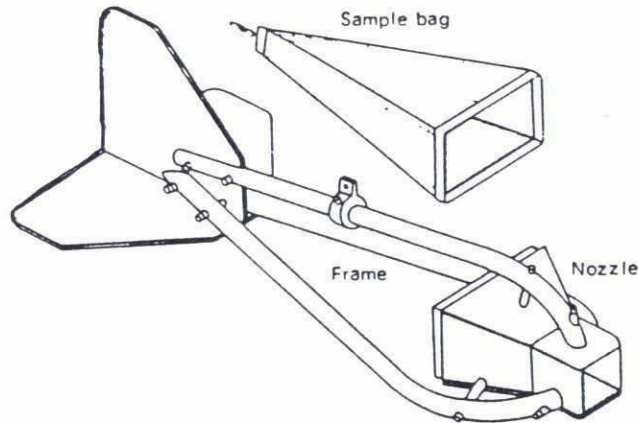
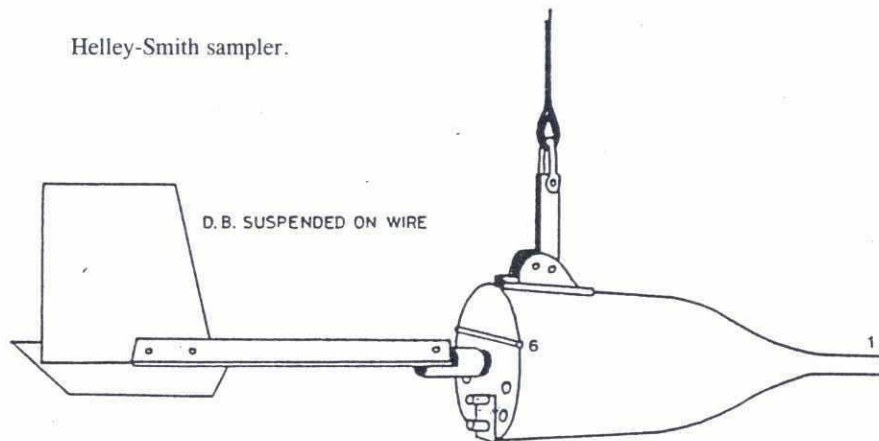


Figure C.2 Helley-Smith sampler.



A. DELFT BOTTLE, ARRANGEMENT FOR SAMPLING FROM WATER-SURFACE TILL 0.5 m FROM RIVER-BED

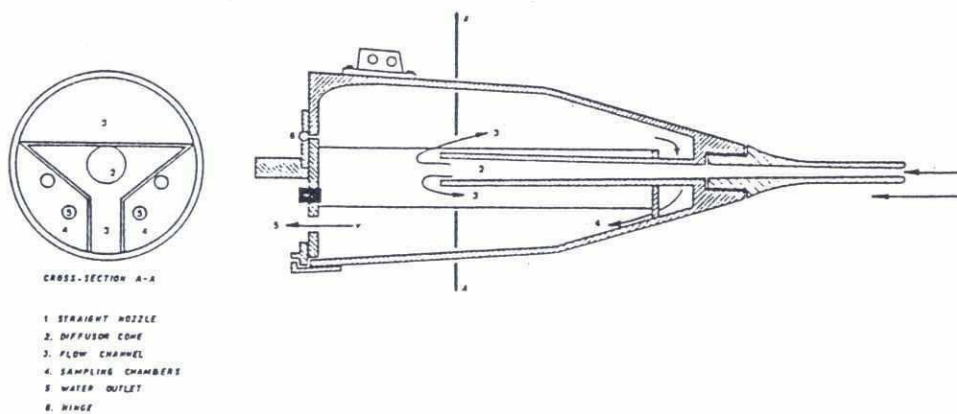


Figure C.3 Delft Bottle sampler.

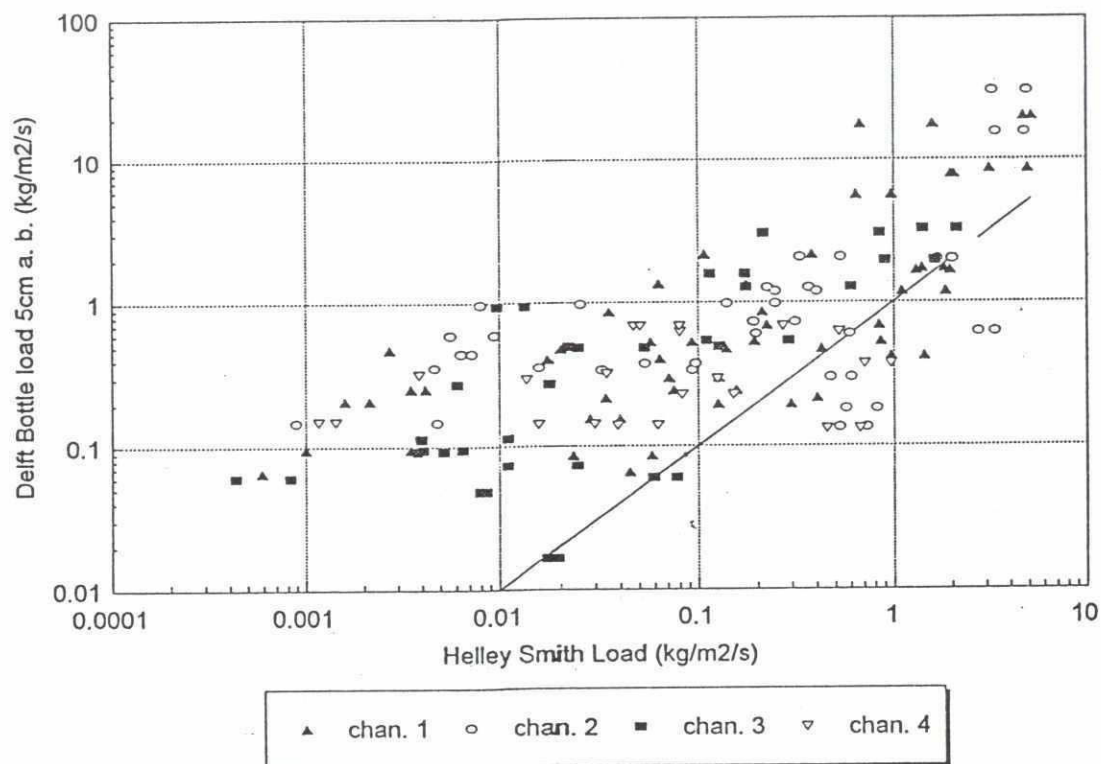


Figure C.4

Comparison of near-bed measurements. Delft Bottle flux at 5cm above the bed vs. Helley-Smith.

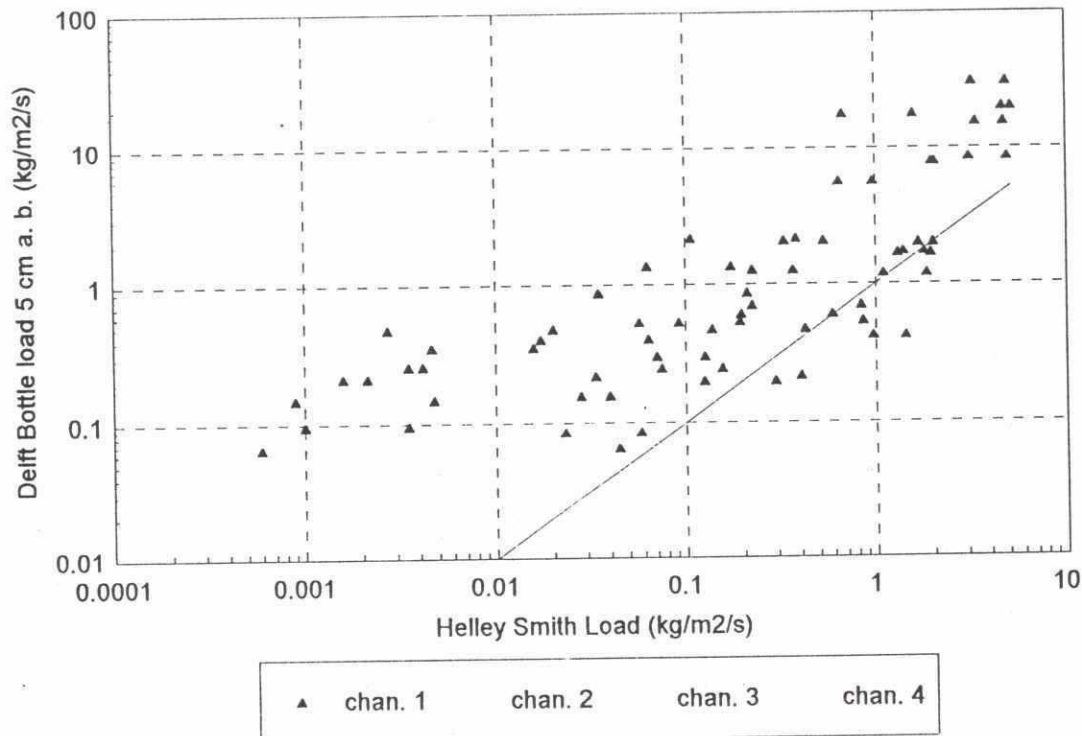


Figure C.4a

Comparison of near-bed measurements (channel 1 only). Delft Bottle flux 5cm above bed vs. Helley-Smith.

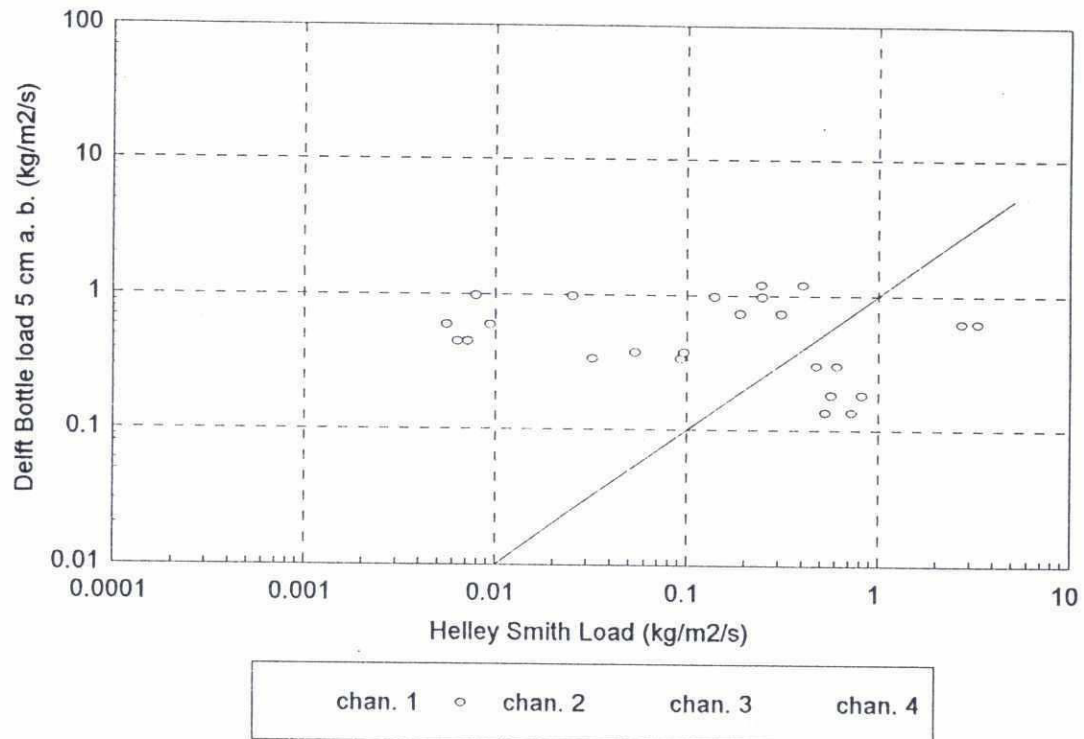


Figure C.4b Comparison of near-bed measurements (channel 2 only). Delft Bottle flux 5cm above bed vs. Helley-Smith.

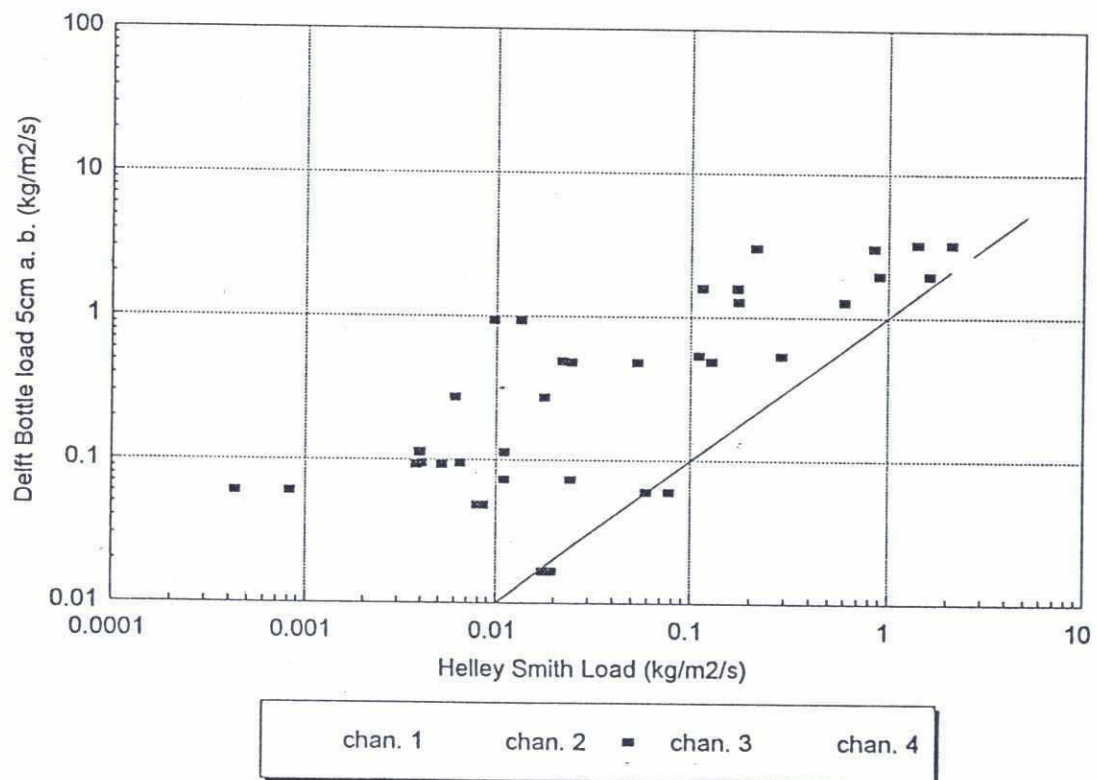


Figure C.4c Comparison of near-bed measurements (channel 3 only). Delft Bottle flux 5cm above bed vs. Helley-Smith.

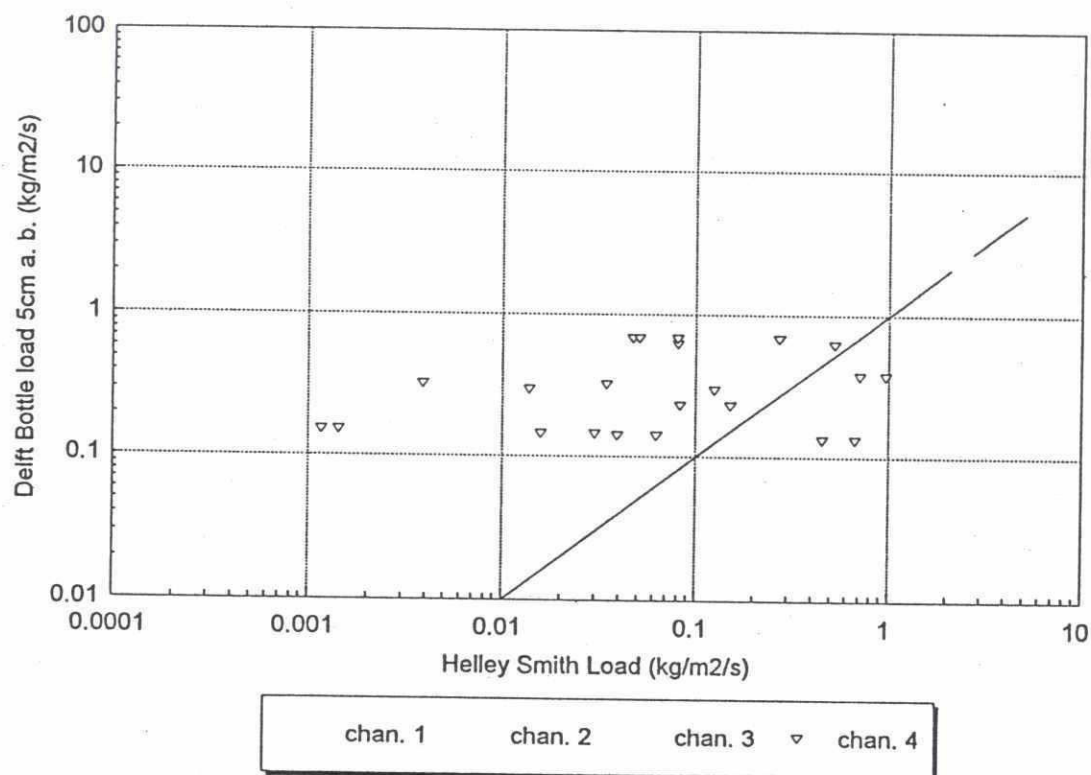


Figure C.4d Comparison of near-bed measurements (channel 4 only). Delft Bottle flux 5cm above bed vs. Helley-Smith.

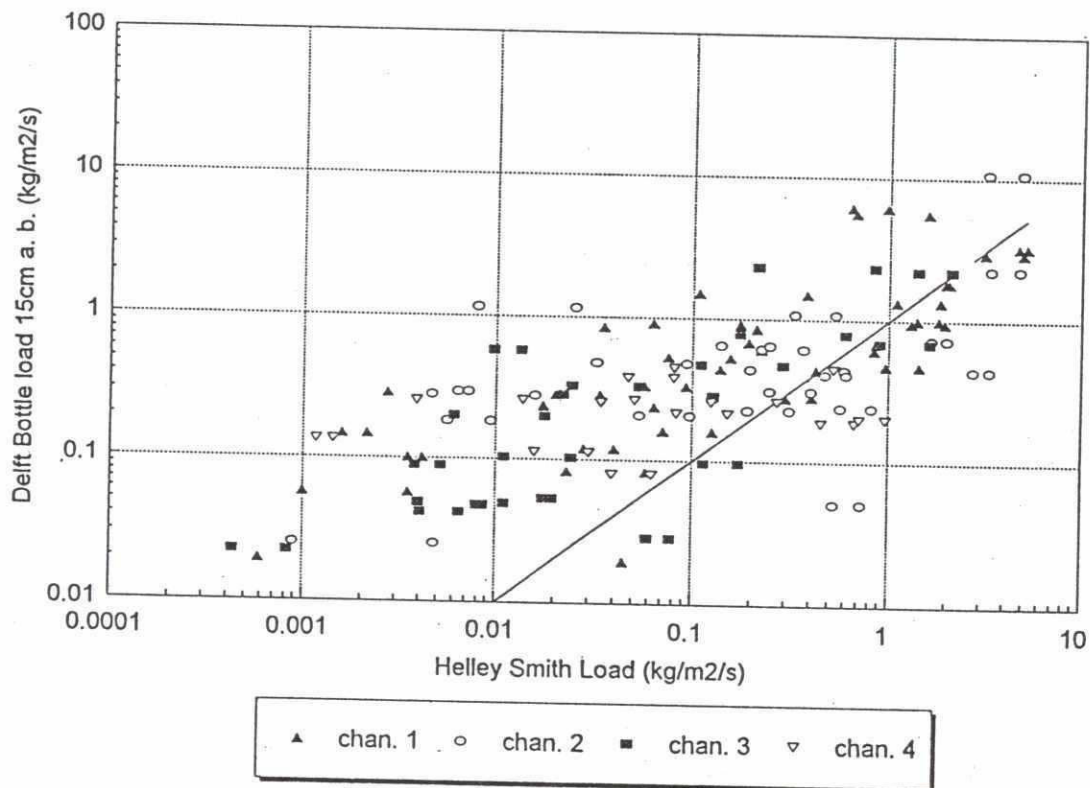


Figure C.5 Comparison of near-bed measurements. Delft Bottle flux 15cm above bed vs. Helley-Smith.

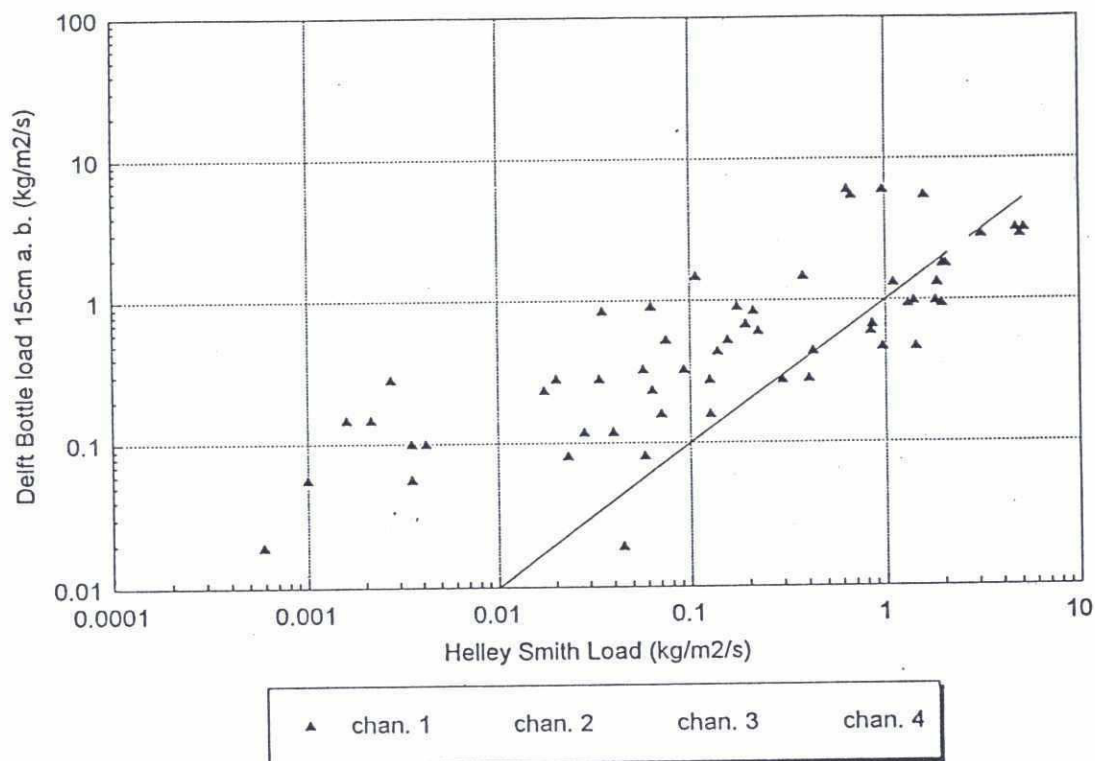


Figure C.5a Comparison of near-bed measurements (channel 1 only). Delft Bottle flux 15cm above bed vs. Helley-Smith.

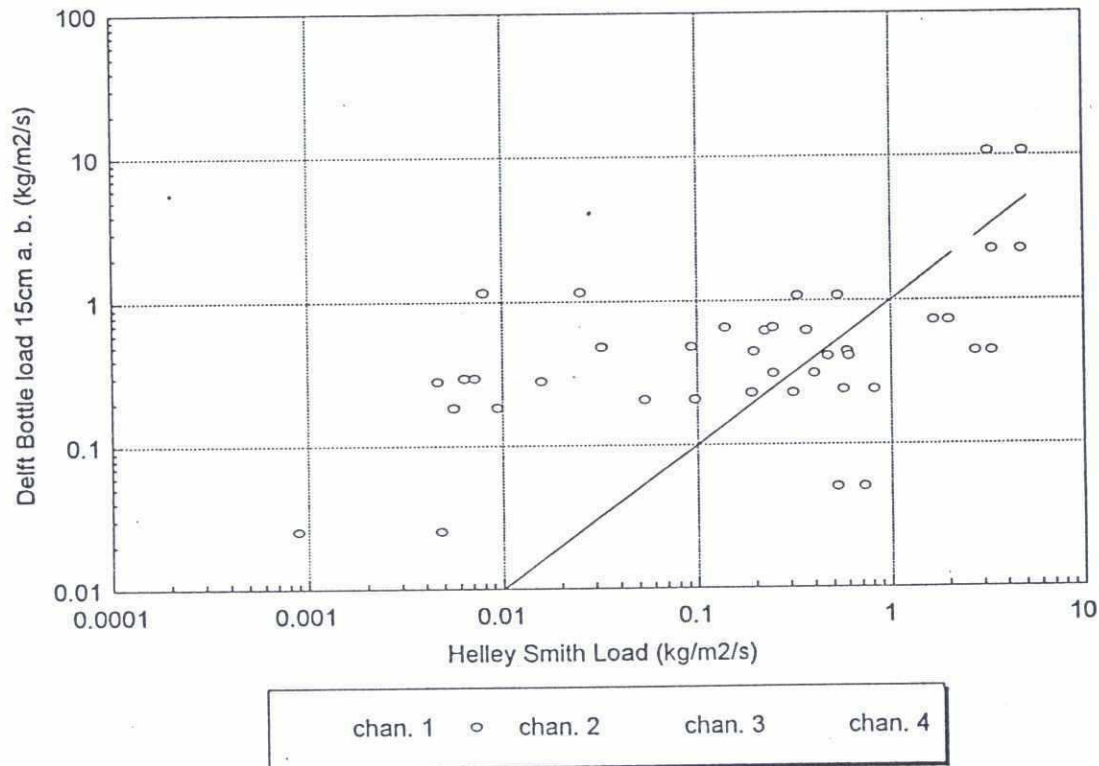


Figure C.5b Comparison of near-bed measurements (channel 2 only). Delft Bottle flux 15cm above bed vs. Helley-Smith.

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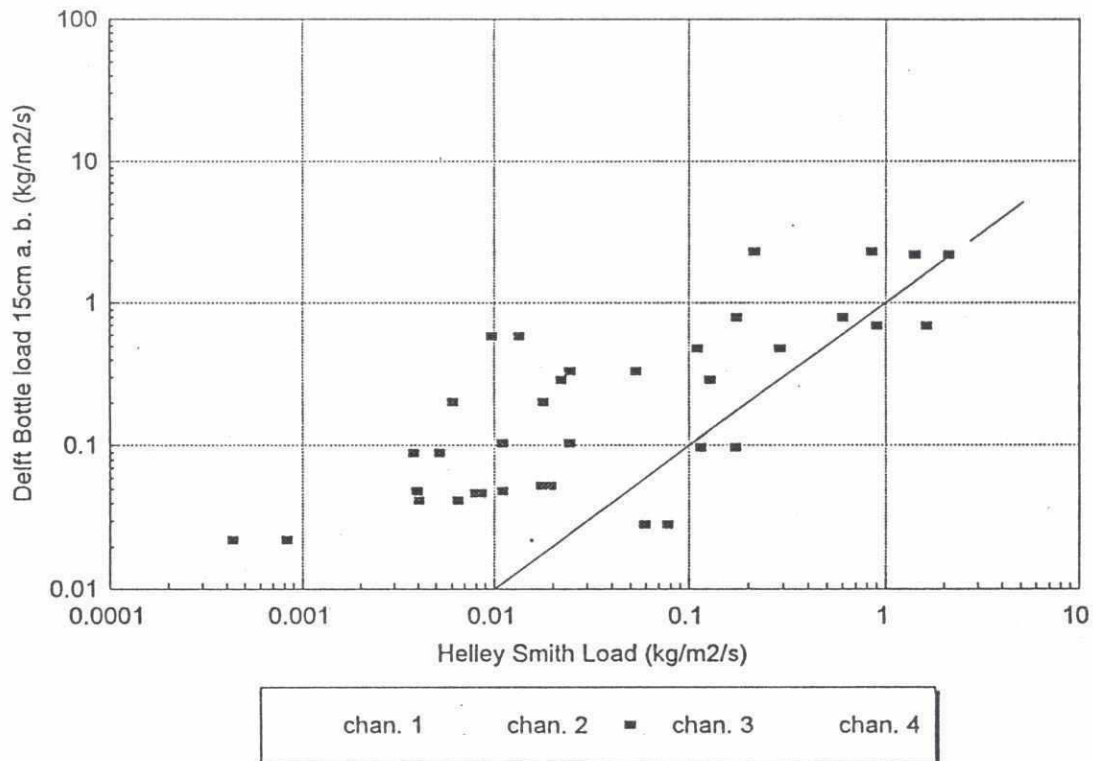


Figure C.5c Comparison of near-bed measurements (channel 3 only). Delft Bottle flux 15cm above bed vs. Helley-Smith.

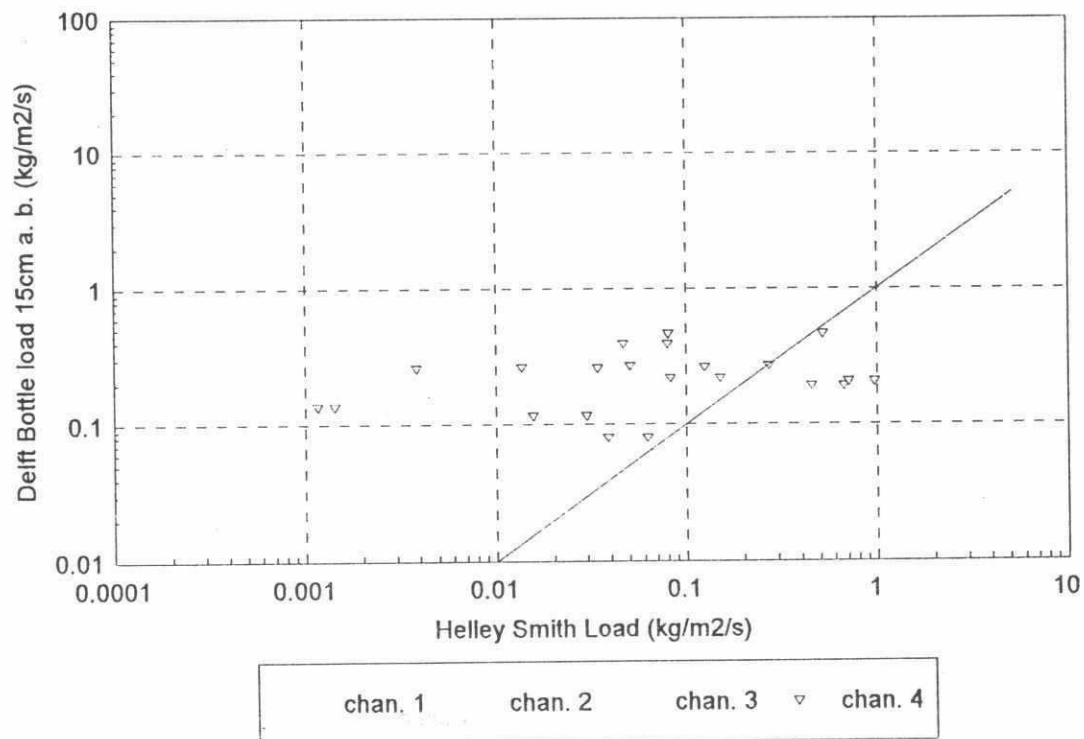


Figure C.5d Comparison of near-bed measurements (channel 4 only). Delft Bottle flux 15cm above bed vs. Helley-Smith.



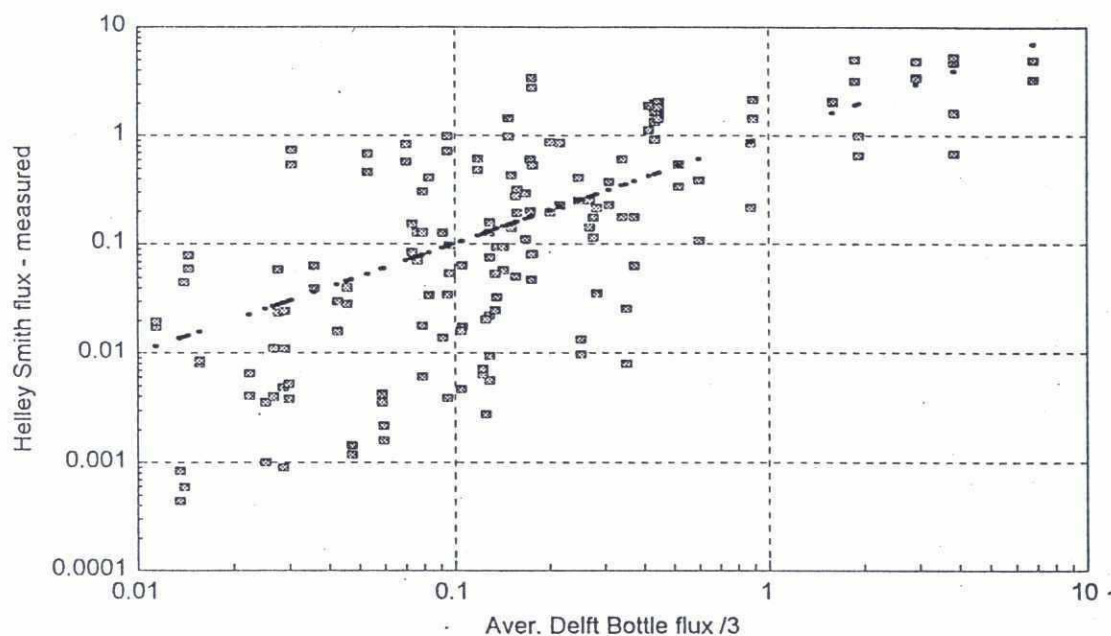


Figure C.6 Helley-Smith vs average Delft Bottle flux divided by 3.

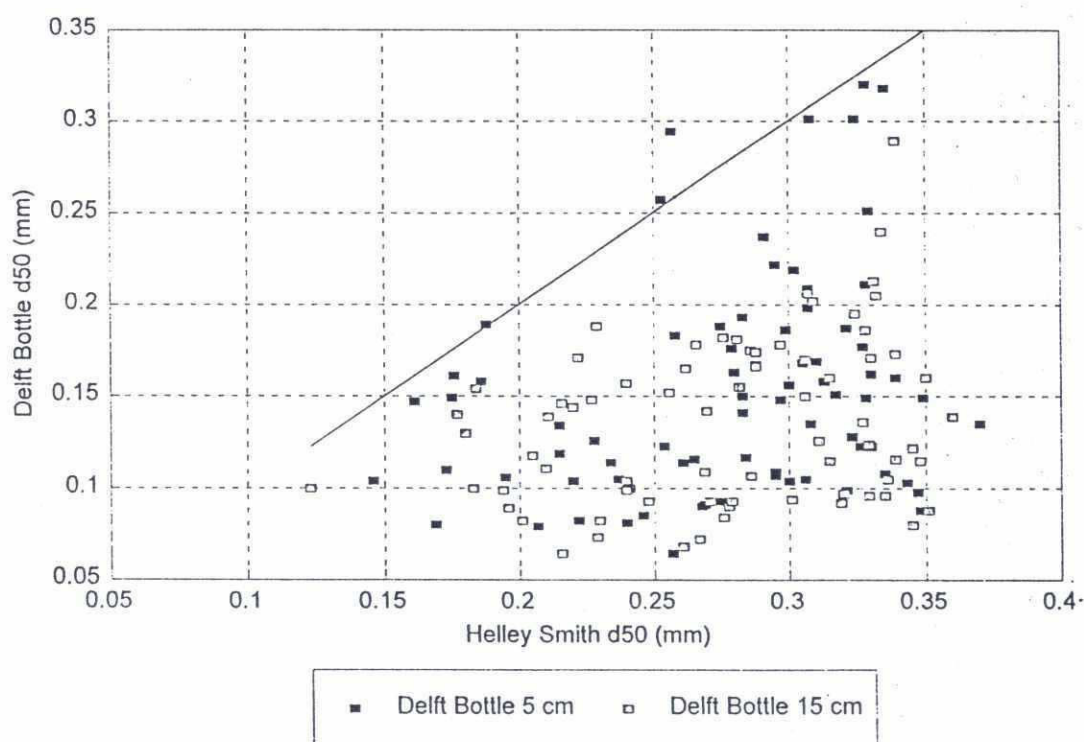


Figure C.7 Median grain diameter of Delft Bottle vs Helley-Smith samples.

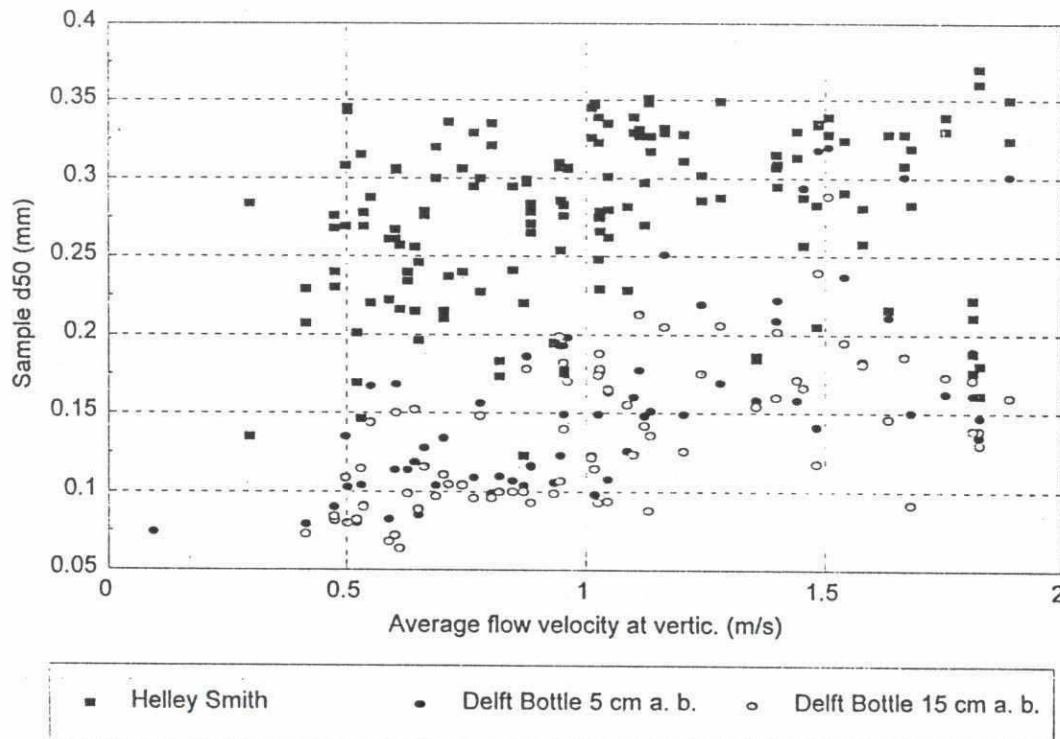


Figure C.8 Correlation of the sample d_{50} with depth averaged flow velocity for Delft Bottle and Helley-Smith.

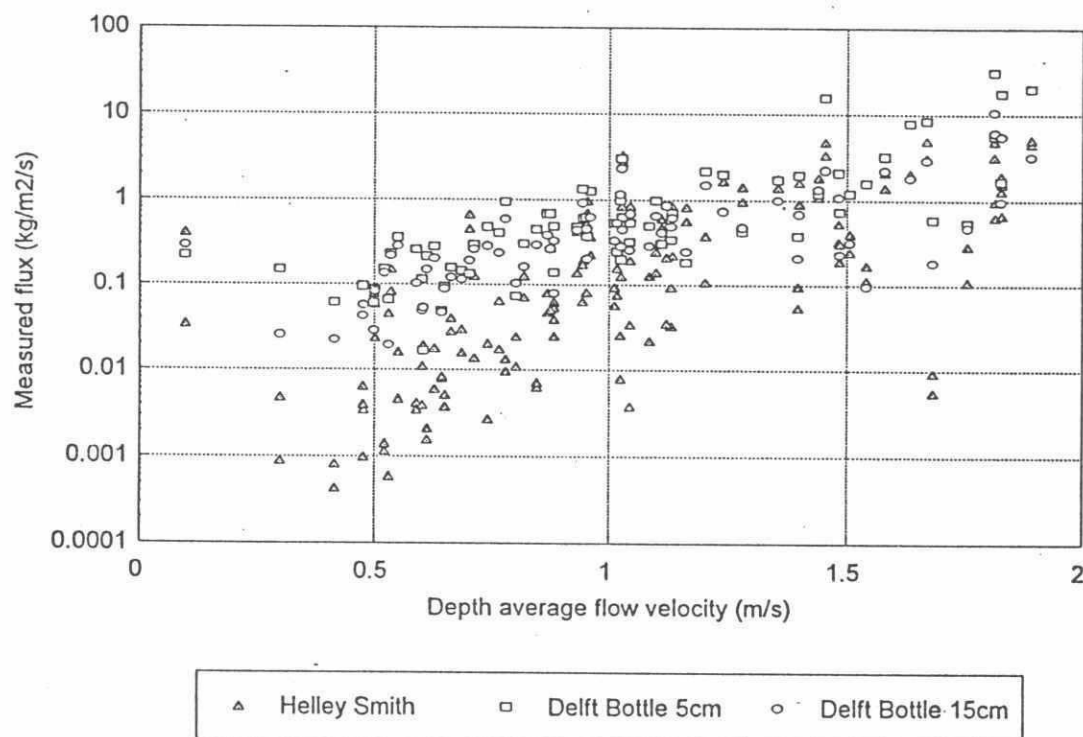


Figure C.9 Correlation of measured sediment flux with depth averaged flow velocity for Delft Bottle and Helley-Smith.

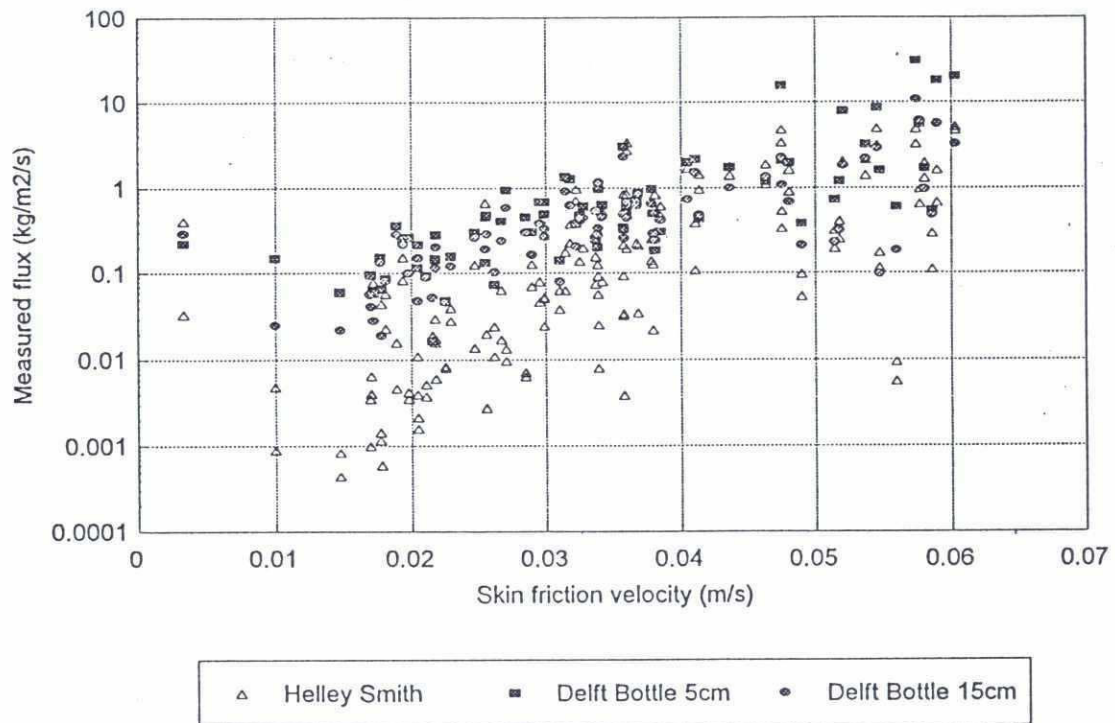


Figure C.10 Correlation of measured sediment flux with skin friction velocity for Delft Bottle and Helley-Smith.

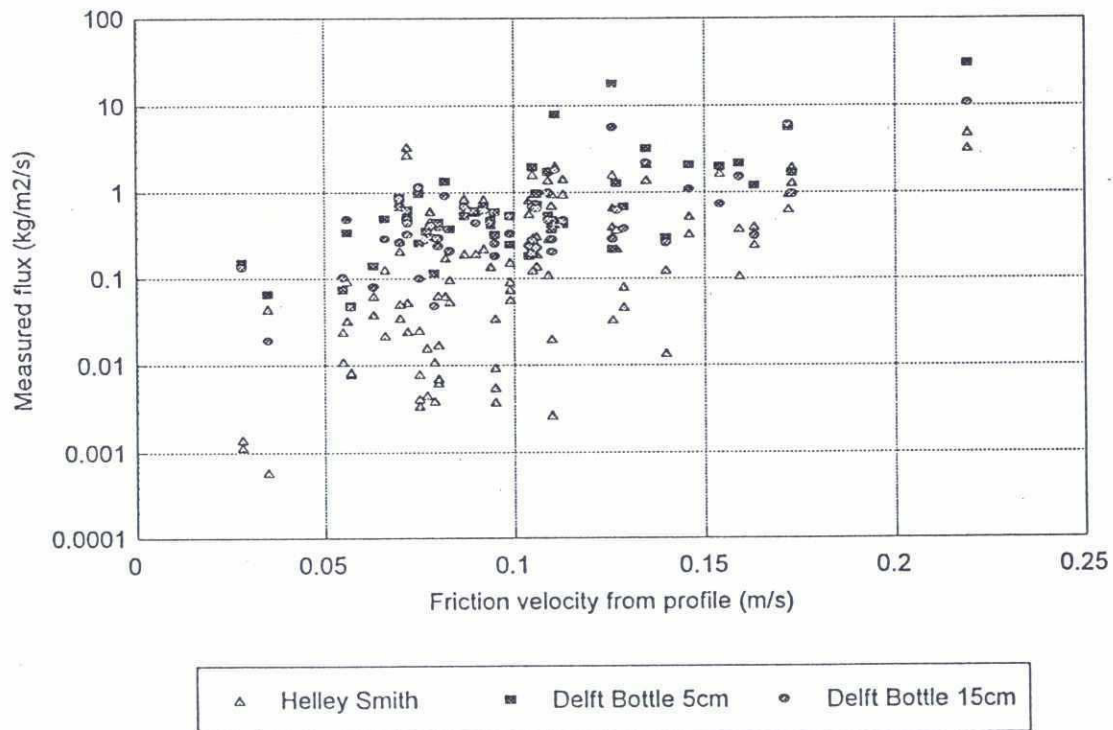
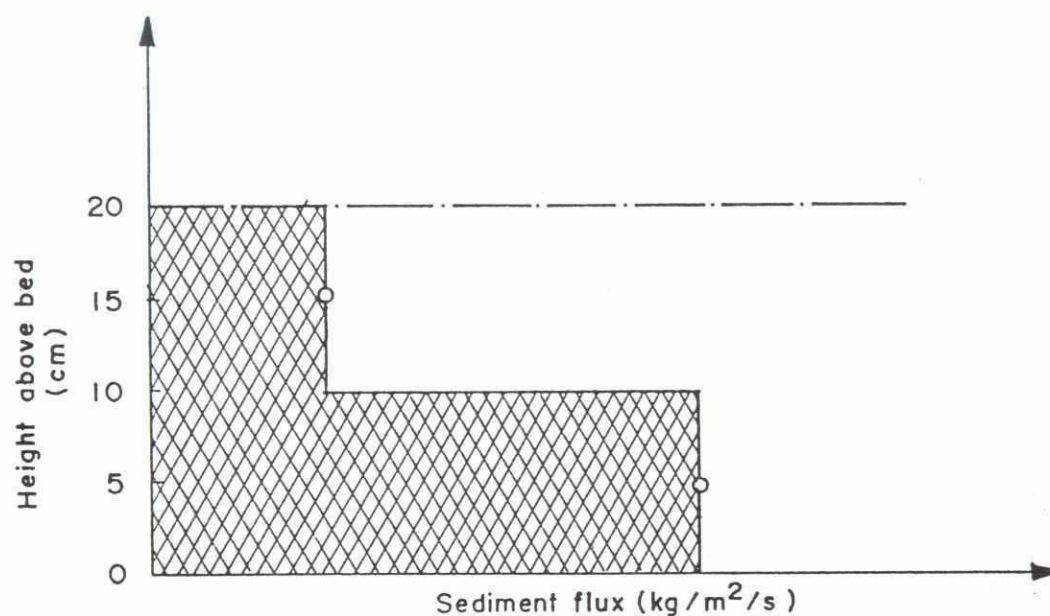


Figure C.11 Correlation of measured sediment flux with friction velocity determined from velocity profile for Delft Bottle and Helley-Smith.



- Measurements by Delft Bottle.
 [X] Near bed transport by simple method.

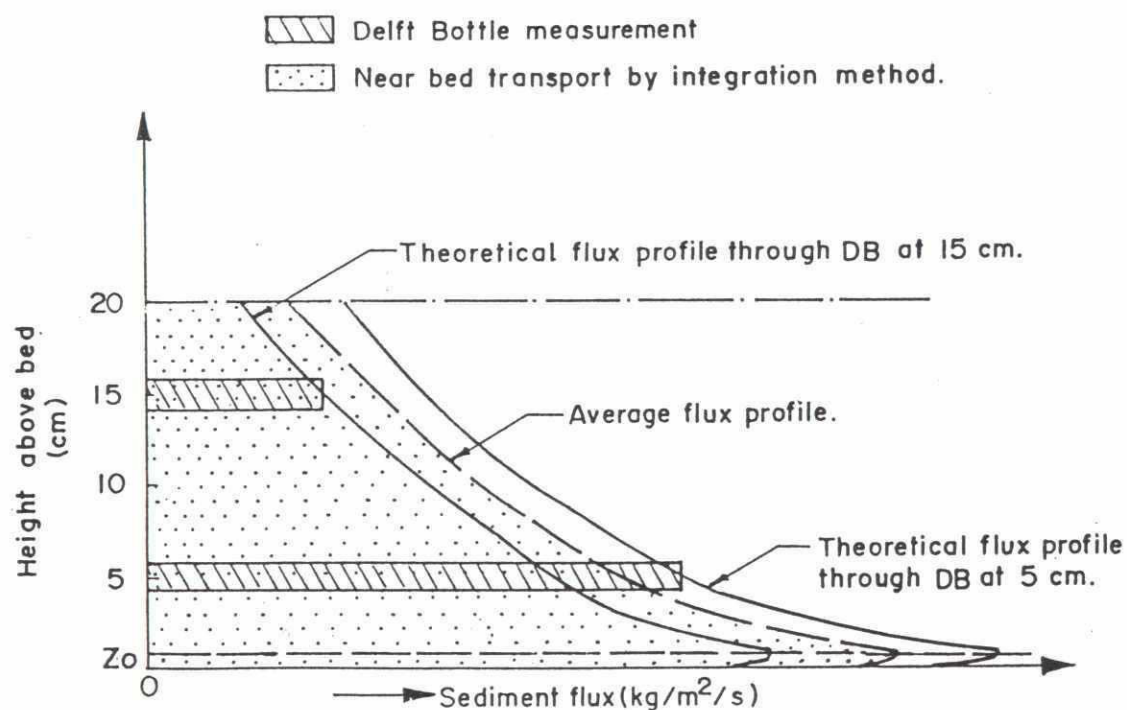


Figure C.12 Estimate of near-bed sediment transport from Delft Bottle measurements by simple method (principle sketch).

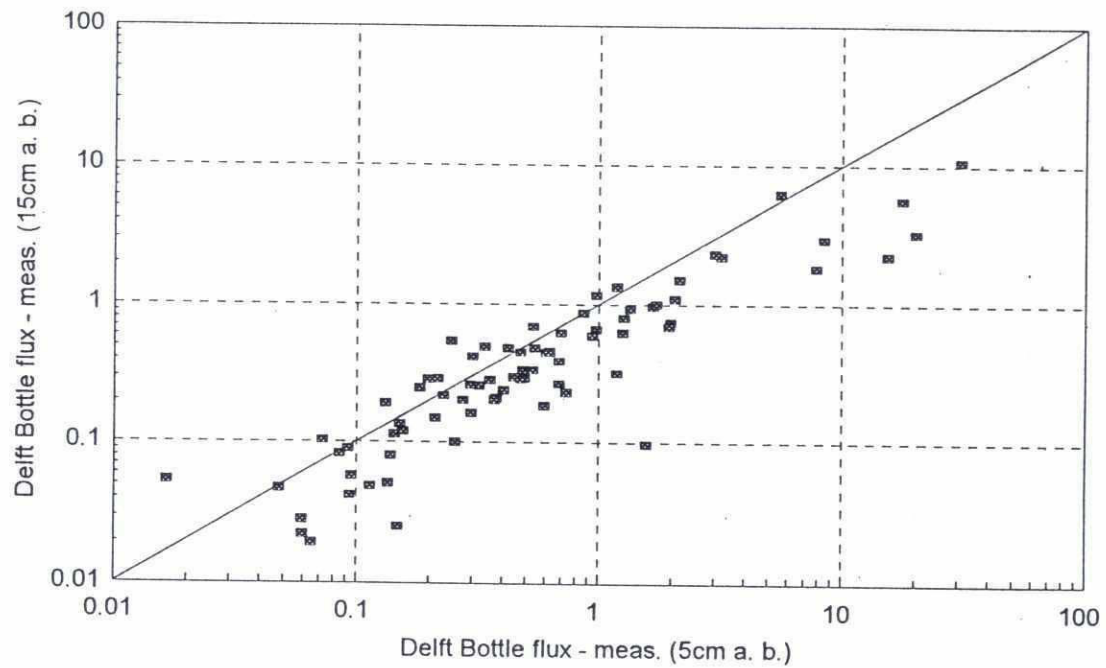


Figure C.13 Comparison of Delft Bottle measurements at two levels (5 and 15 cm above the bed).

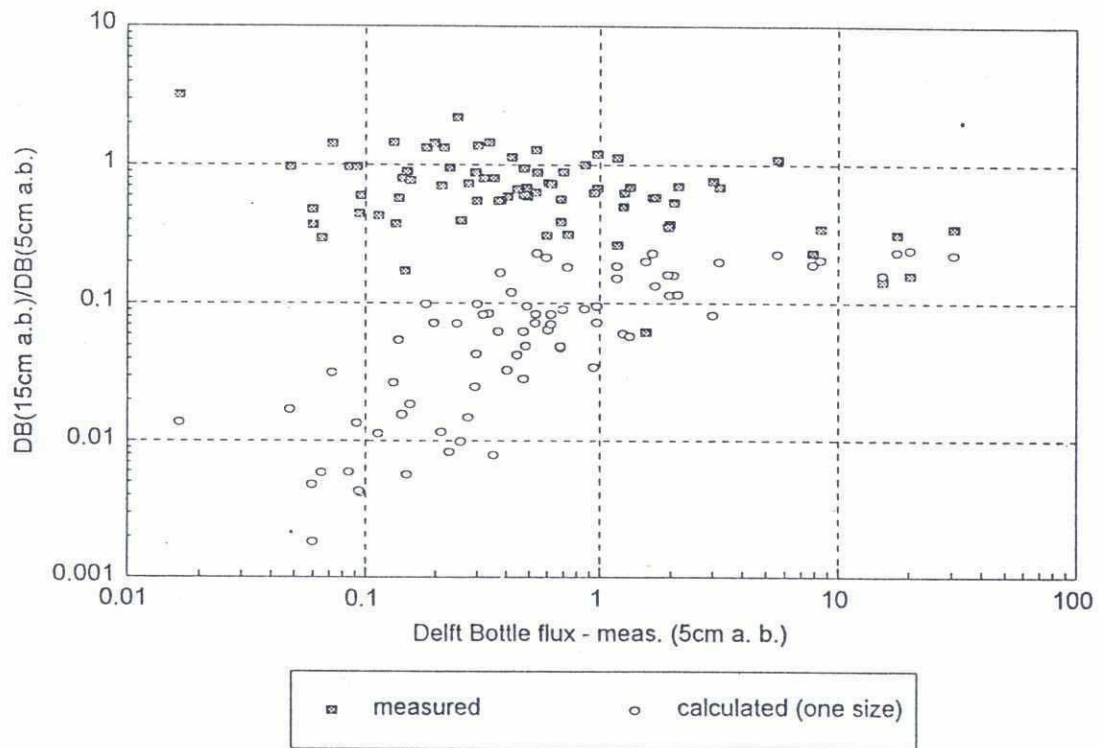


Figure C.14 Ratio between sediment flux at 15 and 5 cm above the bed. Measured and calculated (assuming $d_{50}=0.22$ mm).

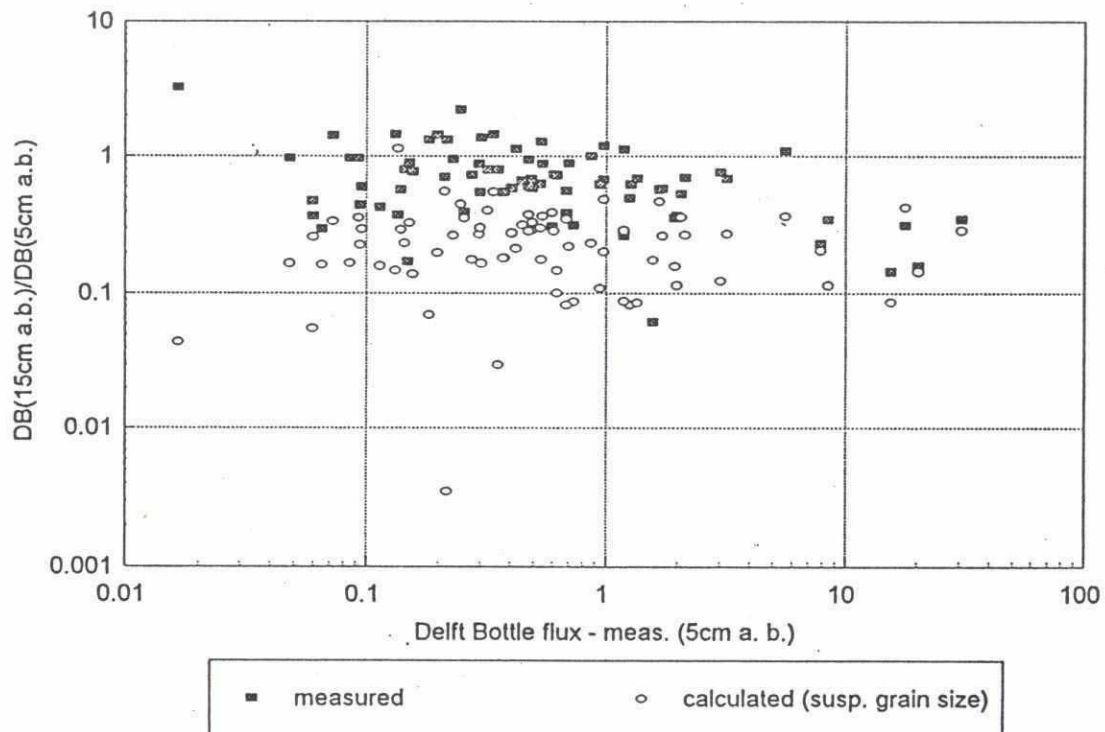


Figure C.15 Ratio between sediment flux at 15 and 5 cm above the bed. Measured and calculated (using the measured grain size from Delft Bottle).

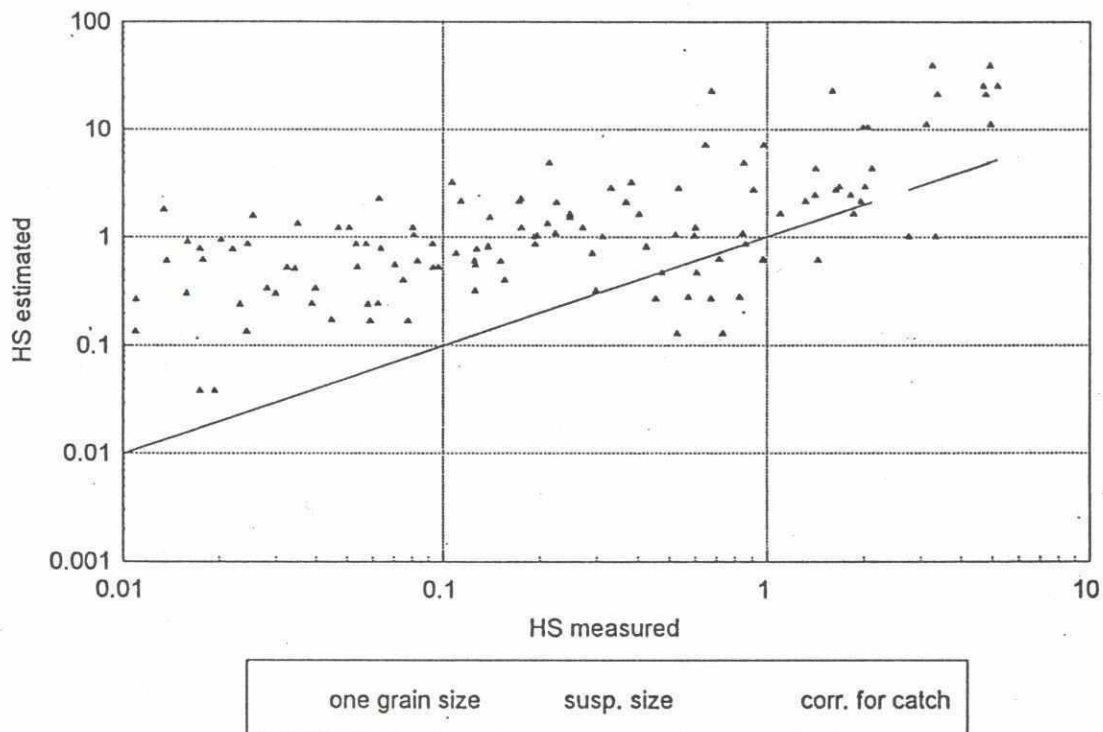


Figure C.16 Estimated vs. measured Helley-Smith flux. One grain size applied for suspended sediment ($d_{90}=0.22$ mm). Bed load not included.

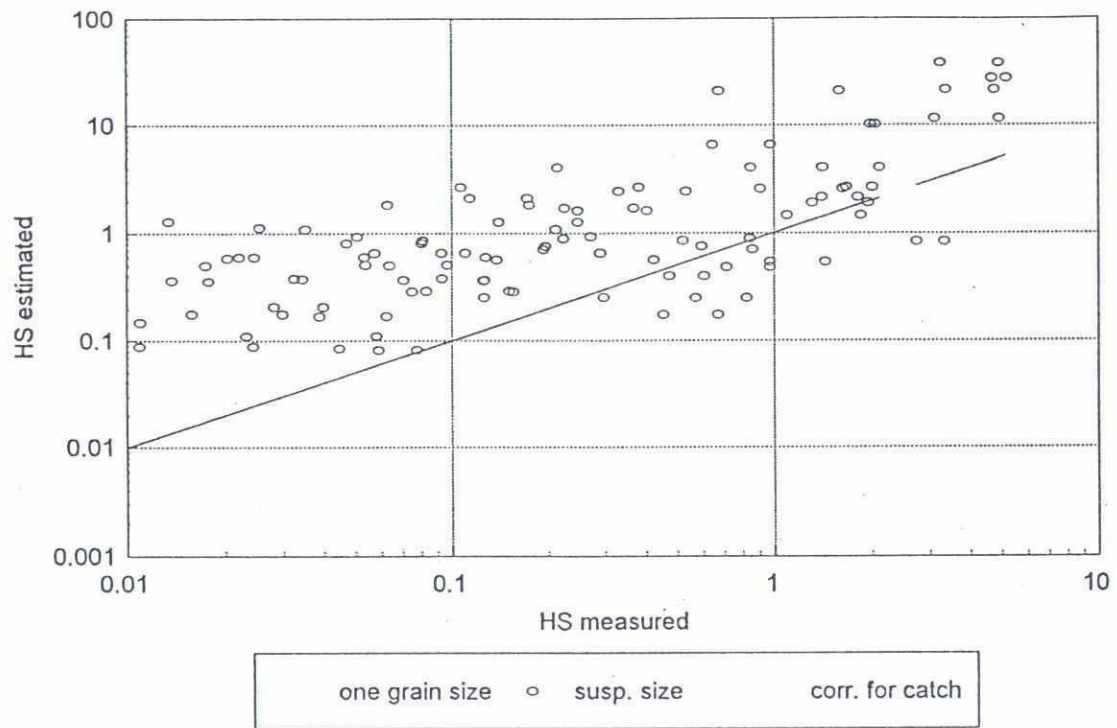


Figure C.17 Estimated vs. measured Helley-Smith flux. Measured grain size from Delft Bottle applied for suspended sediment. Bed load not included.

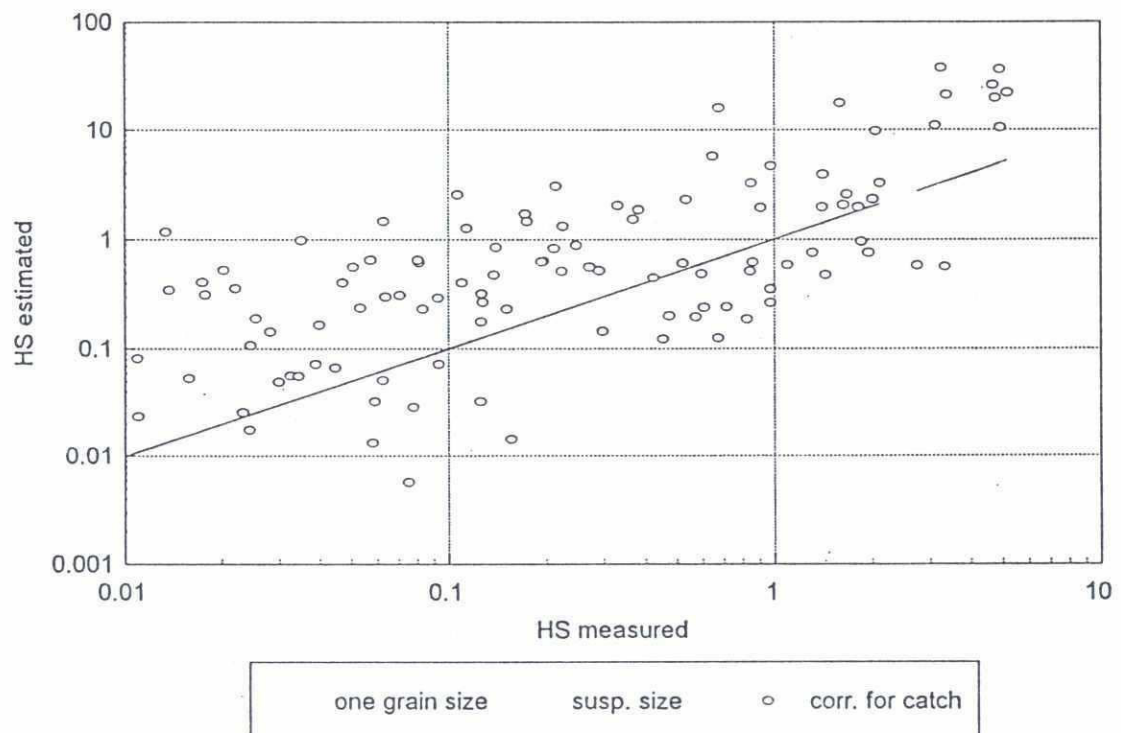


Figure C.18 Estimated vs. measured Helley-Smith flux. Measured grain size from Delft Bottle applied for suspended sediment. Correction for reduced catch of Helley-Smith sampler applied. Bed load not included.

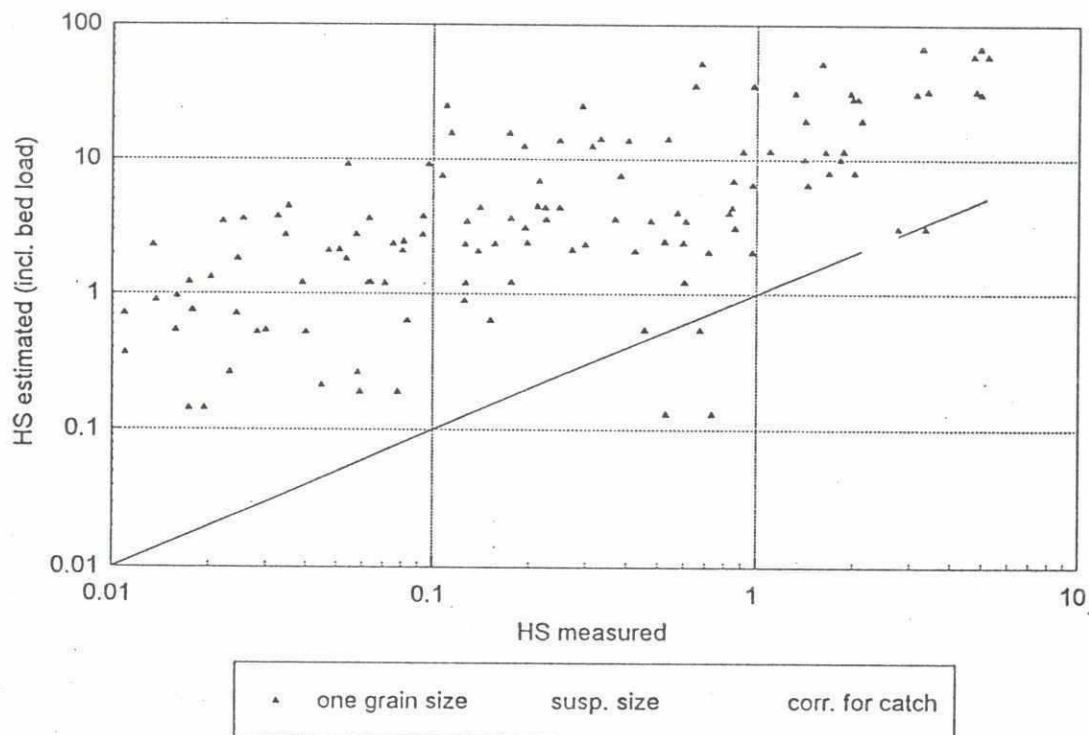


Figure C.19 Estimated vs. measured Helley-Smith flux. One grain size applied for suspended sediment ($d_{50}=0.22$ mm). Bed load included (calculated by van Rijn formula).

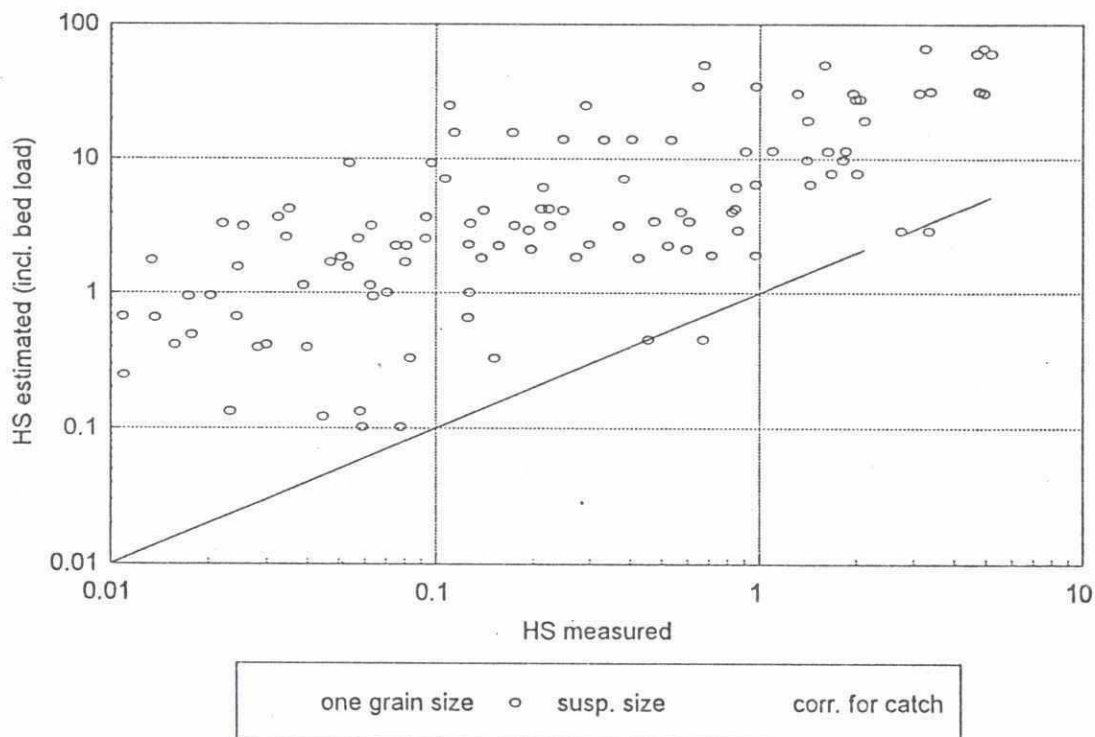


Figure C.20 Estimated vs. measured Helley-Smith flux. Measured grain size from Delft Bottle applied for suspended sediment. Bed load included (calculated by van Rijn formula).

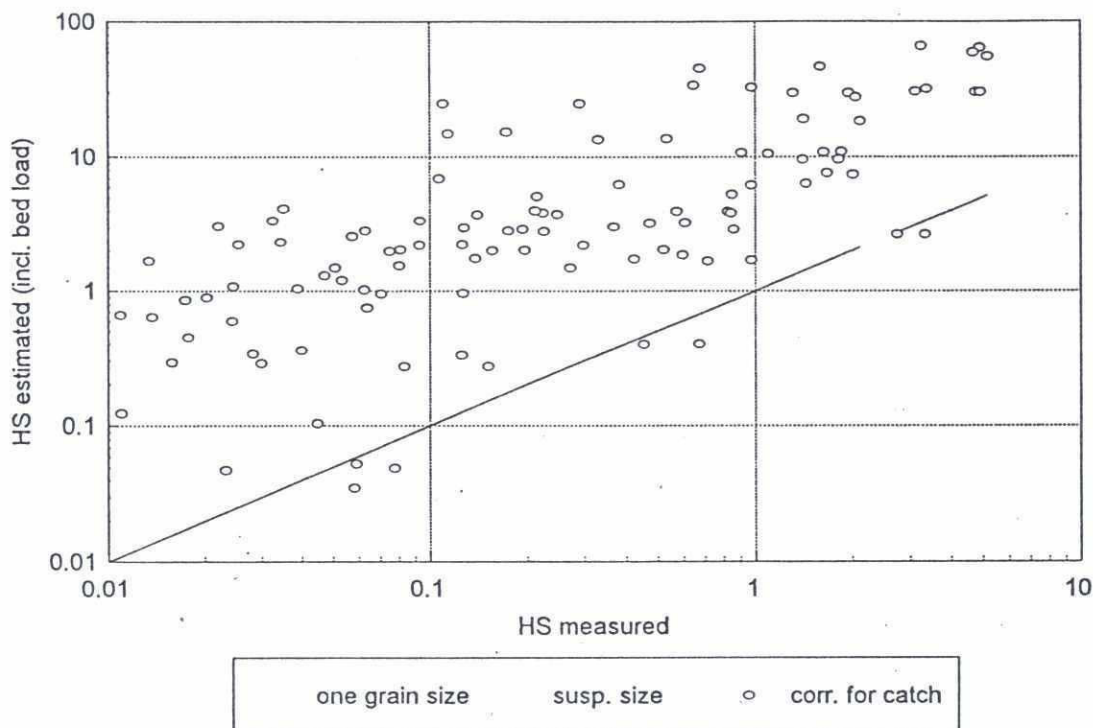


Figure C.21

Estimated vs. measured Helley-Smith flux. Measured grain size from Delft Bottle applied for suspended sediment. Correction for reduced catch of Helley-Smith sampler applied. Bed load included (calculated by van Rijn formula).

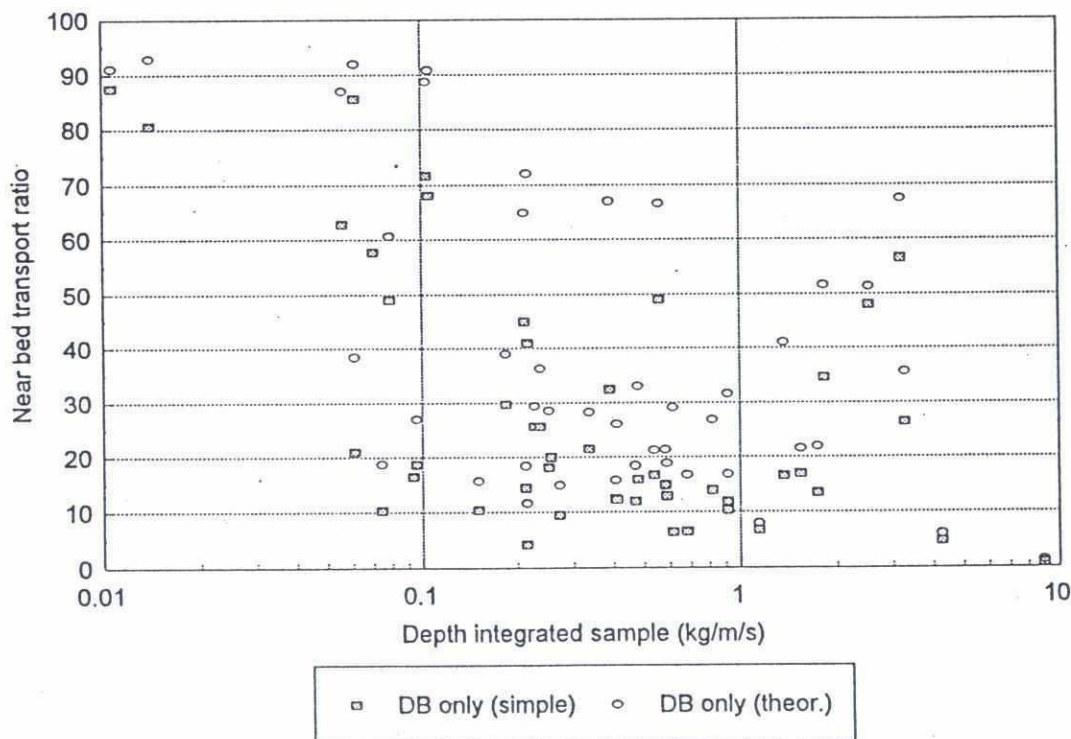


Figure C.22

Bed material transport in the near-bed zone as a ratio of the total bed material transport, estimated from Delft Bottle measurements by two different methods.

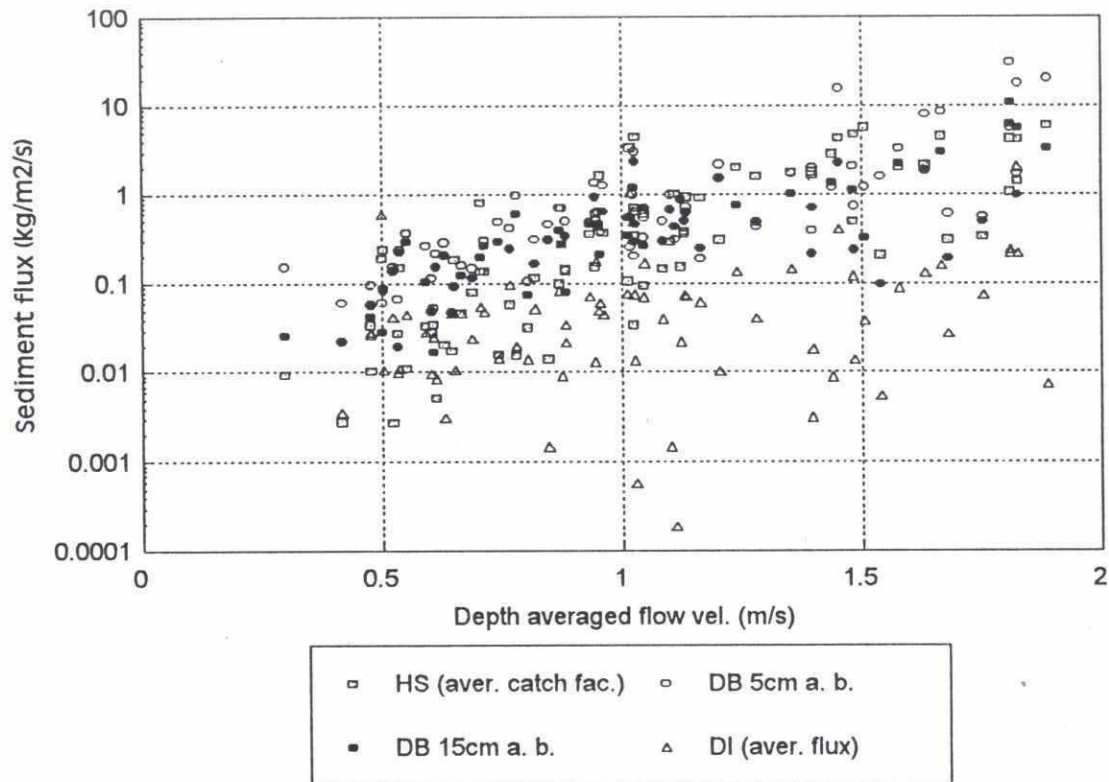


Figure C.23

Correlation of sediment flux with depth average flow velocity for Helley-Smith, Delft Bottle, and depth integrating sampler (catch factor applied for Helley-Smith).

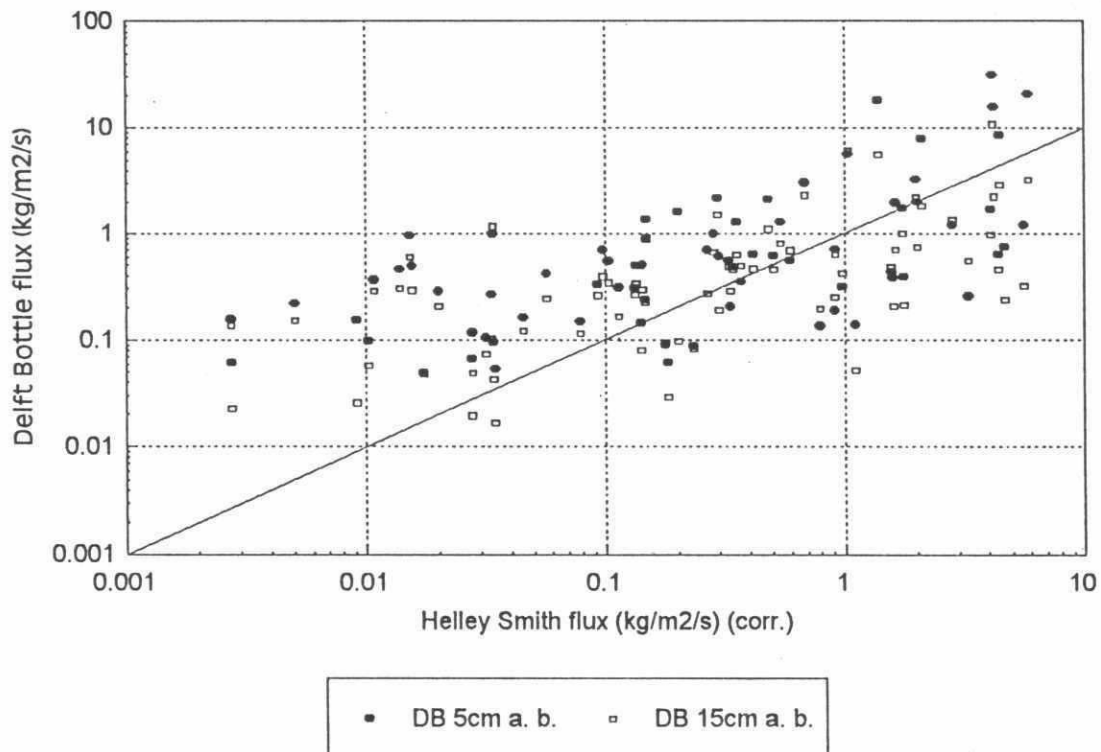


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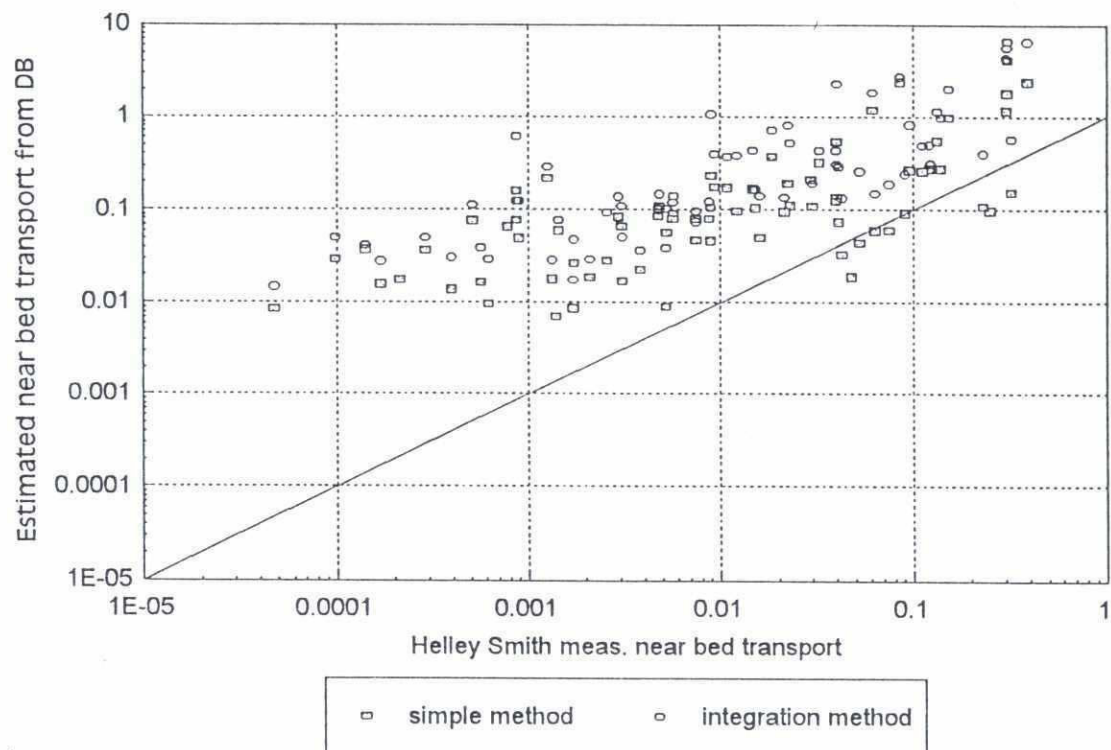


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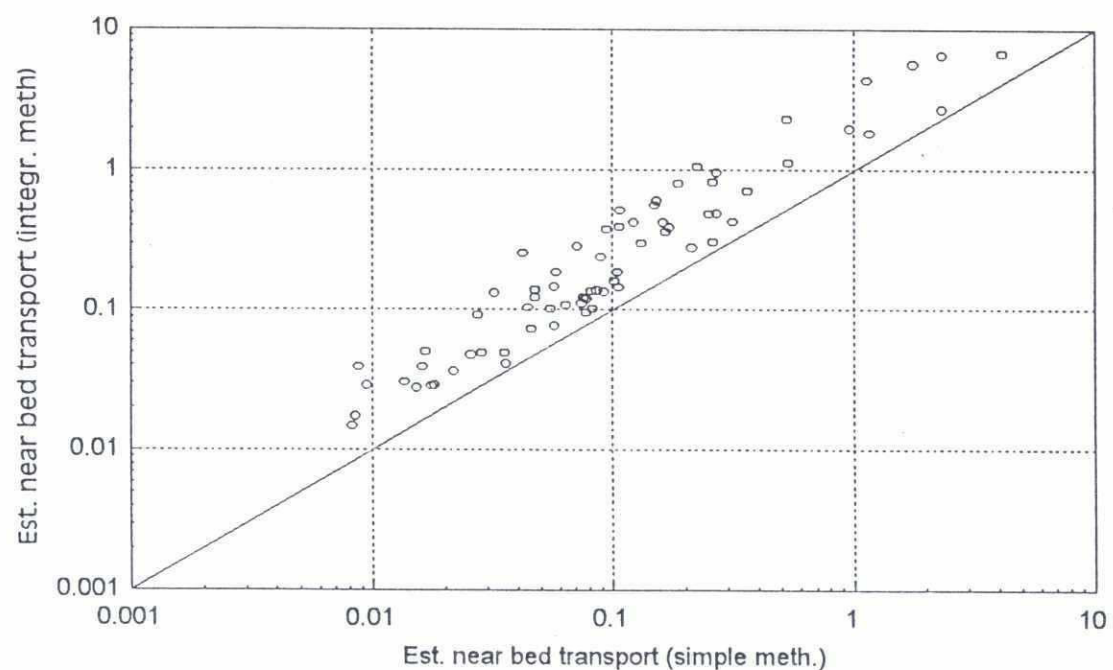


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Annexure D
Estimation of Suspended Sand
Concentration from ADCP Backscatter

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1 Introduction

The Acoustic Doppler Current Profiler (ADCP) was introduced by FAP 24 to estimate discharge in Bangladesh rivers. A moving boat method was used for this purpose. Some principles of the instrument are discussed in Annexure A. This Annexure attempts to relate ADCP backscatter to the suspended sediment concentration.

The theory on the method of estimating sediment concentration by ADCP backscatter is still in the development phase. Researchers working on the subject (e.g., Jansen, 1978; Christopher, 1990; Thorne et al., 1991; Thorne et al., 1994; and Weiergang, 1995) attempted to relate the backscatter signal to the concentration of sediment for different particle sizes and in different environment. Based on the work of previous researchers, it was attempted to relate the backscatter signal to the sediment concentration measured in the Jamuna River at Bahadurabad.

2 Principles of ADCP Backscatter

ADCP measures flow velocity utilizing the principle of the Doppler Effect (Urik, 1983). It sends sound-wave pulses along each of its four beams which are positioned 90° apart horizontally, and directed downward into the water column at an angle of 20° from the vertical. Part of the transmitted acoustic energy is reflected back toward the transducers by particulate matter moving with the water. The particulate matters are zooplankton, sediment particles, and detritus. The ADCP samples reflect signals from each beam at discrete time intervals during the progress of the advancing acoustic sound wave front; this allows velocities to be determined at each depth-interval or bin. The sound wave emitted from the transmitting device spreads with distance and some of it is absorbed by water. The amplitude of acoustic backscatter signal in the far-field region P_b from a single particle can be written as (Thorne et al., 1991):

$$P_b = (k_1/r^2) * e^{-2r\alpha_w} \quad (1)$$

where,

k_1 = a constant,

r = the distance of particle from the ADCP,

α_w = the attenuation co-efficient of the acoustic beam due to absorption by water.

The attenuation coefficient is given as (Fisher and Simons, 1988):

$$\alpha_w = (55.9 - 2.37 * T + 4.77 * 10^{-2} T^2 - 3.84 * 10^{-4} T^3) * 10^{-3} f^2 \quad (2)$$

where,

f = acoustic sound wave frequency in mHz,

T = water temperature in degree Celsius.

The attenuation coefficient α_w increases with the square of sound wave frequency.

For a number of particles P_b , value can be estimated from the following equation (Thorne et al., 1990):

$$\langle P_b \rangle = k_o ([\tau c C(r)]^{1/2} / r) e^{-2r(\alpha_w + \alpha_s)} \quad (3)$$

where,

$C(r)$ = sediment particle concentration at a distance r from transducer,

τ = pulse length,

c = speed of sound in water,

k_0 = a constant,

α_s = an attenuation coefficient, $\alpha_s = f[r, C(r), a_s]$, where a_s is an equivalent sphere radius of the sediment particles.

Hence, the backscatter signal is a function of the square root of the sediment concentration, pulse length, and exponent of the attenuation co-efficient. The P_b value is very sensitive to the exponent α_s for high concentration of sediments. The value of α_s depends on the sediment sizes; finer particles reduce α_s .

Equation (3) is valid where $ka_s \geq 1$, in which a_s is sediment particle radius, and k is the acoustic wave number expressed as $k = 2\pi/\lambda$, where λ is the wave length. The term $ka_s = 2\pi a_s/\lambda$ expresses the ratio of the circumference of sediment particle to the wave length. For $ka_s < 1$, the particles are Rayleigh scatterers (Rayleigh, 1945). Within the Rayleigh range, the sound wave scattering cross-section exhibits a linear relationship with the product of $k^4 a_s^6$. An upper limit of the validity of the Rayleigh scattering law is $ka_s = 0.5$, as suggested by Urik (1983).

Weiergang (1995) derived a relation between backscatter signal with the sediment concentration of sediment particles within Rayleigh scattering range. In his relation, the backscattering signal strength is expressed in decibels (dB), and it considers that the attenuation due to absorption is adjusted in the built-in software of ADCP. The Weiergang relation is stated as:

$$dB = 10 * \log[(3/4)k^4 \sum_{i=1}^m C_i \alpha (a_s)_i^3] \quad (4)$$

where,

C_i = the partial concentration of size class i having class median diameter $(a_s)_i$,

α = a material parameter.

According to Greenlaw (1979), α is expressed as:

$$\alpha = 4 [(1-mn^2)/(3\ln^2) + (1-m)/(1+2m)]^2 \quad (5)$$

where,

m = the ratio of the density of the scattering particle to that of the surrounding medium, n = the ratio of the speed of sound in the particle to the one in the surrounding medium.

For 300 kHz frequency of ADCP (used by FAP 24), the upper limit diameter of sediment particles of the Rayleigh scatterer range is 800 μm , as suggested by Urick (1983). In the Jamuna River, suspended sediment sizes range from 1 μm to 500 μm (see Figure D.1); i.e., all the particle are in Rayleigh scatterer range. Considering the size of the sediment in the Jamuna River, the ADCP frequency and the backscattering value (dB), expressed in the built-in software used by FAP 24 in equation (4), are relevant.

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3 FAP 24 Method of Survey Using ADCP

During the survey, the ADCP is mounted on-board a survey vessel close to the water surface. Four beams of monochromatic sound pulses are emitted through the water column (see Figure D.2). The beams are oriented in a so-called Janus configuration; i.e., each beam is orientated 20° downward from the vertical. The projections of the four beams on the horizontal plane are oriented at 90° intervals. At any depth, the speed of water can be determined by measuring the doppler shift of sound wave along the beam axis. The combination of the four beams yields the three spatial velocity components.

There are two ADCPs mounted on two vessels in FAP 24. One ADCP has 300 kHz sound frequency, and the other has 600 kHz. The selection of the ADCP frequency by FAP 24 was based mainly on the capability of measuring velocity in higher depths. During the discharge measurements in a river, the survey vessel sails from one bank to the other bank. The data from the ADCP is stored at certain time intervals, and the corresponding position from the DGPS is added with the on-board computer's built-in software. Later, off-line processing is needed. During the processing of the ADCP, the backscatter value in decibels (dB) is recorded for the 0.50 m bin-lengths. The minimum depth of water in which the FAP 24 ADCP of 300 kHz can measure is 2.66 m; this is due to the ADCP position in the vessel and the ADCP clearance distance. An ADCP is also not able to measure the last 0.50 m from the river bed.

In almost all cases, an ADCP of 300 kHz is used during sediment gauging at Bahadurabad. In the ADCP built-in software used by FAP 24, the backscatter value is expressed in decibels, and attenuation of sound waves due to absorption by water is adjusted for water with a temperature of 4° Celsius. Due to the low frequency (300 kHz), the absorption coefficient (α_w) in equation (2) is not very sensitive to the temperature. If the prevailing temperature of the water in the Jamuna River is 25° Celsius, the backscatter value (P_b) in equation (3) only vary 2% for a depth variation of 5 to 10 m. If this small influence of the temperature is neglected, however, then the ADCP backscatter value (dB) can be considered to directly reflect the backscattering strength from the sediment particles.

Different methods of measuring suspended sediment concentration are being used by FAP 24, including point-integrated pump-bottle sampling, depth-integrated-bottle sampling, and point-and depth-integrated collapsible bag sampling. During the point-integrated sediment sampling, the ADCP backscatter signal values were also recorded for different depths. A number of point-integrated pump-bottle sampling data are available at Bhadurabad for calibrating the backscatter signal value to the suspended sediment concentration.

4 ADCP and Sediment Data

To calibrate the ADCP backscatter value with the suspended sediment concentration, only sediment gauging at Bahadurabad was used. This limiting approach was accepted because Bahadurabad is the study location where the calibrated backscatter data will be used. It is expected that grain sizes and gradation of sediment particles will be similar at the same location, and hence, a fair correlation between sediment concentration and backscatter value is likely.

The results of the sediment concentration for FAP 24's 1993 sediment gauging are expressed in total concentration only; i.e., the concentration of sand and silt particles were not analysed separately.

During the 1994 sediment gauging, the concentrations for sand and silt fraction were analysed separately. The suspended sediment gauging data of 1994 were used to give an impression of the influence of silt and sand particles on backscatter value (dB). For the calibration of the backscatter, data were used where sediment concentration, simultaneously measured by pump bottle at different depths and backscatter values, were recorded. Table D.1 shows the data used. The dB value was linearly interpolated to relate the sediment concentration of the same depth. Twelve suspended sediment samples collected in August 1994 were used to see the variation of suspended sediment grain sizes with depth.

5 Analyses and Results

To calibrate the backscatter intensity, two types of analyses were performed. Both the relations were compared and evaluated on the basis of their correlations and their consistencies in predicting the concentration.

During the analyses of the data it was assumed that contribution of the attenuation coefficient (α_s) was negligible. Although the concentration of sediment in the Jamuna River was higher, the contribution of the particles in impeding the sound wave through the column of water was negligible because the particles were in Rayleigh scatterer range. The size of particles (a_s), of different fractions of concentration (C_i) of suspended sediment were not analyzed. Therefore, when using equation 4, a single size was assumed for the sediment concentration.

The backscatter value (dB) was related to the logarithm of the sediment concentration ($10 \cdot \log C$) at the same depth. The backscatter value was related to both the total sediment concentration and the concentration of sand fraction. Both relations were evaluated on the basis of their correlation. Figure D.3 shows the relation between backscatter (dB) and the logarithm of the total sediment concentration. The data show two distinct relations. The data, when marked according to the concentration of silt fraction and the period of measurement (see Figure D.4), indicate that data measured in November and December (during which time the silt concentration was within the range of 100 to 200 mg/l) were showing separate relations than the data with higher silt concentrations measured in the early and late monsoon. While the relation between the backscatter (dB) and concentration of sand fraction was less scattered and did not show any differences with respect to their measurement period (see Figure D.5). A linear relation between backscatter value (dB) and $10 \cdot \log(C)$ had a correlation co-efficient (R^2) of 0.80. This indicates a fair correlation between the backscatter value (dB) and suspended sand concentration. The relation between backscatter and concentration of sand fractions can be expressed as:

$$dB = 58.2 + 0.96 \cdot 10 \log(C) \quad (6)$$

where,

C = concentration of sand fraction.

According to equation (4), the slope of the regression is 1. In equation (6), however, the slope is 0.96 which indicates good agreement of the regression equation. In spite of the linear relation between dB and $10 \cdot \log(C)$, it seems that the data in Figure D.5 may have a curvilinear relationship.

