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RIVER SURVEY PROJECT



Final Report

Main Volume

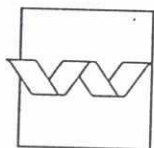
November 1996

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Acronyms and abbreviations

ADCP	:	acoustic Doppler current-profiler
AWLR	:	automatic water-level recorder
BIWTA	:	Bangladesh Inland Water Transport Authority
BoQ	:	Bill of Quantities
BTM	:	Bangladesh Transverse Mercator (a geodetic grid)
BWDB	:	Bangladesh Water Development Board
CEC	:	Commission of the European Communities (presently the EC)
DGPS	:	Differential Global Positioning System
DHA, DIIB etc.	:	(names of FAP24 survey vessels)
EC	:	the European Commission (formerly the CEC)
EG&G	:	(name of an instrument manufacturer)
EGIS	:	Environmental and GIS Support Project for Water Sector Planning (formerly FAP19)
EMF	:	electromagnetic flow meter
FAP	:	Flood Action Plan
FAP24	:	FAP project no. 24 (= The River Survey Project)
FINMAP	:	(a Finnish survey company)
FPCO	:	Flood Plan Coordination Organisation
FFWC	:	Flood Forecasting and Warning Centre (of BWDB)
GIS	:	geographic information system
GPS	:	Global Positioning System
JICA	:	Japan International Cooperation Agency
JMBP	:	Jamuna Multi-Purpose Bridge Project
LAN	:	Local Area Network
MEX	:	(brand name of a turbidity meter)
O&M	:	operation and maintenance
PA	:	Project Advisor
PSD24	:	(= <u>P</u> rocessed <u>S</u> urvey <u>D</u> ata of FAP24) (name of a data base)
PWD	:	Public Works Department (and name of a reference level)
RSP	:	River Survey Project (= FAP24)
RTK	:	real-time kinetic (positioning)
SLW	:	Standard Low Water (a reference level)
SoB	:	Survey of Bangladesh
SWMC	:	Surface Water Modelling Centre
S4	:	(brand name of an electromagnetic current-meter)
ToR	:	Terms of Reference (of FAP24)
UoL	:	University of Leeds
UTM	:	Universe Transverse Mercator (a geodetic grid)
USBM-54	:	(type and brand name of a bed sediment sampler)
VHF	:	very high frequency (radio wave length band)
WARPO	:	Water Resources Planning Organization
WGS84	:	World Geodetic System (a geodetic grid used with GPS)
XRD	:	X-ray determination (of sediment mineralogy)



Preface

The River Survey Project (RSP, or FAP24) was initiated on June 9, 1992, and completed four years later. The Project was executed by the Flood Plan Coordination Organisation (FPCO) under the Bangladesh Ministry of Irrigation, Water Development and Flood Protection, presently the Ministry of Water Resources. By the end of 1995, the FPCO merged with the Water Resources Planning Organization (WARPO) under the same Ministry, at which time WARPO took over the project execution. Funding was granted by the European Commission (formerly the Commission of the European Communities). The Consultant was a joint venture of DELFT HYDRAULICS and the DANISH HYDRAULIC INSTITUTE, in association with Osiris, Hydroland and Approtech.

The objectives of the Project were to *"collect reliable all season data on the hydrology and morphology of the country's main river systems, undertake special studies regarding the behaviour of the river system, provide specialised on-the-job training to Bangladesh professionals, and provide benchmarks against which to assess changes in the river morphology and hydrology"* (Terms of Reference, clause 1.3).

Accordingly, the project was structured into:

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

As a separate project component, project management was done by a River Survey Project Management Unit (RSPMU) with participation by FPCO/WARPO, a Project Advisor, and a Resident Project Advisor.

This Final Report comes in three parts.

- Part A, *Setting the scene*, outlines the context of the RSP, the physical environment of the Project, and the river data collected in the past.
- Part B, *Project activities*, describes the proceedings and the results of the Project, and
- Part C, *Recommendations for further action*, gives a summary of the experience gained and suggestions on the implementation and further development of this experience within the national river planning and management of Bangladesh.

Added to this report are a Glossary of Terms, and four Appendices:

- Appendix A gives an Overview of Survey Bulletins and Data Books;
- Appendix B gives an overview of the Special Reports that have also been issued by the RSP;
- Appendix C gives a PSD24 Overview;
- Appendix D focuses on future studies on survey techniques and river behaviour.

The Annexes to this Final Report come in five volumes, covering:

- 1 Surveys,
- 2 Survey techniques,
- 3 Hydrology,
- 4 Sediment transport, and
- 5 River morphology.

For a more detailed presentation and discussion of specific subjects within the scope of the Project, we refer to the series of *RSP Special Reports*, which describe a range of various survey and study activities. Summaries of these Special Reports are attached as Appendix B of this final report.

Executive summary

Activities carried out

For four years (1992-1996) the River Survey Project (RSP), also known as FAP24, was in operation. This project surveyed and studied the main rivers of Bangladesh comprising the Brahmaputra Jamuna, Ganges, Meghna and Padma Rivers and their distributaries. The objectives of the RSP, as defined in the *Terms of Reference* and summarized here, were:

- to collect reliable all-season data and to do special surveys, introducing new and improved technology where appropriate;
- to undertake special studies of the behaviour of the river system;
- to strengthen BWDB and others via on-the-job-training in surveys and studies.

The aim of the project was to provide benchmark data and to assist other FAP-projects.

During four years 252 routine measurements, 99 special surveys and 38 bathymetric surveys of substantial parts of the rivers (including a braided reach, a confluence and one offtake), were carried out. Joint measurements were carried out with the BWDB to compare measuring techniques. Several new measuring techniques were introduced and tested. Survey Bulletins were prepared on the basis of these measurements and surveys. Two data books were produced, each consisting of a number of volumes. A data base, called PSD24, was developed in which all the processed surveys were stored. Many studies were done on the basis of survey results and data collected in the past, and their results are presented in 27 reports, three being study reports issued during the project and, at the end of the project 24 Special Reports summarizing all survey and study issues. During these studies many data collected in the past were validated and also entered into data bases. Also the sustainability of the various measuring techniques was evaluated. A final report was prepared, consisting of this main volume and five annexes.

What was achieved?

A team of local surveyors and crews were trained in carrying out surveys with a high level of precision. A team of local experts of high quality was formed, both for doing data processing and for doing studies. This staff was recruited through a local consultant and they were trained in doing surveys and studies, with much effort from the international consultant via internal courses, such as sending them abroad for further education and on the job-training. Staff at SWMC were trained in two-dimensional river modelling.

In eleven stations along the main rivers, discharges and sediment transport data and bed material samples were collected on a regular basis, some in joint action with the BWDB. In view of the good quality of these data, they are considered to be bench-mark data. They were used for validation of BWDB data collected in the past. This will provide future users of BWDB and RSP data sufficient insight into the data quality of the vast and impressive sets of data collected by BWDB over the past decades. The RSP data are available in a special data base (PSD24). This data base is available for further detail studies.

Many different measuring techniques – for hydraulic measurement, sediment transport and bathymetric surveys – were used to study their appropriateness for the conditions in the main rivers in Bangladesh. These conditions are not easy: very wide rivers, extreme rapid changes and a hot and humid climate. Data collection, their storage, processing and presentation were completely computerized; the use of GIS for data presentation was explored. Recommendations for sustainable data collection in Bangladesh were formulated.

At seven selected reaches detailed bathymetric surveys were done repeatedly (between three and eight times at each location). This provided a unique data set, which was entered into a GIS by FAP19/EGIS and subsequently studied intensively, deriving from it exciting new ideas about the behaviour of major alluvial rivers. Prediction techniques were developed and tested, allowing for better prediction of short-term changes in these rivers. Also medium-term predictions of planform changes were addressed via the study of morphological processes determining the partly deterministic and partly chaotic behaviour of such systems. The RSP data have already been applied in a number of studies by DHI and SWMC.

In addition to studies on measuring techniques a number of special studies were carried out, aiming at an improved understanding of the behaviour of these large alluvial rivers. Some of these studies were done in association with some Universities. The studies covered a wide range of topics. The relevance of the topics is shown by listing the most important ones in relation to their most direct use:

- 1 *Design levels of levees*
extrapolation of rating curves; overall and local slopes; water balances; backwater effect on rating curves; bedform dimensions and their dynamics; resistance to flow;
- 2 *Design bank protection works*
mineralogy of the bed material; regime and at-a-station-relations; scour: types, predictors, combinations;
- 3 *Prediction bank erosion & need for bank protection*
bank erosion: rates, predictability; flow around bars and bar dynamics; cut-offs: when, how, how quick; bifurcations; confluences; planform development: hind-casting, forecasting;
- 4 *Water supply via distributaries*
changes over time of offtakes; modelling of offtake changes;
- 5 *Long-term river training*
sediment rating curves and sediment balances; geological controls on the main rivers;
- 6 *Modelling of river behaviour*
systematic bed sampling and the role of fine sediments in bed building; appropriate sediment predictors; sediment transport patterns (sediment plumes, sorting, near-bed sediment transport, tidal conditions); exchange of sediment: bed material and fine sediments;
- 7 *Impact assessment on river morphology*
floodplain sedimentation in relation to subsidence in Bangladesh; morphological impact assessment of implementation of proposed FAP measures.

Many of the results obtained are important steps forward towards a better understanding of the behaviour of the major alluvial rivers in Bangladesh.

What was not achieved?

The River Survey Project has closed down after these four years of intensive activities. Although many outstanding results were obtained, the Project lacked in institutional embedding. This was completely due to the initially designed (ref. ToR) institutional setting of the project: no counterpart organisation was appointed. Exchange of knowledge and experience with BWDB, BIWTA and other organizations, was only marginal. Although proposals for training of BWDB personnel were made several times, this never materialized for several reasons.

The local staff of the project (crews, surveyors, study experts) have dispersed, and will probably enter into new fields where their specific expertise may not be needed and hence not maintained. As a consequence, the very much increased understanding of the behaviour of large alluvial rivers remains with individuals but has found little anchorage in Bangladesh within the various institutions in Bangladesh.

How to continue in the future?

Based on the surveys carried out in this report a number of measures are proposed for implementation. Most important is that, in addition to strengthening the in-country data collection, a study unit should be established inside Bangladesh, where the experience on and the improved understanding of the behaviour of the large alluvial rivers is collected, maintained and extended. Linked to this study unit there should be a special survey unit using modern equipment.