To derive an empirical relation, the backscatter value (dB) was related to the square root of the concentration of the sand fraction of sediment particles (see Figure D.6). The regression equation can be expressed as:

$$dB = 68 + 0.77 * \sqrt{C} \quad (7)$$

The co-efficient of determination (R^2) is 0.79, almost nearer to the relation in equation (6). This equation shows zero concentration of sand fraction sediment particles at dB value of 68; however, this is not the case. For dB value near 68 (either above or below), the equation yielded inconsistent sand fraction concentration.

Both the relations expressed in equations (6) and (7) show fair correlations and were evaluated by comparing the measured sediment concentration with the predicted concentration by each of the relations (see Figure D.7). The comparison between the measured concentration of sand fraction sediment particles with the predicted concentration based on equation (6) shows good agreement up to a certain level of concentration. For higher ranges of concentration, for example the concentration above 600 mg/l, equation (6) predicted significantly high concentrations of sediment. According to the equation, 600 mg/l corresponds to dB value of 85. The possible reasons for this will be discussed in the next section.

The comparison between the measured sand fraction concentration and the predicted concentration based on equation (7) (see Figure D.7) show similar agreement in almost all concentration ranges. There were, however, a few scatter in the lower concentrations.

6 Discussion

Considering the acoustic sound wave frequency of ADCP used by FAP 24, all the suspended grain size were in Rayleigh scatterer range. Therefore, the analysis was based on the relation derived by Weiergang (1995) for the Rayleigh scatterer range of particles. There was a fair correlation between dB and the concentration of sand fraction; however, the correlation with the total concentration was rather poor.

From the data, it was observed that concentration of silt fraction varies in a wide range from 15% to 98%. The average median grain size of the suspended sand fraction is about 130 μm , whereas the median size of the silt fraction is about 12 μm , see Figure 1. So there is about a factor 10 in the median grain size of the coarse and fine fractions. According to Equation (4), the backscatter intensity scales with the product of the concentration and the cubic power of the grain diameter. Considering a sediment mixture having the same sand and silt fraction, the product of concentration and cubic power of grain diameter of silt fraction is about 1000 times less than that of the sand fraction. Hence the contribution on of silt fraction to the backscatter intensity of the mixture is very insignificant. Probably this is the reason why the relation between dB and total concentration is rather poor.

The size of the sand fraction of the suspended sediment varied with depth and location. Figure D.8 shows the variation of the median grain size (sand fraction) of suspended sediment with the relative depth. The median size of sand varied significantly with the relative depth. J. J. Peters (1994) observed the same type of sand fraction variation in the Jamuna River. It is expected that given the

same concentration, the dB value will be higher for the deeper samples (see Figure D.9). The concentration of sand fraction was also high for the deeper samples. These are the possible explanations for why the data in Figure D.5 show an apparently curvilinear relationship between dB and $10 \cdot \log(C)$, and why the concentration predicted by equation (6) deviated at higher levels of concentration.

Though the empirical relation (equation 7) was not based on theoretical background, the prediction is fair, except in the lower range of sand fraction concentration of suspended sediment. Therefore, the relation can be used to predict sediment concentration with certain limitations. Weiergang's (1995) relation (equation 6) can be used up to a certain level of concentration (about 600 mg/l); this corresponds to the dB value of 85. The empirical relation (equation 7) should not be used with the lower dB value because the relation showed zero concentration at the dB value of 68, and this was incorrect. The relation yielded inconsistent results for the lower dB value. To obtain consistent results, it is suggested that the lower dB value for equation (7) be 70.

For the ADCP frequency of 300 kHz, all the sediment particles of the main rivers in Bangladesh were in Rayleigh scatterer range. Within this range, the backscatter value dB was highly sensitive to the size and gradation of the suspended particles. Therefore, the relations derived here can only be applied to the Jamuna River, especially around Bahadurabad. In addition, the backscatter data from an ADCP having frequency other than 300 kHz can not be used for predicting sediment concentration with the derived relations.

7 Conclusions

Based on the ADCP backscatter principle, data analyses, and discussion, the following conclusion were made:

- The 300 kHz ADCP backscatter can only be correlated to sand concentration of suspended sediment.
- The derived relations are valid for the Bahadurabad location because the grain sizes and gradation of the particles are similar. For other locations, new relations need to be developed.

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Channel	Date of Survey	Vertical	Depth of Vertical (m)	Sample depth (m)	Interpolated Backscatter (dB)	Sand fraction Concentration (mg/l)	Wash load Concentration (mg/l)	Total Concentration (mg/l)
Left	15/7/94	6	12.60	2.80	77.98	194	363	557
			12.60	5.70	82.42	228	380	608
			12.60	8.50	86.66	274	419	693
			12.60	11.40	90.32	522	376	608
Right	14/7/94	2	7.56	1.70	74.03	27	373	400
			7.56	3.40	74.52	77	450	527
			7.56	5.10	78.54	249	501	750
			7.56	6.80	82.64	425	542	967
Right	9/8/94	7	10.25	4.00	69.47	6	307	314
			10.25	6.10	70.82	17	353	370
			10.25	8.10	73.94	31	350	381
Left	6/8/94	8	14.30	2.80	71.70	36	342	378
			14.30	5.70	74.67	87	337	424
			14.30	8.60	79.31	112	367	479
Left	24/6/94	3	14.30	11.40	84.60	121	395	516
			10.00	4.30	80.68	325	604	929
			10.00	6.40	85.11	509	623	1132
Right	25/6/94	2	10.00	8.60	89.01	825	660	1485
			7.41	3.00	78.06	181	517	699
			7.41	4.50	80.49	216	564	780
Left	3/9/94	10	15.42	3.10	69.15	11	310	321
			15.42	6.20	69.85	30	331	361
			15.42	9.30	73.25	60	372	432
			15.42	12.40	77.66	106	423	529
Left	23/9/94	7	14.20	2.80	76.83	139	333	472
			14.20	5.70	79.98	274	342	615
			14.20	8.50	83.71	321	345	666
			14.20	11.40	88.00	554	380	934
Right	25/9/94	1	8.22	3.28	71.90	113	331	444
			8.22	4.92	73.85	124	339	463
			8.22	6.56	76.19	149	355	504
Right	27/9/94	5	6.82	3.10	71.36	59	329	388
Left	19/10/94	6	15.00	2.80	77.69	166	330	496
			15.00	5.60	80.67	307	366	673
			15.00	8.40	84.40	343	381	724
			15.00	11.20	88.90	509	400	909
Right	22/10/94	3	4.85	2.94	76.46	283	376	659
			4.85	3.92	81.99	332	341	673
			4.85	4.10	83.83	531	363	894
Left	8/11/94	3	12.65	4.80	76.97	93	175	268
			12.65	7.20	80.33	101	218	319
			12.65	9.60	84.87	119	218	337
Right	26/11/94	2	10.78	4.30	66.50	8	158	166
			10.78	6.50	69.49	10	153	163
			10.78	8.60	71.88	23	163	186
Left	27/11/94	3	11.10	4.40	74.00	46	156	202
			11.10	6.60	76.77	75	174	249
			11.10	8.80	80.09	68	171	239
Left	8/12/94	3	5.70	3.40	74.87	60	181	241
			5.70	4.60	76.90	130	185	315
			7.70	3.10	69.26	24	132	156
		4	7.70	4.60	70.57	31	141	172
			7.70	6.20	72.61	39	137	176
			7.70	6.20	72.61	39	137	176
		5	6.90	2.80	66.68	8	113	121
			6.90	4.10	67.05	6	112	118
			6.90	5.50	68.74	9	129	138
			6.90	5.50	68.74	9	129	138
Left	17/8/94	1	10.00	6.00	77.00	124	480	604
			10.00	8.00	81.50	173	484	657
		2	6.60	3.92	83.75	478	500	978
			6.60	5.30	87.00	610	472	1082
		3	7.00	4.20	83.55	554	504	1058
			7.00	5.60	86.24	735	535	1270
		4	7.60	4.56	85.40	534	549	1083
			7.60	6.08	87.30	758	555	1313
		5	4.30	2.58	80.10	412	661	1073
			4.30	3.44	82.38	443	650	1093
		6	5.00	3.00	73.50	135	739	874
			5.00	4.00	75.30	202	826	1028
		7	7.00	5.60	77.00	371	1250	1621
			7.00	5.60	77.00	371	1250	1621
Left	18/8/94	1	6.30	3.78	76.85	186	520	706
			6.30	5.40	81.20	207	421	628
		2	5.60	3.36	82.20	296	461	757
			5.60	4.48	84.80	548	492	1040
		3	6.20	3.72	81.15	150	495	645
			6.20	4.96	84.50	418	511	929
		3	6.20	3.72	81.15	150	495	645
			6.20	4.96	84.50	418	511	929

Table D.1 Data used to calibrate the backscatter value (dB) with the suspended sediment concentration, measured in the left and right channels of the Jamuna River at Bahadurabad.

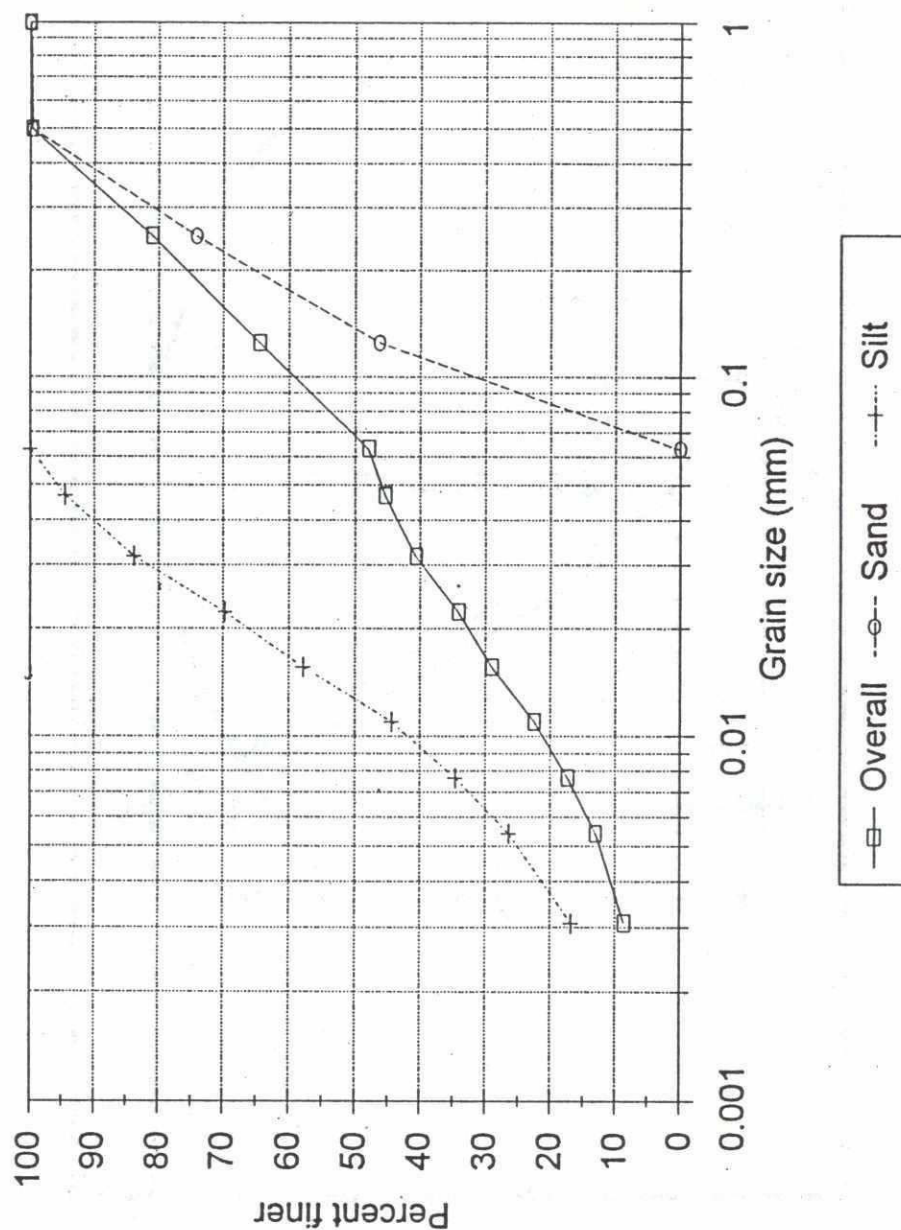


Figure D.1

Average suspended grain size distribution based on the analyses of 12 bulk samples collected at different depths on 12 and 13 August 1994 from the Jamuna River at Bahadurabad.

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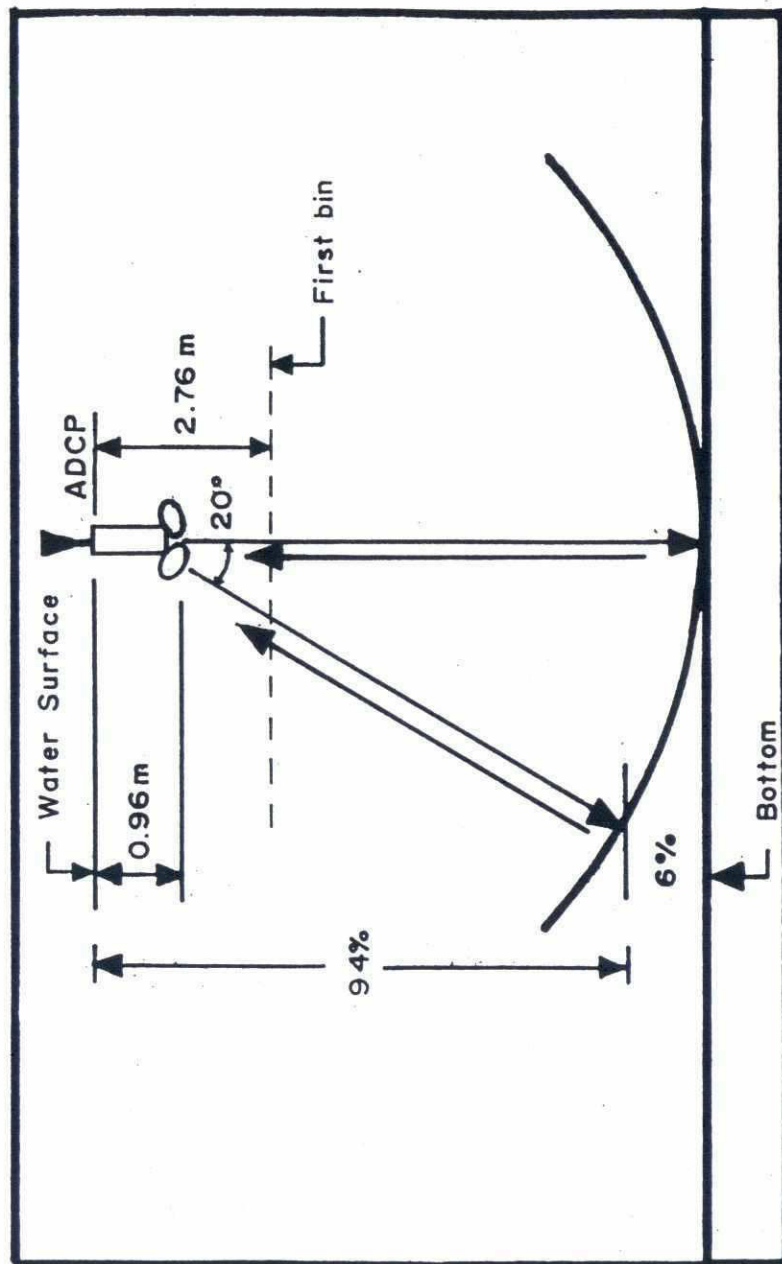


Figure D.2 The ADCP 300 mounted on survey vessel DHA.

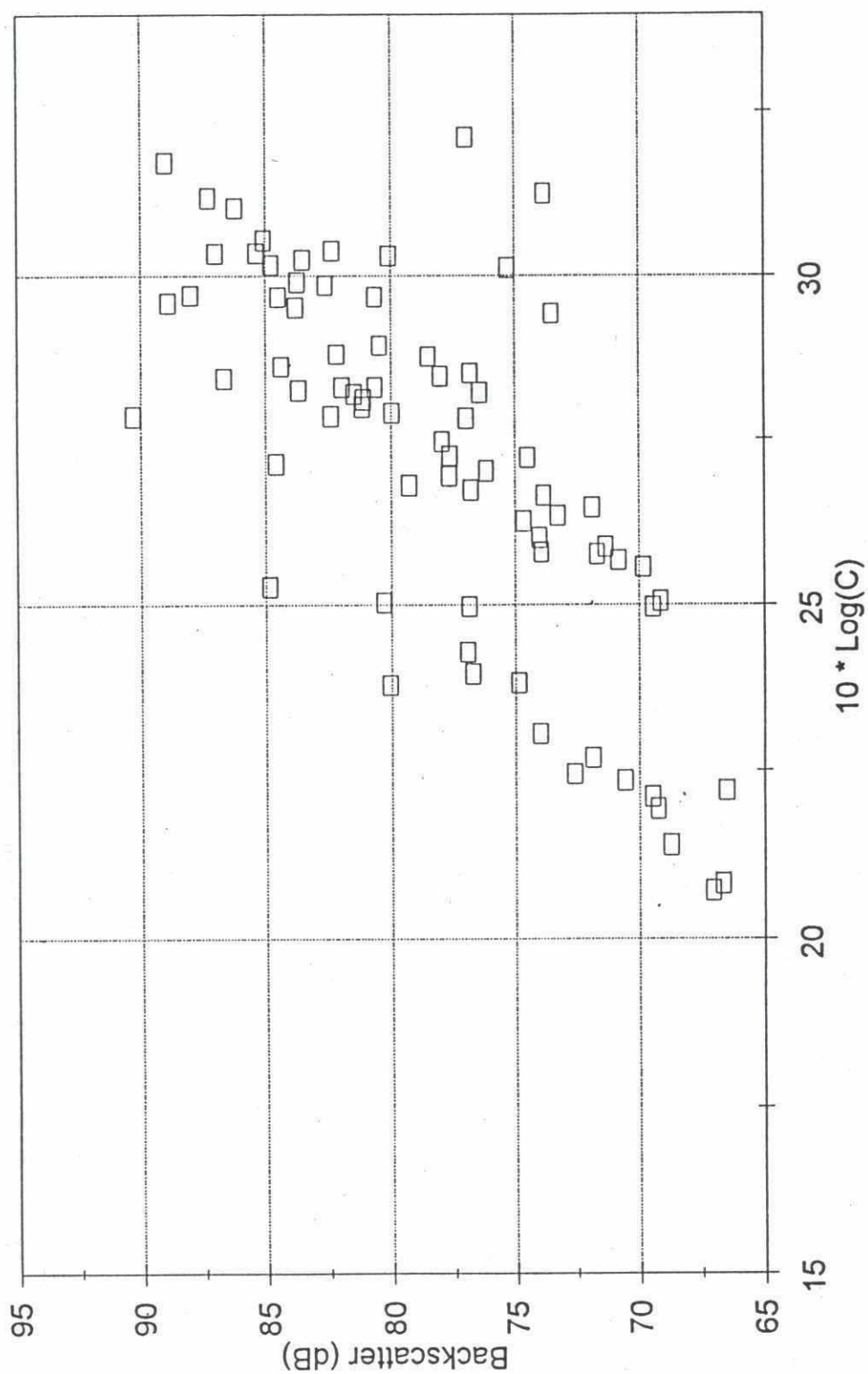


Figure D.3 Relation between total suspended sediment concentration and ADCP backscatter.

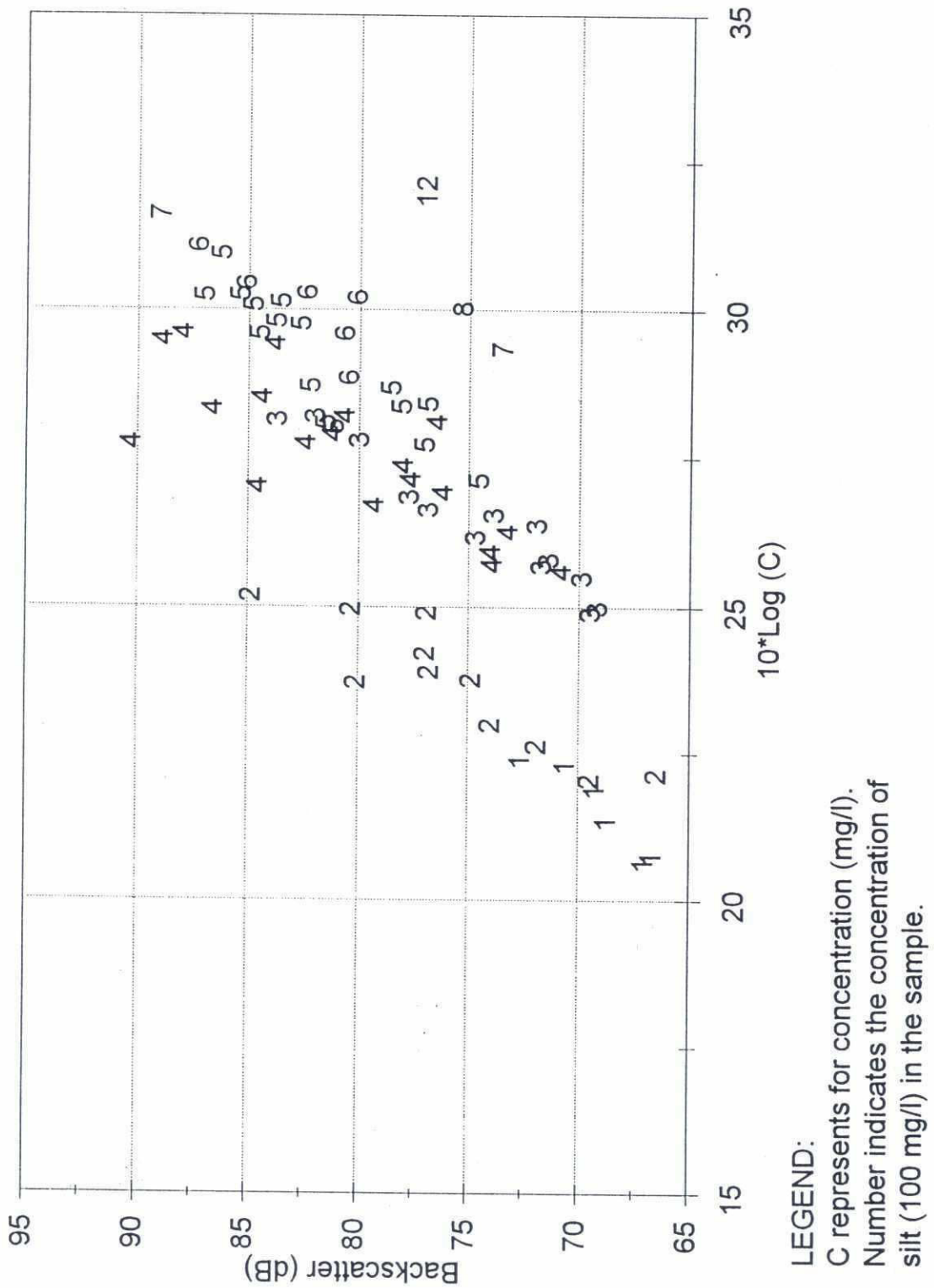


Figure D.4a Relation between total suspended sediment concentration and ADCP backscatter with the indication of silt concentration.

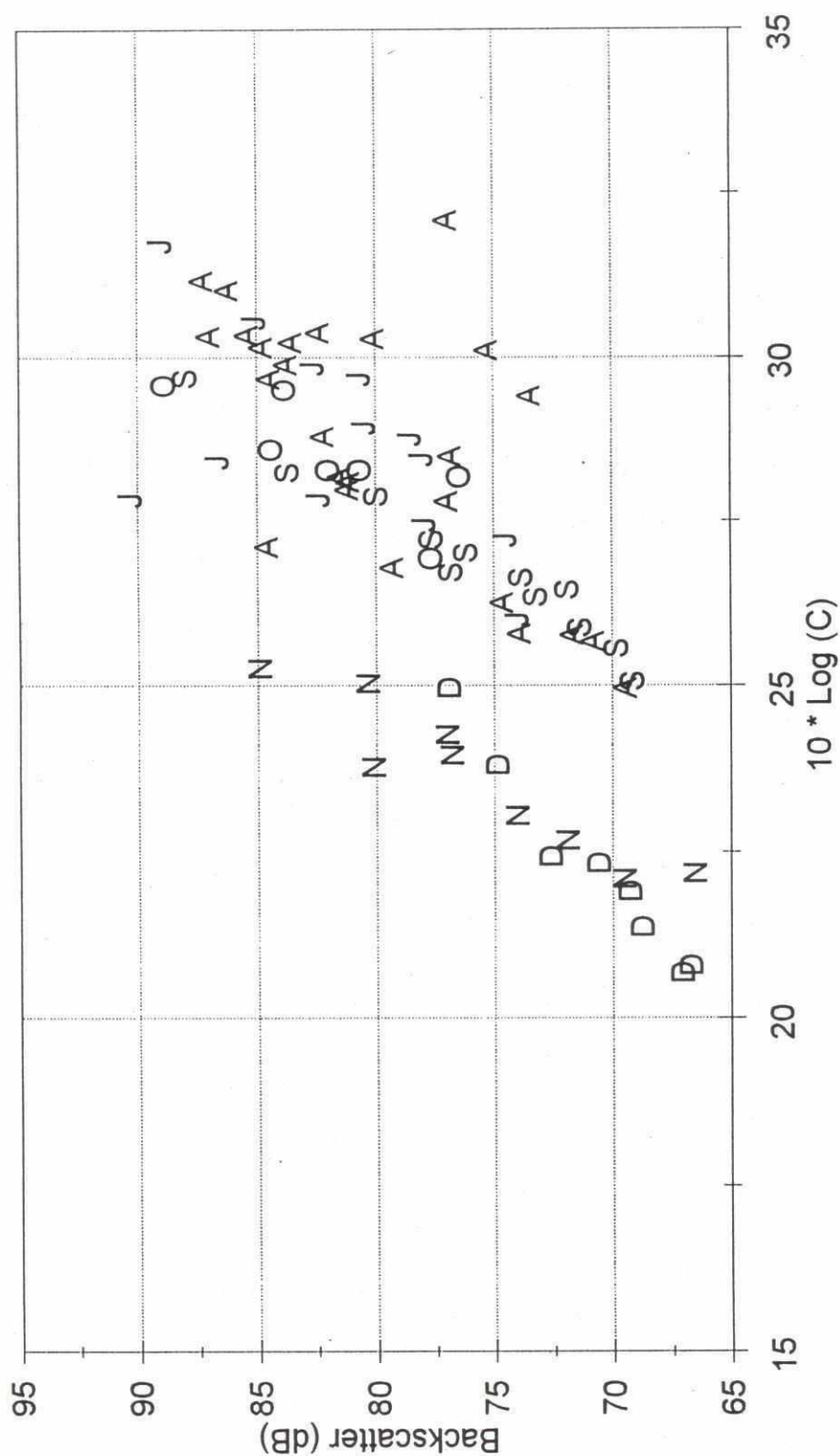


Figure D.4b

Relation between total suspended sediment concentration and ADCP backscatter with the indication of the period of measurement of the samples.

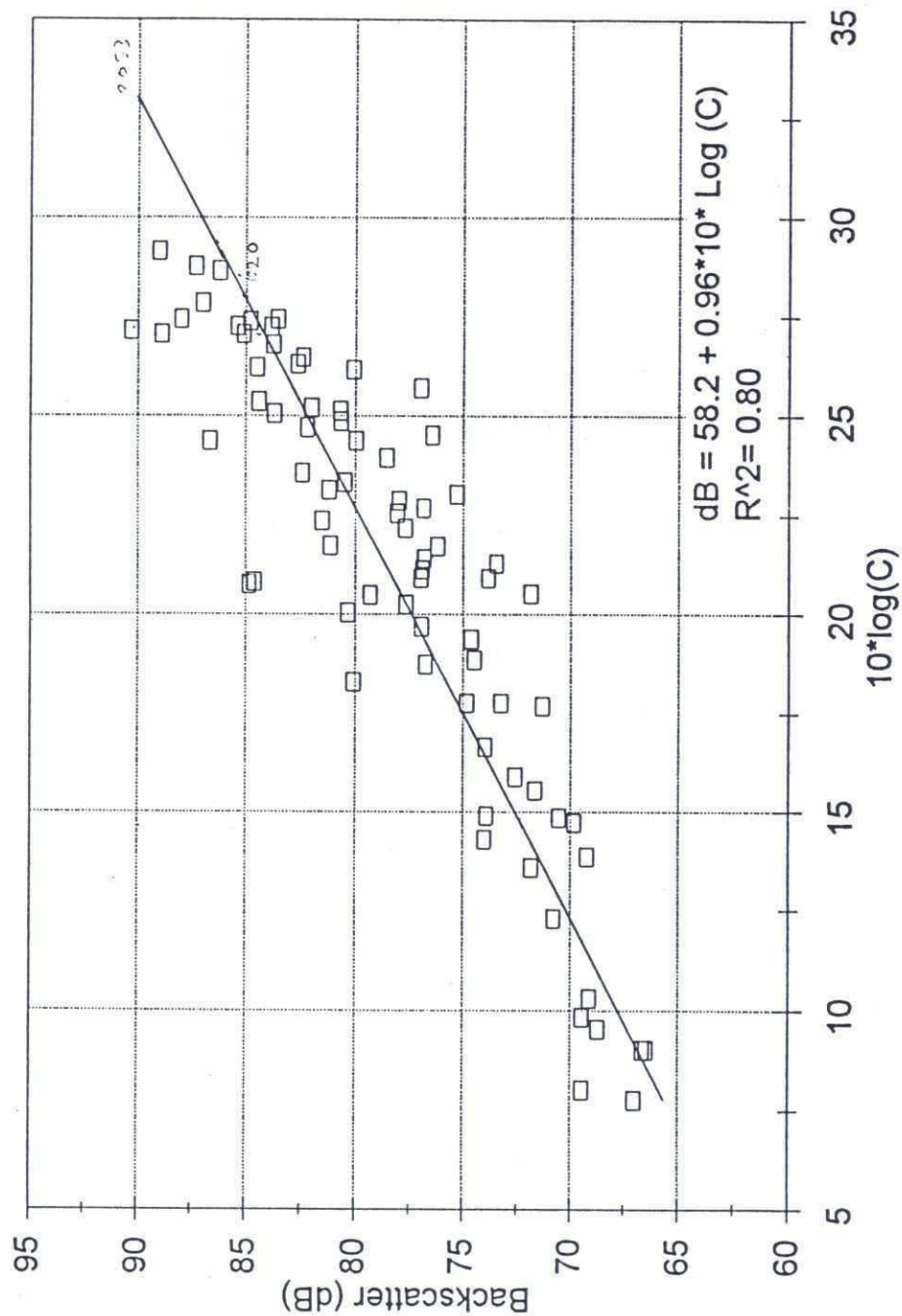


Figure D.5 Relation between the sand concentration of suspended sediment ($10 \cdot \log C$) and the ADCP backscatter.

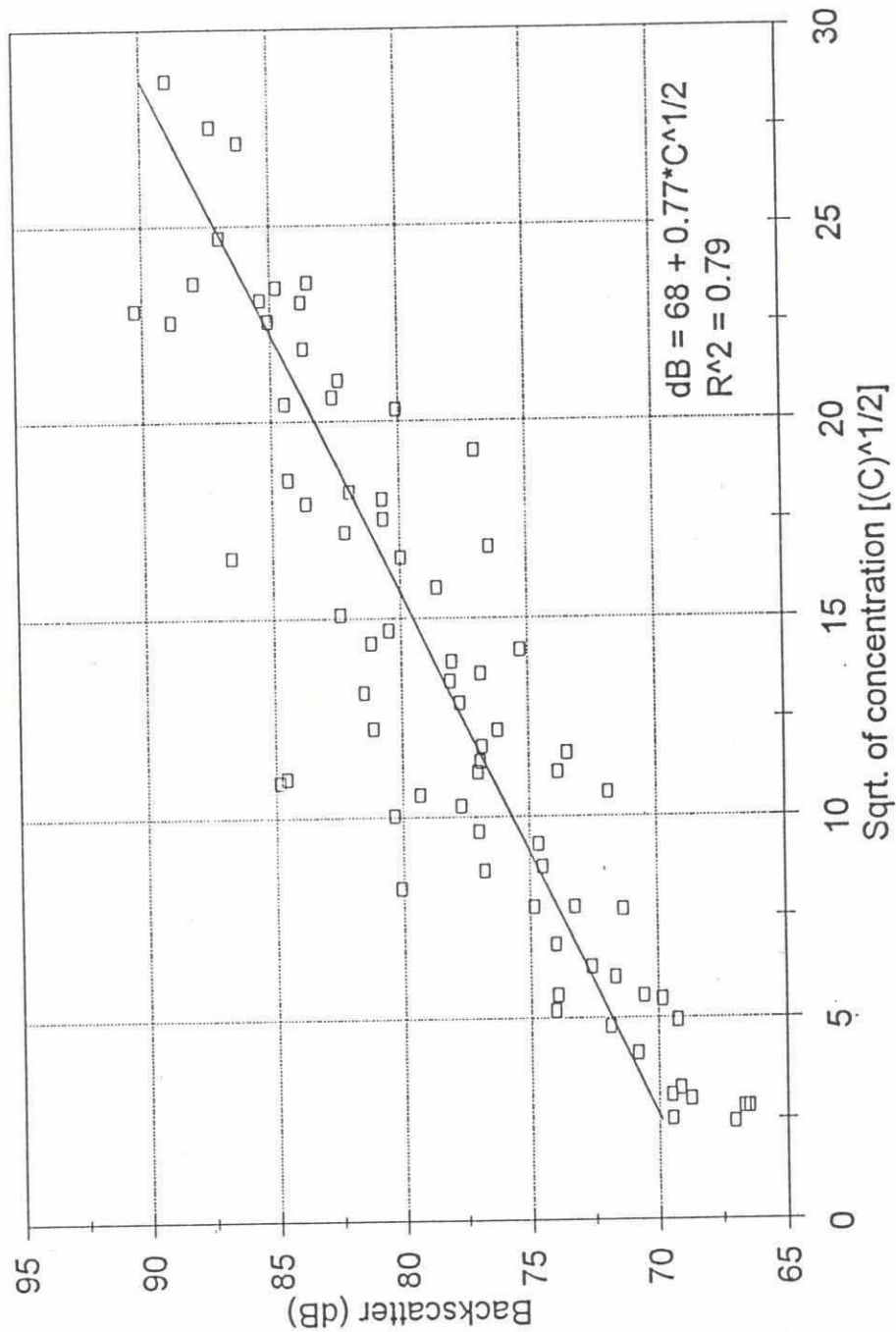


Figure D.6 Relation between the square root of sand concentration of suspended sediment and the ADCP backscatter value dB.

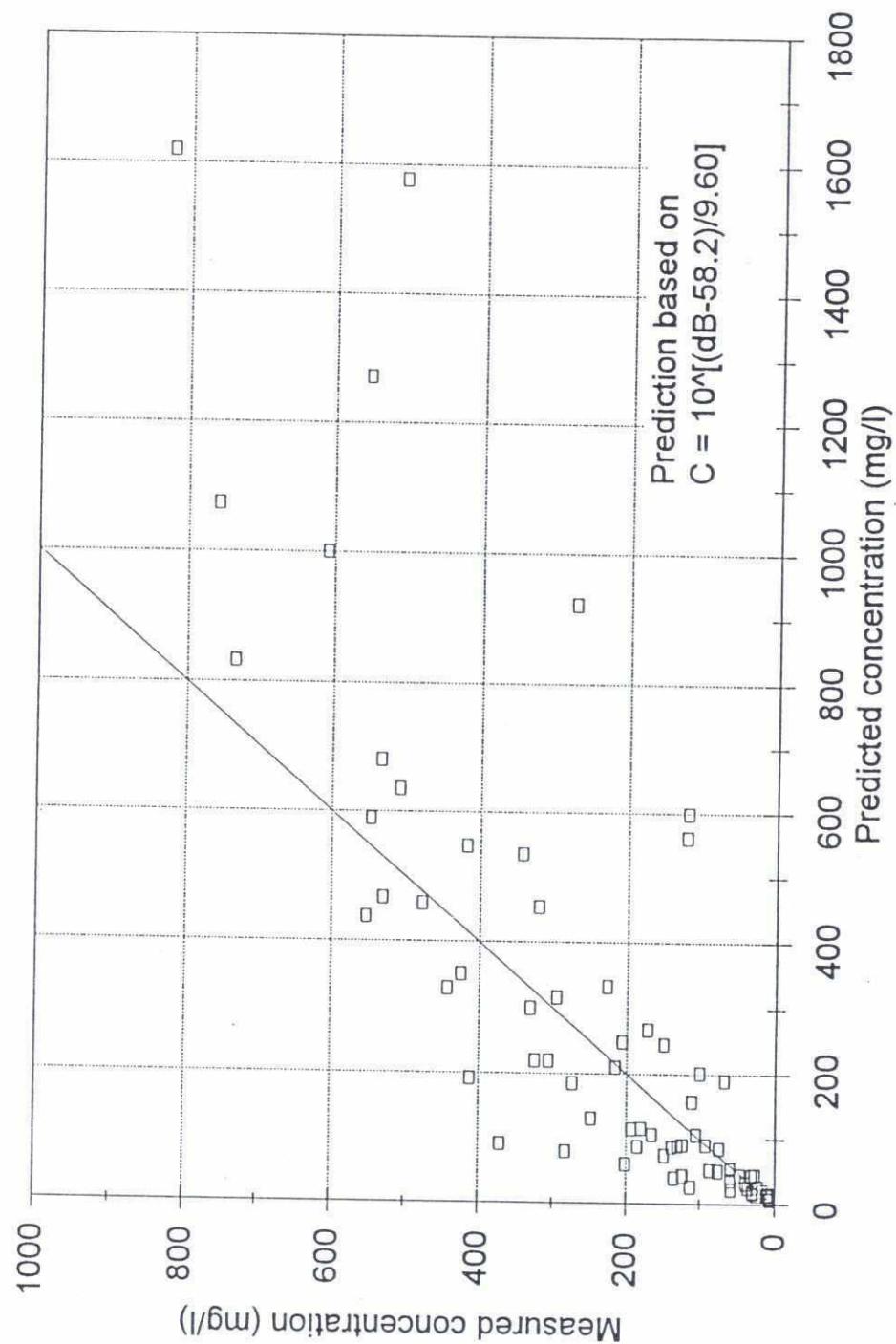


Figure D.7a Relation between the measured and the predicted sand concentration of the suspended sediment based on equation (6).

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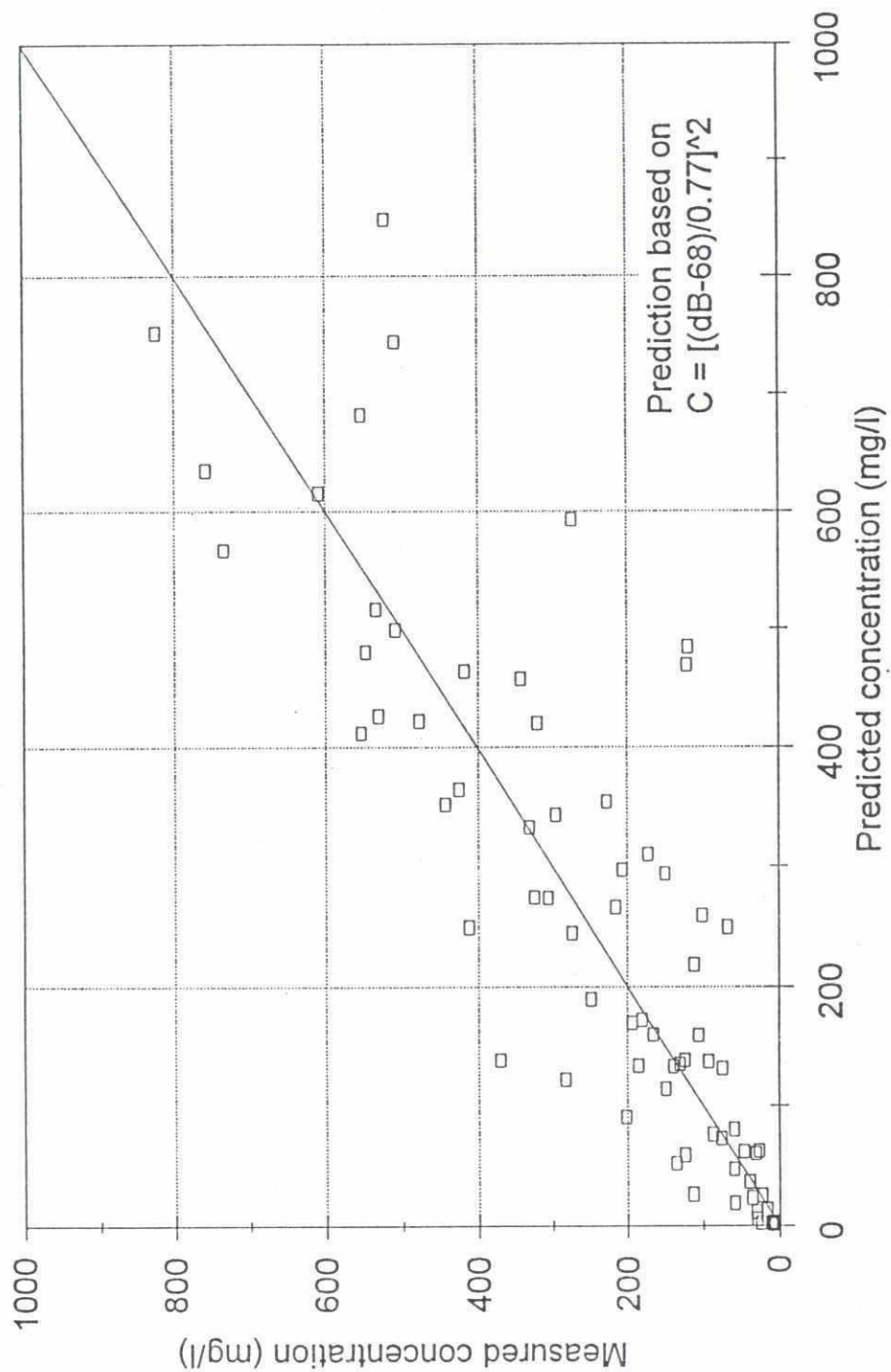


Figure D.7b Relation between the measured and the predicted sand concentration of the suspended sediment based on equation (7).

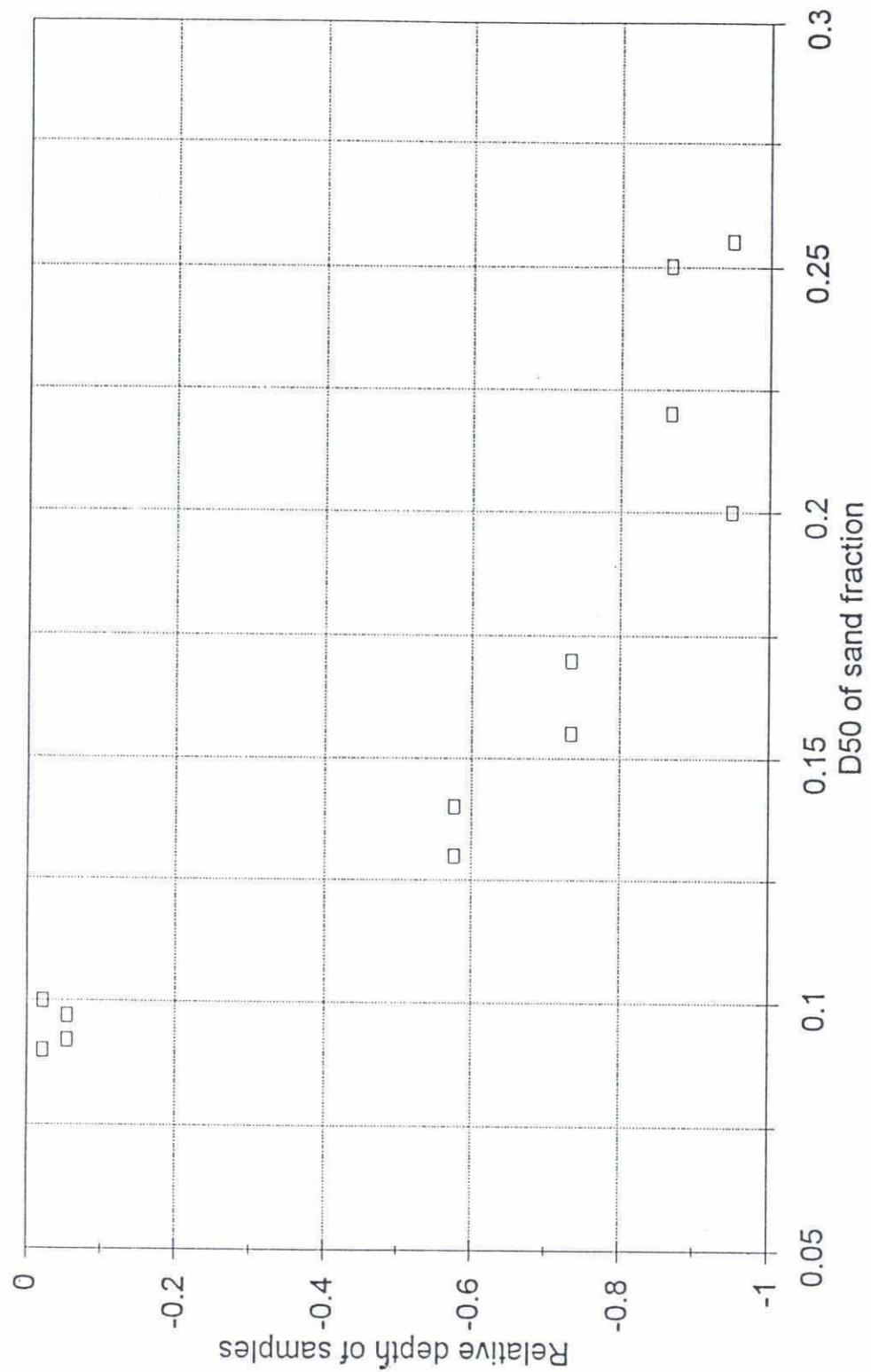


Figure D.8 Variation of median grain size of suspended sand fraction of sediment with the relative depth.

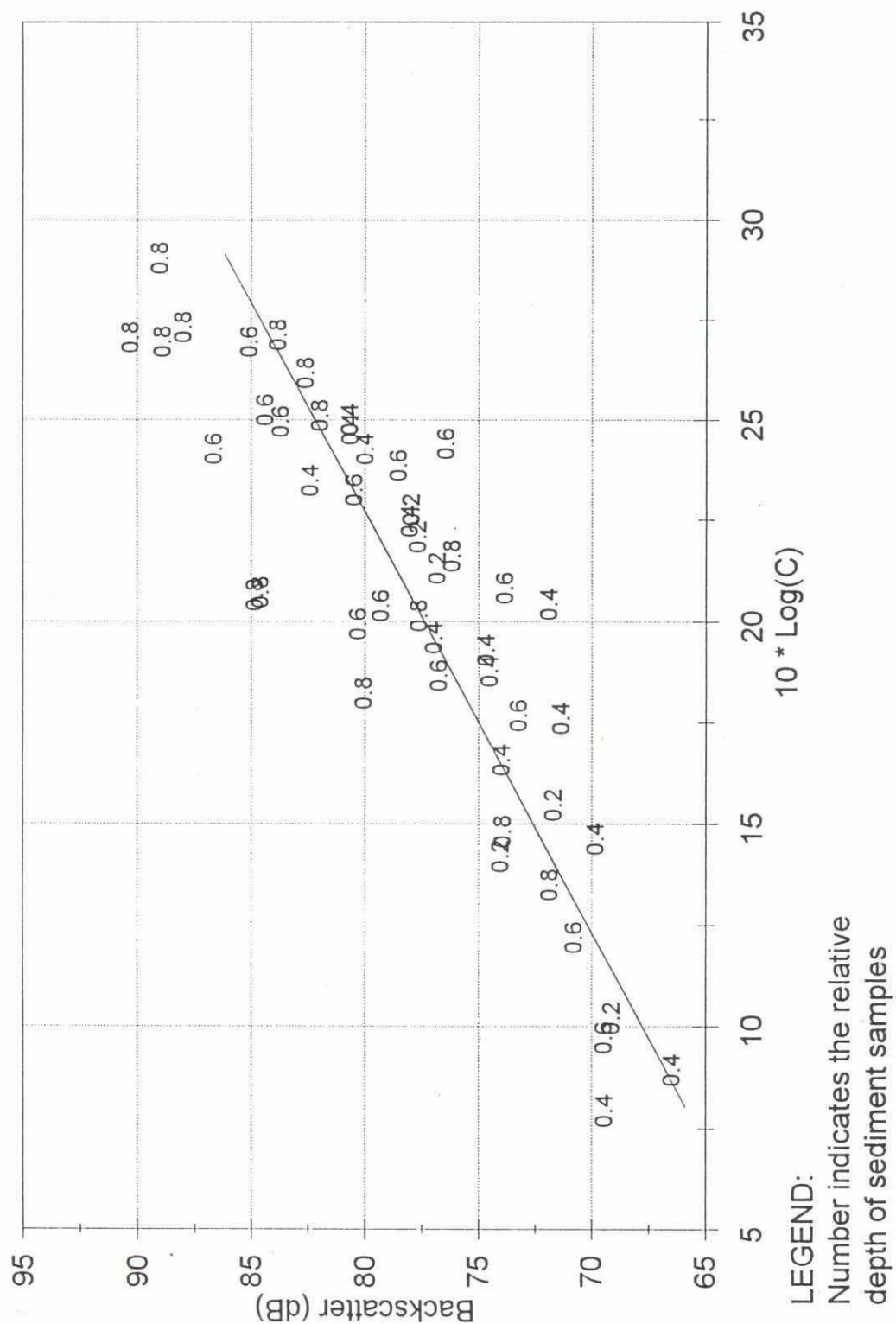


Figure D.9 Relation between dB and $10 \cdot \log(C)$ with the indication of relative depth of the samples.

Annexure E
Fine Sediments:
Their Hydraulic Behaviour and Importance for
Bangladesh Rivers

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1 Introduction

Fine sediments are defined in this Annexure as the silt-clay parts of detritus sediment having a diameter less than $63\ \mu\text{m}$. Conventionally, this sediment fraction is known as the wash load. However, Barua (1995) questioned the applicability of this conventional definition. He gave the arguments that this sediment fraction forms a major part of the transport and that its hydraulic behaviour is partly controlled by local flow conditions. He suggested that the energy criterion proposed by Vlugter (1941) and Bagnold (1962) be used. According to this criterion only particles less than approximately $21\ \mu\text{m}$ can be treated as wash load. However, the conventional understanding of wash load implies that these particles can be transported in unlimited quantities and therefore, are not important to river morphology. Therefore, it is important to ask why should they be measured. In addition, it is important to consider if this fraction, which forms the major part of the transport, can be forgotten (Thorne et al. 1993; RSP, 1994; Barua, 1995). This Annexure attempts to clarify and discuss these issues. A brief introduction is given on the concepts of the matter discussed.

Sediment transport is distinguished according to its origin or source. Sediment that originates in the river bed is called the bed-material load. Sediment that originates primarily from the watershed is known as the wash load. The wash load is supply-rate limited rather than transport-capacity limited. This means that while considerable energy is spent on bed-material transport, no energy is spent on the resuspension and transport of the wash load. In the wash load, we expect a uniform distribution of the load concentration at different depths and a uniform distribution of load concentrations for the entire width of the river. The wash load transport must also be independent of Q (i.e., in $Q_{\text{silt}} = mQ^n$, n is equal to 1). However, conventionally, the distinction between bed-material and wash load is made on the basis of the size of sediments. In Europe, $50\ \mu\text{m}$ is the value that distinguishes between bed-material load and wash load. In the USA, the value is $63\ \mu\text{m}$. Wentworth (1922) chose $63\ \mu\text{m}$ as the value that divides between sand and silt particles.

2 Hydraulic Behaviour of Fine Sediments

Several investigations on the hydraulic behaviour of fine sediments that are based on the paper by Barua (1995) are presented.

2.1 Observational Aspects

Vertical Distribution of Suspended Silt

Some point-integrating samples were collected at different depths in the Jamuna River near Bahadurabad on 3 and 4 August 1994. In Figure E.1, the vertical profiles of sand and silt concentrations are plotted. A vertical gradient in sediment concentration exists both in the sand and the silt fractions. As expected, the sand-concentration has a steeper gradient. The analyses indicate that the suspended silt is not uniformly distributed at different depths and that its concentration is dependent on the flow velocity. Therefore, the suspended silt concentration is transport-capacity limited. Figure E.1 also shows that there are large differences in the magnitude of sand and silt concentrations indicating that the bulk of the suspended material is silt.

Horizontal Distribution of Suspended Silt

Figure E.2 shows the distribution of suspended sand and suspended silt transport measured at different verticals across the Jamuna River at Bahadurabad, the Ganges River at Hardinge Bridge, and the Padma River at Baruria. The silt concentration is not uniformly distributed over the width of the rivers. In fact, the suspended sand and suspended silt concentrations are in phase and roughly correspond to the high transport capacity indicated by the velocity distribution. As indicated earlier in Figure E.1, the bulk of the suspended material is silt.

Silt Transport Rating Curves

The n-value of the silt transport rating curve ($Q_s = mQ^n$) is 1 if the silt transport is supply-rate limited. However, the rating curves created from BWDB silt transport measurements indicate that the n value varies from 0.6 to 1.8 (RSP, 1994). Similar results were obtained by other FAP studies. This shows that the silt-transport is transport-capacity limited.

Sand-Silt Percentage of the Bed-material

33 bed-material samples were collected from the Ganges River at 11 transects (3 from each transect) at water depths over 3 m on 6 August 1994. They show that in most cases the percentage of sand ($> 63 \mu\text{m}$) is higher than the percentage of silt (Fig. E.3). However, in 1/3rd of the samples, the silt percentage is significantly higher than the sand percentage. The average silt percentage is 25. The median grain sizes show a similar trend (Fig. E.4). The average grain size is 0.12 mm. The average sorting coefficient of these samples was 1.7 and the minimum and the maximum values ranged between 1.3 and 3.

The silt percentage of the 26 bed-material samples collected from the Jamuna River by FAP 24 in June 1993 varied from 1 to 20% and the average was 4.5%. The bed-material sand-silt percentage distribution indicates that silt is resuspended from the bed.

Sand-Silt Percentage of the Bank-Material

A significant portion of suspended material comes from bank-erosion. According to Halcrow's (1993) study, which used about forty years of data (1953 to 1992) the net average bank-erosion rate is about 52 m/year in a reach of 200 km of the Jamuna River. If we assume an average bankline height of 5 m, then the annual erosion for the reach amounts to about 87 million tons. This amount is about 15% of the total annual sediment transport of the Jamuna River, based on the RSP 1994 estimate. If the CBJET (1991) estimate is considered, the amount will be about 17%. In addition, ISPAN's (1993) studies indicate that the Jamuna River is currently widening at a rate of about 65 m per year; a width of 5.6 km in 1914 was 10.6 km in 1992. This huge bank-erosion rate brings a considerable amount of silt into suspension because most of the bankline which constitutes the floodplain consists of silty material. Six bore log profiles obtained from the floodplain of the three major rivers show that in most cases the upper 10 m contain sandy silt material (Mollah, 1993). The deeper samples contain mostly silty fine sand with trace mica.

Estimates by Thorne et al. (1993) indicate that 40% of the bank-material in the Jamuna River is silt. Suspended silt constitutes 75% of the total transport, and suspended sand constitutes the remaining 25%.

Grain-size Distribution of the Surface-Water Sediment in the River

Figure E.5 shows the grain-size distribution of 14 surface-water sediment samples. Figure E.6 shows only the median and the 90% sizes. Median grain sizes varied from 12 to 26 μm with a mean of about 21 μm . The mean d_{90} value was 102 μm . The sorting coefficient was large and varied from 2.6 to 4.2. The percentage of silt ($< 63 \mu\text{m}$) varied from 80 to 96%. Interestingly, the d_{50} size was far smaller than the 63 μm .

Surface-Water Suspended Sediment Concentration in the Floodplain

Figure E.7 shows the ratio of silt and sand concentrations for 32 surface-water samples collected from the floodplain near Tangail in August and September 1994 (ISPAN, 1995). The silt-concentration was about 50 times higher than the sand-concentration.

2.2 Theoretical Aspects

Vlugter (1941) and Bagnold (1962) Energy Criteria

Based on energy considerations, Vlugter (1941) and Bagnold (1962) demonstrated that sediments can be transported in unlimited quantities when $W_s < 1.6 \cdot U \cdot I$; where, U = mean velocity (m/s), I = Slope, W_s = Settling velocity (m/s) = $[(s-1)gD^2]/18\nu$, s = specific density, D = median grain size diameter, g = acceleration due to gravity, and ν = kinematic viscosity. Use of the energy criteria proposed by Vlugter (1941) and Bagnold (1962) yields different sediment sizes. With an assumed flow velocity of 1.6 m/s and a river bed-slope of 7×10^{-5} in steady uniform flow conditions in the Jamuna River, the median grain diameter was 14 μm . This may be compared with the 21 μm observed at surface samples. For the Ganges River, with similar values of 1.4 m/s and 5×10^{-5} , the grain diameter was 12 μm .

Rouse Suspension Number Criteria

Similar investigations on the equilibrium suspension profile using the Rouse Number would indicate that a homogenous suspension is possible only when the Rouse Number is 0.01 (de Vries, 1977). The Rouse Number is given as,

$$R = \frac{W_s}{\beta \kappa U_*}$$

where,

β = the sediment diffusion coefficient (~ 1),

κ = the von Karman constant (~ 0.4),

U_* = bed-shear stress velocity,

W_s = settling velocity (Stoke's Law is applied).

For an assumed bed-shear stress velocity of 0.1 m/s, the sediment diameter corresponding to homogeneous suspension is 20.9 μm .

3 Fine Sediment Transport in Bangladesh Rivers

Fine sediment transport constitutes the bulk of the transport in Bangladesh rivers; this is shown in several figures earlier in the Annexure and by different investigations (e.g., Thorne et al., 1993; RSP, 1994; Barua, 1995). Some additional examples are shown in Figures E.8 and E.9. Figure E.8 shows the annual variation in depth-integrated sand and silt concentrations measured by FAP 24 in the reference verticals of the Jamuna River near Bahaduarabad for 1994 and 1995. Both the silt and the sand fractions varied seasonally with river stage. The peak areas of silt and sand concentrations conformed to the monsoon months. The average silt concentration during this time was 324 mg/l and the average sand concentration was 85 mg/l. The ratio of these two average values was about 3.8; it varied from a minimum of 1.5 on 21 June 1995 to 56.2 on 18 October 1994. Figure E.9 shows the annual variation for the Padma River at Baruria. Here, the average silt concentration was 461 mg/l and the average sand concentration was 82 mg/l. The ratio of these two average values was 5.64; it varied from a minimum of 1.84 on 21 August 1994 to 111.3 on 5 February 1994.

These two examples show two very important aspects of suspended sediment transport in Bangladesh rivers. One aspect is the difference in magnitudes of transports. The silt transports were 3.8 to 5.6 times higher than the sand transports. The second aspect is the hydraulic behaviour of silt which is more transport-capacity limited rather than entirely supply-rate limited; this supports earlier observations.

4 Fine Sediments and River Morphology

Sediments containing a large fraction of finer particles in sand and clay fractions had greater resistance to entrainment than coarser sediments consisting only of sands. This is evident from Hjølstrom's (1935) diagram which shows that cohesion became important as particles became less than about 0.1 mm (see Figure E.10). The diagram also shows that for finer sand-sized bed-material, as is found in Bangladesh rivers, the threshold velocity was even less than for finer fractions. Therefore, similar energy was required for entrainment of sand or finer particles into suspension. It should be noted, however, that, once suspended, the silt particles took longer to settle than the sand particles because the settling velocity is proportional to D^2 (where D is the particle diameter).

Since fine sediments are abundant in Bangladesh rivers, they settle immediately in the relatively sheltered low energy environments. The likely low energy environments are,

- Secondary or abandoned channels,
- Eroded bankline embayment,
- Lee-side of the islands, bars, or major bed-forms,
- Abandoned or oscillating scour holes.

This deposition of fine sediments in selective locations introduced heterogeneity in the deformed bed and bank, complicating the morphological behaviour of the rivers. In addition, due to seasonal variation of hydraulic parameters, the hydraulic energy varied widely in space and time, making room for settlement of fine sediments. Evidence of this was found in mud-drapes observed in a variety of hydraulic environments. With high erosion, migration, and wandering of the rivers, as occurs in Bangladesh, the once designated sheltered low energy soon became part of the active river bed; thus, the deposited bed-materials were eroded as the thresholds were exceeded.

The influence of silt-clay sediments in the hydraulic boundary of rivers was demonstrated by Schumm (1968). He showed that meander wave-lengths are inversely proportional to the silt-clay percentage in the hydraulic boundary.

In addition, high suspended sediment concentration caused some hydraulic parameters to change, thus affecting the transport relations. The suspended sediment concentration influenced the velocity profile by affecting the von Karman constant κ , which was reduced in high sediment concentration (Einstein and Chien, 1955). It also affected the particle fall velocity which was reduced as the sediment concentration increased. The effect is important in cases when the concentration is more than about 1000 mg/l (McNown and Lin, 1952). In the near-bed zone, and often in the upper part of the water column, this sediment concentration was exceeded during high river stages.

5 Conclusions

The majority of the suspended sediment transport in Bangladesh rivers are comprised of silt transport. Investigations show that their hydraulic behaviour is dependent on local flow conditions which indicates that their supply is also transport-capacity limited. Their high ratio of suspended sediment transport and their hydraulic behaviour suggest that they should be measured together with sand transport measurements. Unfortunately, most sediment transport predictors can not predict fine sediment transport. Therefore, engineers are often reluctant to accept this concept. However, the modified Einstein method (Colby and Hembree, 1955) can be used. This method, which uses some stream measurements, can provide both sand and silt transport. This issue, discussed briefly in this Annexure, needs further attention from future investigators working in Bangladesh rivers.

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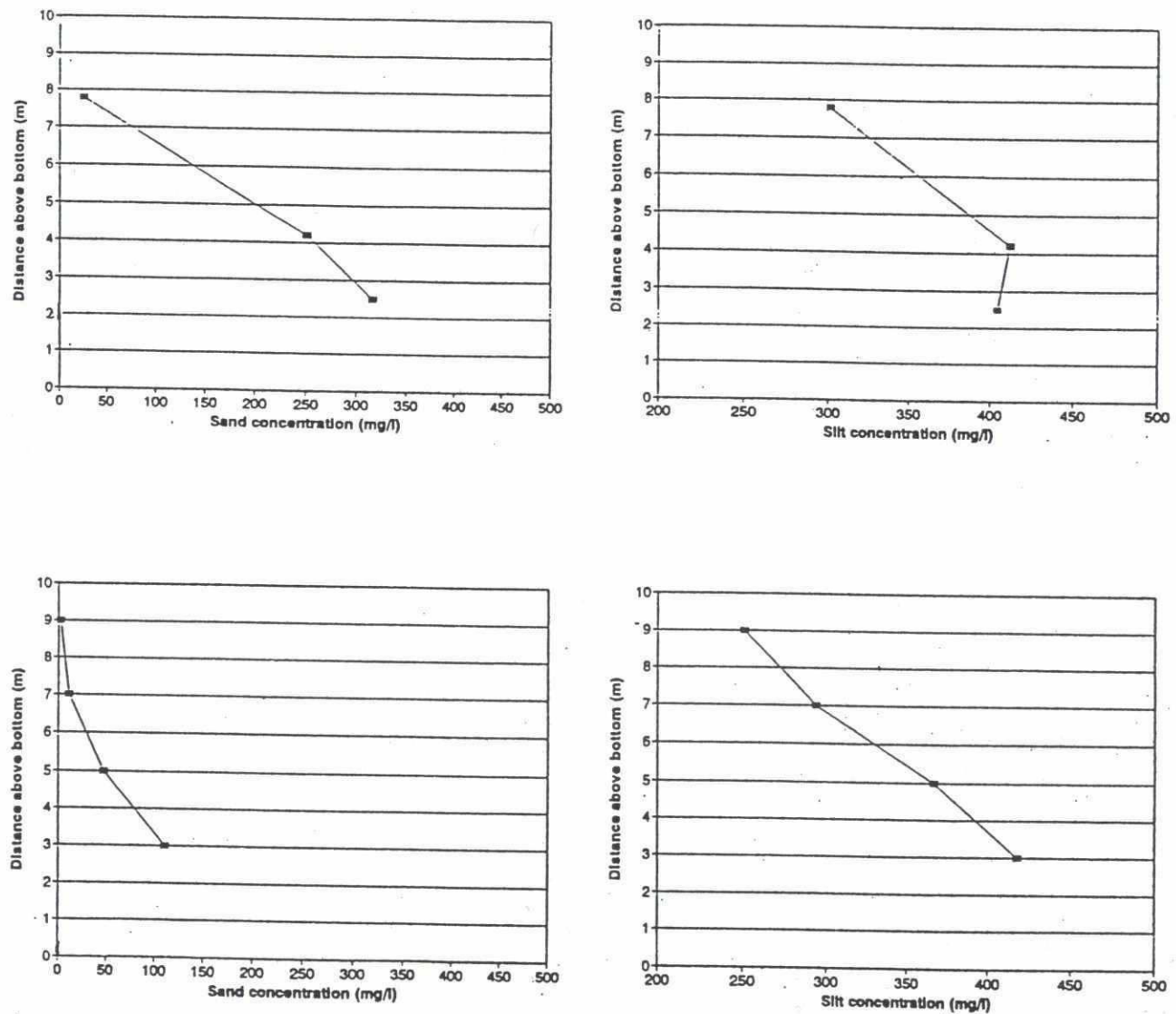


Figure E.1 Vertical profiles of sand and silt concentrations in the Jamuna River near Bahadurabad measured by FAP 24 point-integrated pump-samplers on 3-4 August 1994.

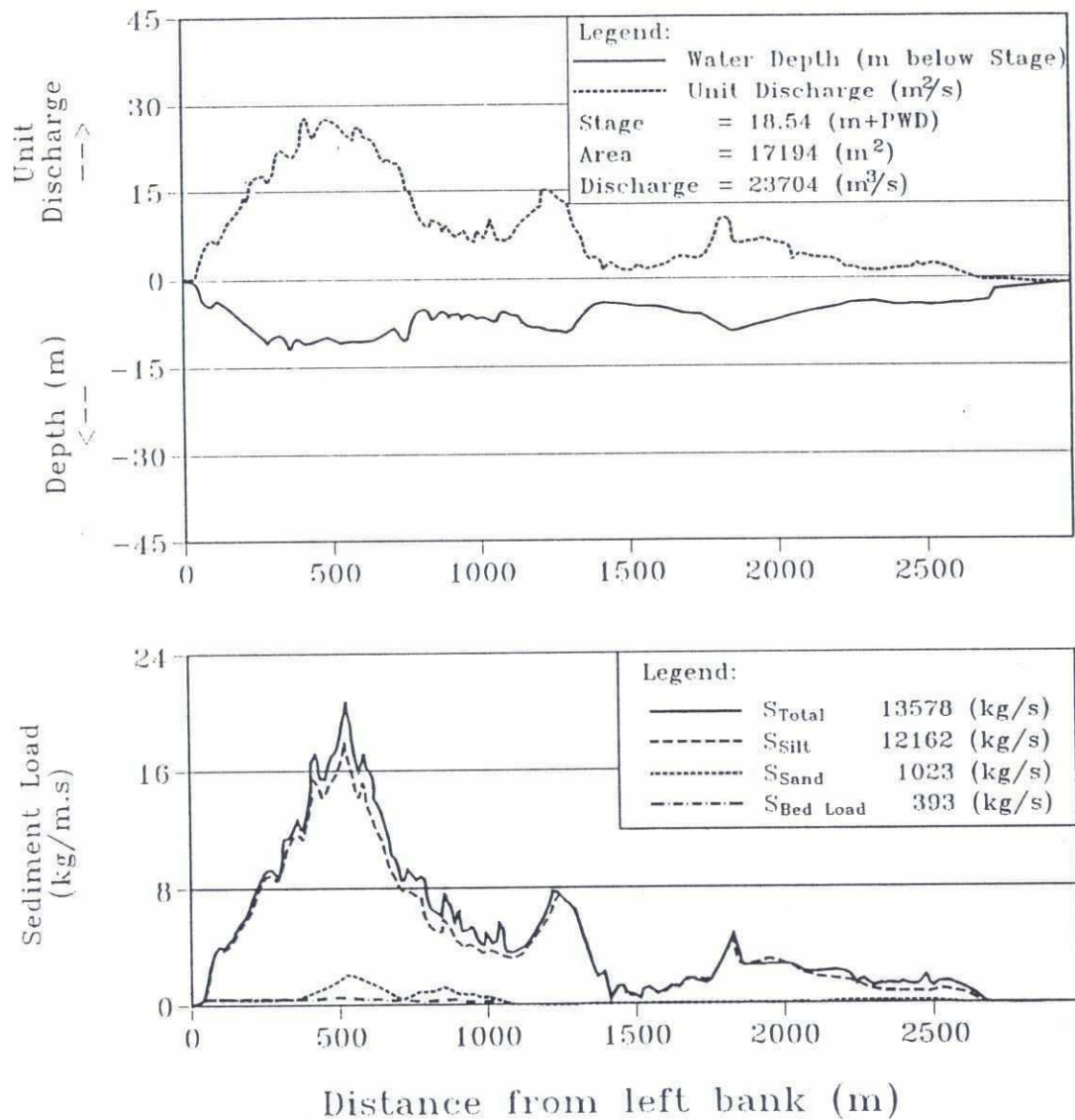


Figure E.2a

Over-the-width variation of unit discharge, sand and silt transport in the Jamuna River at Bahadurabad measured on 24-26 June 1994.

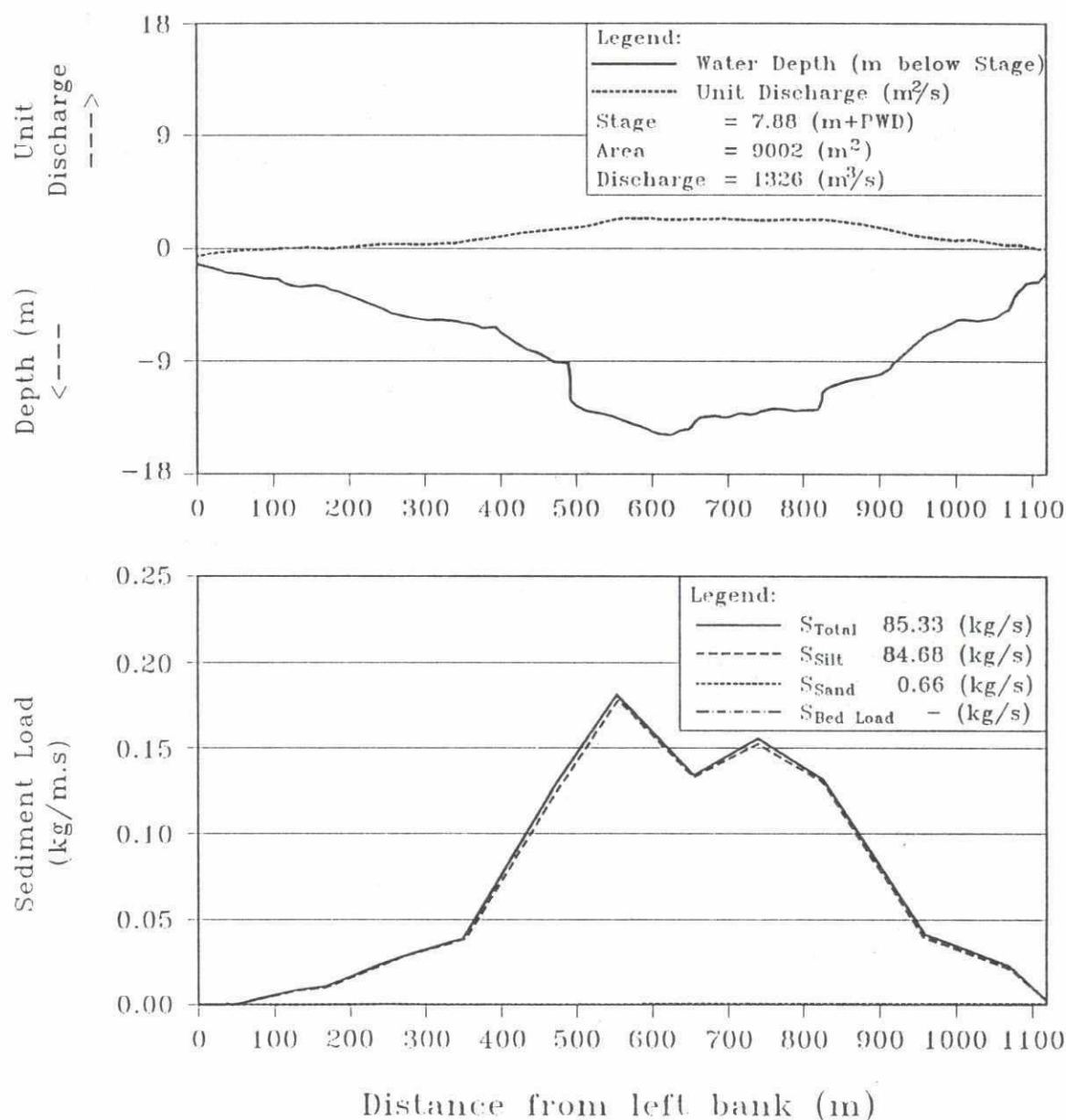


Figure E.2b Over-the-width variation of unit discharge, sand and silt transport in the Ganges River at Hardinge Bridge measured on 20-21 June 1994.

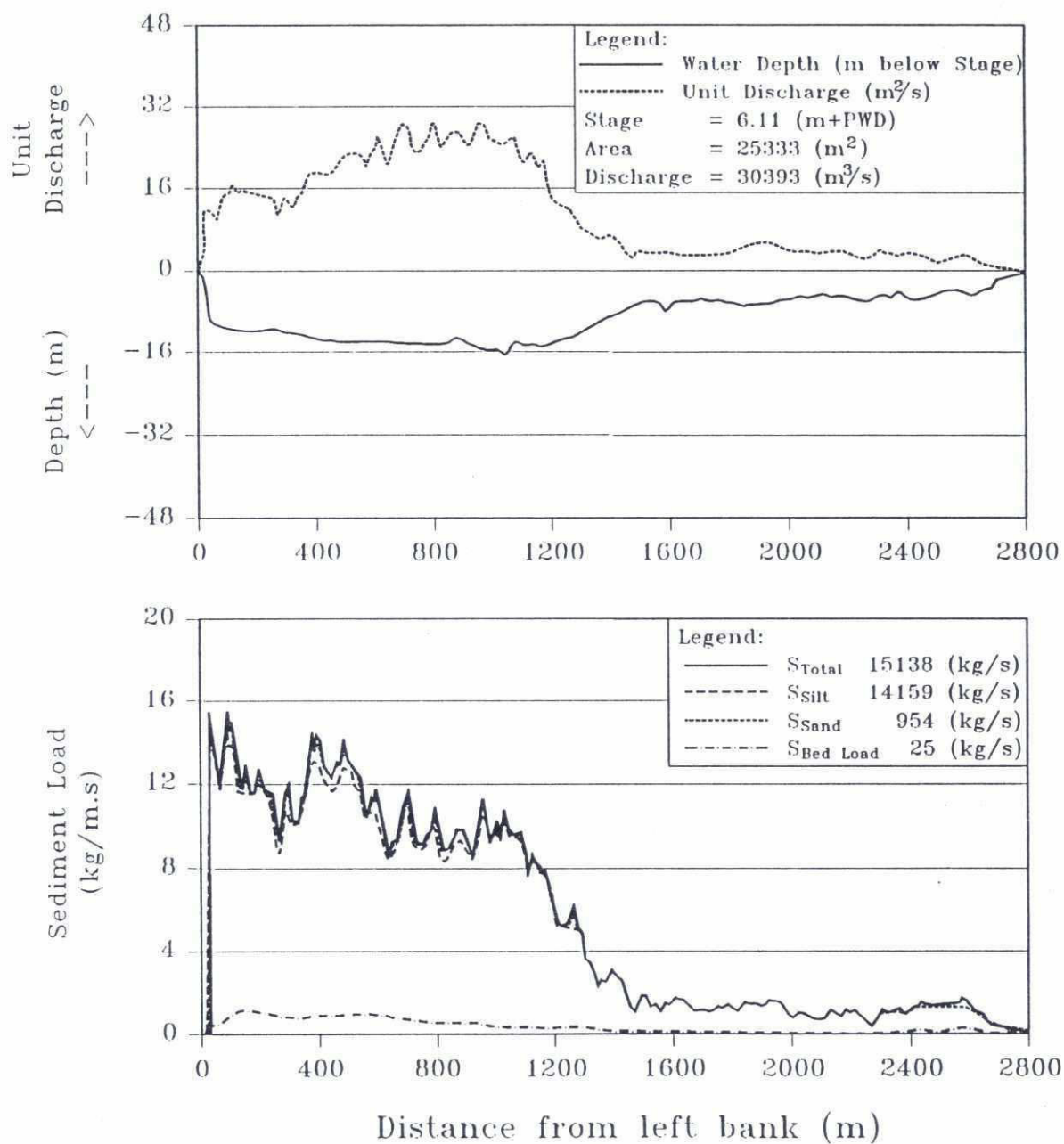


Figure E.2c Over-the-width variation of unit discharge, sand and silt transport in the Padma River at Baruria measured on 12-15 June 1994.

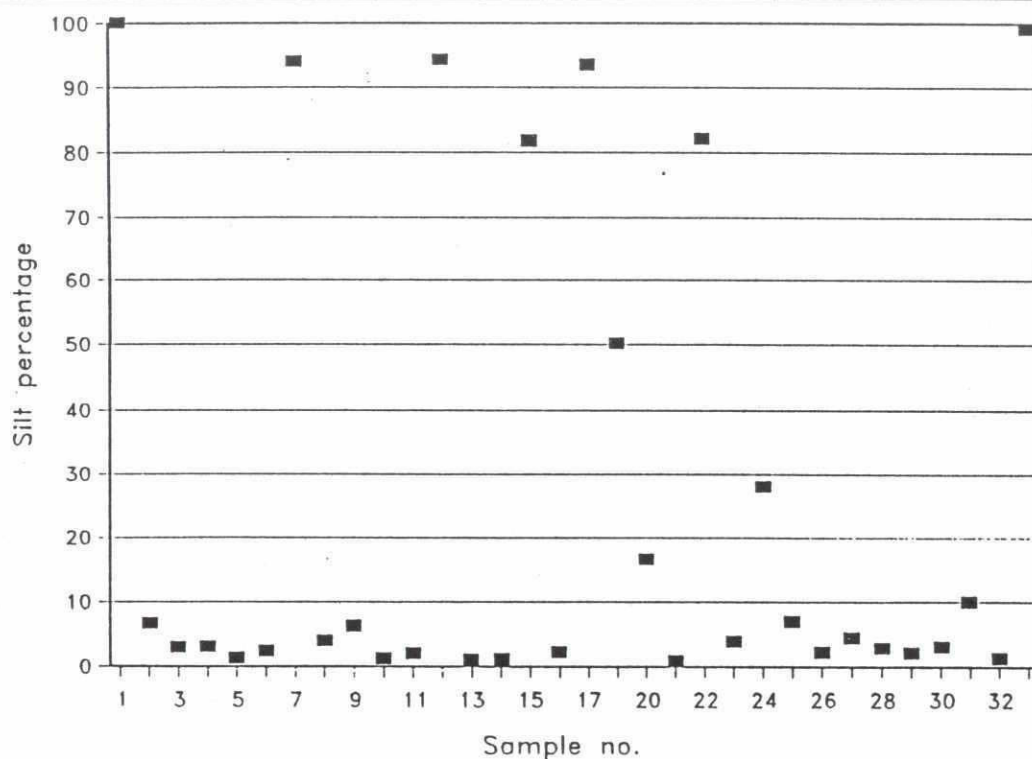


Figure E.3 Silt percentage of the Ganges River bed-materials collected using a US BM-54 scoop sampler by FAP 24 in August 1994.

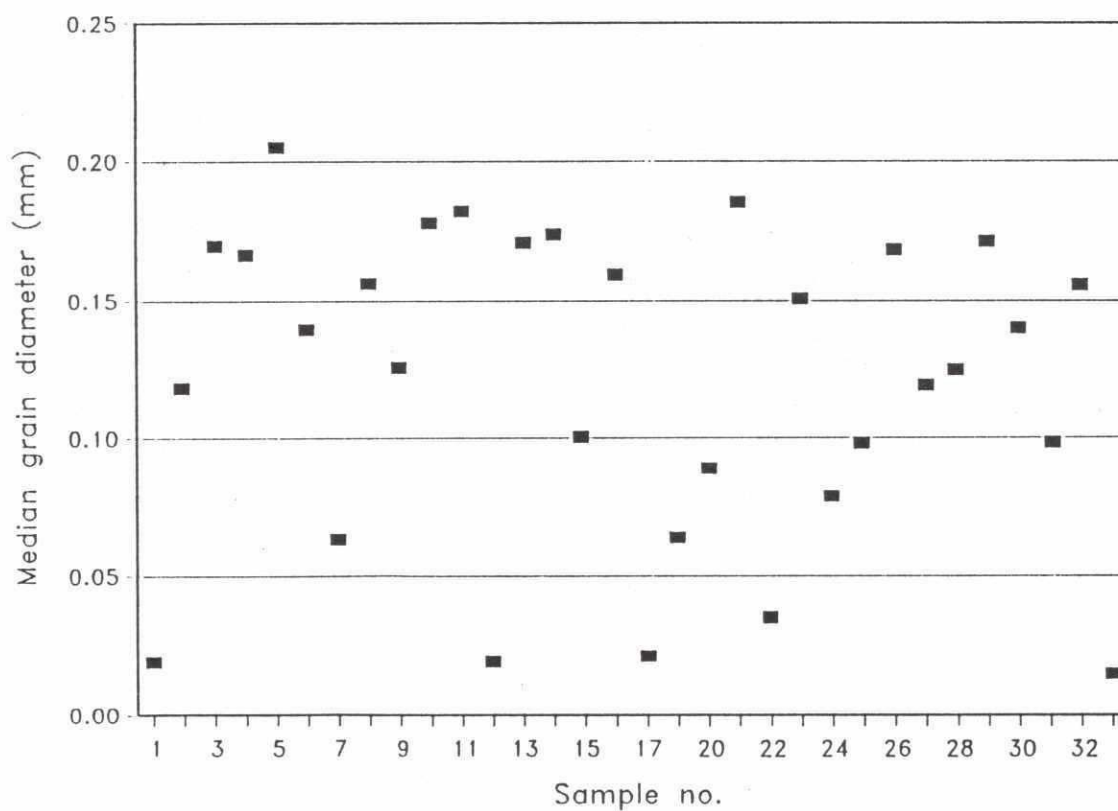


Figure E.4 The median grain sizes of the Ganges River bed-materials collected using a US BM-54 scoop sampler by FAP 24 in August 1994.

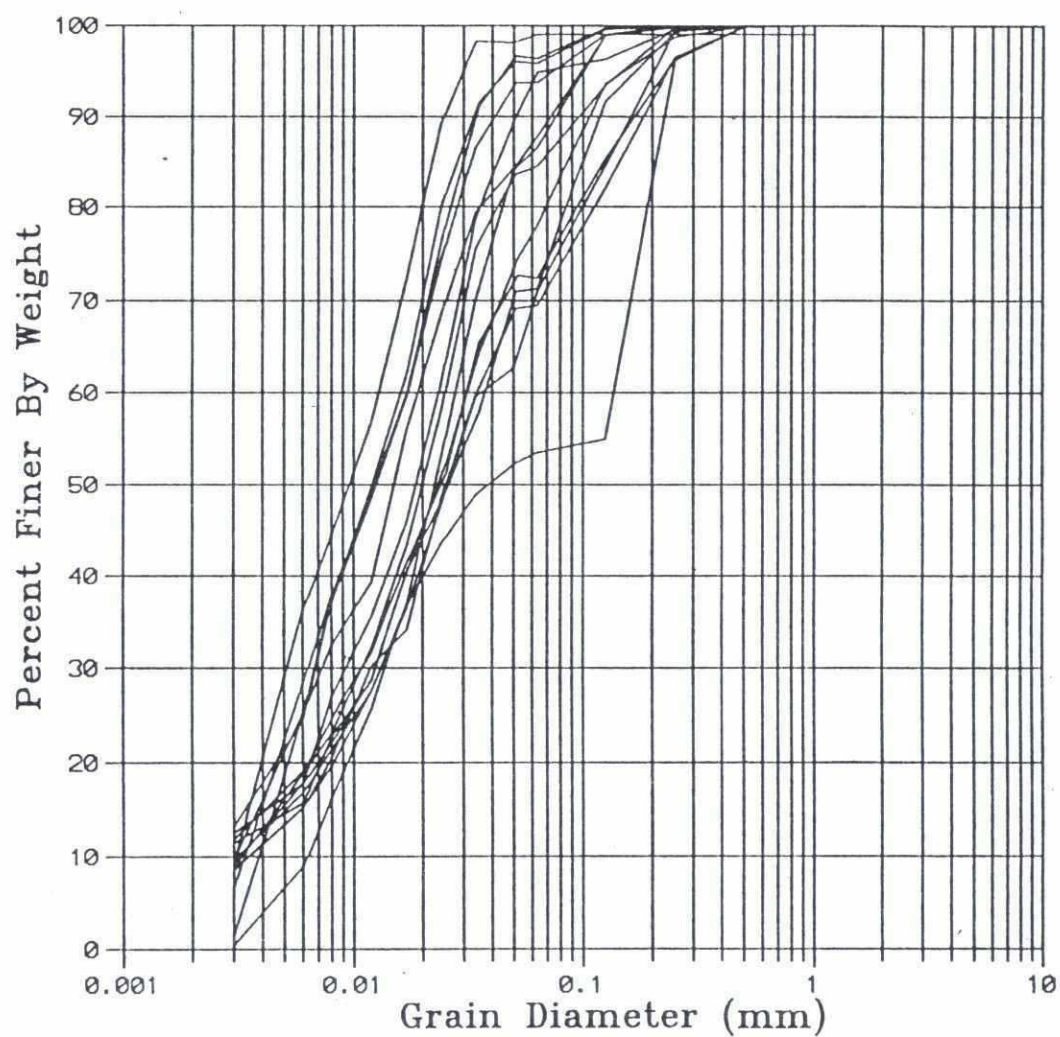


Figure E.5 Grain size distribution of 14 surface-water suspended sediment samples collected from the Jamuna River at Bahadurabad transect by FAP 24 in June 1993.

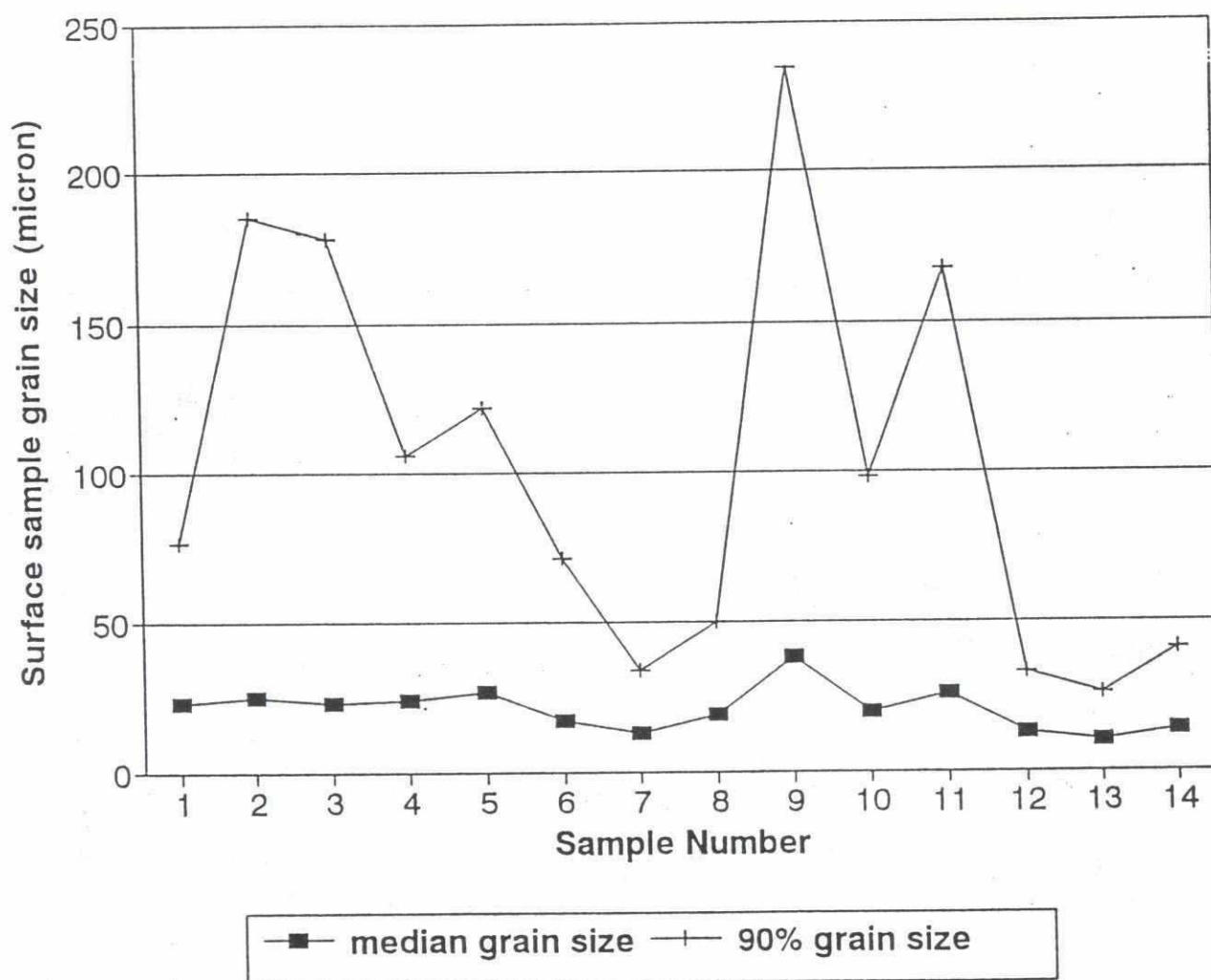


Figure E.6 Median and 90% grain sizes of 14 surface-water suspended sediment samples collected from the Jamuna River at Bahadurabad transect by FAP 24 in June 1993.

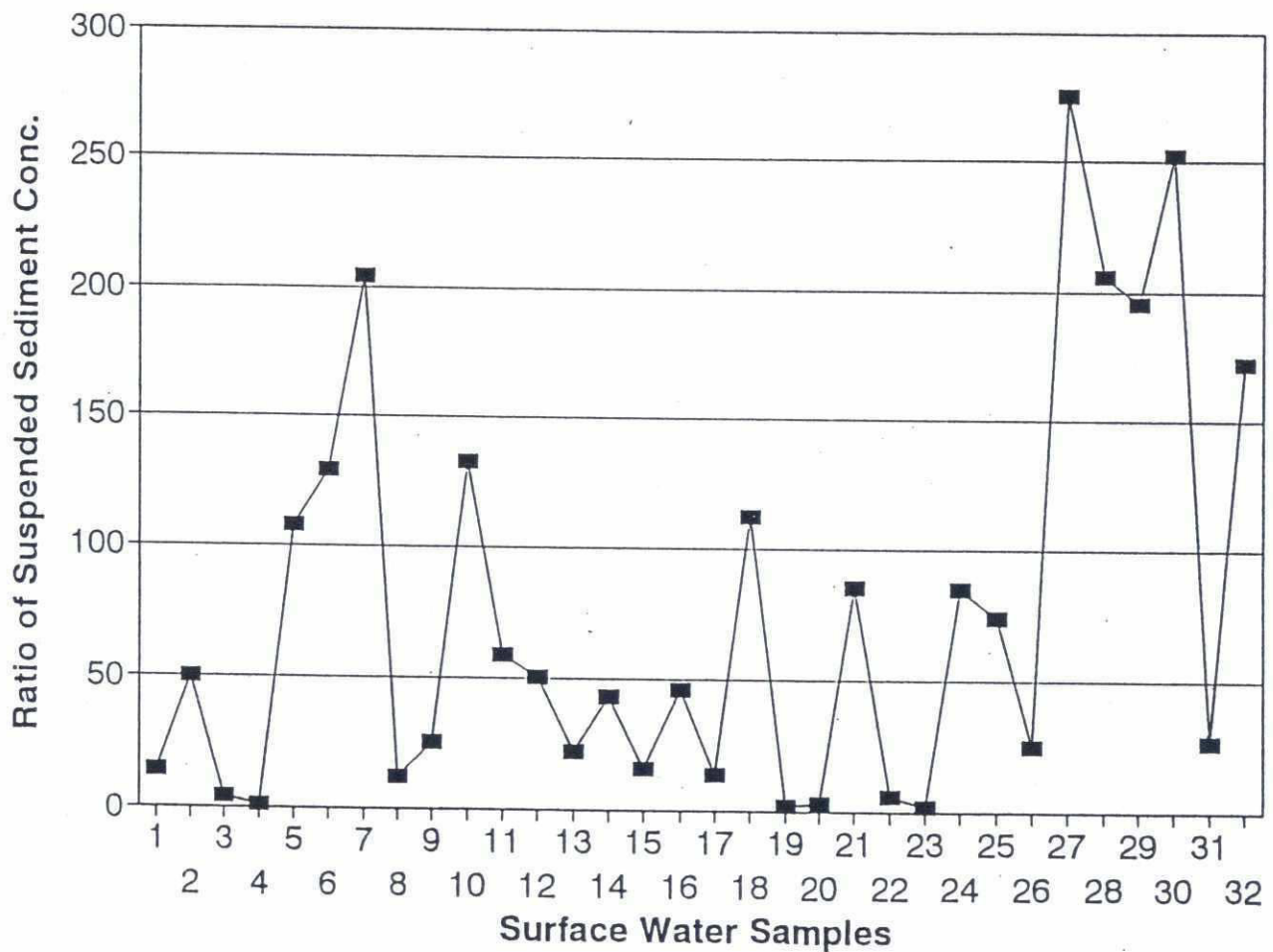


Figure E.7 Ratio of suspended sediment concentration (silt concentration/sand concentration) of the surface water samples collected from the floodplain near Tangail from August-September 1994 (courtesy, ISPAN, 1994).

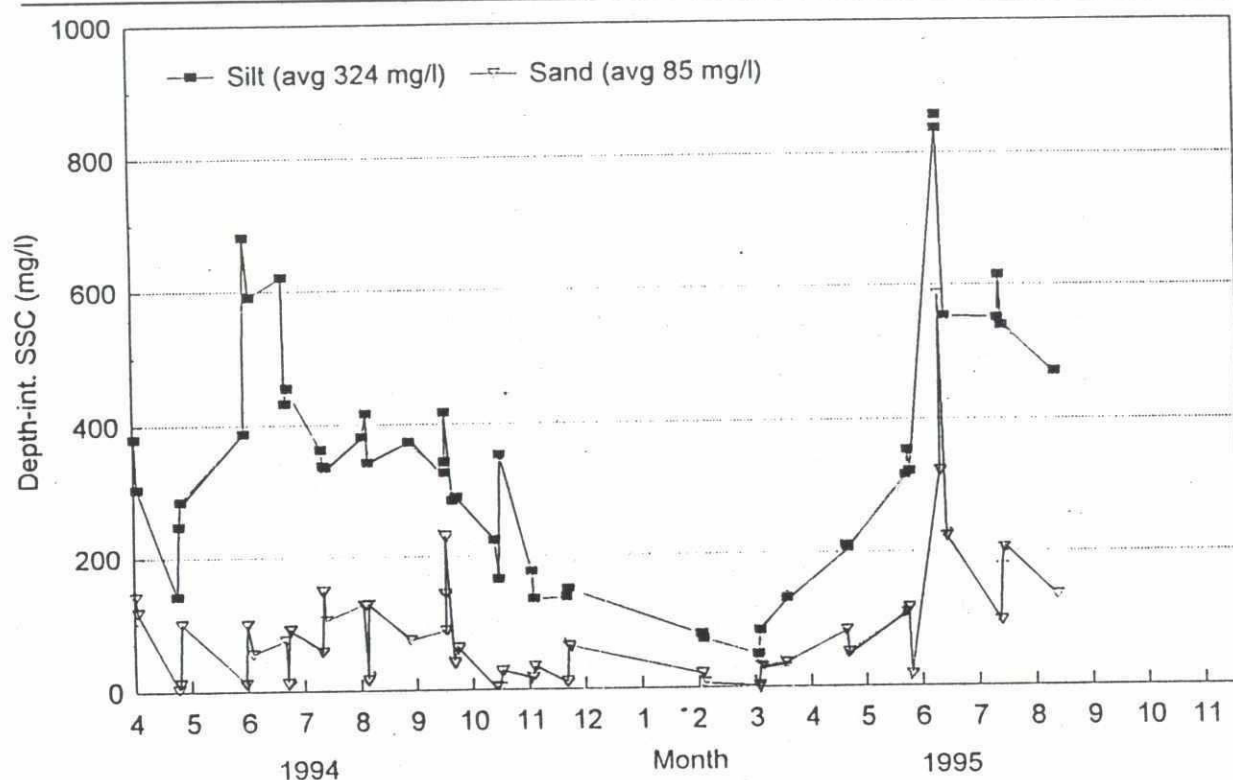


Figure E.8 Depth-integrated silt and sand concentration in 1994-95 in the reference verticals of the Jamuna River at Bahadurabad.