Other recommended measures are related to implementing improved measuring techniques and arrive at better quality control. Very important is also the use of DGPS for routine surveys as well. Another recommendation is to encourage the preparation in due course, of data bases with the aim of achieving a national "water" data base into which all water-related information is stored. Finally, a number of institutional issues are listed, which should be addressed to remove the in-country limitations so as to improve the understanding of the behaviour of the large rivers which, after all, are not only a curse but also a blessing to the nation of Bangladesh.

Harvesting the benefits from Bangladesh's location in the delta of these three rivers is only possible to their full extent, if a better understanding of their behaviour is obtained.

Measures for implementation	Recommended action	Type of Action	Actors/Agencies	Time frame and frequency
Measures re measuring platforms and techniques	Improvements measuring vessels	Project	BWDBHydr	Ongoing and if the need arises
	Improved positioning: introduction DGPS and training	Project	BWDBHydr/Morph	Ongoing
	Other (minor) improvements in hydraulic and sediment transport measurements	Project?	BWDBHydr	Once (shortly)
	Improved cross-sectional measurements	Instruction	BWDBMorph	Once (shortly)
	Introduction ADCP and other advanced equipment and training in the use	Project	SSU (see below)	Together with establishment SSU
	Improved quality control	Instructions	BWDBHydr/Morph/SWMC/EGIS	Once (immediately)
Measures re data storage and presentation	Extension of data bases	Project?	BWDBHydr/Morph	Immediately and continuous
	Publishing of data books	Project?	BWDBHydr/Morph?	Within five years and continuous
Institutional measures	Regular review of measuring activities	Policy/Project	BWDB Hydr/Morph/BIWTA/others	Every five years
	Institutional measures for quality control	Policy/Project	BWDBHydr/Morph	Once (in three years) and continuous
	Improved maintenance	Project	BWDB Hydrology (assistance BUET?)	Once (workshop) later SSU linked
	Establishment Study Group Large Rivers (SGLR)	Project (combined with FAP27-MIA?)	To be decided: BWDBHydr/Morph/SWMC/WARPO)	Once (within three years)
	Set-up Special Survey Unit (SSU)	Project	BWDBHydr/SWMC	Once (within three years)
	National storage of "water" (river/coast) databases	Project	To be decided: BWDBHydr/Morph/RRI/WARPO)/SWMC/EGIS	Once (immediately)

Proposed actions for implementation (for more detail see Table 12.1)

Acknowledgements

The external support extended to the River Survey Project has been decisive for the achievement. The Project received a substantial administrative and professional backing from many government agencies. The Ministry of Water Resources contributed effectively to a smooth execution, and various organisations under the Ministry, such as BWDB, FPCO/WARPO, JRC, SWMC, and RRI extended their full cooperation. The general support of the BWDB Hydrology Division headed by the Chief Engineer, together with its directorates, Surface Water Hydrology Directorates I and II, and Morphology and Research Directorate, was invaluable. Also, these organisations have kindly supplied comprehensive data sets, study reports and information. The UNDP-Bangladesh Water Resources Information System Project (WRIS) advised on survey planning, data processing and validation procedures. The BWDB, Survey and Study Division, made its survey vessel "*Anwesha*" available in the initial phase of the Project. Apart from supplying data to the project, the SWMC participated actively in the hydrodynamic and morphological modelling activities. The Hydrography Directorate of BIWTA and the Jamuna Multi-purpose Bridge Authority provided valuable professional support.

Professor Jahir Uddin Chowdhury, Institute of Flood Control and Drainage Research (IFCDR), BUET, rendered general professional advice on many matters and participated actively in the execution and reporting of the study component; professor A. Nishat, Department of Water Resources Engineering, BUET, advised on both technical and institutional matters; professor Md. Badrul Imam and dr. Syed Humayun Akhter of Geology Department, Dhaka University, performed mineralogical and physical sediment analyses in their laboratory, and assisted in many ways in connection with the analysis and reporting of sediment properties; mr. Kurshid Alam, Director, Geological Survey of Bangladesh, supplied geological information and lectured on 'Geological Controls' at the RSP in November, 1995; and dr. Mahbub Ahmed, Soil Science Department of Dhaka University, executed sediment density analyses in his laboratory.

A close collaboration was maintained with other project organisations within and beyond the Flood Action Plan, comprising exchange of data and other information, and miscellaneous professional support. Particularly close liaisons were maintained with FAP19/EGIS and SWMC. FAP19/EGIS assisted with image processing, and collaborated actively with the RSP within morphological studies. SWMC assisted in carrying out the two-dimensional morphological modelling of the Gorai Offtake and also in one-dimensional morphological modelling.

The Royal Dutch Embassy kindly lent a survey vessel (identified as DHF) to the project for a period of three years.

The Consultant highly appreciates the effective and constructive project management by FPCO/WARPO, and the continuous kind assistance by mr. H.M. Siddiqi, Director General, and Afzalur Rahman, Principal Scientific Officer. Also, FPCO/WARPO supplied SPOT images for the morphological studies. The Resident Project Advisor, mr. Jürgen Heise, maintained effective liaison, was helpful in all matters, and advised on data validation and presentation procedures. The Technical and Administrative Support Capacity (TASC) of the European Commission helped with sorting out the various administrative implications that arose in the course of the project.

Particularly, the Project acknowledges whole-heartedly the advice and guidance by the Project Advisor, professor J.J. Peters, who participated with enthusiasm and full commitment throughout the project, and who extended a comprehensive and highly valued support in connection with the detailed planning and execution of both surveys and studies. He was most effective in solving contractual and other administrative matters and, through this, contributed substantially to the smooth progress of the project. Also, professor Peters has kindly reviewed in detail draft versions of all RSP reports and provided valuable suggestions for improvement.

Part A

Setting the scene



1 Introduction

1.1 Background of the project

The background of the River Survey Project (RSP) is described in Chapter 1 of the ToR (Terms of Reference), from which the following extracts are quoted:

- *"The disastrous 1987 floods in Bangladesh raised considerable international interest in helping the country to find a long term solution to its flood problem. A number of studies were undertaken and, in June 1989, the Government of Bangladesh requested the World Bank to coordinate the preparation of a five-year Action Plan for Flood Control in Bangladesh. The role of the Bank in coordinating international efforts to assist Bangladesh in flood control was endorsed in the Communique of the G7 economic summit meeting held in Paris in July 1989. The Action Plan was discussed and endorsed by a meeting of donors held in London in December, 1989.*
- *The Action Plan consists of project-oriented studies in all the country's main regions, supporting activities to promote improved project design and execution, and execution, of non-structural measures. For each plan component, one or more donors have expressed interest in financing first phase activities, comprising surveys, studies or pilot projects. The various actions are to be implemented by these donors in close cooperation with the Government of Bangladesh and under the co-ordination of the World Bank, as described in the Action Plan. The Government of Bangladesh has established the Flood Plan Co-ordination Organization (presently the Water Resources Planning Organization) to co-ordinate Action Plan projects in Bangladesh.*
- *The River Survey [Project] is one of the supporting activities. ... Although hydrological, morphological and hydrographic data are routinely collected by concerned Bangladeshi organizations (the Bangladesh Water Development Board, BWDB, and also the Bangladesh Inland Water Transport Authority, BIWTA); the limitations of existing boats and survey equipment mean that some essential data needed for the planning of Action Plan projects are either insufficiently accurate or are not collected. The River Survey [Project] would carry out necessary surveys using modern equipment and technology, and provide specialised training in river survey techniques to Government staff. ...*
- *The Project would be carried out over four years in two phases: Phase 1, Preliminary Phase ... and Phase 2, Survey and Study Phase".*

The River Survey Project was funded by the European Commission and executed by the Flood Plan Co-ordination Organization (presently WARPO) as Contracting Authority.

1.2 Scope of the project

According to the ToR, the RSP was structured into different components as follows:

- *'Hydrological and morphological data collection This part of the project will involve river surveys, stage, discharge and sediment measurements etc., using modern equipment ...'*
- *'River behaviour studies ... to investigate key characteristics of behaviour of the river systems. The river studies will address aspects of the main river systems which will not be covered under the various regional studies. The studies will use the data from the river surveys, existing data and some supplementary surveys. ...'*
- *'Training. Specialised on-the-job training in river survey techniques and related areas would be provided to staff of the concerned government agencies (BWDB, BIWTA) as well as to staff of engaged local consultants. This would mostly take the form of on-the-job training in the use of modern equipment and technology. ...'*

A separate project component was the project management, which was undertaken by FPCO/WARPO. To assist in the management and project supervision, a Project Advisor (PA) was appointed, who had the additional scope of advising the Client on institutional development matters, and to co-ordinate in organizing an international workshop on *'Morphological characteristics of alluvial rivers and their behaviour with special reference to Bangladesh rivers'*. This workshop took place in Dhaka, November 6-9, 1993.

The Project began on June 9, 1992, and was completed after four years. Due to a late project start relative to the 1992 flood season, Phase 1 was extended until the end of 1993, enabling the required field performance tests of survey techniques to take place in the 1993 flood season. Phase 2 covered the period from the beginning of 1994 until the end of the Project.

1.3 Liaison with the Client

The Project was executed in a close and fruitful dialogue between the Client and the Consultant.

The River Survey Project Management Unit (RSPMU) was established for the purpose of facilitating the management of the Project, with the objective to advise WARPO on professional and administrative matters, and in order to facilitate the collaboration and support the exchange of information between the Client and the Consultant. The RSPMU was a management team formed by a principle Scientific Officer of WARPO, Mr. Afzalur Rahman, a Project Advisor (PA), Professor J.J.Peters, and a Resident Project Advisor, mr. Jürgen Heise. The RSPMU had its own office in Dhaka.

In the course of the Project, the PA paid quarterly visits to Dhaka. His evaluations, valuable suggestions and recommendations to WARPO were communicated continuously and were compiled in a series of *'PA Mission Reports'*. The role of RSPMU, and particularly of the PA, in the successful completion of the Project was essential. Numerous valuable technical recommendations, comments and suggestions were received, while RSPMU greatly facilitated the smooth handling of administration, contracted and financial matters.