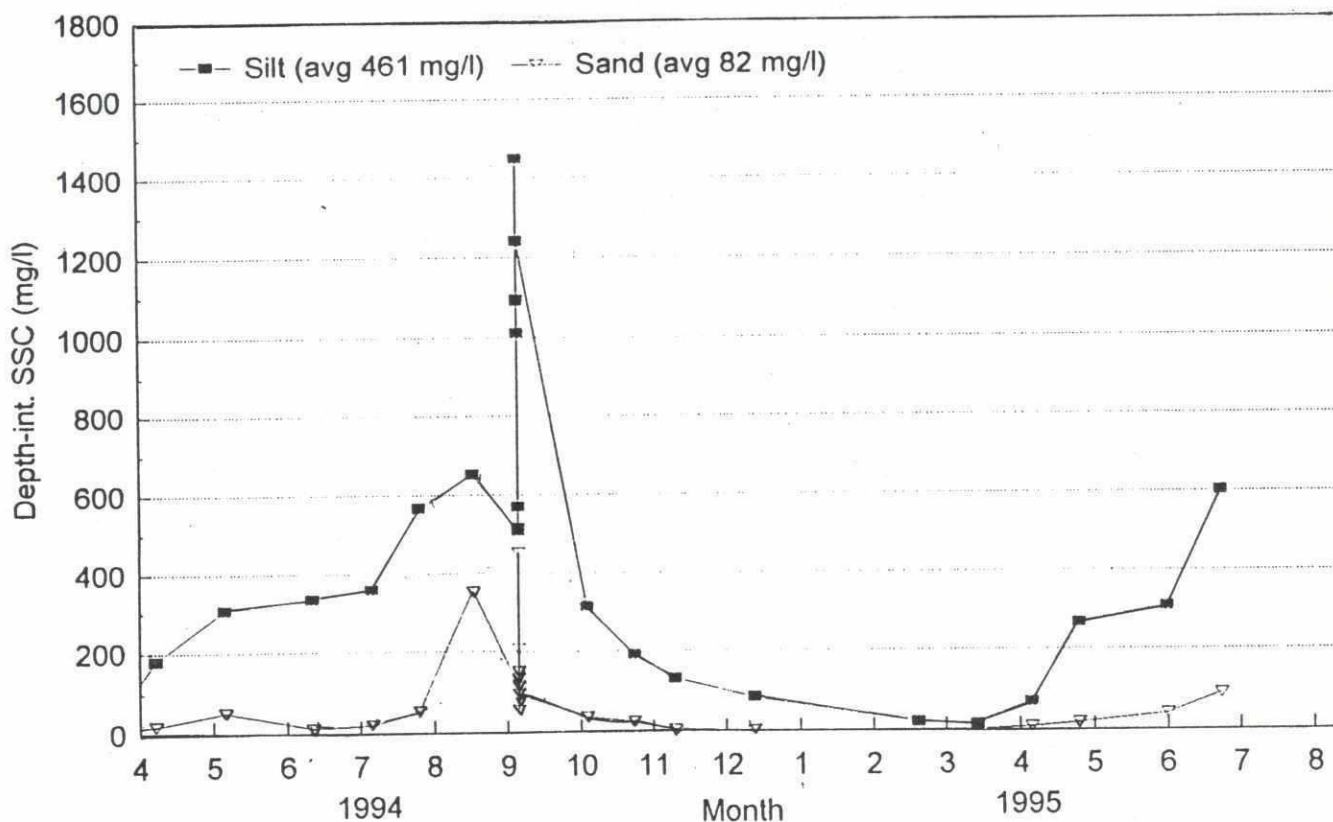


Figure E.9 Depth-integrated silt and sand concentration in 1994-95 in the reference verticals of the Padma River at Baruria.

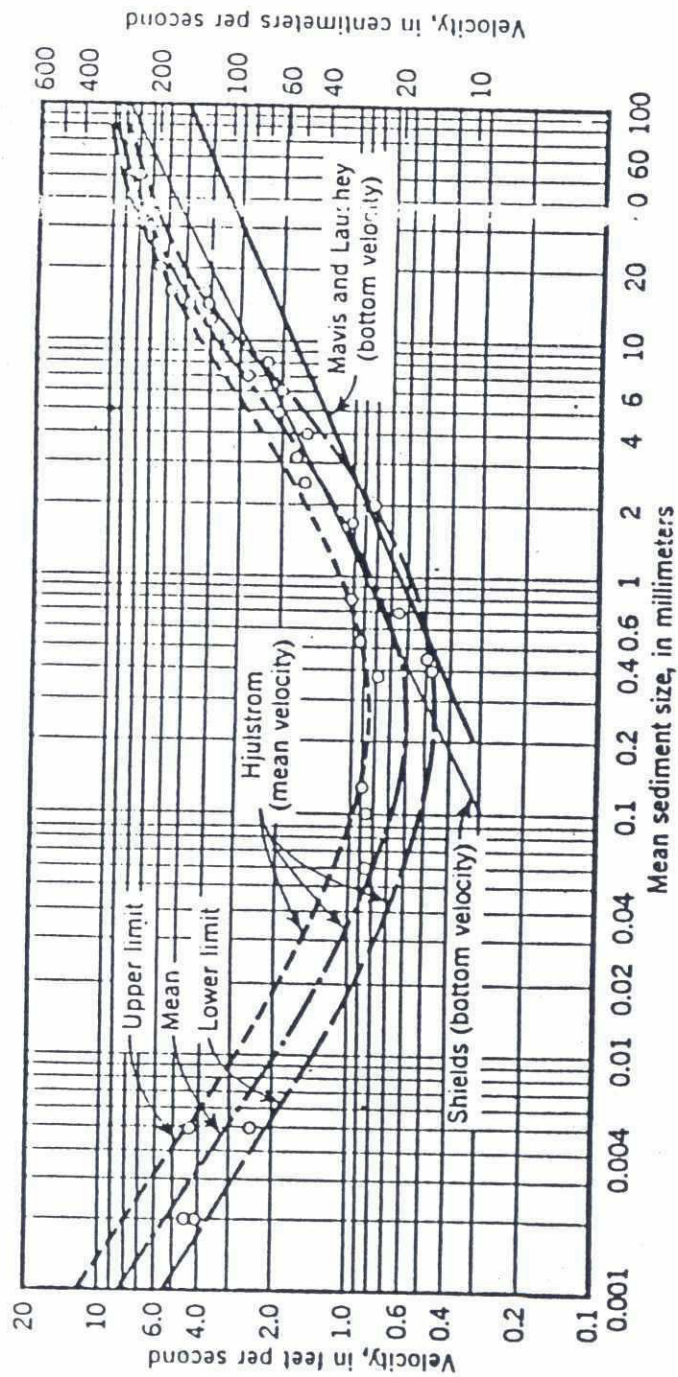


Figure E.10 Threshold velocity as a function of particle diameter according to Hjulstrom (1935).

Annexure F

**Bed-load transport based on 1993
dune-tracking in the Jamuna River
near Bahadurabad**

October 1996

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1 Introduction

Tracking of bed-forms consisting primarily of dune fields can be used to estimate bed load transport (Hubbel, 1964; Fredsoe 1979; van Rijn 1986). The principle is to make repeated sounding at a certain time interval by echosounder and/or by side scan sonar along a certain line. Superimposition of the sounding lines indicates the migration rate of the dunes. Estimation of bed load transport from such data involve computation of the volume of sand transported over the entire dune profile. This is necessary because transport over the bed-form is not same everywhere. It is highest at the crest and lowest at the trough. Engel and Lau (1980, 1981) proposed a simplistic method of estimating bed load transport assuming steady uniform flow.

$$q_b = \alpha_s (1-p) \rho_s v \Delta \quad (1)$$

in which:

q_b	=	bed load transport (kg/m/s)
α_s	=	shape factor (0.5 - 0.6)
p	=	porosity factor (~ 0.4)
ρ_s	=	density of sediment (used 2750 kg/m ³ in this Annexure)
v	=	average migration velocity of the dune (m/s)
Δ	=	average dune height (m)

In developing the above formula, they assumed that the dunes were triangular in shape. Fredsoe (1979) used both triangular and sinusoidal forms of dune for calculating the variation of shear stress along the dune and concluded that the triangular shape gave more accurate results. In the present study, the above principle was applied to estimate bed load transport in the Jamuna River near Bahadurabad based on dune-tracking data collected in June 1993.

Jamuna is a large anabranching braided river. The annual average discharge of the river at Bahadurabad is about 19,600 m³/s with a bankfull discharge of 44,000 m³/s. It is the most powerful stream in Bangladesh. Among the major rivers, the Jamuna River has the highest fluvial discharge, a steepest slope, a largest sediment transport and a highest sediment calibre (Barua, 1994). The river transports some 500 million tons of suspended sediment annually (CBJET, 1991). Examination of Simons and Richardson (1966) bed-form classification diagram indicates that in the Jamuna River, the bed-form disappear and becomes flat if the depth- averaged flow velocity exceeds 3 m/s. Investigations show that the dunes in the Jamuna River migrate faster than expected from any bed load transport formula (Halcrow, 1993). It is suggested that portion of the suspended sediment is deposited in the lee of the sand dune contributing its movement. Coleman (1969) reported the bed-form characteristics of the Jamuna River which are shown in Table F.1. This Annexure describes a dune-tracking exercise made in the Jamuna River near Bahadurabad in June 1993. A bed load transport estimate is made using the dune-tracking data.

Bed-forms	Ripples	Megaripples	Dunes	Sand Waves
height, H (m)	< 0.30	0.30 - 1.50	1.50 - 7.60	7.60 - 15.20
Length, L (m)	< 1.50	3.10 - 152.40	42.70 - 487.80	182.90 - 914.60
Ripple Index	< 1:5 - 1:20	1:6 - 1:100	1:30 - 1:60	1:25 - 1:100
Max. migration (m/day)	-	247.0	158.50	640.20
Average migration (m/day)	3.1	122.0	67.10	204.30

Table F.1 : Bed-forms in the Jamuna River as reported by Coleman (1969)

2 1993 Dune-tracking in the Jamuna

A bathymetric survey was made in the left channel of the Jamuna River near Bahadurabad on June 27 and 28, 1993. The surveys were carried out with the DHA vessel of RSP and the lines were covered as far as the draft of the vessel permitted. The reference line (SOL 468750 E, 786200 N and EOL 468620 E, 786682 N) is the western border of the test area which was surveyed with parallel lines to the east with a line spacing of 50 m. A total of 11 lines were surveyed (the reference line and 10 offset lines) thereby covering an area of 500 x 500 m. The survey area is shown in Figure F.1. During the measurements, it was observed that the side scan sonar did not perform well in the sediment laden water. Therefore, the survey was done by running an echo sounder (Elac Laz 4420). The water-level hydrograph for the period 1993-94 is shown in Figure F.2. The water-level during the measurements was about 18.5 m+PWD. For the computation of bed load, dune-tracking data of lines 3, 4 and lines 8, 9 were utilized for June 27 and 28 respectively. The other lines could not be used because the sounding time interval was not long enough to distinguish the migrated dunes. In addition, the positioning of these lines were also uncertain.

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3 Data analysis and results

To apply Eq. (1), the migration velocity and the bed-form height must be determined from the bed profiles. Dune-tracking data of lines 3 and 4 were used from among the 11 lines measured in June 27. Superimposition of the lines 3 and 4 were made as shown in Figure F.3 to identify the movement of the dunes. By visual scanning of the graphs, each of the identified dunes were marked by A, B, C and D and the movement of the same dune peaks as A', B', C' and D' respectively. Tables F.2 and F.3 show the dimensions of the dune, time-interval and distance.

Dune ID	H_f (m)	H_r (m)	H (m)	X_1 (m)	t_1 (hrs)	Dune ID	H_f' (m)	H_r' (m)	H' (m)	X_1' (m)	t_1' (hrs)
A	2.53	2.43	2.48	87.90	15.53	A'	2.47	2.70	2.59	96.40	17.32
B	2.60	2.60	2.60	145.30	15.54	B'	2.70	2.53	2.62	170.80	17.34
C	3.46	3.07	3.27	192.90	15.55	C'	3.43	2.47	2.95	236.70	17.35
D	2.53	2.83	2.68	236.20	15.56	D'	2.13	1.23	1.68	265.60	17.36

Table F.2: Dune dimensions before and after the peak movement (June 27, 1993)

Dune ID	Δ ($H + H'$)/2 (m)	dX ($X_1' - X_1$) (m)	dt ($t_1' - t_1$) (hrs)	dt (s)	v (X/t) (m/s)
A-A'	2.54	8.50	1.79	6444	0.00132
B-B'	2.61	25.50	1.80	6480	0.00394
C-C'	3.11	43.80	1.80	6480	0.00676
D-D'	2.18	29.40	1.80	6480	0.00454

Table F.3: Average dune dimensions, elapsed time and migration velocity (June 27, 1993)

in which:

H_f	=	height of crest from forward toe (m)
H_r	=	height of crest from rear toe (m)
H, H'	=	average height of crest (m)
X_1	=	position of the dune crest before the movement (m)
X_1'	=	position of the dune crest after the movement (m)
t_1	=	time before the crest movement (hrs)
t_1'	=	time after the crest movement (hrs)

Δ	=	average dune height (m)
dX	=	distance traversed by dune peak (m)
dt	=	time elapsed during dune peak movement (s)
v	=	average migration of the dune

Similar analyses were made with the data of lines 8 and 9 measured on 28 June 1993 as shown in Figure F.4. In this Figure, six dune peaks are identified by A, B, C, D, E and F before the movement and the same dune peaks as A', B', C', D', E and F' after the movement respectively. Tables F.4 and F.5 show the dimensions of the dune, elapsed time and distance.

Dune ID	H_f (m)	H_r (m)	H (m)	X_1 (m)	t_1 (hrs)	Dune ID	H_f' (m)	H_r' (m)	H' (m)	X_1' (m)	t_1' (hrs)
A	3.56	3.61	3.59	97.60	15.02	A'	2.52	3.71	3.12	98.50	15.53
B	2.00	3.09	2.55	155.80	15.03	B'	1.57	1.90	1.74	161.00	15.54
C	3.42	2.66	3.04	230.90	15.05	C'	2.95	2.28	2.62	238.60	15.55
D	1.90	1.76	1.83	281.70	15.05	D'	1.81	1.43	1.62	284.90	15.56
E	2.99	3.04	3.02	445.70	15.09	E'	2.95	2.95	2.95	446.40	15.60
F	2.33	3.04	2.69	491.40	15.10	F'	1.85	2.95	2.40	494.60	15.61

Table F.4: Dune dimensions before and after the peak movement (June 28, 1993)

Dune ID	Δ ($(H+H')/2$) (m)	dX ($(X_1'-X_1)$) (m)	dt ($(t_1'-t_1)$) (hrs)	dt (s)	v (X/t) (m/s)
A-A'	3.36	0.90	0.51	1836	0.00049
B-B'	2.15	5.20	0.51	1836	0.00283
C-C'	2.83	7.70	0.50	1800	0.00428
D-D'	1.73	3.20	0.51	1836	0.00174
E-E'	2.99	0.70	0.51	1836	0.00038
F-F'	2.55	3.20	0.51	1836	0.00174

Table F.5: Average dune dimensions, elapsed time and migration velocity (June 28, 1993)

The bed load transport is estimated by Eq.(1), utilizing the data given in Tables F.3 and F.5 considering an average shape factor of 0.55 (applicable for triangular shaped dune discussed earlier) and a sediment density of 2750 kg/m^3 . This density appears to be a reasonable average value for the major rivers in Bangladesh (RSP, 1996). Note that the usually used density is 2650 kg/m^3 for quartz grains. The reason for higher density is attributed to the presence of heavy minerals in significant proportions. Table F.6 provides the bed load transport estimates.

Date	Dune ID	bed load transport, q_b (kg/m/s)
27 June 1993	A	3.03
	B	9.32
	C	19.08
	D	8.98
28 June 1993	A	1.49
	B	5.53
	C	10.98
	D	2.74
	E	1.03
	F	4.03

Table F.6: Bed load transport from dune tracking data measured in 27-28 June 1993

Date	Dune ID	Height, Δ (m)	Length, L (m)	Ripple Index (H/L) (-)	Migration Rate (m/day)
27.06.93	A	2.54	53.9	1:21	114
	B	2.61	36.7	1:14	340
	C	3.11	31.3	1:10	584
	D	2.18	20.3	1:9	392
28.06.93	A	3.36	84.4	1:25	42
	B	2.15	27.3	1:13	245
	C	2.83	66.4	1:24	370
	D	1.73	33.6	1:19	151
	E	2.99	43.8	1:15	33
	F	2.55	41.4	1:16	151

Table F.7 : Bed-forms characteristics as obtained from the present analysis

4 Discussion and conclusions

Further refinement of Table F.3 and F.5 were made to indicate some parameters for comparison with Coleman (1969). They are shown in Table F.7. The heights of the bed-forms obtained from the present analysis varied between 1.73 and 3.36 m and are comparable with dune height (Table reported F.1) by Coleman (1969). The length of the bed-forms varied between 20.3 m and 84.4 m. The ripple index were found to vary between 1:9 and 1:25. The maximum migration rate was 584 m/day with an average of 242.2 m/day. Comparison of these parameters with Table F.1 indicates that except the dune migration rates other parameters are comparable. The dune migration rates from the survey area are much higher than the rates reported by Coleman (1969).

The bed load transport obtained from dune-tracking shows a maximum of 19.08 kg/m/s and a minimum of 1.03 kg/m/s with an average of 6.62 kg/m/s (Table F.6). There have been no systematic measurements to compare the bed load transport from the dune-tracking data. Instead we used some routine measurements data of June 6 and some measurements in the near-by area on June 30 and 1 July. All these bed load measurements were made by a Helley-Smith trap sampler. The routine measurements were made at 11 verticals as shown in Figure F.5. The transports varied between 0.0004 and 0.719 kg/m/s which are much less than the bed load transport measured by dune-tracking (see Table F.6). The measurements made in the near-by area are presented in Table F.8. Here the situation is slightly better and the transport varied from 0.35 to 1.02 kg/m/s. But again the difference with the dune-tracking results are large. One obvious reason for the difference

is that the comparative Helley-Smith measurements represented different time and space. But the systematic large transport by dune-tracking can not be explained by this argument. Other possible explanations are:

- Systematic bias of the Helley-Smith sampler, representing primarily particles greater than $250 \mu\text{m}$. Since particles less than this size is dominant in the Jamuna River, the Helley-Smith sampler is certain to underestimate the bed load transport.
- Secondly, as discussed previously, earlier measurements reached the similar conclusions and suggested that suspended sediment contributes to the dune migration rate. Indeed the observations in the Zaire River (Peters and Goldberg, 1989) indicated the existence of near-bed sediment layer contributing to the river-bed morphology. For similar observations see also other Annexures of this report.

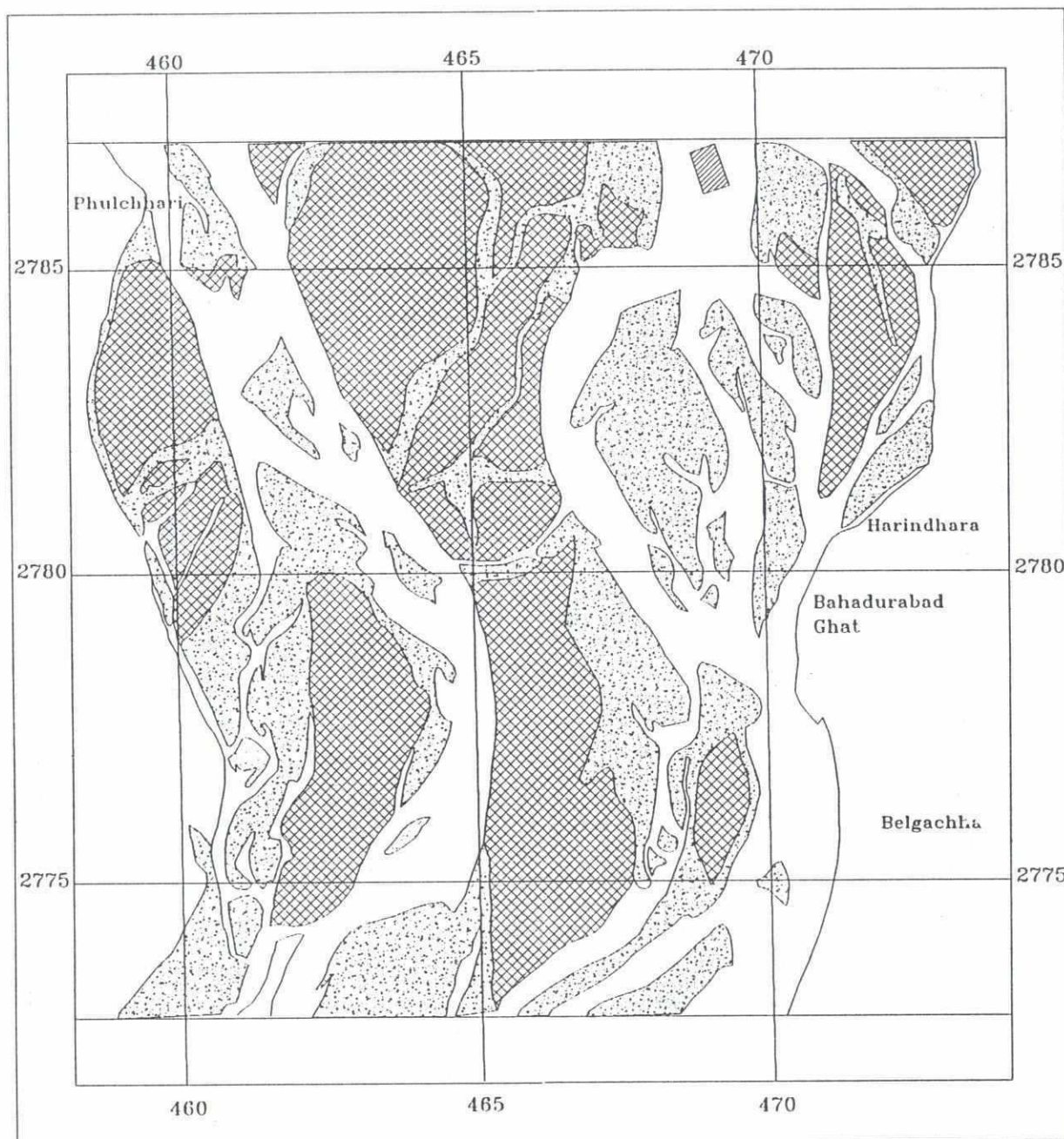
The exercise shows that dune-tracking can not probably be used for estimating bed-load transport on a routine basis. Dune-tracking in fine sand-bed river such as the Jamuna probably represents near-bed transport.

Date	Sample No.	bed load transport, q_b (kg/m/s)
30.06.93	75	0.68
	76	0.40
	77	0.35
	79	0.84
	80	0.71
	89	1.02
01.07.93	91	0.31
	92	0.51
	93	0.43
	96	0.59
	97	0.35
	98	0.48

Table F.8: Bed load transport measured by the Helley-Smith sampler during the survey period

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LEGEND:

-  Covered area by dune tracking
-  High land
-  Low char

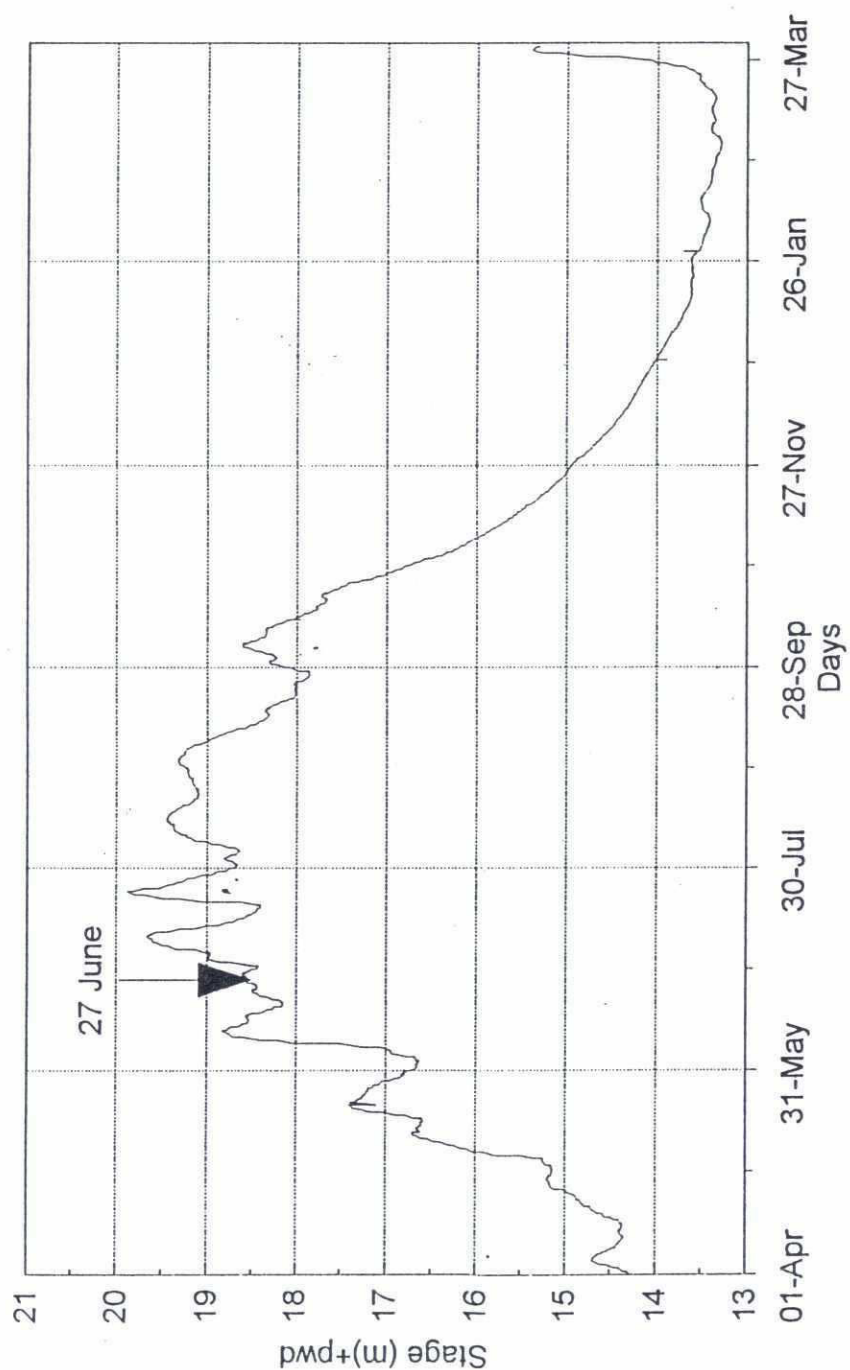


5000m 2500m 0

Map based on satellite
images of March 1993

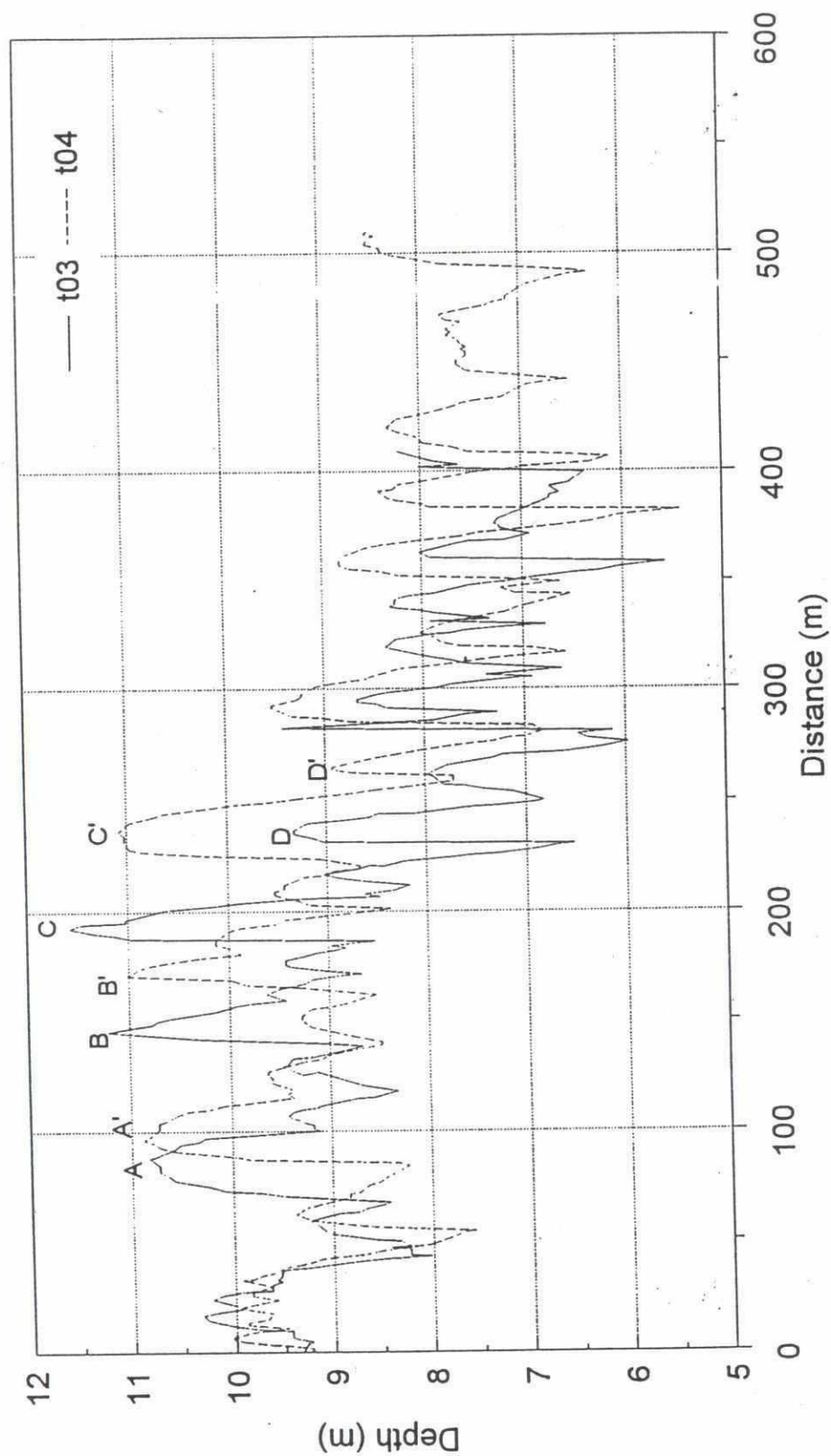
F.1: The location map of the survey area

Jamuna River, Bahadurabad 1993-94



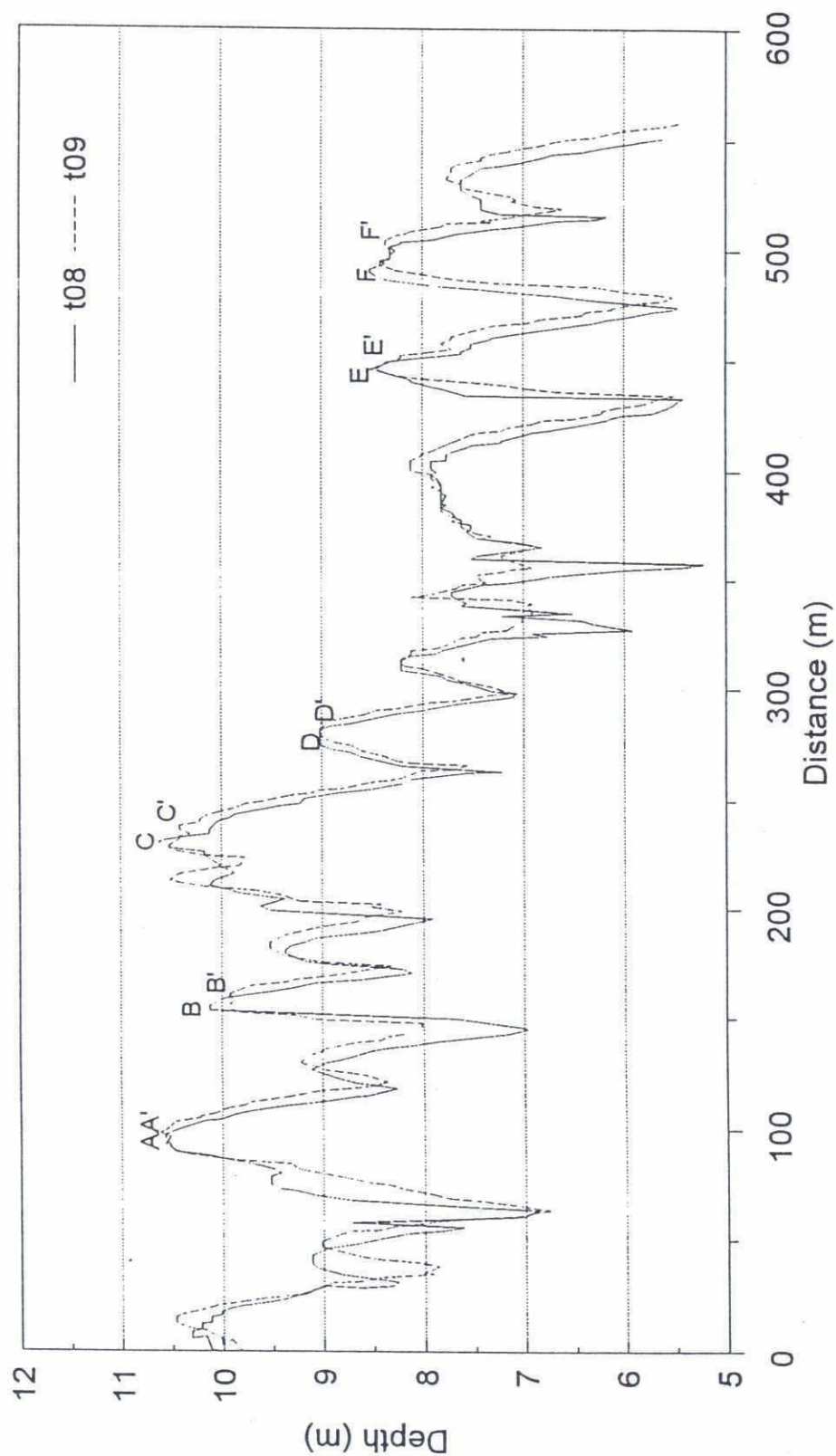
F.2: The water-level hydrograph for the period 1993-94 at Bahadurabad

Jamuna River, Bahadurabad
27 June 1993



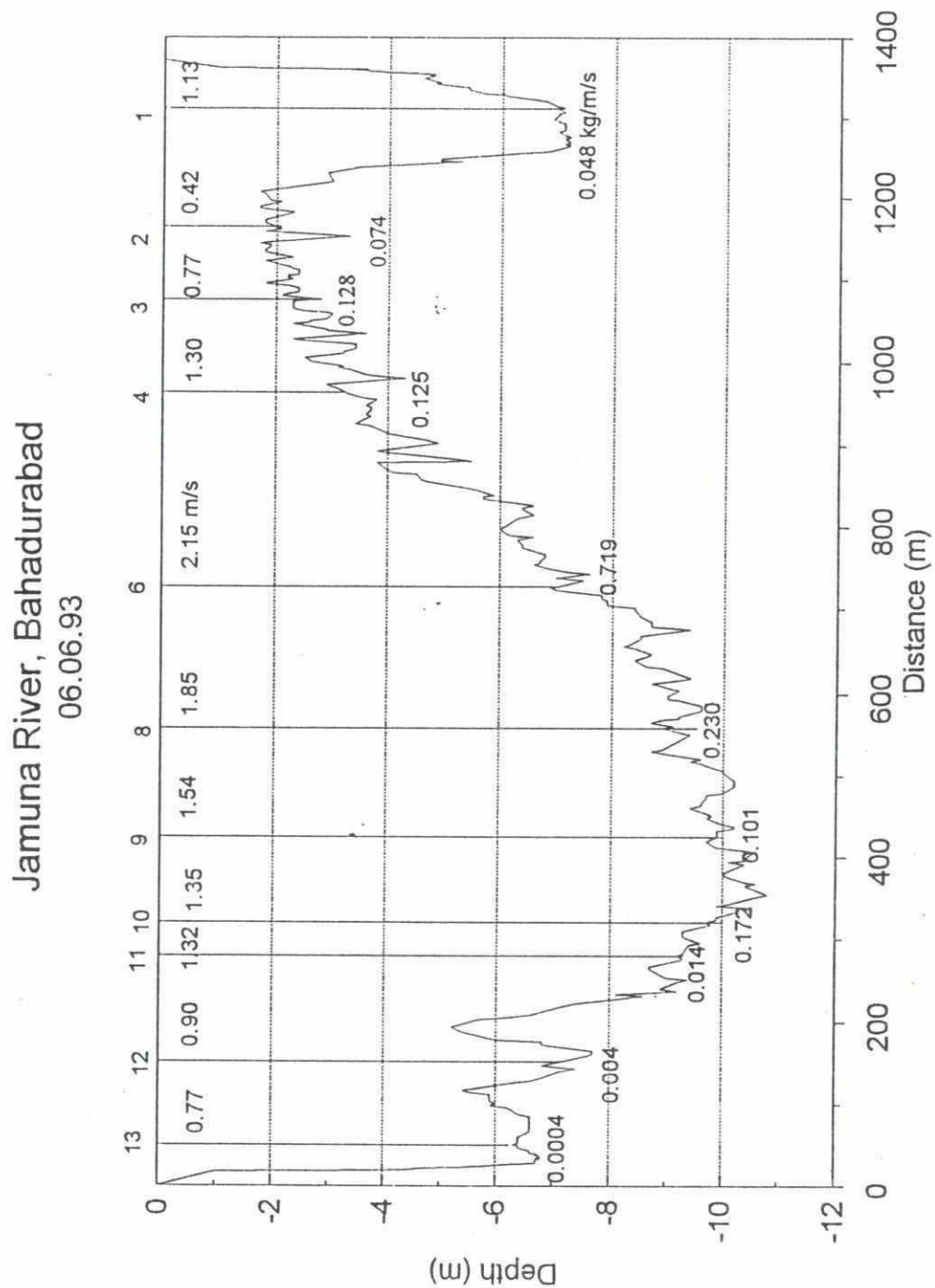
F.3: Superimposition of the lines 3 and 4 surveyed in June 27, 1993

Jamuna River, Bahadurabad
28 June 1993



F.4: Superimposition of the lines 8 and 9 surveyed in June 28, 1993

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F.5: Cross-section showing bed load transport and depth-averaged velocity

Annexure G1

Overview of study surveys for near-bed sediment transport measurements

1 Overview of study surveys

A programme of river studies was undertaken to investigate key characteristics of the behaviour of the river systems. The study programme for phase 1 of the project was concentrated on the collection of existing data and a preliminary assessment of the morphological characteristics of the rivers, their shifting characteristics and expected response as different components of FAP are implemented. The Study programme for phase 2 of the project (RSP, February 1995) covered many aspects of the river system and it included the topic Measuring techniques. And for that topic a series of study surveys were done. The main aspects are the optimization of sediment transport measurements and to describe the phenomena of sediment transport in large alluvial rivers.

Some characteristics of this series of surveys are summarized in Table G1.1. The measurement programme and the results of these surveys are presented in the annexure G2 to G8. The main points are the selected locations for the surveys and the hydraulic conditions during the surveys and the type of measurements.

Selected locations:

The surveys for the optimization of sediment transport measurements were done in different locations to describe phenomena such as sediment plume, sediment transport above a dune and sediment transport above a flat bed. In the series of surveys, no measurements were done on the sediment transport over an eroding steep submerged slope in a channel, also not near an eroding bank or in a deep scour hole.

All the surveys were carried out in the left channel of the Jamuna River near Bahadurabad.

Selected hydraulic conditions

The series of study surveys were aiming at covering a wide range of hydraulic conditions. The water depth in these surveys varied from 6 to 14 m. The sediment transport measurements in water depth less than 6 m will be influenced by the DHA survey vessel (draught of that vessel is about 1.5 m). Water depths more than 14 m are often found in special locations, such as scour holes.

The flow velocities in the surveys varied from 0.7 to 2.5 m/s. If the flow velocity is less than 0.7 m/s than the sediment transport will be very small, close to the initiation of motion of the coarse sediment particles. Flow velocities more than 2.5 m/s occur only during peak flows.

Type of measurements

In these surveys different types of measurements were carried out:

- sediment transport measurements or sediment concentration measurements with different instruments,
- repeated measurements with an instrument.

In addition, measurements of bedforms, water depth, hydraulic conditions were made for the analysis of the sediment transport measurements.

In addition to this series of study surveys the sediment transport measurements in the routine gaugings were analyzed. The results of that analysis are not presented in this series of annexure. Furthermore in this series the main attention is given to the near-bed measurements and the suspended sediment transport measurements higher in the vertical are only presented in relation to the near-bed measurements.

Annexure	Period	Description	h (m)	u (m/s)
G2	28-29 May 1994	Testing of Delft Bottle near sand arrow	7 to 11	1.0 to 1.3
G3	1-4 August 1994	Near-bed measurements on a dune	9 to 13	1.5 to 2.0
G4	4-12 December 1994	Measurements in a channel, low flow	5 to 10	0.1 to 1.1
G5	1-4 April 1995	Measurements in a channel, transition of 2d to 3d dunes, low flow	6 to 8	0.7 to 0.9
G6	27-30 May 1995	Near-bed sediment transport measurements in a channel, medium flow	10 to 14	1.6 to 1.9
G7	23-26 May 1995	Sediment plume survey	7 to 14	1.5 to 2.5
G8	26-30 July 1995	On optimization of density of points in a cross-section, medium flow	8 to 12	1.8 to 2.8

Table G1.1: Overview of the different study surveys with near-bed sediment transport measurements

Annexure G2**Delft Bottle survey, May 1994**

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G2.4: Sediment transport and D50 in vertical 1
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1 Introduction

The optimization of sediment transport measurements is part of study topic 9, Measuring techniques (RSP, Study Programme, February 1995). In this survey the Delft Bottle sampler was tested for the first time in the Jamuna River to measure the near-bed sediment transport. This sampler was suggested by the Project Advisor (Peters, 1994). The measurements by the Delft Bottle sampler were compared with the measurements by Helley-Smith sampler and pump-bottle sampler. This survey was performed in the pre-monsoon when the flow velocities and the sediment transport intensity were rather low.

The programme of the measurements in this survey is described in Chapter 2. Some results, especially the catches by the Delft Bottle sampler, are presented in chapter 3. The analysis of these results directed to some conclusions in Chapter 4.

2 Measurements

The bed load measurements were made at four locations south of Bahadurabad with a flat bed without river dunes at 28 and 29 May 1994. The water depth in those locations varied between 5.6 m and 10.5 m. These four verticals are located on a line almost perpendicular to the channel alignment, which is rather straight upstream of these locations, see the bathymetric map surveyed in November 1993, Figures G2.1 and G2.2. The water levels were measured in Bahadurabad station. The flow velocities in the vertical at these locations were measured with the ADCP.

The Delft Bottle samples were taken at about 0.085, 0.18, 0.28, 0.38 and 0.48 m above the bed. The Helley-Smith samples were taken over a height from 0 to 0.076 m above the bed. The pump-bottle samples and the Delft Bottle samples were taken at 0.2, 0.6 and 0.8 of the local water depth, if the height are measured from the water surface. Samples of the bed material were taken in each of those four locations.

3 Analysis

The analysis of the measurements includes an analysis of the local water depths, the sediment size and the sediment transport.

3.1 Local water depths

The local water depths in those four locations were compared with the bathymetric map. In that map the depths are presented relative to Standard Low Water which is 12.03 m + PWD. The water levels measured in Bahadurabad station have been reduced to the local water levels. Given an average water level slope = 7.6×10^{-5} , see the measured water level slopes along the Jamuna River in Figure G2.3 and the distance is about 5000 m resulting in a reduction of 0.38 m.

The calculated local water depth = the measured water level at Bahadurabad - correction 0.38 - (SLW - depth of bathymetric map). This calculated local water depth is based on a survey in November 1993 and it has an accuracy of about 0.5 m because of the 1 m interval in the contour lines on the bathymetric map. This local water depth is compared with the measured local water depth at 28 and 29 May 1994 in Table G2.1. It seems that the depth of the channel has been constant during November 1993 - May 1994 but that the right char near location 3 has been eroded in that period. The channel has widened or shifted to the west.

Vertical	Calculated local water depth, November 1993 (m)	Measured local water depth, May 1994 (m)
1	7.0	5.6
2	7.0	7.5
3	7.0	10.5
4	9.0	8.9

Table G2.1 Measured and calculated local water depths in four verticals

3.2 Sediment samples

The sediment transport measurements in those four verticals are analyzed. The Delft Bottle and the Helley-Smith samples were processed to determine:

- the sediment size: D35, D50 and D65 and
- the sediment transport, more specifically the bed load transport and the suspended sediment transport.

The bed samples were sieved to determine D35, D50 and D65. The porosity of the sediment samples follows from the given total volume of the Delft bottle samples in vertical 1, the total weight of these samples and assuming the density of the sediment at 2650 kg/m^3 . This results in a porosity of 0.49 to 0.53.

3.3 Grain size distribution

The results of the D50 as function of the sample depth are presented in Figures G2.4 to G2.7. The following tendencies are determined:

- The Helley-Smith sampler does not catch the fine fractions, therefore the D50 of the Helley-Smith samples is relatively higher than the D50 of the bed samples and the Delft bottle samples: this can be seen in verticals 2 and 3.
- In the locations 3 and 4 with 9 to 10 m water depth, the average sediment size increases close to the river bed (logic tendency).
- In the locations 1 and 2 with 6 to 7 m water depth, the average sediment size does not increase significantly close to river bed, may be because these locations are sedimentation areas with lower sediment transport intensities near the bed. The depth average flow velocities in the 4 verticals give some indications, but are not sufficient information on overloading or underloading, see Table G2.2.

Location, vertical	depth averaged flow velocity (m/s)
1	1.00
2	1.15
3	1.25
4	1.05

Table G2.2 The measured depth averaged flow velocity in each vertical

No information has been found on the accuracy of the grain size distribution (more specifically D50) determined from the Delft bottle and the Helley-Smith samples. From the graphs an accuracy of 30 to 50 micron is estimated. The impression is that the accuracy of grain size distribution is higher than the accuracy of the sediment transport. This means that if the sediment gauging strategy includes a number of samples at the same location to improve the accuracy of the sediment transport that the accuracy of the sediment size determined as average of those samples will be sufficient.

3.4 Sediment transport

The sediment transport intensity is calculated with formula (1) from the total weight of the Delft Bottle sample:

$$q_s = \frac{\alpha \cdot G_s}{A \cdot T \cdot 1600} \quad (1)$$

in which

α	= correction coefficient	(-)
G_s	= total weight of the sediment sample	(kg)
A	= area of the opening	(m ²)
T	= sampling time	(s)
q_s	= sediment transport intensity	(m ³ /(m ² .s))

All the measurements were done with the small nozzle which area is 0.00019 m². For the sediment size in the Jamuna River the correction coefficient is 0.8 to 0.9, used is 0.8. The sampling time is 300 s.

The sediment transport intensity is calculated also with formula (1) from the total weight of the Helley-Smith sample. The correction coefficient is assumed at 0.5 (Van Rijn, 1993). The area of the opening $A = 0.076 \cdot 0.076$ m². The sampling time is 120 s.

From the pump-bottle samples the concentration, c , of the total sediment transport was calculated in milligram per liter, and converted in kg per m³. The sediment transport was calculated with formula(2):

$$q_s = \frac{c \cdot \bar{u}}{1600} \quad (3)$$

in which

c	= concentration	(kg/m ³)
$u, \bar{u}$	= depth averaged flow velocity	(m/s)

For comparison with the Delft bottle it is better to calculate the suspended sediment transport and not the total sediment transport which includes the wash load also. Because the Delft bottle does not measure the wash load, only the suspended sediment transport.

The accuracy of the sediment transport intensity depends very much on the accuracy of the applied correction coefficient. For the Delft Bottle sample the correction coefficient varies usually between 0.3 and 0.7 for Jamuna conditions ($D_{50} = 130-220 \mu\text{m}$ and small nozzle, see Figure G2.8). For the Helley-Smith sample the correction coefficient can vary between 0.3 and 0.8. These ranges are rather large. More information on these coefficients can improve the estimation of the accuracy. The accuracy of the pump-bottle samples is estimated at 0.8 to 1.2 (van Rijn, 1993).

The results of the sediment transport intensity in the near bed zone are presented in Figures G2.4 to G2.7. In vertical 4 the sediment catch of the first sample with the Helley-Smith sampler was very small, possibly because the sampler was not in the right position. The catch efficiency of the Helley-Smith sampler is sensitive for small deviations of axis of the sampler with the main flow direction. A deviation of 10 degrees reduces the catch with 10 to 50 %. It was decided to take two new samples and to disregard the first sample.

The sediment transport calculated from the Helley-Smith sample in vertical 2 is about 50 % higher than the sediment transport calculated from the Delft Bottle samples. But the maximum sediment transport from the Delft Bottle samples in vertical 1 which is close to vertical 2 is about the same as this sediment transport calculated from the Helley-Smith sample in vertical 2. This indicates that the measurements are probably correct, but that the average of more measurements at the same location might give more consistent sediment transport intensities.

The maximum sediment transport is measured in vertical 3 at 0.18 m from the bed. As one should expect this maximum sediment transport occurs in an eroding area.

The results of the suspended sediment transport intensity over the vertical are presented in Figures G2.4 to G2.7. The sediment transport intensity measured with the Delft Bottle and the pump-bottle method can be compared. The figure show that the results of the pb measurements are rather scattered and on average lower than the DB values. Initially it was feared that the pump did not functions optimal and that the suction velocity might have been too low. However, too low intake velocities should results in oversampling, see Figure A.4. Hence this can not explain the systematic too low sediment transport.

However, there are also other possible reasons for the scatter in the H-S catches. The main source is obviously the considerable variability of the sediment transport and therefore the need to take a considerable number of samples to come to a reliable average (Peters 1994). During this May 1995 survey

4 Conclusions

- 1 Only single measurements of the bed load transport were taken above a flat bed without river dunes. For a detailed comparison of the characteristics of different instruments repeated samples are recommended, because the variability of the measured sediment transport is high near the river bed.
- 2 Measured sediment transport with the Delft Bottle confirms the measured sediment transport with the Helley-Smith sampler, if the large variability of these measurements is taken into account. To reduce the variability in the results of the Helley-Smith samples it is recommended to determine the average of at least two but preferably more repeated samples.
- 3 The sediment size determined from the samples taken with the Delft Bottle is 0 to 75 micron smaller than the sediment size determined from the samples taken by the Helley-Smith sampler, because a part of the fine fraction passes the gauze of this sampler.
- 4 The sediment size of the bed sample is on average as large as the sediment size from Helley-Smith samples, although the Helley-Smith sampler does not catch all the sediments of the fine fractions.
- 5 Overall conclusion: The results of the Helley-Smith sampler are confirmed by the measurements with the Delft Bottle and the bed samples for the situation of a flat bed without river dunes. The comparison between the pump-bottle method and the Delft Bottle should be done with an optimal functioning pump-bottle system.

References

- 1 Peters, J.J., June 1994, report of Seventh Mission, Annexure IV: Comments on FAP 24-A flow and sediment gauging.
- 2 Van Rijn, L.C. Principles of sediment transport in rivers, estuaries and coastal seas, Aqua Publications, The Netherlands, 1993
- 3 RSP, Study programme phase 2, Study Report 1, February 1995.



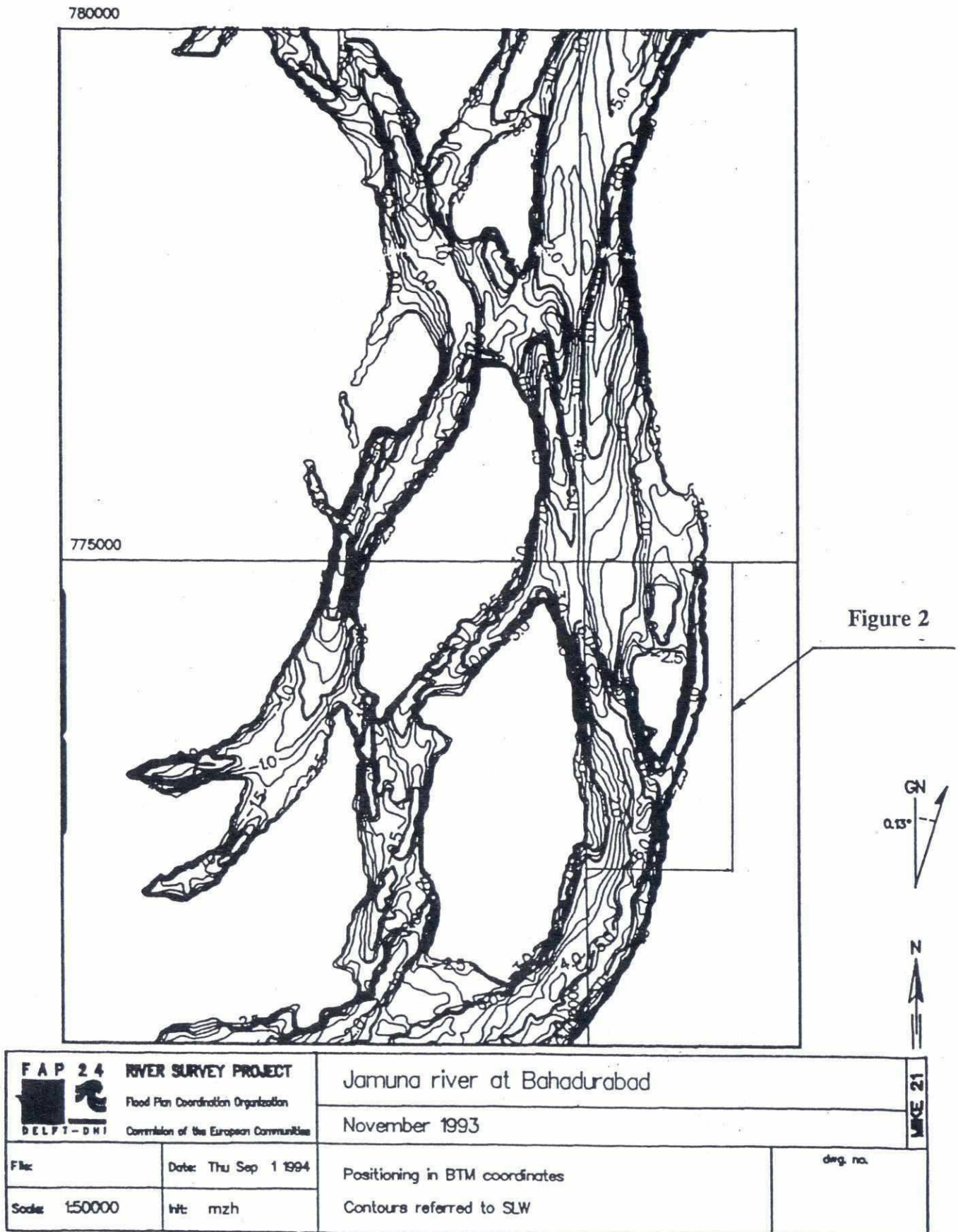


Figure G2.1: Bathymetric map of the left channel in the Jamuna River, November 1993

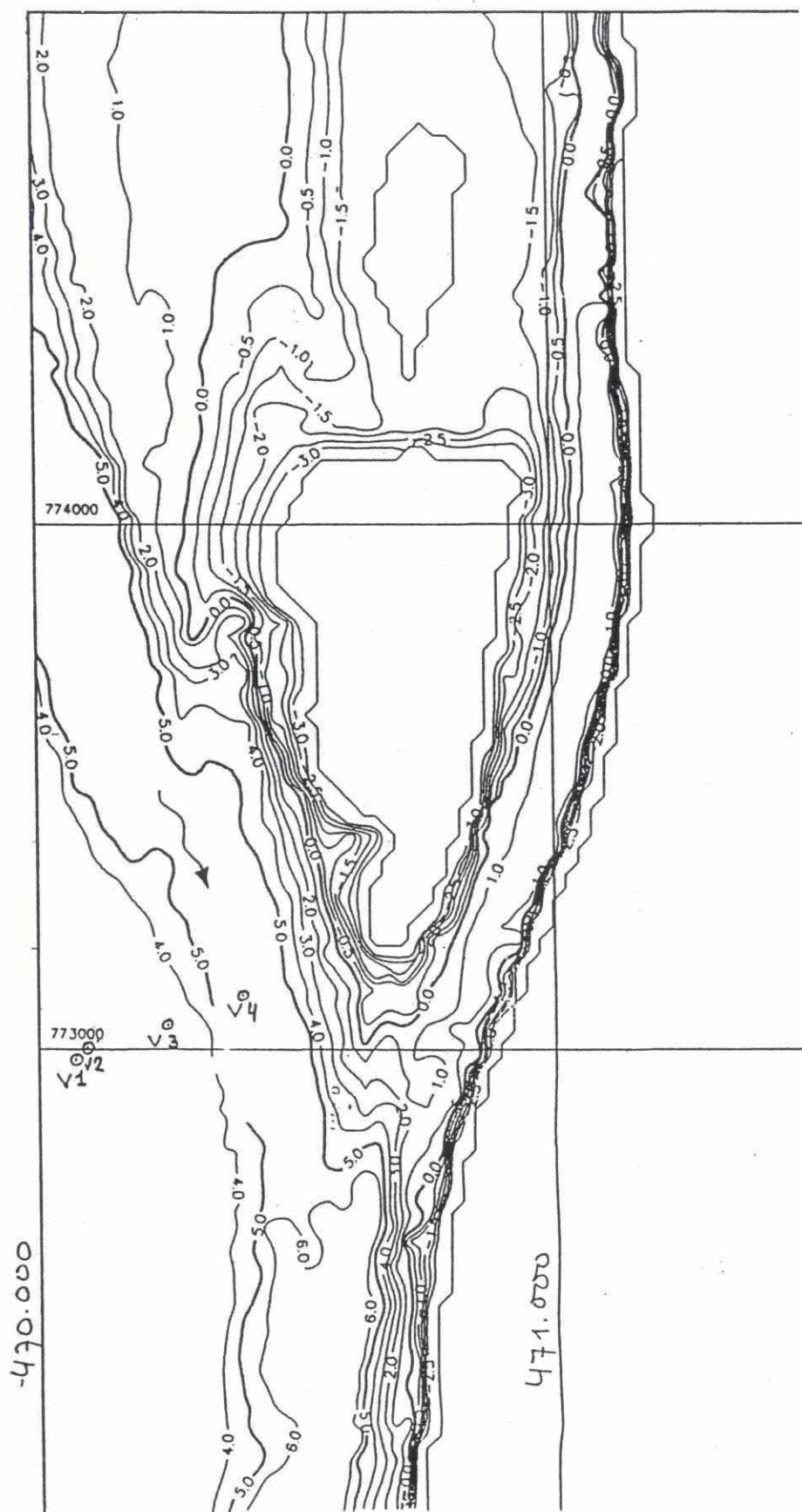


Figure G2.2: Bathymetric map of the survey area, November 1993

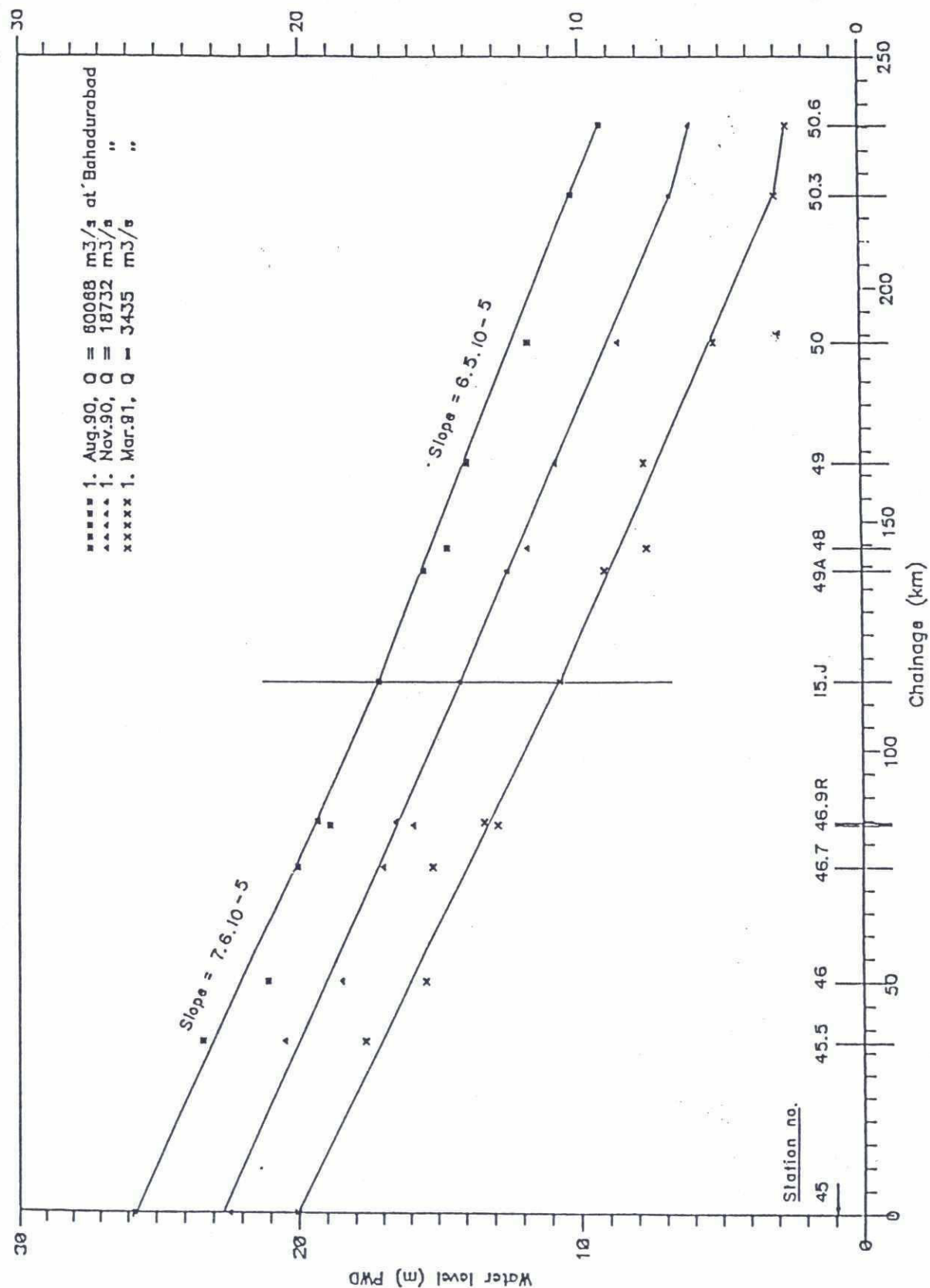


Figure G2.3: Jamuna River, water level profiles

Test of DB measurements, Vertical 1
Jamuna River, B'bad, 27-29 May, 1994

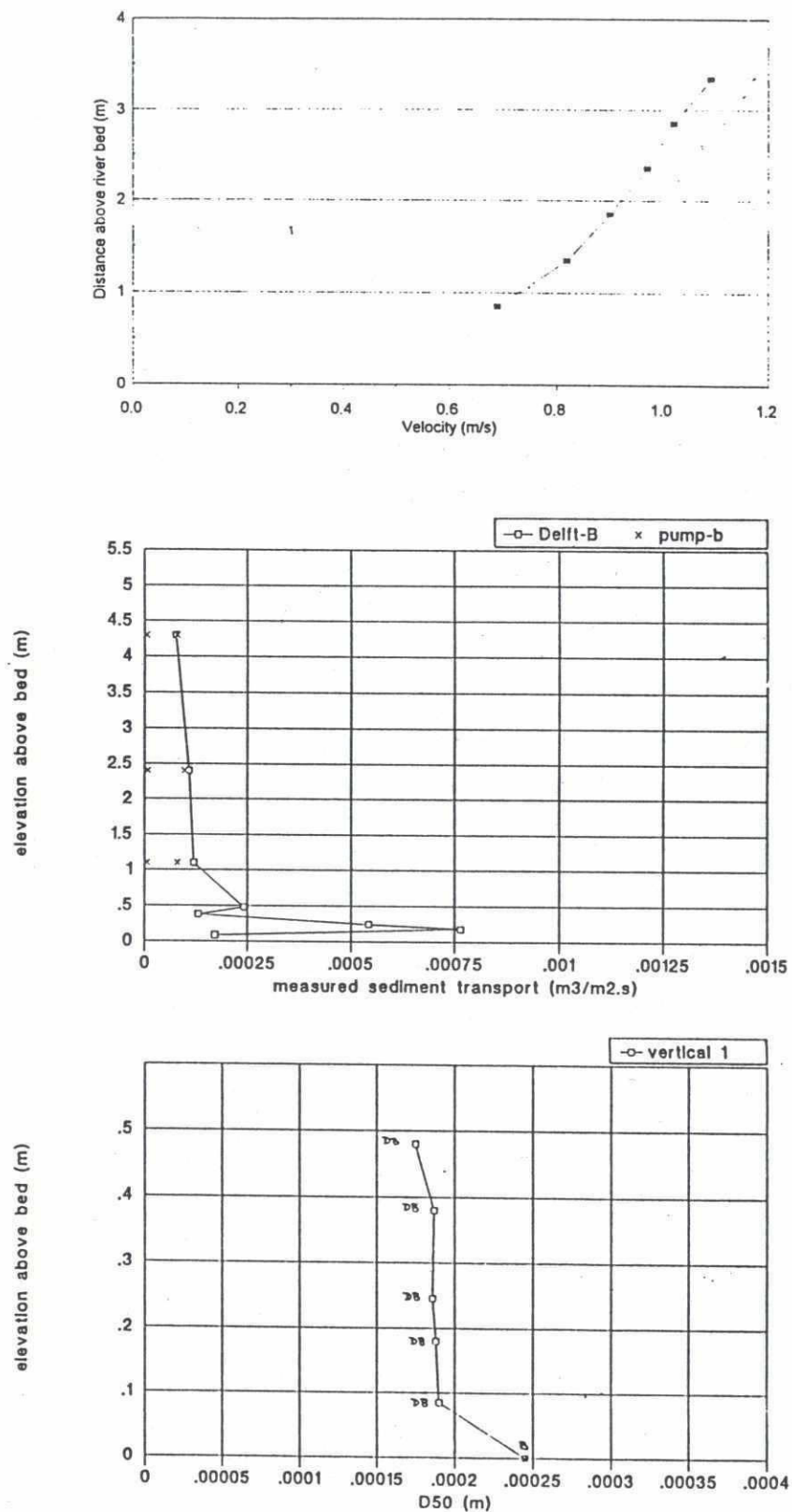


Figure G2.4: Sediment transport and D50 in vertical 1

Test of DB measurements, Vertical 2
Jamuna River, B'bad, 27-29 May, 1994

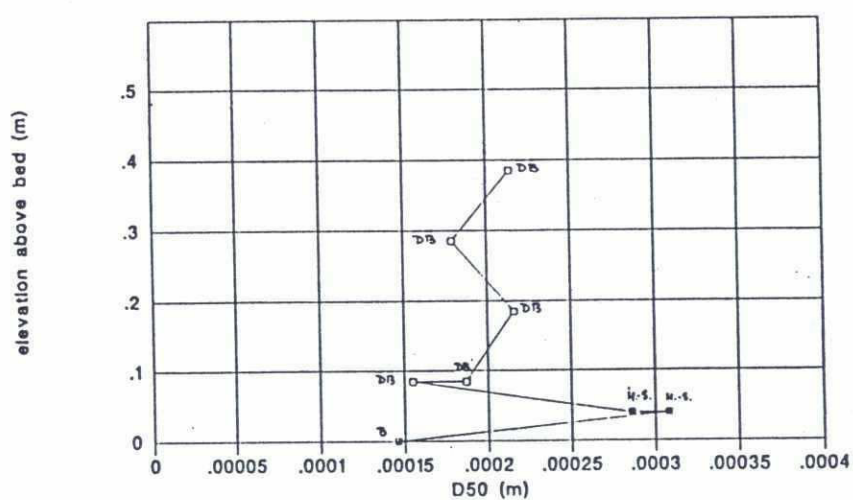
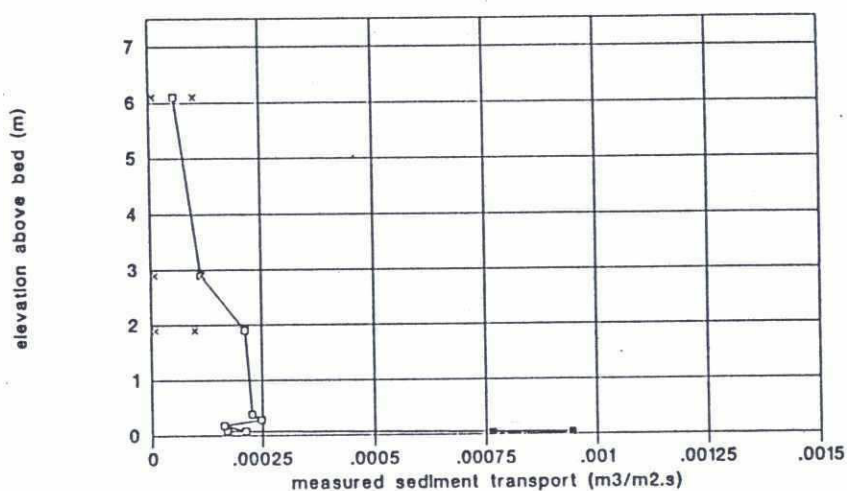
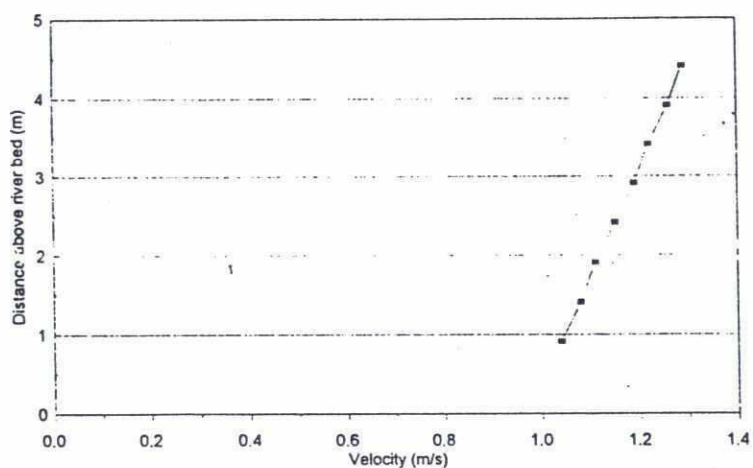


Figure G2.5: Sediment transport and D50 in vertical 2

Test of DB measurements, Vertical 3
Jamuna River, B'bad, 27-29 May, 1994

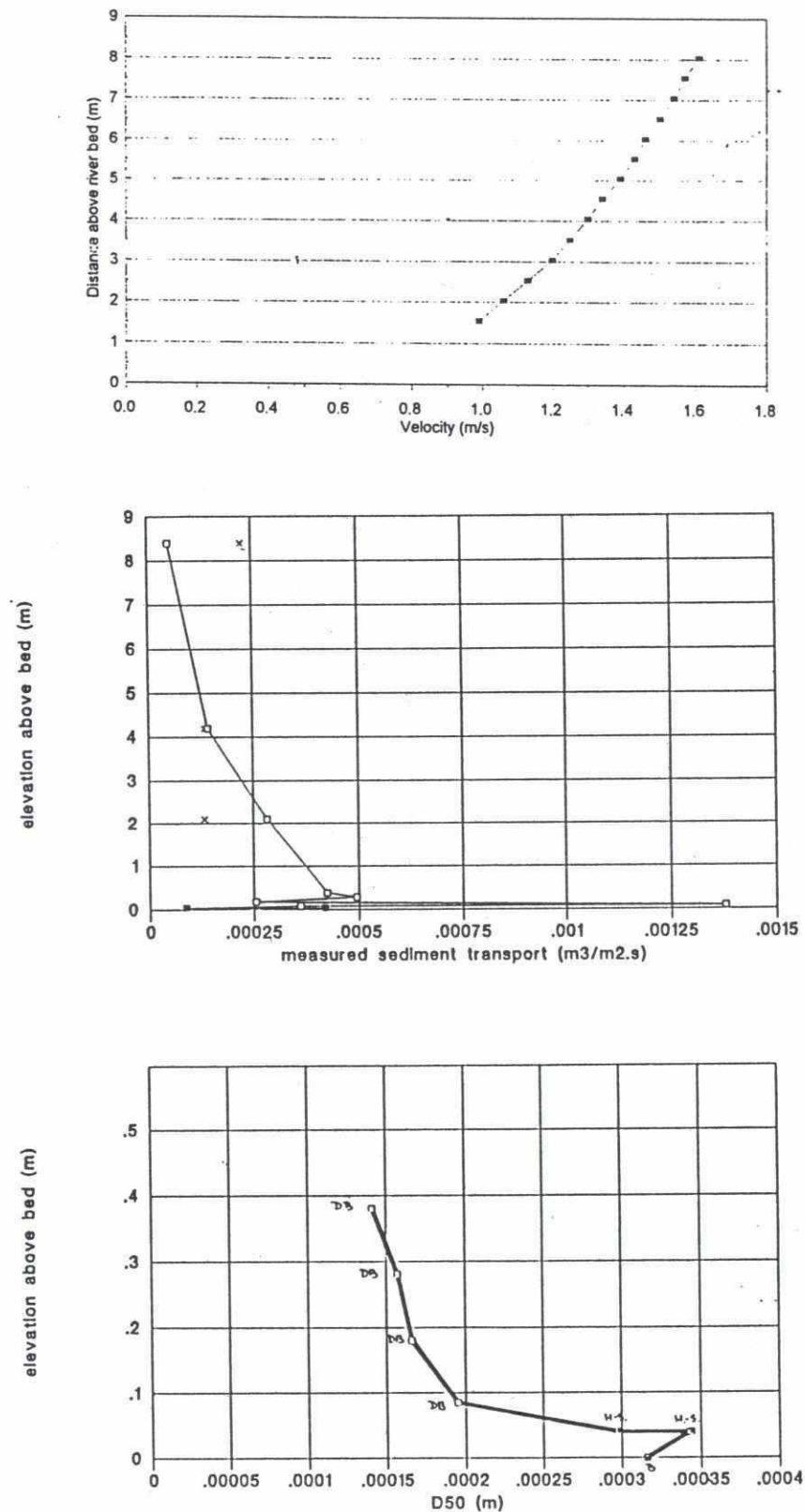


Figure G2.6: Sediment transport and D_{50} in vertical 3

Test of DB measurements, Vertical 4
Jamuna River, B'bad, 27-29 May, 1994

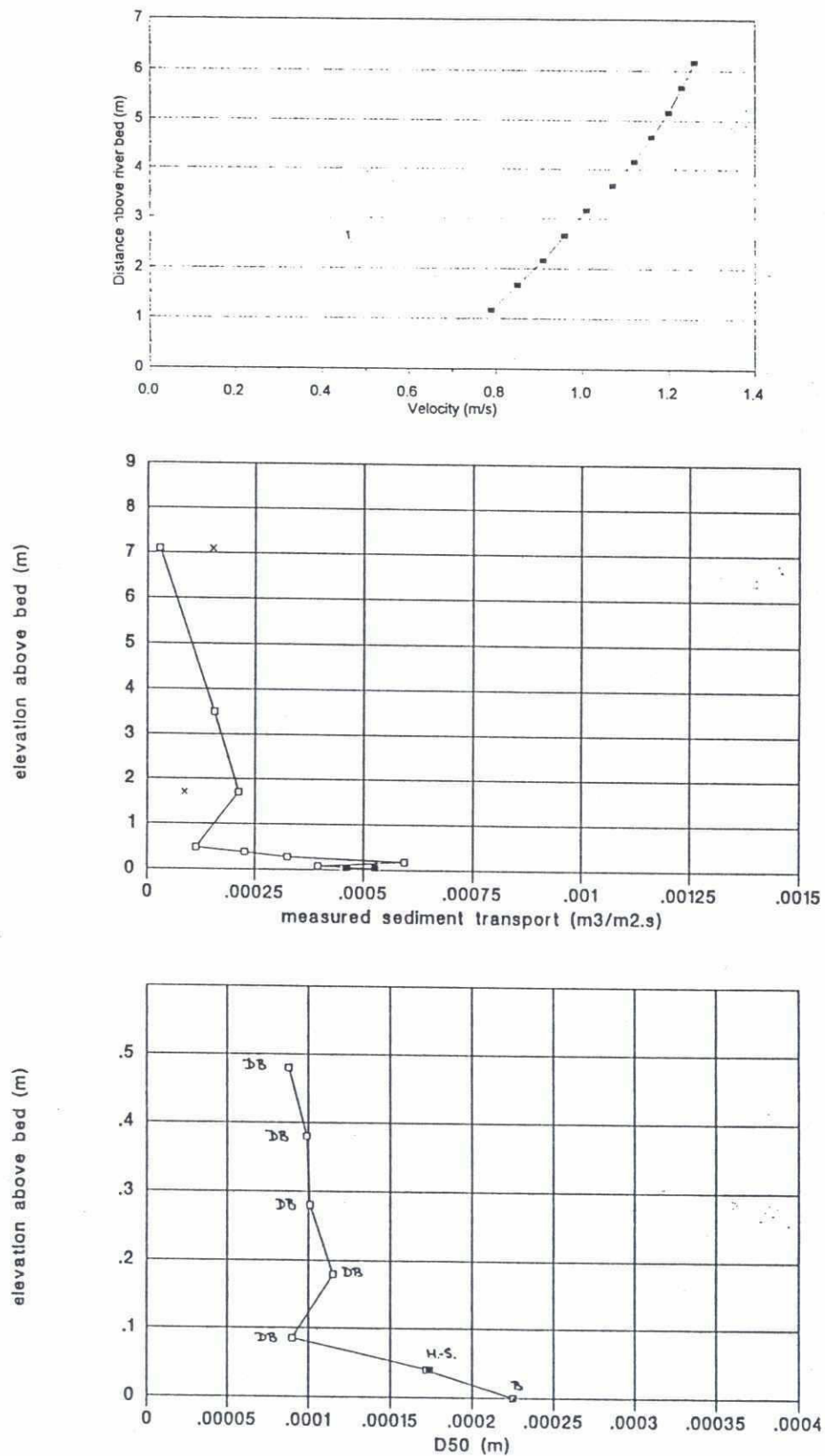


Figure G2.7: Sediment transport and D50 in vertical 4

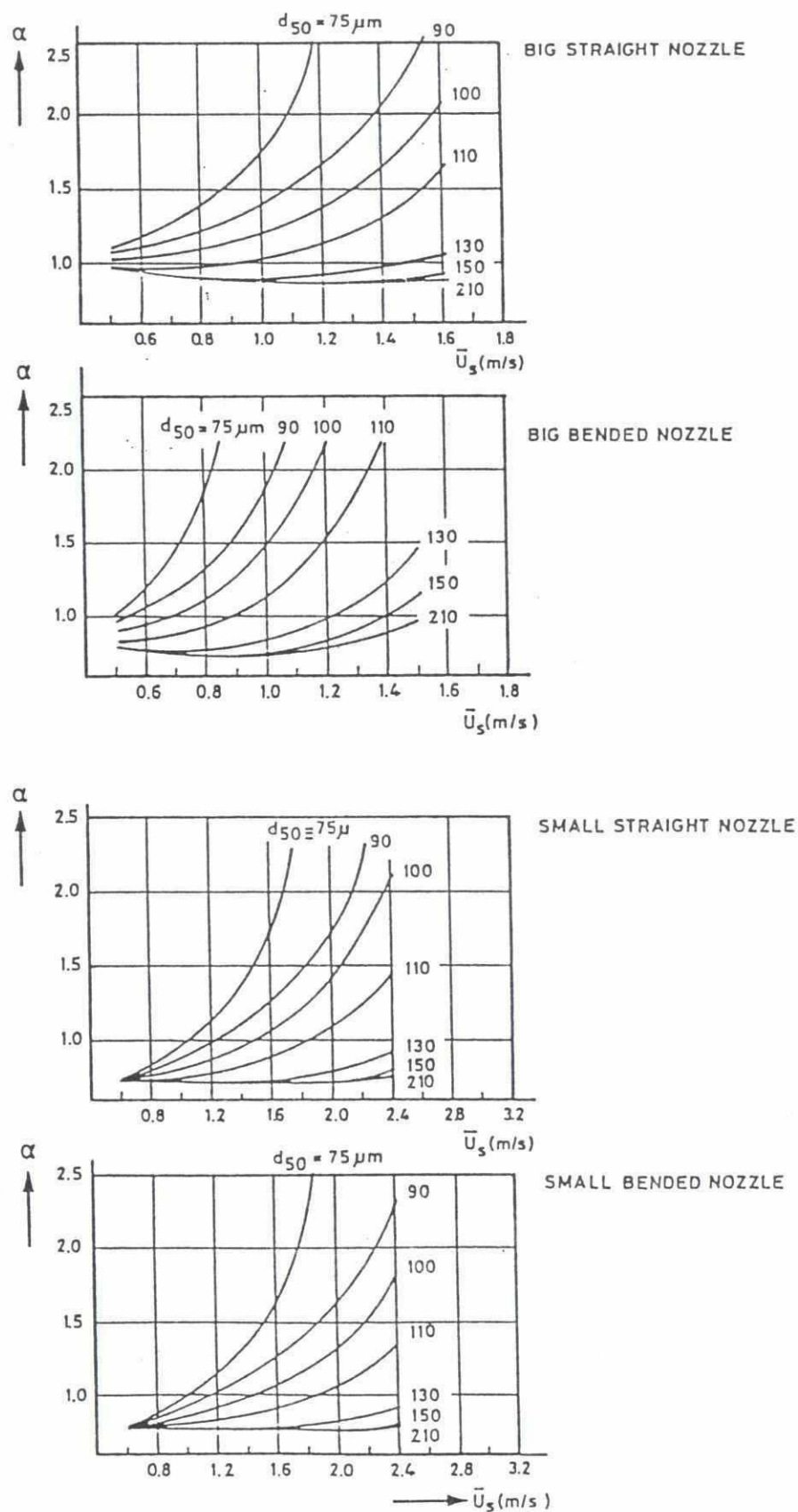


Figure G2.8: Calibration factor Delft Bottle sampler

Annexure G3

Study Survey

Near-bed sediment transport measurements, August 1994

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1 Introduction

The optimization of sediment transport measurements is part of study topic 9, Measuring techniques, see (RSP, Study Programme, February 1995). In several study-surveys measurements of the near-bed sediment transport were done with different types of instruments. The Study-survey in August 1994 was one of the first of this type of surveys and therefore it had a more exploring character compared with the following surveys. The main aspect of this survey is to measure the near-bed sediment transport above a dune in mid flow conditions. The measurements were also used to compare the different instruments to measure flow velocities and sediment transport.

The programme of the measurements in this survey is described in Chapter 2. Some results of this survey are presented in Chapter 3, where some tendencies are given as well, which were found in a preliminary analysis of the measurements.

2 Study survey programme

The reconnaissance survey was made by DHA vessel on 2 August 1994. This survey was made to find both: a dunefield and a flat-bed areas in the left channel of the Jamuna River near Bahadurabad. The following two days all the measurements were done as described below.

Several transects in the left and in the right channel were surveyed on 3 August from 08:51 to 10:08 hours:min. A dune-field was finally chosen on runline BB1Y028. Different verticals were chosen to do profile measurements above a dune and a flat bed, see Table G3.I. The next day, 4 August, a longitudinal survey was made along the same runline as the day before to determine the propagation of the dunes (08:38 to 08:46 hours:min).

Profile	position vertical	Easting (m)	Northing (m)	Depth (m)
6	dune lee	470300	779283	9.6
5	dune trough	470316	779258	12.5
4	dune stoss	470310	779242	10.7
3	dune crest	470334	779175	9.4
7	flat bed	462715	782233	10.0

Table G3.I: Characteristics of the measured verticals

In each vertical some of the following measurements were taken:
flow velocity:

- ADCP velocity-profile
- EMF point velocity
- S4 point velocity

sediment transport :

- Andreasen bulk sample
- Collapsible bag with different nozzles
- Three point-integrated samples
- Depth integrated bottle samples
- Delft-bottle on the sledge at 4 depths near to the bed
- Helley-Smith bed-load sample
- MEX 3 point turbidity

3 Results of measurements

In the study survey the measurements were done at 4 locations on the right side of a deep channel near Bahadurabad in the Jamuna River. In that area the river bed was covered by dunes. In addition some measurements were taken at 1 location in the right channel of the Jamuna River. In that location the river bed was almost flat with only minor bed forms. After a peak flow the water level started to fall in the Jamuna River during the survey of 1 to 4 August 1994.

Flow velocity

In the selected locations flow velocity profiles were measured with different instruments. The comparison of the ADCP-EMF measurements with the S4 measurements shows that the flow velocity by ADCP is systematically lower than the flow velocity by S4. This tendency does not confirm the findings of the test gauging in August 1993, but is in line with later findings, see for instance annexure G8.

Sediment transport measurements

The location of the various profiles are shown in Table G3.1. The suspended sediment concentration profile was sampled by point-integrated pump-bottle system in profiles 6, 4, 3 and 7 (see Table G3.3, G3.6, G3.9 and G3.13). The samples taken in profiles 3 and 7 can be compared with the collapsible depth integrated samples taken in those verticals (see Tables G3.10 and G3.12).

The collapsible depth-integrated measured a significant higher concentration of the sand fraction, 167.9 mg/l, as measured by the depth integrating sampler, 70.8 mg/l. But both samplers measured almost the same concentration of the silt fraction: 395 mg/l versus 379 mg/l.

The comparison of the Delft Bottle catch at 0.05 m above the bed with the Helley-Smith catch indicate generally a good agreement, but in flat-bed and stoss side situations, Helley-Smith sampler was found to measure more than the Delft Bottle. At crest, on the other hand, Delft Bottle was found to measure more than the Helley-Smith sampler.

In general the sediment transport increases close to the river bed. This tendency means that the catch by the Delft Bottle increases going from 0.35 m above the bed to 0.25 m, 0.15 and 0.05 m above the bed (see Table G3.2, G3.4, G3.5, G3.7 and G3.8). This trend was found several times in other surveys. However, the catch by the Delft bottle in profile 7 does not confirm this tendency (see Table G3.11). In how far this is reality (e.g. caused by over-/under loading, some small bedforms, etc.) or the positioning of the Delft Bottle on the river bed can not be judged from a few deviating samples.

The Delft Bottle measurements on a dune show a clear tendency in the thickness of the near-bed sediment layer. Going from the leeside in profile 6 to the through of the dune (profile 5), the stoss side of the dune (profile 4) to the crest of the dune (profile 3) the thickness of the near bed sediment transport layer reduces from more than 0.35 m to about 0.15 m, see Figures G3.1 to G3.5.

25 litre bulk samples were collected at 0.5 m above the river bed for grain size distribution of suspended sediment on profiles 6, 4, 3 and 7 (see Table G3.14 and Figure G3.4). The ADCP backscatter calibration formula was used to determine the sediment transport as presented in those figures. These backscatter sediment transport curves fit rather well with the sediment transport measured by the Delft Bottle.

Profile	Depth (m)	Kp value 3-Aug (m)	Kp value 4-Aug (m)	Shift (m)
6 - Lee	9.6	2	44	42
5 - Trough	12.5	25	60	35
4 - Stoss	10.7	42	76	34
3 - Crest	9.4	74	107	33

Table G3.1: Location of various profiles

Meas. depth (m)	d ₅₀ (mm)	d ₉₀ (mm)	geom. std dev	transport (kg/ms)	meas time (hr)	Silt %
9.55	0.181	0.365	1.539	0.0299	11:25	2.4
9.45	0.168	0.286	1.546	0.0188	11:45	2.2
9.35	0.177	0.360	1.649	0.0278	11:55	2.9
9.25	0.164	0.271	1.604	0.0177	12:03	3.7

Table G3.2: Delft Bottle measurements in Profile 6

Delft Bottle measurements:

Collection period: 180 s

Nozzle: bended 0.00019 m²

sample #	sampling depth (m)	sampling time (hr)	sand conc (mg/l)	silt conc (mg/l)	total conc (mg/l)
A1324/ A1787	1.8	-	26.3	301.4	327.7
A1785/ A1240	5.4	12:30	250.71	412.62	663.33
A1178/ A1398	7.1	12:12	315.8	404.8	720.6

Table G3.3: Point integrating sample in Profile 6

Meas. depth (m)	d ₅₀ (mm)	d ₉₀ (mm)	geom.std dev	transport (kg/ms)	meas time (hr)	Silt %
11.25	0.175	0.309	1.42	0.0832	14:05	1.9
11.15	0.169	0.292	1.53	0.0434	14:15	2.4
11.05	0.154	0.246	1.66	0.0270	14:23	4.4
10.95	0.153	0.243	1.653	0.0266	14:37	4.2

Table G3.4: Delft Bottle measurements in Profile 5

Delft Bottle measurements:

Collection period: 180 s

Nozzle: bended 0.00019 m²

Meas. depth (m)	d ₅₀ (mm)	d ₉₀ (mm)	geom. std dev	transport (kg/ms)	meas time (hr)	Silt %
10.65	0.183	0.339	1.42	0.209	15:57	1.1
10.55	0.169	0.272	1.509	0.0626	16:05	2.1
10.45	0.158	0.247	1.629	0.044	16:15	3.3
10.35	0.152	0.240	1.645	0.031	16:28	3.7

Table G3.5: Delft Bottle measurements in Profile 4

Delft Bottle measurements:

Collection period: 180 s

Nozzle: bended 0.00019 m²

sample #	sampling depth (m)	sampling time (hr)	sand conc (mg/l)	silt conc (mg/l)	total conc (mg/l)
A1405	2.14	15:51	70.36	373.54	443.9
A1781	6.42	15:30	393.61	429.32	822.93
A1780	8.56	15:18	616.9	419.16	1036.06

Table G3.6: Point-integrating sample in Profile 4

Meas. depth (m)	d ₅₀ (mm)	d ₉₀ (mm)	geom. std dev	transport (kg/ms)	Meas. time (hour)	Silt %
9.35	0.197	0.387	1.549	1.022	17:20	0.4
9.25	0.165	0.244	1.498	0.093	17:30	1.7
9.15	0.159	0.242	1.597	0.056	17:38	3.3
9.05	0.151	0.239	1.648	0.036	17:52	4.1

Table G3.7: Delft Bottle measurements in Profile 3, 3 August 1994

Delft Bottle measurements:

Collection period: 60 s

Nozzle: bended 0.00019 m²

Meas. depth (m)	d ₅₀ (mm)	d ₉₀ (mm)	geom.std dev	transport (kg/ms)	meas time (hr)	Silt %
9.35	0.196	0.381	1.532	0.349	12:15	0.6
9.25	0.17	0.259	1.463	0.076	12:27	2.4
9.15	0.162	0.249	1.593	0.042	12:39	3.0
9.05	0.159	0.244	1.594	0.035	12:55	3.6

Table G3.8: Delft Bottle measurement in Profile 3, 4 August 1994

Delft Bottle measurements:

Collection period: 60 s

Nozzle: bended 0.00019 m²

Helley-Smith measurements:

Bed load transport = 0.291 Kg/ms

d_{50} = 0.191 mm

d_{90} = 0.374 mm

Silt % = 1.2

Depth integrated Suspended Sediment Concentration:

Silt conc. = 379.1 mg/l

Sand conc. = 70.8 mg/l

sample #	sampling depth (m)	sampling time (hr)	sand conc (mg/l)	silt conc (mg/l)	total conc (mg/l)
A1271	1.90	-	106.31	381.88	488.19
A1498	5.6	11:51	48.8	314.01	362.81
A1528	7.4	12:37	877.1	455.62	1332.72

Table G3.9: Point-integrating sample in Profile 3

sample #	sampling depth (m)	sampling time (hr)	sand conc (mg/l)	silt conc (mg/l)	total conc (mg/l)	Nozzle size (mm)	Sampling time sec	Sample Vol. ml
A2181	4.6	11:05	43.7	386.7	430.4	4.8	42	1625
A1954	4.6	11:15	140.1	389.7	529.9	4.8	40	1300
A2188	4.6	11:25	120.5	404.6	525.1	4.8	42	1650
A1835	4.6	11:40	289.1	388.3	677.4	3.2	48	1075
A1942	4.6	11:45	279.7	407.4	687.1	6.4	44	2550
A1941/- A1879	4.6	11:52	134.4	391.2	525.6	7.9	43	4025

Table G3.10: Collapsible bag depth-integrating sample in Profile 3

Meas. depth (m)	d_{50} (mm)	d_{90} (mm)	geom. std dev	transport (kg/ms)	meas time (hr)	Silt %
9.95	0.295	0.456	1.63	0.019	17:20	0.7
9.85	0.156	0.365	2.0	0.009	17:30	9.1
9.75	0.199	0.416	1.94	0.015	17:40	5.4
9.65	0.139	0.317	1.85	0.007	17:50	9.5

Table G3.11: Delft Bottle measurement in Profile 7

Collection period: 120 s

Nozzle: bended 0.00019 m²

sample #	sampling depth (m)	sampling time (hr)	sand conc (mg/l)	silt conc (mg/l)	total conc (mg/l)	Nozzle size (mm)	Sampling time sec	Sample Vol. ml
A891	2.6	?	9.9	313.5	323.4	7.8	14	1325
A566	4.5	?	25.8	356.5	382.4	6.4	23	1125
A1931	6.6	?	33.7	377.5	411.2	6.4	30	1400
A2183	8.2	?	73.9	374.2	448.0	4.8	38	950
A1860	8.8	?	80.8	367.3	448.1	4.8	39	900

Table G3.12: Collapsible-bag depth-integrating samples in Profile 7

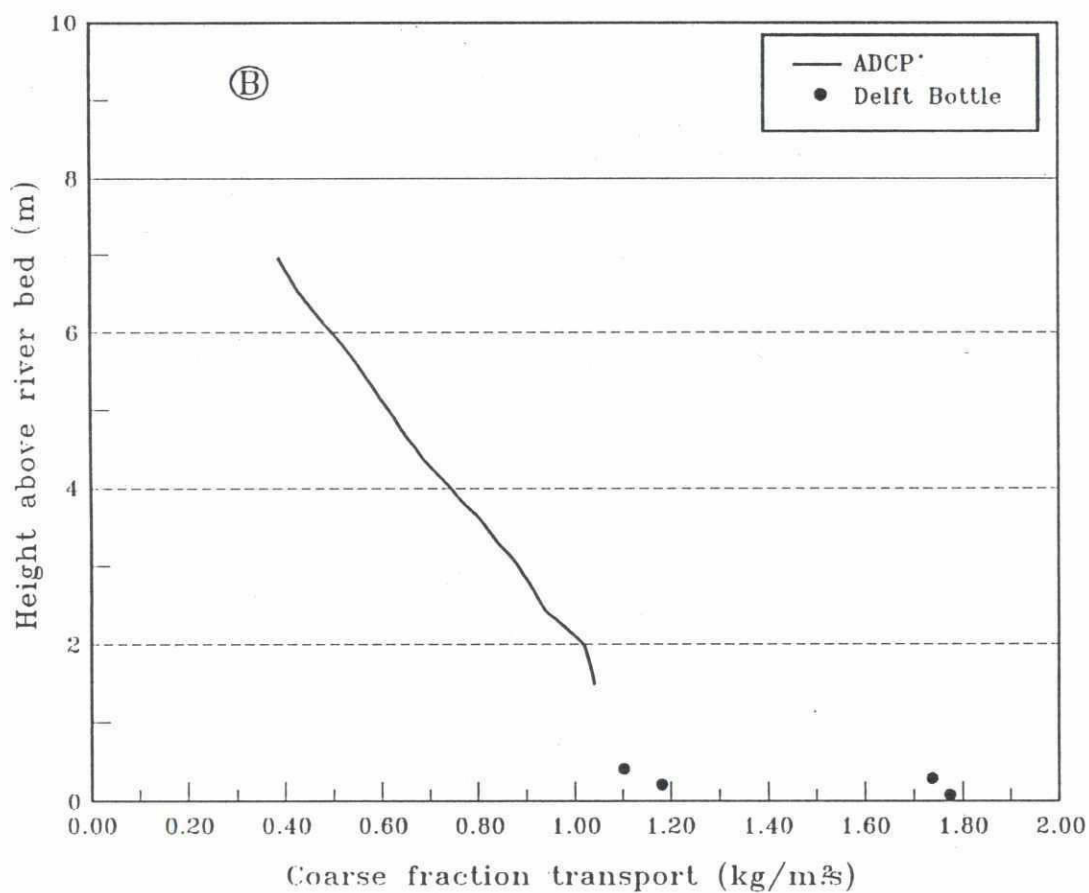
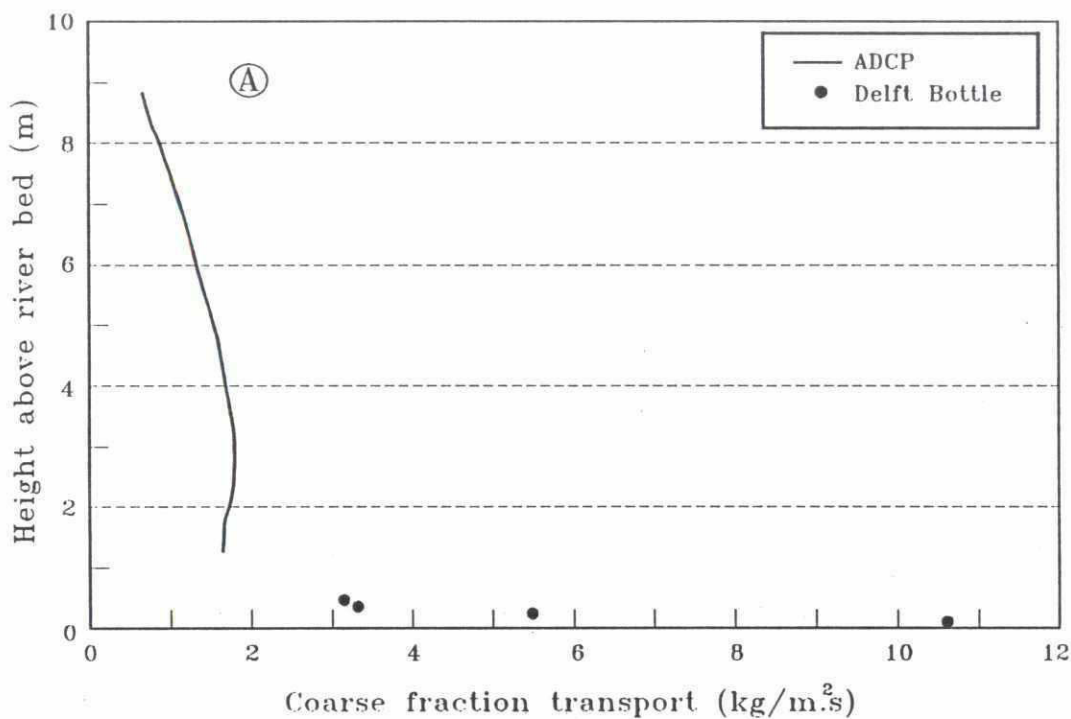
sample #	sampling depth (m)	sampling time (hr)	sand conc (mg/l)	silt conc (mg/l)	total conc (mg/l)
A1279	1.0	?	2.7	250.8	253.4
A1449	3.0	?	11.4	293.5	304.9
A1386	5.0	?	47.1	367.1	414.3
A1453	7.0	?	110.3	418.1	528.4

Table G3.13: Point-integrating sample in Profile 7



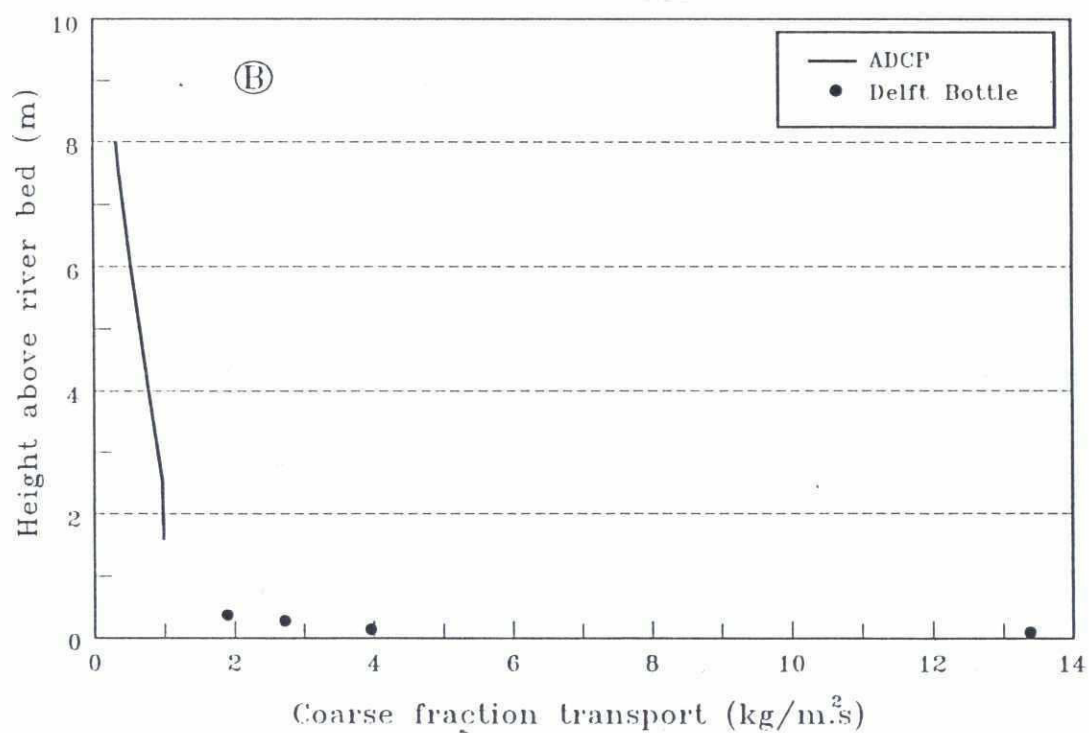
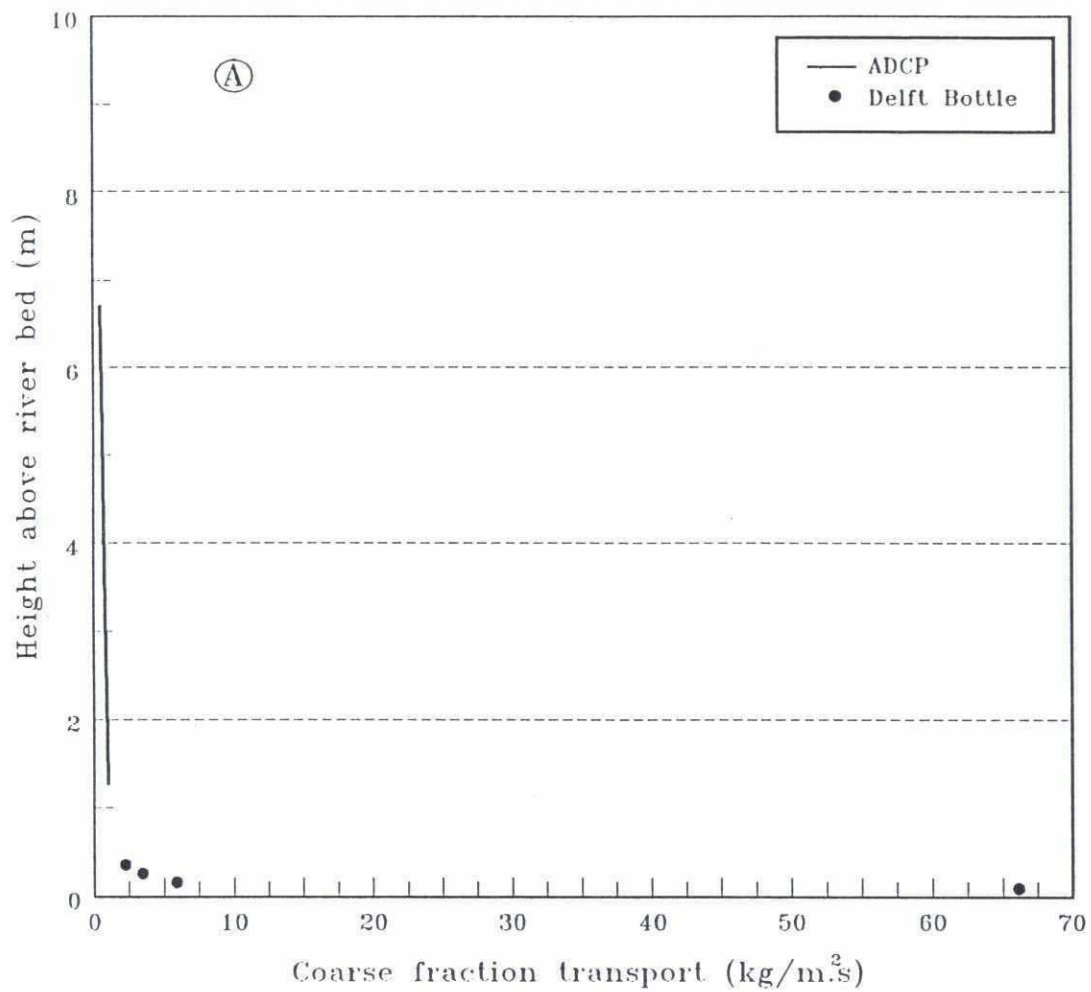
Bulk sample profile	Collection depth (m)	Collection time (hr: min)	d ₅₀ (mm)	d ₉₀ (mm)	Geom. std dev	Silt (%)	Silt conc. (mg/l)	Sand conc. (mg/l)
3	8.9	12:30	0.140	0.234	2.83	19.7	531.2	1996.0
7	9.5	12:45	0.040	0.196	5.30	57.7	457.4	297.7
4	10.2	16:15	0.118	0.229	4.57	28.1	531.3	1199.3
6	9.1	12:55	0.083	0.220	5.78	41.0	499.9	678.8

Table G3.14: Bulk samples



Note : transport scale varies strongly due to the wide range of near bed transport values

Figure G3.1: Sediment transport vertical in profiles 5 and 6, 3 August 1994. (a) trough of dune (b) leeward side of dune



Note : transport scale varies strongly due to the wide range of near bed transport values

Figure G3.2: Sediment transport vertical in profiles 3 and 4, 3 August 1994. (a) crest of dune (b) stoss side of dune

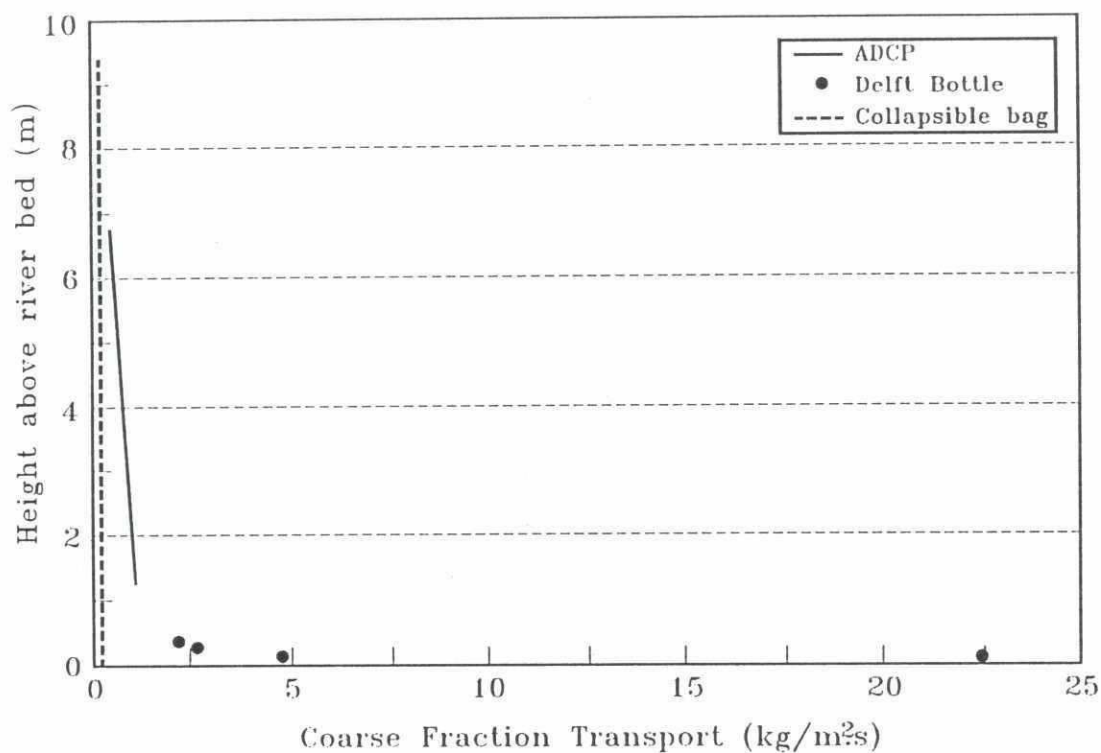


Figure G3.3: Sediment transport vertical in profile 3, crest of dune, 4 August 1994

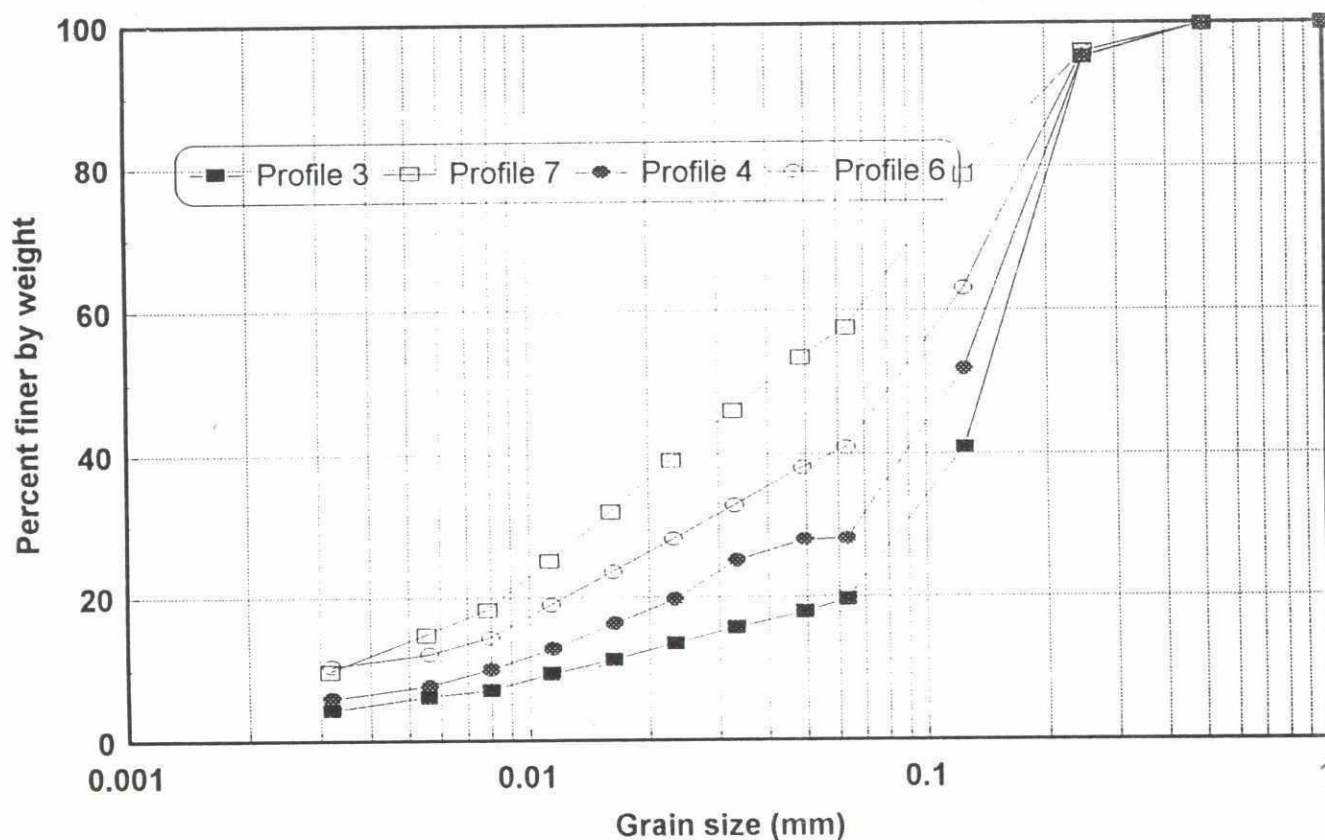


Figure G3.4: Sieving curves

Annexure G4

**Study survey on
sediment transport measurements
in low flow conditions, 4-12 December 1994**

Contents

1	Introduction	1
2	Water levels/ depths	1
3	Flow conditions	1
4	Sediment concentration verticals	1
5	Variability of sediment concentration in low flow	1
6	Conclusions	2

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Figures

- G4.1: Location of the survey area
- G4.2: Velocity and concentration vertical. (a) velocity vertical (b) sediment concentration vertical
- G4.3: Variation of suspended sediment concentration in low flow. (a) variation of suspended sediments (from ADCP backscatter intensity) (b) variation versus exposure time

1 Introduction

This study survey was part of a combined study survey carried out in December 1994. The survey, which was done in the area of Jim's bar near Bahadurabad (see Figure G4.1) included aspects like optimization of sediment measuring techniques, bar topography, bed-form inventory, measurement on sediment transport near eroding banks and mapping of bed levels. The main results of this survey are used for and discussed in Special Reporting. Relevant data in the database of the River Survey Project can be found via the Survey Bulletin of appendix 1. This annexure is limited to some results of the sediment measurements.