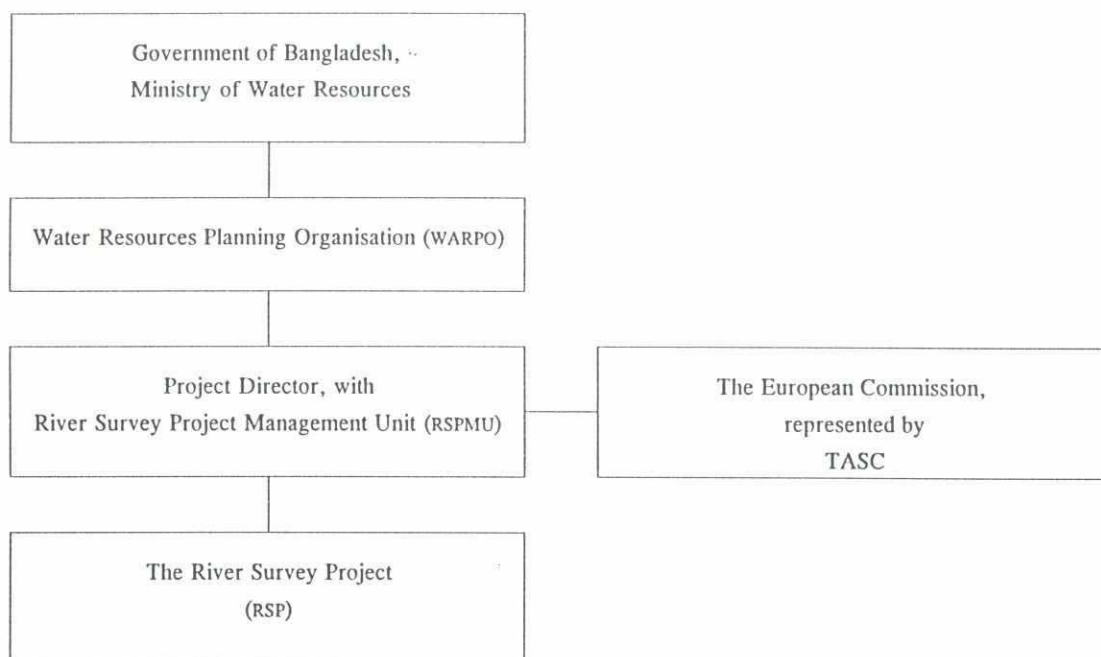


Figure 1.1: The organisational framework of RSP

The Client was formally informed about the progress through the Consultant's Quarterly Progress Reports, and by the general project progress reporting, which comprised an Inception Report, a Phase 1 Interim Report, a Phase 1 Final Report, two Phase 2 Interim Reports, and the present Final Report.

Day-to-day liaison between the Client and the Consultant took place via RSPMU and was maintained by regular formal and informal correspondence and meetings.

1.4 Organisation of the project

1.4.1 Project organisation

The Project was executed by a team of full-time and part-time professional specialists and support staff from Bangladesh and abroad. The RSP project organisation is shown in Figure 1.2.

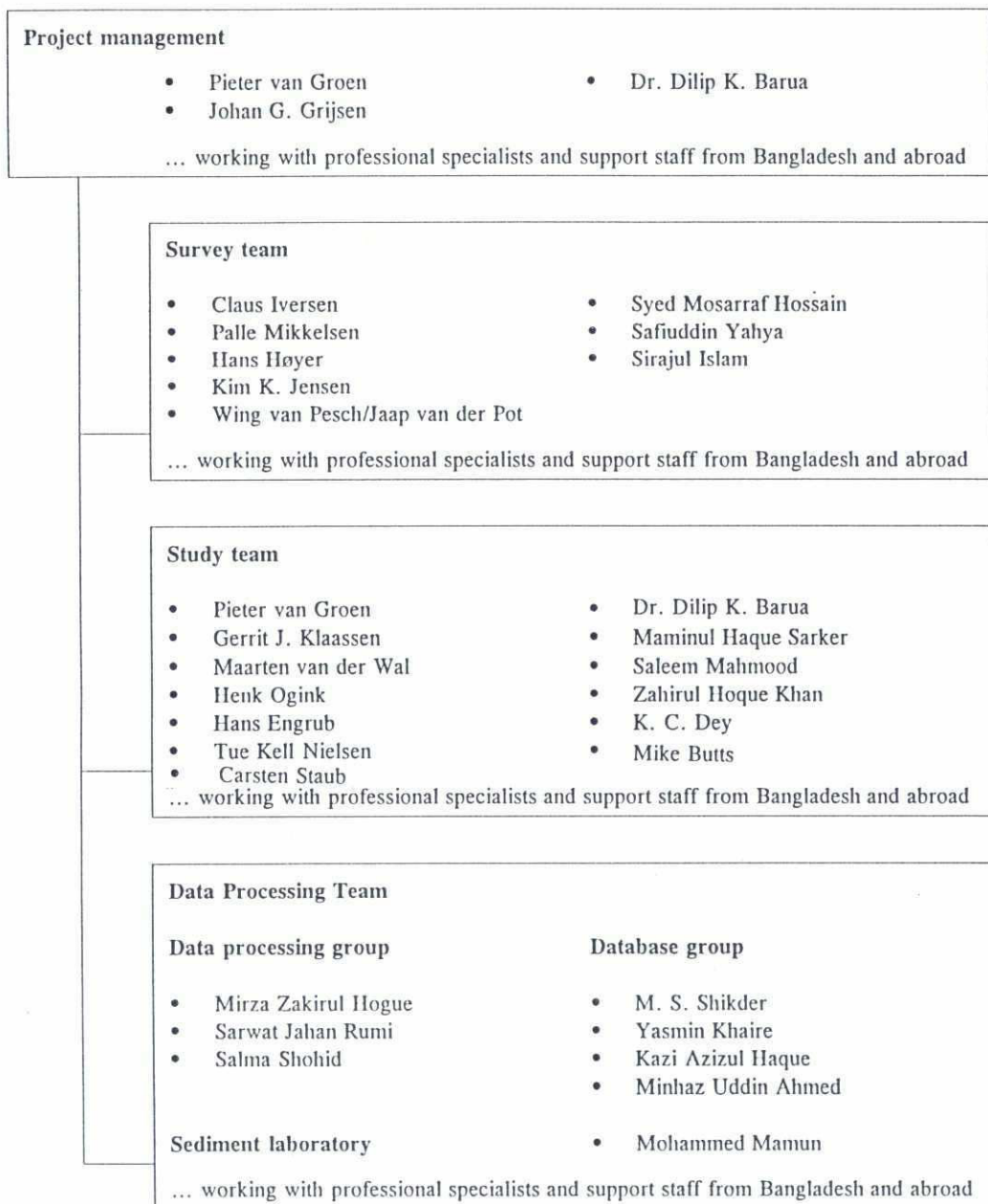


Figure 1.2 The RSP project organisation

1.4.2 External liaison

Several activities within both the survey and the study component of the Project were executed in active collaboration with external institutions or project organisations in Bangladesh and abroad.

The Institute of Flood Control and Drainage Research, BUET, participated in the hydrological study that is described in *RSP Special Report 4: 'Stage-discharge relationship for the Jamuna at Bahadurabad'*. The University of Leeds (UK) participated in field surveys and carried out the study reported in *RSP Special Report 9: 'Bars and dunes in Jamuna River'*. The Geology and Soil Science Department, Dhaka University, participated in the study of sediment mineralogy described in *RSP Special Report 14: 'Mineralogical and physical properties of river sediments'*; Surface Water Modelling Centre (SWMC) collaborated on hydrodynamic and morphological modelling as reported in *RSP Special Report 10: 'Morphology of Gorai Off-take'*. The University of Nottingham (UK) undertook the studies that are reported in *RSP Special Report 16: 'Study of secondary currents and morphological evolution in a bifurcated channel'*; and EGIS participated in a joint study which is reported as *RSP Special Report 17: 'Spatial representation and analysis of hydraulic and morphological data'*.

Mr. Maminul Haque Sarker has prepared *RSP Special Report 24: 'Morphological developments at Bahadurabad'* as his M.Sc. thesis for submission at the Institute of Hydraulic and Environmental Engineering (IHE) Delft (The Netherlands). The Virginia Institute of Marine Sciences (USA) collaborated with RSP in connection with their field surveys and studies of floodplain geology. Programmes of joint comparative field surveys were undertaken with the BWDB, Surface Water Hydrology I, and with the BWDB, Morphology and Research Circle. These programmes are summarised in Section 6.6 of the present report and elaborated in *RSP Special Reports 19 and 20*.

1.4.3 Facilities

The Project Office was established in Banani, Dhaka, and accommodated the entire project organisation. It had a library, facilities for data processing and data base operation, reporting, a sediment laboratory, an electronic workshop, and storage facilities for consumables and spare equipment. Computers were connected by a LAN network in order to expedite data flow and exchange of other information.

The Project maintained its own guest house in the top floor of the Project Office building. Other guest houses were operated in Gaibanda (near Fulchari, on the right bank of Jamuna opposite of Bahadurabad), and in Paksey (on the left bank of Ganges, near Hardinge Bridge). A small accommodation facility was available in Bahadurabad.

The Project operated eight cars, while two cars were supplied by the Project to the RSPMU.

For the field work, the RSP mobilised five survey vessels and an additional small boat. The largest vessels were DHA (20 m), DHB (11 m) and DHC (9 m). All survey vessels had differential GPS positioning and VHF radio. The DHA and DHB were equipped with ADCP (Acoustic Doppler Current Profiler) instruments and a SAFECOM telex link with the Project Office.



Figure 1.3 The Project Office



Figure 1.4 Another view of the Project Office

2 The main rivers of Bangladesh

2.1 Introduction

The main rivers of Bangladesh comprising two major eastern Himalayan rivers, the Ganges and the Brahmaputra and a non-Himalayan river, the Meghna, together with their numerous tributaries and distributaries, form a dense network of river systems in Bangladesh. Jointly, draining to the Bay of Bengal, they represent the lowermost alluvial deltaic reach of the fluvial system with 92% of the upper reaches lying outside the territorial boundary of Bangladesh. Being located in the lowermost reach of the fluvial system, the fluvial loading and geomorphology are governed by several multivariate environmental control variables. These factors include climate, geology, basin-relief, secular variation in base level, anthropogenic factors, etc. Interactive importance of these and other factors are discussed in Barua, 1994 and RSP, 1994. The combined influence of these long time-scale variables determine the hydrological, sedimentological and morphological aspects of the rivers. In various sections of this chapter these aspects are described briefly based on information derived from different known studies. A brief overview is presented here of the most important studies on Bangladesh rivers.

During the British period the study of the large delta comprising Bangladesh, began with a large effort of mapping the rivers. This effort of documenting the river course took about 30 years, and the produced map is known as the Rennel's map (Rennel, 1781). Part of the Rennel's map was later updated between 1821 and 1834 in a survey by Wilcox (Wilcox, 1840). Apart from these mapping exercises, the 1922 flood triggered a flood problem study of North of Bengal. This study known as the Mahalanobish study (Mahalanobish, 1927) made an hydrological and flood study of the years from 1870 to 1922. The Wilcox report (Wilcox, 1930) (who appeared to be a different author than the earlier mapping investigator) made a study on the irrigation system in Bengal. After the emergence of East Pakistan in 1947, three devastating floods occurred consecutively in 1954, 1955 and 1956. This prompted the government to request the technical assistance of the United Nations which sent a mission to study the flood problem in East Pakistan. This report, published in 1957, is known as 'Krug Mission Report' and laid the foundation of forming the East Pakistan Water and the Power Development Authority (EPWAPDA). In 1959, the EPWAPDA was created by the Government and in the same year the International Engineering Company (IECO) was appointed as the general consultant. The IECO master plan was published in 1964 (IECO, 1964). Along with these efforts, the East Pakistan Inland Water Transport Authority made the first survey of the country's rivers for navigation (NEDECO, 1967). Other notable studies during this period were made by Hardin (1963), Thijsse (1964) and Leedshill-de-Liew Engineers (1968). Along with these efforts of EPWAPDA engineers and several other consulting organizations, efforts continued by individual researchers to do scientific investigations on the river morphology. Pioneering work in this regard was done by Coleman (1969) who laid the foundation of scientific investigations of river morphology in the country. It was followed by a paper on the alluvial roughness by Stevens and Simons (1973). A complete review of these and other subsequent studies are presented in RSP reports (RSP, 1993; RSP, 1994). The latest of these efforts was realized after the launching of the Master Plan Organization (MPO) and Flood Action Plan projects (World Bank, 1989) under the Water Resources Ministry. The MPO studies include (MPO-HARZA, 1987) and (SPARRSO, 1985). The notable studies, in which the river behaviour aspects were considered, include the following:

- FAP1 - River Training Studies of the Brahmaputra River (HALCROW et al., 1993a),
- FAP4 - Southwest Area Water Resources Management Project (HALCROW et al., 1993b),
- FAP9B - Meghna River Bank Protection Short-term Study (HASKONING-DELFT, 1990),
- FAP19 - Geographic Information System (ISPAN, 1993),
- FAP21/22 - Bank Protection & River Training/Active Floodplain Management Pilot Project (RRI-LR-CNR-DELFT, 1993) and,
- FAP25 - Flood Modelling and Management (KRUGER-BCEOM-DIII, 1992).

In these studies various interesting aspects of the hydro-morphological behaviour of the rivers were studied which helped in forming a better understanding of the rivers. A very important contribution to all these studies has been made by the BWDB. Hydraulic, sedimentological and morphologic databases of the Surface Water Hydrology, and Morphology and Research Directorates were used extensively during these studies. Systematized by the FAO (1969), a large database exists at the BWDB with a gap in the data in 1971.

2.2 Channel network

The channel network of the major rivers are formed by the Ganges, the Brahmaputra (Jamuna River in Bangladesh) and the Meghna rivers and several of their tributaries and distributaries. Figure 2.1 shows the river network with tributaries and distributaries of these and other rivers. The remarkable aspect of the Bangladesh rivers is that they form an intricate network influencing each other hydraulically and morphologically and debauching together into the Bay of Bengal. Among the major rivers, the Brahmaputra-Jamuna River is the most energetic having the highest stream power (Barua, 1994). This river, despite having a smaller drainage basin than the Ganges, has a steeper slope, a larger discharge and sediment transport and a higher sediment content. Table 2.1 summarizes some of the known parameters in the rivers. With a brief description of the rivers, this section reviews the historic mobility of the rivers.

The Brahmaputra River draining the northern and eastern slopes of the Himalayas, is 2,900 km long and has a command area of 573,500 km². In the Bangladesh reach the river has a major right-bank tributary, the Teesta, and two left bank distributaries – the Old Brahmaputra River and the Dhaleswari River. It is a wandering braided river with an average bankfull width of some 11 km. The Ganges River draining the southern slope of the Himalayas has a command area of 1,090,000 km² and a length of 2,200 km. It is a wide meandering river with a bankfull width of some 5 km. In the Bangladesh reach, a left-bank tributary, named the Mahananda, joins the river upstream of the Hardinge Bridge and a right-bank distributary, the Gorai, carries part of the high stage Ganges flow to the Bay of Bengal. The Upper Meghna River originates in the Shillong Plateau and foothills. It is a relatively small river having a bankfull width of some 1 km. The river has a catchment area of 77,000 km² and a length of some 900 km. The Ganges and the Jamuna rivers meet near Aricha forming the Padma River, which flows southeastward until it reaches the Upper Meghna River near Chandpur. It is a relatively straight reach of some 120 km. A right bank distributary – the Arial Khan River – carries part of the Padma River flow and debauches directly into the bay.

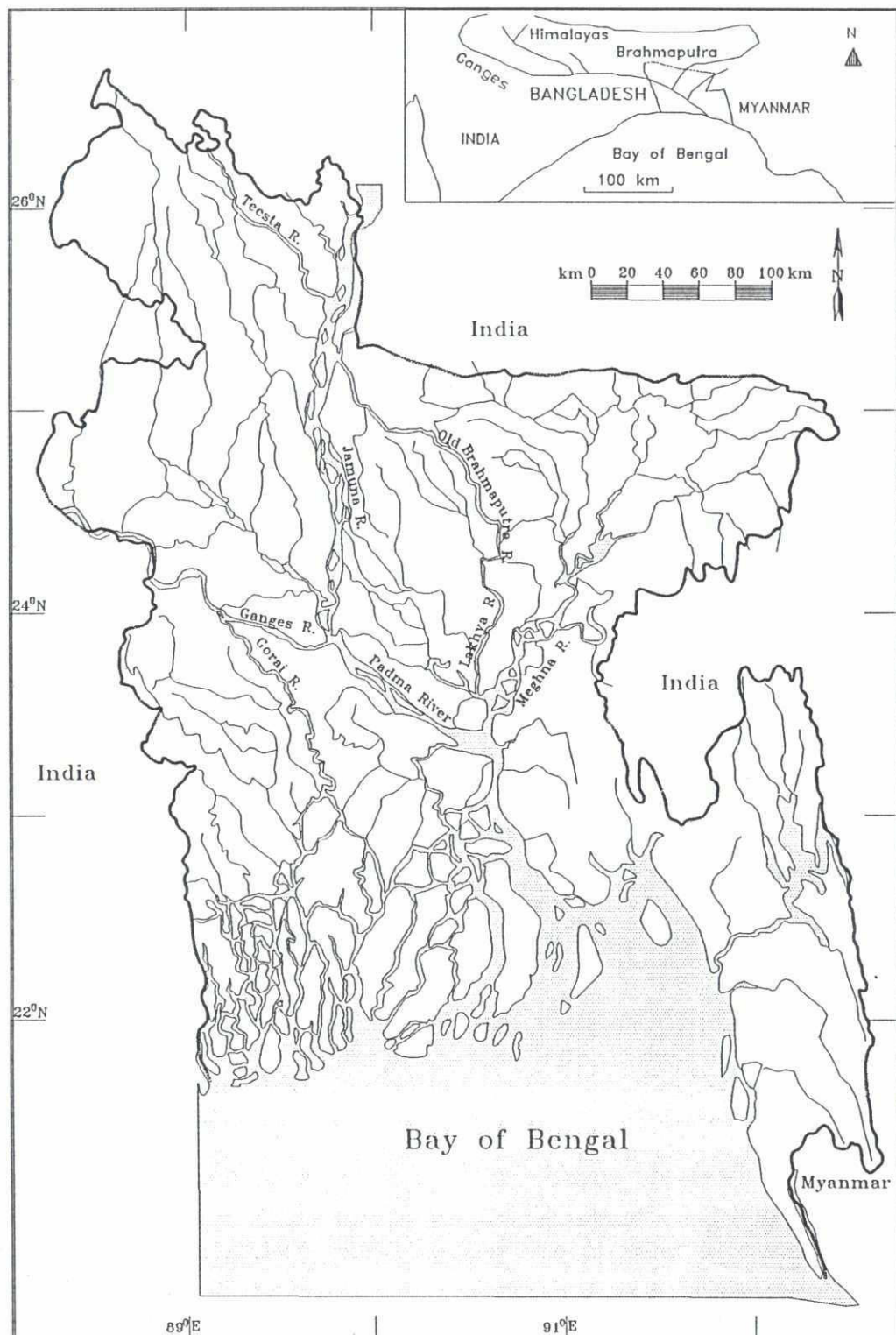


Figure 2.1 The river network of Bangladesh

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 sort. coeff (–)	1.40	1.45	1.52	1.80	1.57	1.52	1.57	2.54
Dependent Var.								
Width (m)	5,000	–	11,000	330	256	7,000	–	1,000
Depth (m)	4.5	–	5.0	7.0	9.0	–	–	4.7
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 Wave-length (m)	29,000	9,200	–	5,500	–	–	4,160	9,000
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 2.1 Time- and space-averaged morphological parameters of the major rivers in Bangladesh obtained from various sources.

The rivers changed their courses in the past. The history of the developments of Bangladesh rivers is a history of channel switching and gradual migration. Figure 2.2 summarizes the developments of the main rivers beginning from Rennel's map of 1764-93 (Figure 2.2a) to the 1991 AVHRR image (Figure 2.2c) processed by ISPAN (1993). The Wilcox map (1821-1834), representing an intermediate period, is shown in Figure 2.2b. In this geologically short period notable changes occurred in the river network. Comparison between Rennel's map and Wilcox map indicates that the Brahmaputra River switched from its eastward course in favour of a southward course along its small distributary, the Jamuna River. As shown in Figure 2.3c, gradually, the Old Brahmaputra course became a small distributary of the Brahmaputra-Jamuna River. This switching is either attributed to the 1787 catastrophic flood (La Touche, 1910) or to the neotectonic uplift of the Modhupur Tract (Hossain, 1989). In the Rennel's map of 1764-93, the Teesta-Atrai River was a tributary of the Ganges River. The river later shifted and became a right-bank tributary of the Brahmaputra River. This development is attributed to the neotectonic uplift of the Barind Tract (Krishnan, 1968). The development of the Dhaleswari River can also be noted. During Rennel's time it was a distributary of the Ganges River, by 1991 it became a distributary of the Jamuna River. The gradual north-eastward shifting of the Padma River can also be noted.