2. Water levels/depths

The water level were falling from 14.00 to 13.79 m+PWD at the Bahadurabad gauge, which is less than 1 m above SLWL.

3. Flow conditions

In the period considered, especially on 4 to 7 and 12 December when the vertical sediment profiles were measured, the average flow velocities encountered in the channels were ranging from 0.5 to 0.9 m/s. So typical low flow conditions were prevailing. As an example see Figure G4.2a.

4 Sediment concentration verticals

Sediment concentration verticals are measured with the pump-bottle system. During these measurements, also the ADCP was running in the stationary profile mode. As an example a concentration vertical is presented in Figure G4.2b.

The measurements lasted from about 10.50 hrs till 11.15. So the profile derived from the ADCP backscatter intensity is an example over 25 minutes, while the pump-bottle sampling took about 100 s per sample.

5. Variability of sediment concentration in low flow

The time series of the ADCP back scatter have been visualized at a number of levels in the vertical notably at 0.3, 0.5 and 0.8 of the water depth, see Figure G4.3a. Each time series can be divided in a considerable number of time increments representing a chosen exposure time. After calculation of the average concentration per exposure time, the standard deviation can be calculated. By dividing the standard deviation by the depth and time averaged concentration (of 66 mg/l in the example) the relative standard deviation is determined, see Figure G4.3b.

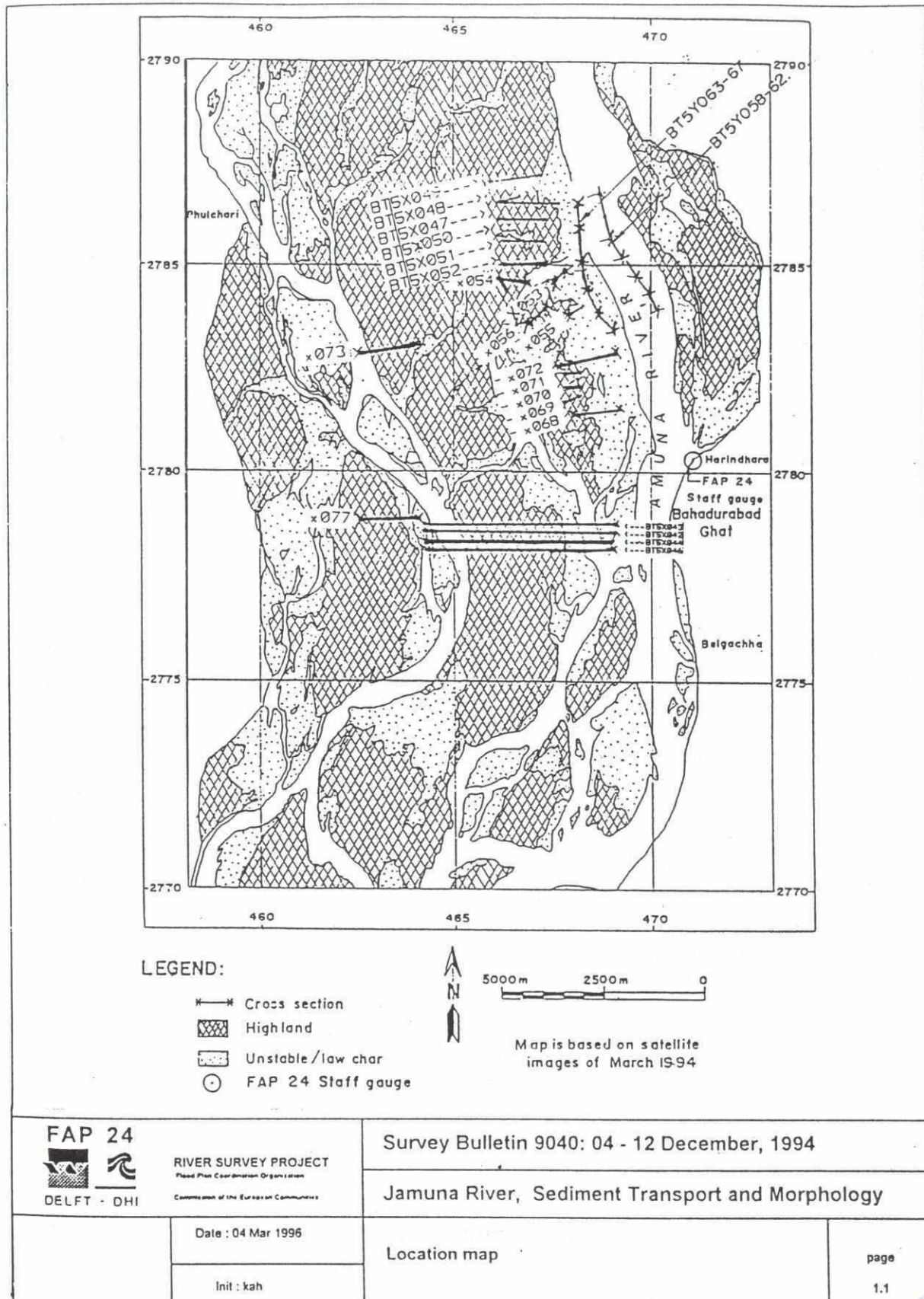
6. Conclusions

If we assume that the fluctuations of the ADCP backscatters intensity is representative for the variation of the suspended sediment concentration a number of conclusions can be drawn

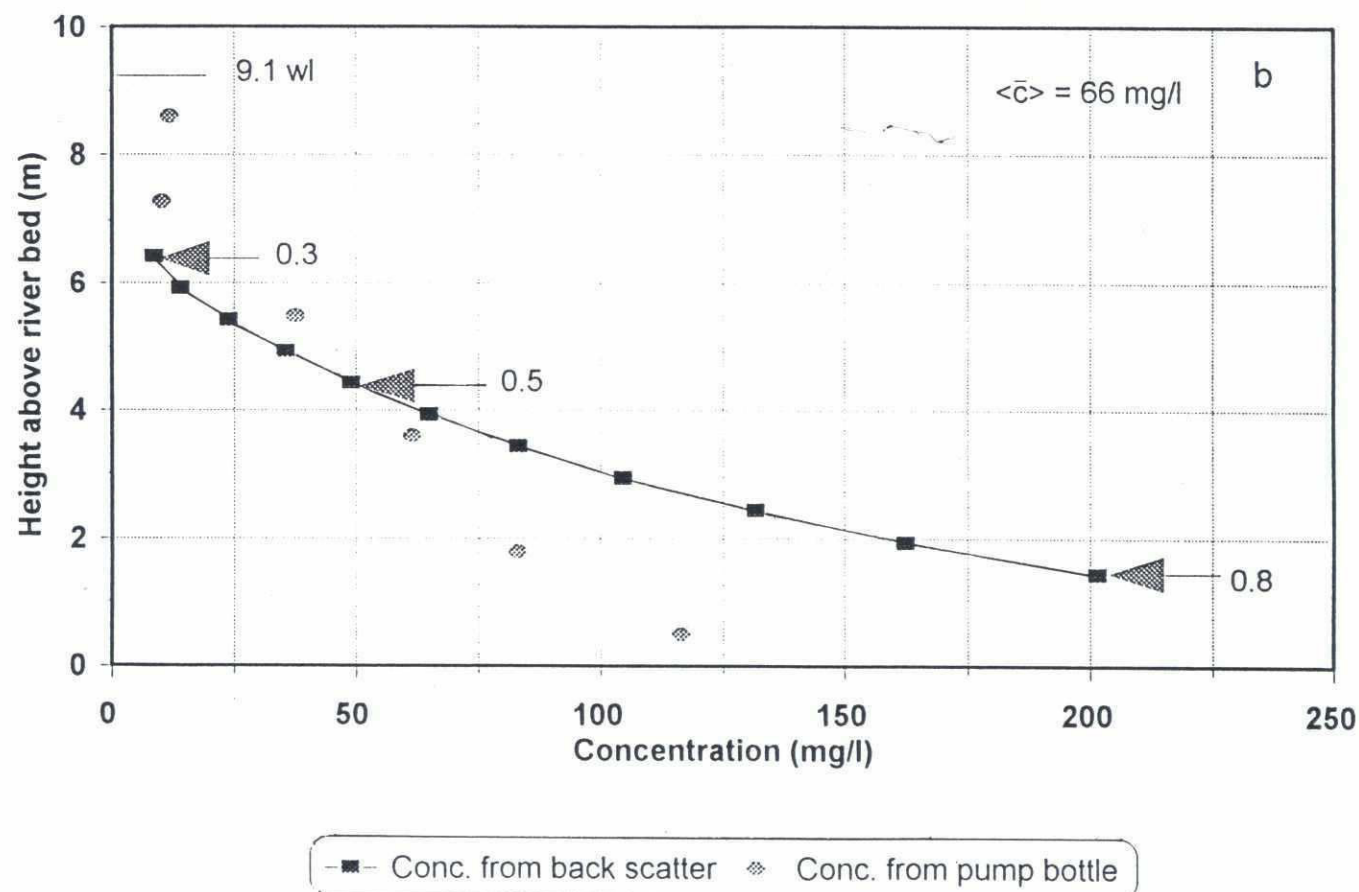
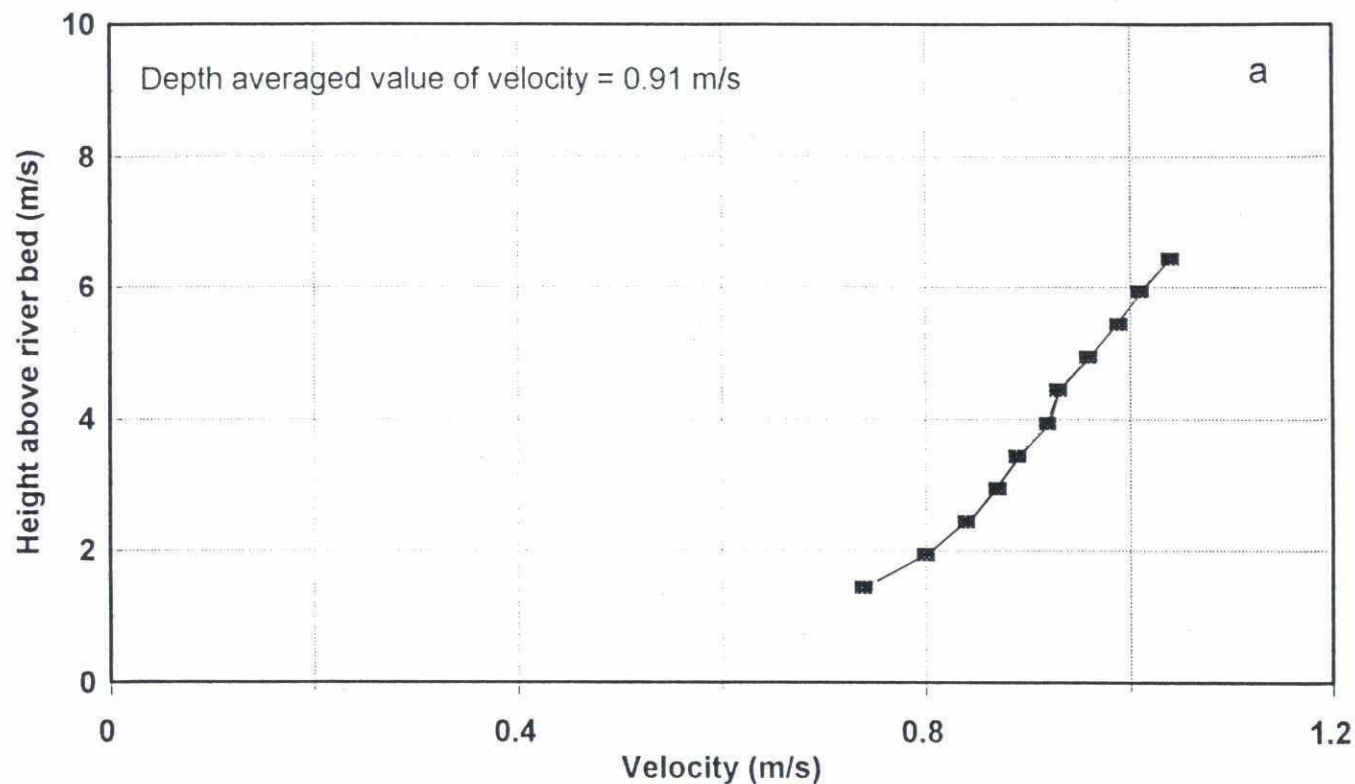
- the variation of the concentration increases closer to the river bed (in time with many other observations, see also Peters 1994)
- the variation decreases for longer exposure times (as may be expected)
- an exposure time of 100 s in low flow conditions may lead to an acceptable uncertainty level

Reference

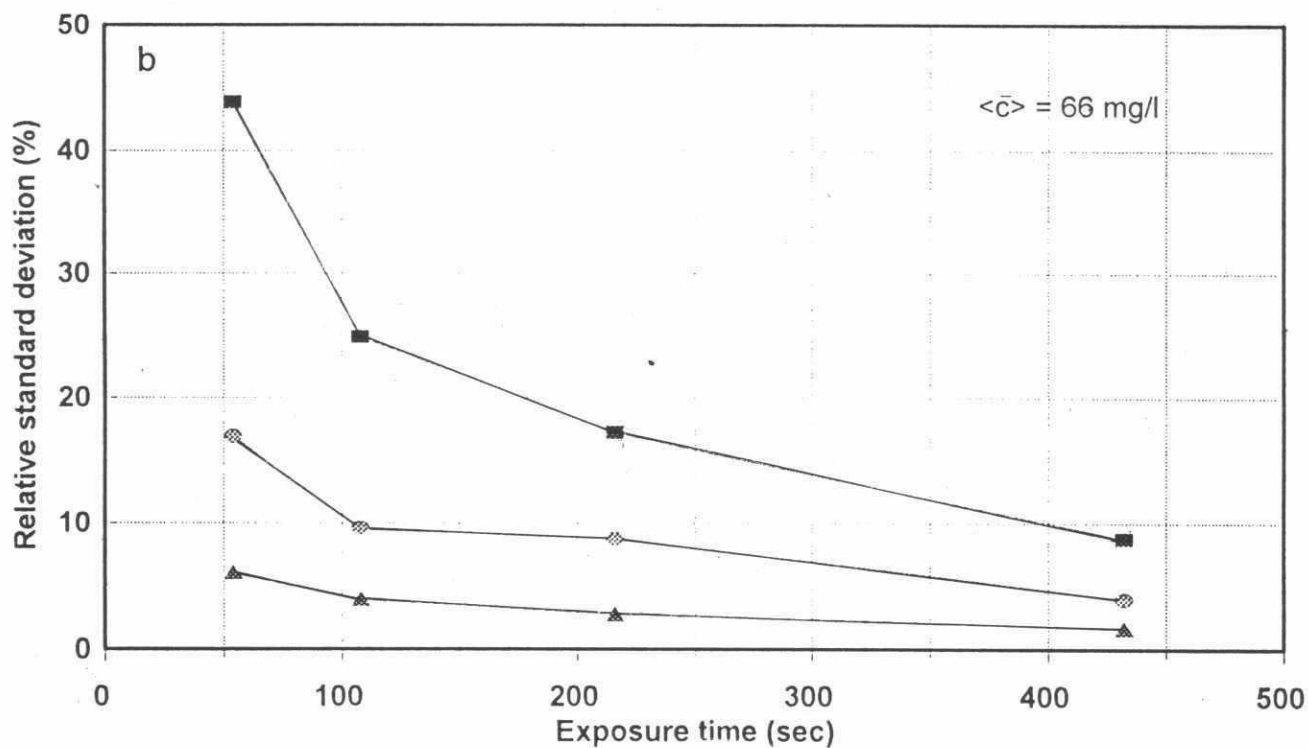
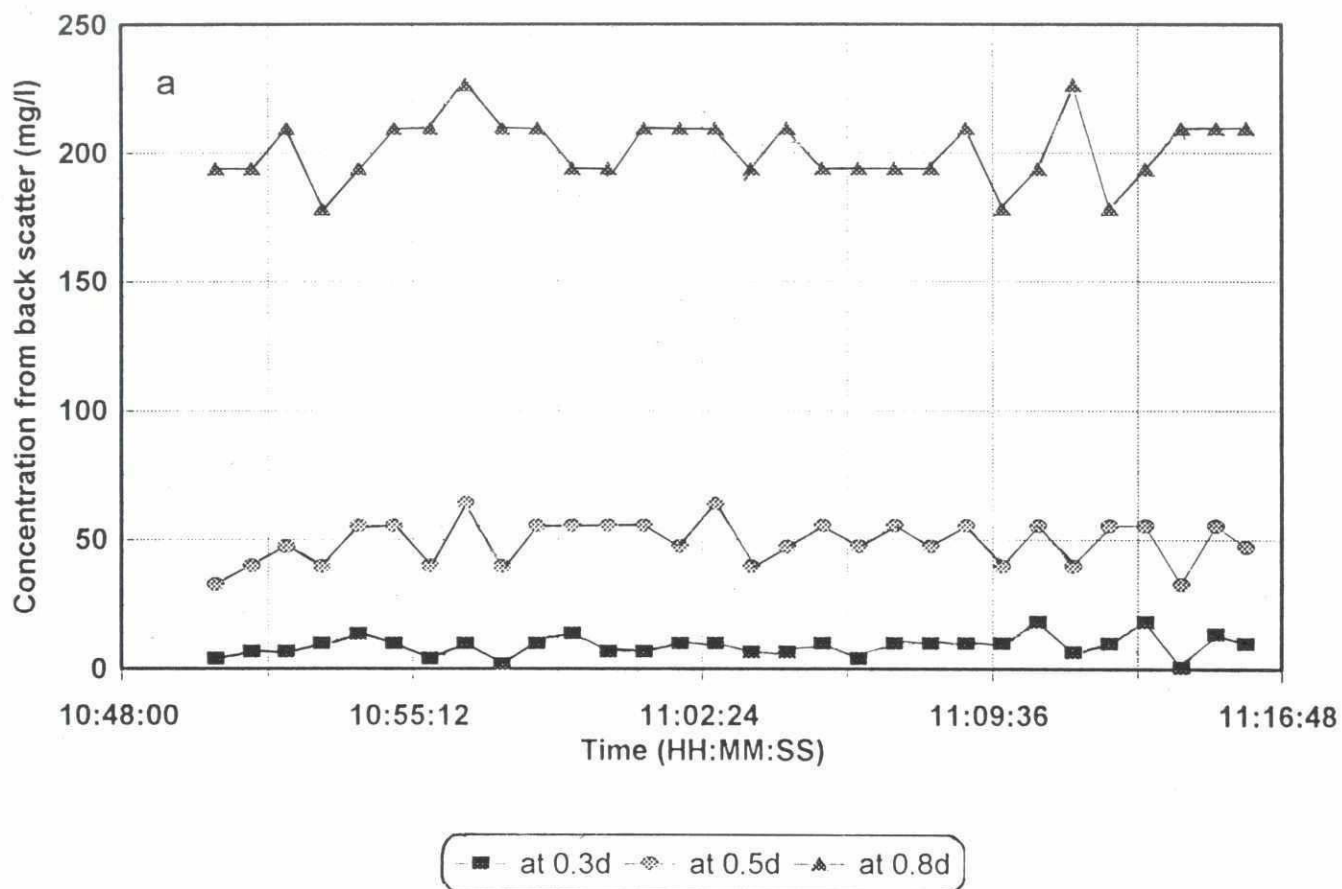
Peters J.J (1994), Report on seventh mission



G4.1: Location of the survey area



G4.2: Velocity and concentration vertical. (a) velocity vertical (b) sediment concentration vertical



G4.3: Variation of suspended sediment concentration in low flow. (a) variation of suspended sediments (from ADCP backscatter intensity) (b) relative standard deviation versus exposure time

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Appendix 1

Type of measurement	Method	No. of measurements in Lines													
		BT5X BT5X	BT5X	BT5X	BT5X	BT5X	BT5X	BT5X	BT5X	BT5Y	BT5Y	BT5Y	BT5Y	BT5Y	BT5Y
		042	043	044	046	052	053	055	056	058	059	061	063	008	
Discharge	ADCP transect	3	1	1	1	1	1	1	1	1	1	1	5	1	
	EMF transect	3	1	1	1	1	1	1	1	1	1	1	5	1	
	Echo-Sounding	3	1	1	1	1	1	1	1	1	1	1	5	1	
Vertical current profile	No of verticals in channel	2	-	2	1	6	-	-	-	-	-	-	-	-	
	ADCP	2	-	2	1	6	-	-	-	-	-	-	-	-	
	S4 current meter	2	-	2	1	6	-	-	-	-	-	-	-	-	
	Ott current meter	-	-	-	-	-	-	-	-	-	-	-	-	-	
Vertical sediment profile	Pump bottle sampling	18	-	18	9	30	-	-	-	-	-	-	-	-	
	Andreasen settling tube	-	-	-	-	-	-	-	-	-	-	-	-	-	
	MEX turbidity meter	20	-	-	-	47	-	-	-	-	-	-	-	-	
	Integrated bottle sampling	6	-	5	3	6	-	-	-	-	-	-	-	-	
	Collapsible bag	-	-	-	-	-	-	-	-	-	-	-	-	-	
Bed load	Dune tracking	-	-	-	-	-	-	-	-	-	-	-	-	-	
	Helley-smith sampler	5	-	-	-	12	-	-	-	-	-	-	-	-	
	Delft Bottle	6	-	6	3	19	-	-	-	-	-	-	-	-	
Bed material	US BM-54 bed sampler	-	-	-	-	-	-	-	-	-	-	-	-	-	
	Van Veen bed sampler	2	-	2	1	6	-	-	-	-	-	-	-	-	

Table 2.1 : Survey programme as made

Line no	Width (m)	Area (m ²)	Stage h (m+PWD)	Discharge Q (m ³ /s)	Bed load transport Sb (kg/s)	Suspended Sediment transport Ss total (kg/s)
BT5X042	555.23	5489.78	14.00	3055.31	3.82	630.44
BT5X043	396.90	3547.34	14.00	2039.62	-	-
BT5X044	734.92	5801.17	13.95	2543.39	0.00	738.76
BT5X046	679.24	5091.82	13.95	4362.53	-	-
BT5X052	1462.53	7681.94	13.94	5373.79	12.39	1050.38
BT5X053	406.63	2536.35	13.92	2704.38	-	-
BT5X055	726.59	3514.23	13.92	2907.27	-	-
BT5X056	453.84	2099.46	13.89	2041.75	-	-
BT5Y058	3209.12	18953.93	13.89	2576.25	-	-
BT5Y059	3129.24	13666.15	13.89	1296.99	-	-
BT5Y061	3226.11	22632.32	13.89	2979.44	-	-
BT5Y063	3241.99	22178.94	13.85	905.94	-	-
BT5Y008	3281.73	27275.01	13.85	3959.45	-	-

Table 2.2 : Key figures

Gauge Location	Date	Water level (Daily average) (m + PWD)	Gauge
Bahadurabad	04 Dec 94	14.00	FAP24
Bahadurabad	05 Dec 94	13.97	FAP24
Bahadurabad	06 Dec 94	13.95	FAP24
Bahadurabad	07 Dec 94	13.94	FAP24
Bahadurabad	08 Dec 94	13.92	FAP24
Bahadurabad	09 Dec 94	13.89	FAP24
Bahadurabad	10 Dec 94	13.85	FAP24

Table 2.3 : Water levels

Short Description : The survey which was done in the Jim's Bar area, North of Bahadurabad included parts relevant for different study topics : Optimization of sediment measuring techniques; bar topography and dune inventory, measurements of sediment transport near eroding banks and mapping of bed levels.

 FAP 24 RIVER SURVEY PROJECT Flood Plain Commission Organization Commission of the European Communities	Survey Bulletin 9040: 04 - 12 December, 1994		
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			2.1

Type of measurement	Method	No. of measurements in Lines													
		BT5X		BT5X	BT5X	BT5Y	BT5Y	BT5X	BT5X	BT5Y	BT5Y	BT5X	BT5Y	BT5Y	
		069	070	071	072	013	014	074	075	015	016	077	018	020	
Discharge	ADCP transect	2	2	2	2	1	1	1	1	1	1	1	1	1	
	EMF transect	2	2	2	2	1	1	1	1	1	1	1	1	1	
	Echo-Sounding	2	2	2	2	1	1	1	1	1	1	1	1	1	
Vertical current profile	No of verticals in channel	-	-	-	-	-	-	-	-	-	-	2	-	-	
	ADCP	-	-	-	-	-	-	-	-	-	-	2	-	-	
	S4 current meter	-	-	-	-	-	-	-	-	-	-	2	-	-	
	Ott current meter	-	-	-	-	-	-	-	-	-	-	-	-	-	
Vertical sediment profile	Pump bottle sampling	-	-	-	-	-	-	-	-	-	-	1	-	-	
	Andreasen settling tube	-	-	-	-	-	-	-	-	-	-	-	-	-	
	MEX turbidity meter	-	-	-	-	-	-	-	-	-	-	1	-	-	
	Integrated bottle sampling	-	-	-	-	-	-	-	-	-	-	-	-	-	
	Collapsible bag	-	-	-	-	-	-	-	-	-	-	-	-	-	
Bed load	Dune tracking	-	-	-	-	-	-	-	-	-	-	-	-	-	
	Helley-smith sampler	-	-	-	-	-	-	-	-	-	-	2	-	-	
	Delft Bottle	-	-	-	-	-	-	-	-	-	-	4	-	-	
Bed material	US BM-54 bed sampler	-	-	-	-	-	-	-	-	-	-	-	-	-	
	Van Veen bed sampler	-	-	-	-	-	-	-	-	-	-	1	-	-	

Table 2.1 : Survey programme as made

Line no	Width (m)	Area (m ²)	Stage h (m+PWD)	Discharge Q (m ³ /s)	Bed load transport Sb (kg/s)	Suspended Sediment transport Ss total (kg/s)
BT5X069	3174.02	23810.33	13.83	2273.03	-	-
BT5X070	470.39	3628.11	13.83	3503.31	-	-
BT5X071	694.47	4049.76	13.83	3573.73	-	-
BT5X072	1173.36	5832.84	13.83	4942.81	-	-
BT5Y013	1660.15	15206.65	13.83	425.65	-	-
BT5Y014	1313.81	7260.96	13.83	2090.54	-	-
BT5X074	698.29	3260.28	13.83	2928.62	-	-
BT5X075	868.23	4126.13	13.83	3287.29	-	-
BT5Y015	948.57	2841.66	13.83	418.45	-	-
BT5Y016	628.51	2242.09	13.83	575.7	-	-
BT5X077	558.82	5946.76	13.79	4916.01	2.00	2230.44
BT5Y018	1001.4	8022.78	13.79	1207.97	-	-
BT5Y020	4117.87	32336.7	13.79	7304.31	-	-

Table 2.2 : Key figures

Gauge Location	Date	Water level (Daily average) (m + PWD)	Gauge
Bahadurabad	11 Dec 94	13.83	FAP24
Bahadurabad	12 Dec 94	13.79	FAP24

Table 2.3 : Water levels

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Int : kah			2.2

Transect file name	Profile file name	Line no	Survey date	Type of data
B4C41T03 *		BT5X042	1994-12-04	ADCP/EMF+Echosounding
B4C41T05 *		BT5X043	1994-12-04	ADCP/EMF+Echosounding
B4C51T03 *		BT5X042	1994-12-05	ADCP/EMF+Echosounding
	B4C51P03	BT5X042	1994-12-05	ADCP/S4/EMF+Echosounding+Sediment
	B4C51P04	BT5X042	1994-12-05	ADCP/S4/EMF+Echosounding+Sediment
B4C61T01 *		BT5X044	1994-12-06	ADCP/EMF+Echosounding
B4C61T03 *		BT5X046	1994-12-06	ADCP/EMF+Echosounding
	B4C61P02	BT5X044	1994-12-06	ADCP/EMF+Echosounding+Sediment
	B4C61P03	BT5X044	1994-12-06	ADCP/EMF+Echosounding+Sediment
	B4C61P06	BT5X046	1994-12-06	ADCP/EMF+Echosounding+Sediment
B4C71T02		BT5X048	1994-12-07	ADCP/EMF+Echosounding
B4C71T03		BT5X049	1994-12-07	ADCP/EMF+Echosounding
B4C71T04		BT5X050	1994-12-07	ADCP/EMF+Echosounding
B4C71T05		BT5X050	1994-12-07	ADCP/EMF+Echosounding
B4C71T06		BT5X051	1994-12-07	ADCP/EMF+Echosounding
B4C71T07 *		BT5X052	1994-12-07	ADCP/EMF+Echosounding
	B4C71P03	BT5X052	1994-12-07	ADCP/S4/EMF+Echosounding+Sediment
	B4C71P04	BT5X052	1994-12-07	ADCP/S4/EMF+Echosounding+Sediment
	B4C81P01	BT5X052	1994-12-08	ADCP/S4/EMF+Echosounding+Sediment
	B4C81P02	BT5X052	1994-12-08	ADCP/S4/EMF+Echosounding+Sediment
	B4C81P03	BT5X052	1994-12-08	ADCP/S4/EMF+Echosounding+Sediment
	B4CA1P01	BT5X052	1994-12-10	ADCP/S4/EMF+Echosounding+Sediment
B4C81T01 *		BT5X053	1994-12-08	ADCP/EMF+Echosounding
B4C81T02 *		BT5X055	1994-12-08	ADCP/EMF+Echosounding
B4C81T03 *		BT5X054	1994-12-08	Echosounding
B4C91T02 *		BT5X056	1994-12-09	ADCP/EMF+Echosounding
B4C91T03		BT5X057	1994-12-09	ADCP/EMF+Echosounding
B4C91T05 *		BT5Y058	1994-12-09	ADCP/EMF+Echosounding
B4C91T06 *		BT5Y059	1994-12-09	ADCP/EMF+Echosounding
B4C91T07		BT5Y060	1994-12-09	ADCP/EMF+Echosounding
B4C91T08 *		BT5Y061	1994-12-09	ADCP/EMF+Echosounding
B4CA1T01 *		BT5Y063	1994-12-10	ADCP/EMF+Echosounding
B4CA1T03 *		BT5Y063	1994-12-10	ADCP/EMF+Echosounding
B4CA1T04 *		BT5Y063	1994-12-10	ADCP/EMF+Echosounding
B4CA1T05 *		BT5Y063	1994-12-10	ADCP/EMF+Echosounding
B4CA1T06 *		BT5Y008	1994-12-10	ADCP/EMF+Echosounding

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Transect file name	Profile file name	Line no	Survey date	Type of data
B4CB1T01		BT5X068	1994-12-11	ADCP/EMF+Echosounding
B4CB1T02		BT5X068	1994-12-11	ADCP/EMF+Echosounding
B4CB1T03		BT5X069	1994-12-11	ADCP/EMF+Echosounding
B4CB1T04 *		BT5X069	1994-12-11	ADCP/EMF+Echosounding
B4CB1T05		BT5X070	1994-12-11	ADCP/EMF+Echosounding
B4CB1T06 *		BT5X070	1994-12-11	ADCP/EMF+Echosounding
B4CB1T07		BT5X071	1994-12-11	ADCP/EMF+Echosounding
B4CB1T08 *		BT5X071	1994-12-11	ADCP/EMF+Echosounding
B4CB1T09 *		BT5X072	1994-12-11	ADCP/EMF+Echosounding
B4CB1T10 *		BT5X072	1994-12-11	ADCP/EMF+Echosounding
B4CB1T11 *		BT5Y013	1994-12-11	ADCP/EMF+Echosounding
B4CB1T12 *		BT5Y014	1994-12-11	ADCP/EMF+Echosounding
B4CB1T13 *		BT5X075	1994-12-11	ADCP/EMF+Echosounding
B4CB1T14		BT5X076	1994-12-11	ADCP/EMF+Echosounding
B4CB1T15 *		BT5Y015	1994-12-11	ADCP/EMF+Echosounding
B4CB1T16		BT5Y016	1994-12-11	ADCP/EMF+Echosounding
B4CB1T17 *		BT5Y016	1994-12-11	ADCP/EMF+Echosounding
B4CB1T18 *		BT5X074	1994-12-11	ADCP/EMF+Echosounding
B4CC1T01		BT5X042	1994-12-12	ADCP/EMF+Echosounding
B4CC1T03 *		BT5X077	1994-12-12	ADCP/EMF+Echosounding
B4CC1T04 *		BT5Y018	1994-12-12	ADCP/EMF+Echosounding
B4CC1T06 *		BT5Y020	1994-12-12	ADCP/EMF+Echosounding
	B4CC1P01	BT5X077	1994-12-12	ADCP/S4/EMF+Echosounding+Sediment
	B4CC1P02	BT5X077	1994-12-12	ADCP/S4/EMF+Echosounding+Sediment

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	Init : kah		

Survey date	File name	Line no	.ase	.ech	.lrs	.sed	.bdl	.bdm	.ssc	.ssz	.prf	.lng
1994-12-04	B4C41T03	BT5X042	+	+	+							
	B4C41T05	BT5X043	+	+	+							
1994-12-05	B4C51T03	BT5X042	+	+	+	+	+	+	+	+		
1994-12-06	B4C61T01	BT5X044	+	+	+	+	+	+	+	+		
	B4C61T03	BT5X046	+	+	+							
1994-12-07	B4C71T01	BT5X052	+	+	+	+	+	+	+			
1994-12-08	B4C81T01	BT5X053	+	+	+							
	B4C81T02	BT5X055	+	+	+							
	B4C81T03	BT5X054	+	+	+							
1994-12-09	B4C91T02	BT5X056	+	+	+							
	B4C91T05	BT5X058	+	+	+							
	B4C91T06	BT5X059	+	+	+							
	B4C91T08	BT5X061	+	+	+							
1994-12-10	B4CA1T01	BT5X063	+	+	+							
	B4CA1T03	BT5X063	+	+	+							
	B4CA1T04	BT5X063	+	+	+							
	B4CA1T05	BT5X063	+	+	+							
	B4CA1T06	BT5Y008	+	+	+							
1994-12-11	B4CB1T04	BT5X069	+	+	+							
	B4CB1T06	BT5X070	+	+	+							
	B4CB1T08	BT5X071	+	+	+							
	B4CB1T09	BT5X072	+	+	+							
	B4CB1T10	BT5X072	+	+	+							
	B4CB1T11	BT5Y013	+	+	+							
	B4CB1T12	BT5Y014	+	+	+							
	B4CB1T13	BT5X075	+	+	+							
	B4CB1T15	BT5Y015	+	+	+							
	B4CB1T17	BT5Y016	+	+	+							
1994-12-12	B4CC1T03	BT5X077	+	+	+	+	+	+	+			
	B4CC1T04	BT5Y018	+	+	+							
	B4CC1T05	BT5Y020	+	+	+							
Total number of files			32	32	32	4	4	4	4	2		
Table 4.1: PSD24 Database file description												

 FAP 24 RIVER SURVEY PROJECT Food and Agriculture Organization of the United Nations DEFT - DHI	Survey Bulletin 9040: 04 - 12 December, 1994	
	Jamuna River, Sediment Transport and Morphology	
Date 04 Mar 1996	Psd24 database file description	page 41
Init kan		

Annexure G5

Study Survey

Near-bed sediment transport measurements 1-4 April 1995

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1 Introduction

The optimization of sediment transport measurements is part of study topic 9, Measuring techniques, see RSP, Study Programme, February 1995. In several study surveys measurements of near-bed sediment transport were done with different types of instruments, such as the Delft Bottle sampler, Helley-Smith trap sampler and a pump-bottle sampler. The main objectives of this part of study topic 9 are the selection of an optimal gauging strategy and the description of the physical phenomena of near-bed sediment transport. The comparison of the results of different instrument is used to recommend measuring methods which are optimal for the main rivers in considerations of accuracy, cost and sustainability. The measurements were analyzed to describer the near bed sediment transport indetail. Several similar surveys each taking a few days, were carried out to cover the whole range of flow conditions in the Jamuna River.

In the first days of April 1995 a study survey has been executed in the left channel of the Jamuna River near Bahadurabad at the end of the lean season. The specific objectives of this study survey are:

- comparison of the bed load measured by different instruments
- assessment of the variability of the sediment samples by series of repeated samples
- to relate the sediment transport to the flow conditions and the bedforms.

The programme of the measurements in this survey is described in Chapter 2. A primary analysis of the different parameters is presented in Chapter 3, followed by a discussion of the results in Chapter 4. The conclusions of this surveys are summarized in Chapter 5.

2 Study survey programme

The programme of the near bed sediment transport measurements consisted of four types of measurements:

- Measurements by the Delft Bottle in one vertical at different heights from the bed.
- Sounding with side scan and dual frequency echosounder to determine the shape of the bedforms in the area of the measurements.
- Measurements to compare the sediment transport measured by different instruments. The sediment transport rate and the grain size distribution were determined. Samples of the bed material were taken to determine also the grain size distribution of the bed material.
- Time series of repeated measurements by a sampler.

For all measurements were taken from the DHA survey vessel. The instruments used for these measurements, are listed in Table G5.1.

The reconnaissance survey was made 31 March 1995. The measurements started 1 April and continued for the next three days. On April 2 the Project Management Unit participated in the surveys.

The survey was done in the left channel of the Jamuna river near Bahadurabad, (see Figure G5.1). The planform in that figure was traced from the SPOT image of 24 March 1995. It may be assumed that the planform did not change between 24 March and the date of the survey, about one week later. All the samples were taken in one vertical, located Easting 469,641 Northing 775,273 on 1 April. The next days this vertical was shifted a few meters in downstream direction to maintain the same position of the vertical relative to the dunes on the river bed.

In a reconnaissance survey this location was selected because the flow field was homogeneous, the water depth was between 5 and 10 m and the river bed was covered by a regular pattern of dunes indicating sufficient sediment transport rate.

3 Results of measurements

3.1 Introduction

The near bed sediment transport depends very much on the hydraulic conditions, especially the flow velocities. The measurements of the flow velocities by different instruments are indicated in Table G5.2. These measurements together with the water levels are presented in Section 3.2.

The propagating dunes in the selected survey area were measured by dune tracking using an echosounder or a side scan-sonar, Section 3.3.

The measurements of the near bed sediment transport with different instruments are presented in Section 3.4, where also a preliminary analysis of these measurements is given together with the bed material samples. The sampling of the near bed sediment transport is listed in Table G5.2. In this survey also measurements of the suspended load were made, see Table G5.2, but these are presented partially only in this Section.

3.2 Hydraulic conditions

The water-levels as read from the gauges of BWDB and RSP in Bahadurabad were stable during the survey 13.47 to 13.53 m + PWD, after a gradually rise of the water level in the previous week, see Figure G5.2. After the survey was completed on 4 April the water level raised quickly to a peak of 14.03 m + PWD at 10 April.

The flow velocities were measured in one vertical, see figure G5.3. In the low flow conditions the flow velocity ranged from 0.7 to 0.9 m/s in the selected vertical. The flow velocity tended to increase with about 0.02 m/s per day. The ADCP measured the flow velocities in moving boat method while sailing transects and longitudinal lines. The vector-plots of the flow velocities measured by the ADCP in a cross-section give an impression on the homogeneity of the flow.

On the last day of the survey the results obtained with the Ott current meter are checked against the results of comparative measurements with the S4 and the ADCP. After cleaning of the instrument the flow velocity according to the Ott current meter was comparable with the flow velocities measured by ADCP and S4.

3.3 Bedforms

At the measuring site the side-scan sonar indicated that the mainly two-dimensional dunes in the beginning of the survey changed gradually in more three-dimensional dunes at the end of the survey, see the examples in Figure G5.4, covering an area 50 m by 200 m. This significant change took place in spite of the relatively stable hydraulic conditions (stable water level and a slight increase of the flow velocities).

In longitudinal tracks passing the measuring verticals the size of the bedforms was determined, see for example the echosounder signal in Figures G5.5 and G5.6. At the site regular dunes with a height of 0.7 to 1.3 m and a length of 20 to 30 m were found.

3.4 Near-bed sediment transport

The near bed sediment transport measured and bed material sampled during this study survey is indicated in the Table G5.2.

This programme enables to compare the results per day and also the results of different days because the hydraulic conditions did not change much. Therefore the results of the near bed measurements are summarized per day in a series of tables and graphs.

Delft Bottle and Helley-Smith samples

The variability of 6 DB05 samples collected during 5 minutes periods, is 0.03 to 0.15 kg/(m².s) and the average transport is 0.09 kg/(m².s), see Figure G5.7. All these samples contained organic material. The data is presented in Table G5.3. From 12 to 14.15 hours the sediment transport is rather constant but from 14.15 to 14.45 hours the sediment transport tends to decrease and the grain size distribution tends to shift to finer fractions. This variability seems to differ from the natural variability. A possible reason is the propagation of a dune front. The results in Figure G5.7 probably mean that in low flow conditions the coarse fraction hardly reaches the level of 0.05 m above the bed. This would be expected if the coarse fraction is transported as bed load. Therefore the DB curves in that graph show small D₅₀ values in spite of loosing part of the fine fractions.

After these measurements 2 H-S samples were taken. The sediment transport in the H-S samples is higher than the last DB05 samples. The grain size distribution is considerably more coarse than of the DB05 samples or the bed material sample, because of considerable loss of the fine fraction through the gauze of the H-S sampler.

The sediment transport measured by the Delft Bottle at four distances from the river bed are compared with 10 H-S samples in Figure G5.8. The average sediment transport of DB05 is 0.24 kg/(m².s) which is twice the sediment transport rate measured the day before (0.09 or 0.12 kg/(m².s)). The variation in the sediment transport measured at 0.15, 0.25 and 0.35 m above the bed is small compared with the small variation in the sediment transport of repeated samples, see Figure G5.7.

The average sediment transport measured by H-S sampler is 0.09 kg/(m².s) on 1 April, 0.18 kg/(m².s) on 3 April and 0.060 kg/(m².s) on 4 April, see the data of all these samples in Table G5.4. This variation in the H-S sediment transport is dependent on the position of the sampler relative to the dunes, although via soundings the relative position was kept constant as far as feasible, see also chapter 2. Also the constant hydraulic conditions (during the survey) would not cause a strongly varying sediment catch by the H-S. So again the erratic process of the near bed transport (Peters 1994) may be the main reason. The H-S sediment transport on 3 April is slightly less than measured by the DB05. It should be noted that in case the H-S catches zero the measurement is repeated. Because it is assumed that in that case the sampler is not well positioned on the river bed.

The grain sizes are increasing considerably from 0.35 m to 0.05 m above the bed, to the bed material samples. This increase follows a certain pattern. If this result is combined with the small variation in the sediment transport in the samples at 0.15, 0.25 and 0.35 m above the bed than it seems to be sufficient for the sampling of the near bed sediment transport measurements in the routine gaugings to take samples at 0.05 and 0.15 m above the bed only.

The grain size distribution of the DB05 samples in Figure G5.9 is similar to the distribution of the DB05 samples collected one day earlier in Figure G5.7.

The grain size distribution of the H-S samples is more coarse than the grain size distribution of the bed material samples because a part of the fine fraction can pass the gauze of the H-S sampler. The variability of sediment transport and of grain size distribution of the DB15, DB25 and DB35 samples is small, but the variability of the DB05 samples is significantly larger: towards the bed the variability increases, see Figure G5.9.

The variability of the H-S samples is large, probably slightly larger than the variability in DB05 samples, and significantly larger than DB25 samples, see Figure G5.10. This larger variability in the samples taken close to the bed is probably partly caused by dragging the sampler over the bed at the moment to start hoisting the instrument and the different sampling times: 5 minutes for DB and 2 minutes for H-S. Because the survey vessel DHA was anchored on one anchor therefore it was swaying in the flow.

There is no clear tendency in the transport as a function of time on 3 April.

Comparison pump-bottle and Delft Bottle catch

The grain sizes of the pump-bottle samples are considerably lower than the Delft-bottle results, see data of all pump-bottle samples in Tables G5.5 and G5.6. This is caused by the loss of fine sediments through the Delft Bottle. This loss can be estimated by comparing the samples taken by both instruments at the same distance (0.25 m) to the bed and on the same day. The pump-bottle samples indicate that the percentages of the fine and the coarse fraction are both about 50 %. The Delft Bottle caught about 20 % fine material, that is about 1/4 of the coarse material (80 %). This means that the DB25 is missing 37.5 % of the catch resulting in a correction factor of $1/0.625 = 1.6$, see Table G5.3.

In the above considerations it is implicitly assumed that the catches of the pump-bottle are correct and that the Delft Bottle is only losing part of the fine fraction. To check whether the coarse fractions of the catches of both the instruments are the same, the sieving curves are given for the coarse fraction only in Figure G5.11. It can be concluded that the composition of the coarse sediment fraction as collected by the pump-bottle system and the Delft Bottle are very similar.

Pump-bottle sampler

Several pump bottle samples were taken with different pump speeds on the last day of the survey, 4 April, see Figure G5.12. The wash load does not change if the pump speed is increased from 5 l/minute to 10 l/minute. But a higher pump speed seems to increase the concentration of the bed material load 10 to 20 %. This increase is small compared with the variability in sediment concentration measurements.

4 Conclusions

The conclusions from these tests in low flow conditions are as follows :

- The flow conditions : water-levels and velocities were rather steady during the survey period from 1 to 4 April 1994. The river bed was covered by two- and three dimensional dunes, with a typical height of 1 m.
- The near bed sediment transport is considerably increasing in the lowest 0.1 m of a vertical. Also the variability of the transport is strongly increasing towards the river bed, because of the increased turbulence intensity in the flow and the sampling technique (dragging the sampler over the bed and inaccuracies in positioning of the sampler). That's why the H-S. results are more scattered than the DB05. Moreover it explains why the H-S catch (giving an average transport over 0.076 m height) should be smaller than the DB05 catch, especially when the maximum transport is near the 0.05 level. This also implies that quite a number of samples with the H-S have to be taken to get a reliable average value. A gauging strategy for the Helley-Smith sampler should include at least two samples.
- In a vertical the grain sizes are substantially increasing towards the river bed. This also holds for the variability of the grain sizes See figure G5.14.
- Comparison of the near bed grain size distributions from samples taken by different type of instruments in the same flow field reveals that:
the grain size distribution of pump-bottle samples < grain size distribution of Delft Bottle samples < grain size distribution of bed material samples < grain size distribution of H-S samples. The catches of the pump-bottle sampler and the Delft Bottle sampler of the coarse fraction are about the same. So the Delft Bottle is mainly losing part of the silt and clay fraction ($D < 0.06$ mm). This explains why the grain size distribution of the pump-bottle samples is finer than the grain size distribution of the Delft Bottle samples.

Delft Bottle measurements are not done lower than at 0.05 m above the river bed. The above figure explains why the grain size distribution of the Delft Bottle samples is finer than the grain size distribution of the bed material samples.

H-S sampler is not catching material finer than 0.125 mm and also part of the 0.125 to 0.25 mm fraction will be lost, as the bag of this sampler is made of a gauze with mesh sizes of 0.25 mm. This explains why the grain size distribution of the bed-material samples are finer than the grain size distribution of the H-S samples.
- From the above comparison it seems justified to limit the use of the H-S sampler. On the other hand it should be noted that only with the H-S the coarsest fractions are caught as the pump-bottle sampler and the Delft Bottle sampler cannot measure in the last few cm above the river bed.

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- From the above figures it is concluded that the layer thickness of the near bed zone in low flow condition is only 0.15 m. This indicates that a gauging strategy for the Delft Bottle sampling should include at least two samples: one taken at 0.05 and one at 0.15 m above the bed.

References

Delft Hydraulics and Danish Hydraulic Institute, River Survey Project, Study programme, February 1995, Dhaka, Bangladesh

Peters, J.J (1994). Report on Mission Project Advisor, Seventh mission. River Survey Project (FAP 24), Bangladesh.

Item	instruments
Flow velocity	ADCP, S4, EMF, Ott current meter
Suspended sediment transport	Depth-Integrating-bottle, collapsible bag, pump-bottle sampler,
Near-bed sediment transport	Pump-bottle (25 L bulb samples), Helley-Smith sampler, Delft
Bed forms	Echosounder, side scan sonar

Table G5.1 : Type of measurements and the instruments used

Sampling Activities	April				
	31	1	2	3	4
Reconnaissance, side scan sonar, transects	xxxx				xxxx
Northing of vertical (m)		775,273	775,269	775,267	775,263
Flow velocities 7 ADCP + 1 S4 14 ADCP + 14 S4 5 ADCP 3 ADCP + 1 EMF + 8 S4 + 1 Ott		xxxx	xxxx	xxxx	xxxx
Suspended sediment transport 7 ADCP backsc. + 4 p-b + 2 DIS + 2 C.Bag + 3 DB420 14 ADCP backsc. + 8 p-b + 14 DIS + 14 C.bag + 14 MEX + 12 DB400 + 3 DBdi 5 ADCP backsc. + 5 DIS + 5 DBdi 3 ADCP backsc.		xxxx	xxxx	xxxx	xxxx
Near-bed sediment transport 6 DB05 + 2 H-S 1 p-b 25 litre 3 DB05 + 3 DB15 + 3 DB25 + 3 DB35 + 10 H-S + 3 p-b 25L 6 DB25 + 6 H-S + 8 p-b 2 litre 2 p-b20		xxxx	xxxx	xxxx	xxxx
Bed material samples 2 USBM bed material samples - 5 USBM bed material samples 2 USBM bank material samples 2 USBM bed material samples * numbers are the numbers of samples		xxxx	xxxx	xxxx xxxx	xxxx

LEGEND :

p-b = pump-bottle sample, ADCP = Acoustic Doppler Current Profiler,
 S4 = an electromagnetic current meter, EMF = Electromagnetic Flow Meter
 DB05 = Delft Bottle sample at 0.05 m above the river bed, Ott = a mechanical current meter
 H-S = Helley-Smith sample, Mex = Optical turbidity meter, C.Bag = collapsible bag
 USBM = instrument to take bed material samples, DIS = depth integrating bottle sampler

Table G5.2 : Main survey activities and the number of samples taken

Vertical No.	Sample No.	Date	Time	Total Depth(m)	Collection Depth(m)	D35 (mm)	D50 (mm)	D65 (mm)	Weight. <0.063(mm)	Percent >0.063(mm)	G. Standard Deviation	Transporte Rate (kg/(m ² -s))
1	A398	01/04/95	12:00	6.70	6.65	0.108	0.141	0.174	10.823	89.177	1.805	0.145847
1	A508	01/04/95	12:07	6.70	6.65	0.101	0.133	0.166	10.612	89.388	1.781	0.124408
1	A170	01/04/95	12:25	6.70	4.00	0.069	0.082	0.096	25.863	74.137	-	0.031978
1	A173	01/04/95	12:35	6.70	4.00	0.069	0.080	0.094	26.816	73.184	-	0.027709
1	A150	01/04/95	13:55	6.70	4.00	0.071	0.083	0.096	23.452	76.548	-	0.030509
1	A658	01/04/95	14:15	6.70	6.65	0.101	0.134	0.167	12.183	87.817	1.806	0.129546
1	A148	01/04/95	14:25	6.70	6.65	0.076	0.094	0.116	21.322	78.678	-	0.065247
1	A428	01/04/95	14:32	6.70	6.65	0.076	0.093	0.113	21.160	78.840	-	0.046058
1	A430	01/04/95	14:45	6.70	6.65	0.071	0.086	0.104	25.230	74.770	-	0.032621
1	A392	02/04/95	10:10	7.10	4.20	0.073	0.085	0.099	21.244	78.756	-	0.023066
1	A434	02/04/95	10:22	7.10	4.20	0.074	0.086	0.100	19.566	80.434	-	0.024173
1	A443	02/04/95	10:34	7.10	4.20	0.072	0.085	0.099	21.420	78.580	-	0.022099
1	A424	02/04/95	10:45	7.10	4.20	0.072	0.084	0.099	21.870	78.130	-	0.023703
1	A426	02/04/95	10:56	7.10	4.20	0.072	0.084	0.098	21.150	78.850	-	0.023934
1	A673	02/04/95	11:07	7.10	4.20	0.072	0.084	0.098	22.870	77.130	-	0.023441
1	A154	02/04/95	11:20	7.10	4.20	0.071	0.083	0.097	23.373	76.627	-	0.028059
1	A387	02/04/95	11:31	7.10	4.20	0.071	0.084	0.099	23.405	76.595	-	0.019978
1	A523	02/04/95	11:42	7.10	4.20	0.074	0.086	0.100	18.677	81.323	-	0.023860
1	A500	02/04/95	11:54	7.10	4.20	0.074	0.087	0.101	18.657	81.343	-	0.022178
1	A174	02/04/95	12:05	7.10	4.20	0.074	0.087	0.101	18.544	81.456	-	0.024435
1	A672	02/04/95	12:16	7.10	4.20	0.071	0.083	0.097	24.393	75.607	-	0.026280
1	A662	02/04/95	14:15	7.10	Depth Intg.	0.070	0.081	0.095	25.223	74.777	-	0.021113
1	A474	02/04/95	13:42	7.10	Depth Intg.	0.070	0.082	0.096	24.674	75.326	-	0.019776
1	A206	02/04/95	14:45	7.10	Depth Intg.	0.068	0.080	0.095	28.044	71.956	-	0.016241
1	A171	03/04/95	11:55	6.60	0.50	0.068	0.079	0.092	28.227	71.773	-	0.014273
1	A524	03/04/95	12:08	6.60	1.50	0.067	0.079	0.092	29.210	70.790	-	0.021968
1	A190	03/04/95	12:19	6.60	2.50	0.066	0.078	0.093	30.536	69.464	-	0.015898
1	A147	03/04/95	12:34	6.60	3.50	0.068	0.080	0.094	28.439	71.561	-	0.031109
1	A441	03/04/95	12:50	6.60	4.50	0.073	0.086	0.100	20.101	79.899	-	0.031401
1	A577	03/04/95	13:46	6.60	6.55	0.108	0.140	0.173	8.665	91.335	1.766	0.147241
1	A194	03/04/95	13:54	6.60	6.45	0.081	0.100	0.124	16.618	83.382	-	0.080323
1	A433	03/04/95	14:02	6.60	6.35	0.076	0.093	0.113	20.394	79.606	-	0.066324
1	A429	03/04/95	14:10	6.60	6.25	0.073	0.089	0.108	23.044	76.956	-	0.047812
1	A151	03/04/95	14:42	6.60	6.55	0.127	0.153	0.183	6.360	93.640	1.708	0.251631
1	A513	03/04/95	15:00	6.60	6.45	0.087	0.110	0.142	15.187	84.813	1.773	0.098937
1	A184	03/04/95	15:08	6.60	6.35	0.084	0.103	0.129	14.906	85.094	1.732	0.095000
1	A625	03/04/95	15:16	6.60	6.25	0.076	0.092	0.111	20.211	79.789	-	0.062883
1	A224	03/04/95	16:00	6.60	6.55	0.148	0.178	0.214	3.986	96.014	1.746	0.317000
1	A177	03/04/95	16:08	6.60	6.45	0.082	0.102	0.127	16.771	83.229	-	0.083857
1	A494	03/04/95	16:16	6.60	6.35	0.073	0.089	0.108	23.234	76.766	-	0.064948
1	A498	03/04/95	16:23	6.60	6.25	0.075	0.091	0.111	20.870	79.130	-	0.061401
1	A847	04/04/95	10:29	7.10	6.85	0.081	0.099	0.121	16.889	83.111	-	0.081054
1	A217	04/04/95	11:04	7.10	6.85	0.083	0.104	0.132	16.331	83.669	-	0.083985
1	A221	04/04/95	11:17	7.10	6.85	0.082	0.100	0.122	15.581	84.419	1.739	0.081604
1	A153	04/04/95	11:27	7.10	6.85	0.085	0.104	0.128	12.619	87.381	1.721	0.073948
1	A208	04/04/95	11:44	7.10	6.85	0.081	0.098	0.119	15.353	84.647	1.699	0.084534
1	A593	04/04/95	12:09	7.10	6.85	0.080	0.097	0.119	17.578	82.422	-	0.086299

Table G5.3 Analysis Delft Bottle samples, 1 to 4 April

GGY

Vertical No.	Sample No.	Date	Time	D35 (mm)	D50 (mm)	D65 (mm)	Weight. Percent		G. Standard Deviation	Transport Rate (kg/m-s)	Average D50 (mm)
							<0.063(mm)	>0.063(mm)			
1	C254	01/04/95	15:00	0.262	0.304	0.354	0.102	99.898	1.556	0.007456	
1	C222	01/04/95	15:05	0.251	0.295	0.347	0.191	99.809	1.585	0.006012	0.300
1	A339	03/04/95	12:06	0.284	0.327	0.378	0.078	99.922	1.483	0.011706	
1	A1138	03/04/95	12:09	0.265	0.309	0.360	0.099	99.901	1.550	0.005461	0.318
1	A56	03/04/95	12:32	0.264	0.307	0.357	0.077	99.923	1.547	0.012959	
1	A366	03/04/95	12:36	0.226	0.279	0.334	0.075	99.925	1.609	0.024457	0.293
1	A739	03/04/95	14:27	0.241	0.290	0.344	0.052	99.948	1.598	0.031524	
1	A348	03/04/95	14:31	0.270	0.313	0.362	0.072	99.928	1.529	0.028728	0.302
1	A337	03/04/95	15:30	0.280	0.323	0.373	0.101	99.899	1.495	0.006235	
1	A1360	03/04/95	15:34	0.203	0.251	0.310	0.376	99.624	1.614	0.001855	0.287
1	A1145	03/04/95	16:38	0.249	0.294	0.347	0.505	99.495	1.596	0.001699	
1	A59	03/04/95	16:40	0.256	0.300	0.351	0.191	99.809	1.570	0.002250	0.297
1	C003	04/04/95	10:43	0.214	0.268	0.327	0.122	99.878	1.632	0.020302	
1	A362	04/04/95	11:10	0.263	0.307	0.358	0.270	99.730	1.560	0.002739	0.288
1	A2255	04/04/95	11:25	0.252	0.298	0.352	0.069	99.931	1.598	0.007626	
1	A3025	04/04/95	11:38	0.272	0.316	0.366	0.102	99.898	1.529	0.010558	0.307
1	A1931	04/04/95	11:52	0.271	0.315	0.365	0.551	99.449	1.547	0.003777	
1	A2220	04/04/95	12:08	0.207	0.257	0.315	0.294	99.706	1.619	0.002036	0.286

Table G5.4 Analysis Helley-Smith samples, 1 to 4 April 1995

Sample No.	Vertical No.	Date	Total Depth (m)	Collection Depth (m)	Weight. Percent		D10 (mm)	D16 (mm)	D35 (mm)	D50 (mm)	D90 (mm)	Geometric Standard Deviation
					<0.063(mm)	>0.063(mm)						
A851	-	02/04/95	-	-	64.086	35.914	0.007	0.008	0.021	0.034	0.109	3.537
A858	1	03/04/95	7.20	6.32	57.004	42.996	0.007	0.009	0.025	0.042	0.118	3.583
A725	1	03/04/95	7.20	6.30	45.949	54.051	0.010	0.017	0.042	0.069	0.173	3.000
A452	1	03/04/95	7.20	6.30	51.846	48.155	0.009	0.012	0.029	0.055	0.125	3.310

Table G5.5 Analysis pump-bottle 25 liter samples, 2 and 3 April 1995



Sample No.	Vertical No.	Date	Time	Total Depth (m)	Collection Depth (m)	Suspended Sediment Concentration		
						Wash Load (mg/l)	Bed Material Load (mg/l)	Total (mg/l)
One Liter Samples								
B048	1	01/04/95	13:55	6.70	4.00	91.47	38.02	129.49
B082	1	01/04/95	15:00	6.70	4.00	90.99	23.42	114.41
B046	1	01/04/95	15:10	7.00	?	94.78	24.97	119.75
B115	1	01/04/95	15:15	7.00	?	88.37	24.02	112.39
B177	1	02/04/95	10:25	7.10	4.00	91.15	27.59	118.75
B233	1	02/04/95	10:38	7.10	4.00	88.99	23.64	112.62
B120	1	02/04/95	10:50	7.10	4.00	79.80	29.68	109.48
B237	1	02/04/95	11:07	7.10	4.00	88.03	34.46	122.49
B227	1	02/04/95	11:23	7.10	4.00	82.24	29.27	111.51
B226	1	02/04/95	11:54	7.10	4.00	97.65	25.76	123.41
B121	1	02/04/95	11:38	7.10	4.00	102.24	32.43	134.66
B118	1	02/04/95	12:08	7.10	4.00	98.10	29.04	127.14
B025	1	03/04/95	12:38	7.20	4.00	95.55	33.82	129.37
B089	1	03/04/95	12:59	7.20	4.00	100.92	34.52	135.44
Two Liter Samples								
C061	1	04/04/95	10:16	6.80	6.60	109.89	81.10	190.99
C224	1	04/04/95	10:22	6.80	6.60	132.45	94.20	226.65
A2142	1	04/04/95	10:30	6.80	6.60	137.43	62.50	199.93
C239	1	04/04/95	10:32	6.80	6.60	124.42	93.60	218.02
C267	1	04/04/95	11:36	6.80	6.60	80.75	85.20	165.95
C055	1	04/04/95	11:39	6.80	6.60	169.33	250.50	419.83
C044	1	04/04/95	11:42	6.80	6.60	132.20	99.30	231.50
C034	1	04/04/95	11:45	6.80	6.60	125.97	109.20	235.17

Table G5.6 Analysis pump-bottle 1 and 2 liter samples, 1 to 4 April 1995

Instrument	Fine fraction (percentage)	Coarse fraction (percentage)
Pump-bottle	50	50
Delft Bottle DB25	12½	50

Table G5.7 Comparison of the fine and the coarse fractions caught by the pump-bottle sampler and the Delft Bottle.

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Sample No.	Vertical No.	Date	Time	Total Depth (m)	Suspended Sediment Concentration		
					Wash Load (mg/l)	Bed Material Load (mg/l)	Total (mg/l)
C236	1	01/04/95	15:20	6.70	86.96	21.00	107.96
C246	1	01/04/95	15:25	6.70	91.46	23.50	114.96
C228	1	02/04/95	10:22	7.10	97.26	34.30	131.56
C251	1	02/04/95	10:40	7.10	84.81	32.30	117.11
C244	1	02/04/95	10:55	7.10	98.59	114.20	212.79
C241	1	02/04/95	11:10	7.10	90.80	83.20	174.00
C248	1	02/04/95	11:24	7.10	88.61	30.00	118.61
C223	1	02/04/95	11:41	7.10	87.18	21.50	108.68
C238	1	02/04/95	11:52	7.10	90.06	23.70	113.76
C265	1	02/04/95	12:04	7.10	80.45	24.90	105.35
C060	1	02/04/95	14:00	7.10	63.74	5.20	68.94
C263	1	02/04/95	14:13	7.10	59.55	13.00	72.55
C264	1	02/04/95	14:30	7.10	69.51	10.00	79.51
C247	1	02/04/95	14:43	7.10	80.00	11.90	91.90
C001	1	02/04/95	15:02	7.10	80.00	38.10	118.10
C014	1	02/04/95	15:13	7.10	83.24	28.50	111.74
C266	1	03/04/95	12:16	7.20	80.98	26.00	106.98
C069	1	03/04/95	12:31	7.20	77.27	14.70	91.97
C225	1	03/04/95	14:25	7.20	107.34	82.70	190.04
C042	1	03/04/95	15:25	7.20	87.50	62.30	149.80
C040	1	03/04/95	16:34	7.40	93.49	34.90	128.39

Table G5.8 Analysis samples by depth integrating sampler, 1 to 3 April 1995

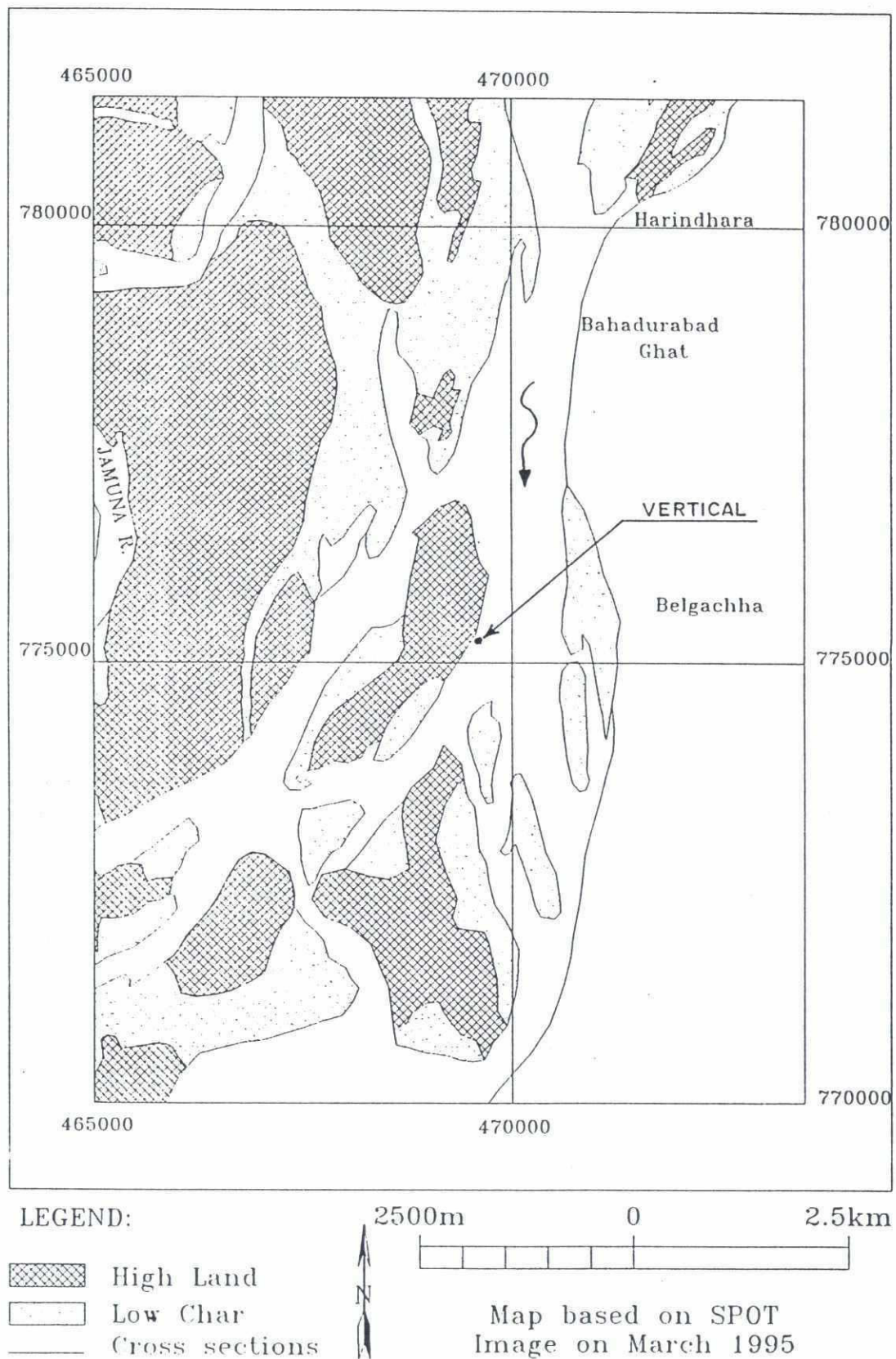


Figure G5.1 : Location Map

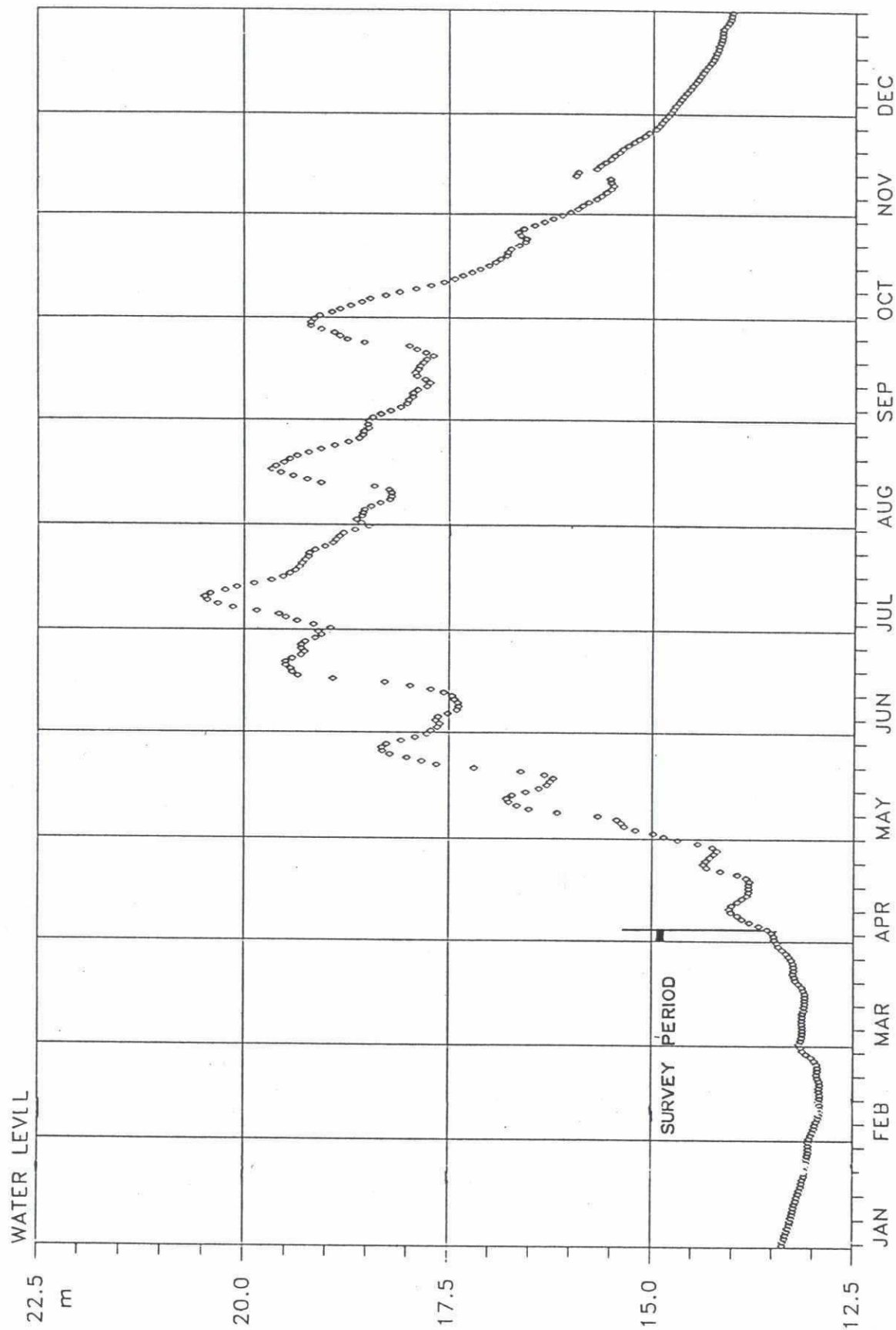


Figure G5.2 : Water levels at Bahadurabad in 1995

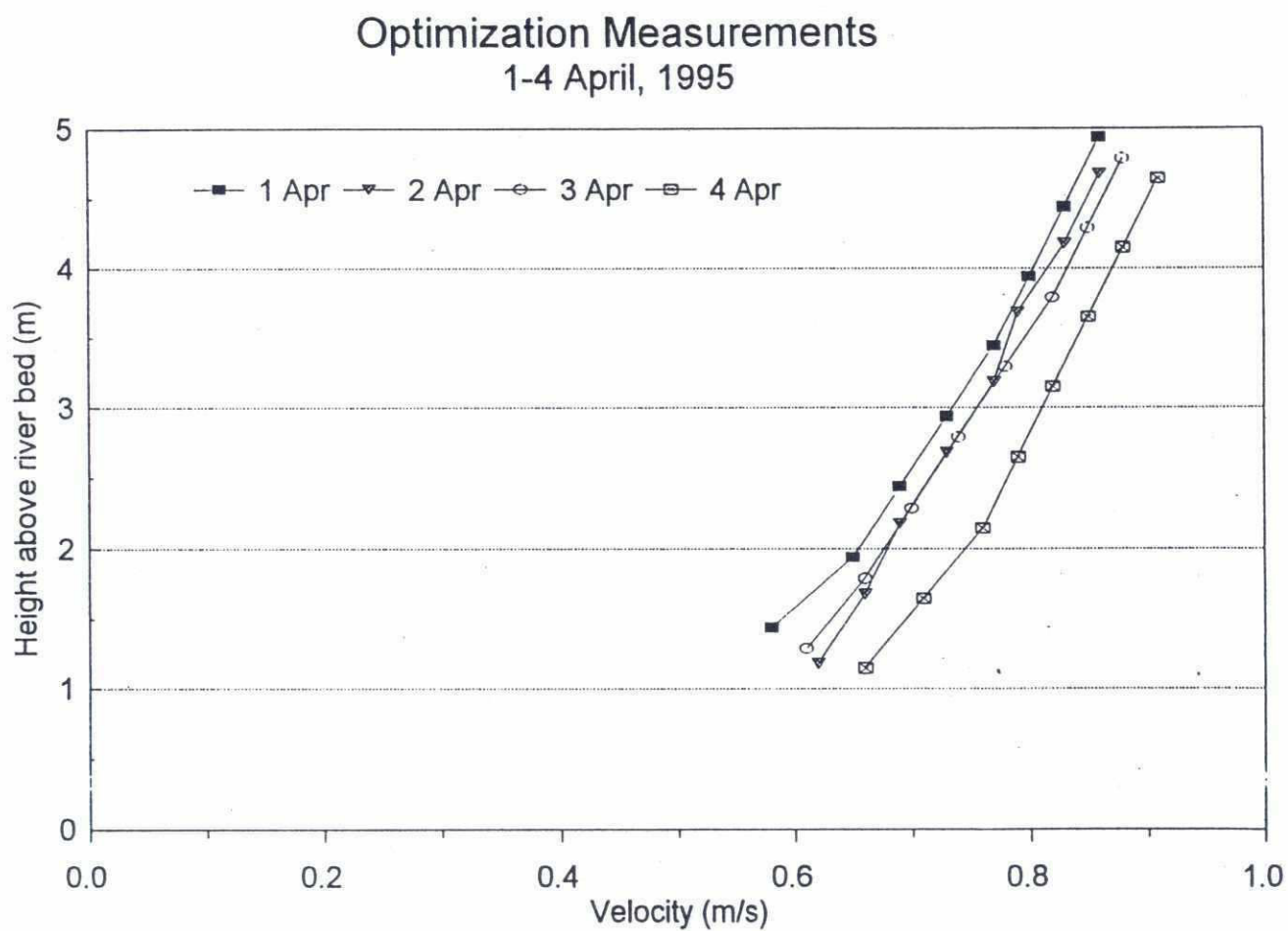


Figure G5.3 : Flow velocities in vertical measured by ADCP

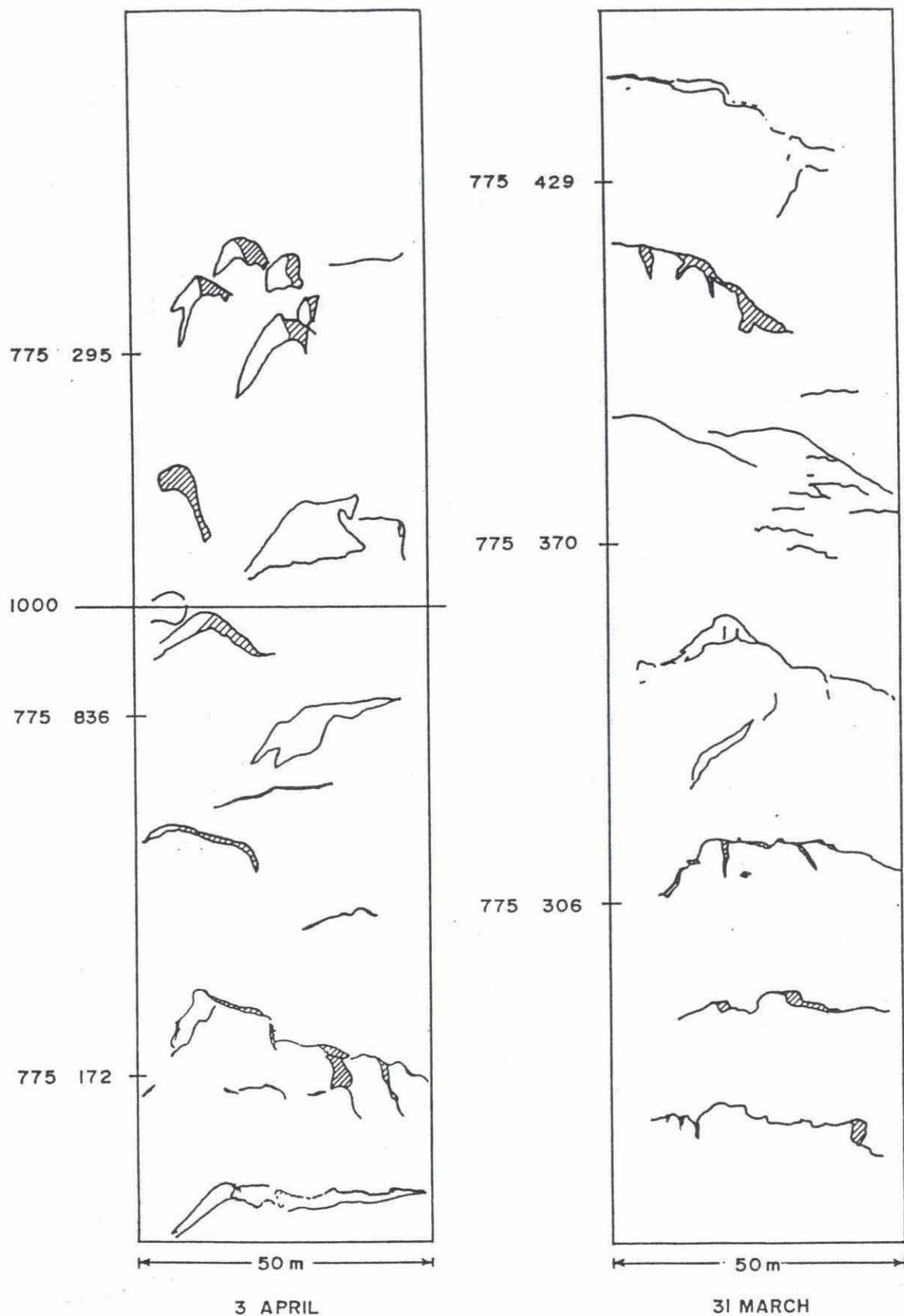


Figure G5.4 : Example of a side-scan sonar registration

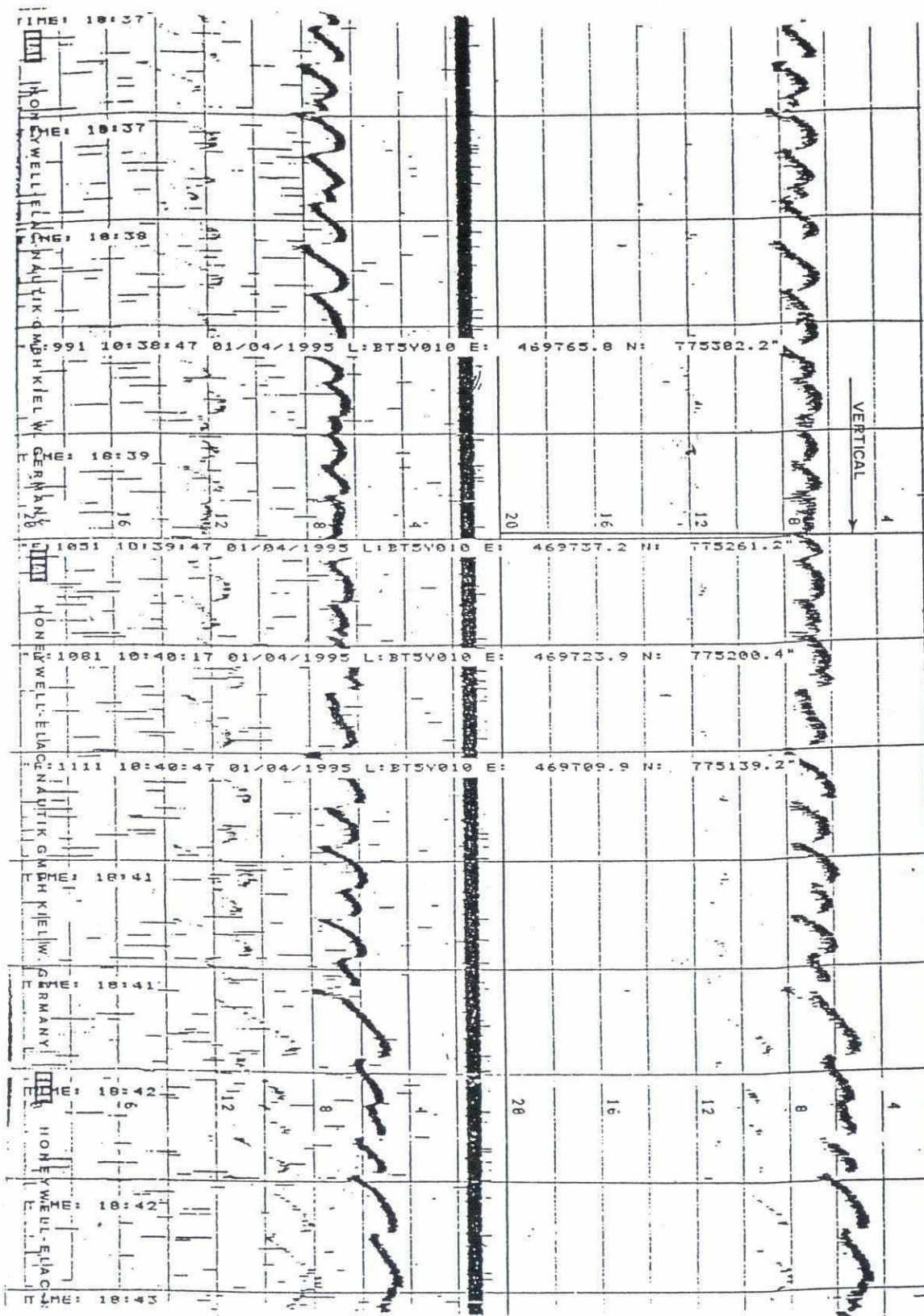


Figure G5.5 : Bed forms measured 1 April 1995

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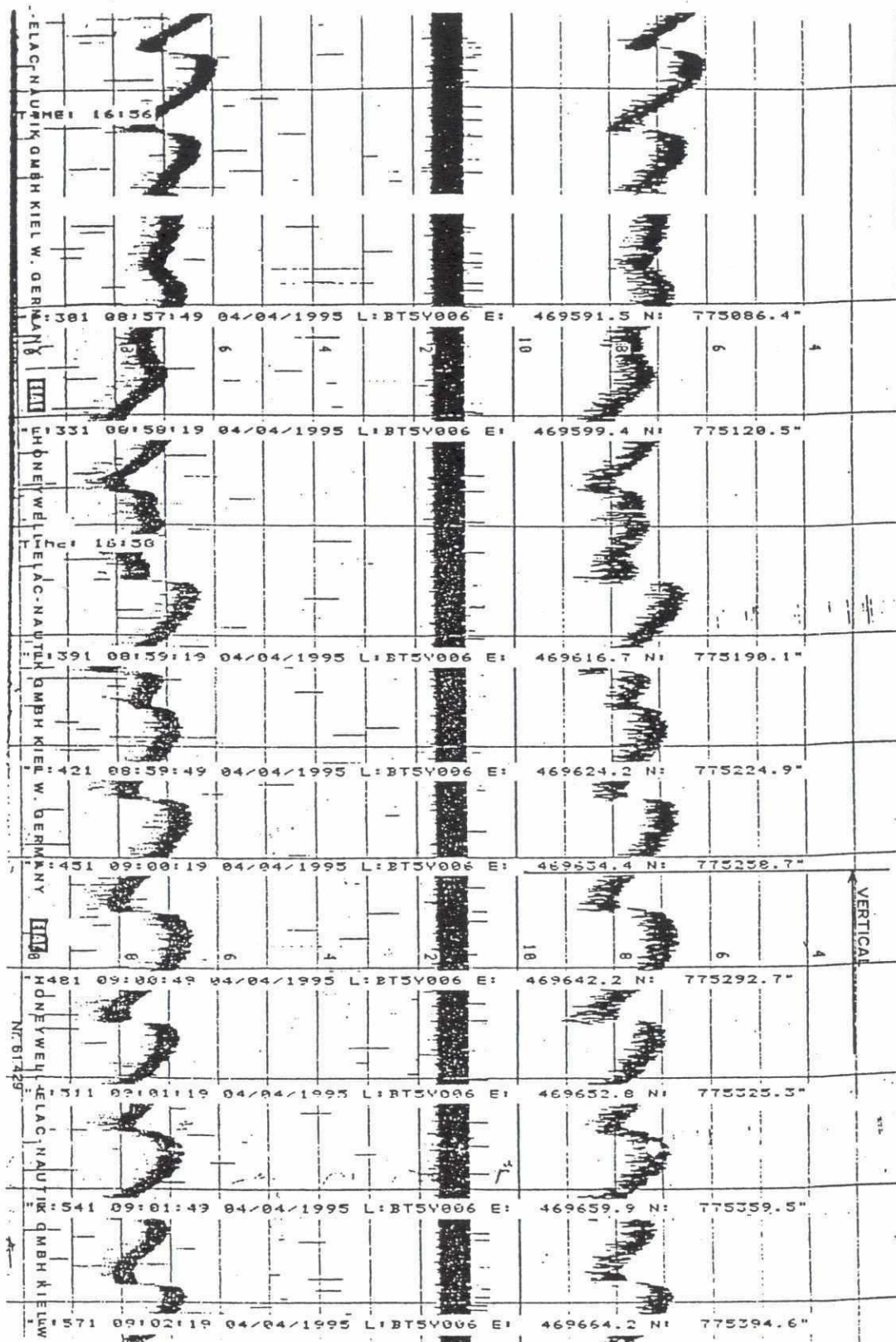
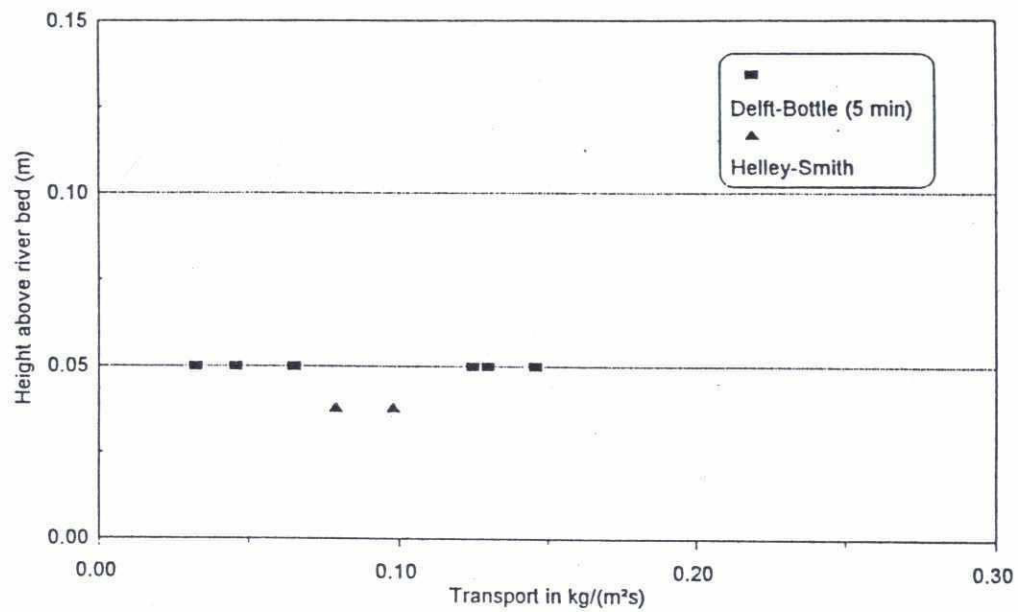