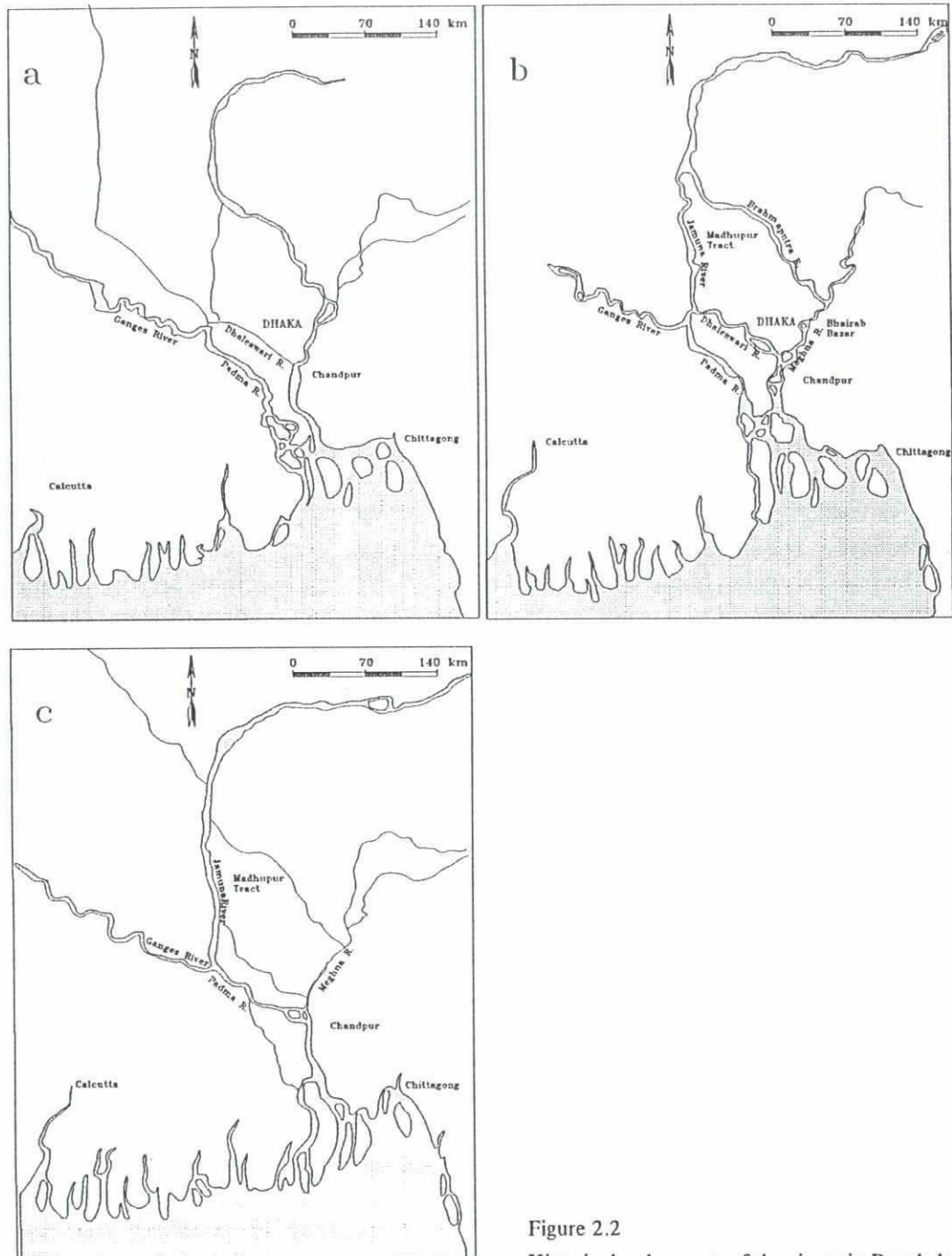


Figure 2.2
Historic developments of the rivers in Bangladesh

Previously the Ganges used to empty into the Bay of Bengal through the Arial Khan River; but after capture of the Jamuna River flow it shifted northeastward joining the Upper Meghna River near Chandpur. Other notable changes to mention are the reduction in sinuities of the Ganges River and reduction in the size of the Upper Meghna River. Coleman (1969) made a reconstruction of the rivers based on identification of abandoned or moribund channels. The reconstruction indicates a gradual southwestward migration of the Jamuna River and a gradual northeastward migration of the Ganges River.

2.3 Environmental controls

Several long time-scale factors comprise the environmental controls of a fluvial system. These factors include climate, basin-size, basin-relief, natural vegetation, geological factors, anthropogenic factors, episodic events, etc. Only some important factors are highlighted here; details are provided in Barua, 1994 and RSP, 1994. Climate is an important environmental control of a river system because it governs the amount of surface runoff and river discharge, the extent and intensity of basin denudation and sediment yield, and partly the natural vegetation type. The important climatic factors in this regard are precipitation and temperature. The climatic region of the Ganges and the Brahmaputra basins can be broadly categorized under humid tropics with major areas subclassified as humid subtropical warm climate, while a small southeastern area of Bangladesh has a tropical rainforest climate. It is characterized by the seasonal reversal of the monsoon. The average precipitation over the entire drainage basin ranges from over 1,000 mm during May - October to 120 to 250 mm during November-April. More locally in Bangladesh, the mean annual rainfall varies from 1,220 mm in Rajshahi to 5,000 mm in Sylhet.

The most important environmental control modifying the river behaviour are the geological factor. Its importance can be discerned by the fact that the drainage basin is located in an active tectonic region related to the convergence and collision of Eurasian and Indian Plates and active orogeny of the Himalayas. The results of such tectonic activity are the existence of several deep-seated faults, structural upwarping or downwarping and episodic earthquakes. The tectonic movement manifests itself through several surface and subsurface faults and lineaments as identified by Hunting Geology and Geophysics Ltd. (1980). According to the tectonic classification proposed by Bakhtine (1966), Bangladesh consists of three tectonic regions which are the Indian Platform or Stable Shelf, Bengal Foredeep and Eastern Folded Belt (Figure 2.3). The influence of this factor on the Bangladesh river course were demonstrated by Morgan and McIntire (1954) and Hartmann et al. (1993). The present preferred course of the Ganges-Jamuna-Padma is attributed to a 'structural zone of weakness' due either to a subsiding trough or to a single fault at depth (Morgan and McIntire, 1959). Structural deformation through downwarping or upwarping causes the relative vertical movement of the earth's crust known as neotectonic activity. Neotectonic sinking of the Sylhet depression occurs at a rate of some -2 mm/year as opposed to the simultaneous uplift of the Shillong Plateau (MPO-HARZA, 1987). Most importantly, seismicity has a considerable effect. High seismic activity occurs in and around the Bengal Basin. During the past one hundred years about 20 major earthquakes (> 7.0 on the Richter Scale) occurred in and around the Bengal basin (Khandoker, 1990). Of these, the western Assam earthquake of 1887 (8.7), the Bihar earthquake of 1934 (8.3) and the Eastern Assam earthquake (8.7) of 1950 had their epicentres at the Himalayan Arc Thrust Fault. According to Khattri and Wyss (1978), the occurrence of earthquakes in the region has a return period of some 30 years.

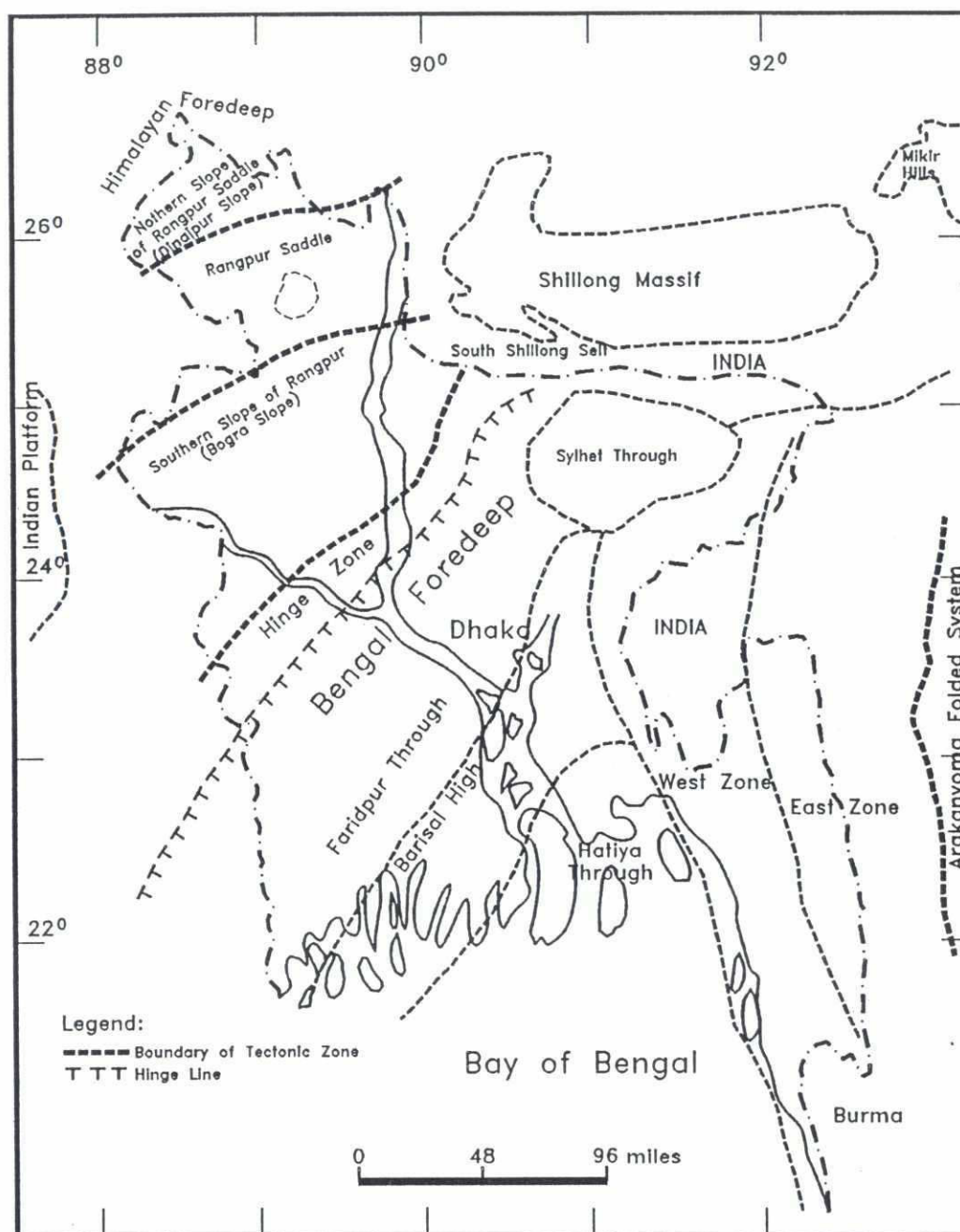


Figure 2.3 Tectonic classification map of Bangladesh

As discussed earlier, these factors are believed to be responsible for the switching of the Brahmaputra River and the Teesta River (Krishnan, 1968; Hossain, 1986). The results of such tectonic activities and their influence on the river behaviour led Barua et al. (1995) to hypothesize that Bangladesh rivers could hardly attain a dynamic equilibrium; they rather remain in an adaptation phase. In addition, the lithological structure of surface soil determines the calibre and quantity of sediment yield from the drainage basin. The basin consists of a spectrum of rocks ranging from the oldest Precambrian Metamorphics to the recent Pleistocene Alluvium (Sarin et al., 1989).

The Pleistocene Alluvium derived and built by the rivers covers most parts of the drainage basins. The shifting nature of the Ganges and the Jamuna rivers caused the geomorphic relationships of the various sedimentary units to be highly complex and lithologic variation highly inhomogeneous.

Among other environmental controls, anthropogenic factor has an important contribution for the densely populated Ganges-Brahmaputra basin. With rapid population growth and exploitation of resources, changes are occurring in the land-use pattern through increased deforestation and cultivation of watershed areas, water management initiatives and floodplain developments. The vast floodplain of Bangladesh is changing considerably with rapid population growth. Human settlement and infrastructured building on the floodplains are causing impeded drainage of flood-flows and affect the drainage basin.

2.4 Hydrological aspects

The hydrological aspects of the rivers in the region are governed by the annual reversal of the wind system. The northeastern monsoon occurs in the winter with the presence of a high pressure zone in the Asian Highlands near the Gobi Desert. Therefore, the region receives relatively moisture free continental winds. During the summer a low pressure zone develops in Central Asia near the Thar Desert generating onrush of moisture-laden winds from the Arabian Sea and the Bay of Bengal. The results of such a wind system is manifested in a distinct seasonal distribution of rainfall. A light rainfall of about 25 mm occurs in January-February. During March-May, early summer thunderstorms known as Northwesterlies occur with a rainfall of about 90 mm in the northwest to about 420 mm in the northeast. The southwest monsoon occurs during the June-September period with heavy rains. The surface and subsurface runoff generated by such rainfall distribution governs the hydrology of the rivers. A brief river-wise description of the hydrological aspects of the rivers are provided, some of which are summarized in Table 2.1.

The Brahmaputra-Jamuna River basin represents a higher rainfall area than the Ganges basin. With an annual average rainfall of some 1,900 mm, the water yield per km² of the drainage basin is about 0.03 m³/s. In response to the rainfall distribution, the river stage varies by about 6 m. In the Jamuna River hydrograph seven phases can be distinguished as shown in Table 2.2. They range from a nearly constant low stage during January-February to peak stages during July-August. The characteristic feature of the hydrograph is the existence of a broad peak between July and September. Having an annual average discharge of 19,600 m³/s, the river drains an estimated 620x10⁹ m³ of water annually to the Bay of Bengal. The discharge varies from a minimum of 8,000 m³/s to a maximum of about 100,000 m³/s. Each year the river reaches a bankfull discharge at approximately 48,000 m³/s. It has an average surface water slope of some 7 cm/km (7x10⁻⁵).

Phases	Months	Variability Characteristics
1	March - May	Slow rising
2	June	Rapid rising
3	July - August	Varying peaks
4	September	Very slow falling
5	October	Rapid falling
6	November - December	Slow falling
7	January - February	Nearly constant low flow

Table 2.2
Phases of the annual
hydrograph of the Jamuna River
at Bahadurabad.

Among the three main rivers, the Ganges River has the lowest water yield. With an annual average rainfall of some 1,200 mm, the water yield is about $0.01 \text{ m}^3/\text{s}$ per km^2 of the catchment. The river drains $252 \times 10^9 \text{ m}^3$ of water annually to the Bay of Bengal. The annual average discharge of the river is about 56% of the Jamuna River. The discharge varies from a minimum of $1,000 \text{ m}^3/\text{s}$ to a maximum of $70,000 \text{ m}^3/\text{s}$. The dominant discharge of the river is about $38,000 \text{ m}^3/\text{s}$. A seasonal water-level variation of about 8 m occurs at Hardinge Bridge. The water surface slope of the river is 5×10^{-5} . One significant development of the river is the decrease in the dry-period discharge. The dry-period discharge decreased from $2,250 \text{ m}^3/\text{s}$ before 1975 to only $650 \text{ m}^3/\text{s}$ after 1975 (RSP, 1994).

- *The Upper Meghna River*, smallest among the three main rivers, has the highest water yield. Representing the highest rainfall area in the world with an annual average rainfall of some 4,900 mm, the water yield from the catchment is about $0.06 \text{ m}^3/\text{s}$ per km^2 . With an annual average discharge of about $4,800 \text{ m}^3/\text{s}$ the river drains some $151 \times 10^9 \text{ m}^3$ of water annually to the Bay of Bengal. The dominant discharge of the river is about $9,500 \text{ m}^3/\text{s}$. The lower reach of the river becomes tidal during the December-April period with negligible residual flow and reaches a maximum discharge of $30,000 \text{ m}^3/\text{s}$ during the monsoon. The seasonal water level variation is about 5 m.
- *The Padma River*, draining the combined flow of the Ganges-Brahmaputra rivers, has an annual average discharge of about $28,000 \text{ m}^3/\text{s}$. The lower reach of the river becomes weakly tidal during the December-April period. The discharge variation at Baruria is from a minimum of $10,000 \text{ m}^3/\text{s}$ to a maximum of about $120,000 \text{ m}^3/\text{s}$. The seasonal water-level variation is about 6 m.
- *The Lower Meghna River* is a tidal reach carrying almost the entire fluvial discharge of the Ganges, the Brahmaputra and the Upper Meghna River. The net discharge through this river varies from $10,000 \text{ m}^3/\text{s}$ in the dry season to $160,000 \text{ m}^3/\text{s}$ in the wet season.

One important hydrological aspect of the Bangladesh rivers is that the rise and fall of the river stages are very weakly dependent on the local rainfall. This is because, as pointed out earlier, 92% of the catchment lies outside the territorial boundary of Bangladesh. In addition, the seasonality of the Bangladesh rivers can be best described by defining a seasonality index. This was attempted by Khan and Barua (1995) for the Ganges River. For surface water elevation the seasonality index (mean monthly/mean annual) varies from 0.7 in April to 1.5 in August. The same for discharge is 0.1 in April to 3.5 in August. This can be compared with the Jamuna River where the surface water elevation seasonality index varies from 0.8 in February to 1.2 in July and the same for discharge varies from 0.2 to 2.4. The authors also indicated non-linearity in the stage-discharge and discharge-sediment transport relations.

2.5 Sedimentological aspects

Sedimentological aspects of the Bangladesh rivers are characterized by a fine sedimentary environment. The consequence is that the threshold velocity for sediment mobility is very low, approximately about 0.2 m/s (Hjulstrom, 1935). Due to this low threshold velocity, the rivers are highly mobile with continuous reworking and deformation of their beds and banks transporting huge quantities of sediments. Mean annual transports were estimated by various organizations by fitting a regression line between BWDB-observed sediment transports (Q_s) and discharge data (Q). The relations read as $Q_s = c Q^e$ (Q_s in tons/day; Q in m^3/s), with different c and e values obtained in different investigations. A brief river-wise description of the sedimentological aspects is given.

Among the three major rivers, the Brahmaputra River has the highest sediment calibre and transports the largest sediment load (see Table 2.1). The median bed-material diameter varies from 165 μm near Aricha to 220 μm near Chilmari. As shown in Table 2.3, the mean annual suspended sediment transport estimates of the river varies from 387 (MPO-HARZA, 1987) to 650 million tons (Hossain). The coefficient (c) and the exponent (e) of the sediment transport rating equation are 0.4 and 1.3-1.4, respectively (RSP, 1994).

The Ganges River has a more fine-sedimentary environment than the Jamuna. The median bed-material diameter is about 120 μm (NEDECO, 1967). The mean annual suspended sediment transport varies from 196 (CBJET, 1991) to 549 million tons by the RSP (1994). The coefficient and the exponent are 7.2×10^{-6} and 2.5, respectively.

River	Coleman	CBJET	MPO	FEC	Hossain	RSP	BWDB
Jamuna	608	499	387	431	650	586	500
Ganges	479	196	212	338	480	549	450
Padma	–	581	563	–	–	894	694

Table 2.3 Mean annual suspended sediment transport through the Jamuna, the Ganges and the Padma rivers according to various investigators. The gauging stations are located in the Jamuna River at Bahadurabad, the Ganges River at Hardinge Bridge and the Padma River at Baruria and Mawa.

Padma River bed-material sediment diameter varies from 90 μm in the lower reaches to 140 μm in the upper reaches. Carrying the combined flow of the Ganges-Brahmaputra rivers, the mean annual suspended sediment transport estimate varies from 563 (MPO-HARZA, 1987) to 894 million tons by the RSP (1994). The coefficient, c varies from 1.2×10^{-9} to 0.0062 and the exponent e varies from 1.8 to 3.1.

The Upper Meghna River has a median diameter of 140 μm and it transports some 13 million tons of suspended sediment annually. Among the distributaries, the Dhaleswari River transports some 19 million tons and the Gorai River transports some 47 million tons annually.

One important aspect of the sedimentology of Bangladesh rivers is the overabundance of silty materials. Thorne et al (1993) indicated that in the Jamuna River silt transport occupies 75% of the total transport. The RSP (1994) estimates for all the major rivers indicate that the silt transport is about 59 to 84% of the total transport.

2.6 Morphological aspects

In this section only the morphological aspects of the main rivers are briefly described. The planform pattern, general migration trend and temporal evolution are discussed.