Figure G5.6 : Bed forms measured 4 April 1995

Jamuna River, Bahadurabad
1 April 1995



Jamuna River, Bahadurabad
1 April 1995

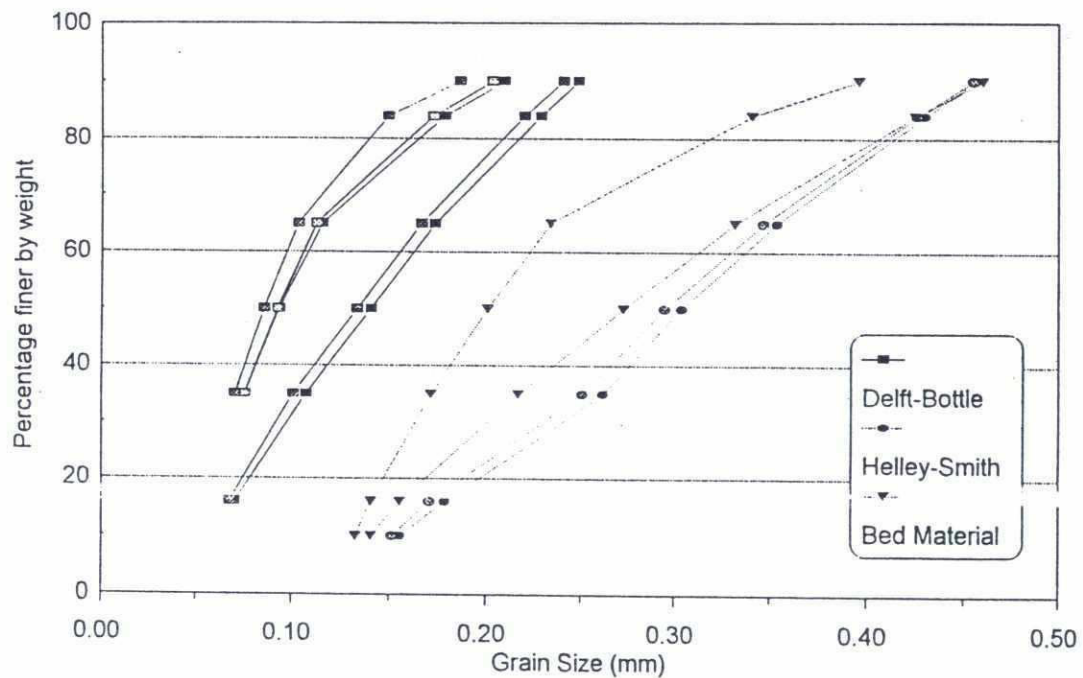
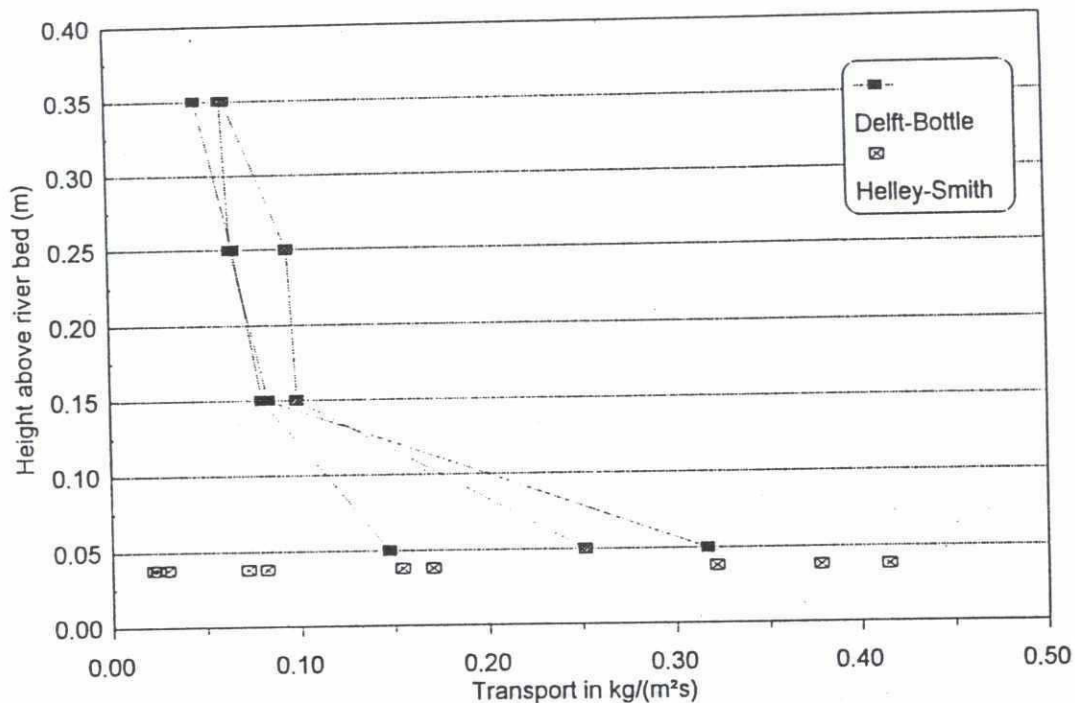


Figure G5.7 : Near bed sediment transport and sieving curves, Delft Bottle, Helley-Smith and bed material samples

Jamuna River, Bahadurabad
3 April 1995



Jamuna River, Bahadurabad
3 April 1995

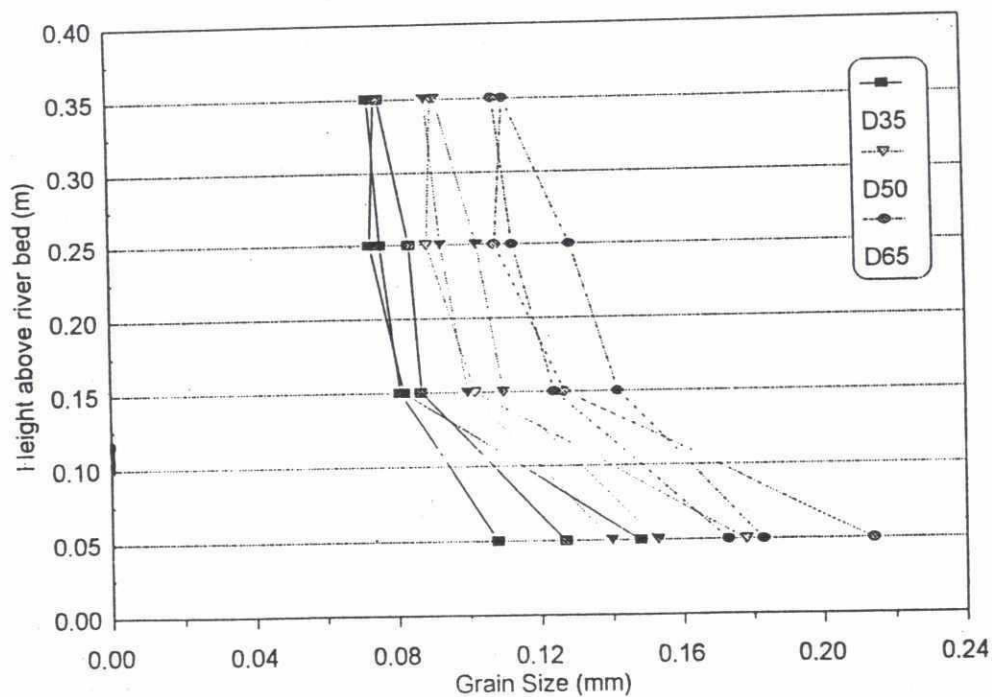
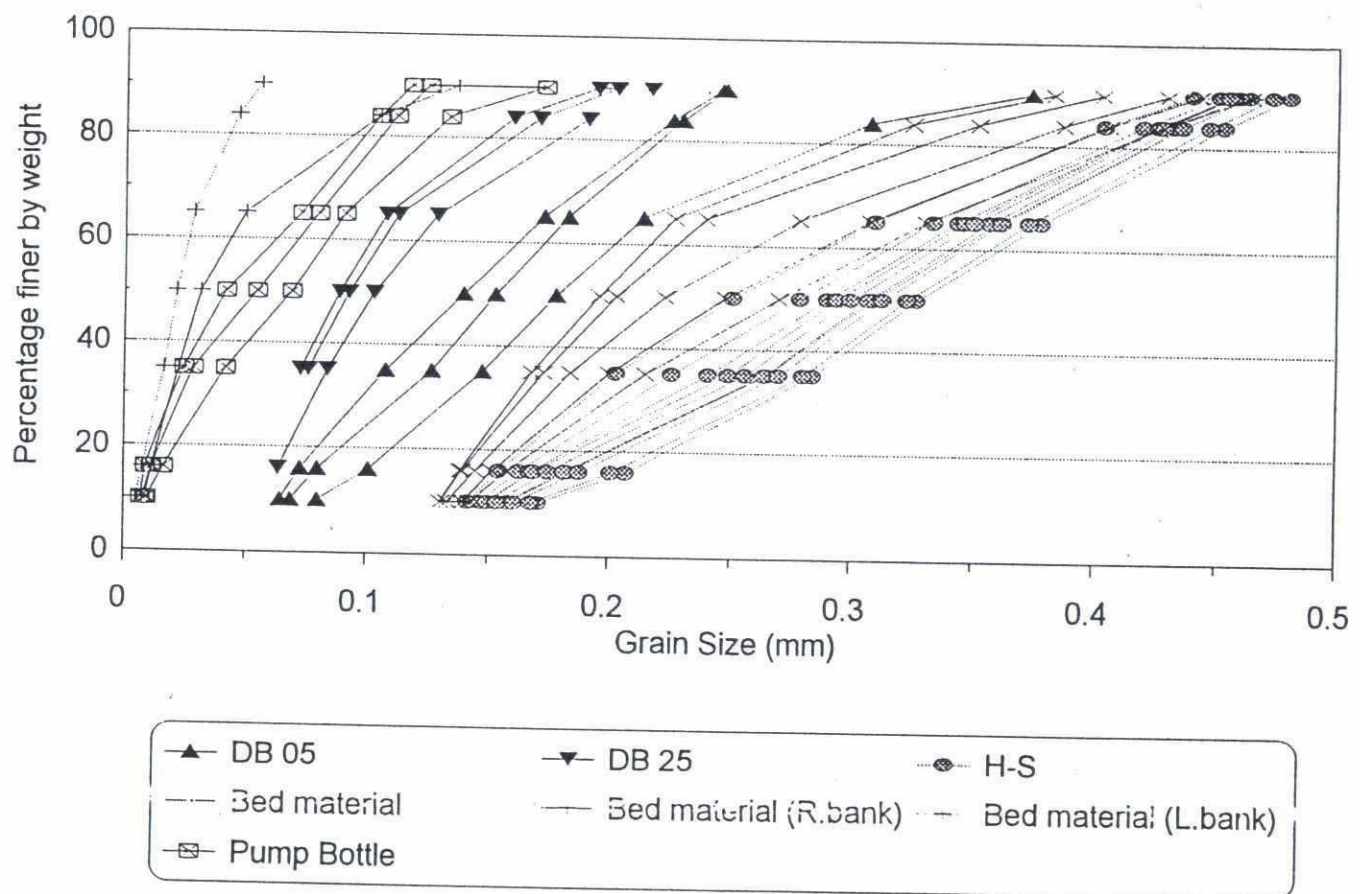


Figure G5.8 : Near bed sediment transport and grain sizes, Delft Bottle

Jamuna River, Bahadurabad 3 April, 1995



Note : all samples, except the bed material ones, were taken in vertical 1 (left channel; water depth 6.6 m; distance from bank 225 m)

Figure G5.9 : Sieving curves Delft Bottle, Helley-Smith and bed material samples

Jamuna River, Bahadurabad
4 April 1995

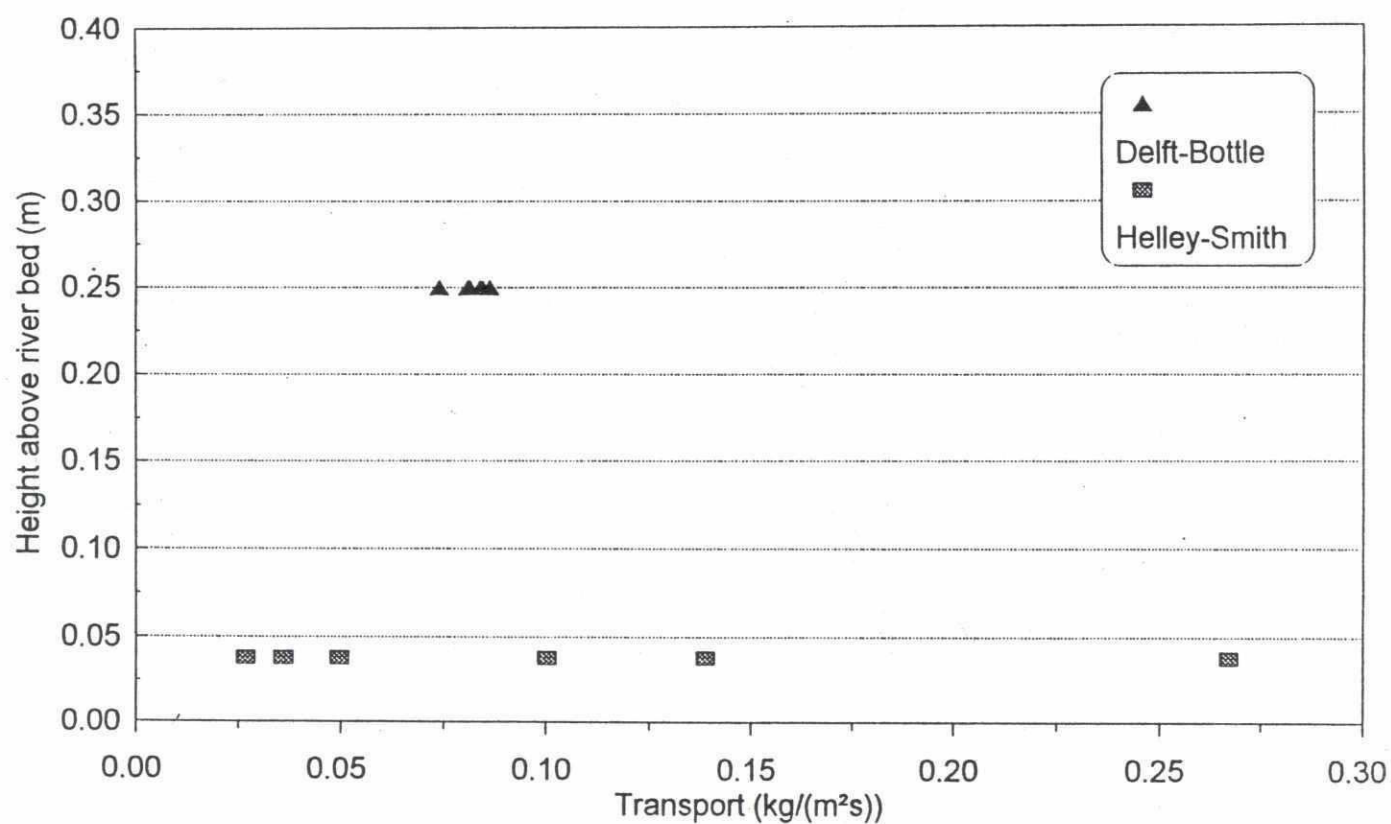


Figure G5.10 : Near bed sediment transport and sieving curves, Delft Bottle and Helley-Smith samples

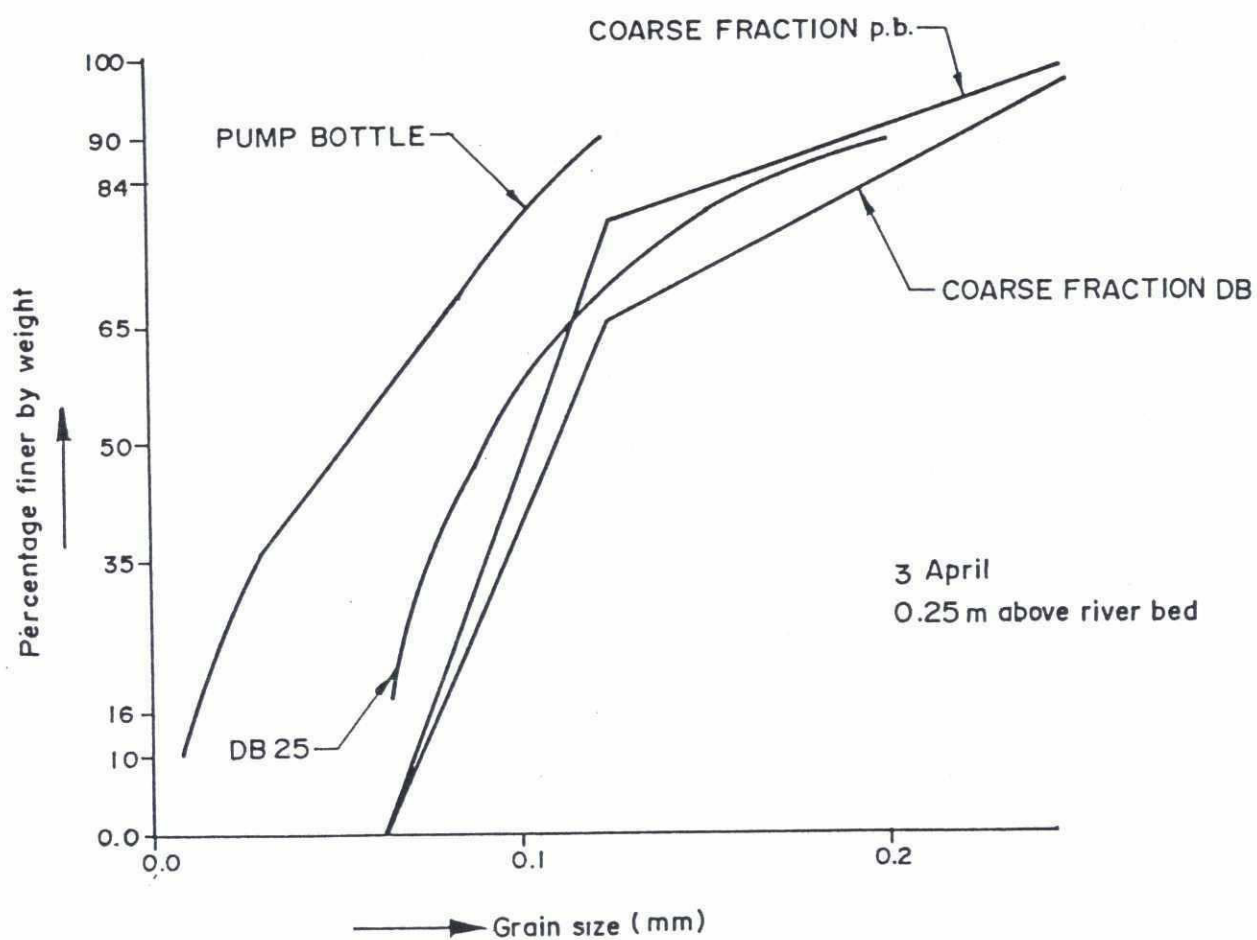


Figure G5.11 : Comparison of coarse sediment fraction caught by different instruments

G5.12

Jamuna River, Bahadurabad 4 April, 1995

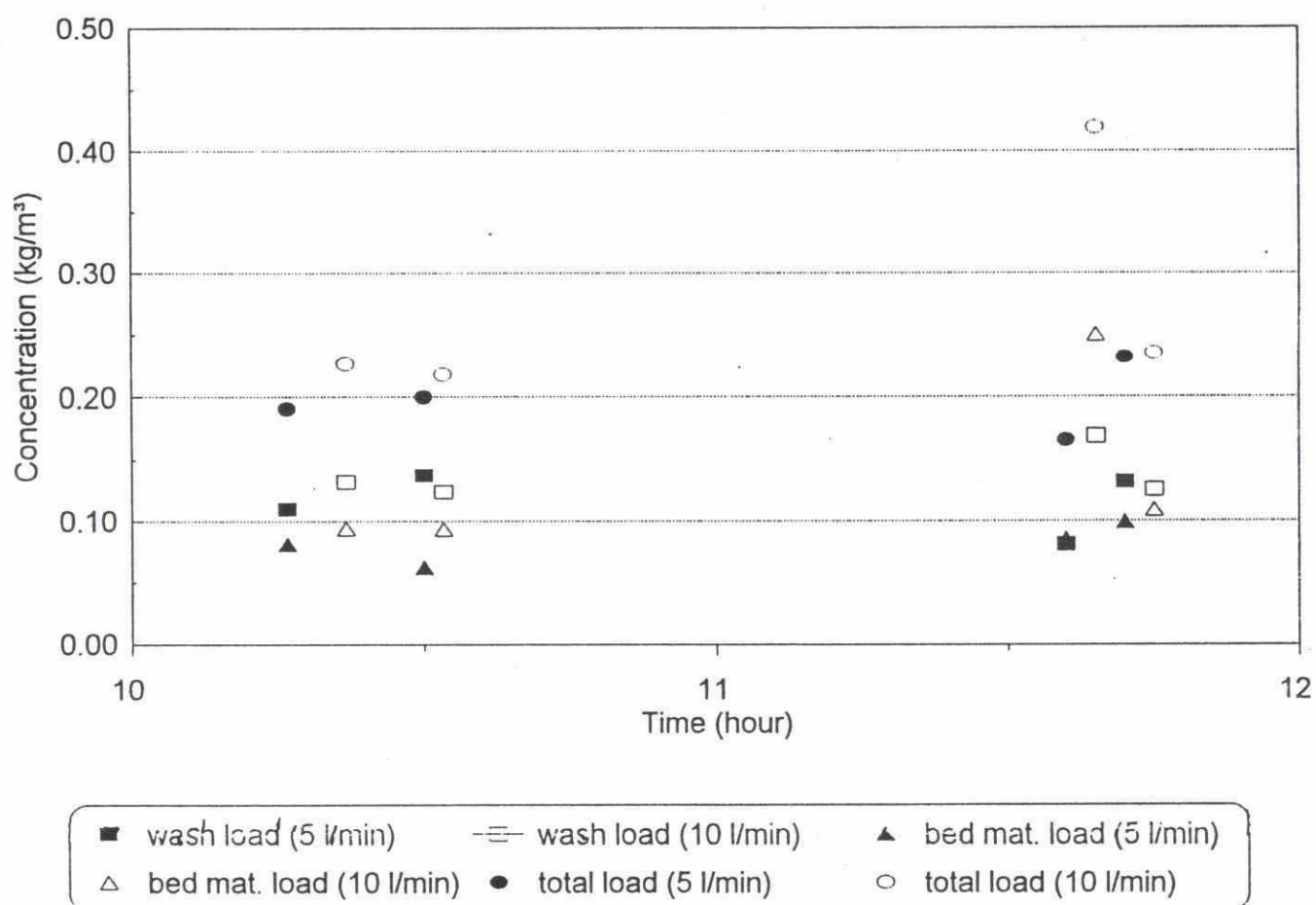


Figure G5.12 : Fine and coarse sediment concentration as function of the pump speed

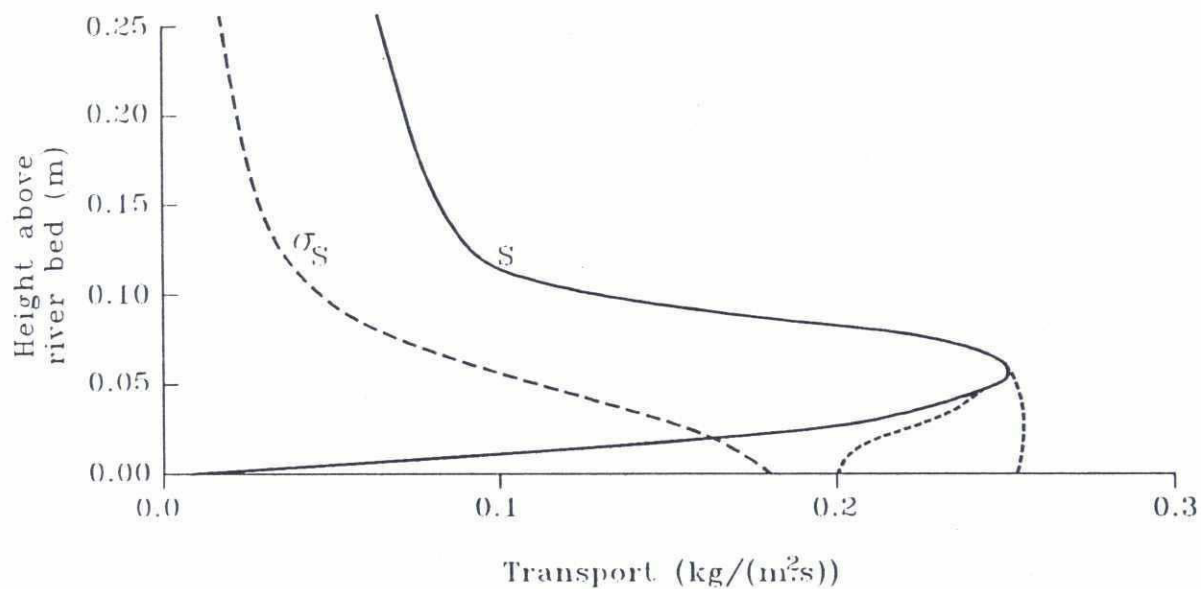


Figure G5.13 : Near bed sediment transport in low flow conditions

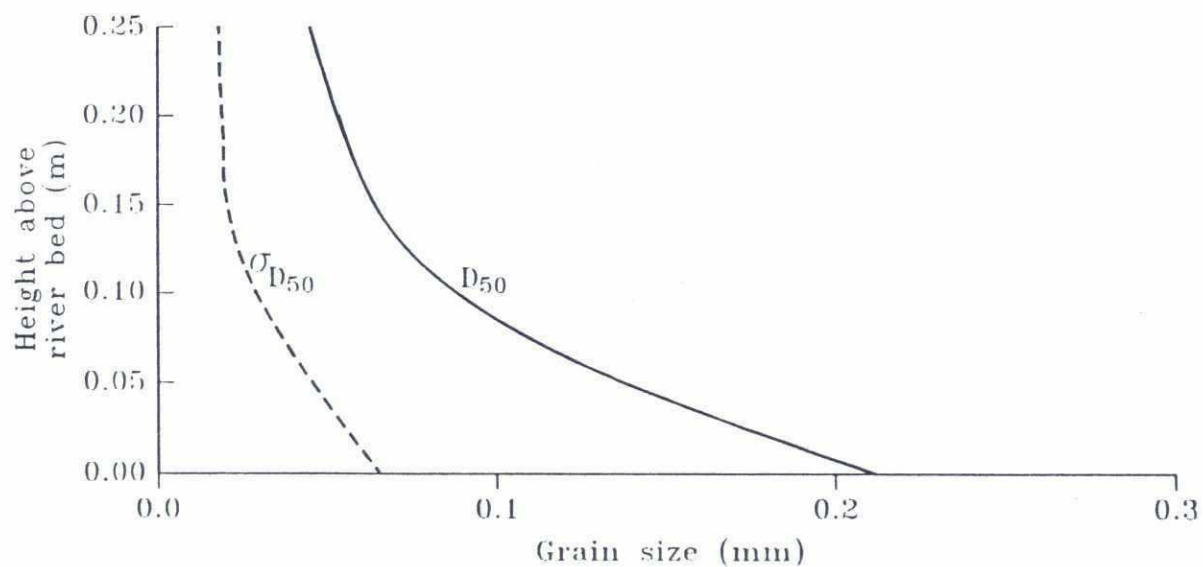


Figure G5.14 : Grain size distribution near the river bed in low flow condition

Annexure G6

Study Survey

Near-bed sediment transport measurements, 27-30 May 1995

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1 Introduction

The optimization of sediment transport measurements is part of study topic 9, Measuring techniques, see (RSP, Study programme, February 1995). In several study-surveys measurements of the near-bed sediment transport were done with different types of instruments, such as Delft Bottle sampler, Helley-Smith trap sampler, and a pump-bottle sampler. The main objectives of this part of study topic 9 are the selection of an optimal gauging strategy and the description of the physical phenomena of near bed sediment transport. The comparison of the results of different instruments is used to recommend measuring methods which are optimal for the main rivers in considerations of accuracy, cost and sustainability. The measurements were analyzed to describe the near bed sediment transport phenomena in detail. Several surveys which were carried out cover the whole range of flow conditions in the Jamuna River.

A special study-survey was done at the end of the lean season, in May 1995. This study survey was executed in the Jamuna River near Bahadurabad along the lines of the proposal for this survey. The specific objectives are:

- comparison of the sediment transport or the sediment concentration measured by different samplers, and the behaviour of these samplers during the measurement,
- optimization of the sampling technique,
- optimization of the number of measurements in a vertical and of the sampling duration,
- assessment of the importance of the near-bed transport in relation to the total transport.

The programme of the measurements in this survey is described in Chapter 2. A primary analysis of the different parameters is presented in Chapter 3. This analysis is discussed in Chapter 4, where also some conclusions are included.

2 Measuring programme

The programme of the near-bed sediment transport measurements consisted of four types of measurements:

- 1 measurements of the Delft Bottle in one vertical at different heights from the bed,
- 2 bed form tracking to determine the size of the bed forms in the area of the measurements,
- 3 measurements to compare the sediment transport measured by different samplers,
- 4 time-series of repeated measurements with a sampler.

The time schedule of the measurements in this study survey is depicted in the following barchart (Table G6.1).



Item no.	Type of measurements	27 May	28 May	29 May	30 May
1	DB 4 series at 4 heights	XXXX			
2	Bed form tracking			XX XX	
3	Near bed comparison DB25, pump-bottle, Mex			XXXX	
4	Near bed time series DB05, Helley-Smith, Mex				XXXX

LEGEND :

DB	=	Delft Bottle sampler
DB25	=	DB at 0.25 m above the river bed
Pb	=	Pump-bottle system
Mex	=	Optical turbidity meter
Helley-Smith	=	Helley-Smith sampler

Table G6.1: Time schedule of the near-bed sediment transport measurements

On May, 27th and 29th the near bed measurements were done in the left channel of the Jamuna River about 5 km south of Bahadurabad (2,775,000 N), in transect 1 and vertical 1, see Figure G6.1. This location was selected after a reconnaissance survey in which the following criteria were used: flow velocities 1.5 to 2 m/s, a 7 to 10 m water depth and regular bed topography in active river bed. The near-bed time series on May 30th were executed 2.5 km south of Bahadurabad (2,777,500 N), in transect 2 and vertical 2 in Figure G6.1.

3 Results of near bed measurements

3.1 Introduction

The near bed sediment transport depends very much on the hydraulic conditions, especially flow velocities and waterlevels. The measurements of these parameters are presented in Section 3.2.

The presence of propagating bedforms (dunes) has also some influence on the near bed transport and the near bed part of the flow velocity verticals. The results of bedform tracking are presented in Section 3.3.

Special measurements were done for an accurate comparison of the near-bed sediment transport measured by different instruments, Section 3.4.

Time series of near-bed sediment transport measurements in one position in a vertical were made with Delft Bottle sampler and Helley-Smith sampler, Section 3.5.

3.2 Hydraulic conditions

The water-levels as read from the gauges of BWDB and RSP in Bahadurabad felt at a rate of 0.15 m/day during the study survey after reaching a peak level of 18.29 m + PWD at May 26th and 27th, see Figure G6.2. The water levels varied considerably between 17.91 and 18.29 m + PWD.

Flow velocities were measured in 2 verticals, transects and longitudinal profiles during the near bed measurements, see Table G6.2. The water depth in these two verticals varied: 10 m in V1 and 14 m in V2. The flow velocities in verticals V1 and V2 were in the range of 1.5 - 2.5 m/s, see Figure G6.3. In vertical 1 the flow velocity above 0.2 h increased from 1.5 - 2.0 m/s on May 27th to 2.0 - 2.5 m/s two days later, while the water level dropped about 0.3 m. In vertical 2 the flow velocity above 0.2 h ranged from 1.5 to 2.5 m/s on May 30th, see Figure G6.4.

The ADCP flow verticals in vertical 1 on 27th and 29th show that the flow velocities averaged over half an hour are stable and consistent with the measured flow velocities in a vertical. The flow velocities measured in vertical 2 on the 30th were averaged over 8 minutes and the flow velocity profile in that vertical is less stable than the profile in vertical 1.

The hydraulic conditions in the survey area can be characterized as unsteady (see water-levels) mid-flow conditions.

Date	Period	Type	Vertical transect	Figure
27 May	12:49 - 13:00	ADCP transect	T1	3
	14:26 - 16:10	ADCP verticals	V1	3
29 May	09:01 - 10:20	ADCP long profile		10
	14:26 - 16:11	ADCP verticals	V1	9
	14:41 - 15:54	Ott	V1	9
	17:15 - 17:27	ADCP long profile		10
30 May	08:12 - 08:19	ADCP transect	T2	4
	12:03 - 12:30	ADCP verticals	V2	4

Table G6.2: Type, timing and location of velocity measurements

3.3 Bedform tracking

In the area of vertical 1 bedforms were measured on May 29th along 3 parallel tracks with a length of about 1200 m, see Figure G6.5. These tracks are perpendicular to the transect, but not parallel to the main direction of the flow velocity. Therefore track 4 makes an angle of about 60 degrees with

the transect, but it is parallel to the main direction of the flow. Track 4 has a length of about 1600 m and it passes also vertical 1. Simultaneously ADCP (longitudinal) profiling was executed. At the end of the day track 1, which passes vertical 1, was repeated to check the propagation of the bedforms. The river bed was covered by dunes with a maximum height of 4 m, see Figures G6.6 and G6.7.

3.4 Comparison of instruments

In vertical 1 near-bed sediment transport measurements were done at a fixed level (being 0.25 m) above the river bed on May 29th with different type of instruments viz. :

- pump-bottle system to take 25 liter samples,
- Delft Bottle in frame,
- Mex 3 optical turbidity meter

Simultaneously samples were taken with the pump-bottle system and with the Delft Bottle. This was repeated five times. In between these measurements the Mex 3 was operated. The sediment transport measured by the Delft Bottle and the pump-bottle are compared in Figure G6.8. In the same graph the turbidity measured by the Mex 3 is shown as a function of time. The characteristic diameters D35, D50 and D65 of the grain size distribution of these samples a rather small variation, see Figure G6.8.

The flow conditions during these measurements were taken with an ADCP. The near- bed flow conditions were measured with an Ott current meter. For the flow conditions see Figures G6.9 and G6.10. The averaged flow velocity increased slightly during the measurements.

3.5 Time series of sediment transport measurements

Two time series of sediment transport measurements were taken with different instruments: Delft Bottle and Helley-Smith samplers.

Four times the near bed transport was measured on May 27th in vertical 1 at 0.05, 0.15, 0.25, 0.35 m above the river bed, using a Delft Bottle sampler in a frame. So in total sixteen samples were taken. During these measurement the velocity vertical was measured with an ADCP. The results of these measurements are presented in Table G6.3 and Figure G6.11. Sediment transport and the characteristic diameters D35, D50 and D65 as a function of the height of the mouth of the sampler above the river bed. These table and graphs show a good consistency between the samples of these four series.

Although the preferred sampling time was at least 2 minutes (if possible longer in view of the variability of the near-bed sediment transport) the big catches forced the survey team to shorten the time sometimes to 1 minute and in case of the DB05 even to 0.5 minute, for practical reasons. It is mentioned that these volumes were read from a measuring glass, in which the catch deposited. The porosity of these volumes can be high, especially if the catch contained parts of plants.

HEIGHT (m) ABOVE RIVER BED (m)	SERIES				average
	1	2	3	4	
0.35	60/2	70/2	60/2	52/2	61/2
0.25	75/2	70/2	69/2	72/2	71/2
0.15	109/2	60/1	61/1	68/1	122/2
0.05	180/0.5	-/0.6	-/0.5	-/0.5	-

X/Y = Volume of catch in cm³/sampling time in minutes

Table G6.3: Catches with Delft Bottle in time series in vertical 1 on May 27th.

Helley-Smith samples

In vertical 2 near bed sediment transport was measured with the Helley-Smith sampler on May 30th. Within one hour 12 samples were taken. Sampling time was 30 s. For reasons of comparison also 5 DB05 measurements were done in the preceding hour. During the Delft Bottle and Helley-Smith measurements a Mex recording was made with two short interruptions. The flow conditions were measured with the ADCP, see Figure G6.10.

The results of the sediment transport measurements are summarized in the Figure G6.12. Sediment transport measured by the Delft Bottle, turbidity by the Mex and D35, D50 and D65 from the Delft Bottle samples as a function of time from 10 to 11 am. This means a period of one hour. In the next hour the Helley-Smith samples were taken. Sediment transport measured by the Delft Bottle, turbidity by the Mex and D35, D50 and D65 from the Delft Bottle samples as a function of time in Figure G6.13.

4 Discussion, conclusions

Hydraulic conditions

The near-bed measurements were executed during unsteady mid flow river conditions in the left channel south of Bahadurabad. The results of this survey should be combined with the results of surveys in low flow conditions and high flow conditions, to obtain results covering all flow conditions in the Jamuna River. The measurements of the last day (30 May) were done in deeper water and slightly higher velocities.

As the ADCP measures the flow velocities in a vertical up to some distance from the river bed, the Ott current meter was applied in this unmeasured zone. The flow velocities measured by the Ott current meter show some scatter, see Figure G6.9. Probably this scatter is due to the uncertainty of the position of the current meter above the river bed. The applied measuring technique starts with lowering the meter through a flow field of upto 2 m/s on a very irregular river bed. At the moment the signal is received that the instrument had touched the river bed, the instrument is hoisted by pulling the suspension cable a few decimeter. This procedure results in a comparatively low accuracy of a few decimeter in the position of the Ott current meter relative to the bed. But the average flow velocity measured by Ott current meter fits well with the extrapolated flow velocities measured by ADCP.

Bedforms in the survey area

Considerable dunes with heights upto 4 m and lengths upto 130 m were detected in the area of vertical 1. These large dunes have a propagation speed of 40-60 m/24 hours. This was determined from track 1 which was oblique to the main flow direction.

Considering the interdistance of 100 m between the longitudinal profiles 1, 2 and 3 in survey area 1 the strong three-dimensionality of the bedforms can be seen from Figure G6.7. The survey was done in an area with an active river bed.

On the 29th the river bed rises 0.5 m in vertical 1 because of propagating bedforms. The water level drops slowly 0.15 m/day. The flow velocities reduce within 14 minutes, 12.19 to 12.33 hours, probably due to a passing long wave, but they accelerate slightly from 12.33 to 16.11 hours, see Figure G6.6. Also the average flow velocities measured by the Ott current meter increases slightly in that period, see Figure G6.9.

Delft Bottle measurements in a vertical

The Delft Bottle measurements in vertical 1 of 27 May show typical results Figure G6.11:

- strong increase of sediment transport near the river bed,
- strong increase of the variability of the sediment transport near the river bed, but this variability is small in the sediment transport measured at 0.15, 0.25 and 0.35 m above the bed,
- consistent increase of the grain size near the river bed.

These measurements show that the samples at 0.25 and 0.35 m above the bed measure almost the same sediment transport as the sample at 0.15 m above the bed. This confirms the gauging strategy for the routine gaugings where a Delft Bottle sample at 0.05 and 0.15 m above the bed were taken.

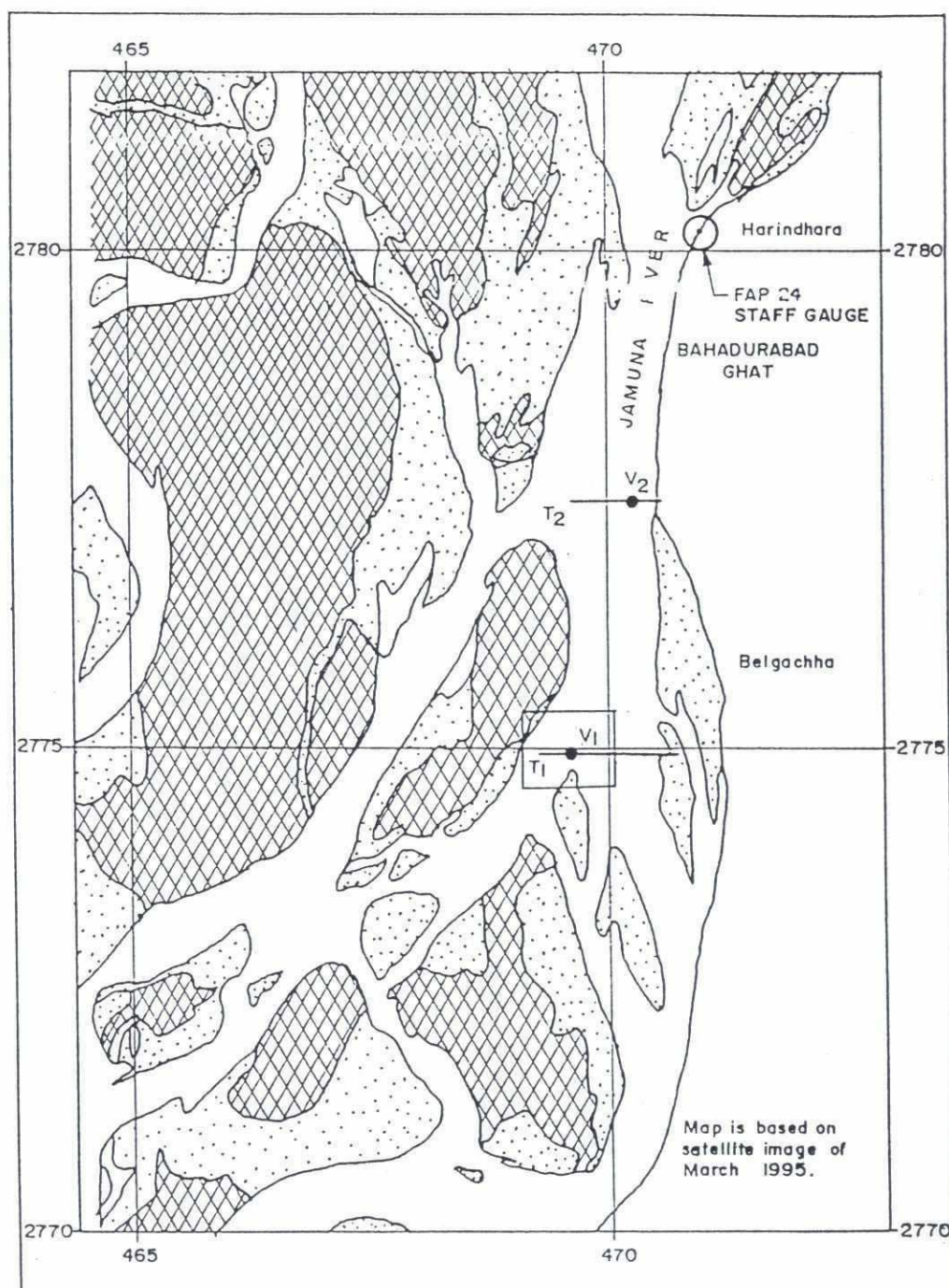
Comparison of different samplers

The sediment transport according to the Delft Bottle (5 samples) varies slightly more than the sediment transport according to the pump-bottle (also 5 samples), see Figure G6.8. However, the variability in the Delft bottle samples also measured 0.25 m above the bed two days earlier, May 27th, is much smaller, see Figure G6.11. This small variability indicates that in a gauging strategy only one Delft Bottle sample at each distance from the bed is sufficient.

The sediment transport according to the 5 Delft Bottle samples tends to be higher than the sediment transport according to only 5 pump-bottle samples. In fact it should be the other way around because the Delft Bottle is losing the finer fraction of the sediment. For the same reason the values of the D_{35} , D_{50} and D_{65} of the pump-bottle samples should be slightly lower (more fine sediments) than these values of the Delft Bottle samples and that is not always the case, see Figure G6.8. Therefore the comparison of the results obtained with the pump bottle, the Delft Bottle and the Mex were reason to improve the calibration of the pump-bottle system.

The catch of the Helley-Smith is on average higher (5 to 6 kg/(m².s)) versus 3 kg/(m².s) than the Delft Bottle catch at 0.05 m above the bed but that is not unusual because the sediment transport increases sharply near the bed in spite of the higher losses through the Helley-Smith sampler (compare Figure G6.12 with G6.13). The grain sizes in the Helley-Smith catch are about 0.1 mm larger than those of the Delft Bottle (compare Figures G6.12 with G6.13). The variation in the sediment transport determined from different Delft Bottle samples is similar to the variation in D_{35} , D_{50} and D_{65} from these samples. These results that 2 or 3 samples of the Helley-Smith sampler are required to obtain reliable average values.

The Mex indicate a constant turbidity with a variation of less than 10%. (It is noted that the Mex and the pump bottle system cannot be operated simultaneously because of interference between pump power and Mex signal). In time the decreasing tendency in the Mex signal is similar to the tendency in the Delft Bottle sediment transport.



V_1, V_2 = Measuring verticals.

T_1, T_2 = ADCP Transects.

LEGEND:

-  High land.
-  Low char.

Figure G6.1 Location of near bed measurements

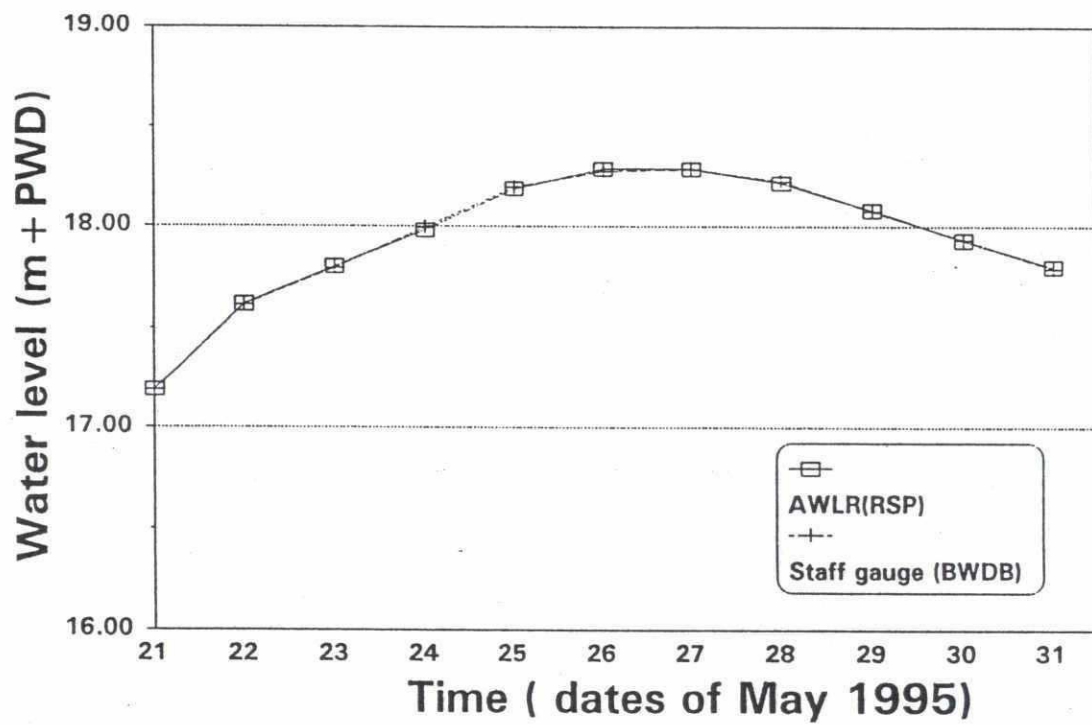


Figure G6.2 Water levels at Bahadurabad

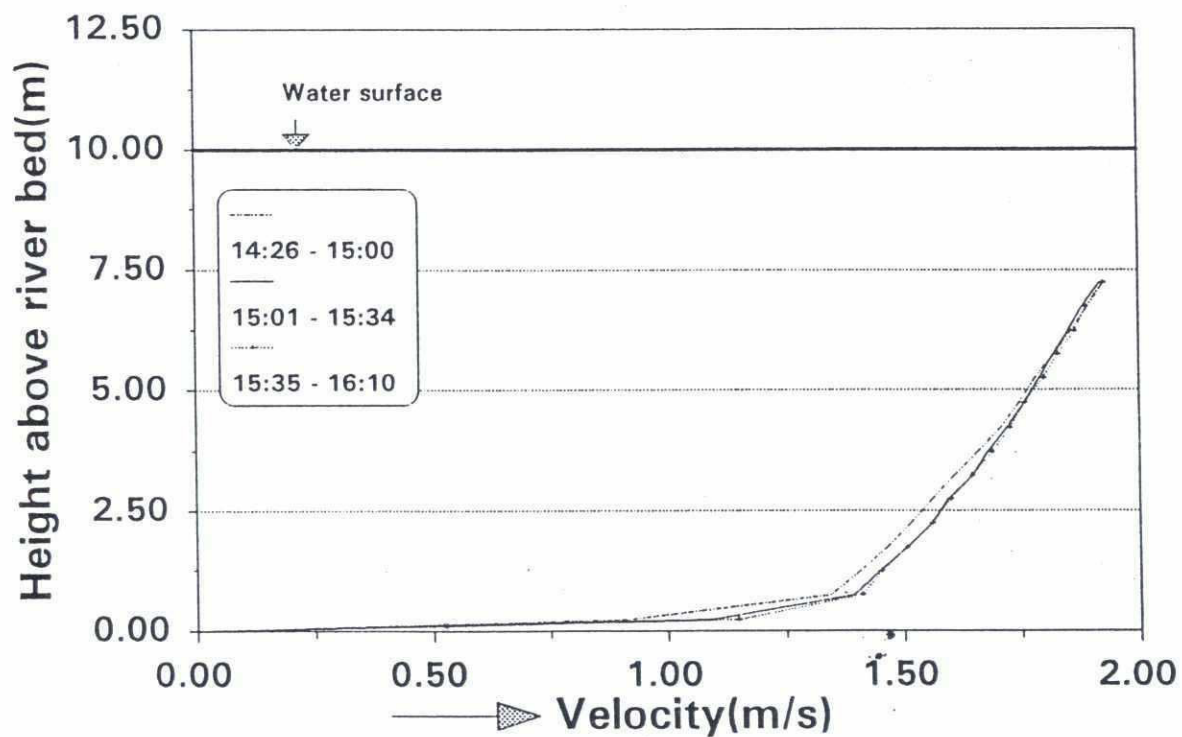
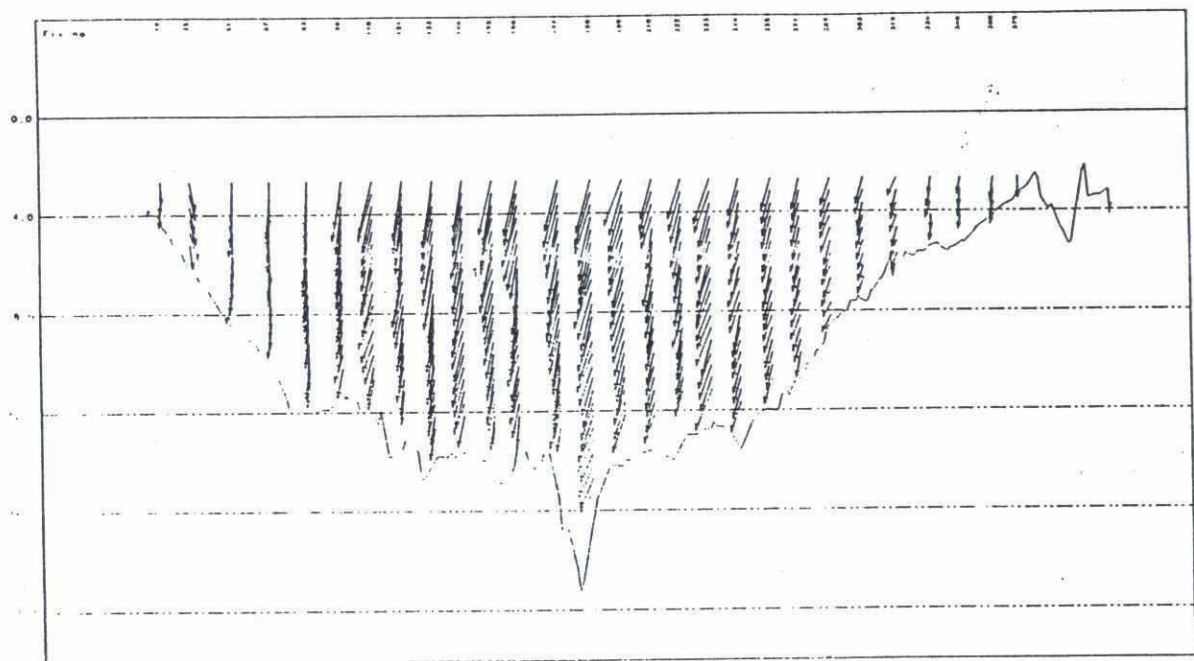


Figure G6.3 Flow conditions measured by ADCP along transect T1, May 27th

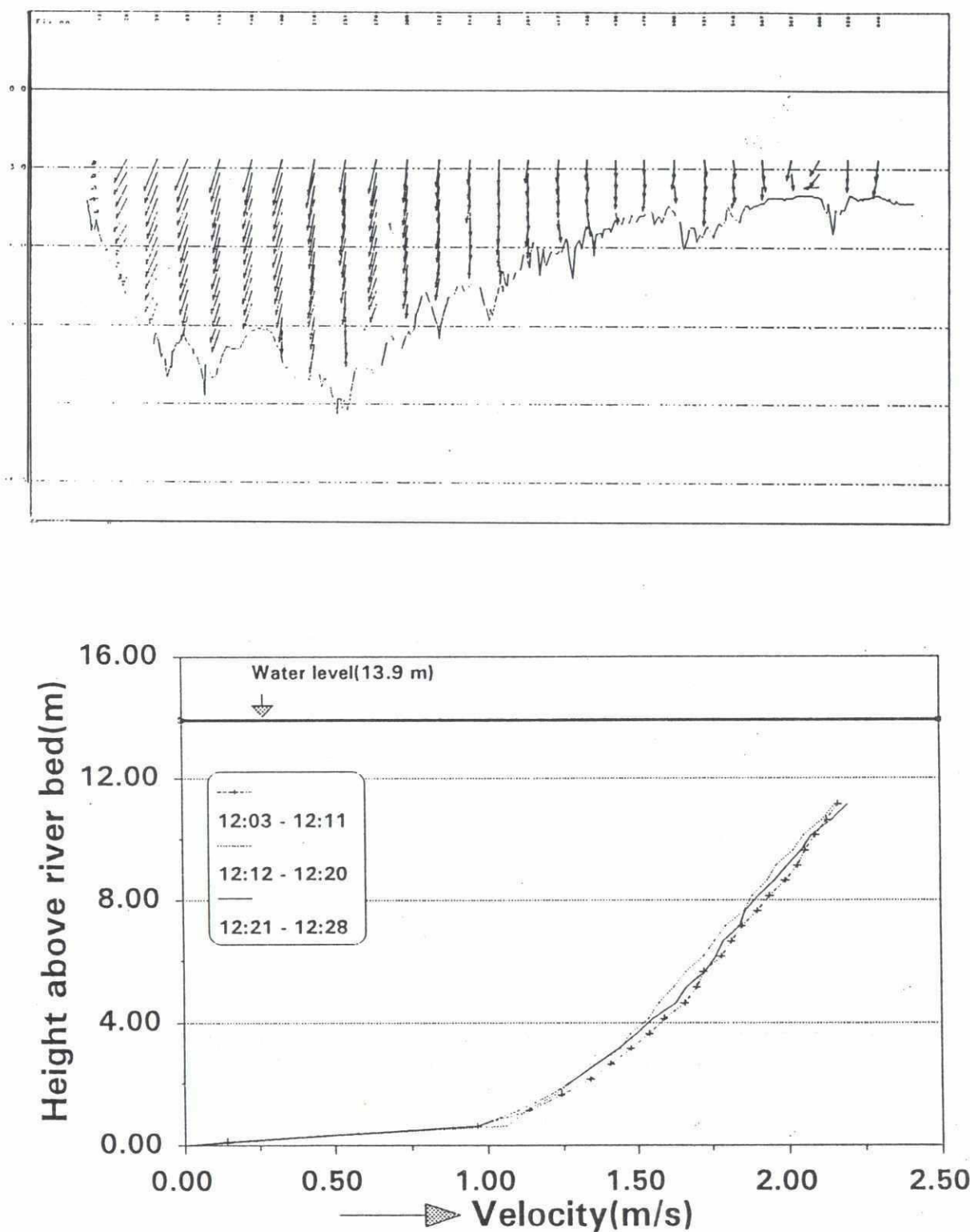


Figure G6.4 Flow conditions measured by ADCP along transect T2, May 30th

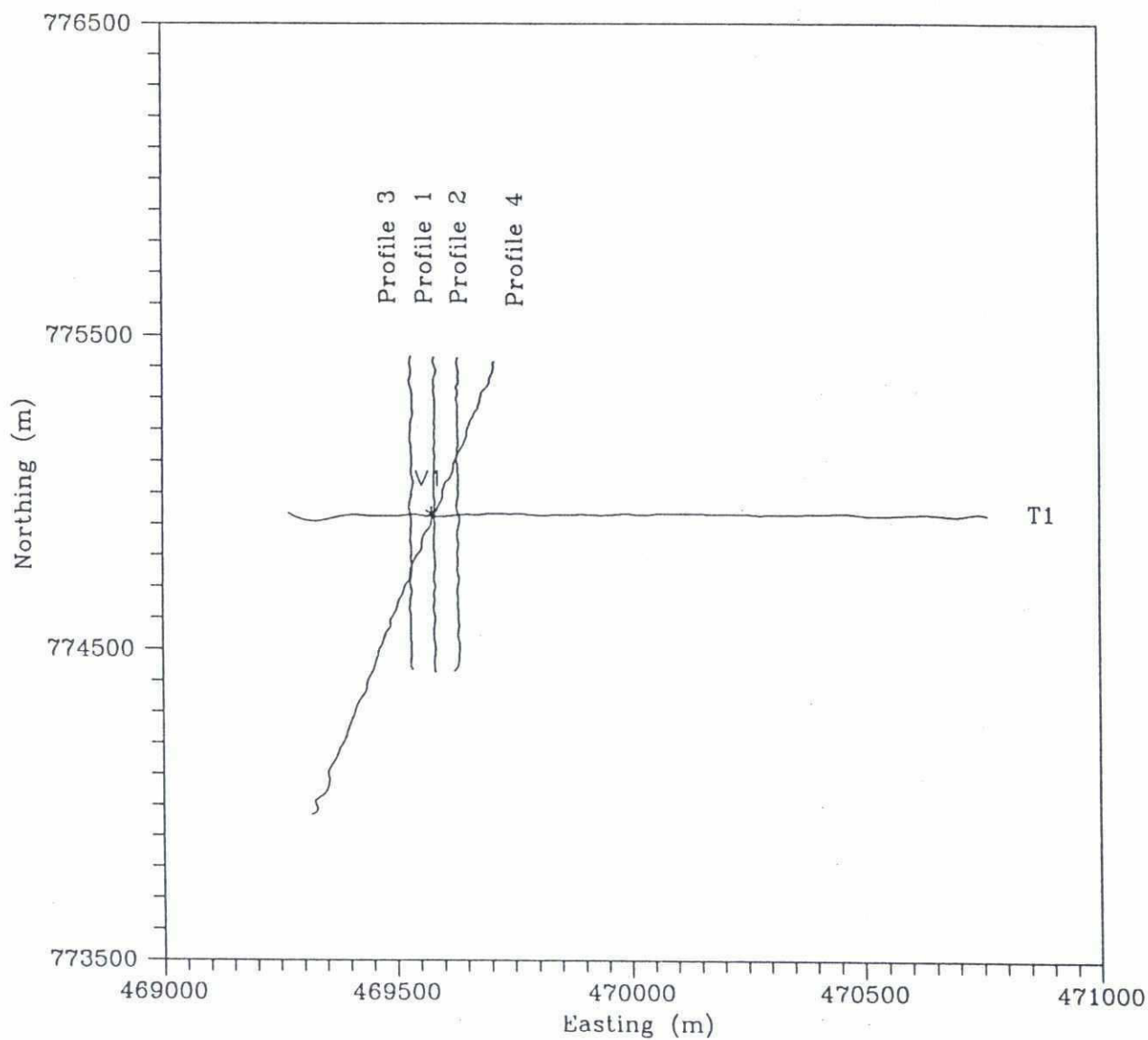


Figure G6.5 Plot bedform tracking in area 1

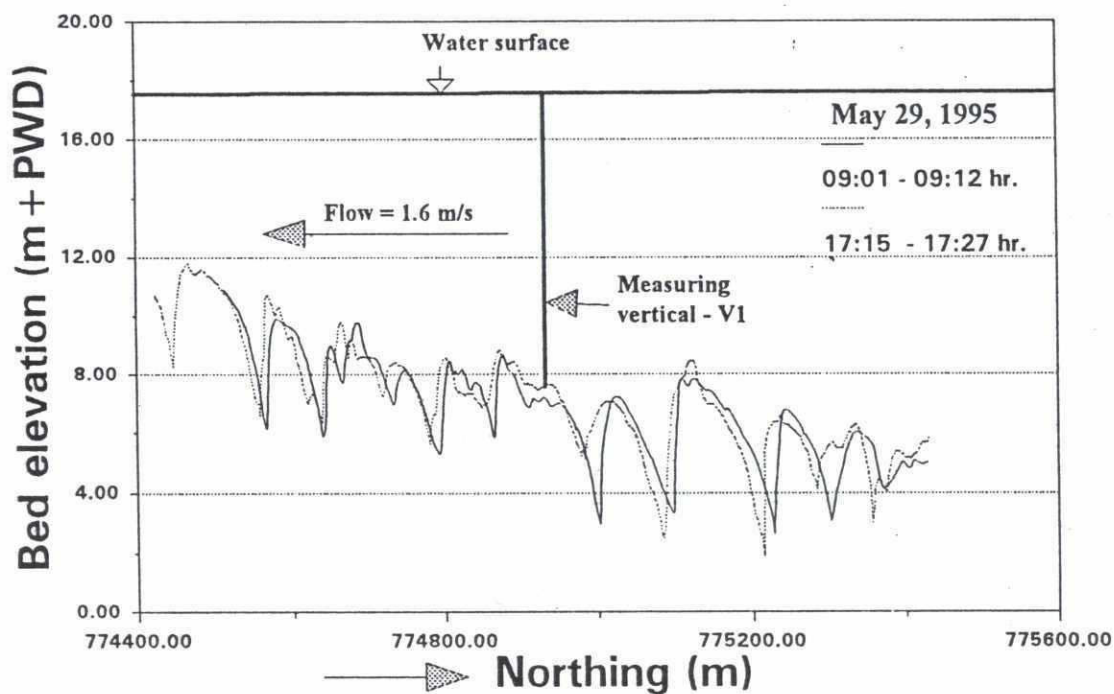


Figure G6.6 Propagation of bedforms in area 1, May 29th

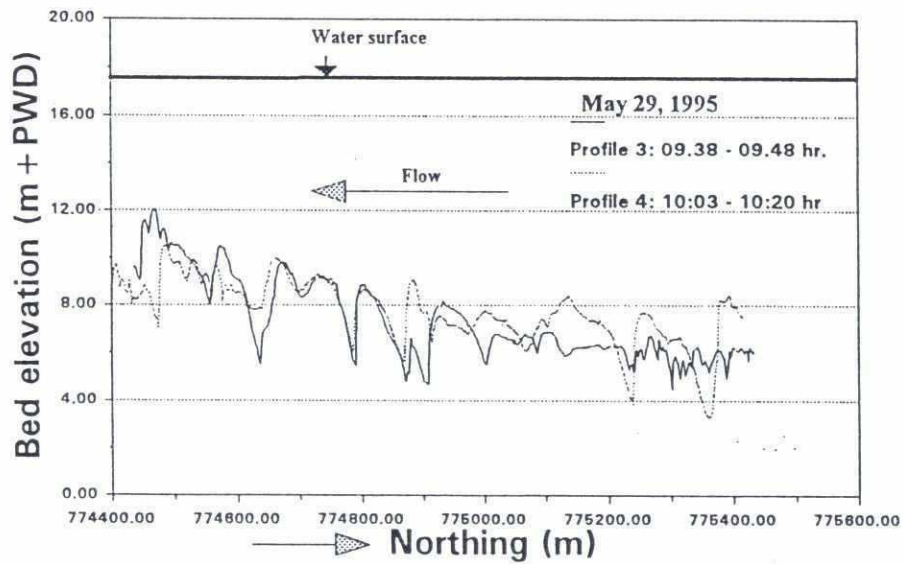
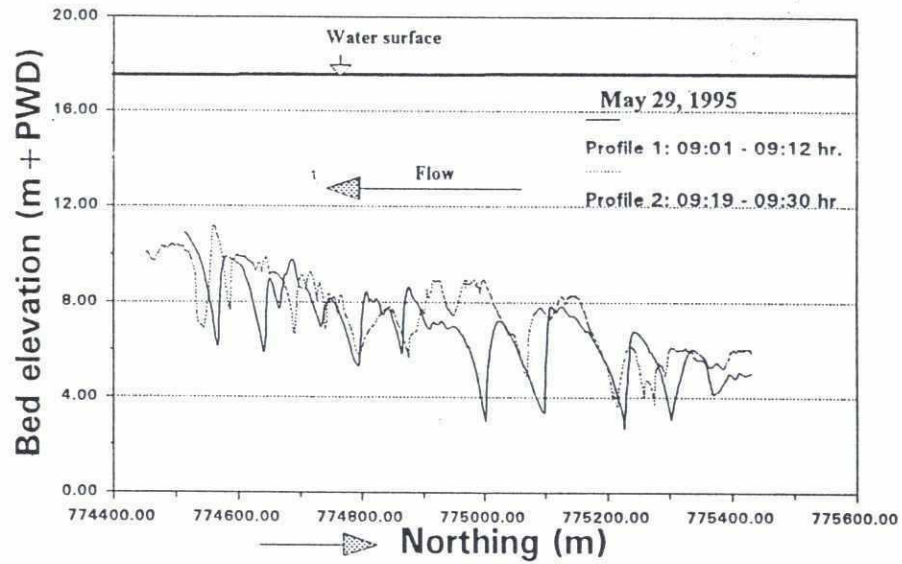


Figure G6.7 River bed profiles in area 1, May 29th

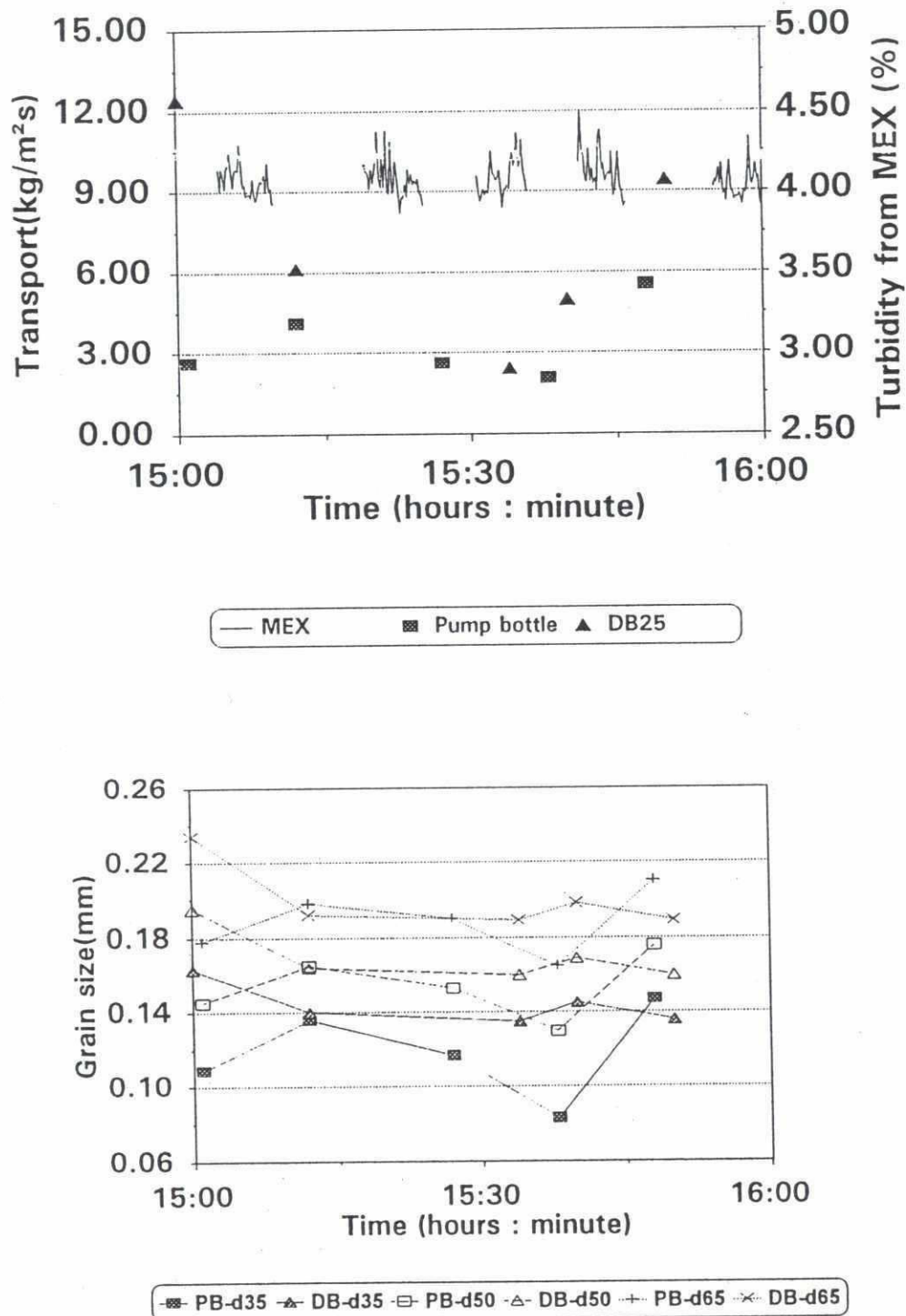


Figure G6.8 Comparison of sediment transport and grain sizes, in vertical 1 at 0.25 m above the bed, May 29th

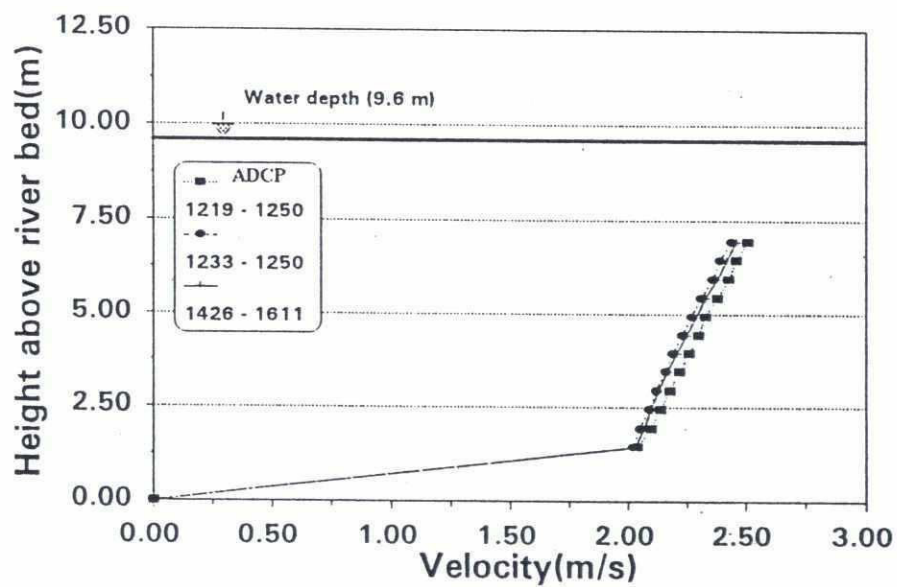
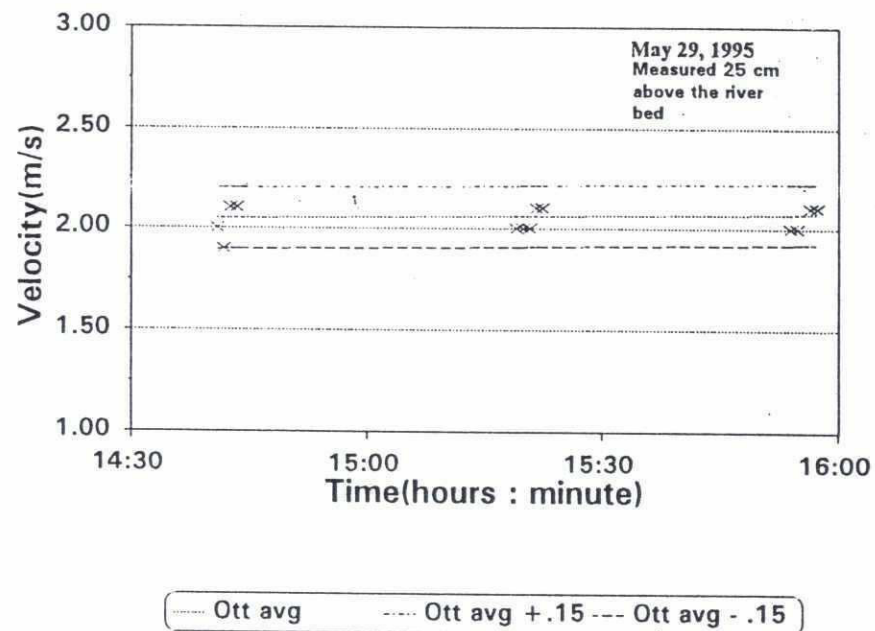


Figure G6.9 Flow conditions in vertical 1, May 29th

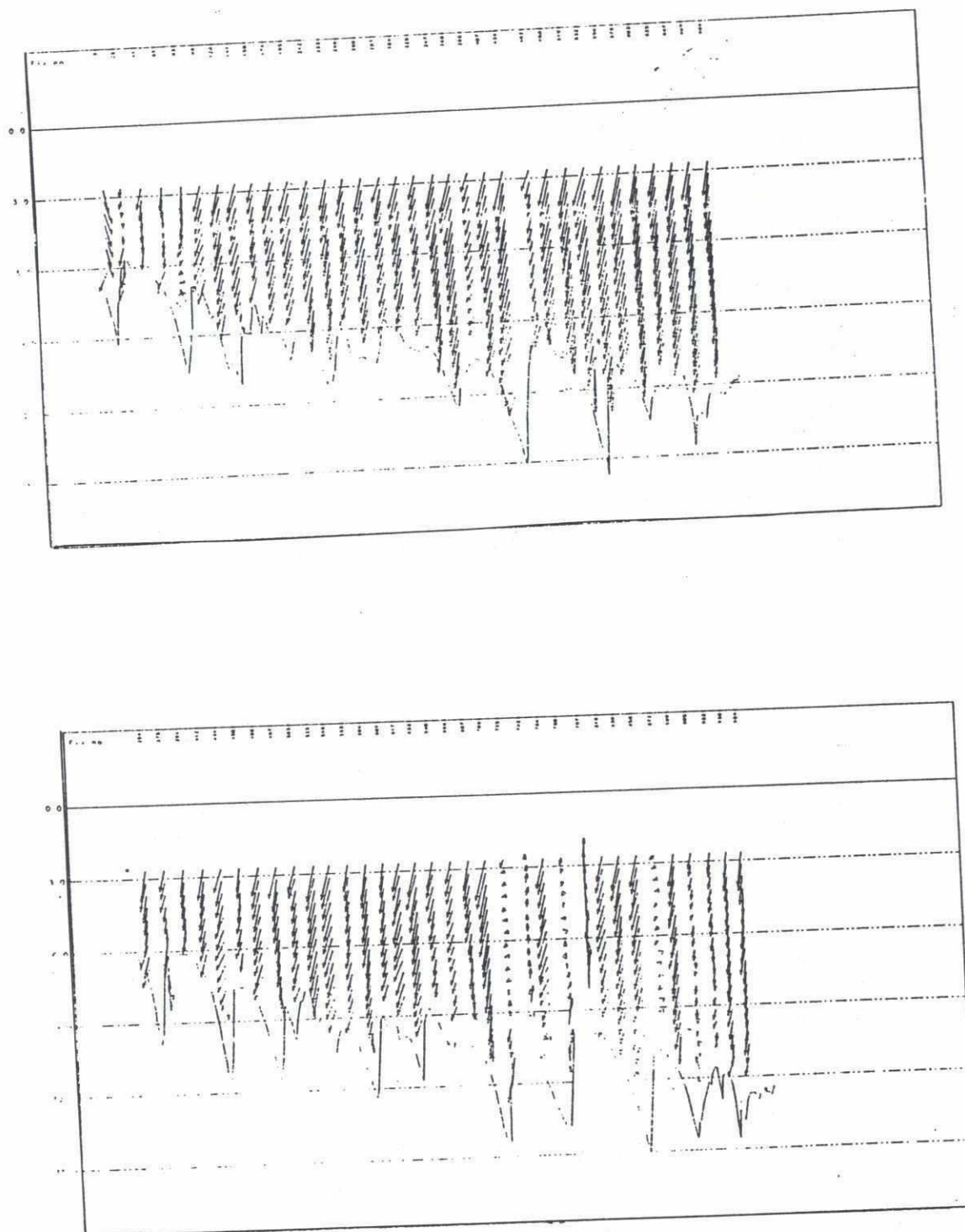


Figure G6.10 ADCP longitudinal profiles

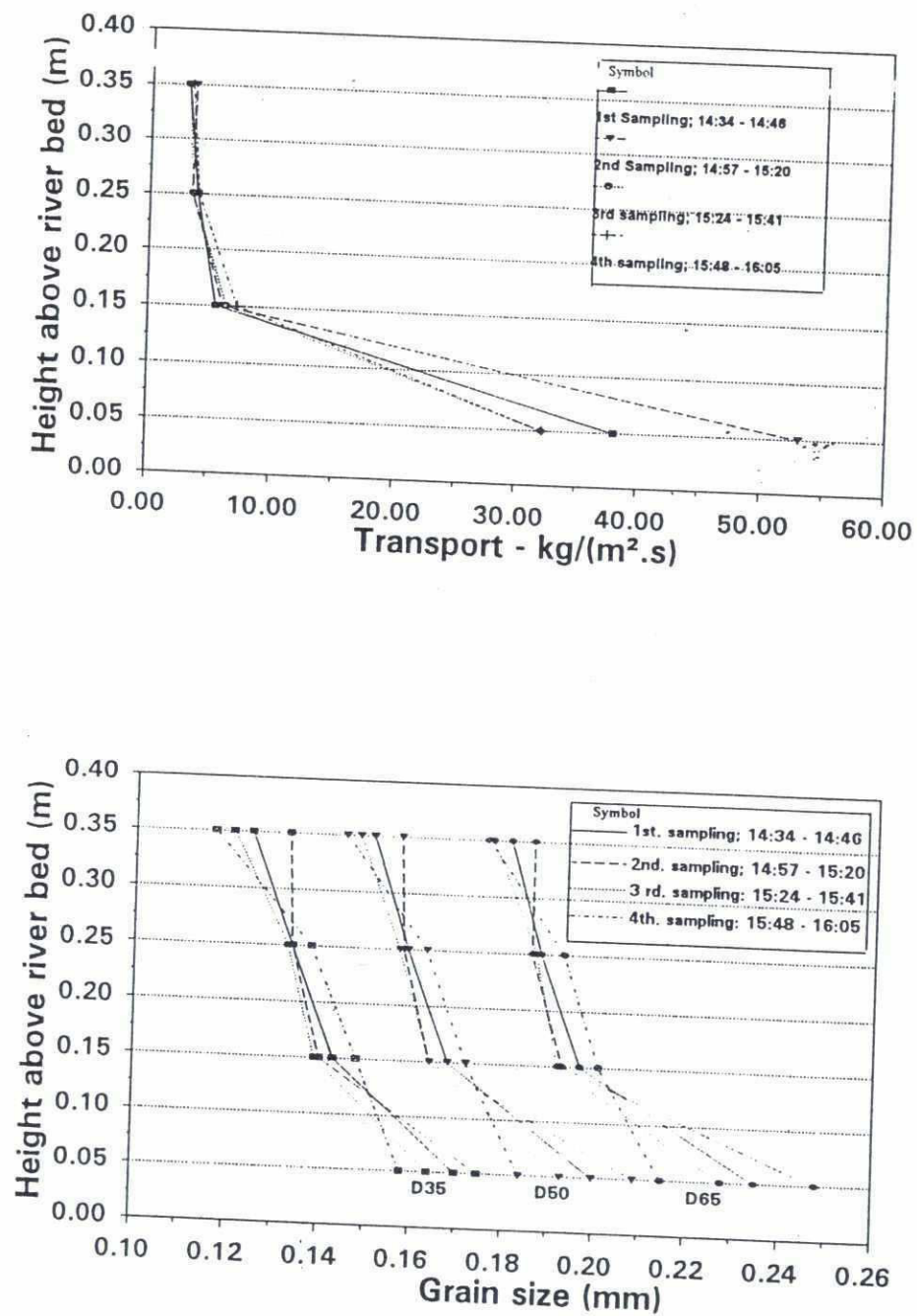


Figure G6.11 Near bed transport and grain sizes Delft Bottle in vertical 1, May 27th

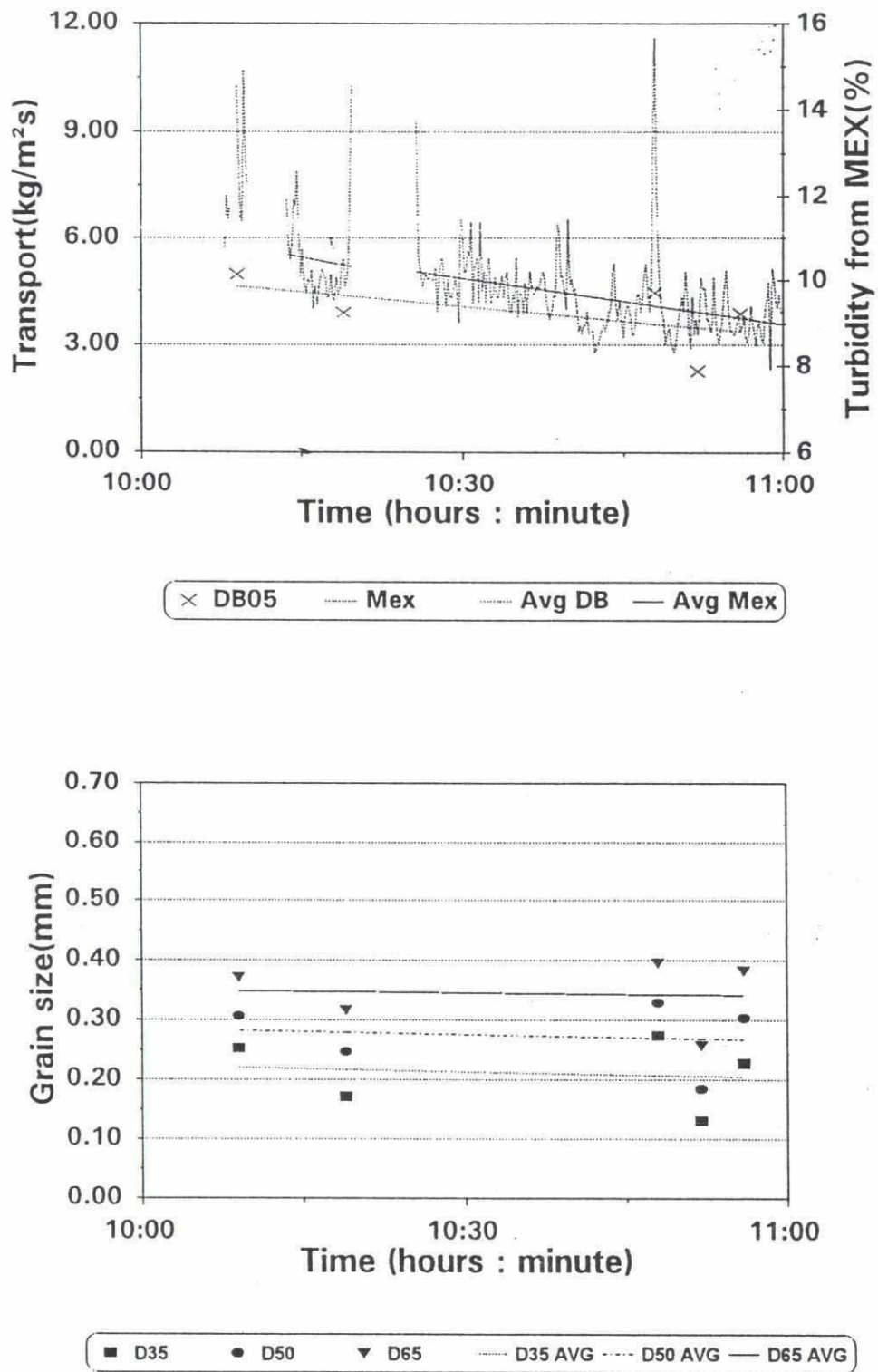


Figure G6.12 Time series Delft Bottle transport in vertical 2, May 30th

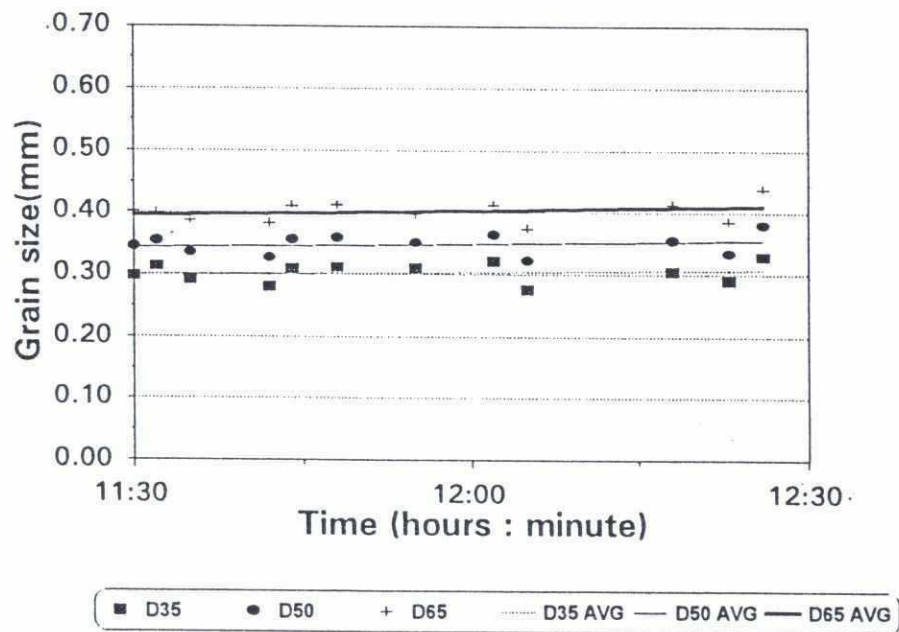
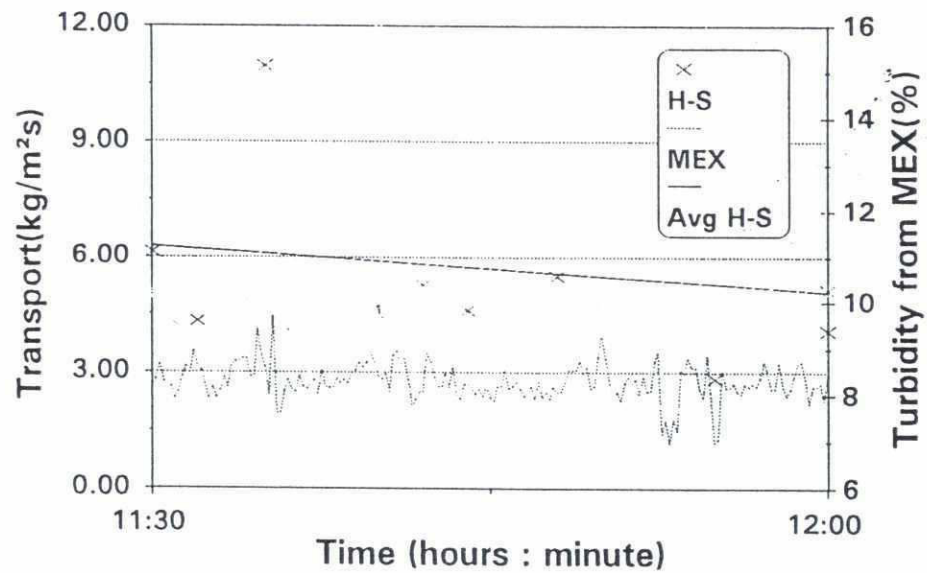


Figure G6.13 Time series Helley-Smith transport in vertical 2, May 30th

Annexure G7

Study Survey

Sediment Plume Survey, 23-26 May 1995

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Appendix 1 Comparison of sediment transport measurements by BWDB and RSP

G99

1 Introduction

The study programme for sediment transport measurements included a special survey for local erosion processes during the lean season, see RSP Study Programme February 1995. These processes result in small but probably not negligible changes in the planform and the channel dimensions. These local erosion processes can result in overloading of the flow with sediment, downstream of the eroded area. These phenomena are part of study topic 2.7 of the study programme. This sediment overloading is also called a sediment plume.

This special survey was done at the end of the lean season, in May 1995. This survey was postponed earlier, when during a special survey in December 1994 no proper location could be identified. A proposal for this special survey was discussed with the PMU. After a study of the planform and a reconnaissance survey an eroding char near a confluence of two main channels upstream of Bahadurabad was selected as the area for this survey in concert with the suggestions of the Project Adviser.

The rationale for this plume survey is that the local sediment plumes contribute to the local sedimentation processes (such as sorting of grain sizes) and to the local changes in planform. Improved understanding of this phenomena will also improve the short-term prediction of local morphological changes in the planform of a braided river.

The objectives of the sediment plume survey is to determine sediment overloading and to explain the reasons for that phenomena, and to determine the diffusion of sediment plumes in downstream direction.

In this report the measuring programme (Chapter 2), the results of the measurements (Chapter 3) are described and these results are discussed in Chapter 4.

2 Measuring programme

The study of the overall morphological developments was done using SPOT images and the study showed a few promising locations near Bahadurabad, especially upstream of that location. First a field reconnaissance was made May 22nd in that area using the online presentation of the flow velocities and backscatter measured by the ADCP. With these results the transects, verticals and longitudinal survey lines were selected, see map in Figure G7.1.

Three temporary staff gauges were installed along the eroding bank of the char, see Figures 1 and 2. The temporary bench-marks of these staff gauges were levelled to connect the staff gauges. From the readings the local water level slopes can be calculated, not the absolute water levels relative to PWD or an other datum. The readings were made two or three times per day on May 24th, 25th and 26th.

These staff gauges do not cover the whole sediment plume because it extended downstream of the most downstream staff gauge at the most downstream point of the char. Therefore the calculated water level slopes cover the upstream part of the sediment plume.

Bathymetric survey was carried out in the survey area from Northing 794500 to 796250, with a line spacing of 100 m.

Sediment transport measurements were done in 8 verticals, see Table G7.1. In all the verticals ADCP backscatter was measured to calculate the concentration of the coarse fraction. In total 61 Delft Bottle samples, 2 pump-bottle samples and 9 bed material samples were taken.

No side scan sonar was used to determine the pattern of dunes on the river bed, because the sediment concentration in the water was too high for reliable information from that instrument.

The time schedule for this survey was as follows:

22 May : a reconnaissance survey
 23 May : several transects, longitudinal lines and vertical 1 measured
 24 May : float track survey, transects and start with vertical 2 measurements
 25 May : float track survey, bathymetric survey, vertical 2 completed, verticals 3 and 4
 26 May : completion bathymetric survey, longitudinal lines, verticals 5, 6, 7 and 8 were measured.

Vertical	Delft Bottle depth integrating	Delft Bottle near bed samples	Delft Bottle suspended samples	Bed material samples by USBM
1		4	-	1
2	3	3	12	1
3		4	4	2
4		3	4	2
5		3	4	1
6		3	4	1
7		3	4	1
8		3	4	1

Table G7.1: Sediment transport measurements in 8 verticals

3 Results of measurements

3.1 Location

The plume survey was done in the Jamuna River halfway between Bahadurabad and Kamarjani which is a village on the right bank about 44.7 km north (upstream) of Bahadurabad. The plume survey was located near the confluence of the main channel and the mid-left channel, Northing of the survey area 794000 to 798000. In the main channel just upstream of that survey area the right channel flowing to Fulchari branches off. A map of the survey area is shown in Figure G7.1 which shows the planform of 24 March 1995 as presented on a SPOT image. In that figure also the transects, longitudinal lines and the verticals are indicated.

This location was suggested by the Project Adviser when he analyzed the available bathymetric charts and topographic maps. He mentioned already in his seventh mission report (Peters, 1994) that this is a method to identify qualitatively the presence of sludge-wise movement of the sediment load.

3.2 Bathymetry

The data of the bathymetric survey was processed following the method used by RSP. The resulting bathymetric map is presented in Figure G7.2 together with the survey lines. The bathymetric survey did not cover the complete survey area, for which it should have been extended in upstream direction. Instead the contours lines were interpolated from the transects, see dashed contour lines in that map. On the other hand the survey covered the complete channel width.

This bathymetry can be compared with a bathymetric map of an earlier Kamarjani survey which covers also the area of the plume survey, see Figure G7.3A, G7.3B and G7.3C.

3.3 Water levels

During the survey the water level raised about 0.2 m per day, see Table G7.2

Day	Water level (m + PWD)	Daily increase in water level (m)
23 May	17.78	
24 May	17.98	0.20
25 May	18.18	0.20
26 May	18.27	0.09

Table G7.2 Water level measured by RSP in Bahadurabad during the survey period.

Along the eroding right bank of the mid left channel three staff gauges were placed for this survey, see Figures G7.1. The water level was read about 2 to 3 times per day. The middle staff gauge was stolen after two days. The readings of the staff gauge were used to calculate the local water level slope. The readings are presented in Table G7.2. In the downstream section an extreme local water level slope of 0.18 m/km was measured. In the upstream section the water level slope was very mild, only 0.01 to 0.02 m/km.

3.4 Flow velocities

In the verticals and in the transects the ADCP measured the flow velocities, see Figures G7.4, G7.6, G7.8, G7.9, G7.10, G7.11, G7.12 and G7.13. In the upper layer the ADCP did not measure the flow velocities. The flow velocities in the lower 5% of the vertical were also not measured. The flow velocities were in the range of 1 to 2 m/s. In the transects the flow velocities were measured with the moving boat method. Two contours of the maximum flow velocity near the water surface are shown in Figure G7.14. The maximum flow velocity does not occur at the location with largest water depths.

The general flow pattern is illustrated by 6 float tracks in Figure G7.15. Upstream of the deep hole near vertical 5 the tracks of float 1 and 2 converge and downstream they diverge as the water depth reduces. Upstream the float tracks 2 and 3 diverge, in the middle part they are parallel and in the downstream part they tend to converge. But the water depth is rather constant in that area.

In the verticals the flow velocities were measured by an anchored vessel, see the verticals in Figures G7.5 and G7.7. These measurements are averaged values over a measuring interval of 5 or more minutes.

3.5 Sediment measurements

In a vertical the sediment transport was measured at 0.2, 0.4, 0.6 and 0.8 h and near the river bed at 0.05, 0.15 and 0.35 m from the bed, see the results in Table G7.3. In vertical 2 some tests were done to use the Delft Bottle as an depth integrating sampler. The catch was well repeated in the tests. This sampling was repeated after 1 hour with some tests in which an additional weight was attached to the Delft Bottle. This resulted in about 10 to 20 % higher catch. It was preferred to continue to take point samples with the Delft Bottle without any additional weight in the other verticals.

All samples with the Delft Bottle were taken with a straight nozzle of 1.9 cm² for the suspended measurements and a bended nozzle for the near bed measurements. In the back of the Delft Bottle 2 holes were left open.

Height in vertical	verticals							
	1	2	3	4	5	6	7	8
0.2 h	-	6.7/5	18 /5	4.5/5	2 /5	32 /5	28 /5	31 /5
0.4 h	-	12 /5	13 /5	9 /5	3 /5	39 /5	36 /5	34 /5
0.6 h	-	16 /5	25 /5	16 /5	5 /5	36 /5	50 /5	37 /5
0.8 h	-	22 /5	25.5/5	27 /5	16 /5	30 /5	54 /5	48 /5
0.35	24 /5	20 /2	26 /2	14.5/1	20 /2	38 /2	54 /2	42 /2
0.15	49.5/5	25 /2	44 /2	14 /1	20 /2	73 /2	56 /2	42 /2
0.05	69 /5	-	238 /2	-	-	-	-	-
0.05	41 /5	128 /5	153 /2	308 /1	40 /2	68 /2	60 /2	30 /2

x/y = volume of each in cm³ / sampling time in minutes

Table G7.3 Total catches of the silt and the sand fraction with Delft Bottle in verticals

The sampling in vertical 2 was repeated the next day, 25th May, see Table G7.4. On that day the position of the vertical was shifted less than 10 m from the position on the 24th.

Height in vertical	vertical 2			
	May 24th	May 25th,#	May 25th	May 25th,*
0.2 h	6.7/5	14 /5	8 /5	8 7 9
0.4 h	12 /5	13.5/5	10 /5	
0.6 h	16 /5	20.5/5	18 /5	
0.8 h	22 /5	32 /5	28 /5	

= an extra weight of 10 kg was attached to the Delft Bottle

* = volume of catch in cm³ of depth integrating Delft Bottle sample

x/y = volume of catch in cm³ / sampling time in minutes

Table G7.4 Total catches of the silt and the sand fraction with Delft Bottle in additional tests in vertical 2

The analysis of these Delft Bottle samples showed that the porosity of the sediment in the measuring glass is about 0.6. In the flow line of vertical 6, 7 and 8 the porosity was on average 0.6 to 0.67. These higher porosities indicate parts of

plants in the catch. Along the bank in verticals 1, 5, 4 and 2 the average porosity per vertical was lower 0.51 to 0.58. Some measurements of the Delft Bottle at 0.05 m above the bed showed an extreme high porosity of 0.7 to 0.9. This is because parts of vegetation and roots were collected as well. The average of 0.6 can be considered as the maximum value for fresh deposited sediments in the Jamuna River.