- The Brahmaputra-Jamuna* is a generally anabranching, wandering braided river. The present course of the river is only about 200 years old. The number of major channels varies from three in the upstream reaches to two in the lower reaches. During high river stages, two to three major channels are noticeable, separated by large vegetated islands, giving the general impression of an anabranching river. During low river stage, a braided planform is obvious with the emergence of numerous large sand bars. The average Brice braiding index varies from 4 in the downstream reaches to 6 in the upstream reaches (Halcrow, 1993). RPT-NEDECO-BCL (1989) studies indicate that the degree of braiding increased since 1981. Several-years map compilation by ISPAN (1993) indicates that in about 158 years (1834-1992), the entire Bangladesh reach of the river migrated westward by bank-erosion with an average rate of some 50 m per year. Apart from this secular westward migration, erosion occurs at different rates in different hierarchies of channels (Bristow, 1987; HALCROW, 1993a; Thorne et al, 1993; RRI-LP-CNR-DELFT, 1993). For example, Bristow (1987) showed that first-order channels comprising the entire river width of some 10 km migrate at a rate of some 70 m/year. The next lower order channels having a maximum width of some 5 km, migrate as much as 1,000 m/year. Migration of third order channels is very erratic and occurs in response to local hydraulic conditions. The erosion is mostly concentrated at outer bank embayments. Satellite imagery interpretations by Klaassen and Masselink (1992) showed that bank erosion in curved channels occurs at various rates ranging from 0 to 500 m with a maximum of some 1,000 m/year. And they mostly occur perpendicular to the primary flow direction (in the east-west direction). Gradual trends of development are shown by some studies. Studies by ISPAN (1993) indicate that the river widened in the 1834-1992 period from 6.2 to 10.6 km representing a widening of some 27 m per year. Recent trends show an acceleration phase in channel widening. For example, in the past 19 years (1973-92) the rate accelerated to some 140 m/year. Bhuyia and Rahman (1988) reached the same conclusion of secular widening of the river. They found widening at a rate of some 172 m/year between 1972 and 1986. The Form Number (width/depth) changed from 1.2 in 1972 to 1.9 in 1986. This increase in the Form Ratio is primarily in the change of width as the average depth was found to be nearly constant. As the discharge appeared not to have changed during the period, the widening is attributed to the increase in sediment supply (Bhuyia and Rahman, 1988). These previous studies were primarily concentrated at studying the first-order channels, where widening took place at the cost of the growth of bars and islands. This can be confirmed from the studies by Klaassen and Vermeer (1988) and Klaassen et al. (1988). They observed that after 1981 the braiding increased in line with the observed widening. The hypothesis of increase in sediment supply can probably be related to the studies by Goswami (1985). In the 607 km Assam-reach of the Brahmaputra River, Goswami (1985) showed that the riverbed aggraded by about 16-21 cm in the 1971-79 period. In addition, water-level analyses for the 1955-63 period at specific discharges indicated a rapid aggradation of the riverbed. This is attributed to the great earthquake of 1950. In the 1992 LANDSAT TM images it is clearly noticeable that the braiding decreases downstream over the whole reach from Assam to Bangladesh, indicating probably the influence of sediment overloading by the Assam earthquake. In the Bangladesh reach the downstream decrease in the braiding was observed earlier by Klaassen and Vermeer (1988).

- *The Ganges* is a wide wandering river with irregular point bars. As discussed earlier, historically, the river on its northeastward migration built and abandoned several deltas before finally occupying the present course (Niyogi, 1972). However, Chowdhury (1978) questioned this and showed that the present course of the river was always the original river course. Map compilation by ISPAN (1993) shows that the river has not shifted significantly over the past 200 years. Similarly very insignificant widening took place between 1984 and 1993. The apparent stability of the Ganges River is probably influenced by the existence of some clay banks, for example, one at the Hardinge Bridge. However, the sinuosity of the river appears to have decreased from some 1.6 in 1780 to 1.2 in 1973 (Halcrow, 1993b).
- *The Upper Meghna River* is a canaliform type of meandering river and locally anabranching. As discussed earlier, the Upper Meghna River lost a large portion of its sediment-laden flow after the historic switching of the Brahmaputra River. Its size decreased during historic time and the river is probably adapting to the new conditions (HASKONING-DELFT, 1990). Among the three major rivers, the water yield from the drainage basin of the river is the highest but the sediment yield is the lowest (Barua, 1994).
- *The Padma River* draining the combined discharge of the Ganges and the Brahmaputra rivers is a reach of some 120 km from the Ganges-Jamuna confluence at Aricha to the Padma-Upper Meghna confluence near Chandpur (Fig. 2.1). Prior to the avulsion of the Brahmaputra River, it was just the lower reach of the Ganges River debouching into the Bay of Bengal through the Arial Khan River. After the historic change of the Brahmaputra River, the river, swollen to a big size, initially followed the same Arial-Khan course and later made a rapid shift to the northeast joining the Upper Meghna River near Chandpur. The Padma River has roughly a straight course in the upper reaches and a double-thread braided lower reach. ISPAN (1993c) studies indicate that the river widened considerably. In the lower reaches some 46% widening took place between 1984 and 1993, the middle reach widened by 21% during the same period. The upper reach remained relatively stable, which may be attributed to a stable hard-clay bank on its left bank near Baruria. This hard clay, slightly oxidized, probably represents a Pleistocene block. The right bank of the middle and the lower reaches, on the other hand, is experiencing considerable erosion with some 200 m/year in the lower reach to some 110 m/year in the middle reach (ISPAN 1993). At the left bank the erosion is negligible, some 50 m/year. Rahman and Alam (1980) have shown that the thalweg sinuosity of the entire Padma River is decreasing over the years, from 1.3 in 1967 to 1.1 in 1977. They indicated that the river has a tendency of shifting from a meandering to a braiding pattern.

2.7 Distributaries

- *The Brahmaputra-Jamuna River* has two major left-bank distributaries – the Old Brahmaputra River and the Dhaleswari River. The only Ganges River distributary is known as the Gorai. The Padma River right bank distributary is known as the Arial Khan. In the true sense of the term, the Old Brahmaputra River and the Dhaleswari River are loop channels carrying a small part of the Jamuna River flow to the Upper Meghna River. A brief description of their hydrological and morphological characteristics are given.

Major tributaries and distributaries of the Brahmaputra-Jamuna River include two right-bank tributaries and two left-bank distributaries. The two major right-bank tributaries are the Teesta River and the Atrai-Gur River. The Teesta River changed its course some two hundred years ago. It is a coarse sand-bed braided river. In 1990, a 615 m long barrage was constructed in the river. Very limited information and data are available for these two rivers.

There are two major left-bank distributaries of the Brahmaputra-Jamuna River; they are the abandoned course of the Brahmaputra River (now known as the Old Brahmaputra) and the Dhaleswari River. Both these rivers debouch into the Upper Meghna River, often through some smaller distributaries. As discussed earlier on historical perspectives, both the rivers appear to be losing their conveyance functions. The Old Brahmaputra River appears to be going through a secular period of aggradation. The river is at present reduced to a mere spill channel of the Brahmaputra-Jamuna River, active only during high river stage. Therefore, its hydrological regime is more flashy than perennial. The annual average discharge of the river appears to be showing a decreasing trend, from being a $800 \text{ m}^3/\text{s}$ in 1964 to $500 \text{ m}^3/\text{s}$ in 1991 (RSP, 1994). The former discharge represents only 4% of the Jamuna River flow. The sinuosity of the upper reach of the river appears to be decreasing from 1.6 in 1973 to 1.4 in 1989. In the lower reach, the sinuosity is about 1.3. Another interesting feature of this river is the development of the offtake during the past 20 years. A study of satellite imageries revealed that its offtake was nearly closed during the 1973-82 period; became wider again during the 1983-89 period and nearly closed again after 1990. The offtake is affected by the overall westward migration of the Brahmaputra River. In the mean time, however, an interesting development occurred: The capture of the Jinjiram River as its tributary.

At present the Dhaleswari River offtakes at two locations, the downstream offtake being more active than the upstream offtake. The upstream offtake was closed by the Jamuna Bridge construction activities, though a large spill channel developed just downstream of the bridge site during the 1995 monsoon. The annual average discharge of the Dhaleswari River reduced from about $1,750 \text{ m}^3/\text{s}$ in 1969, to $600 \text{ m}^3/\text{s}$ in 1987 (RSP, 1994). This range of discharge represents some 7% and 4% of the Jamuna River discharge. The sinuosity of the river is 1.6 in the upper reaches and 1.3 in the lower reaches. The bed slope of the river also reduces downstream, from 6×10^{-5} in the upper reaches to 3×10^{-3} in the lower reaches.

The Ganges and the Padma rivers have two major distributaries. *The Gorai* is a right bank distributary of the Ganges River debouching independently into the Bay of Bengal after capturing some local flows. Historic records indicate that the river was once a major course of the Ganges River. *The Arial Khan* is a right bank distributary of the Padma River emptying independently into the Bay of Bengal. This was also an old course of the Ganges River. While the entire reach of the Arial Khan is tidally affected, only the lower reaches of the Gorai River is tide-dominated. The Gorai River is fast losing its conveyance function. At present, the average discharge of the river is only about $1,400 \text{ m}^3/\text{s}$ representing some 13% of the Ganges river flow. Even this represents only the wet months from June to October. During the rest of the year the offtake remains dry. This is primarily due to a right bank point bar of the Ganges River which virtually chokes the Gorai mouth. Water stage analyses at specific discharges indicate that the river is going through a secular period of aggradation. The average sinuosity of the river also appeared to be increasing from some 1.5 to 2.3.

- *The Arial Khan River* has an average discharge of $2,600 \text{ m}^3/\text{s}$ representing some 9% of the Padma river flow. The mean annual flow appeared to be increasing at a rate of some $42 \text{ m}^3/\text{s}$ (RSP, 1994). It has more than one offtake. A comparison of the Padma River at the Arial Khan Offtake between 1960 and 1989 shows the continued right bank erosion of the Padma with consequent shift of the offtake location. Also, water level analyses at specific discharge show degradational trend of the river (Halcrow, 1993b). The sinuosity in the upper reach of the river appeared to have decreased from 1.8 to 1.5 in about 16 years (1973-89).

2.8 Chars and floodplains

Having a low relief with a gentle slope of about 0.3×10^{-5} , the greater part of Bangladesh forms the floodplains of its numerous rivers. Brammer (1971) divided the whole Bangladesh area into three basic physiographic zones, namely the hill areas, the terrace areas and the floodplains. Floodplains occupy 80% of the total Bangladesh area (FAO, 1988). Physiographically, floodplains in Bangladesh can be divided into three distinct zones.

Active floodplain comprising natural levee and chars

When a river spills over its banks during flood, relatively coarser fractions of sediments are deposited through splays and overbank flooding along a strip of land along the bank. This strip is known as a natural levee which is topographically higher than the rest of the floodplain. The vegetated chars or islands within the rivers also belong to this group. Deposition in natural levees are characterized both by lateral accretion (mostly coarse fraction) and vertical accretion (mostly fine fraction in thin layers). The elevation of natural levees generally conform to a flood level having a 2 to 5 years return period (Volker, 1981). The geological map of Bangladesh shows these areas characterized by alluvial sand and silt deposits (Alam et al, 1990). Natural levees vary in width between one-half and four times the channel width, and in elevation vary from a few decimeters to as much as 8 m depending on river size and calibre of sediment load (Allen, 1970). The downslope gradient of levees is a few to many times the slope of the adjacent channel. Natural levees are usually cut in different places by sizable channels, called crevasses, which serve to route flood water from the main channel on to the floodplain. Examples of crevasse splays in the Jamuna River are shown by Coleman (1969).