The backscatter of the ADCP measures the concentration of the sand fraction. In the transects and the longitudinal survey lines the concentration varied between 100 to 1000 mg/l, see Figures G7.5, G7.7, G7.8, G7.9, G7.10, G7.11, G7.12 and G7.13.

3.6 Bedform tracking

Bed forms were measured along 2 tracks, see B55Q1T01 and B55Q1T07 in bathymetric map in Figure G7.2. Simultaneously ADCP longitudinal profiling was executed. The ADCP flow velocities and the sediment concentration calculated from the backscatter are presented in Figures G7.4 to G7.7. The maximum height of the bedforms was about 4 m, but the majority of the dunes had a height between 1 and 3 m, only in the deep channel upstream of vertical 1 the bedforms have a height of several decimeters.

4 Discussion and conclusion

Increased flow during the rising limb of the hydrograph in May 1995 created high sediment transports and erosion over a shallow in the mouth of the left channel along the right bank of that channel.

The extra weight to reduce the drag of the suspended Delft Bottle is not recommendable. Because this weight affects the flow in the wake of the bottle and consequently the pressure difference over the bottle. And this will affect the sediment catch in the bottle also.

The sediment transport calculated from the Delft Bottle measurements and the backscatter are almost the same in the verticals 6, 7 and 8 where the D_{50} = about 0.100 mm (see Table G7.5 and Figures G7.18 and G7.19) of the sand fraction of the Delft Bottle samples. In this comparison it should be expected that a considerable fraction of these fine sediments is not trapped in the Delft Bottle. Therefore the sediment transport measured by the Delft Bottle should be smaller than the sediment transport calculated from the backscatter. The shape of the concentration verticals deviates from the equilibrium concentration profile.

In the verticals 5, 4 and 2 the Delft Bottle measured much less transport than the backscatter, and the D_{50} varied between 0.120 to 0.180 mm (see Table G7.5 and Figures G7.17 and G7.18). The shape of the sediment verticals also deviate from the equilibrium concentration profile.

The total sediment transport in a vertical calculated from the backscatter underestimates the sediment transport, if the concentration below the lowest measuring point is assumed to constant. Therefore it is combined with the near-bed Delft Bottle measurements to have a better approximation of the total sediment transport.

The porosity of some Delft Bottle samples of relatively fine sand was about 60 %, which is much higher than the average of 40 %.

The local slope was only measured along the bank of the char. The local slope is probably not constant over the width of the channel, because of the complicated bathymetry and the variation in dune heights. The distribution of the local slopes in the verticals in the channel were calculated with the Chezy equation. The Chezy coefficient is a function of the hydraulic roughness of the river bed, k_s , was estimated as 17 % of the height of the rounded dunes upstream of the vertical. The local slopes along the bank (verticals 5, 4 and 2) are interpolated from the measured local slopes, see Table G7.5. The k_s -values in that table are about half the height of the bed forms.

The measured local slope of the water level of 0.18 m/km is much higher than the average water level slope of 0.07 to 0.08 m/km.

In each vertical a bed material sample was taken. The D_{50} of the grain size distribution of these samples is presented in Table G7.5. The same tendencies as in the D_{50} of the Delft Bottle samples can be seen in those samples.

Vertical	k_s (m)	D_{50} (mm) Delft Bottle	D_{50} (mm) bed material	local slope (-)	Porosity (-)	
					min	max
5	0.6	0.123	0.331	0.00007	0.52	0.63
4	1.5	0.180	0.345	0.00014	0.51	0.61
2	2.5	0.167	0.313	0.00016	0.49	0.52
6	1.2	0.100	0.282	0.00011	0.60	0.75
7	0.5	0.104	0.296	0.00011	0.60	0.69
8	1.5	0.100	0.208	0.00014	0.59	0.61

Table G7.5 Estimated hydraulic roughness, characteristic grain sizes, porosity and the estimated local slope in the verticals

It is noted here that if local high sediment transport coincides with local high flow velocities there is not necessarily overloading. It seems to be that overloading can be determined in field as a function of the local water level slope. An example of a sediment plume in the Zaire River is shown in Figure G7.20 (Peters, 1993). This sediment plume was produced by a large sand bar and it triggered a channel shift.

The sediment transport was calculated using the sediment transport formula presented in Appendix 1 comparison of sediment transport measurements by BWDB and RSP. This formula is based on the measured verticals in the routine gaugings of RSP in Bahadurabad right channel, Sirajganj, Tilly and Mymensingh. For the data of Bahadurabad and Sirajganj a combination of assumed Chezy values 70 and 50 was taken, while for Tilly the hydraulic roughness was assumed to be $k_s = 0.4$ m.

$$\Phi = 81.3 * \theta^{1.82} \quad (1)$$

An incomplete analysis of the measurements seems to suggest that a fair estimate of the sediment transport in a plume can be obtained in two ways:

- To substitute the overall water level slope or an assumed combination of chezy values 70 and 50 in the sediment transport formula for the Jamuna River,
- Or to substitute the local slope in a general sediment transport formula, such as a Englund-Hansen or an Bagnold type formula.

The results are shown in Figures G7.21 to G7.23. However, the complicated hydraulic and morphological phenomena on one side and the limited measurements in this survey on the other hand does not allow a firm conclusion.



References

- 1 Peters, J.J. (1993) Morphological studies and data needs, a paper prepared for the International Workshop on the behaviour of large rivers in Bangladesh, Dhaka
- 2 Peters, J.J. (1994) Report of the seventh mission of the project adviser, Flood Plan Coordination Organization, Dhaka, Bangladesh
- 3 River Survey Project (February 1995), Study programme, Dhaka, Bangladesh

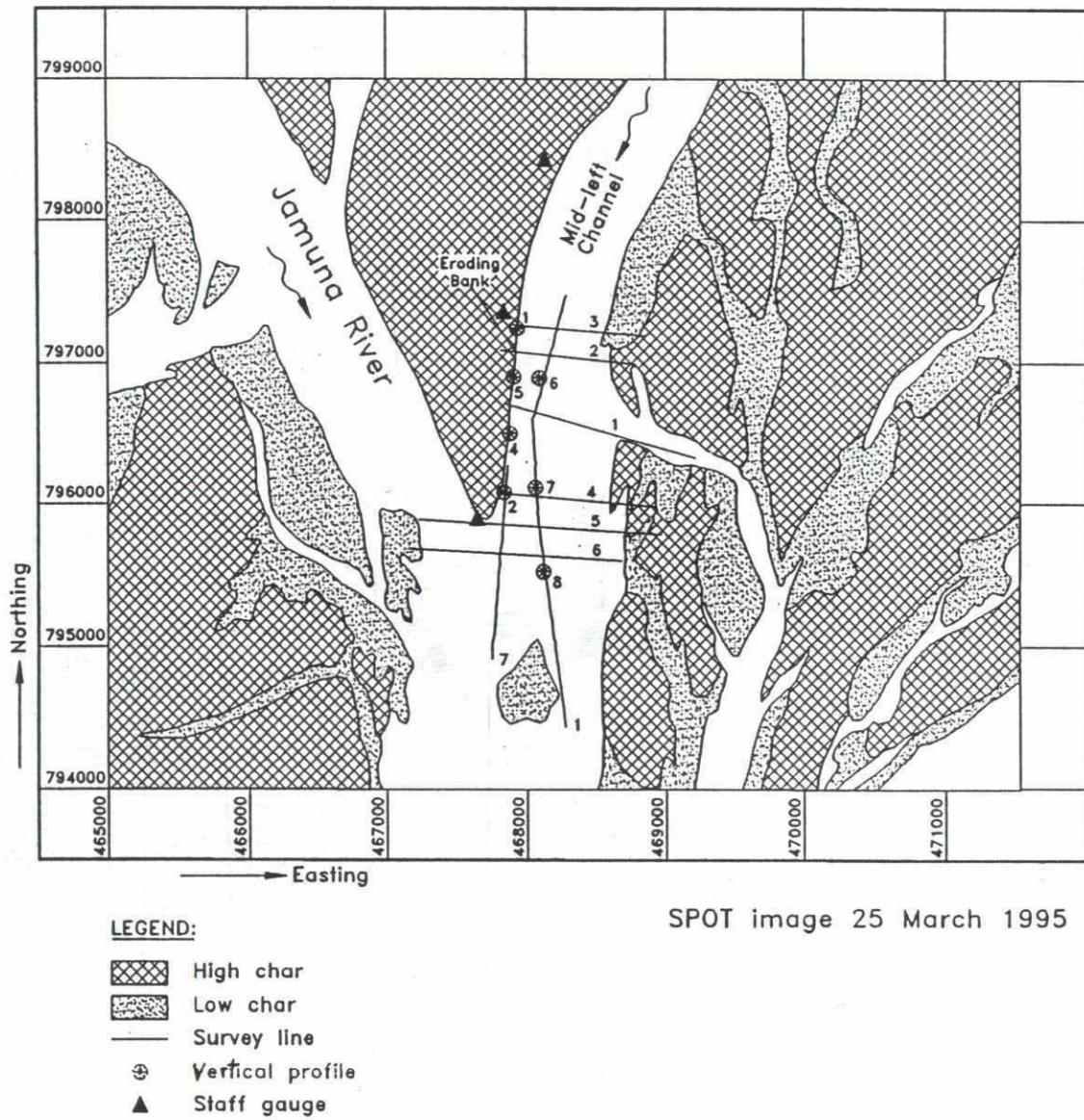


Figure G7.1: Map of survey area

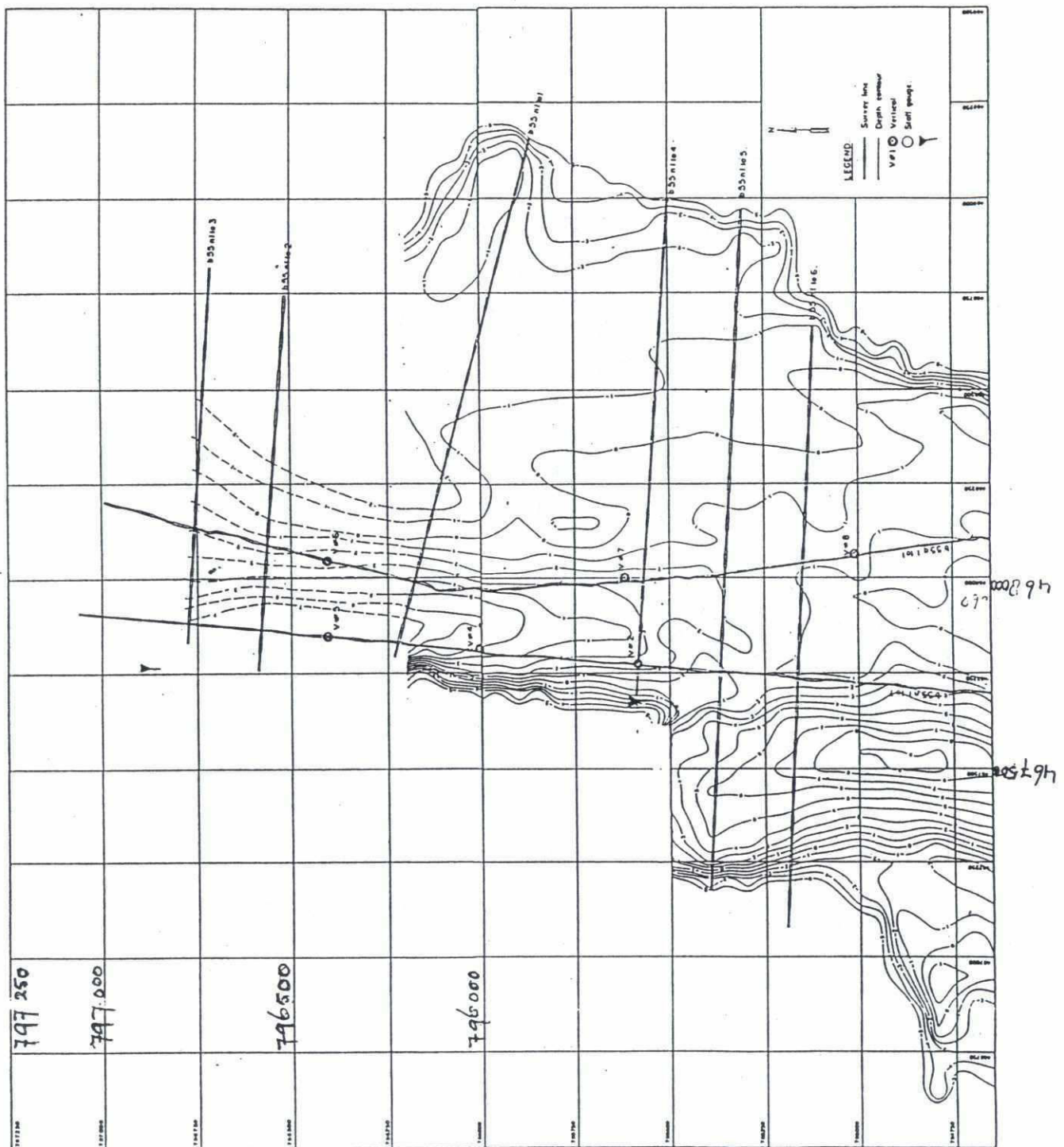
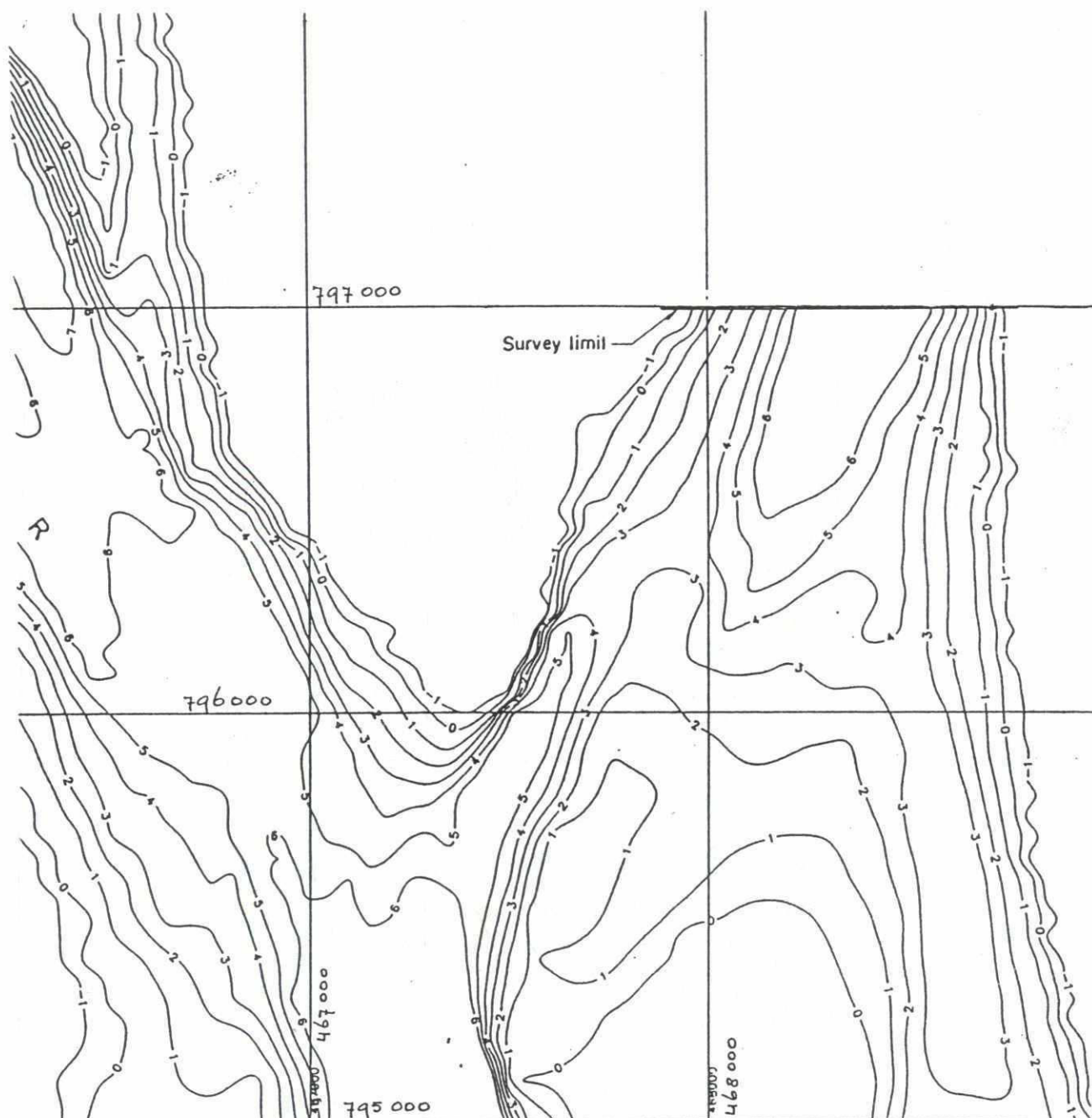


Figure G7.2: Bathymetric map with survey lines



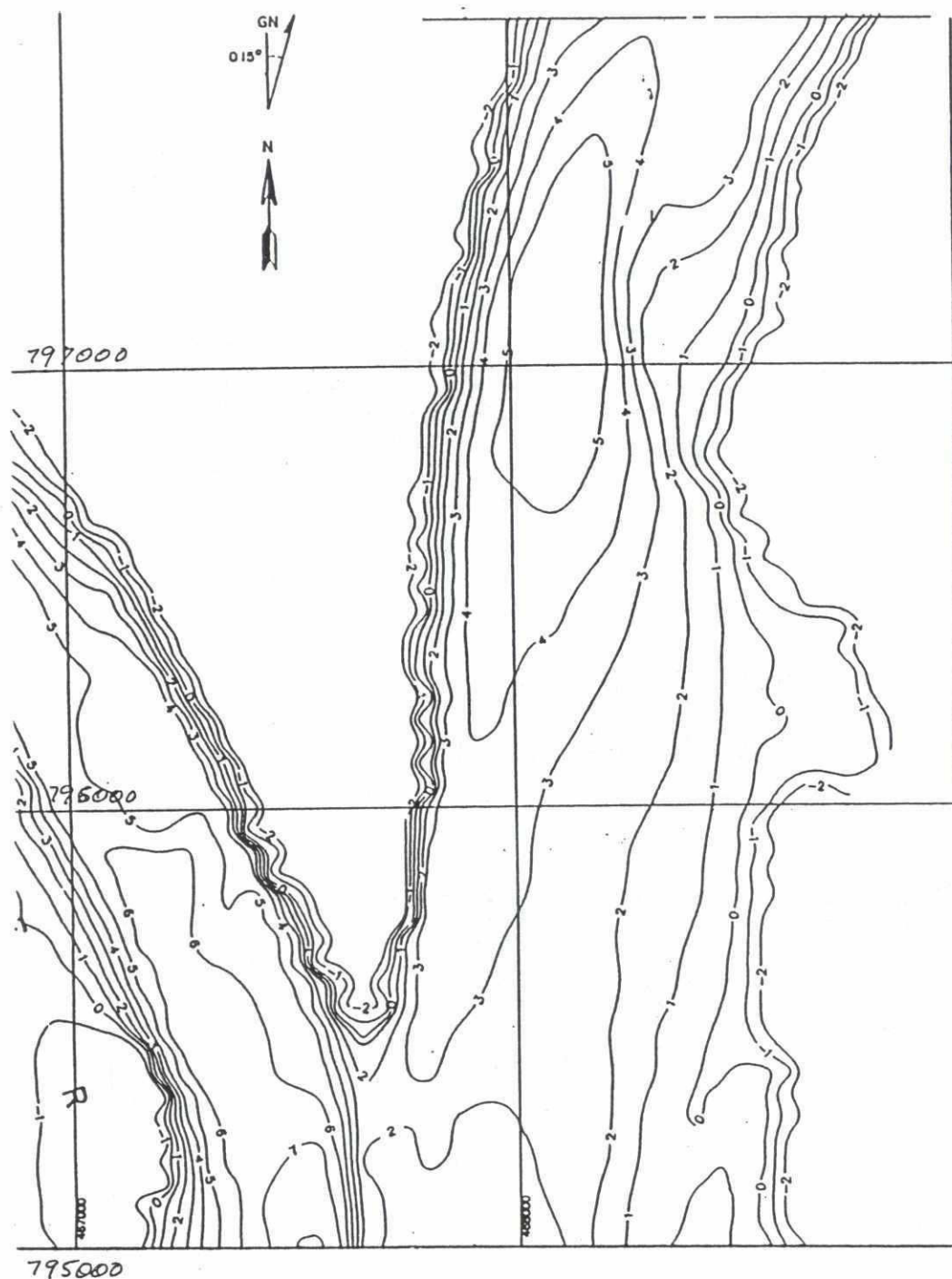
FAP 24  DELFT • DHI		RIVER SURVEY PROJECT Water Resources Planning Organization European Commission		Bathymetric Survey JAMUNA RIVER AT KAMARJANI Survey period : 24 Nov - 14 December, 1995	
Original Scale : 1:10,000	Processed : Feb 07, 1996		Contour Lines refer to SLW at Kamarjani WL gauge SLW = 13.87 m+PWD Average W.L. = 15.28 m+PWD Estimated W.L. slope during survey = 8.2 cm/km		Sheet no : 8030-6-C
	File : nov95kam				

Figure G7.3A: Bathymetric survey map 24 - 14 Dec 1995



FAP 24  DELT - DHI	RIVER SURVEY PROJECT Water Resources Planning Organization European Commission	Bathymetric Survey JAMUNA RIVER AT KAMARJANI Survey period : 07 - 13 March, 1995
	Original Scale : 1:10,000	
	Processed : Oct 25, 1995 File : mar95kam	Contour Lines refer to SLW at Kamarjani WL gauge SLW = 13.87 m+PWD Average W.L. = 14.18 m+PWD Estimated W.L. slope during survey = 8.0 cm/km

Figure G7.3B: Bathymetric survey map 07 - 13 March 1995



Projection/Grid:
Bangladesh Transverse
Mercator (BTM) System

FAP 24  DELFT · DHI	RIVER SURVEY PROJECT Water Resources Planning Organization European Commission	Bathymetric Survey JAMUNA RIVER AT KAMARJANI Survey period : 10 - 20 November, 1994
	Original Scale : 1:10,000	
	Processed : Feb 09, 1995 File : feb94kam	Contour Lines refer to SLW at Kamarjani WL gauge SLW = 13.87 m+PWD Average W.L. = 15.97 m+PWD Estimated W.L. slope during survey = 8.4 cm/km

Figure G7.3C: Bathymetric survey map 10- 20 Nov 1994

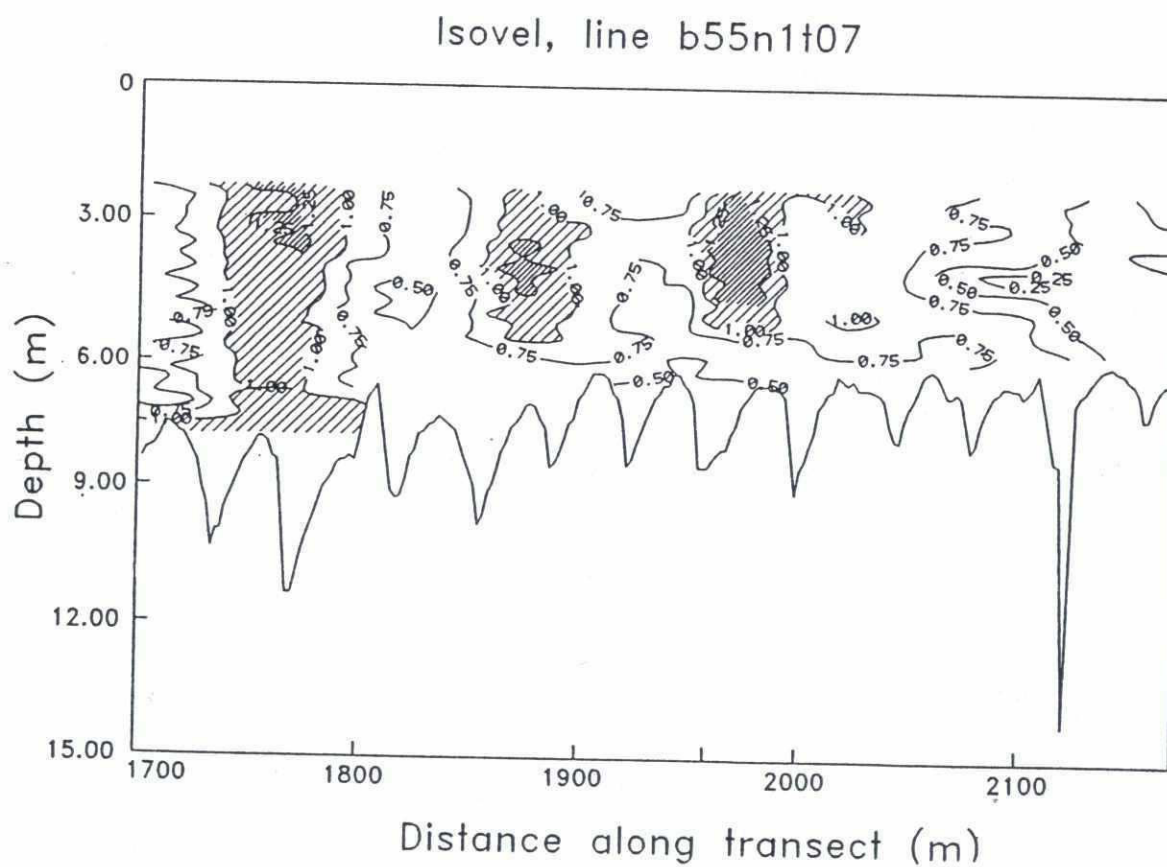
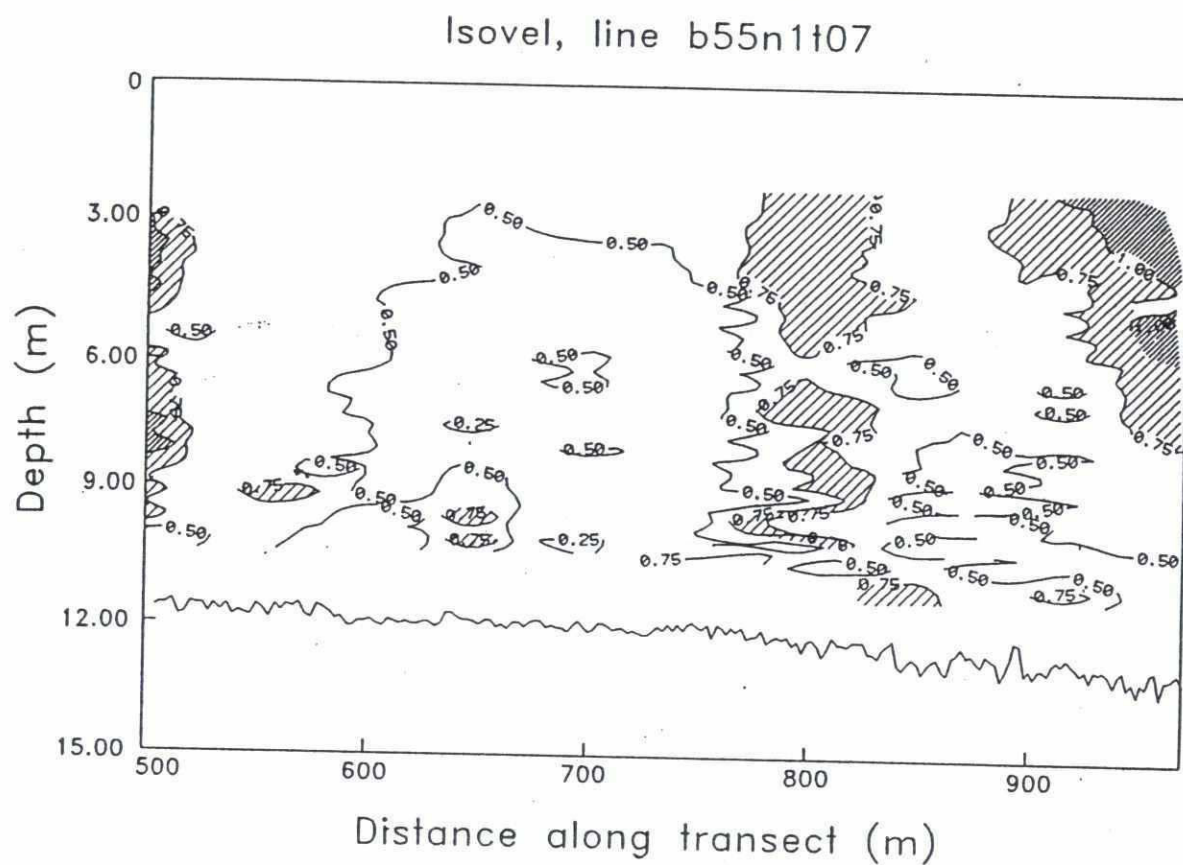
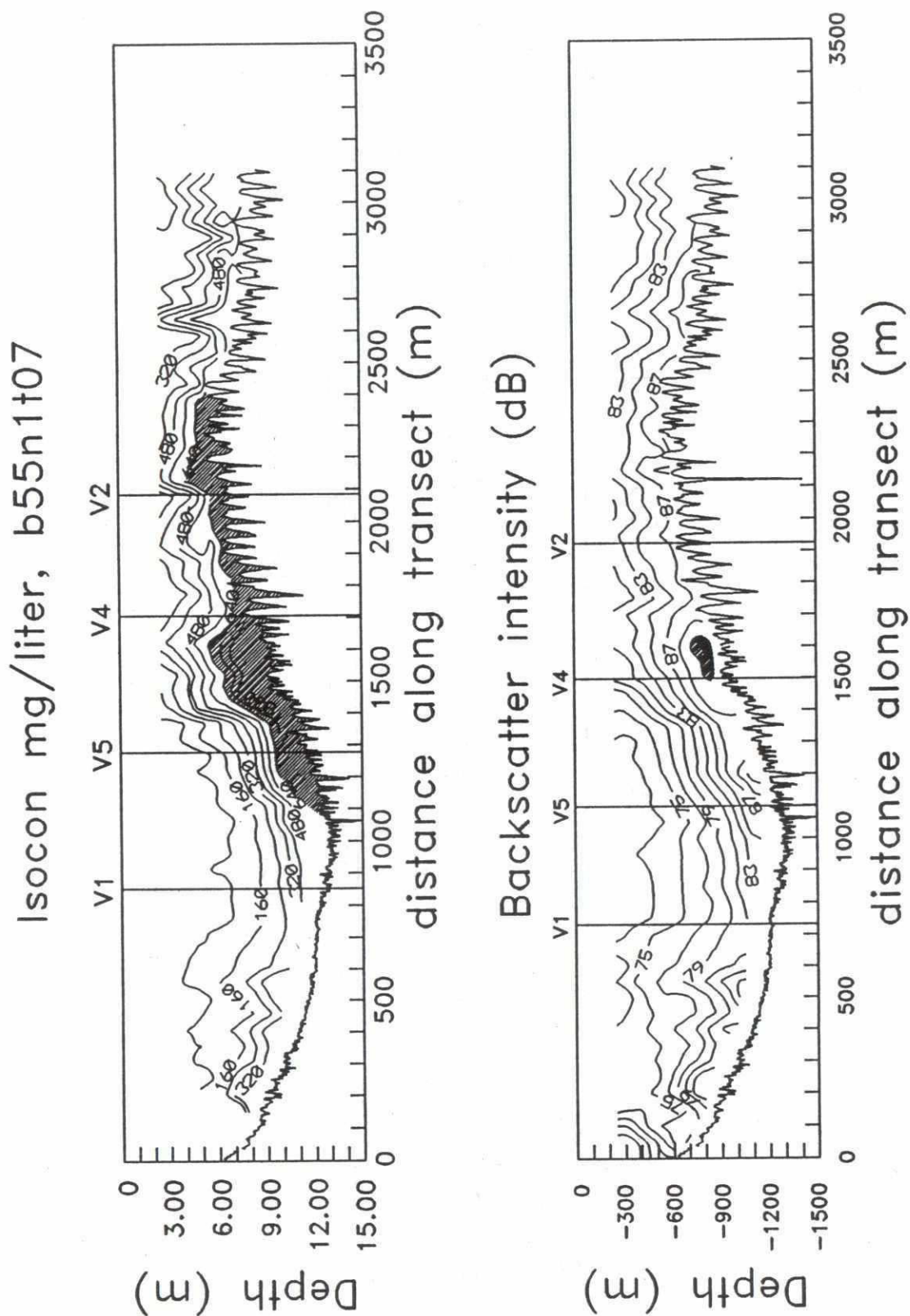


Figure G7.4: ADCP velocities in longitudinal survey line 7



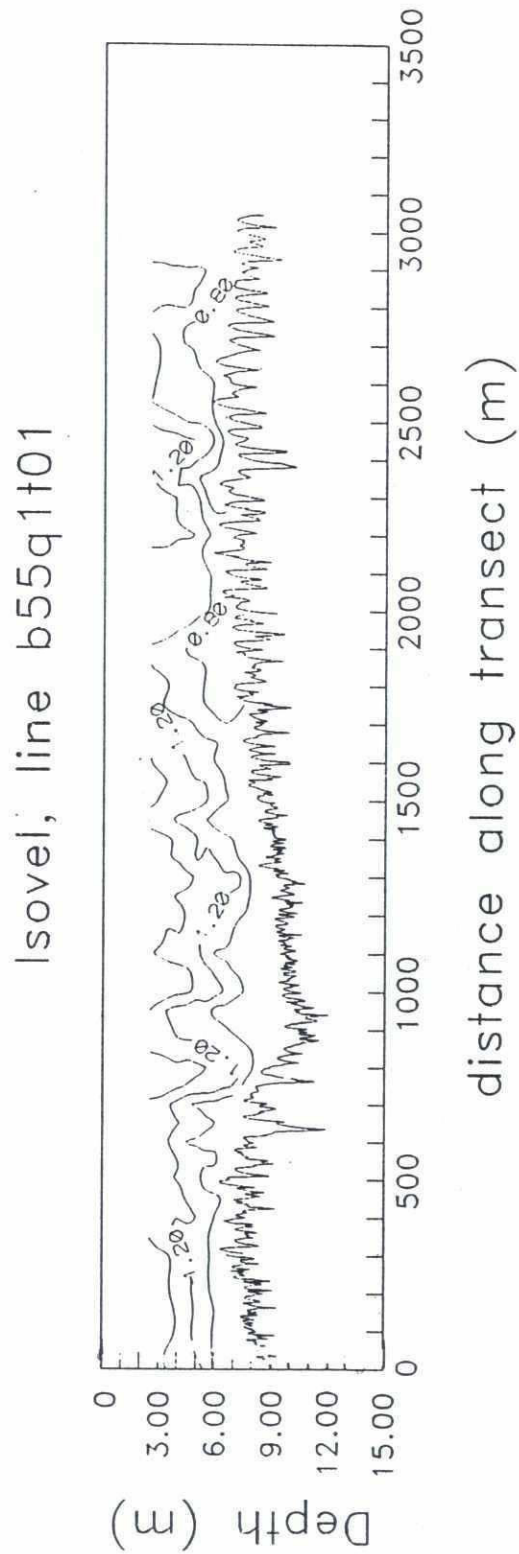


Figure G7.6: ADCP velocities in longitudinal survey line 1

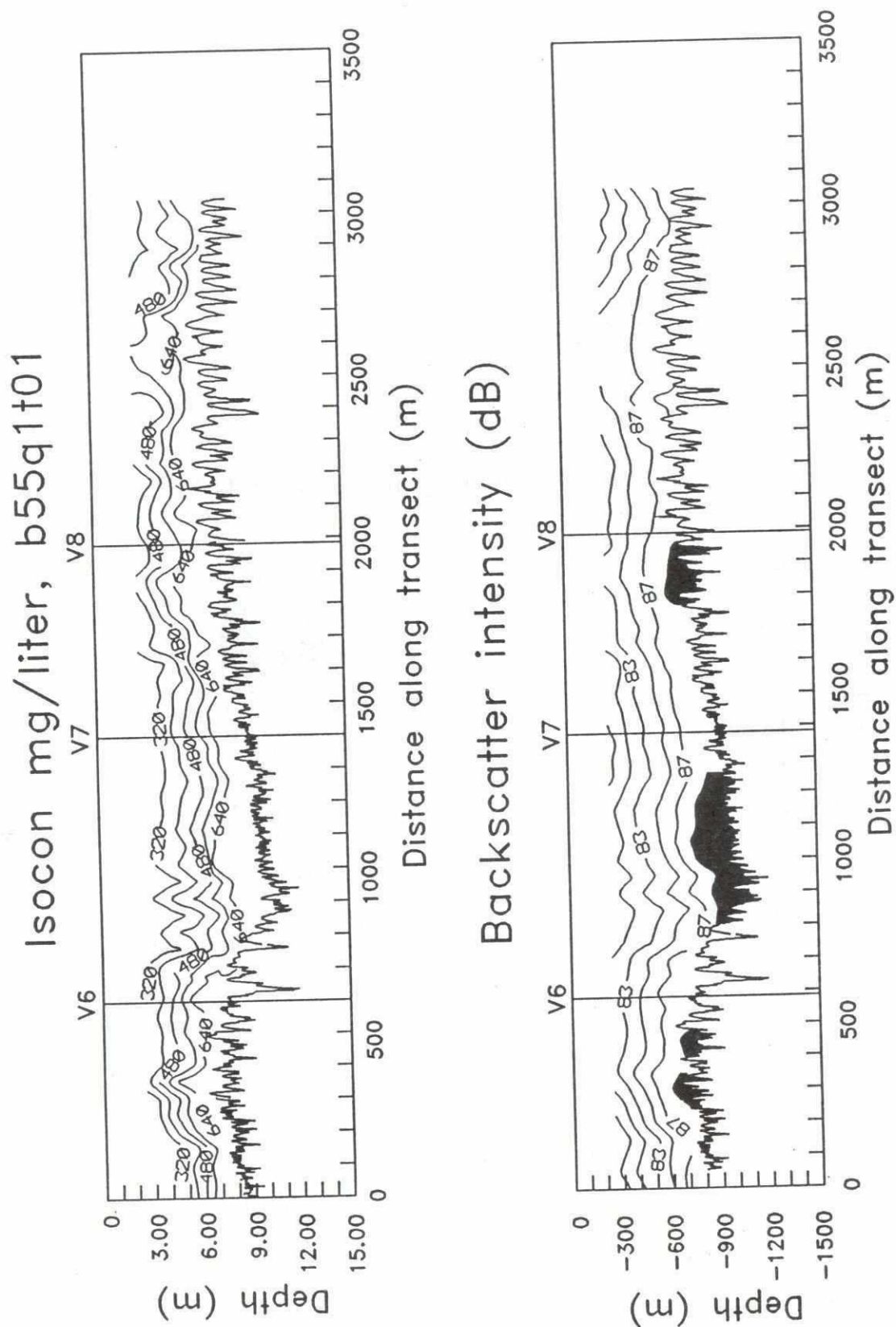


Figure G7.7: Coarse sediment transport and backscatter in longitudinal survey line 1

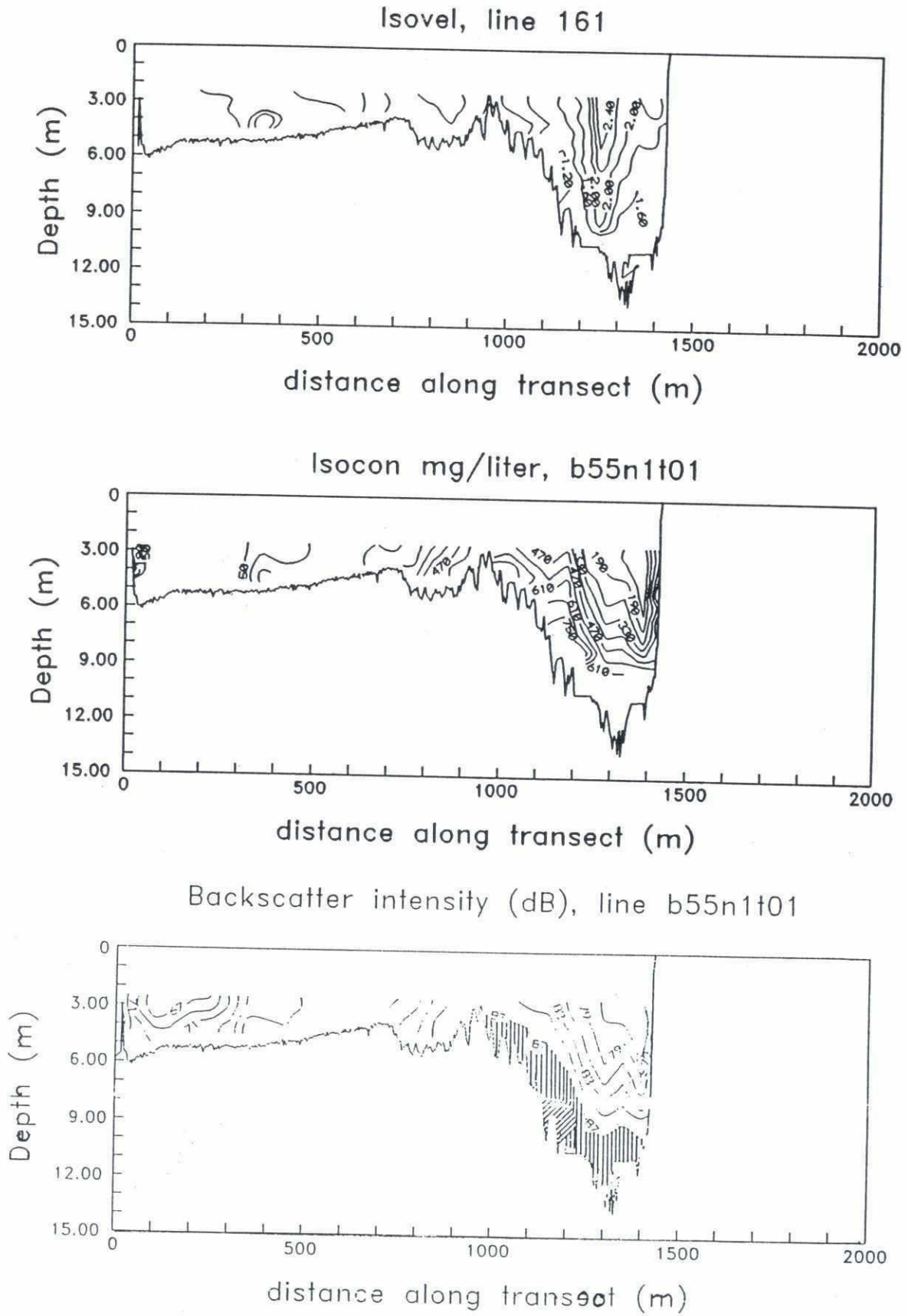
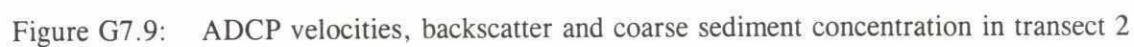


Figure G7.8: ADCP velocities, backscatter and coarse sediment concentration in transect 1



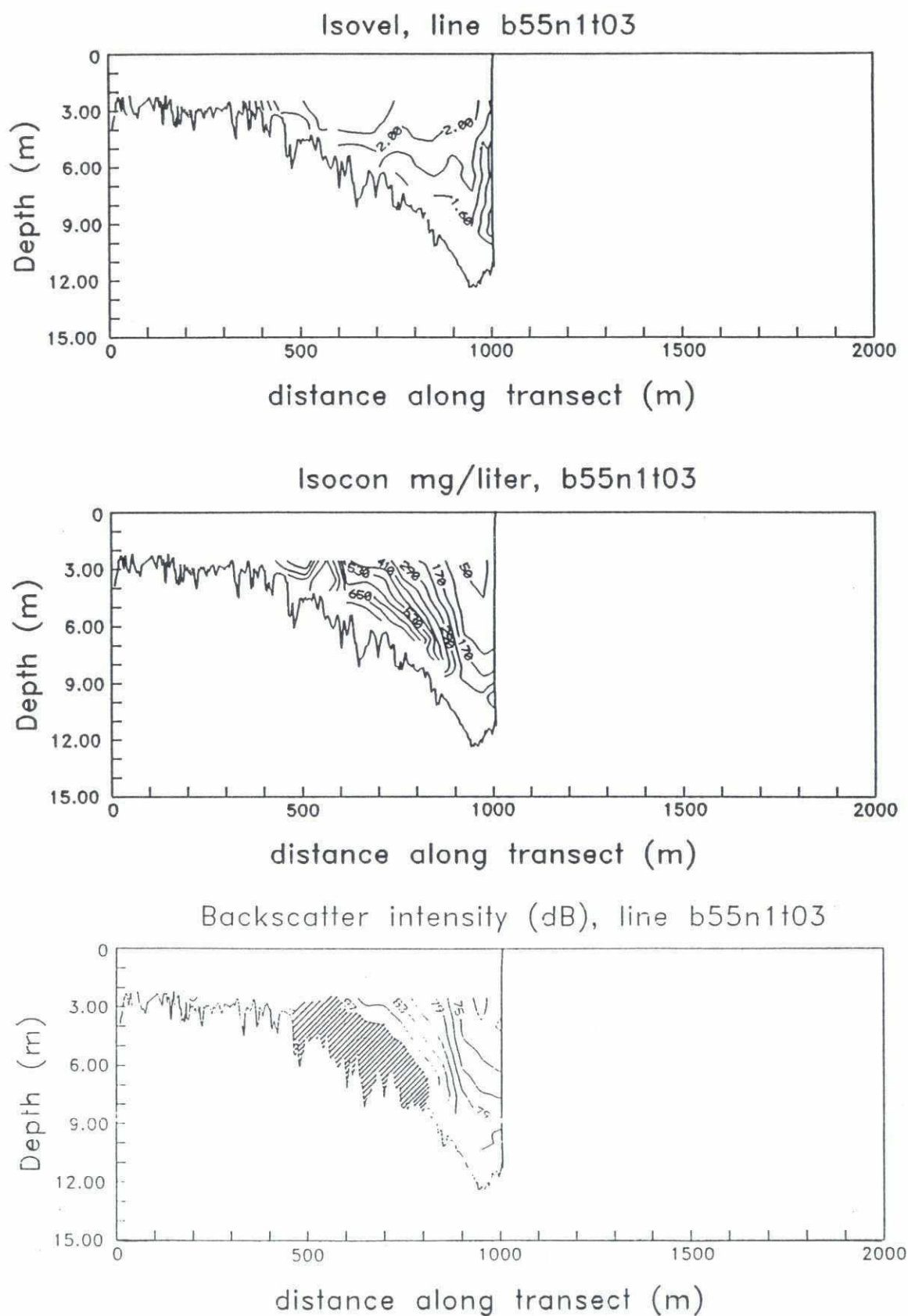


Figure G7.10: ADCP velocities, backscatter and coarse sediment concentration in transect 3

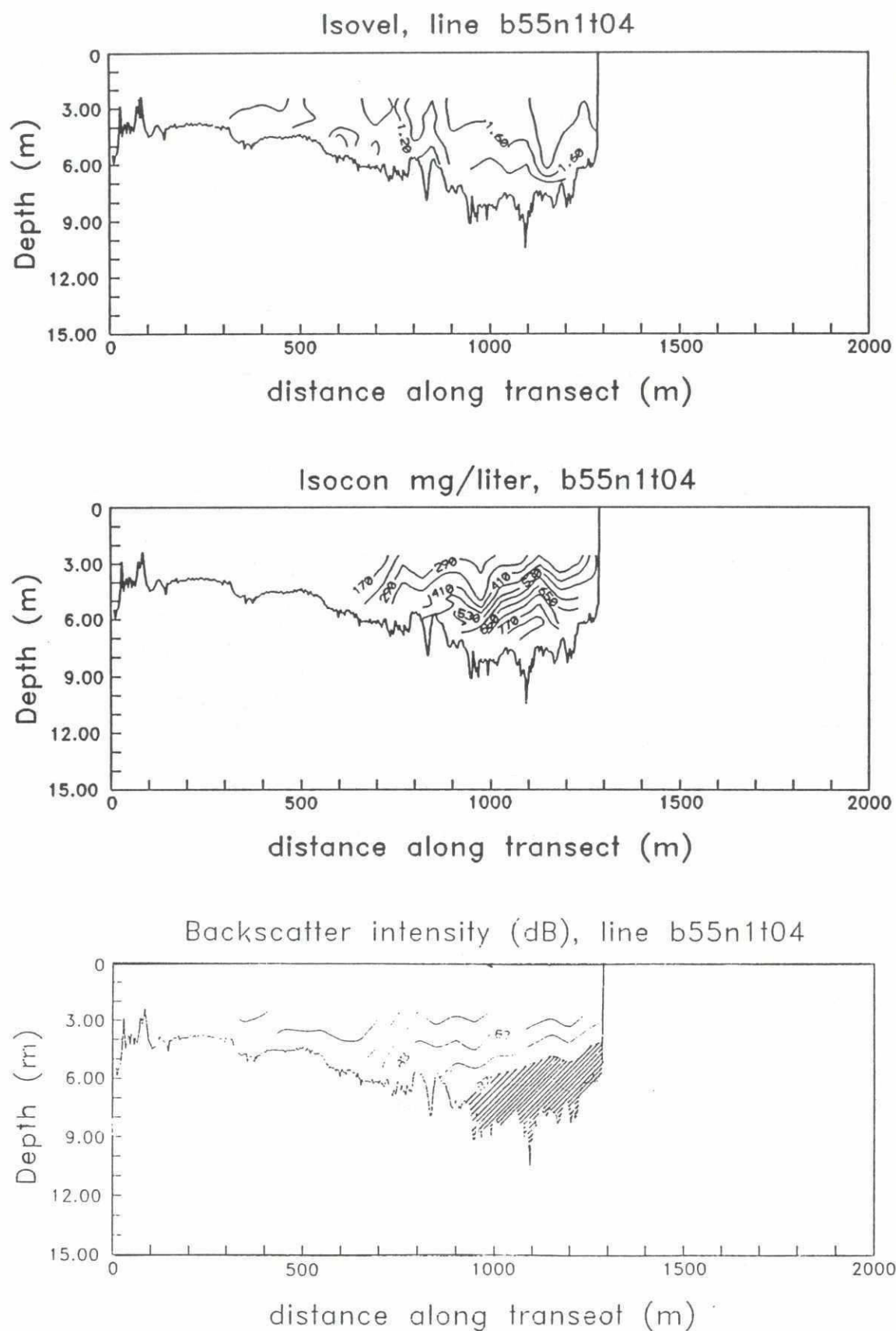


Figure G7.11: ADCP velocities, backscatter and coarse sediment concentration in transect 4

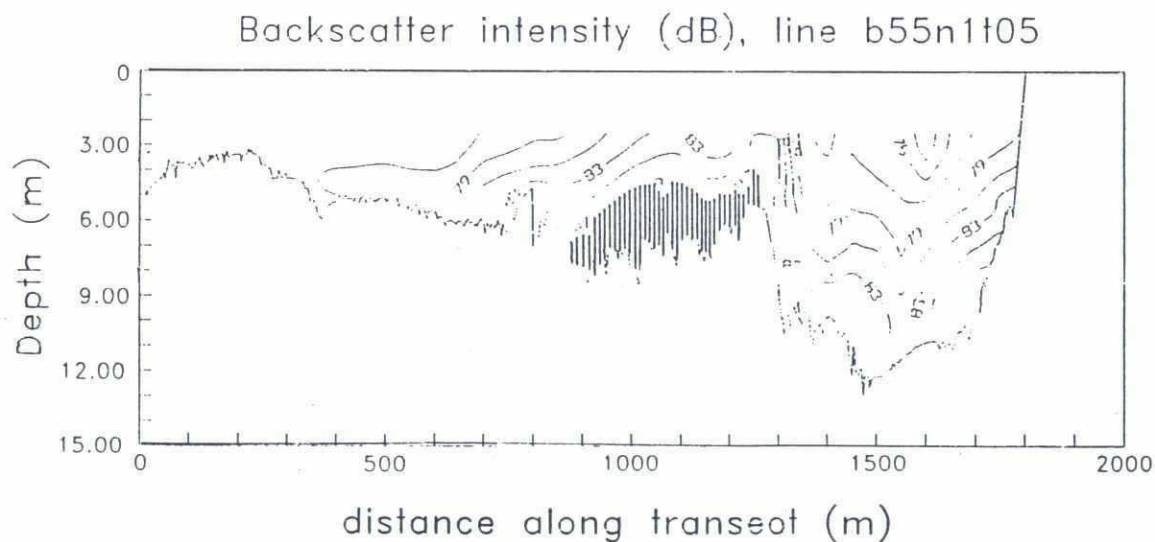
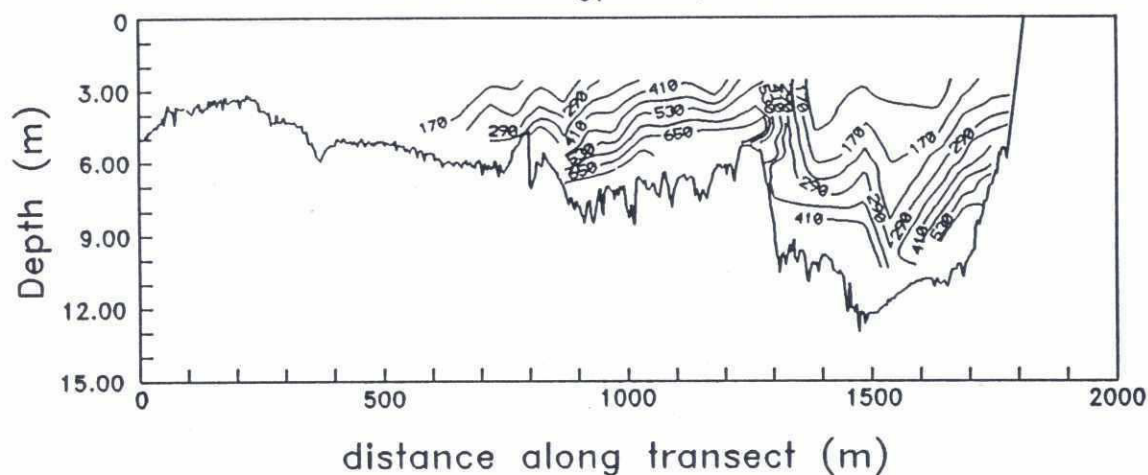


Figure G7.12: ADCP velocities, backscatter and coarse sediment concentration in transect 5

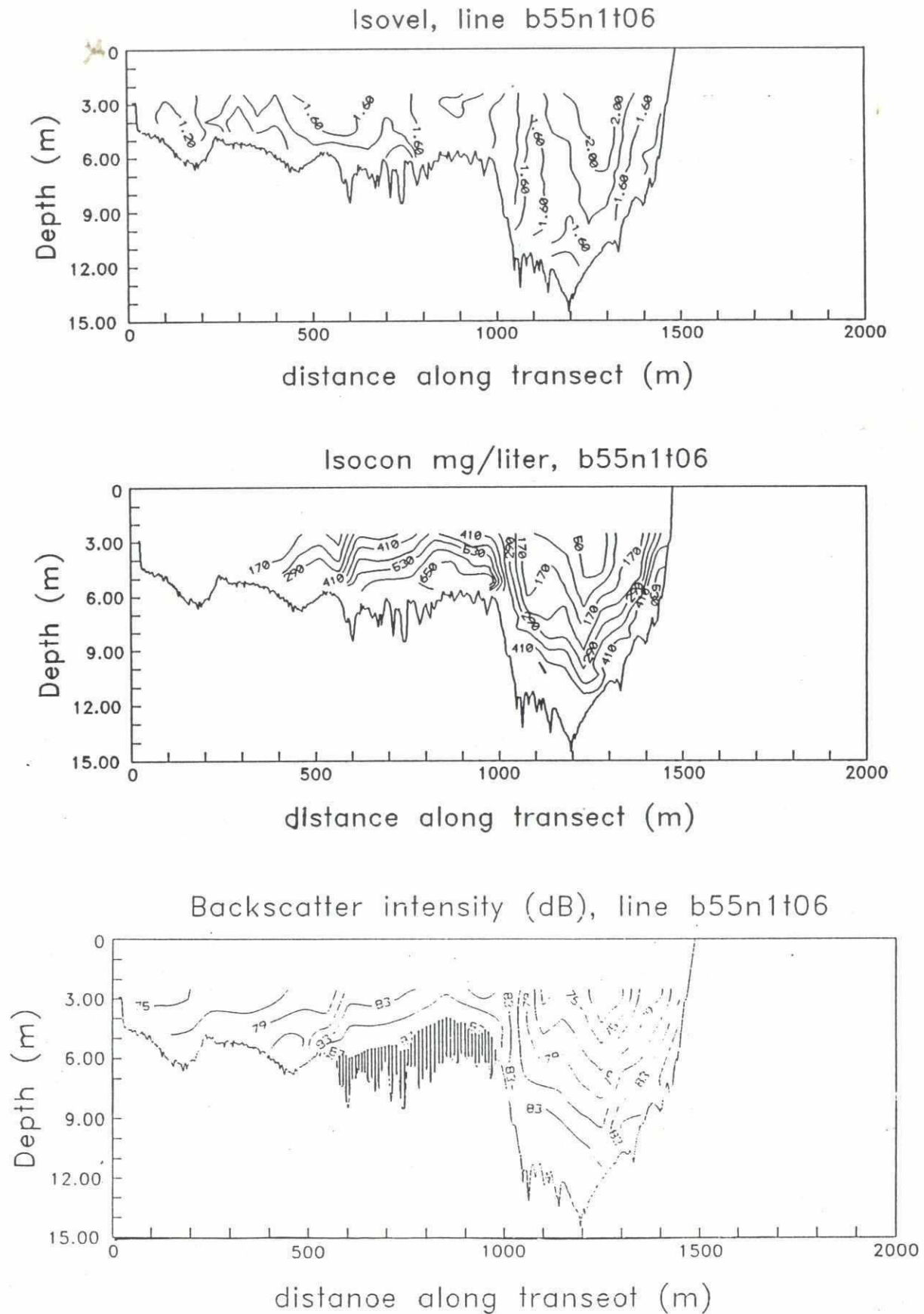


Figure G7.13: ADCP velocities, backscatter and coarse sediment concentration in transect 6



Figure G7.14: Map of survey area with iso-velocity contours

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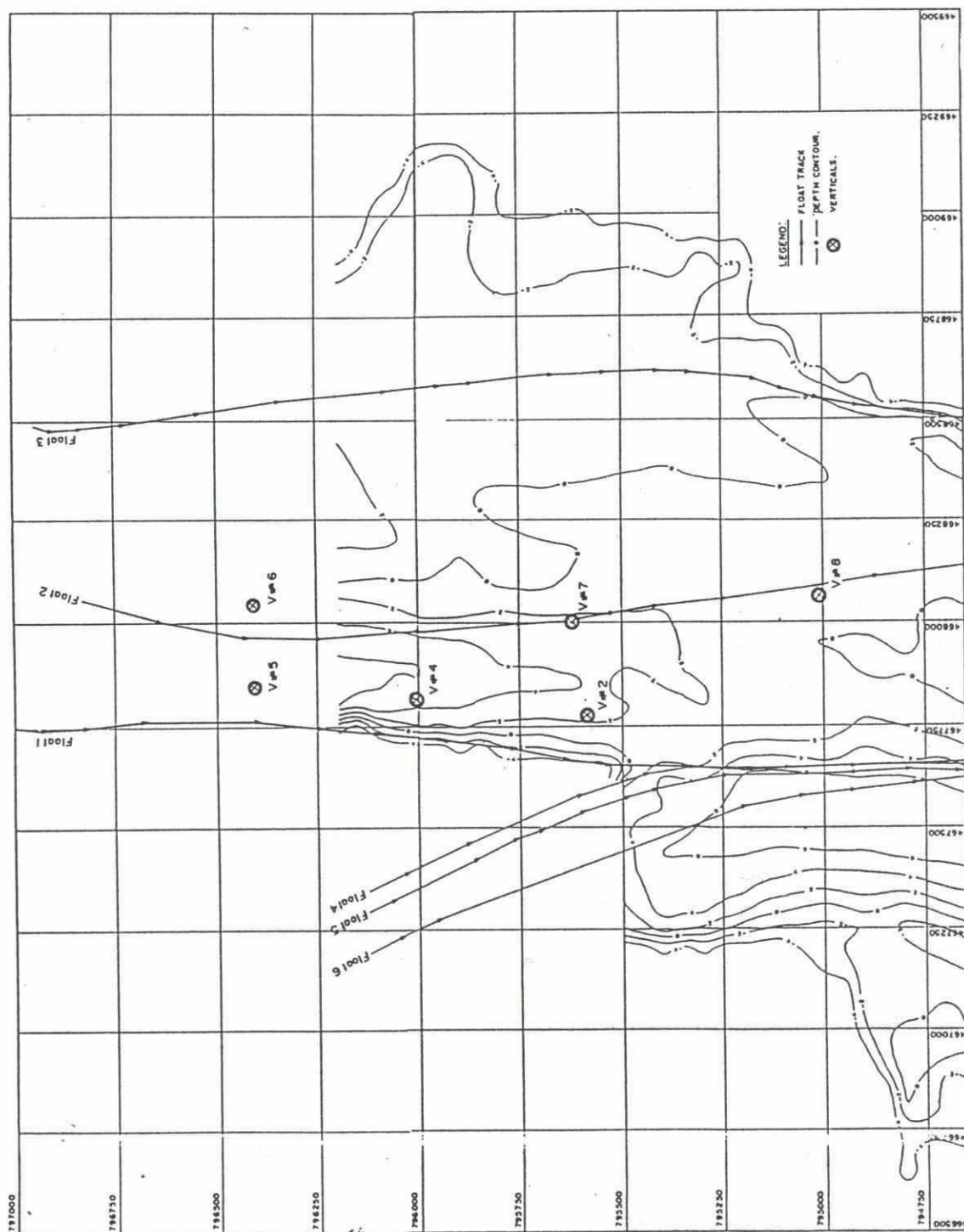


Figure G7.15: Map of survey area with float tracking

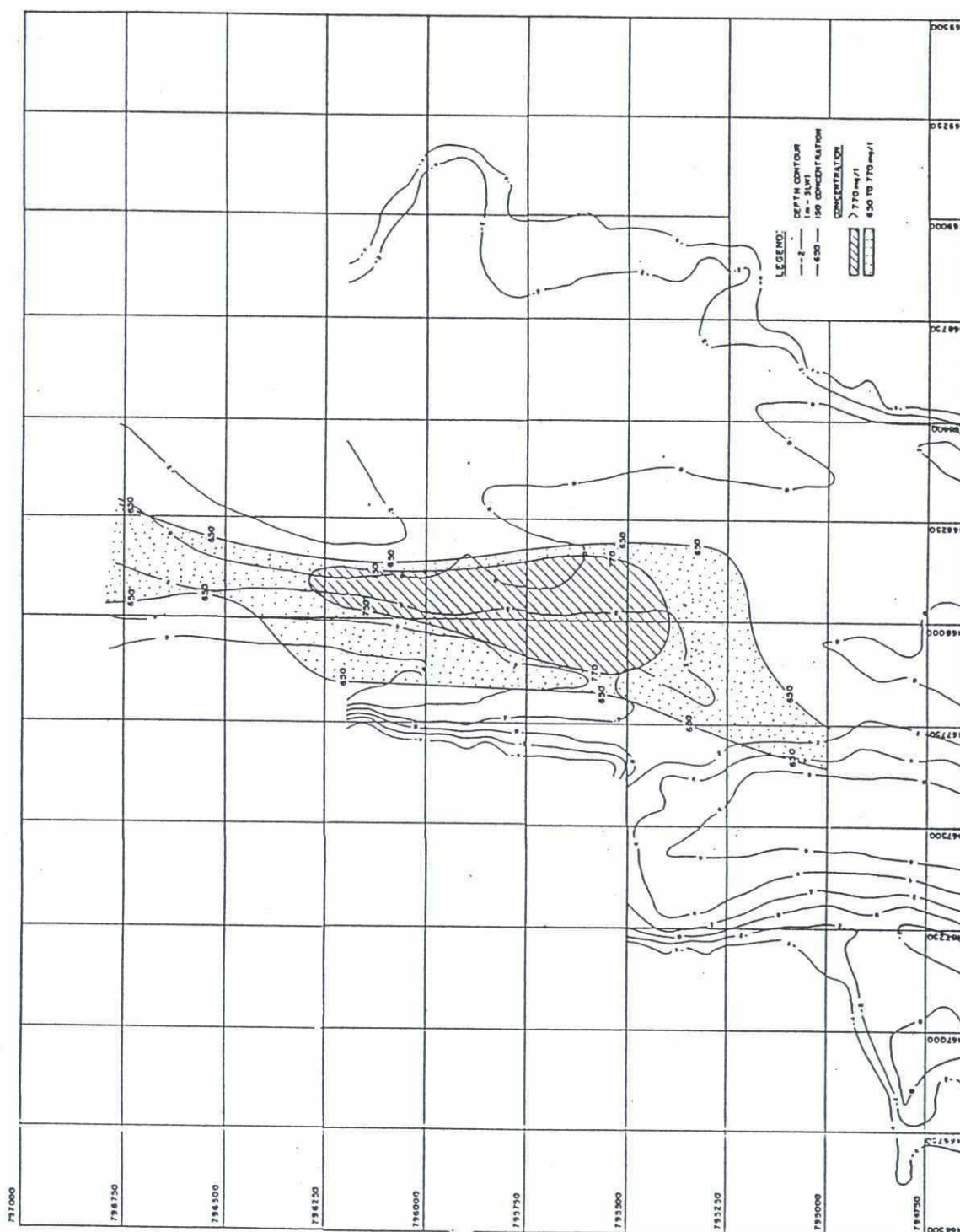


Figure G7.16: Map of survey area with iso-concentration contours

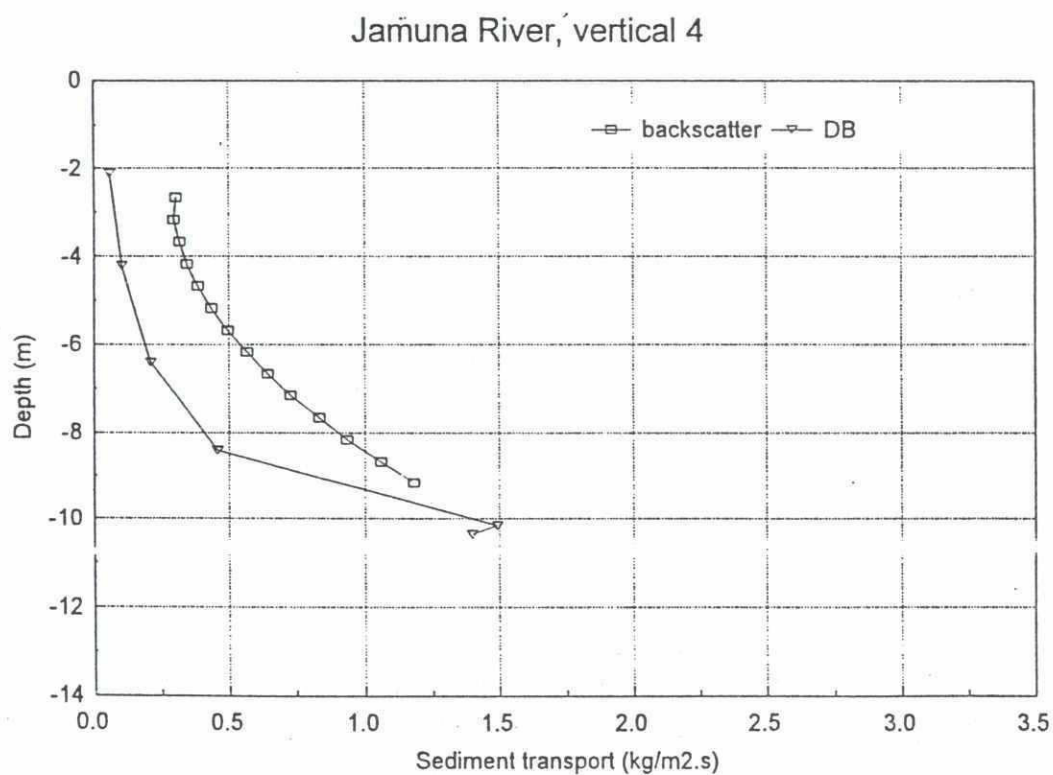
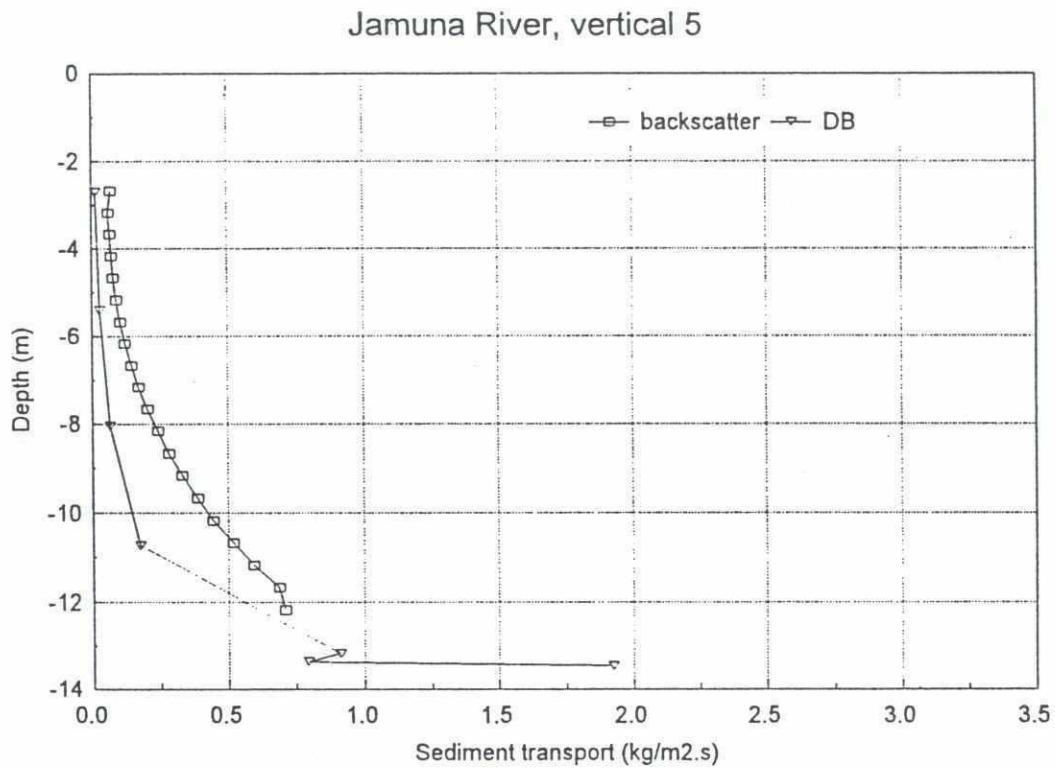


Figure G7.17: Sediment transport of sand fraction in verticals 5 and 4

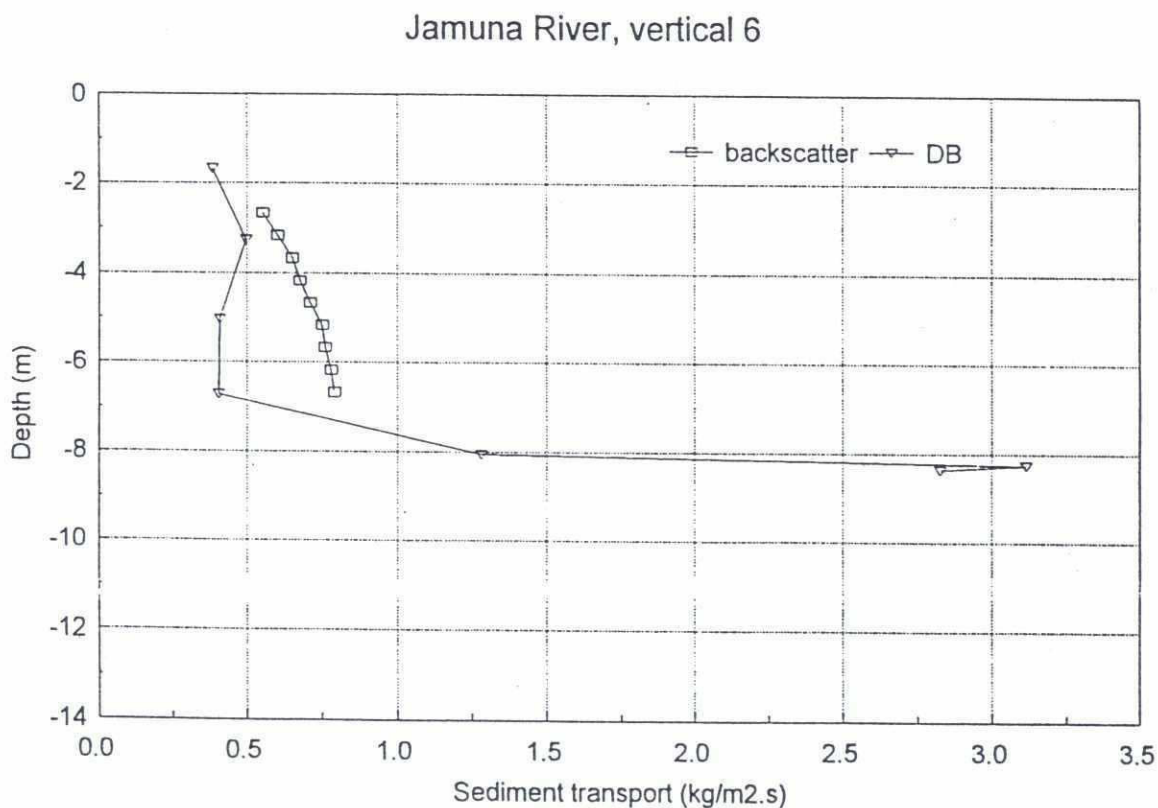
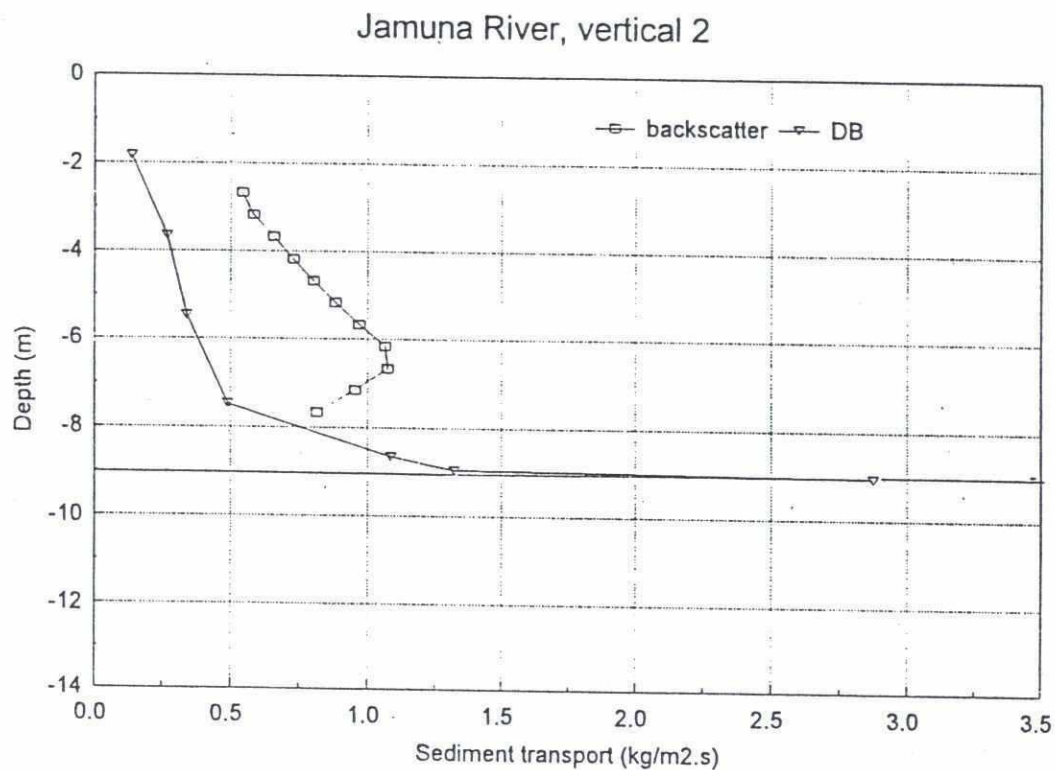
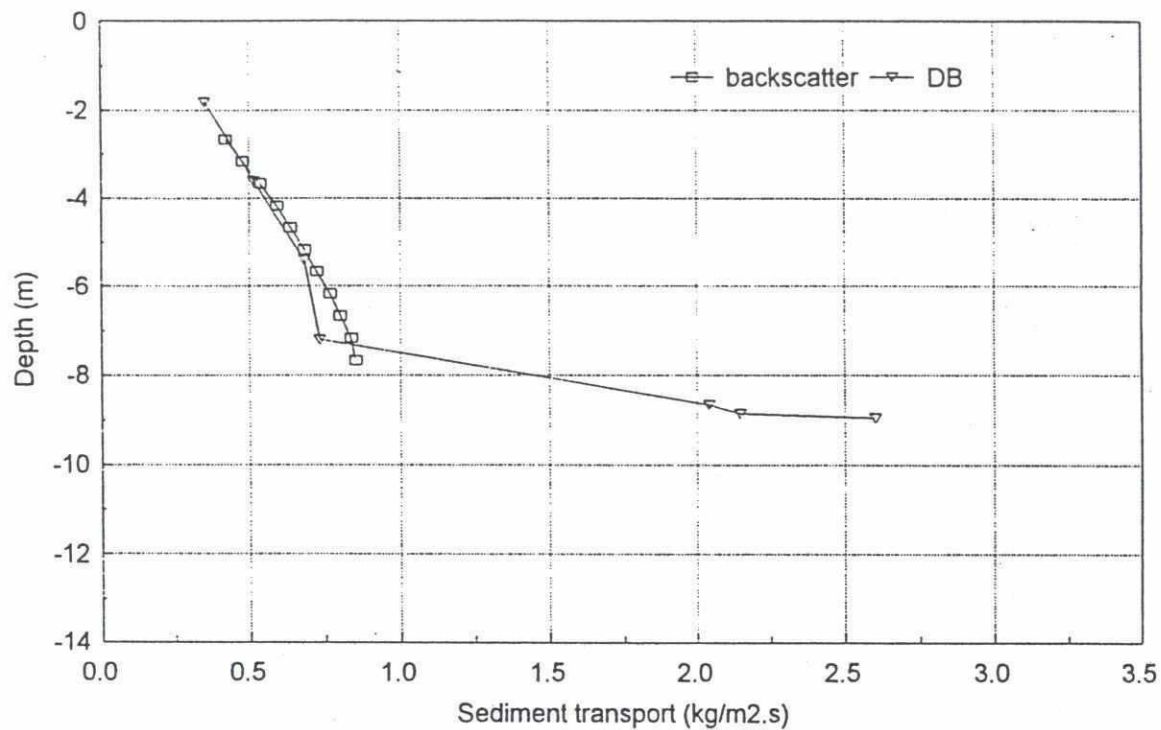


Figure G7.18: Sediment transport of sand fraction in verticals 2 and 6

Jamuna River, vertical 7



Jamuna River, vertical 8

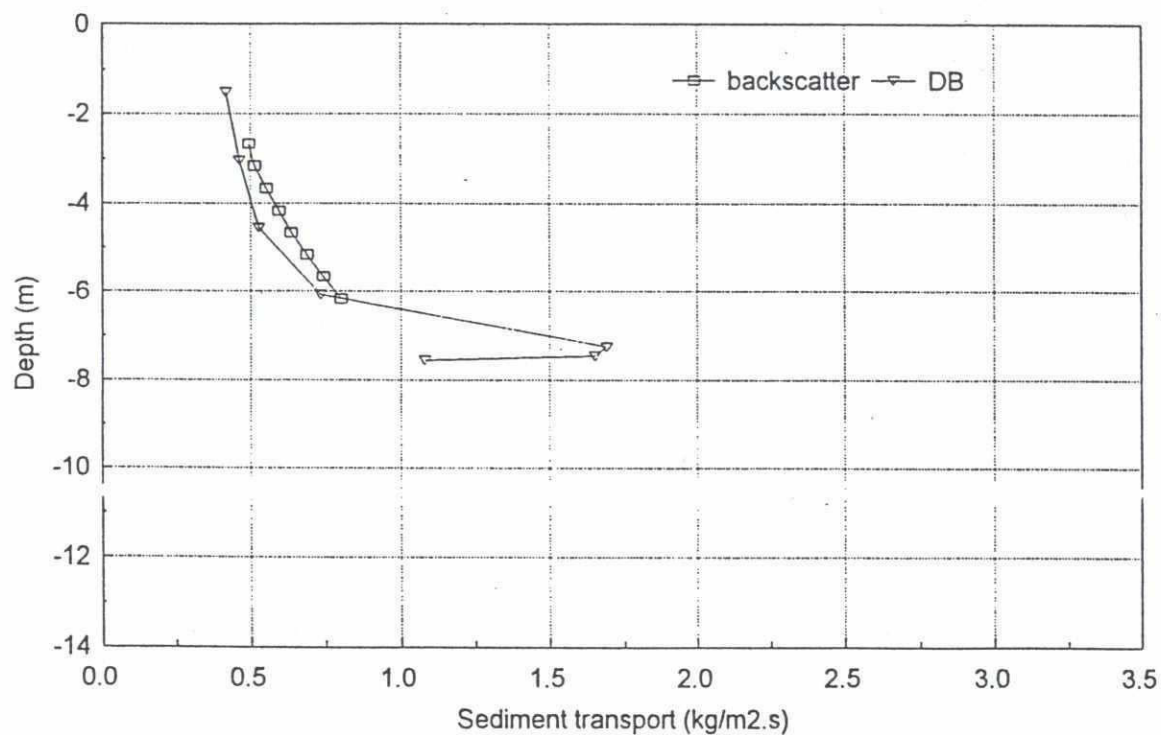


Figure G7.19: Sediment transport of sand fraction in verticals 7 and 8

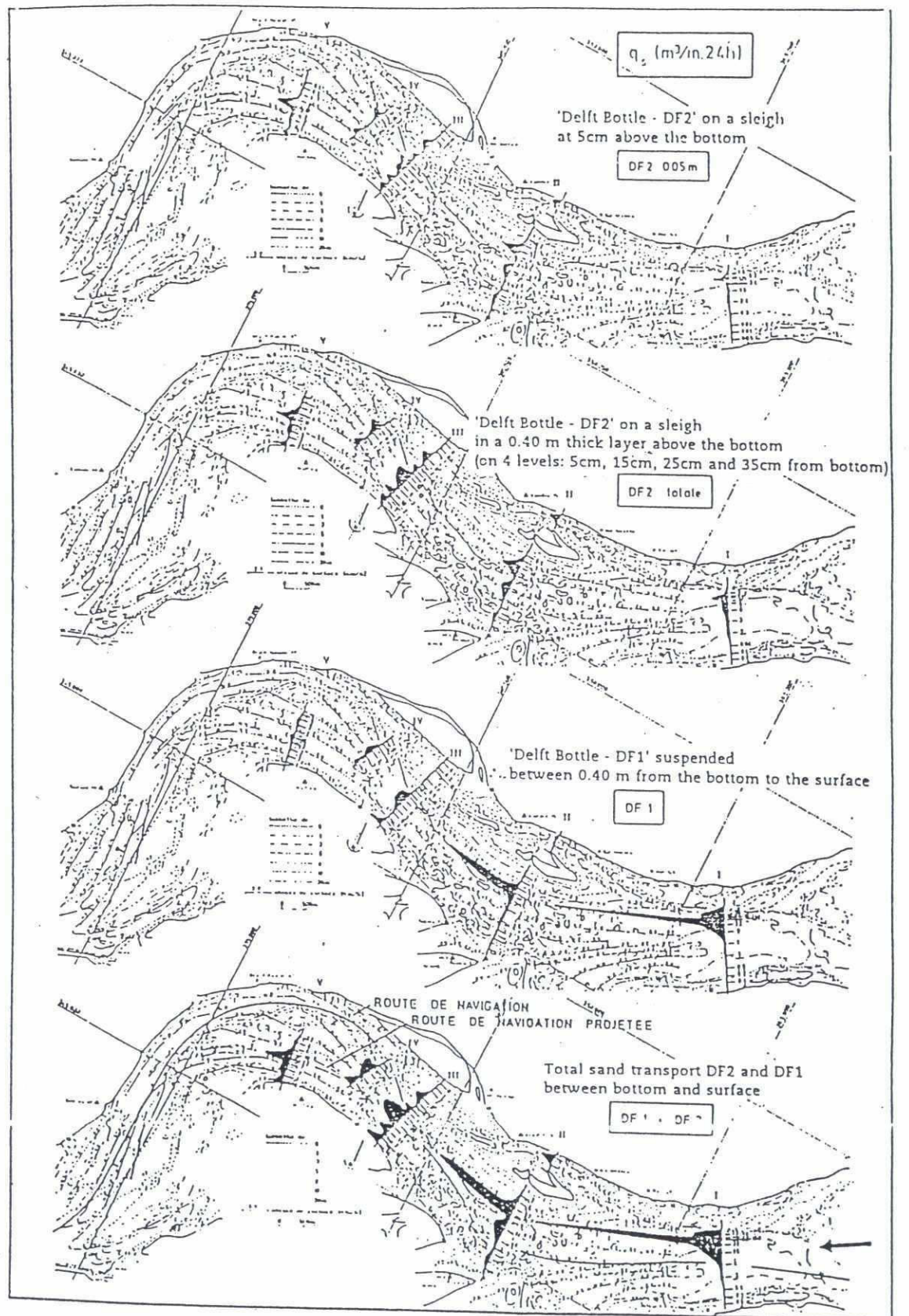
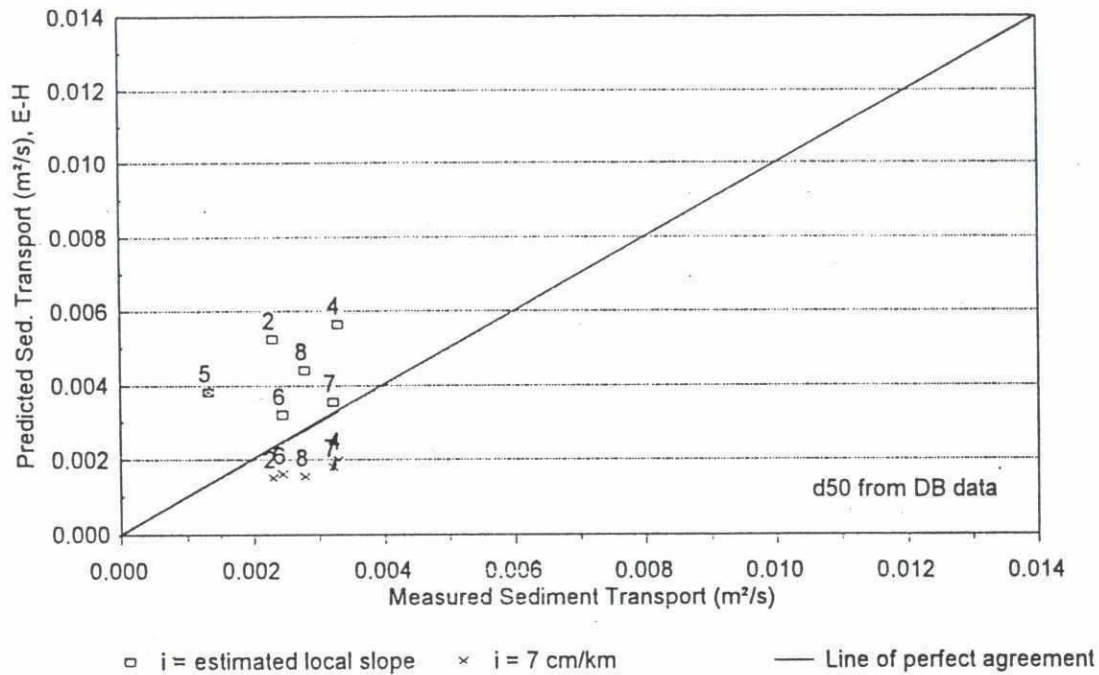


Figure G7.20: Example of a sediment plume in the Zaire River

Plume Survey, Bahadurabad
DB data, May 24-26, 1995



Plume Survey, Bahadurabad
Backscatter + DB data, May 24-26, 1995

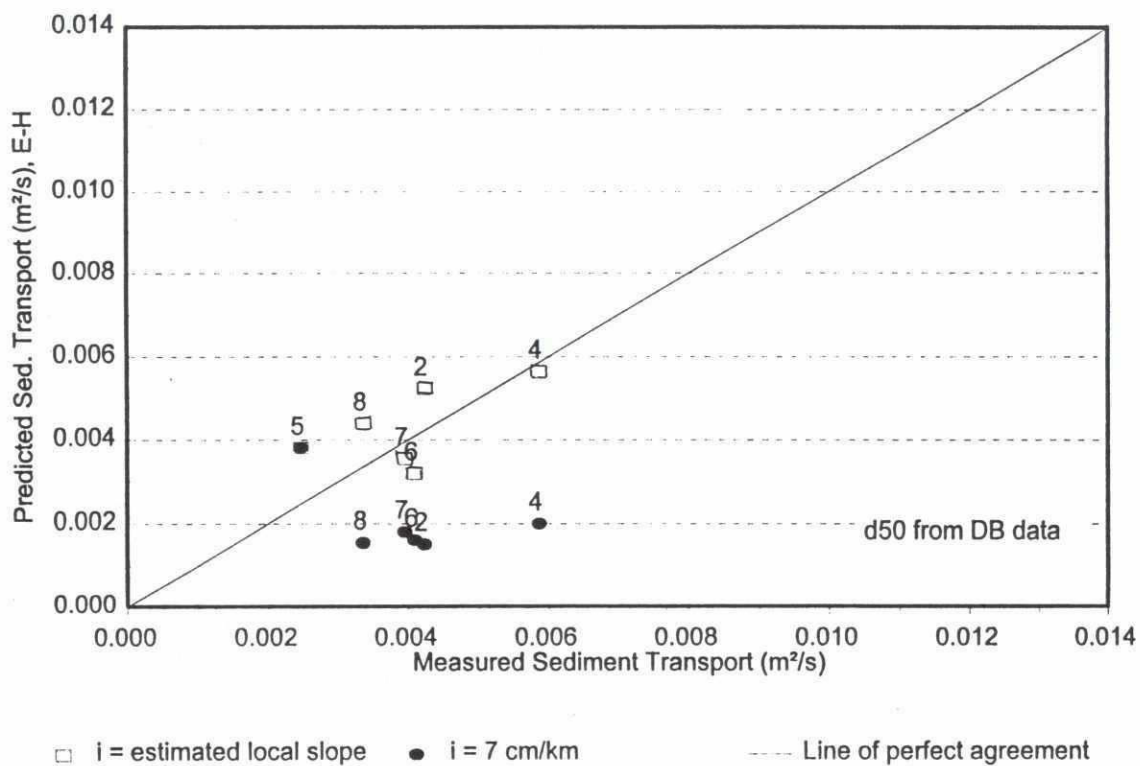
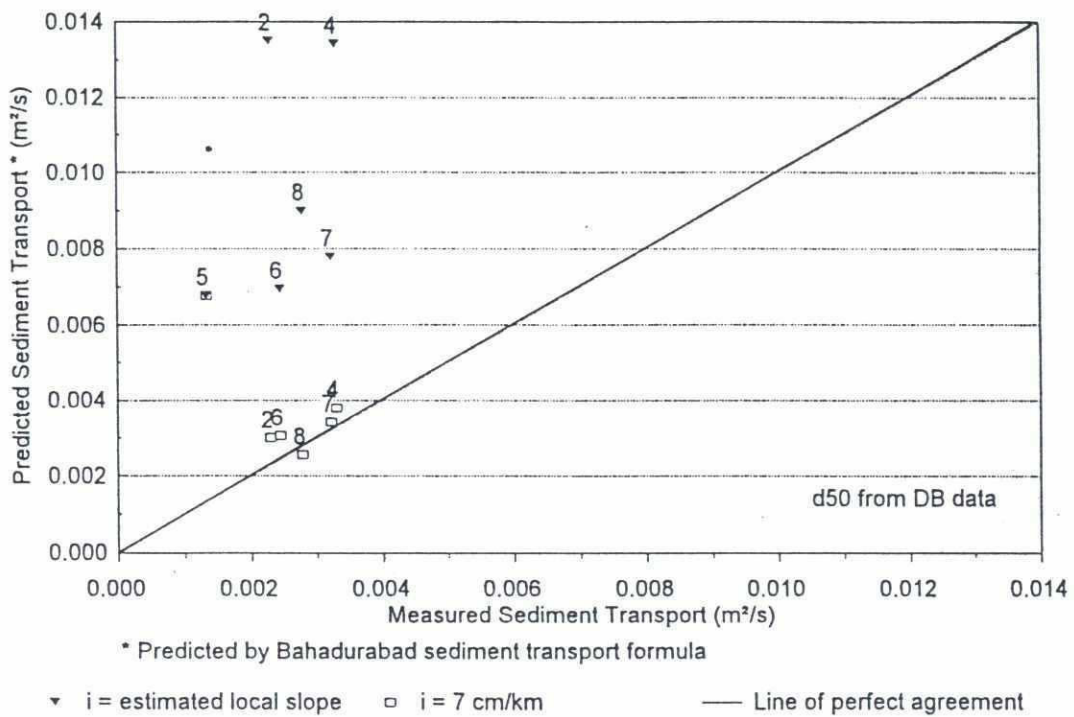


Figure G7.21: Sediment transport compared with Engelund-Hansen transport formula

Plume Survey, Bahadurabad
DB data, May 24-26, 1995



Plume Survey, Bahadurabad
Backscatter + DB data, May 24-26, 1995

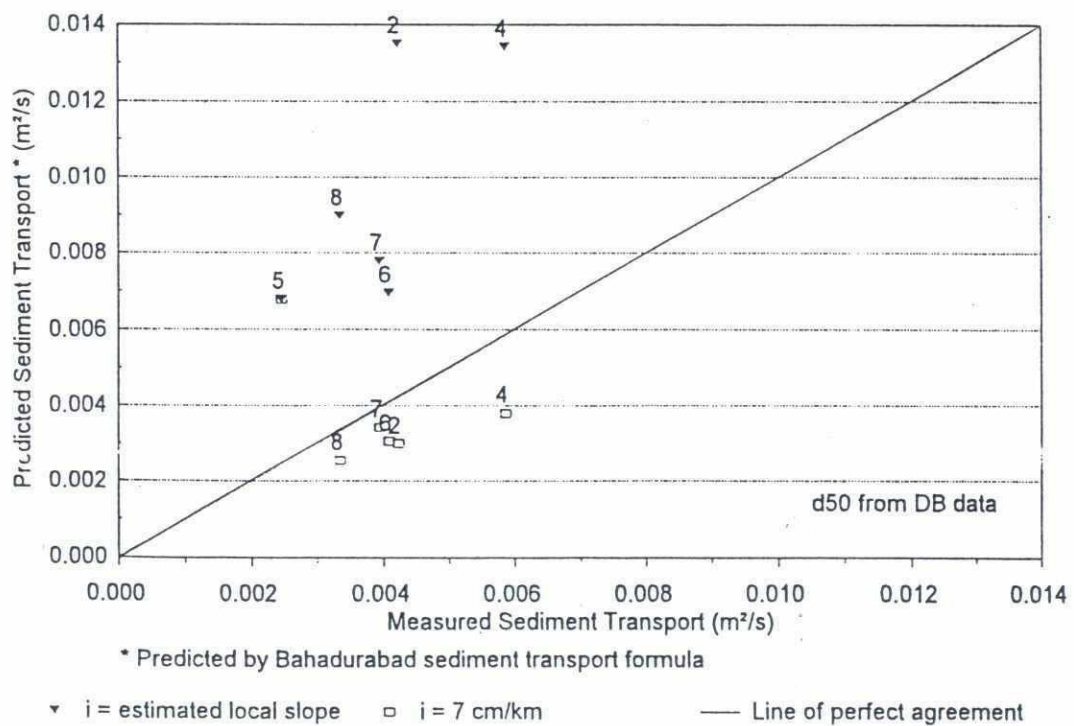
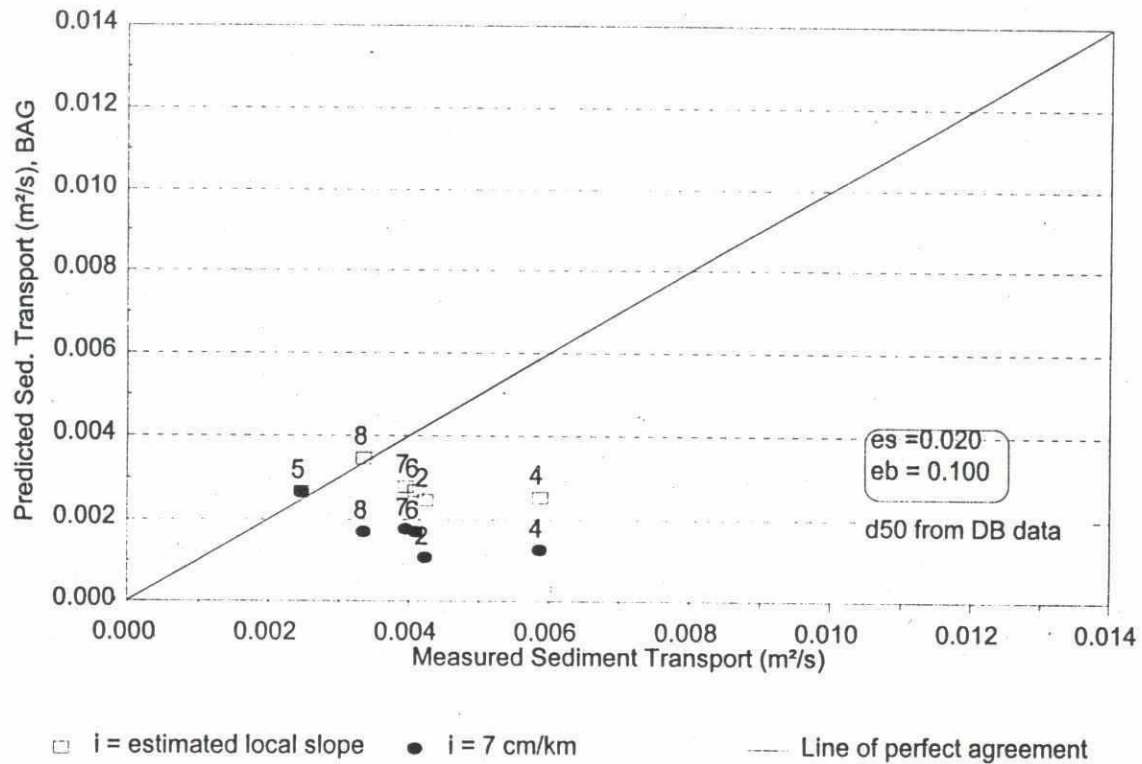


Figure G7.22: Sediment transport compared with Bahadurabad transport formula

Plume Survey, Bahadurabad
Backscatter + DB data, May 24-26, 1995



Plume Survey, Bahadurabad
Backscatter + DB data, May 24-26, 1995

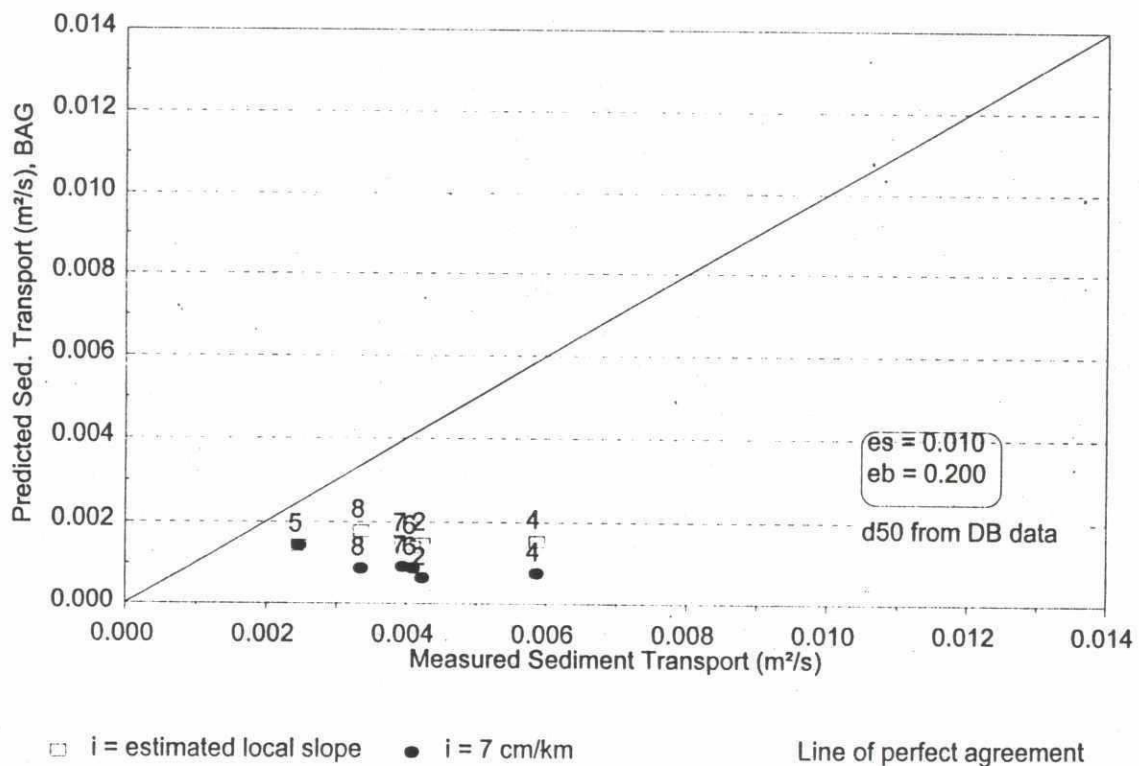


Figure G7.23: Sediment transport compared with Bagnold formula

Appendix 1

Comparison of sediment transport measurements by BWDB and RSP

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1 Introduction

The BWDB carries out regularly sediment transport measurements in the main rivers of Bangladesh. In this note the regular weekly sediment transport measurements by BWDB in Bahadurabad are compared with the sediment transport measurements in the reference vertical in the routine gaugings by RSP. The objective of this comparison is to have a confirmation of the main results of the joint sediment transport measurements.

The results of these measurements showed that BWDB measures too low sediment concentrations if the flow velocity > 2 m/s, see Survey Report on these joint measurements.

2 Data used

The BWDB measured in a standard transect north of Bahadurabad ghat. In their standard procedure the sediment concentration was measured at 0.2 and 0.8 depth in each vertical. First the water depth was measured. The concentration of fine and coarse sediment was measured with a Binckley Silt Sampler. In the analysis only the concentration of coarse sediment (with $D_{50} > 0.063$ mm) was determined. These measurements were done without anchoring (dynamic positioning).

The RSP performed routine gauging in different transects a few kilometer downstream and upstream of the standard BWDB transect. In a vertical the sediment concentration was measured by pump-bottle system (point integrated). The flow velocity was measured with an electro-magnetic flow meter (S4 type). In general 3 to 6 points were selected in a vertical depending on the local water depth of that vertical. For these measurements the survey vessel was anchored.

With the following data two comparisons were made:

- The BWDB measurements compared with the RSP measurements, both were done in Bahadurabad in 1994 and 1995.
- To observe any trend in the BWDB data, the BWDB measurements in 1994 and 1995 were compared with their measurements in 1984 - 1987 (also in Bahadurabad).

3 Data analysis

The measured suspended sediment transport per unit width (q_s) is calculated from the measured sediment concentration, the depth averaged flow velocity and water depth of the vertical. This was done for the data from BWDB as well as for the data from RSP. The comparison is based on the relationship between the dimensionless shear-stress parameter, or Shields parameter (θ) and the dimensionless sediment transport parameter (ψ). The dimensionless Shields parameter (θ) and the dimensionless sediment transport (ψ) are defined as follows:

$$\theta = \frac{h \cdot i}{\Delta \cdot D_{50}} = \frac{u^2}{C^2 \cdot \Delta \cdot D_{50}} \quad (2)$$

and

$$\psi = \frac{q_s}{\sqrt{g \cdot \Delta \cdot D_{50}^3}} \quad (3)$$

where

h = the water depth (m),

i = the water surface slope (-),

Δ = the relative density (-),

D_{50} = the median particle diameter (m),

u = the depth averaged flow velocity (m/s),

C = the Chezy roughness coefficient ($m^{0.5}/s$),

g = the acceleration due to gravity (m/s^2).

The water surface slope should be the local water level slope at the considered vertical, but this parameter was not measured. Only a rough estimate for the overall water level slope over a large distance is available. Also the Chezy coefficient cannot be measured directly. this means the Chezy coefficient follows normally from an empirical White-Colebrook formula or the Chezy equation.

To assess the sensitivity of the comparison the following values of the Chezy coefficient were selected, see Table 1:

assumption	June to September C ($m^{0.5}/s$)	October to May C ($m^{0.5}/s$)
1	85	50
2	70	50
3	65	65

Table A-1 Selected combinations of Chezy values.

The computation of Shields parameter (θ) is based on the assumed Chezy roughness value which is presented in Table A-1.

All the sediment samples from the RSP and BWDB for the period of 1994-95 are plotted in a dimensionless graph relating Shields parameter and sediment transport considering Chezy roughness value 70 for June-September and 50 for October-May, see Figure A-1. The other comparisons for the other two selected combinations of Chezy values are presented in Figures A-2 and A-3. From these graphs, it is seen that in the monsoon period the sediment transport measured by BWDB is up to 10 times less than the sediment transport measured by RSP. In the lean period, BWDB measures the same sediment transport as RSP. This confirms the results of the joint sediment transport measurements. This confirmation is not sensitive for the selected Chezy coefficients.

To complete the analysis also the regression lines were fitted to the data points, see Table A-2:

$$\psi = A \cdot \theta^B \quad (4)$$

in which A and B coefficients (-).

Chezy coeff.	BWDB		RSP	
	A	B	A	B
	-	-	-	-
85 / 50	28	1.09	123	1.63
70 / 50	20	1.14	79	1.82
65 / 65	19	1.15	86	1.76

Table A-2 Regrssion coefficients in sediment transport formula

Comparison with the Engelund-Hansen sediment transport formula in graphs A-1 to A-3 shows that the transport of sediment with grain size $D_{50} > 0.063$ mm in the Jamuna River is higher than calculated with that transport formula. It is mentioned that the Engelund -Hansen sediment transport formula was calibrated for sediments with $D_{50} > 0.190$ mm. In the Jamuna River an important part of the particles have a diameter > 0.063 mm and < 0.190 mm. This explains that in the Jamuna River higher sediment transports were measured.

The main factor to explain the underestimation of the sediment transport by BWDB during the monsoon period is most probably the large deflection angle of the Binckley Silt Sampler supporting cable in high flow velocities, because no sinker was used to increase the weight hanging on this cable (refer to the Survey Report on the Joint Measurements). Probably no corrections were made to increase the length of the cable to compensate a large deflection angle. The difference in the transects of the BWDB and the RSP can not explain these differences in sediment transport data.

To investigate if this underestimation of the BWDB sediment transport data is limited to 1994-1995 period, the sediment transport data measured in the period 1984-1987 are compared with the 1994-1995 sediment transport data in a seperate graph in Figure A-4. From this figure, it is observed that the 1984-1987 sediment transport data measures slightly higher than the 1994-95 sediment transport data (about 2 times). This is still less than the factor 10 in the RSP sediment data. This means that probably this under-estimation of the sediment transport during the monsoon exists over a much longer period than 1994-1995 period.

4 Conclusions

- 1 The weekly sediment transport data measured by the BWDB in Bahadurabad underestimates the sediment transport in the monsoon compared with the RSP sediment transport data. The different transects can not explain this difference.
- 2 In the lean season, the sediment transport data measured by BWDB are very close to the sediment transport data measured by RSP.
- 3 This tendency to underestimate the sediment transport during the monsoon probably existed for a longer period, at least up to 10 years.

Jamuna River, Bahadurabad, 1994-95

C = 70 for Jun-Sept & 50 for Oct-May

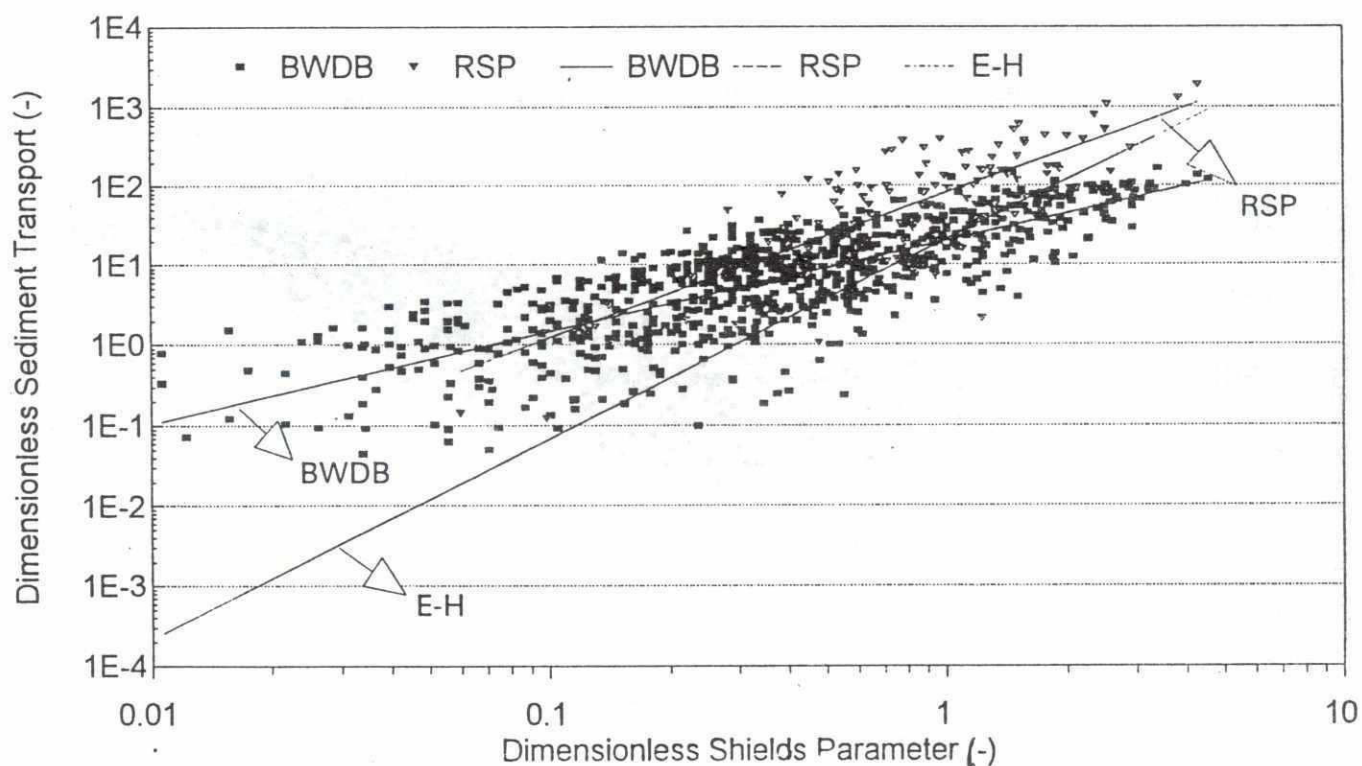


Figure A-1 Measured and calculated sediment transport (sand fraction) in verticals in the transect near Bahadurabad

Jamuna River, Bahadurabad, 1994-95
C = 85 for Jun-Sept & 50 for Oct-May

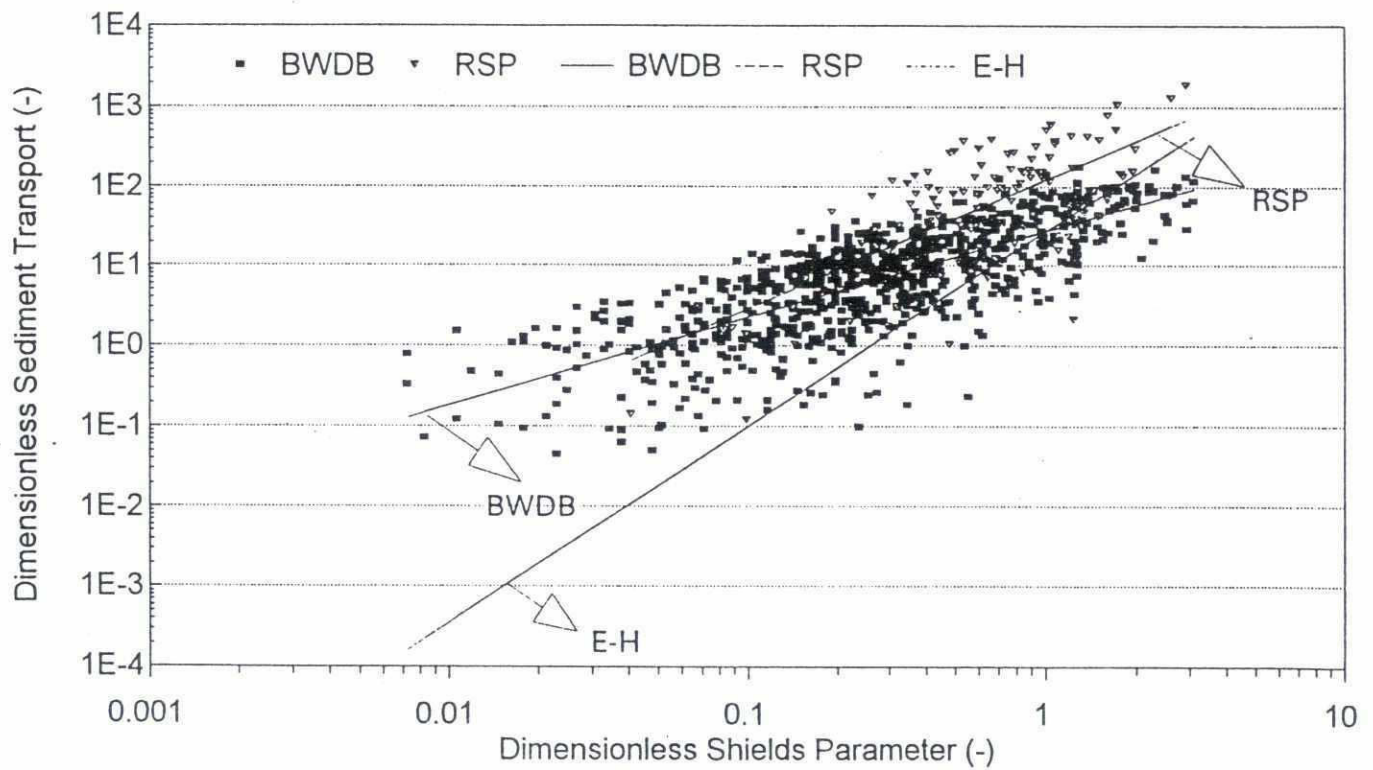


Figure A-2 Measured and calculated sediment transport (sand fraction) in verticals in the transect near Bahadurabad

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Jamuna River, Bahadurabad, 1994-95

C = 65 for all season

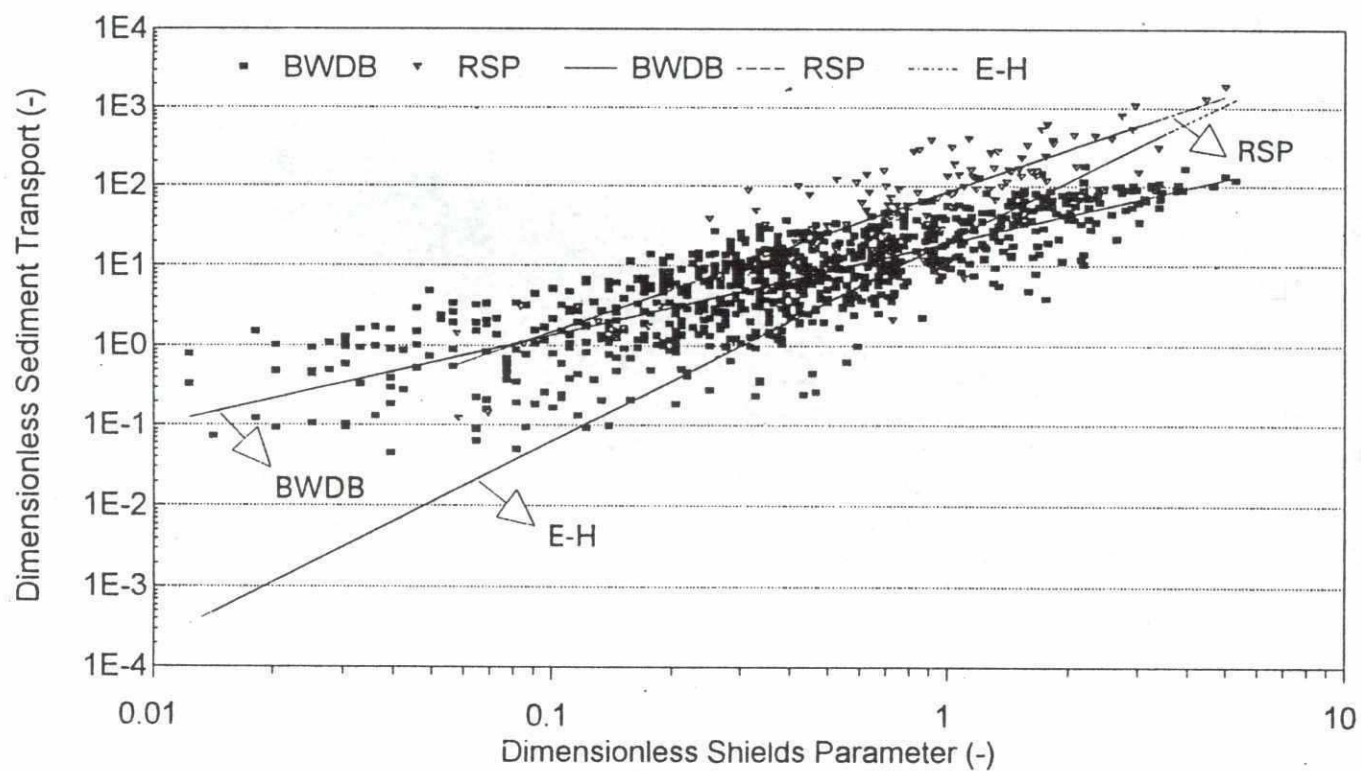


Figure A-3 Measured and calculated sediment transport (sand fraction) in verticals in the transect near Bahadurabad

Comp. of BWDB different period data 1984-87 and 1994-95

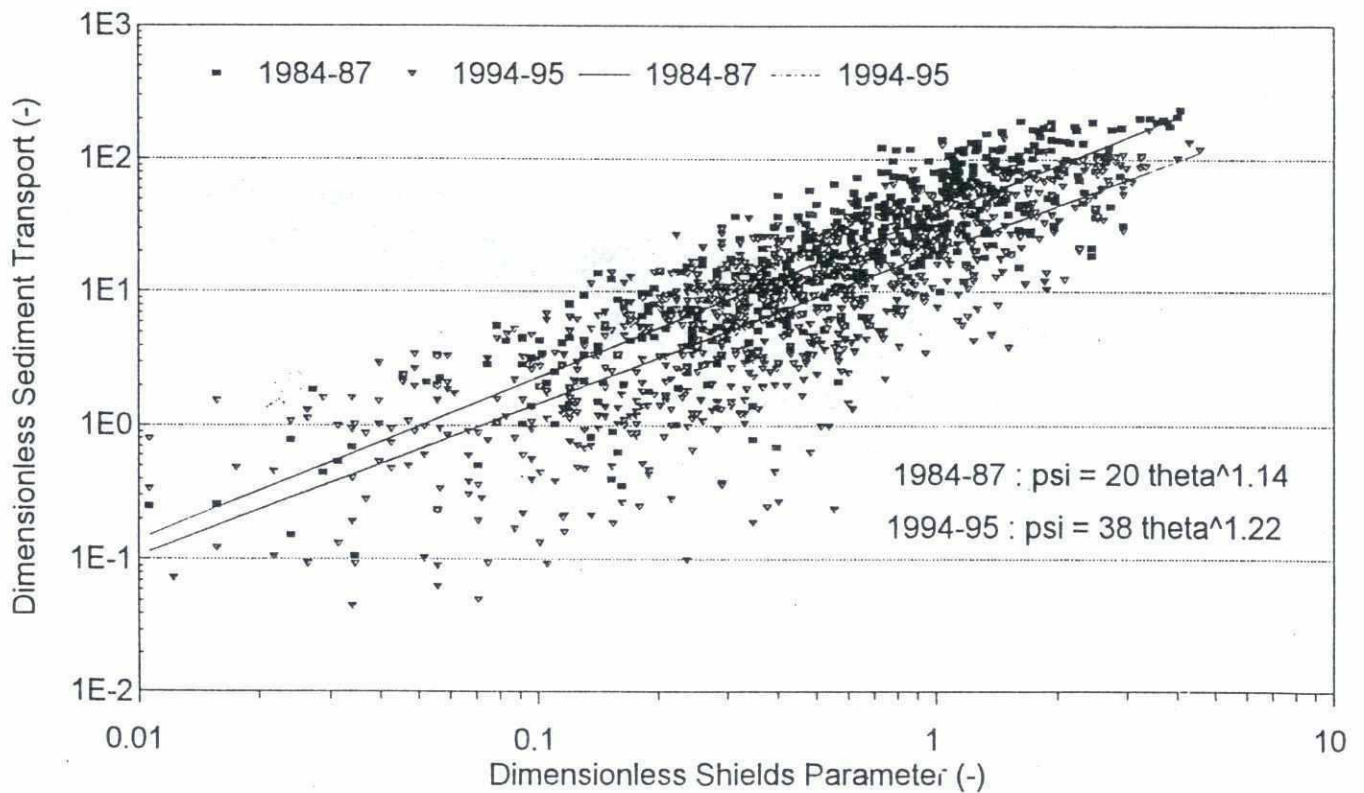


Figure A-4 Measured sediment transport (sand fraction) in the BWDB-transect near Bahadurabad 1984-1987 and 1994-1995

Annexure G8

Study Survey, Bahadurabad, 26-30 July 1995

(On density of points in cross-section)

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1 Introduction

In the last week of July 1995 a study survey was executed near Bahadurabad along the lines of the proposal : "Special measurements on the optimization of the number of points in a vertical and the number of verticals in a transect". The main aim of the survey was to collect a dataset with a high density of points in a cross-section.

The actual work done is summarized in the following chapter. In the subsequent chapters the results are presented, emphasizing the sediment transport measurements. For the hydraulic measurements please refer to Study Report 11.

2 Measuring programme

The survey activities are depicted in the following bar-chart :

	Main survey activities	July 1995				
		26	27	28	29	30
1.	reconnaissance					
2.	fast verticals in the transect					
3.	detailed measurements in the vertical					
4.	transects	4	2 2	2 1	3 1	
		← right channel →			← left channel →	

Bar-chart 1 : Study Survey, Measurements of July 1995

In the right channel a section with a flat river bed was selected, a few days later in the left channel dunes were detected and the last detailed measurements were executed there.

The first verticals were measured in two transects T1 and T2 with dynamic positioning using the ADCP/EMF for velocities and the collapsible bag for the depth integrating sediment transport measurements. For the detailed measurements, in total in five verticals, the following instruments were used :

Velocity : ADCP/EMF, S4
 Suspended load : collapsible bag, pump-bottle, Mex, ADCP
 near bed sediments : DB



3 Results

3.1 Locations

The locations of the measurements, the two transects and the first detailed vertical in the right channel just downstream of Fulchari Ghat and the other detailed verticals in the left channel near Bahadurabad are given in Figure G8.1.

As in the left channel upstream of Bahadurabad, in the cross channel between left and right channel and in the right channel downstream of Fulchari no dune fields were detected, the transects were selected on the flat river bed in a regular cross-section (T1) and in an irregular cross-section (T2). When at the end of the survey some dunes were detected downstream of Bahadurabad, it was decided to limit the measurements there to two detailed measurements in verticals in the middle (LD) and on top (LE) of a dune.

3.2 Water-levels and depths

Although the water-levels during the survey dropped from 18.9 to 18.4 m + PWD, they are still rather high considering that 19.5 m + PWD is the danger level in Bahadurabad, see also Figure G8.2. On July 27 a wave run down the river, Figure G8.3. The depth measured in the various verticals are given in the following table:

Vertical	depth (m)
RA	9.2
LB	13.8
LC	11.3
LD	10.5
LE	9.2

Table G8.: Water depths at verticals

3.3 Velocities

The velocities in the right channel were less strong than the water-levels suggested. There the maximum velocities were upto 1.8 m/s. However, in the left channel upto 2.8 m/s was found.

The following velocities were measured during this survey.

Date	Period	Type	File no.	Figure
26 July	1619 - 1623	1 ADCP transect	B 57 To 37	-
	1635 - 1640	"	38	-
	1648 - 1654	"	39	-
	1706 - 1712	"	40	-
27 July	0842 - 0848	" T1	41	-
	8051 - 0857	" T1	42	no. 4
	1237 - 1520	14 ADCP verticals	B 57 Po49 - 63	-
	1520 - 1743	1 ADCP vert RA	B 57 PO 64	no. 5
28 July	0854 - 0907	1 ADCP transect T2	B 57 TO 43	-
	0908 - 0925	1 ADCP transect T2	44	no. 6
	1126 - 1719	23 ADCP verticals T2	B 57 P 065 - 087	-
	1735 - 1750	1 ADCP transect	B 57 TO 45	-
29 July	0919 - 0930	1 ADCP transect	B 57 TO 46/47	-
	0937 - 0945	1 ADCP transect	48	-
	0954 - 1008	1 ADCP transect	49	-
	1130 - 1335	1 ADCP verticals LB	B 57 P 089	no. 7
		9 S4	-	-
	1425 - 1631	1 ADCP verticals LB	B 57 P 090	-
		9 S4	-	-
30 July	1655 - 1722	1 ADCP transect LC	B 57 TO 050	no. 7
	0803 - 1027	1 ADCP vertical LD	B 57 P 092	8
		11 S4	-	-
	1112 - 1502	1 ADCP vertical LE	B 57 P 093	8
		11 S4	-	-

Table G8.1: Type of velocity measurements

3.4 Suspended load

With the collapsible bag depth integrating sediment sampling was executed as summarized in the following table :

Date	Time	Location	No. of samples	Figure
27 July	1237 - 1520	T1, 14 verticals	15	09
	- 1630	vertical # RA	2	10
28 July	1126 - 1719	T2, 22 verticals	24	11
29 July	in 1130	vertical LB	1	12
	in 1500	vertical LC	1	13
30 July	in 0900	vertical LD	2	14
	in 0900	vertical LE	1	15

Table G8.2: Deployment collapsible bag

With the pump-bottle system point integrating suspended sediment sampling was executed as depicted in the following table:

Date	Time	Location	No. of samples	Figures
27 July	1552 - 1729	T1, vertical RA	10	10 16 22
29 July	1150 - 1318	vertical LB	9	12 17 23
	1459 - 1612	vertical LC	9	13 17 23
30 July	0821 - 1009	vertical LD	11	14 18 24
	1159 - 1449	vertical LE	11	15 18 24

Table G8.3: Deployment pump-bottle system

The pump-bottle sampling was executed as part of the detailed measurements, Only one liter samples were taken nearly simultaneously with both the S4 velocity measurements and the MEX turbidity measurements.

During the ADCP velocity measurements also the backscatter intensity was recorded in dB. Applying the relation between dB and coarse sediment concentration as suggested for Bahadurabad, the backscatter plots were converted into concentration plots :

$$dB = 68 + 0.77 \sqrt{c}$$

dB = backscatter signal (dB)

c = concentration (mg/liter)

The results are presented in the figures as mentioned in the following table :

Date	Period	ADCP file no.	remarks	Figure
27 July	1237 - 1520	B 57 P 049 - 063	14 verticals	19, 20
	1550 - 1743	B 57 P 064		21, 22
28 July	1126 - 1719	B 57 P 065 - 087	23 verticals	-
29 July	1130 - 1335	B 57 P 089	1 vertical	23
	1425 - 1631	B 57 P 090	1 vertical	23
30 July	0803 - 1027	B 57 P 092	1 vertical	24
	1112 - 1502	B 57 P 093	1 vertical	24

Table G8.4: Backscatter intensity and sediment concentrations

Time	Measuring depth (m)	Percent of total depth (%)	Sand Concentration (mg/l)
16:05	1.84	20	13.9
16:12	2.76	30	76.9
16:24	3.68	40	112.3
16:34	4.60	50	140.6
16:45	5.52	60	193.5
16:55	6.44	70	192.6
17:06	7.36	80	302.2
17:16	7.82	85	336.9
17:27	8.28	90	534.8
17:36	8.74	95	720.7

Table G8.5 10-point suspended sediment sampling at station RA (see Figure G8.1 for locations) on 27 July 1995 by pump-bottle.

Time	Measuring depth (m)	Percent of total depth (%)	Sand Concentration (mg/l)
12:00	2.76	20	313.9
12:09	4.14	30	281.5
12:19	5.52	40	231.6
12:29	6.90	50	601.1
12:52	8.28	60	336.9
13:00	9.66	70	599.1
13:09	10.35	75	519.3
13:19	11.04	80	501.3
13:25	11.73	85	3333.1

Table G8.6 9-point suspended sediment sampling at station LB (see Figure G8.1 for locations) on 29 July 1995 by pump-bottle.

Time	Measuring depth (m)	Percent of total depth (%)	Sand Concentration (mg/l)
15:06	2.26	20	311.9
15:15	3.39	30	343.8
15:25	4.52	40	371.3
15:32	5.65	50	314.3
15:42	6.78	60	338.4
15:48	7.91	70	409.7
15:57	8.48	75	402.4
16:08	9.04	80	463.0
16:20	9.41	85	1824.7

Table G8.7 9-point suspended sediment sampling at station LC (see Figure G8.1 for locations) on 29 July 1995 by pump-bottle.

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3.5 Near bed transport

The near bed transport was measured with the Delft Bottle (DB) at four points in the vertical. This was done as part of the detailed measurements. In the first vertical the DB measurements were done twice, in the other verticals one time only, see the following tables:

Date	Time	Location	No. of samples	Figures
27 July	1556 - 1630	T1, vertical RA	8	25, 26, 16
29 July	1110 - 1128	vertical LB	4	27 17
	1430 - 1443	vertical LC	4	28 17
30 July	0800 - 0813	vertical LD	4	29 18
	1159 - 1449	vertical LE	4	30 18

Table G8.8: Deployment Delft Bottle

Distance above river bed (m)	27 T1 vert # RA		29		30	
	1556-1612	1617-1630	LB	LC	LD	LE
			1110-1128	1430-1443	0800-0813	~ 1130
0.05	30	30	500	24	56	260
0.15	41	17	150	15	40	41
0.25	18	20	75	12	31	54
0.35	19	14	60	85	35	34

Table G8.9: Catches with Delft Bottle (cm³) (nozzle size 1.9 cm², sampling time 1 min)

3.6 Summary of detailed measuring results

In five measuring verticals detailed measurements have been executed. The main results are summarized (for easy reference) in the following table.

Vertical code date of survey		RA * 27/7	LB * 29/7	LC * 29/7	LD * 30/7	LE * 30/7
Parameter	Instru- ment					
depth averaged veloc- ity in (m/s)	ADCP	1.5 (5)	2.6 (7a)	1.4 (7b)	1.8 (8a)	1.9 (8b)
	S4	1.6	2.7	1.5	2.0	2.0
depth averaged susp. fine sed. conc. (mg/l)	Pb	800 (10a)	620 (12a)	550 (13a)	810 (14a)	870 (15a)
	CB	640	620	550	810	850
depth averaged susp. coarse sed. conc. (mg/l)	Pb	200 (10b)	500 (12b)	360 (13b)	600 (14b)	700 (15b)
	CB	200	500	290	770	700
	ADCP	200 (22)	400 (23a)	500 (23b)	600 (24a)	700 (24b)
depth averaged coarse sediment transport (kg/ m ² s)	Pb	0.4 (16)	2.0 (17a)	1.0 (17b)	1.2 (18a)	1.5 (18b)
near bed coarse sedi- ment transport range (kg/m ² s)	DB	1.2 (16)	6.0 (17a)	0.9 (17b)	3.0 (18b)	3.0 (18b)
		4.1	58 ?	4.8	32 ?	32 ?
near bed mediun grain size range (mm)	DB	0.10 (25)	0.14 (27a)	0.11 (29a)	0.13 (30a)	
		0.18	0.18	0.15	0.28	

* please refer to Figure G8.1

Table G8.10 Summary of detailed measuring results

4 Discussions

The subjects of this discussion are split into the following main issues :

- physics mainly of sediments
(sediment characteristics and transport phenomenon)
- instruments
(particulars, comparisons)
- measuring methods
(density of points and verticals)

4.1 Physics (of sediments)

- The river conditions can be characterized as high flow conditions. The currents in the right channel are moderate (less than 2 m/s) in the left channel, however, velocities are high (upto 2.8 m/s in vertical LB).
- Although no sieving curves are presented the coarse - fine distribution can be seen from the Figures G8.10 to G8.15 and G8.25, G8.27 to G8.30. It can be seen that half to 2/3 of the sediment is fine, the other part coarse.
- The concentration verticals of coarse sediments show that there is some times a lot of coarse material high in the vertical, see e.g. Figures G8.13 and G8.15. The ADCP vertical show mostly a triangular shape, Figure G8.20. In some cases however, verticals 12, 3A and 2, the shape is different.
- The variation of the sediments over the width of the river Figure G8.9 has more similarity with the shape of the cross-section than with the velocity distribution Figure G8.4.
- The variations of the concentrations at various depths as given in Figure G8.21. The picture is highly interesting but should be treated with caution for the time being. Some observations are :
 - the coarse sediment concentrations are reasonable constant over the measuring period of about 100 minutes.
 - the variation is small at the surface, but increases rapidly going deeper. Below half depth the variation is nearly constant (relative small difference between 0.5 and 0.8 depth).
 - there seems to be a dominant frequency in the fluctuations of about 5 minutes. This needs further attention also in view of exposure times and accuracies of measurements
 - the variations at the various depths are hardly related. This means that the gradient of the concentration vertical varies considerably
 - the near bed transport is rather erratic in vertical RA (Figure G8.26) but regular in

- the left channel (Figures G8.27 to G8.30) with a strong increase in the lowest dm.
- In the verticals with the lowest velocities (RA and LC) lower coarse sediment concentrations are found.
- In the verticals with the highest velocities (LB and LE) the DB catches at 0.05 m above the river bed are extremely high. The figures deserve some reservations as the vertical position is somewhat uncertain in relation with scour. During the sampling period (1 minute) the front legs of the DB frame may sink a few cm by which the intake nozzle gets close to the riverbed. So, easily some scooping of the instrument may occur. On the other hand, the considerable "as seen by the ADCP (see next section) indicate that high concentrations of sediments move with considerable velocity near (say in the lowest few cm of) the river bed.
- The medium grain size of the near bed transport ranges from 0.10 to 0.18 with in general coarse material nearer to the river bed. The near bed material of vertical LE is extremely coarse ($D_{50}=0.28$ mm).

4.2 Instruments

- An alternative version of the collapsible bag was applied. To reduce the unmeasured zone (of 0.5 m when the bag is above the sinker) the bag was placed in a frame under the sinker, thus reducing the zone to 0.2 m. Also this configuration has some disadvantages. Although the flow towards the tail of the sinker is not disturbed anymore by the bag and the self orientation seemed to be improved, still some instability was observed. The best solution is most probably an in-built bag in a fish shape sampler carefully designed (shapes) for high flow conditions.
- The ADCP showed on line much lower values than the S4. The quality control software gave a warning for a moving bed. This was most obvious in the highest currents in vertical LB (Figure G8.31). The river bed velocity indicated by the ADCP was about 0.6 m/s.

For the comparison between the ADCP and the S4 first the ADCP signal was corrected by deleting the ground speed of the survey vessel as measured via the doppler shift with the ADCP and replacing the signal by the vessel speed according to the DGPS system. For results see Figure G8.31.

- The comparison of velocities between ADCP 300 and S4 as given in Figures G8.5, G8.7 and G8.8 show that S4 is always measuring more. Especially in high flows the results are rather close (Figure G8.7).
- The collapsible bag versus the pump-bottle (Figures G8.10, G8.12 to G8.15) show that the results are close both in the fine and the coarse fractions.
- The shape of the concentration verticals as determined via the ADCP backscatter intensities needs further attention. Especially the in-built software which processes the dB information need to be analyzed.

4.3 Measuring method

- The number and method of spacing determining (the inter-distance) as given in Figure G8.32 show some results for transect T1 as measured 27 July 1995. In other words much more of these measurements are needed to arrive at general conclusions. Nevertheless some tentative conclusions can be drawn such as :
 - with a few verticals the u^2/h method gives the best results. This is probably true for near cross-sections with not much overloading or underloading
 - in cross-sections with considerable transport variation over the width of the river the second method is expected to give the best result/distribution of verticals adjusted to the concentration gradients. There is obviously a problem when the gradients are not known. A method of trial and error may then give a solution
 - with 7 to 10 verticals in the channel of about 650 m width an accuracy of about 10% can be reached. This holds both for the discharge and the suspended sediment transport
- The number and location of measuring points in a vertical was analysed using the results of the detailed measurements in the right and the left channel of the Jamuna near Bahadurabad. From the concentration verticals of coarse sediment as measured with the pump-bottle (Figures G8.10, G8.12 to G8.15) depth averaged values were computed using one to about 10 points information. The results are given in Figure G8.33. Some tentative conclusions are :
 - results are obviously depending on the shape of the concentration vertical which obscures clear general conclusions
 - mostly a limited no of points implies under sampling (20 to 50%)
 - about 6 points in a vertical gives in general still bad results, but if the points are carefully selected (at 0.2h, 0.4h, 0.6h, 0.8h and 0.5m above the river bed as is done by the RSP) then considerable better results are obtained.
- use of ADCP backscatter is very promising compare e.g. the concentration verticals in RA of the coarse sediments as measured with the collapsible bag and the pump-bottle (Figure G8.10) and as determined via the backscatter (Figure G8.20). For further comparisons see Figures G8.22 to G8.24.
- The duration curves (Figure G8.21a) have been cut in series of different exposure times (54s, 108s, etc.) per exposure interval the average concentration was calculated. From a series of average values the standard deviation was computed and divided by the time and depth average value of the concentration (Figure G8.21b). The tendency of the relative standard deviation shows the increasing uncertainties for shorter sampling closer to the river bed.
- the transport verticals of coarse sediments as measured with the Delft Bottle near bed and the pump-bottle higher in the vertical show no heavy discrepancies in the vertical which means that the combination of collapsible bag and DB is expected to give good results.

- the near bed measurements with the DB show not much variation in the transports in the points 0.15, 0.25 and 0.35m above the bed. The main increase in the transport is between 0.15 and 0.05 which means in fact over the lowest dm.

This was observed earlier in previous study survey (April and May 1995). These were study surveys done in low and mid flows, but now similar observations are done for the high flows. This implies that if one has to reduce the nos. of points in the vertical (e.g. in case of routine surveys) the nos. of near bed points can be reduced to two (at 0.05 and 0.15 m above the river bed).

Note : Although it is observed that a number of measuring points don't fit in the expected range, they are not omitted but only marked with a question mark. See Figures G8.12, G8.13, G8.17 and G8.23.

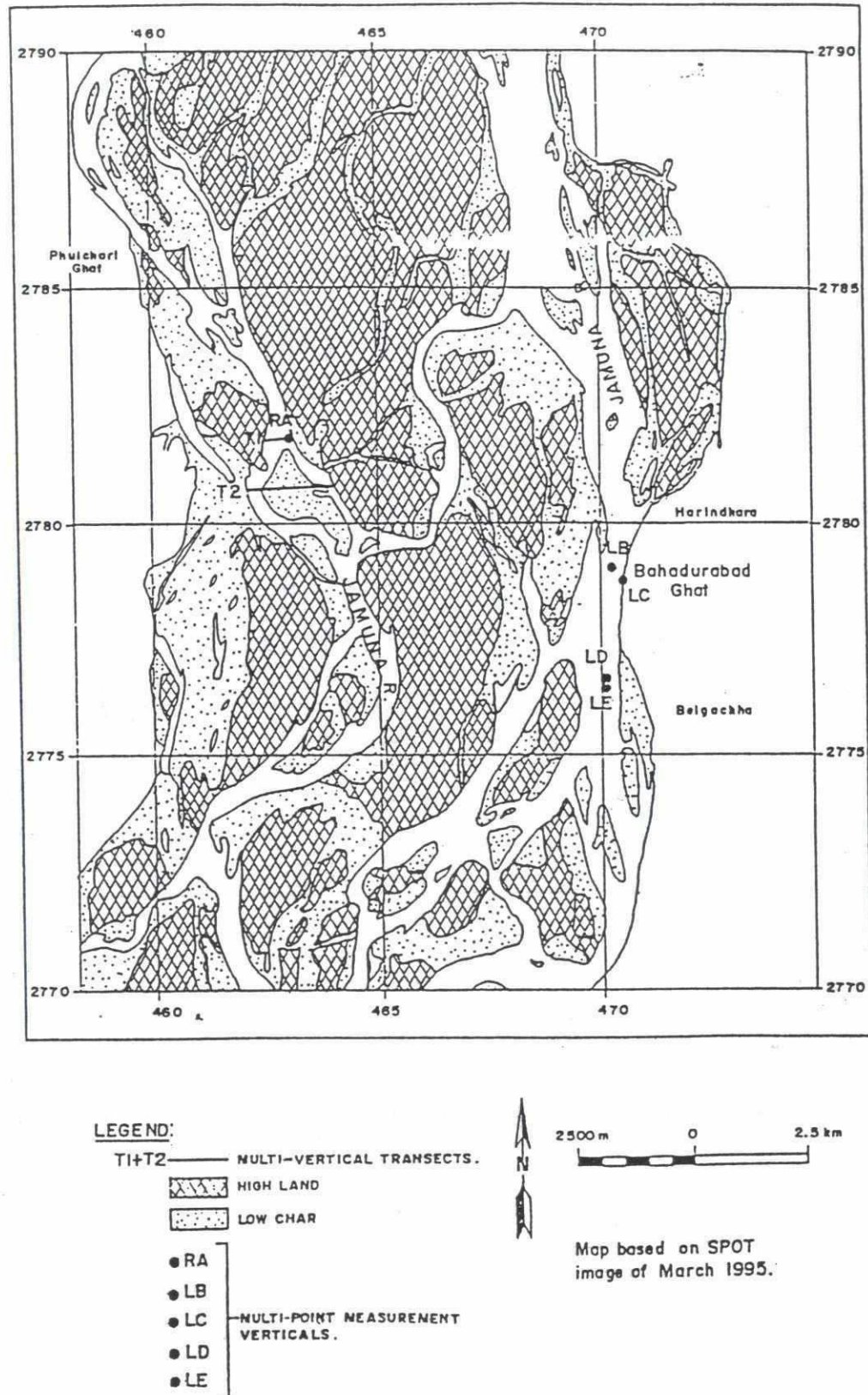


Figure G8.1 Location of measurements July 1995

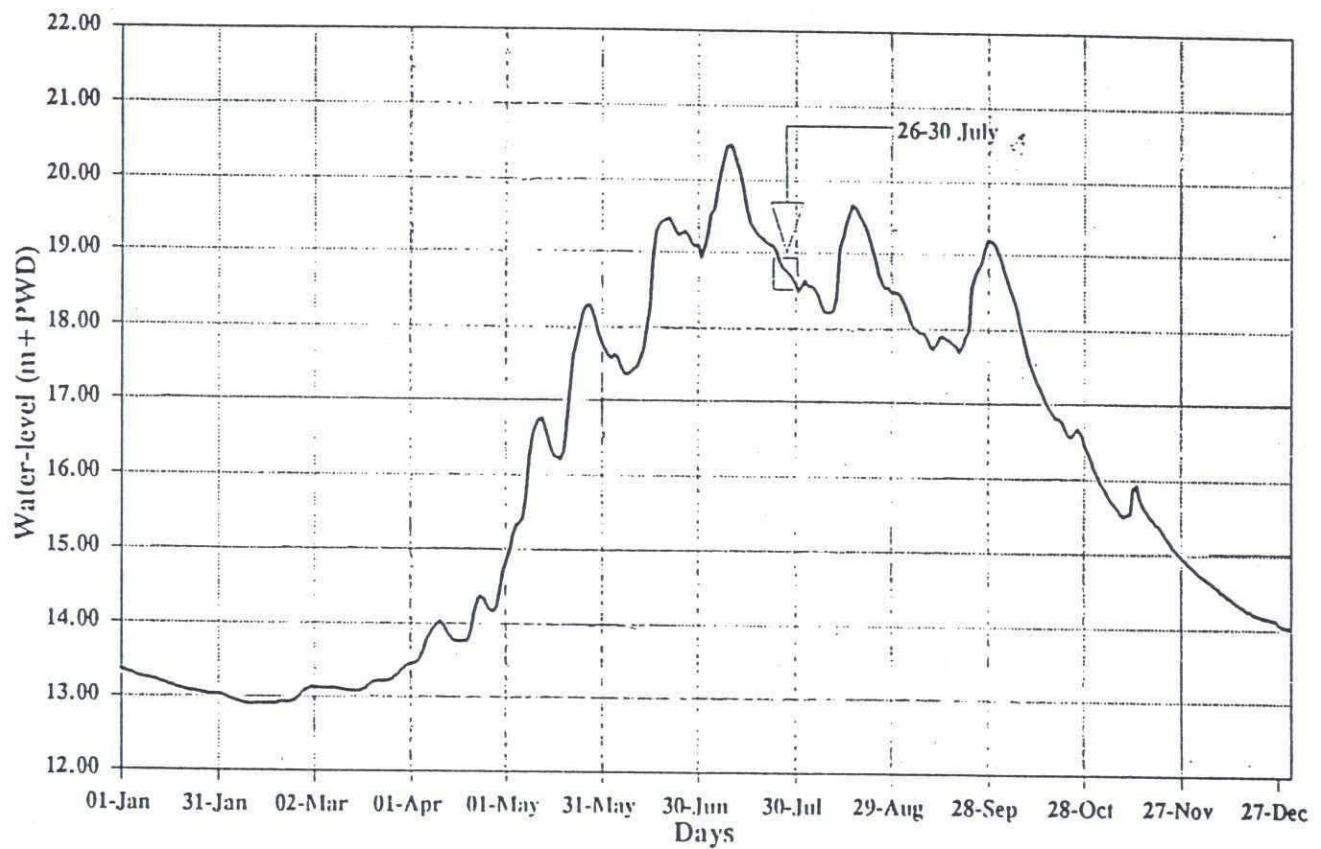


Figure G8.2 Water-levels Bahadurabad 1995

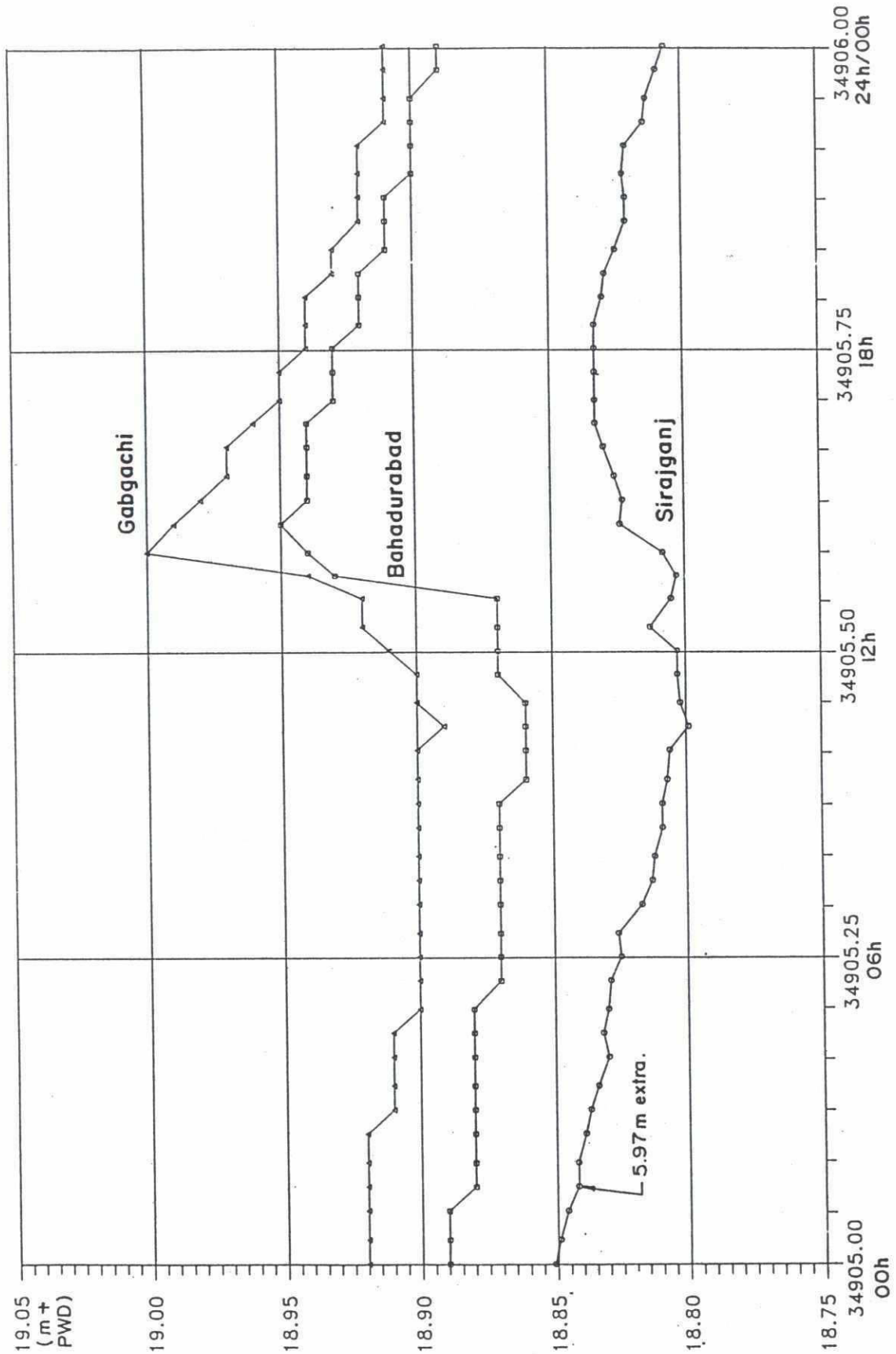
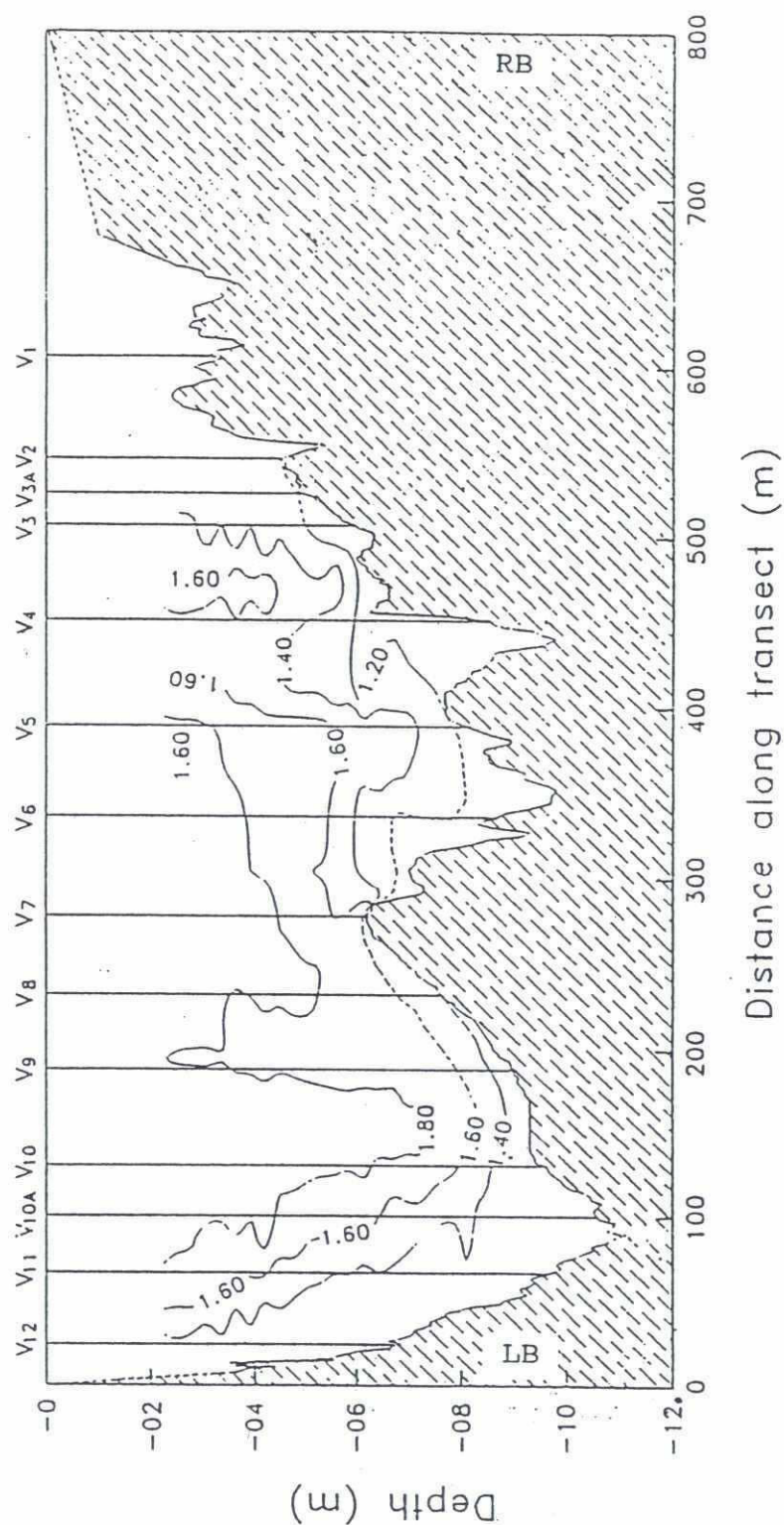


Figure G8.3 Water-levels along Jamuna 27 July 1995



Notes : V_{3A} and V_{10A} represent the additional verticals.
Isovels are shown in m/s

Figure G8.4 Cross-sectional profile with isovels and locations of measuring verticals along transect T1

Jamuna River, Bahadurabad, Vertical RA

27.07.95, Time : 15:50 - 17:43

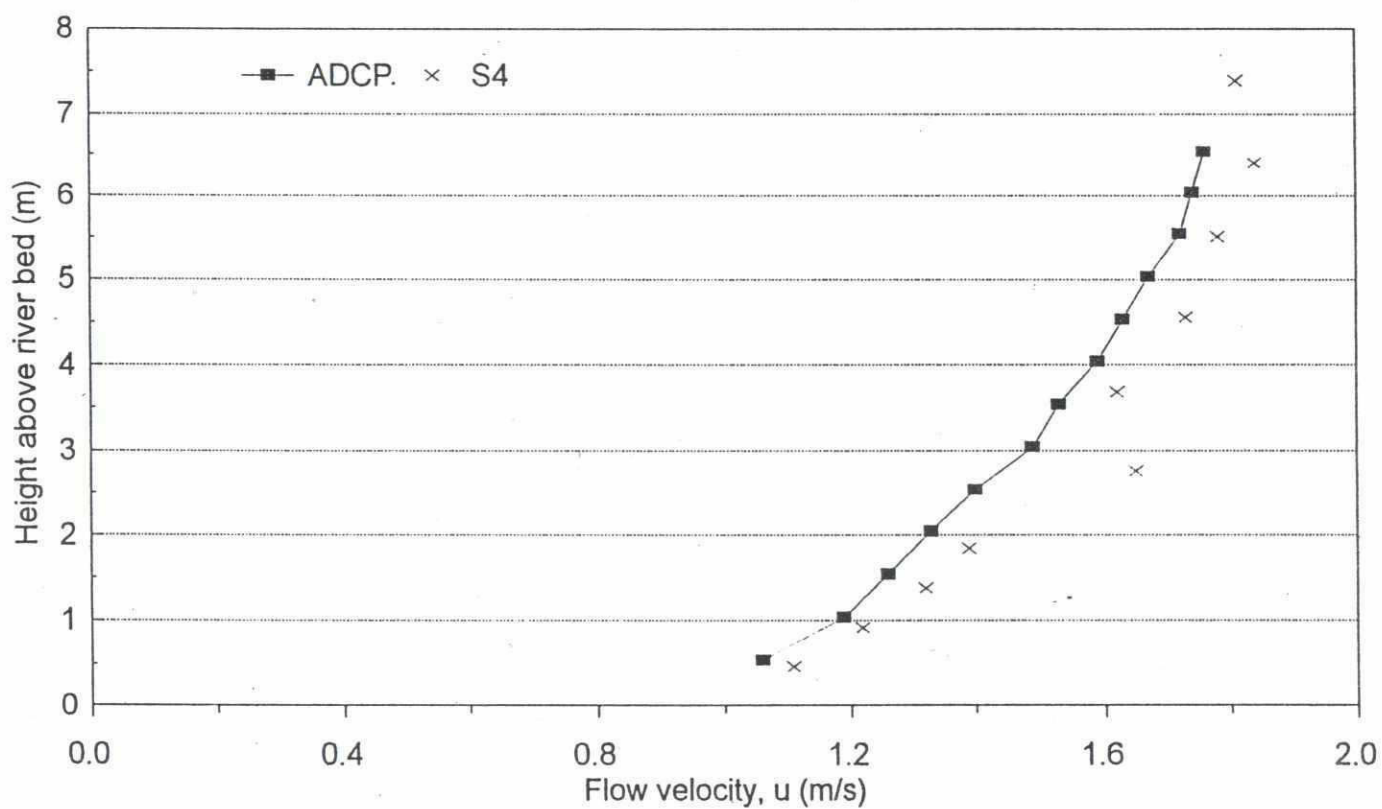
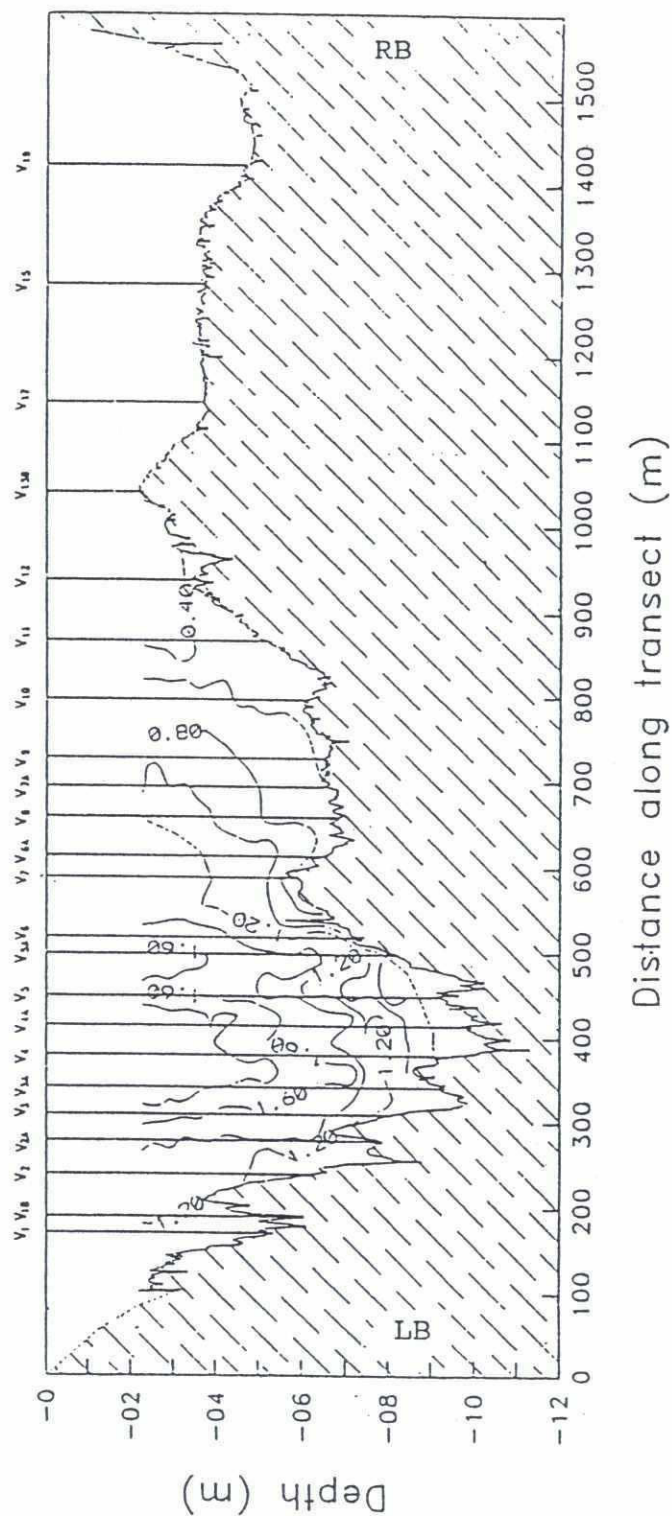


Figure G8.5 Velocity vertical RA



Note : Subscripts A and B represent additional verticals.
Isovels are shown in m/s

Figure G8.6 Cross-sectional profile with isovets and locations of measuring verticals along transect T2

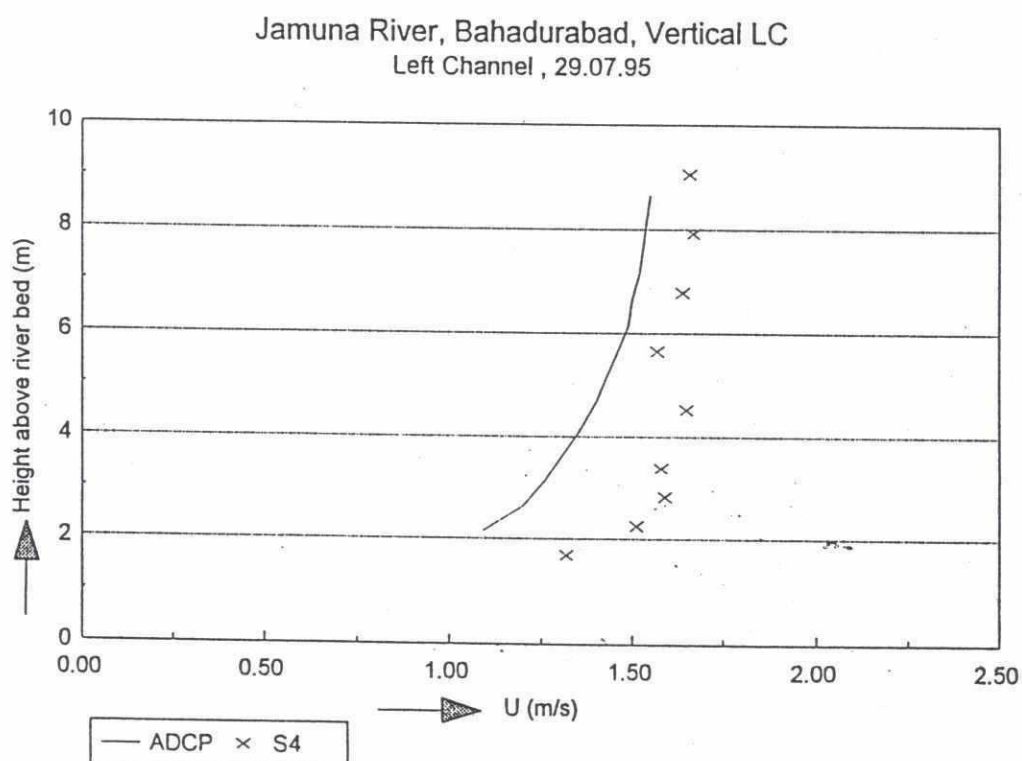
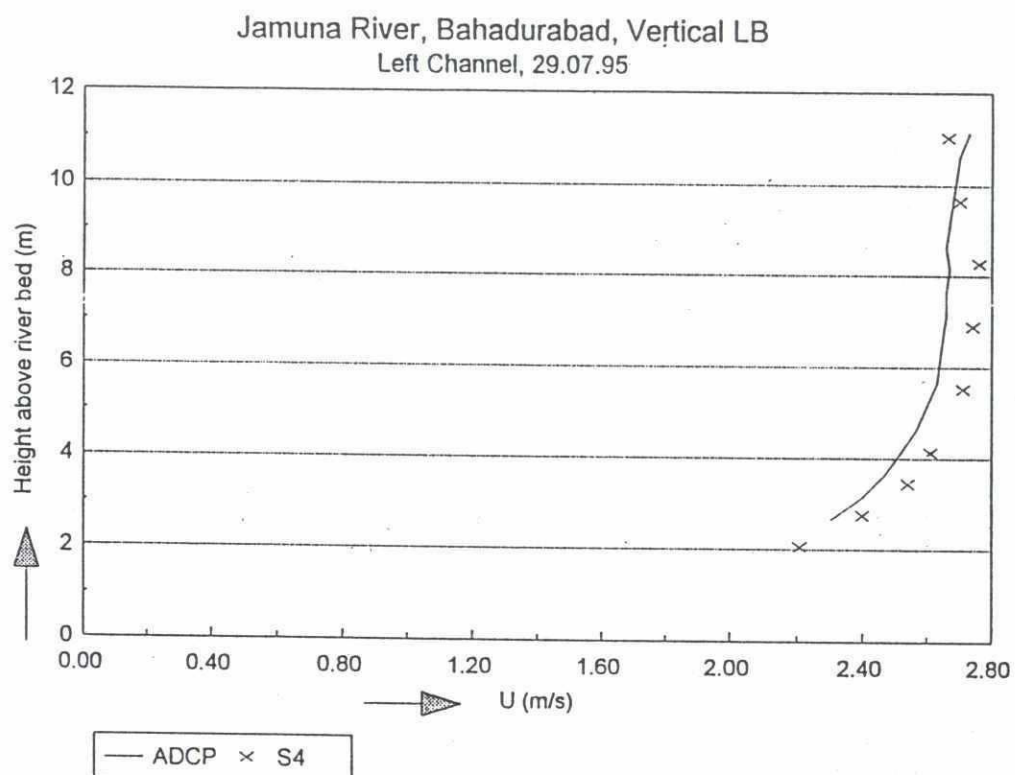


Figure G8.7 Velocity verticals in LB and LC

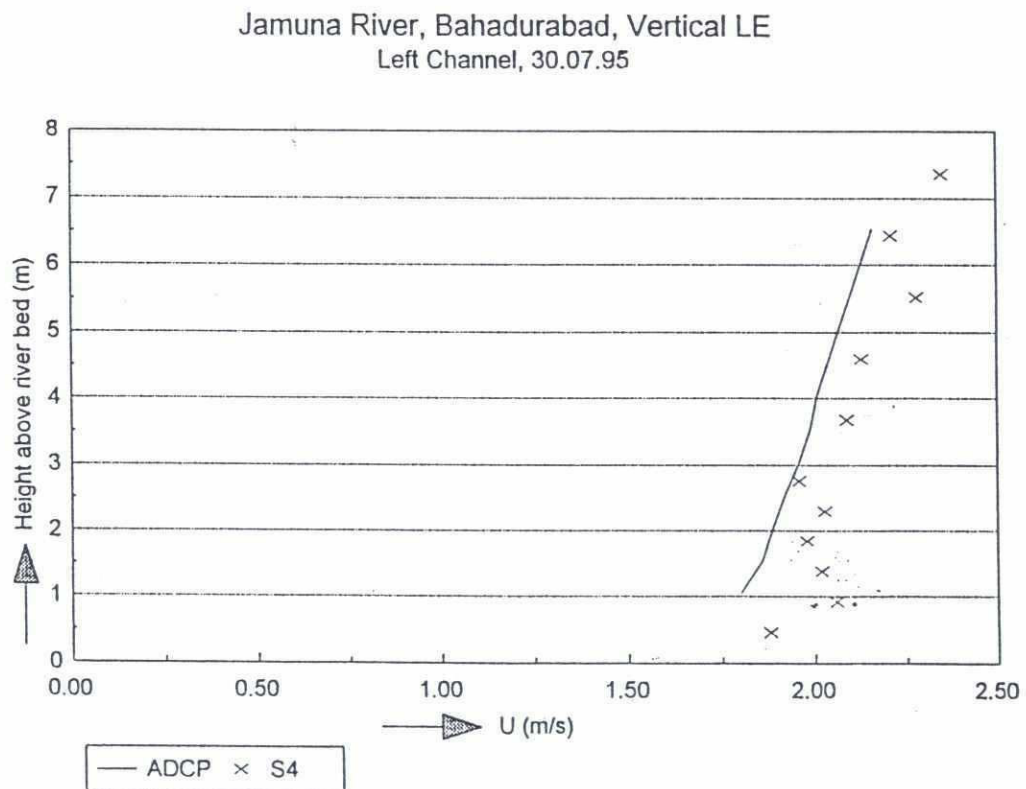
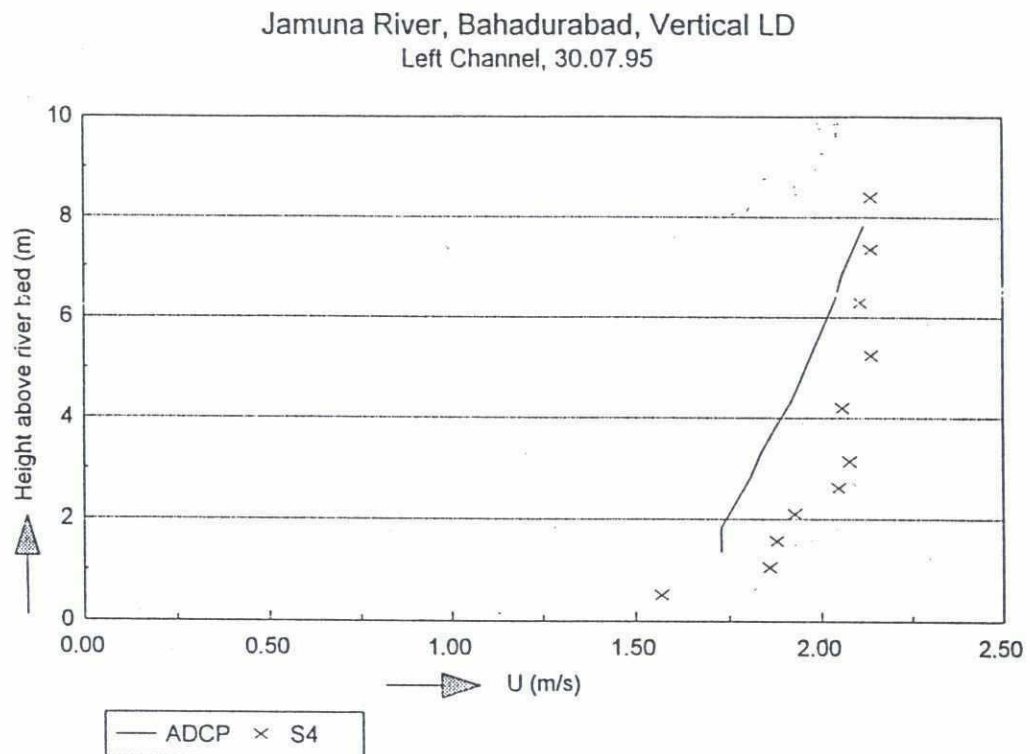
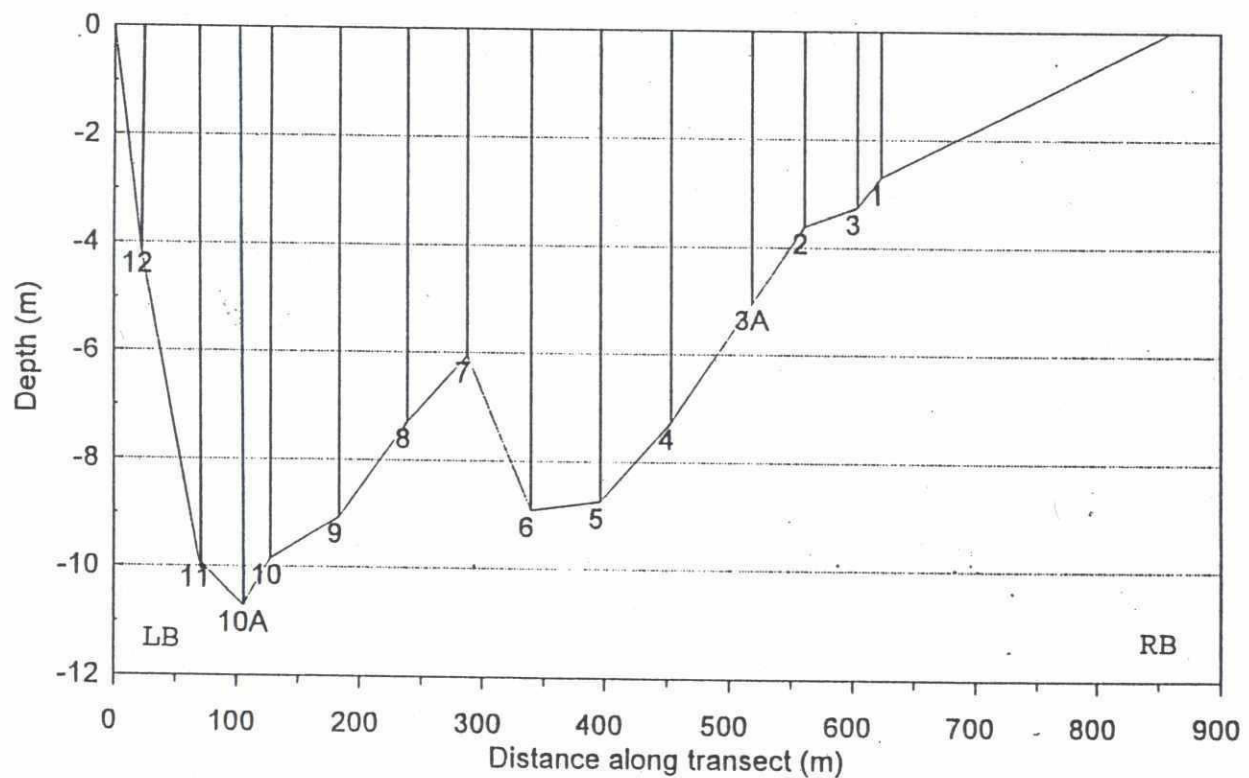
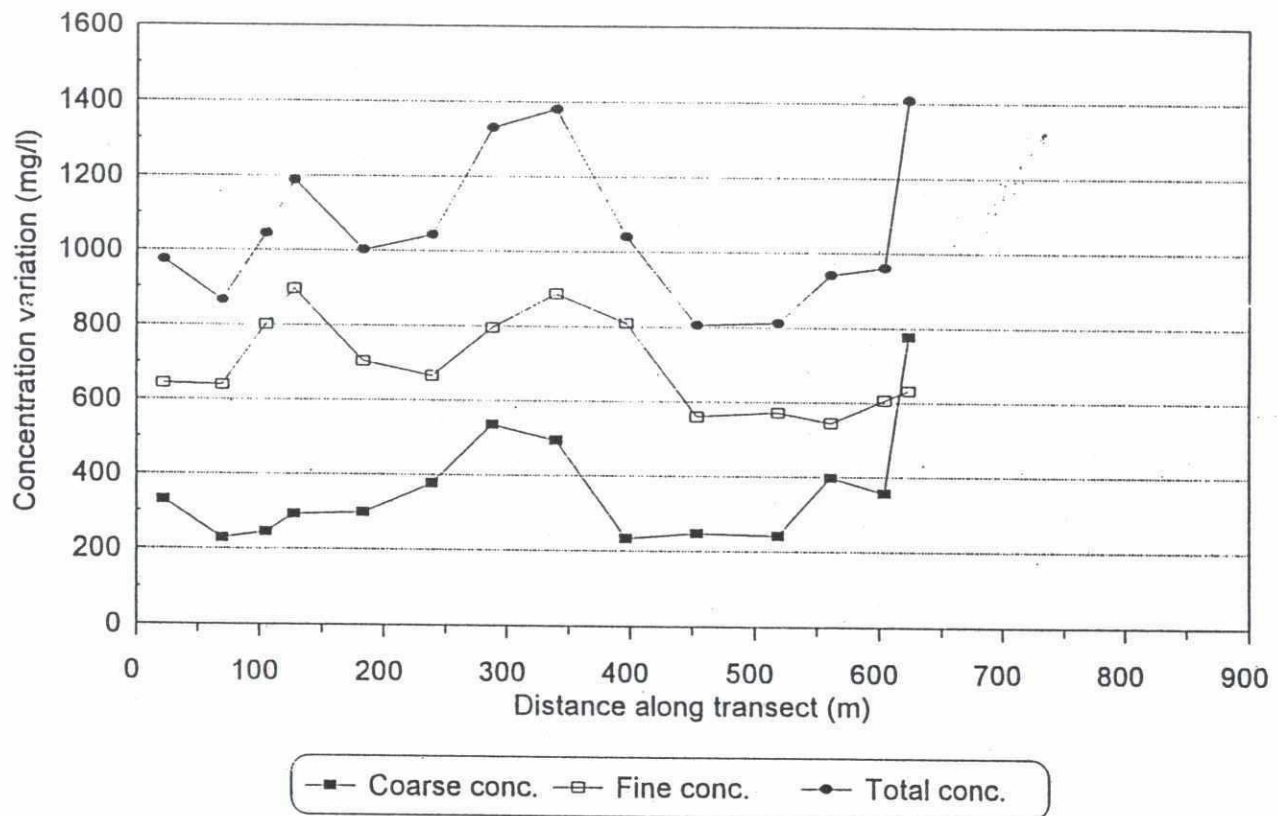


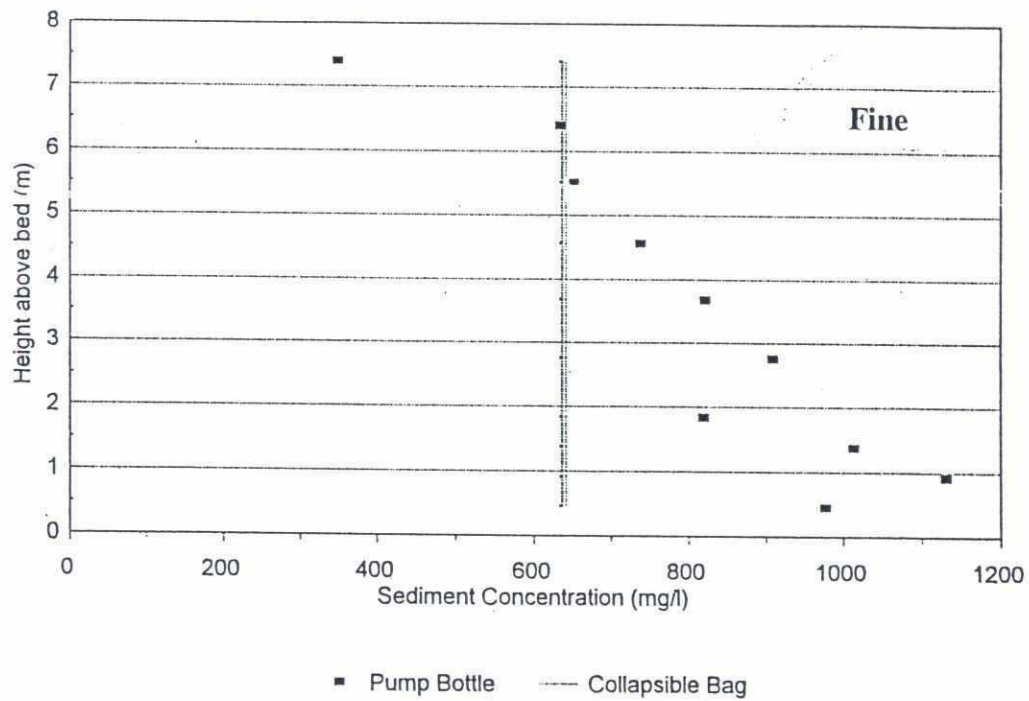
Figure G8.8 Velocity verticals in LD and LE



Note : Concentrations was measured in the verticals, depth integrating with a Collapsible bag

Figure G8.9 Suspended sediment concentrations in transect T1

Jamuna River, Bahadurabad, Vertical RA
27.07.95



Jamuna River, Bahadurabad, Vertical RA
27.07.95

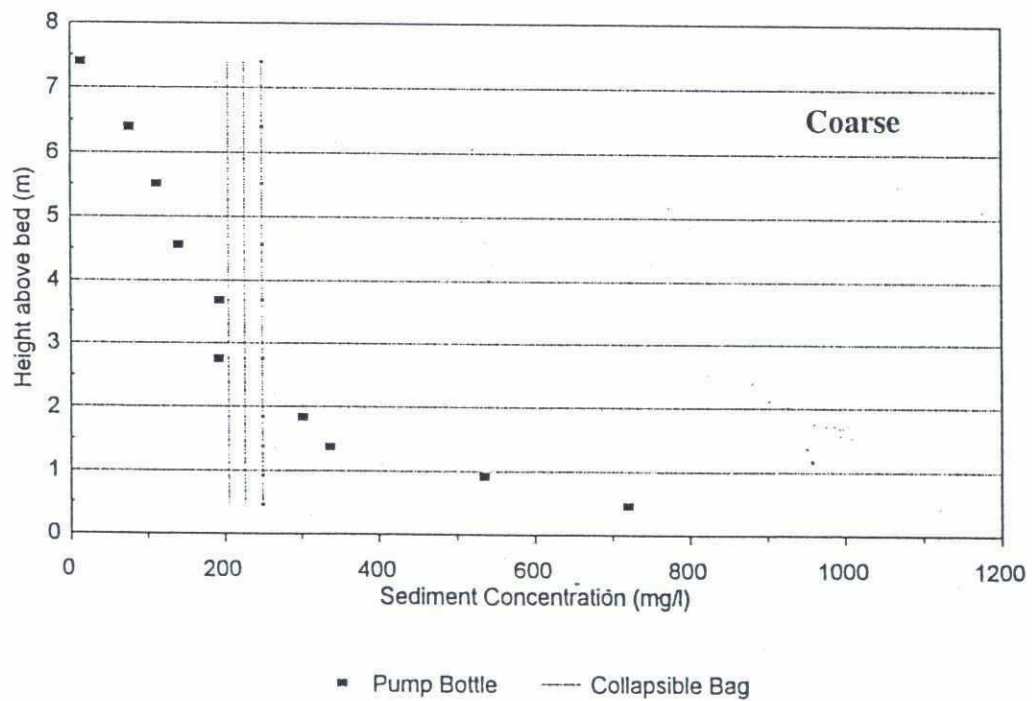


Figure G8.10 Sediment vertical RA

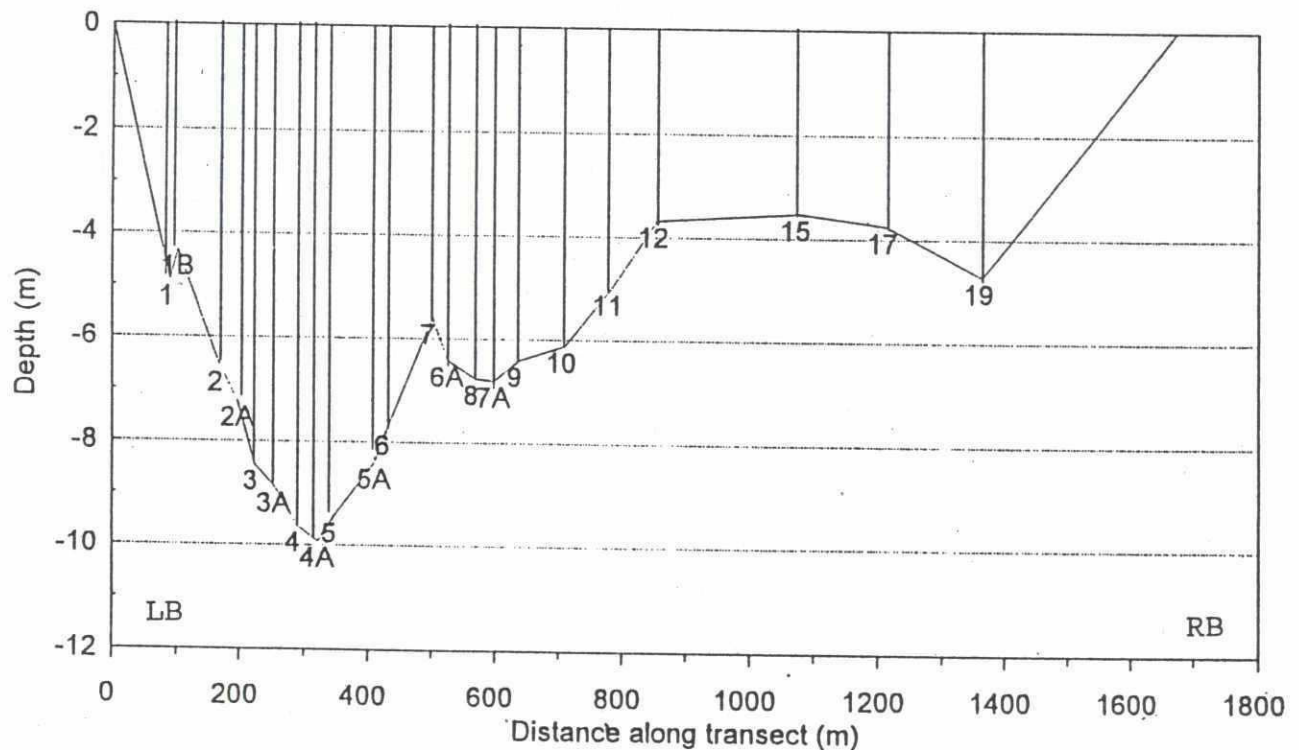
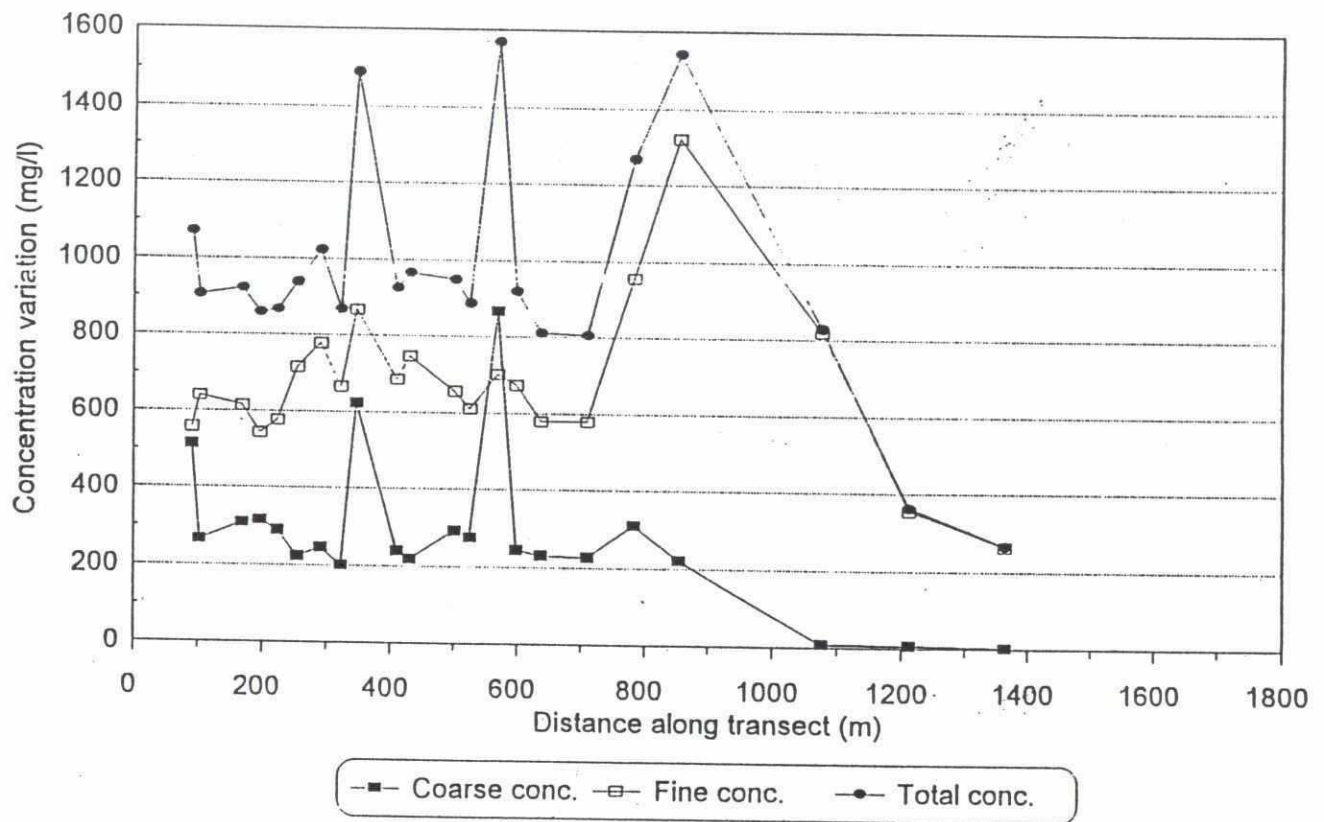
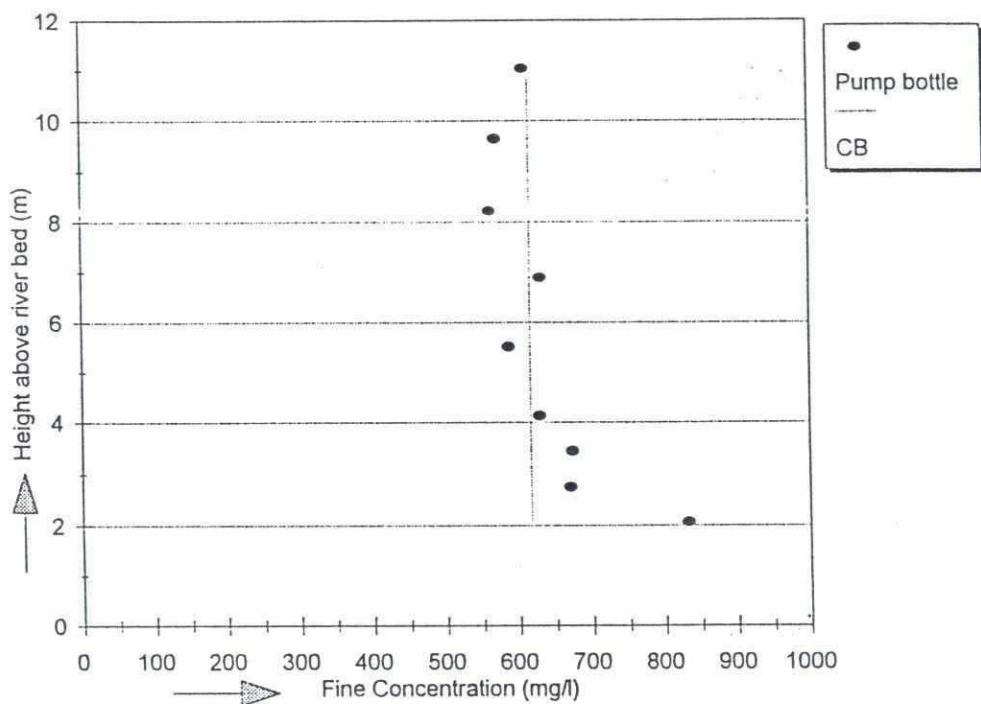


Figure G8.11 Suspended sediment concentrations in transect T2

Jamuna River, Bahadurabad, Vertical LB
Left Channel, 29.07.95



Jamuna River, Bahadurabad, Vertical LB
Left Channel, 29.07.95

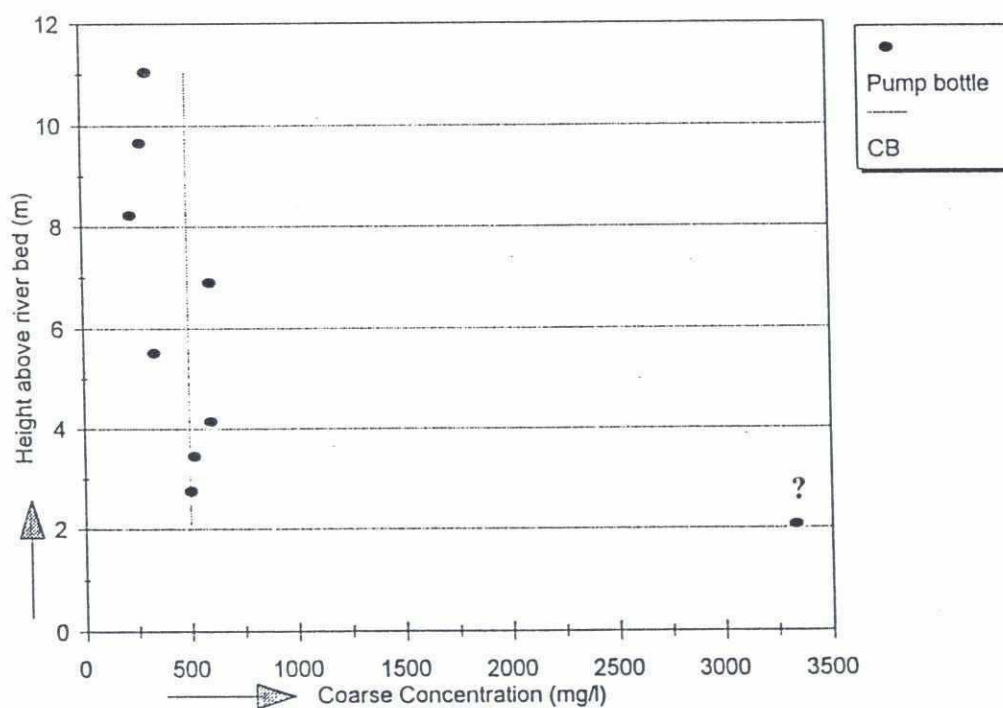
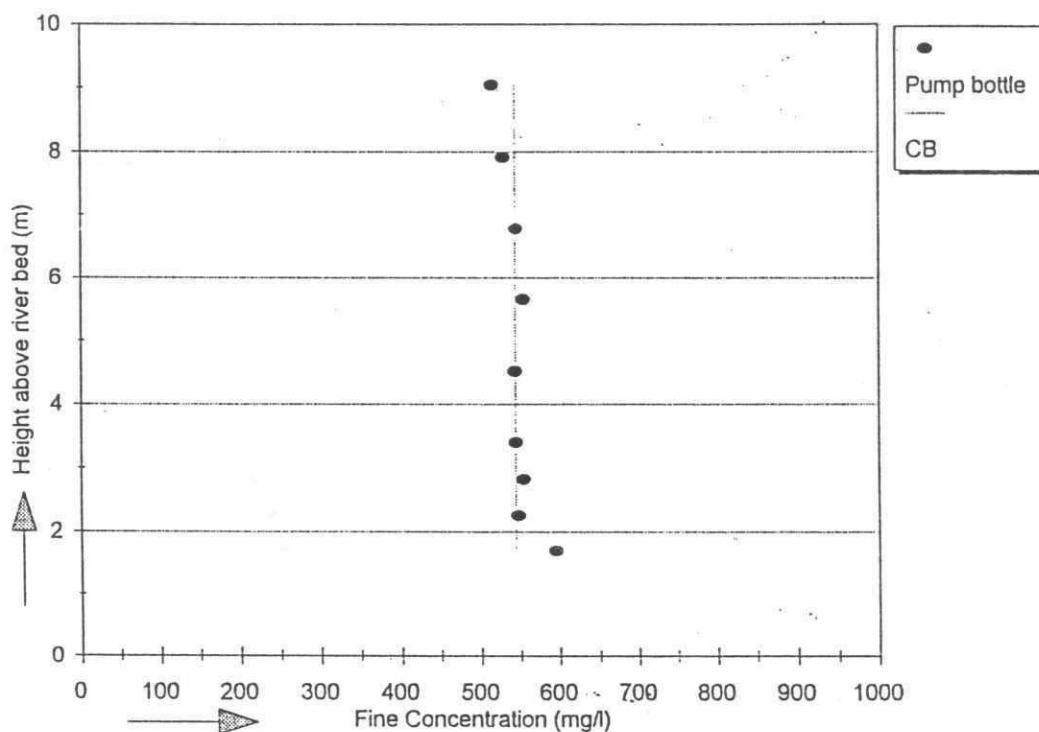


Figure G8.12 Sediment vertical LB

Jamuna River, Bahadurabad, Vertical LC
Left Channel, 29.07.95



Jamuna River, Bahadurabad, Vertical LC
Left Channel, 29.07.95

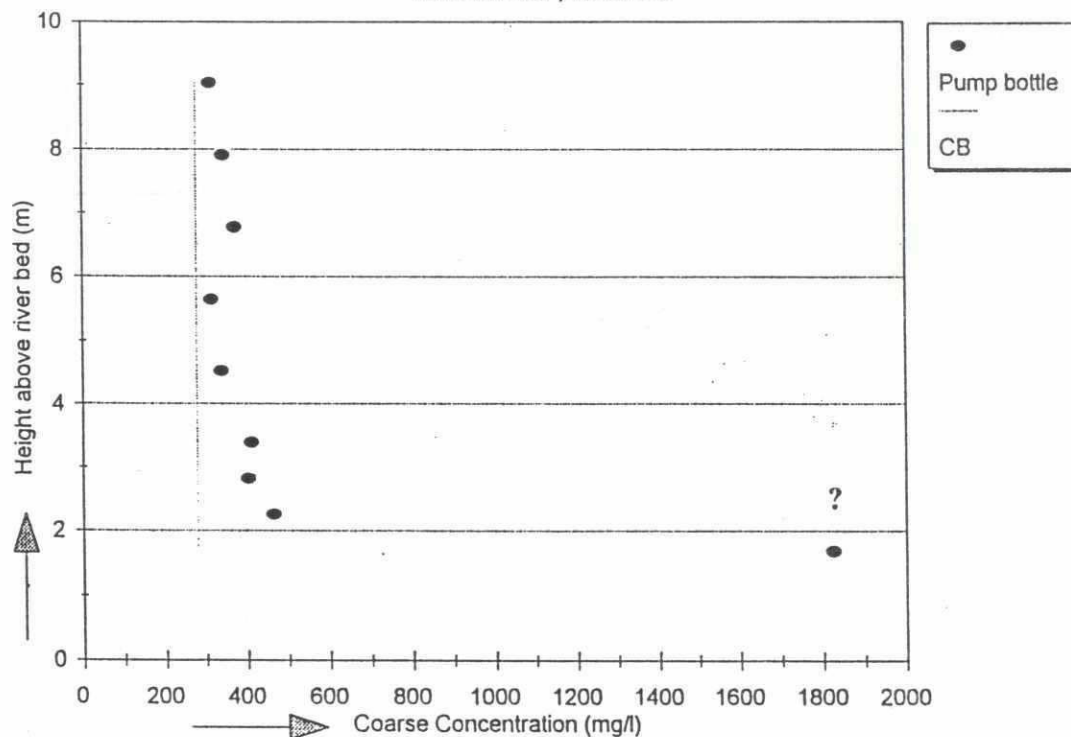


Figure G8.13 Sediment vertical LC

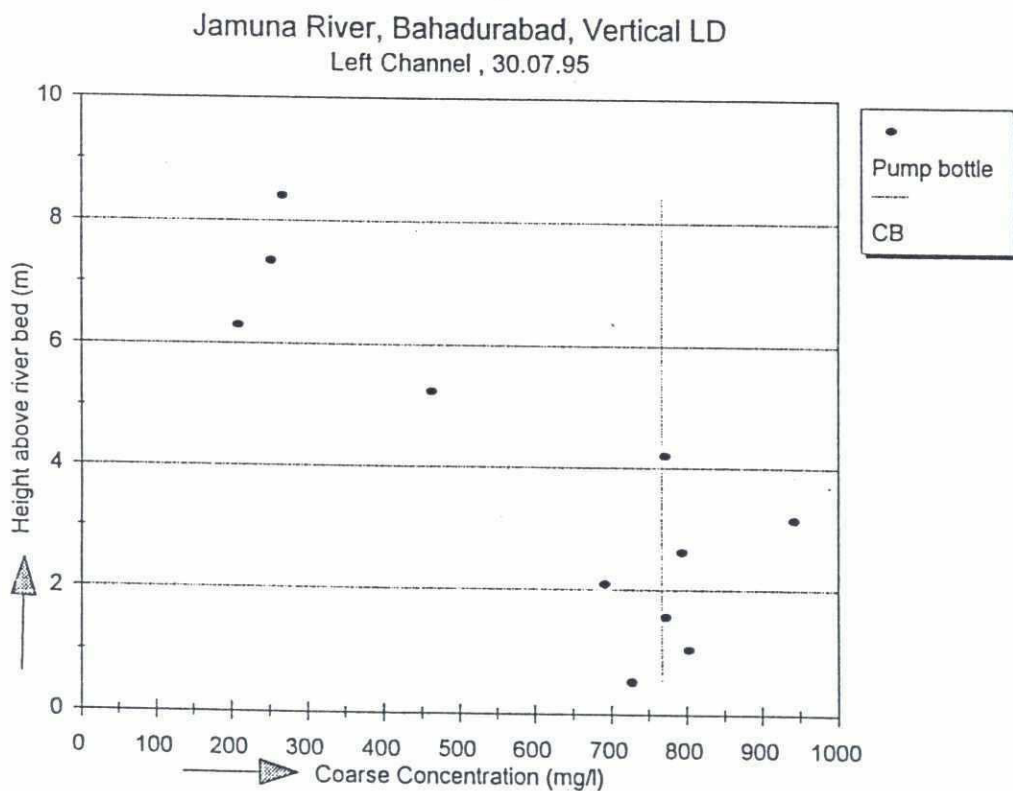
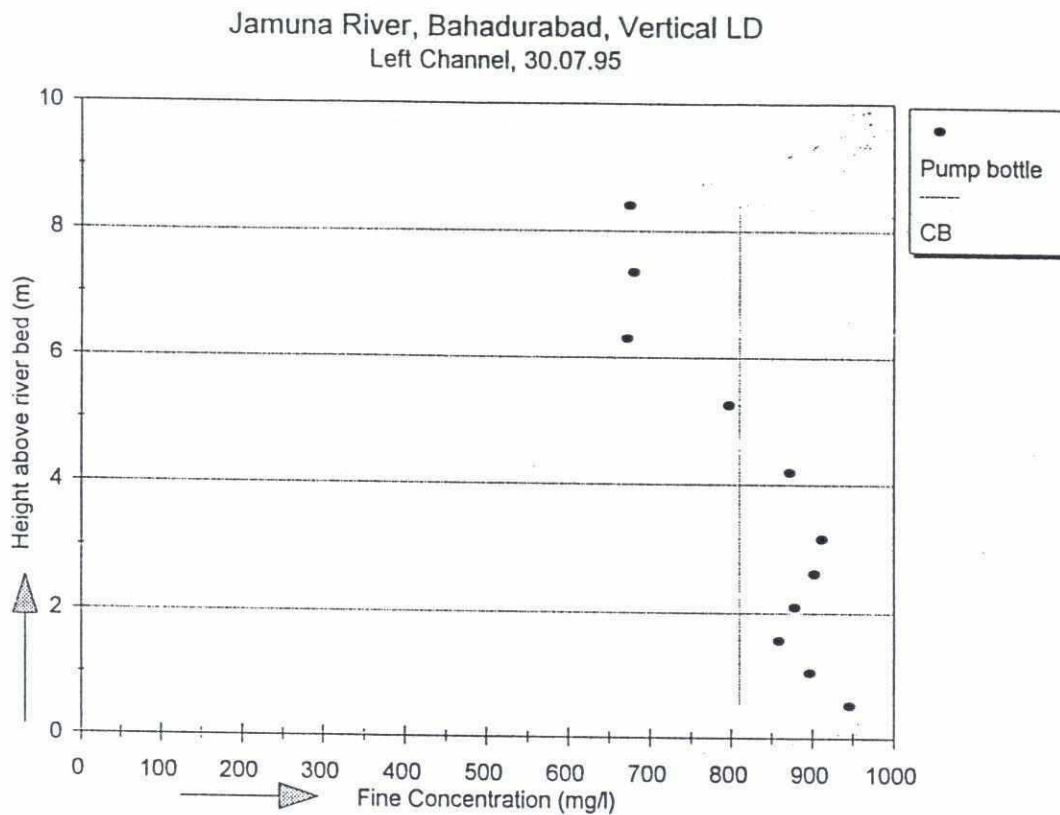
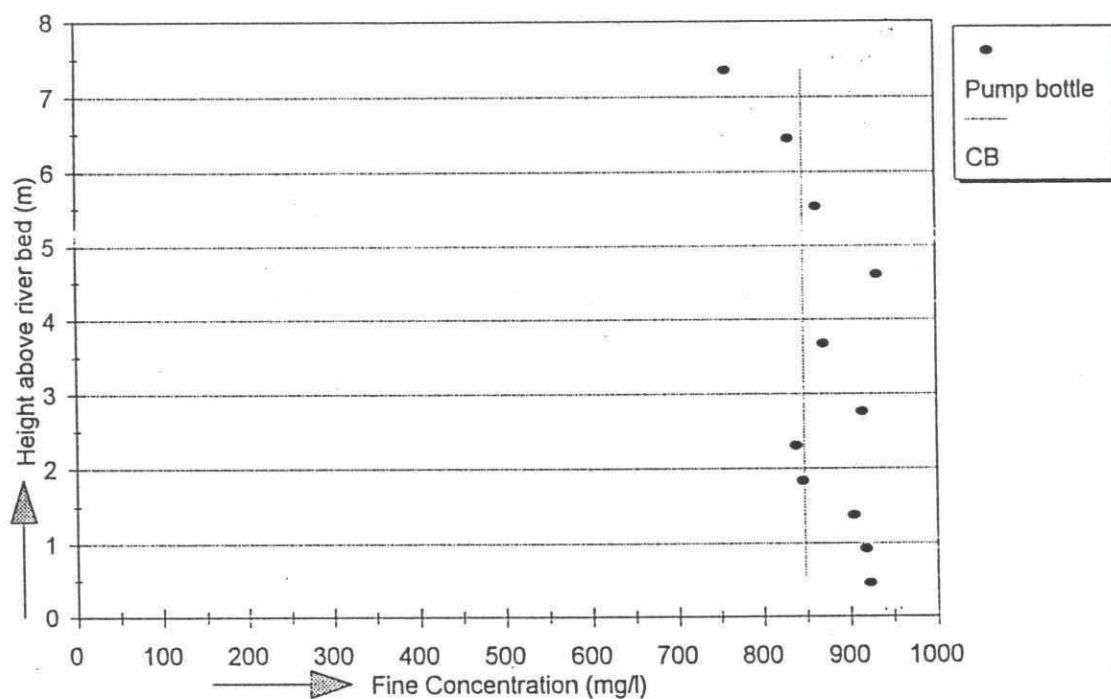


Figure G8.14 Sediment vertical LD

Jamuna River, Bahadurabad, Vertical LE
Left Channel, 30.07.95



Jamuna River, Bahadurabad, Vertical LE
Left Channel, 30.07.95

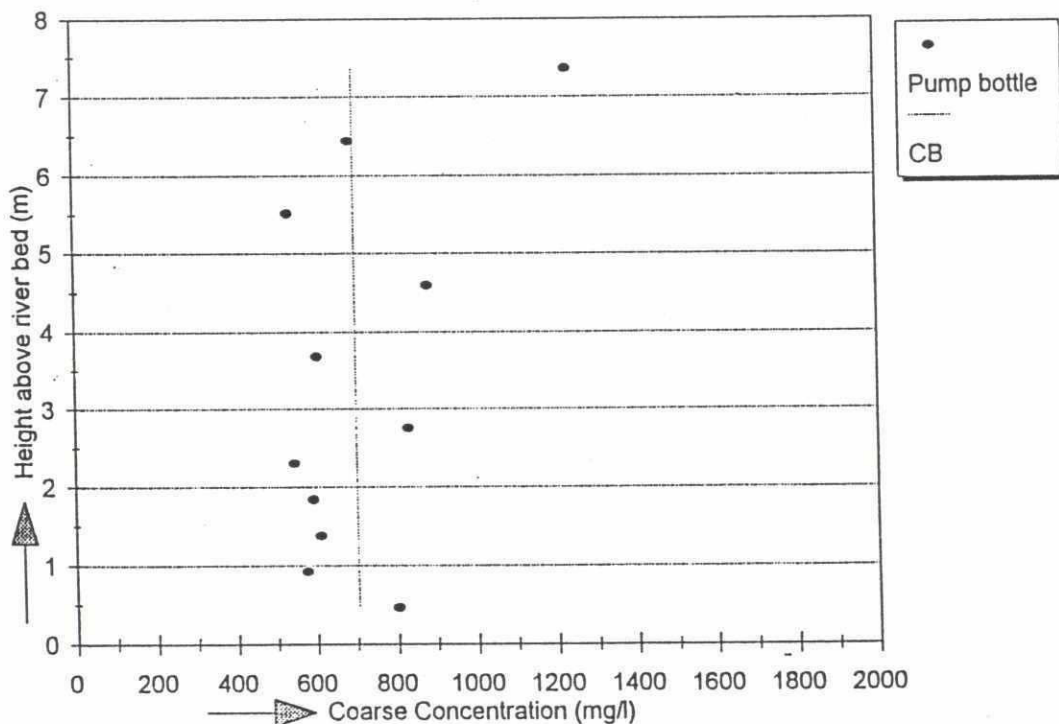


Figure G8.15 Sediment vertical LE

800

Jamuna River, Bahadurabad, Vertical RA 27.07.95

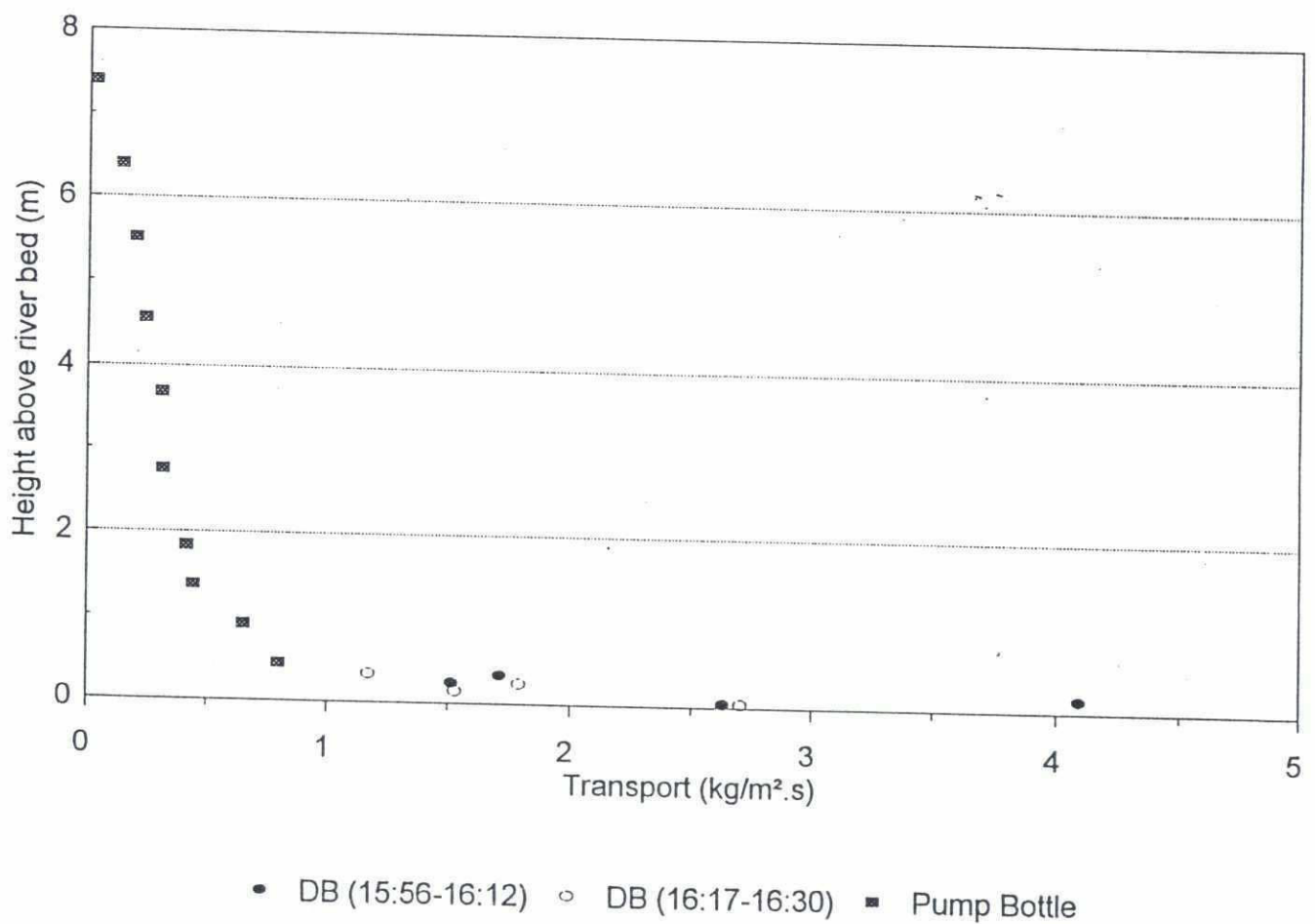
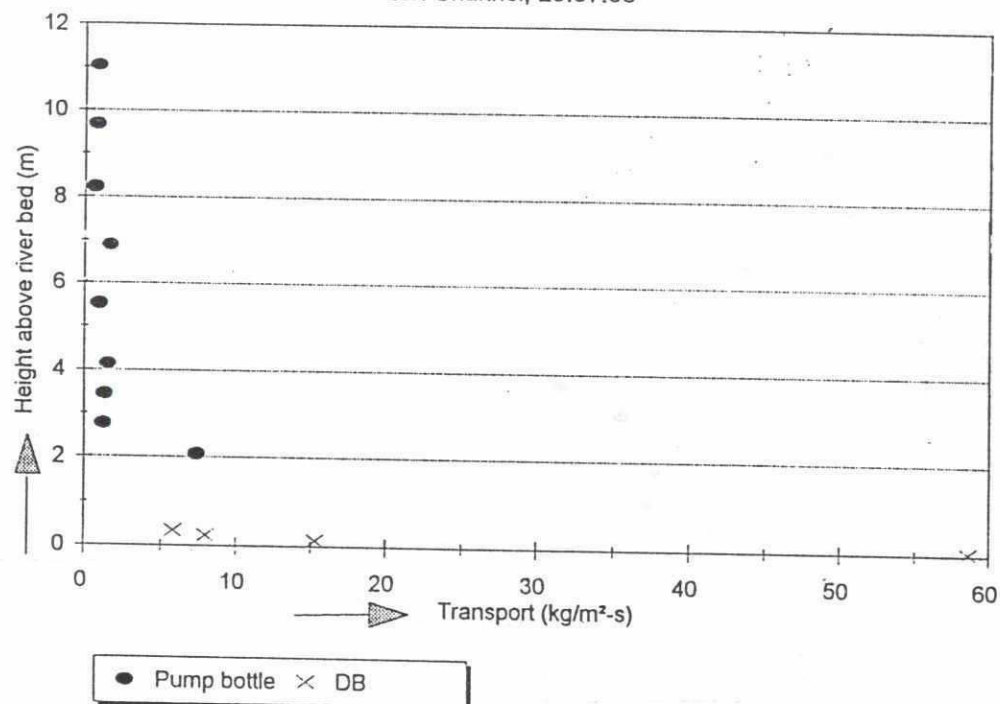


Figure G8.16 Sand transport vertical RA

Jamuna River, Bahadurabad, Vertical LB
Left Channel, 29.07.95



Jamuna River, Bahadurabad, Vertical LC
Left Channel, 29.07.95

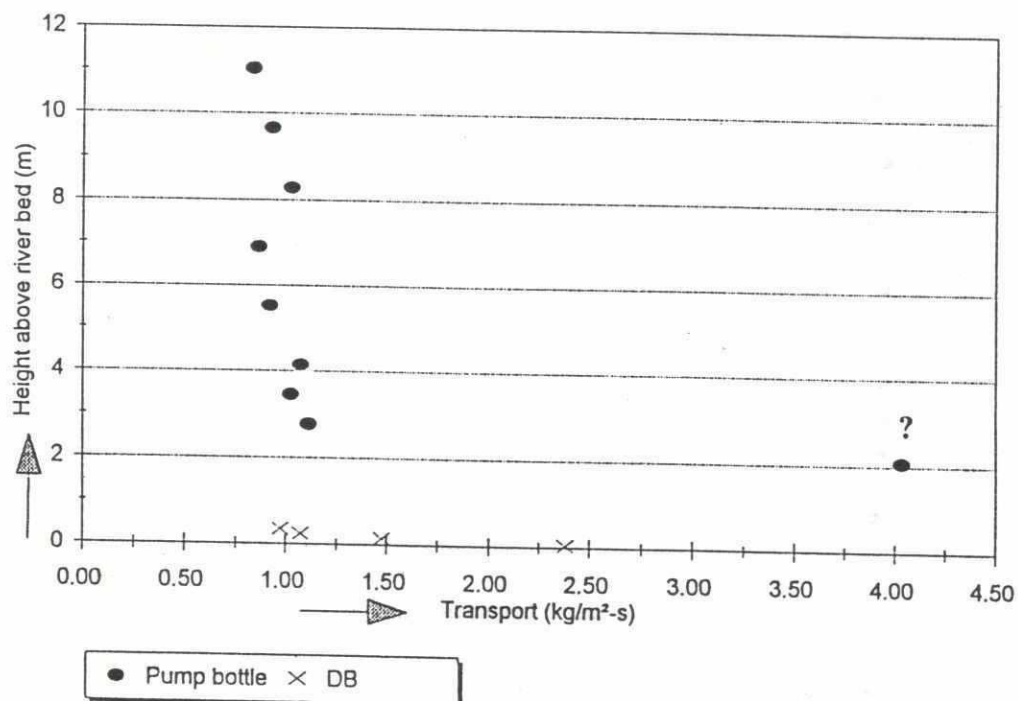
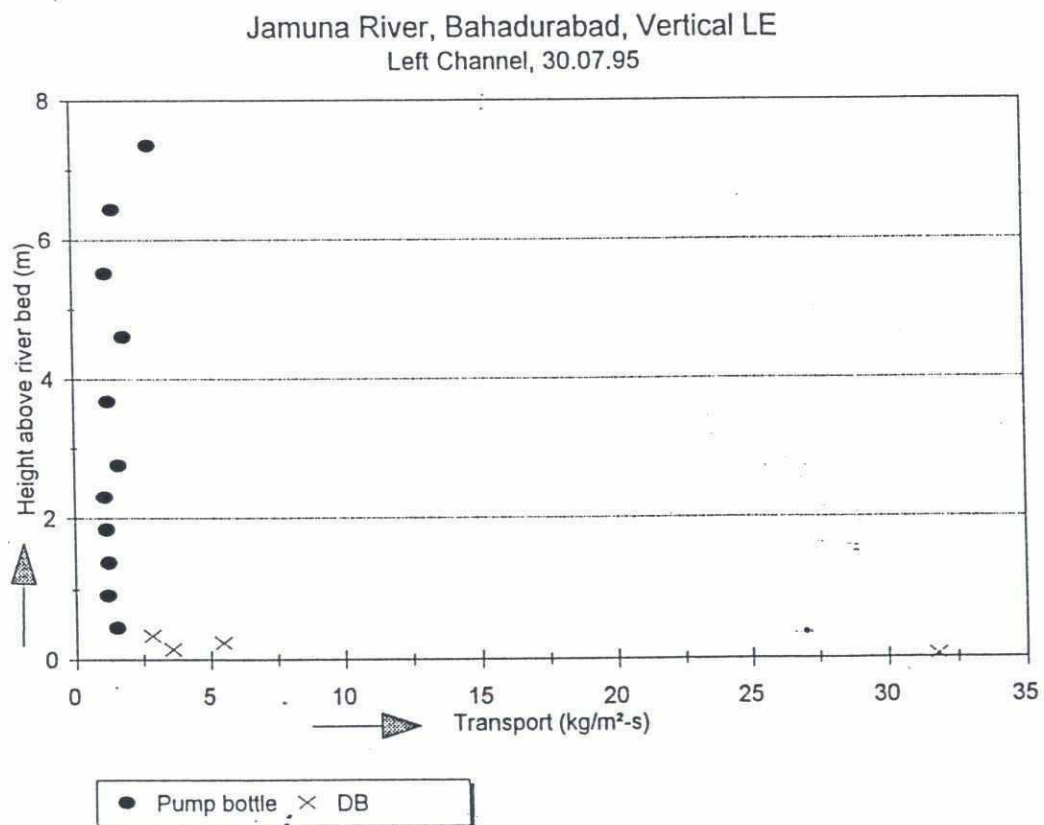
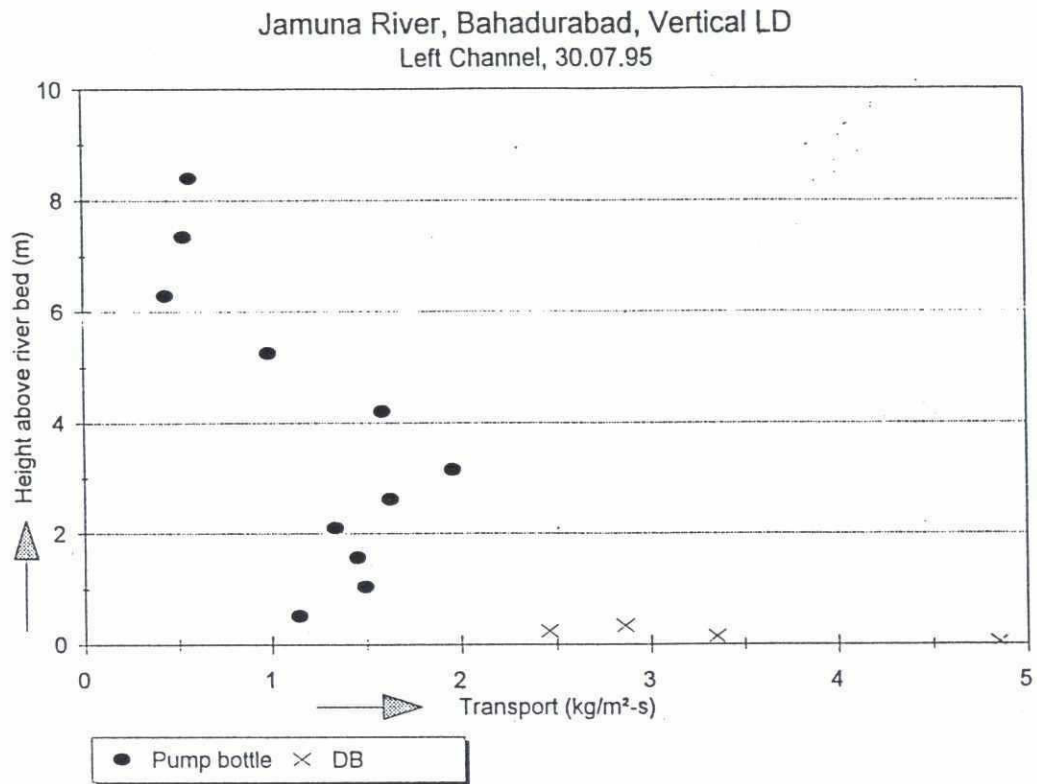


Figure G8.17 Sand transport vertical LB and LC



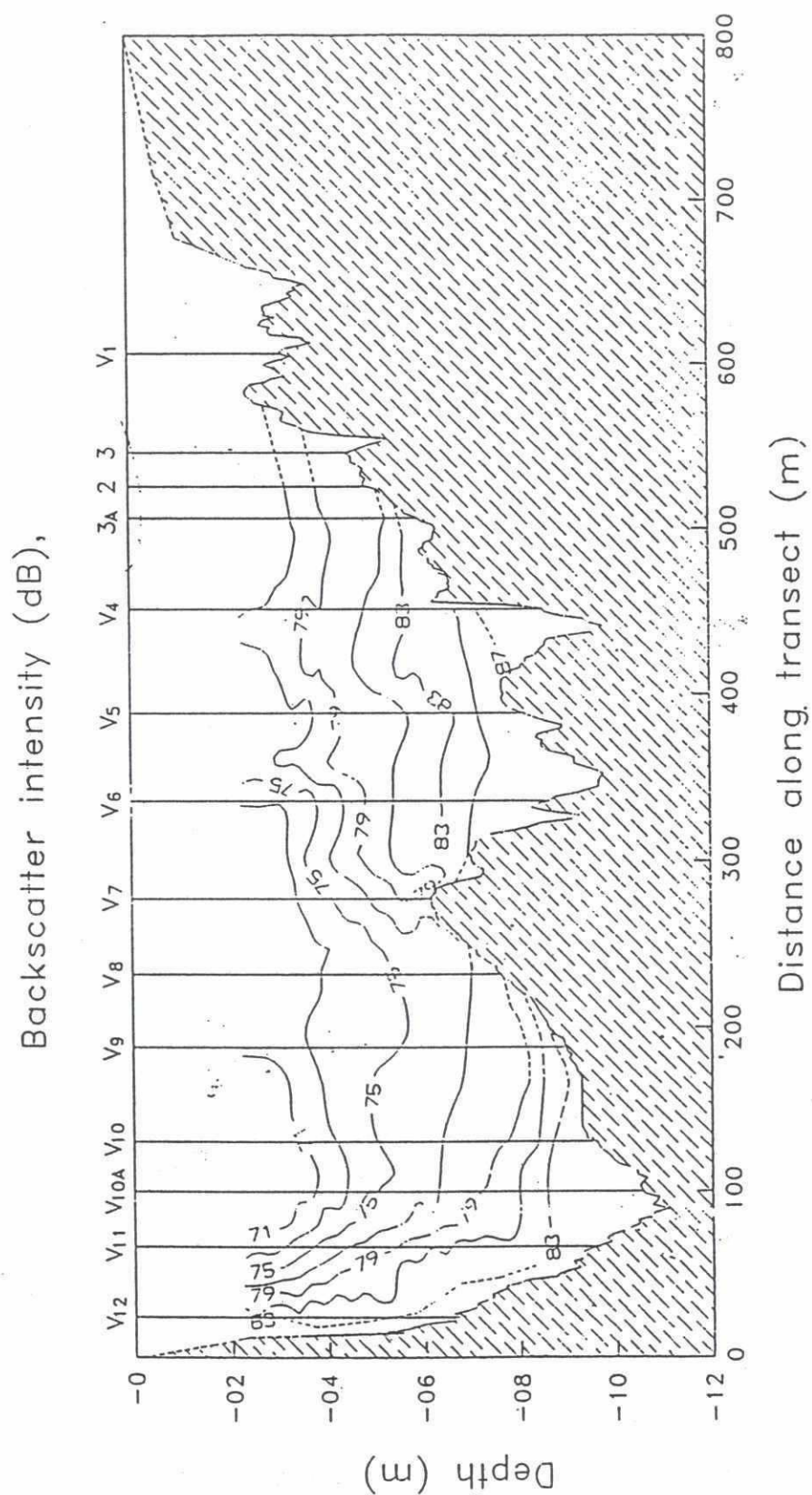
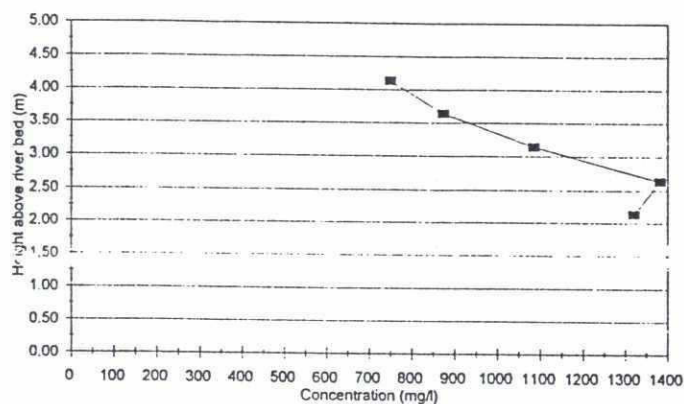
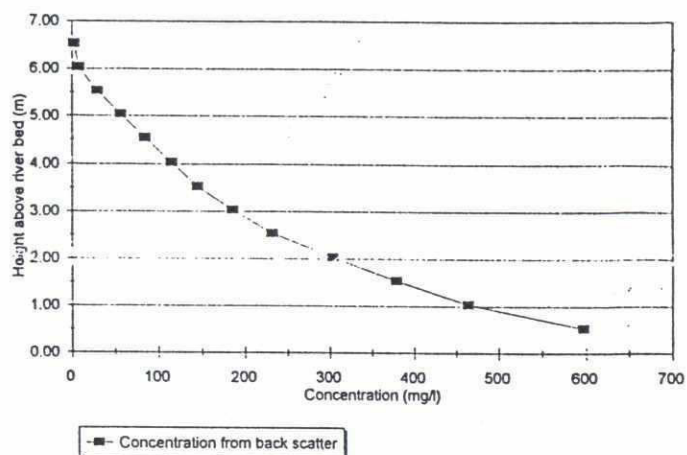


Figure G8.19 Backscatter intensity in transect T1

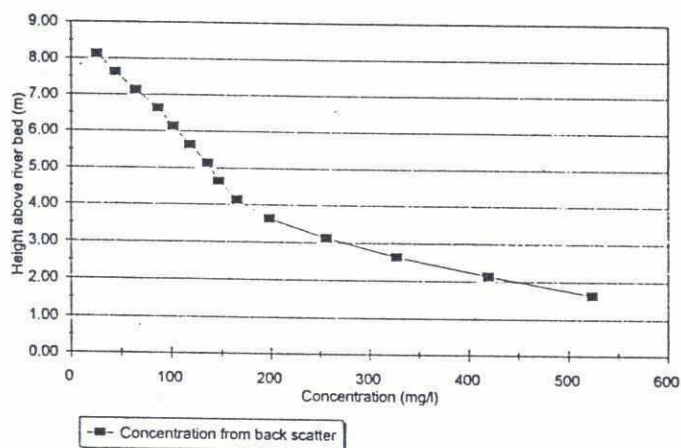
Jamuna River, Bahadurabad, Vertical 12
Right Channel, 27.07.95



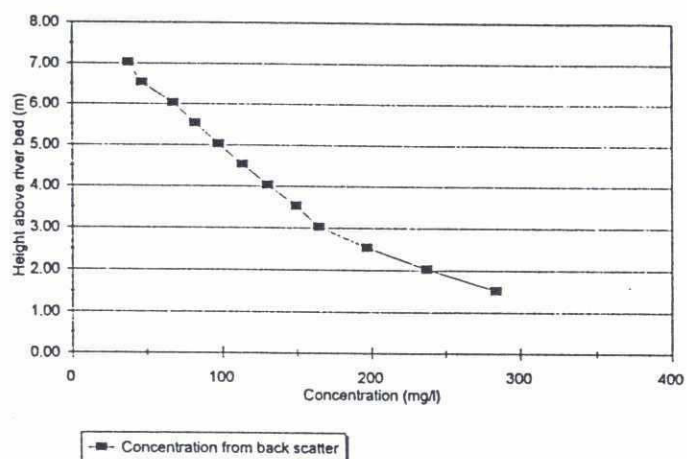
Jamuna River, Bahadurabad, Vertical RA
Right Channel, 27.07.95



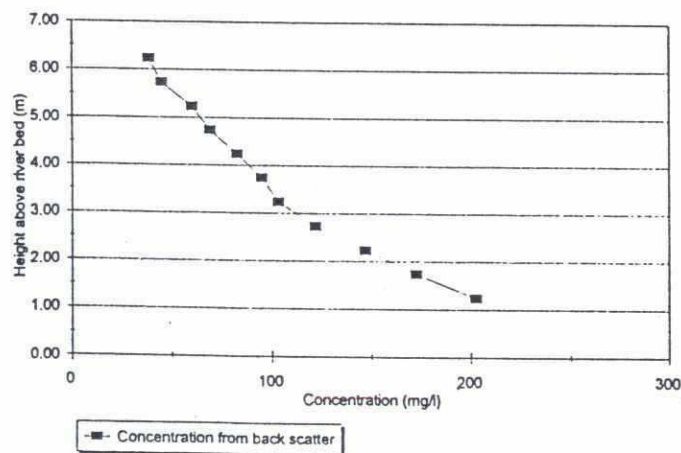
Jamuna River, Bahadurabad, Vertical 10A
Right Channel, 27.07.95



Jamuna River, Bahadurabad, Vertical 10
Right Channel, 27.07.95



Jamuna River, Bahadurabad, Vertical 9
Right Channel, 27.07.95



Jamuna River, Bahadurabad, Vertical 8
Right Channel, 27.07.95

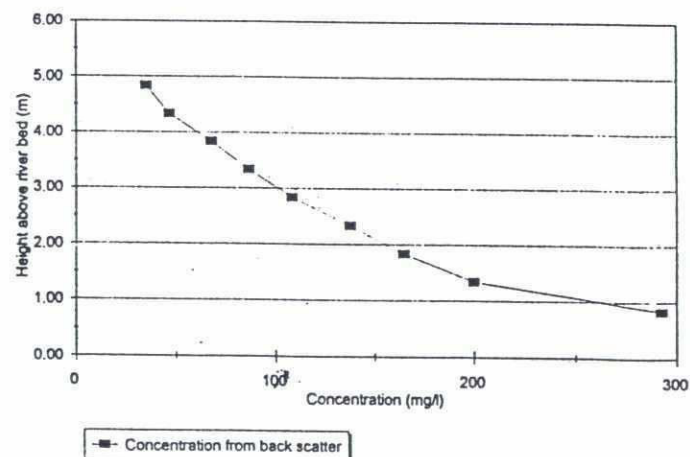


Figure G8.20 Suspended sediment concentration verticals in transect T1 from backscatter

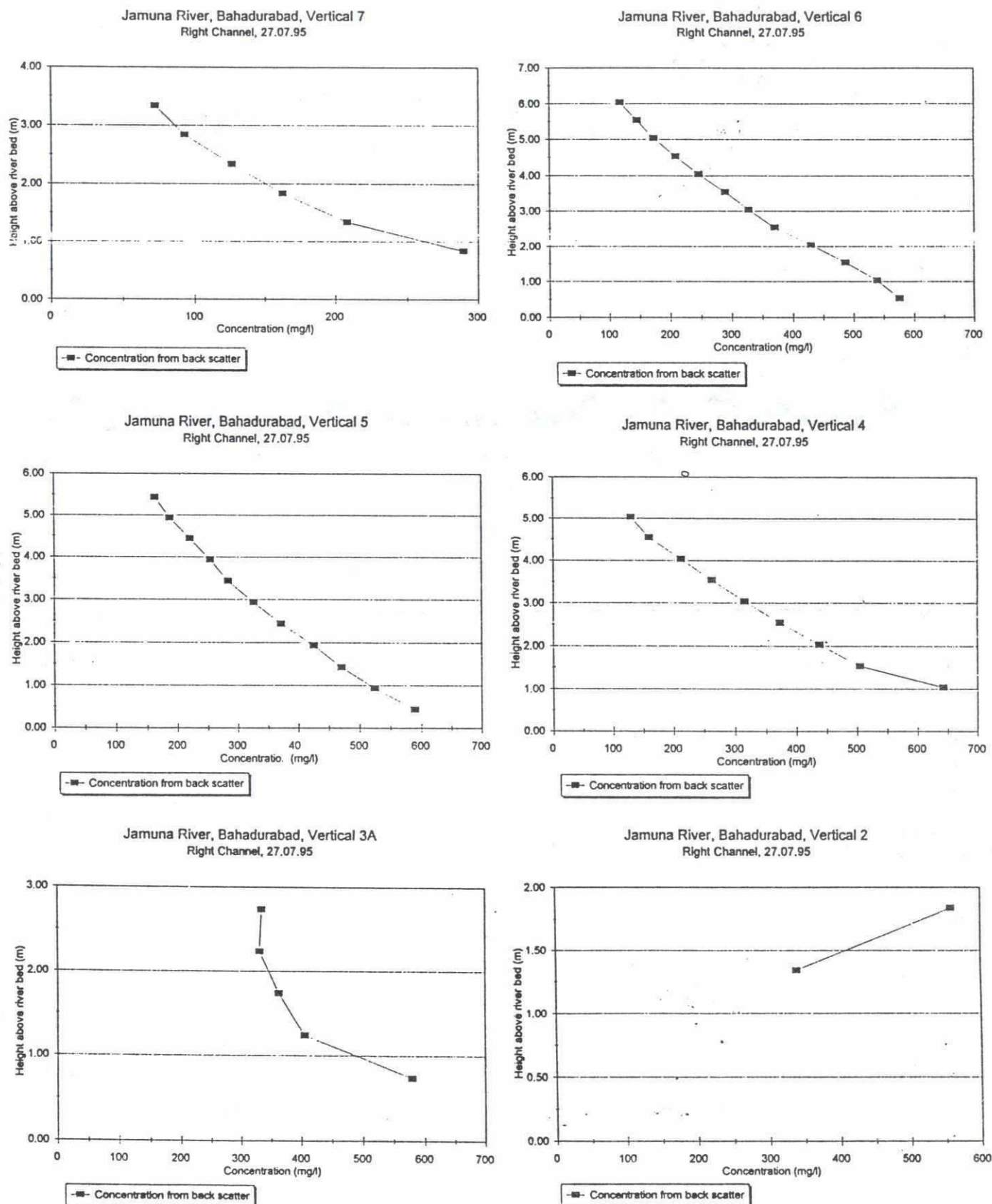


Figure G8.20 Suspended sediment concentration verticals in transect T1 from backscatter

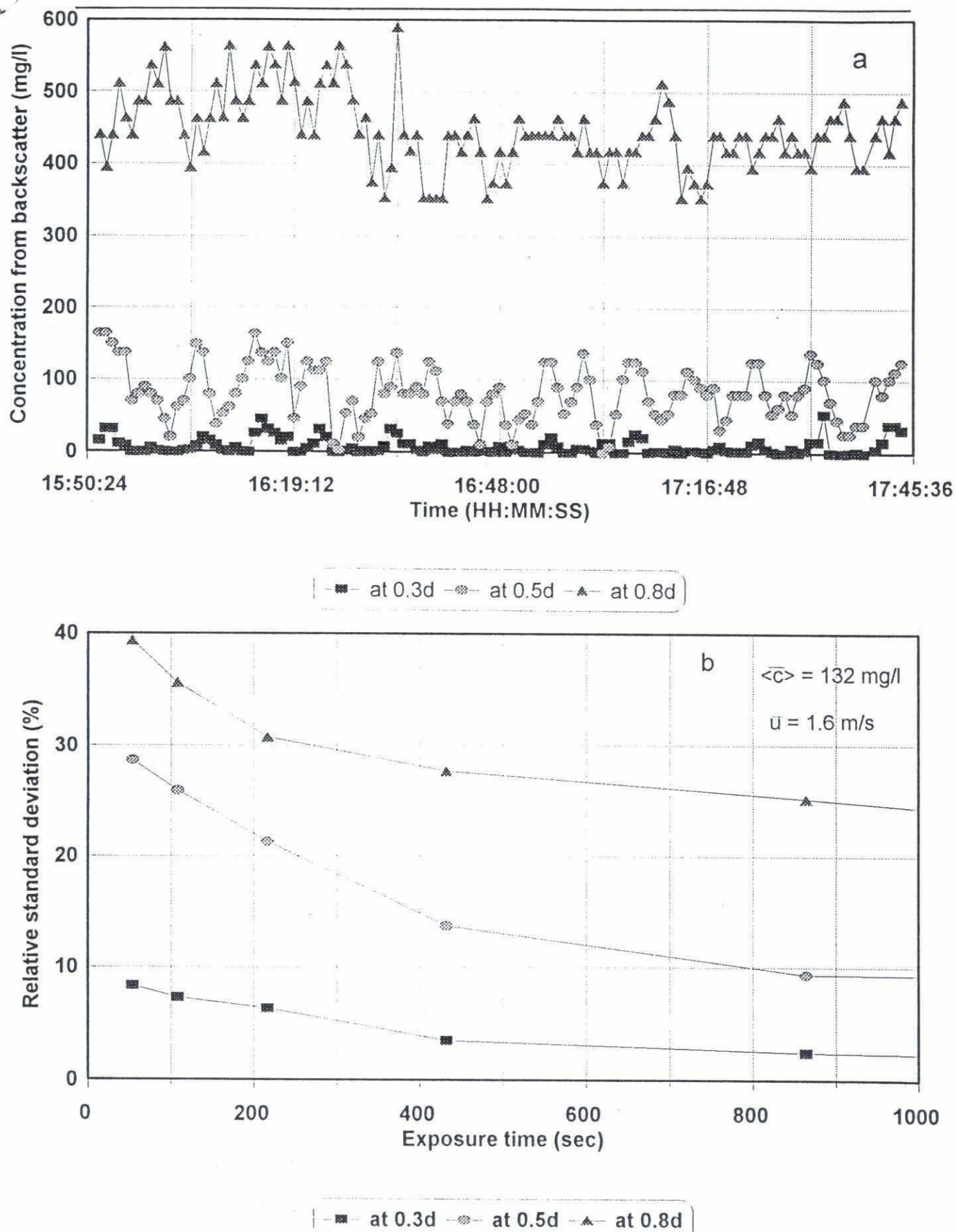


Figure G8.21 Variation of suspended sediment concentration in higher flows. (a) ADCP backscatter intensity (b) Relative standard deviation versus exposure time

Jamuna River, Bahadurabad, Vertical RA
Right Channel, 27.07.95

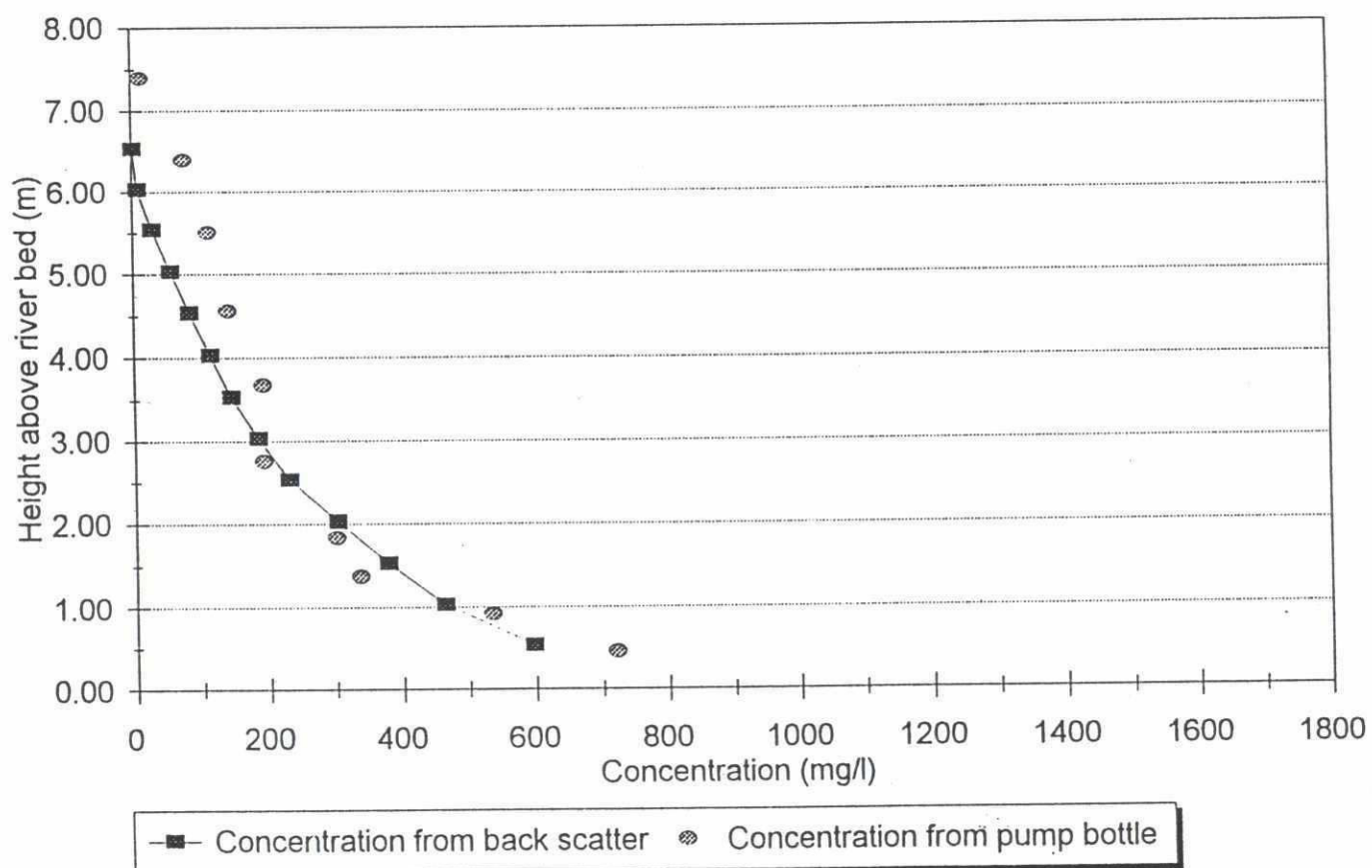
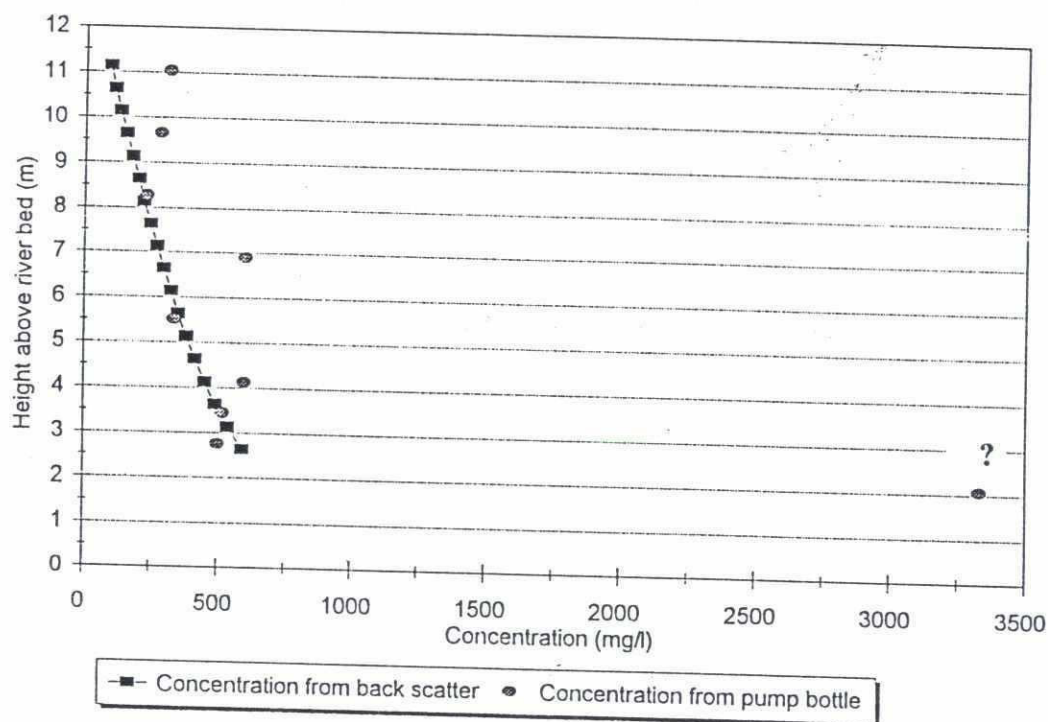


Figure G8.22 ADCP vs pump-bottle in vertical RA

Jamuna River, Bahadurabad, Vertical LB
Left Channel, 29.07.95



Jamuna River, Bahadurabad, Vertical LC
Left Channel, 29.07.95

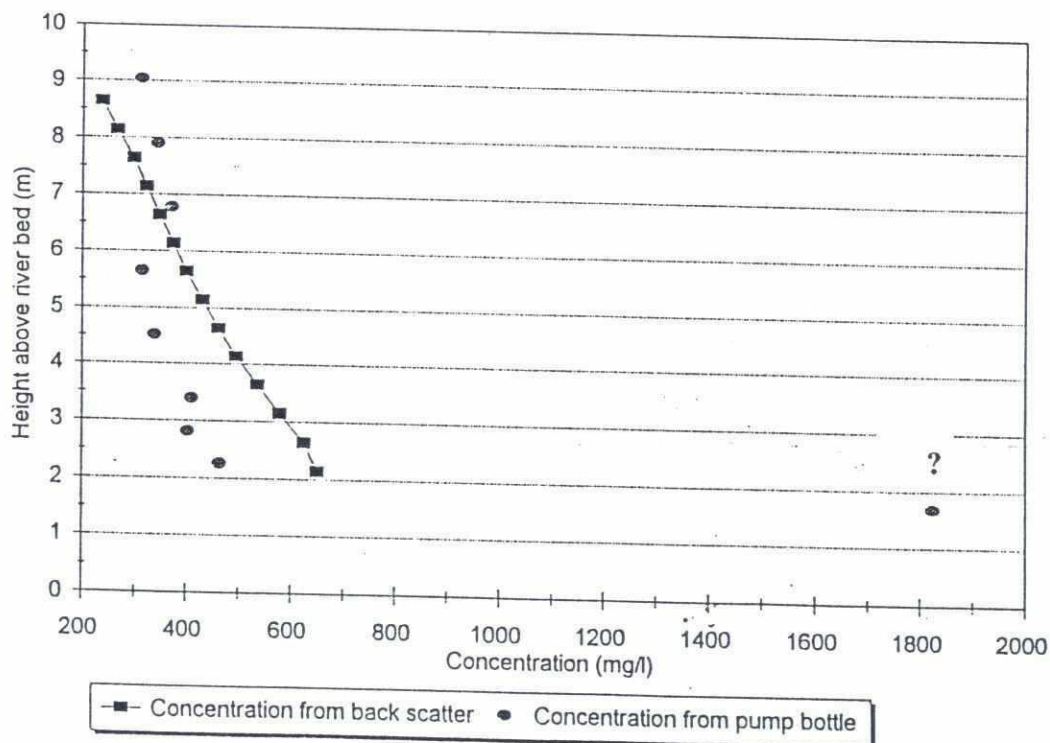
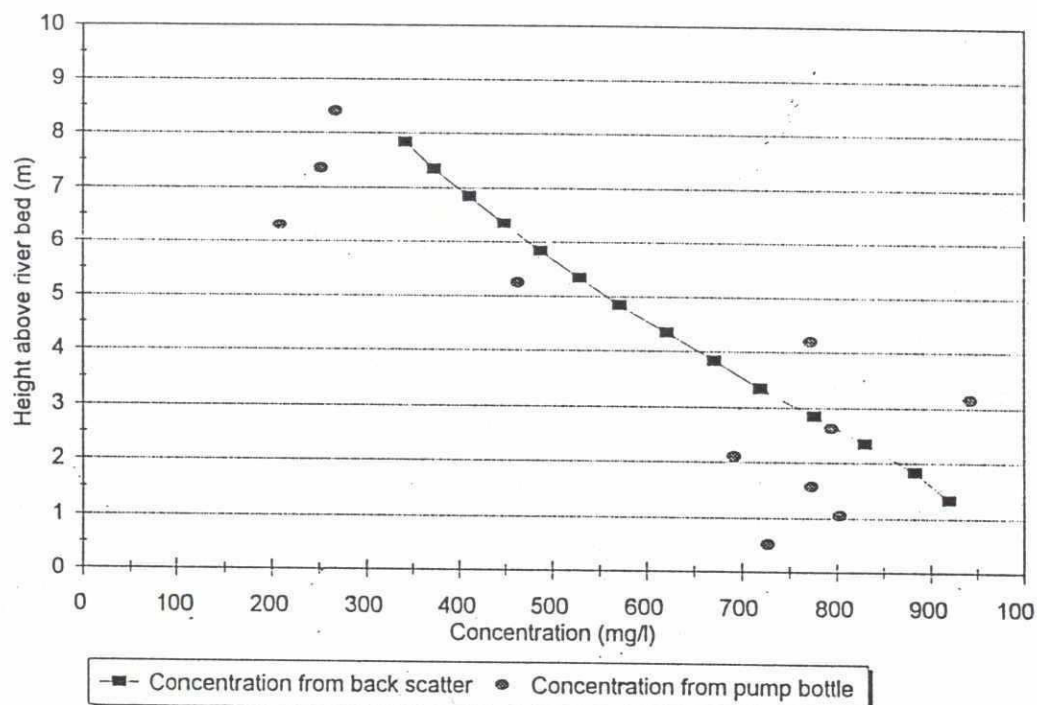


Figure G8.23 Suspended coarse sediment concentration verticals in LB and LC

Jamuna River, Bahadurabad, Vertical LD
Left Channel, 30.07.95



Jamuna River, Bahadurabad, Vertical LE
Left Channel, 30.07.95

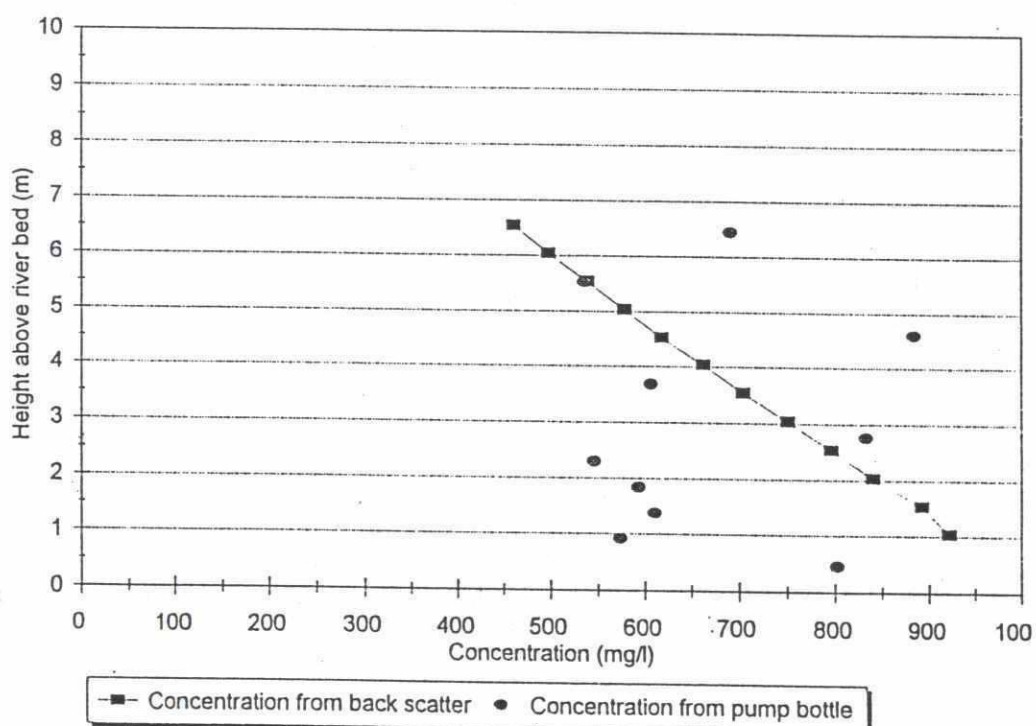
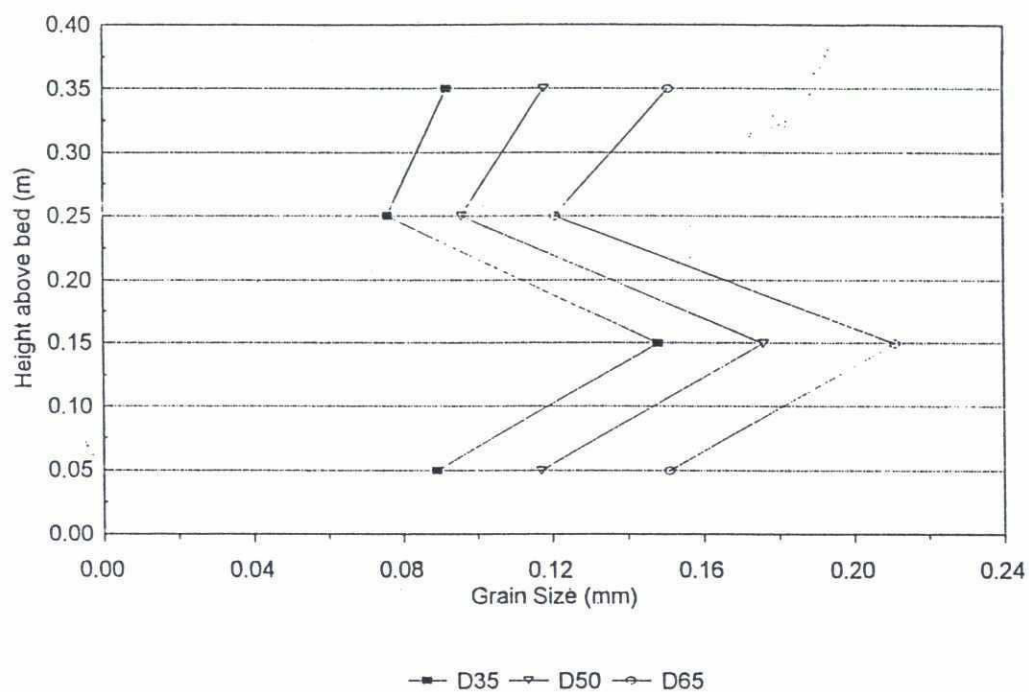


Figure G8.24 Suspended coarse sediment concentration verticals in LD and LE

Jamuna River, Bahadurabad, Vertical RA

27.07.95, Time : 15:56-16:12



Jamuna River, Bahadurabad, Vertical RA

27.07.95, Time : 16:17-16:30

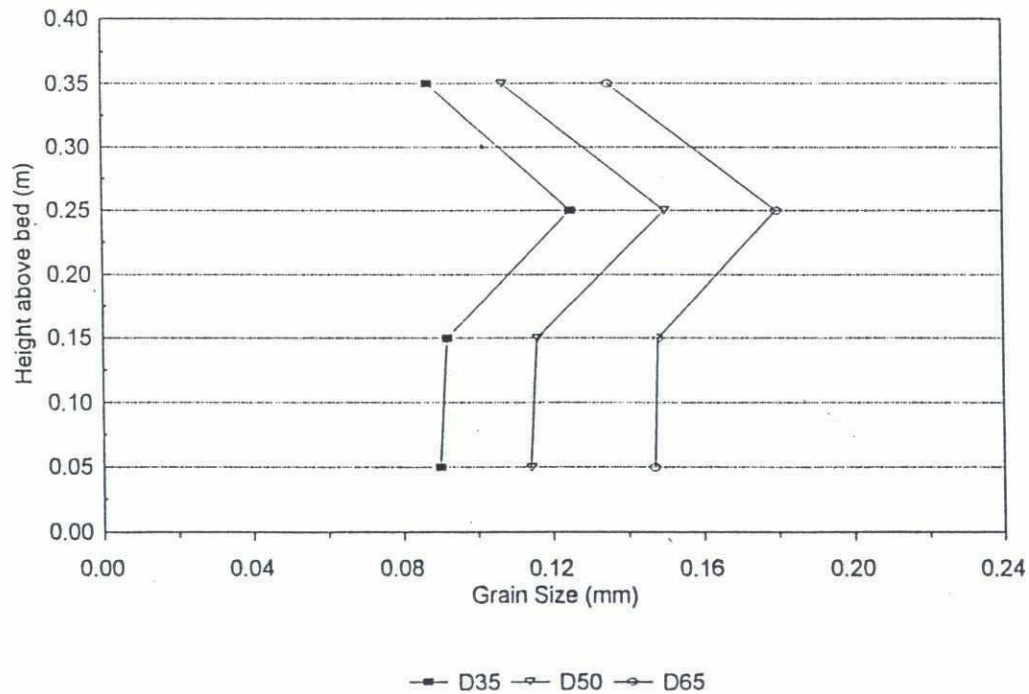
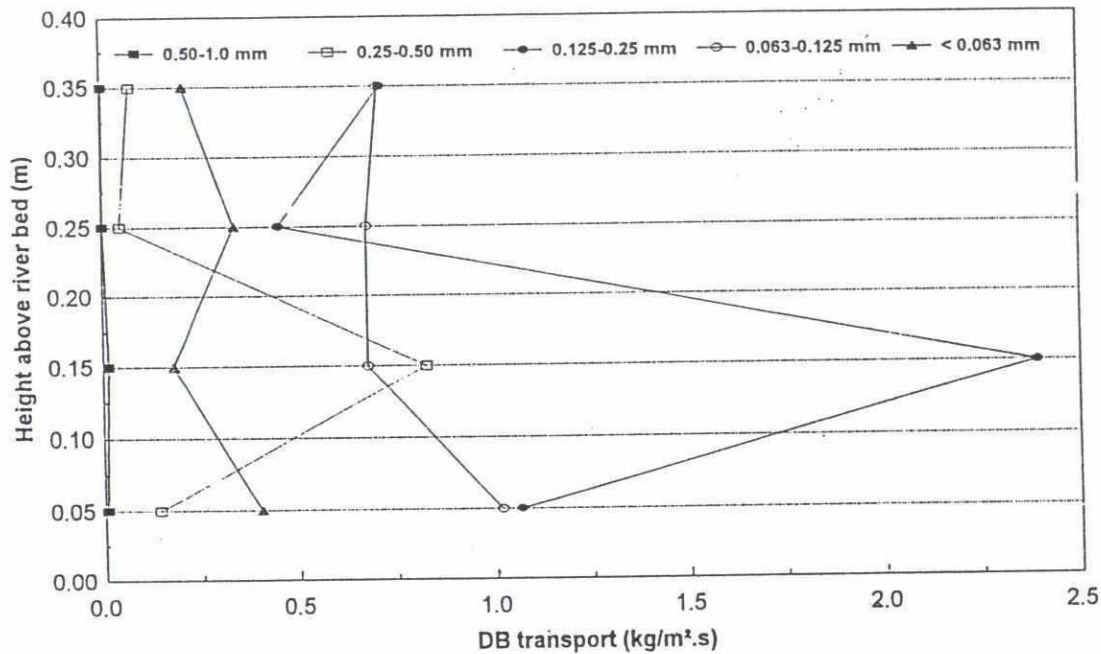


Figure G8.25 Grain size distribution near bed in vertical RA

Jamuna River, Bahadurabad, Vertical RA
27.07.95, Time : 15:56-16:12



Jamuna River, Bahadurabad, Vertical RA
27.07.95, Time : 16:17-16:30

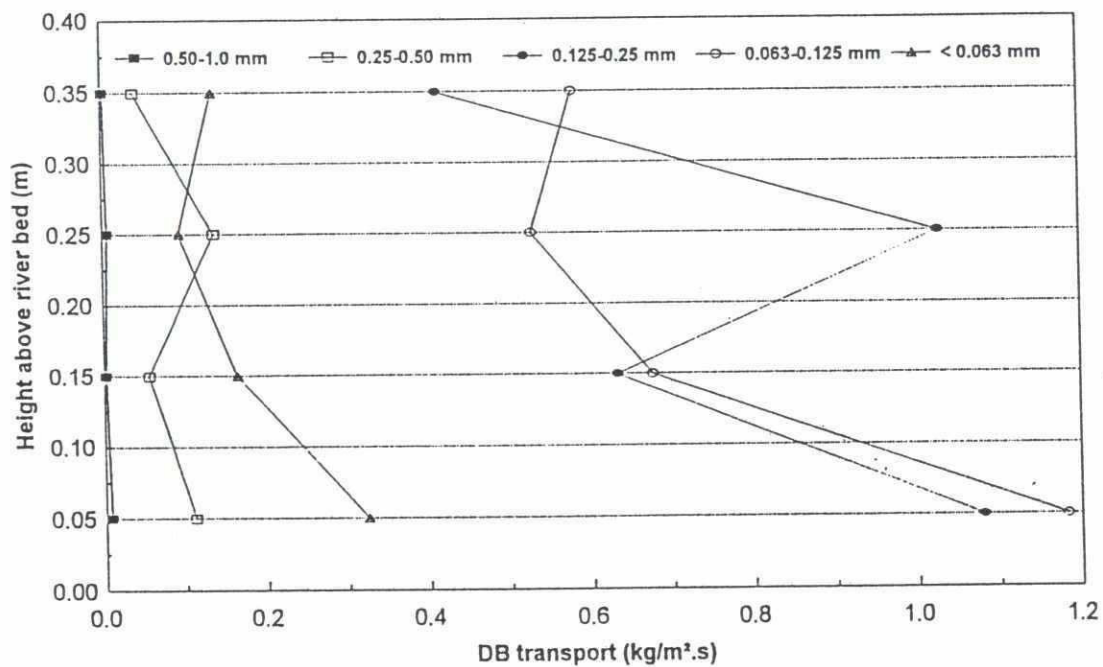


Figure G8.26 Near bed transport in vertical RA

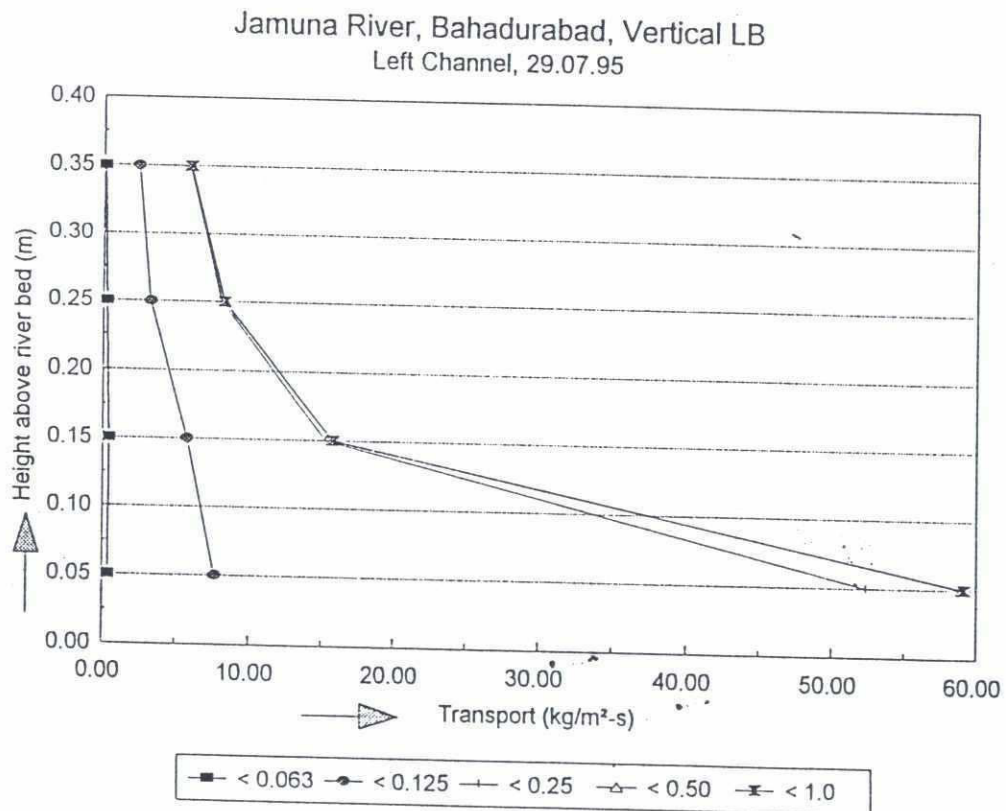
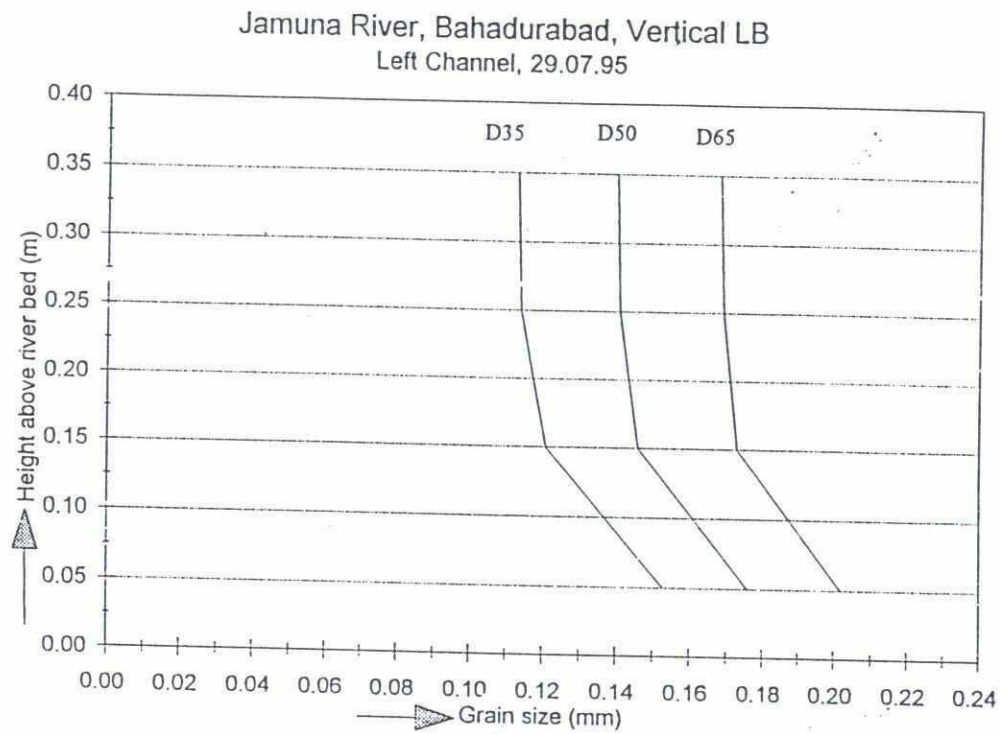
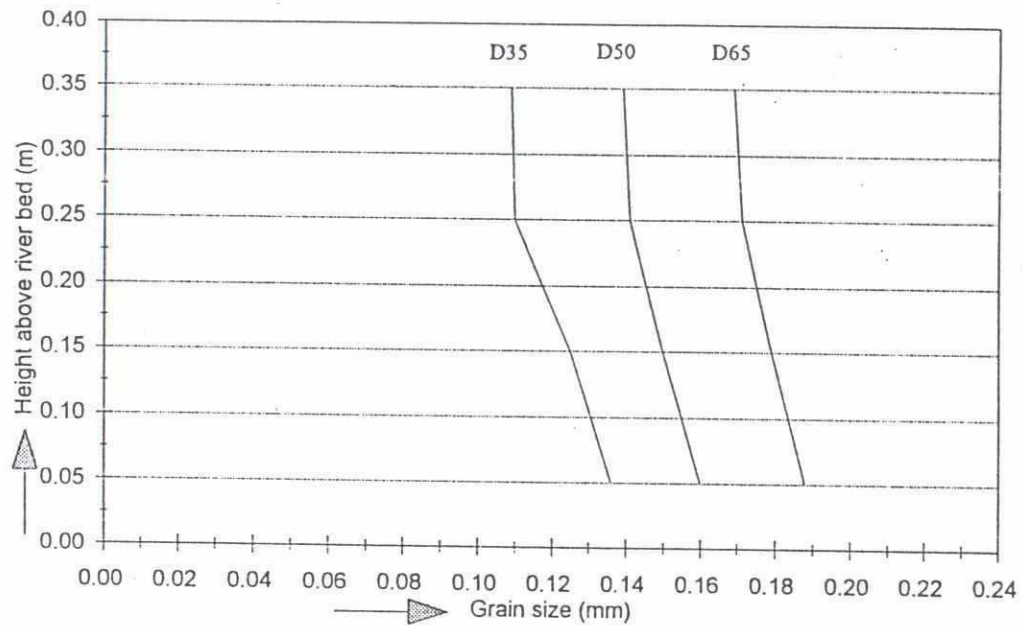


Figure G8.27 Near bed grain sizes and transport in vertical LB

Jamuna River, Bahadurabad, Vertical LC
Left Channel, 29.07.95



Jamuna River, Bahadurabad, Vertical LC
Left Channel, 29.07.95

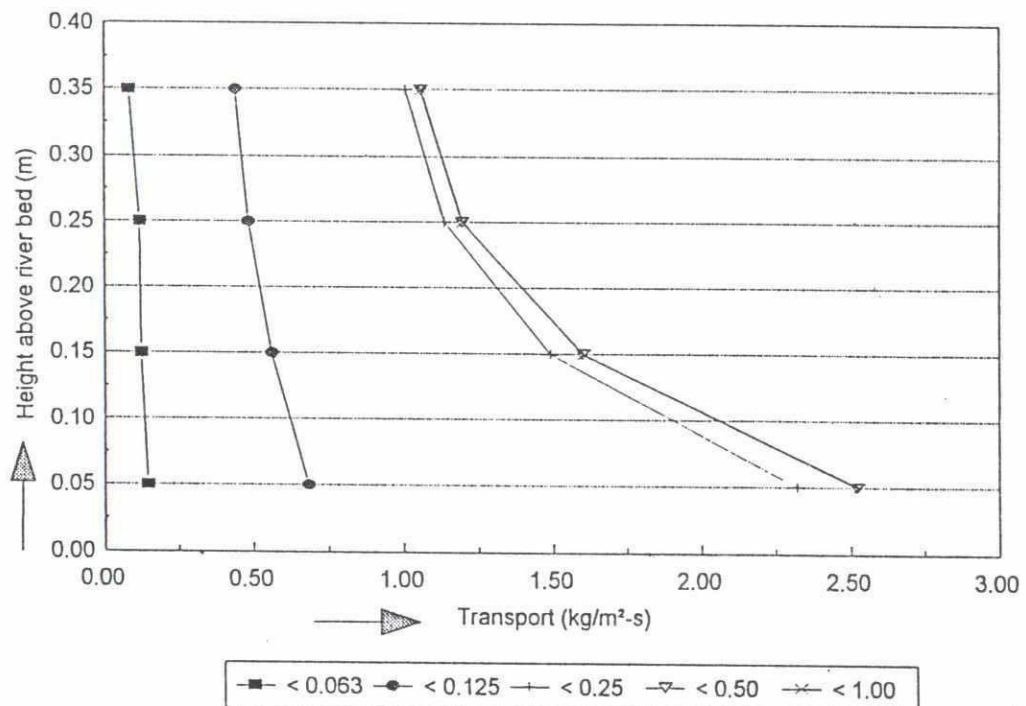


Figure G8.28 Near bed grain sizes and transport in vertical LC

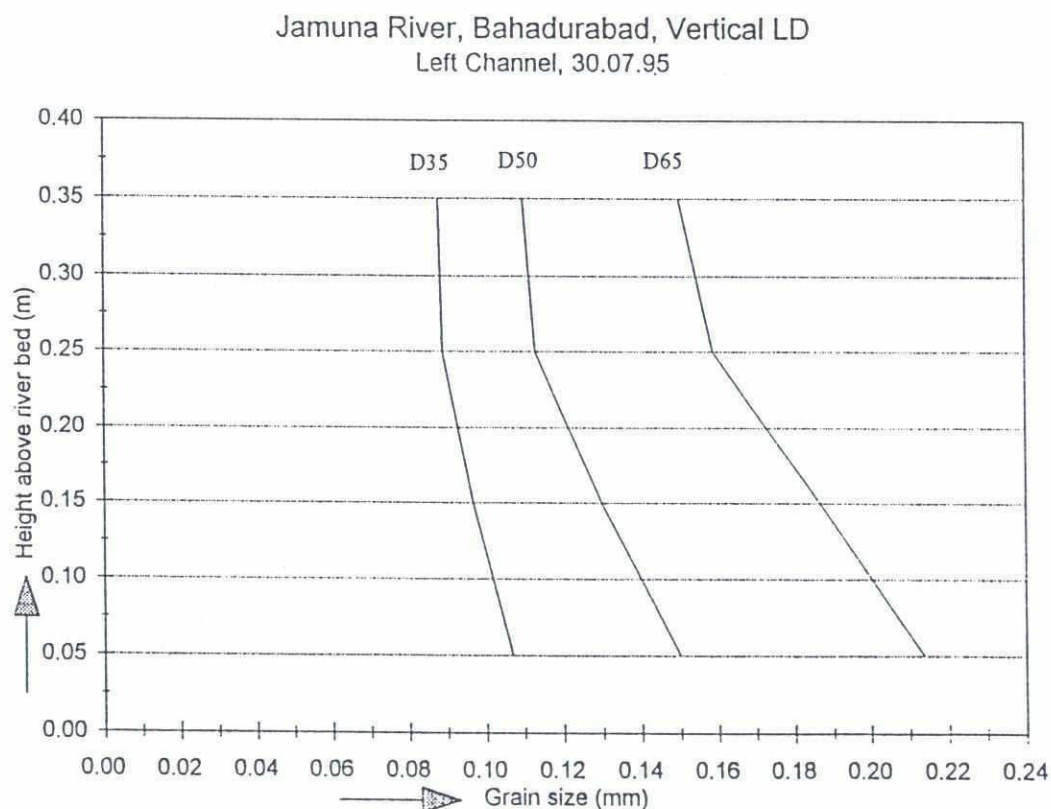
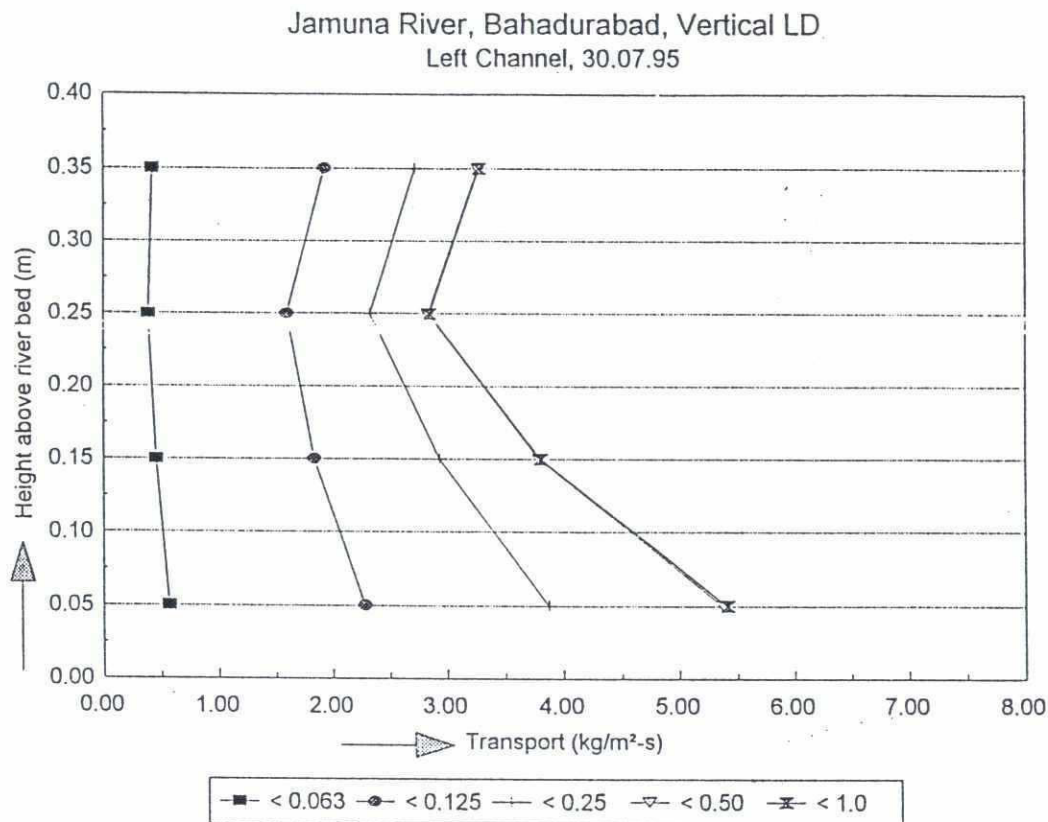


Figure G8.29 Near bed grain sizes and transport in vertical LD

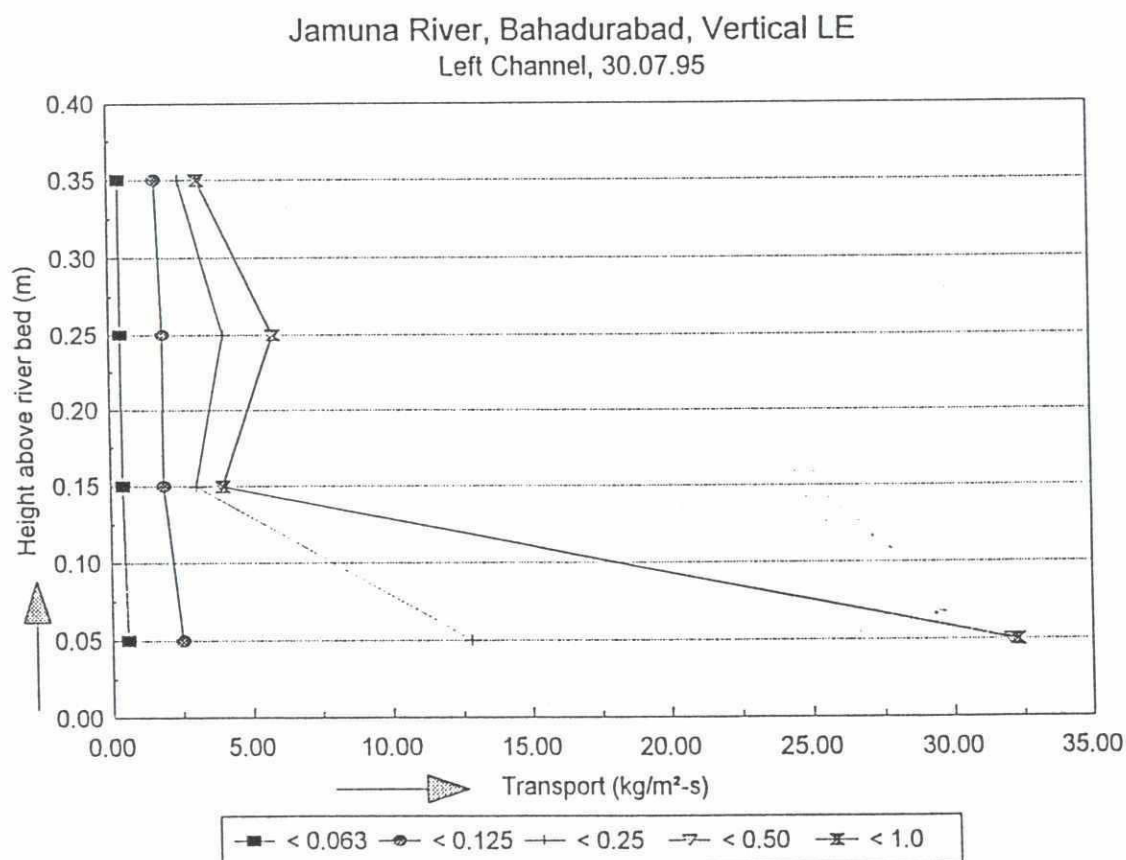
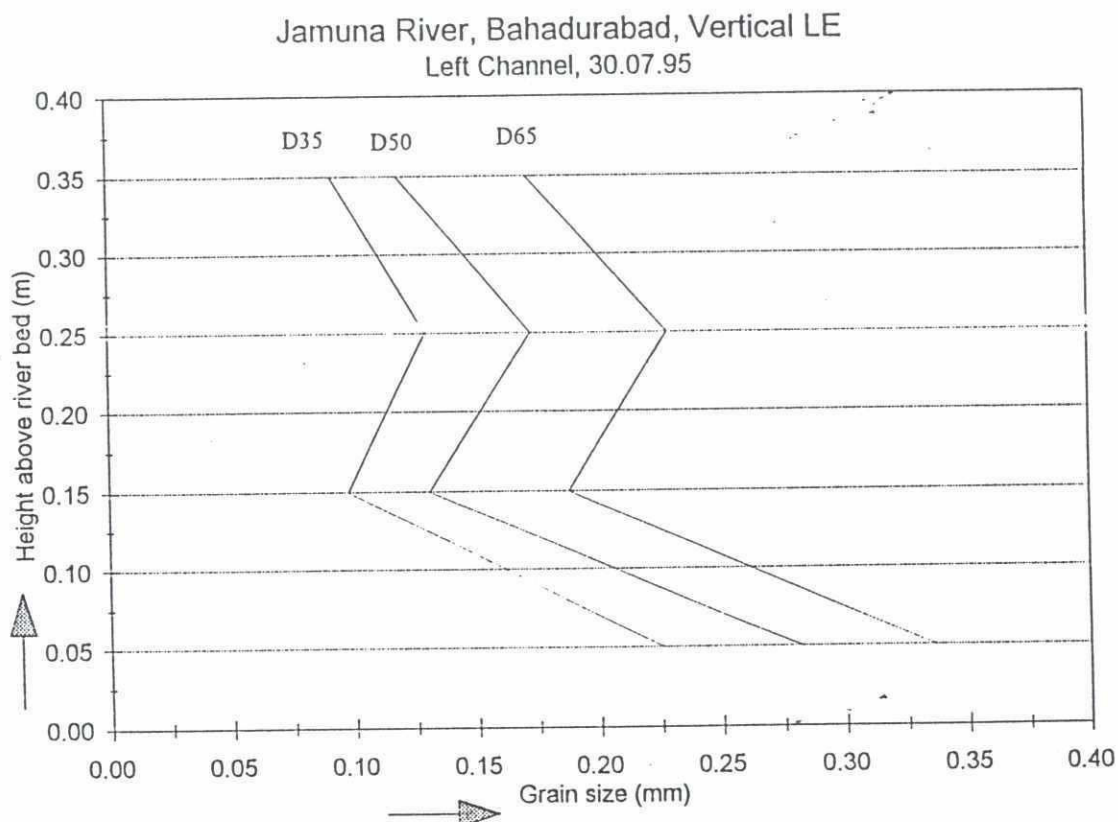


Figure G8.30 Near bed grain sizes and transport in vertical LE

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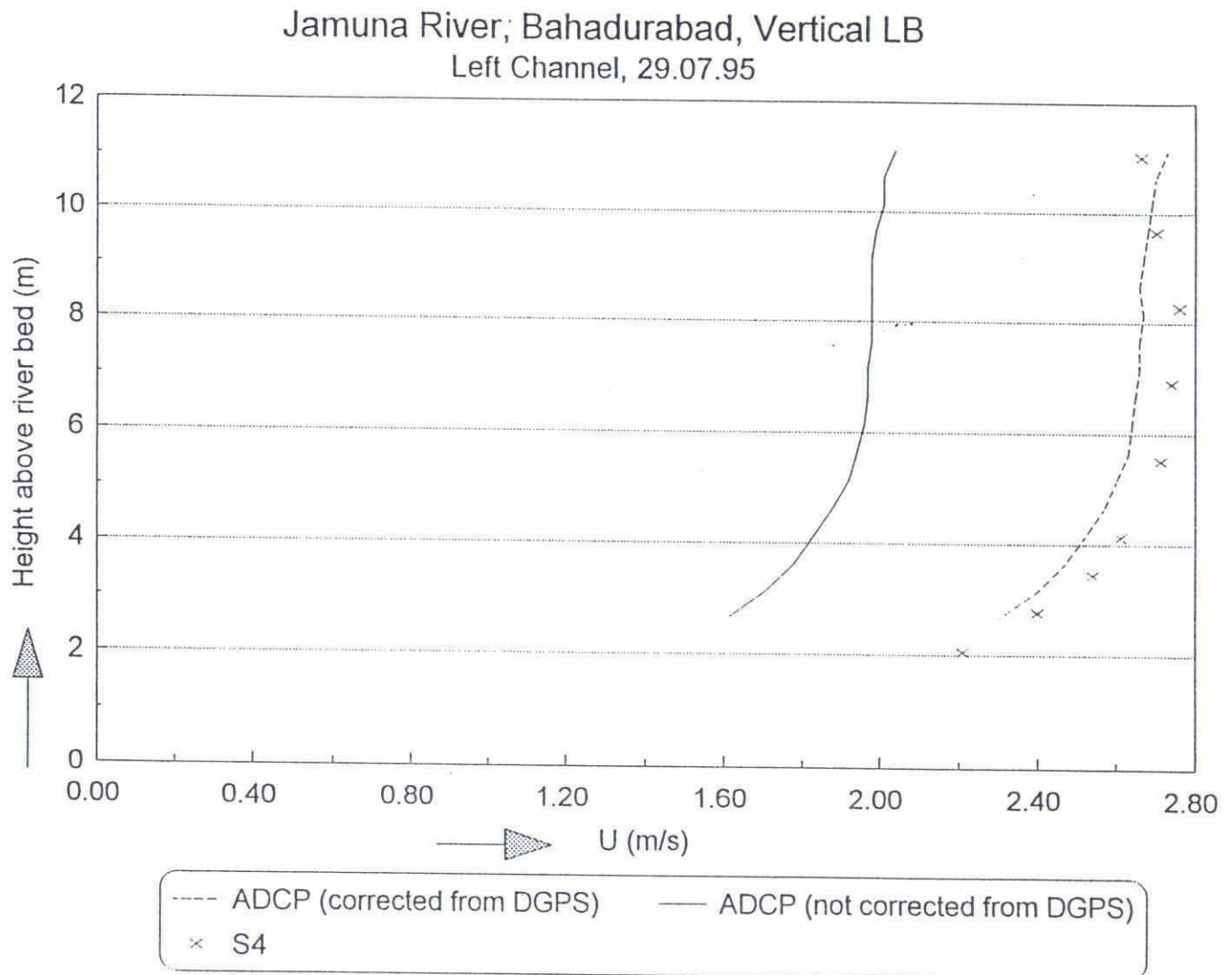


Figure G8.31 ADCP velocity shift due to mobile river bed

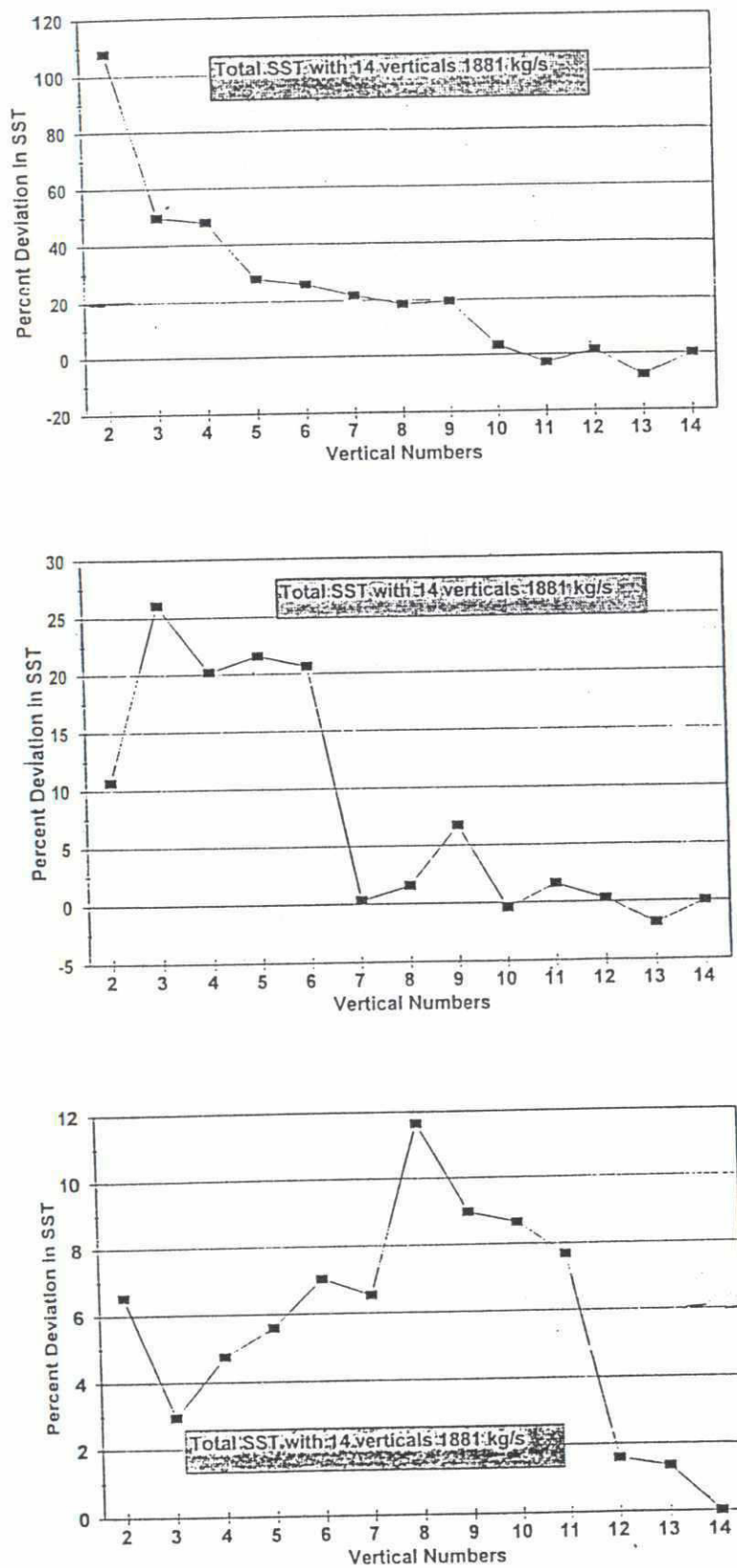


Figure G8.32 Accuracy vs number and spacing of measuring verticals in transect T1

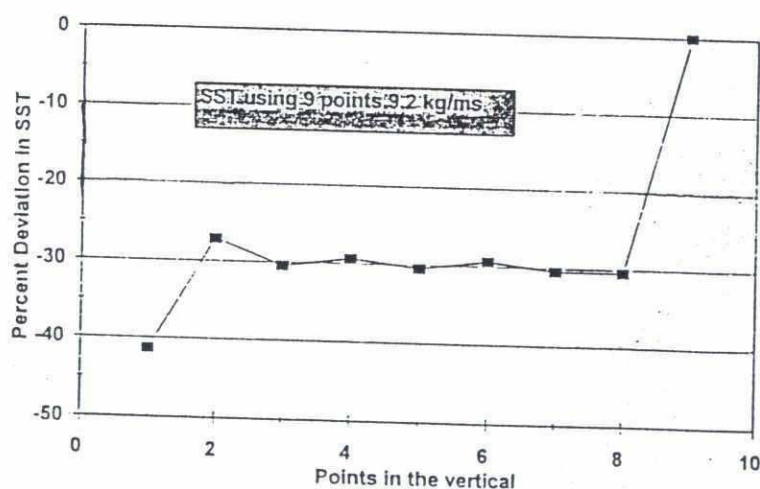
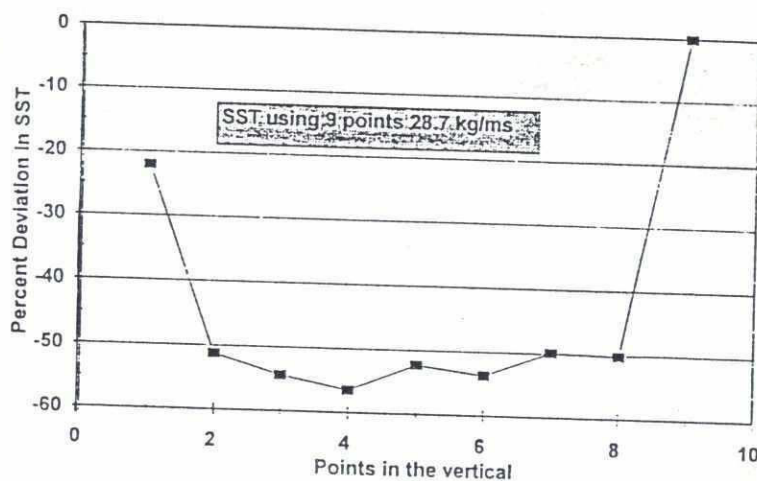
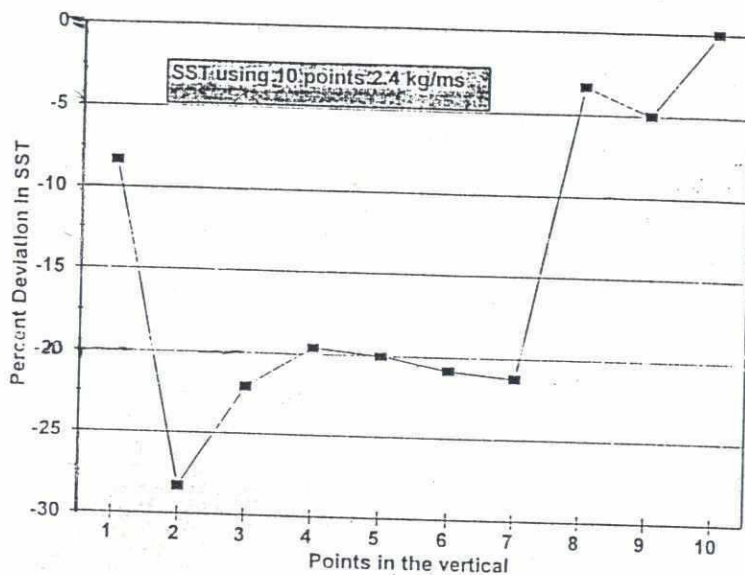


Figure G8.33 Accuracy vs number of measuring points in the vertical