The active floodplains of Bangladesh rivers are the most dynamic regions with high bank-erosion rates and channel migration. Some characteristic erosion and migration rates of the Jamuna River are presented in an earlier section. Analysis of the 1992 LANDSAT imagery of the Brahmaputra-Jamuna River by ISPAN (1993) shows that the river has some 56 chars longer than about 3.5 km and 226 chars having lengths between 0.35 to 3.5 km. These chars have widened considerably, with widening of the river course over the years.

Seasonally drained floodplains or backswamps

These are next topographically lower areas which work as storage basins with low flows both in transverse and longitudinal directions. Mostly fine sediments are deposited in these areas through vertical accretion. These areas are mostly characterized by alluvial silt and clay deposits (Alam et al, 1990). The backswamps are at least a few decimeters lower than the natural levees (Volker, 1981).

Standing water bodies or marshes

Standing water bodies or marshes belong to topographically depressed areas known as haors, boars and beels with negligible flows. According to SPARRSO (1985), the total standing water bodies in Bangladesh are about 1,236 km² or 0.9% of Bangladesh area, 60% of which is located in the northeastern region. These areas are mostly characterized by paludal deposits (marsh clay and peat). Standing water bodies in proximal locations to the sources of sediments may also have fan-type deposits locally.

3 Data collected in the past

3.1 Introduction

Various government agencies collect hydrological, sedimentological and morphological data in the rivers of Bangladesh. The Bangladesh Water Development Board (BWDB) collects discharge, sediment transport and cross-sectional data in the main rivers of Bangladesh. Earlier these data were published in hydrological yearbooks. Presently, the data on different parameters can be bought from these agencies. The BIWTA collects data on water level and bathymetry. Other agencies that collect similar but dedicated data according to their specific needs include Bangladesh Railway, Chittagong Port Authority and Mongla Port Authority. This chapter contains brief descriptions of all these data collected in the past. Earlier a brief review was presented in the RSP Study Report No. 3 (RSP, 1994).

3.2 Measuring methods and instruments

3.2.1 Introduction

In the following sections measuring methods and instruments are discussed. Most hydrological instruments and related methodologies introduced in the seventies by the FAO are still in use at the relevant government agencies. Using these techniques, a commendable database was made by these agencies which have been used for several studies. In order to understand the quality of these data it is necessary to review the techniques used. Detailed discussions on the use of these instruments are presented in the RSP Special Reports 11 and 12 (RSP, 1996a, 1996b). They indicate that while some of the used techniques are sustainable, most require improvement in instrumentation and methodology considering the growing demand for high quality data. Positioning, water-level gauging, discharge and sediment transport measurements, cross-sectional surveys and bathymetric surveys are discussed separately.

3.2.2 Positioning system

Traditionally Bangladesh government agencies use two types of positioning systems for hydraulic and hydrographic measurements. BIWTA, BWDB (the past Land Reclamation Project), Chittagong Port Authority and Mongla Port Authority use the Decca navigation system for positioning during bathymetric surveys. Decca is a hyperbolic position fixing system based on continuous transmissions from four shore-based stations known as master and slave stations. Decca is a multi-user position fixing system where the vessel-based receivers measure phase differences between transmissions from the shore-based stations. The Master station is located at Chandpur and the three slave stations are located at Patiya in Chittagong, Khulna and Mymensingh. These stations are operated and maintained by BIWTA. The system is dependent on specially drafted Decca hyperbolic charts. The accuracy of the system is ± 100 m. For navigation purposes the system works alright but its inaccuracy is too high for applications in smaller rivers. The other disadvantages of the system are that the system depends on the operation and maintenance of Decca stations. The system is getting obsolete and out of use.

An angular method utilising optical devices such as sextant or theodolite is used for position fixing by Bangladesh Water Development Board. Figure 3.1 illustrates an example. The sextant is used along a transect during discharge and sediment gauging by the Hydrology Directorate of BWDB. As shown in the figure, the distance VC is computed by measuring the angle β . The distance CT is measured accurately between beacons C and T. As can be seen for large distances (a smaller angle), a small mistake in the angle measurement gives a large error. The Morphology Directorate of the BWDB uses either a sextant or a theodolite during their cross-sectional measurements. While a theodolite is used, the angle α is measured. The system makes larger errors for smaller angles (i.e. smaller channels).

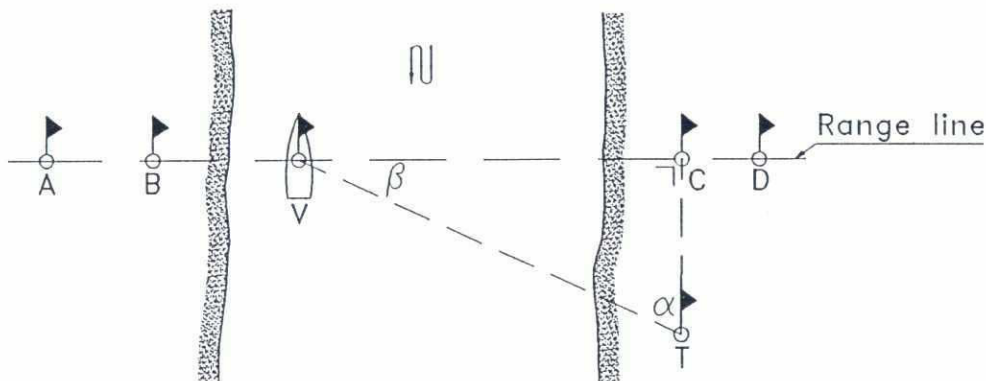


Figure 3.1 Positioning through sextant

3.2.3 Water-level gauging (BWDB)

The BWDB maintains a network of hydrometric stations all over Bangladesh, see the Hydrological network map, (Hoque, Shamsul, 1993). In most stations the water level is measured from wooden staff gauges and in some important stations an auto water-level recorder has been installed recently. Surface Water Hydrology Circle I (SWH-I) is responsible for the field work in connection with the BWDB network of hydrometric stations. The staff gauges are read five times a day, at 06.00, 09.00, 12.00, 15.00 and 18.00 hours. The accuracy of the reading can reduce significantly by wind waves and wind set-up of the water level. Since the seasonal water level variations exceed by far the reach of a staff gauge, its reach is regularly adjusted by fixing a new gauge close to the previous one. The relation between the data from the two gauges is obtained by simultaneous readings. Due to bank erosion or non-accessibility of the gauge site during high flows the gauge may be shifted to another location, sometimes up to one kilometre upstream or downstream of the old gauge site. Regular shifts of a staff gauge often implies loose fixation of the staff gauge. This may lead to gradual as well as sudden uncontrolled shifts, particularly if the gauge pole is used to anchor boats. Check-levelling of the gauge datum from a nearby benchmark is carried out weekly or fortnightly. Water-level corrections resembling from these checks are carried out at the field offices before the data are transferred to SWH-II for further processing.

Automatic water-level gauges measure the water level more frequently and with a constant high accuracy. Each month the cassette is collected and sent to Dhaka office for further processing and analysis. If the measurements stop because of an electronic failure, it takes some time to discover this failure and to repair it.

The location of a water level gauge should be selected carefully, preferably not close to a bridge pier, or in an almost disconnected side branch. It should be protected against collisions by country boats and it should be less attractive for mooring a country boat.

Each staff gauge is connected to the PWD-datum through a network of benchmarks. The position of the staff relative to the nearest benchmark should be levelled regularly. Infrequent or inaccurate levelling lead to a temporary bias in the gauge readings, which in general are of the order of less than one decimeter to some decimeters. The Land Survey Water Level Gauging of the BWDB staff-gauges (RSP, June 1993) showed an average difference of 0.05 m and a standard deviation of 0.08 m, with at three sites a difference of over 0.25 m. In the long run the error has a random character as positive and negative biases may occur. An error in the level of the benchmark is a systematic error, which may persist for several years. The levelling of the existing benchmarks showed an average difference of 0.16 m and a standard deviation of 0.15 m between the BWDB benchmarks and those established by FINNMAP (RSP, June 1993). Inaccuracies in the levels of the benchmarks affect the study and design parameters, which are dependent on the absolute value of the readings.



Figure 3.2
Staff Gauge with staff reader
near Bahadurabad, July 1995

3.2.4 Discharge measurements

The discharge is measured at five transects in the main rivers, generally at intervals of one week during the monsoon season (May-November) and of one fortnight during the rest of the year. At Hardinge Bridge on Ganges River and at Bahadurabad on Jamuna River daily flow measurements are made during the lean season.

The BWDB measures the flow velocities from a catamaran type survey vessel by non-directional Ott or SEBA current meter in a transect. Along the transect the locations of the verticals are predetermined. The flow velocities are measured in each vertical at 0.2 and 0.8 depth. If the depth < 1 m, then a single measurements is made at 0.6 of the depth. The depth averaged flow velocity is calculated by the Straub method. The number of verticals applied varies according to the actual flow conditions, but a rule used by BWDB is that one vertical should not represent more than 10% of the total flow in a channel. The required number of verticals becomes often high and it takes about two days to complete one measurement of the total discharge in the Jamuna river. In each measurement the revolutions of the current meter are counted during 100 s. If the propeller has caught some vegetation transported by the flow, then the current-meter has to be cleaned and the measurement has to be repeated. During the measurement the survey boat is dynamically positioned, i.e. the boat is not anchored. Its location in the transect is determined by measuring the angle to two land markers with a sextant. The depth in a vertical is measured by the length of the suspension cable with the current-meter or by an echo-sounder. The direction of the flow at the water surface is determined at each vertical by following the path of a floating bottle. The float positions are measured by sextants. The discharge is calculated by the conventional velocity-area method in accordance with the ISO standards.

A detailed investigation on the possible sources of errors in measuring the average flow velocity, the flow direction and the depth in a vertical as well as the distance between successive verticals is discussed in Annex 2. The propeller type current-meter needs a regular recalibration to maintain its accuracy.

3.2.5 Sediment transport and other sedimentological measurements

The BWDB measures suspended sediment transport in a few selected stations in the main rivers. In these rivers suspended sediment transport is considered to be more important than bed load transport. Therefore, the attention is focused on suspended sediment transport measurements. The BWDB has selected the Binckley silt sampler made by Kelvin Hughes as the standard instrument for suspended sediment sampling. This point sampler consists of three short brass cylinders of about 10 cm in diameter, in line, and connected to each other by rubber sleeves. The two ends of the cylinders are fixed, but the central cylinder resolves by pulling on a wire which has one turn round the cylinder and is fastened to a lug on it. A retaining catch ensures that the cylinder remains in the turned or closed position after the sample has been taken. The Binckley sampler has a tail unit to keep the instrument headed into the stream. The sediment sampler is supported by a suspension cable and it is raised and lowered by means of a winch. After entrapping a quantity of water and suspended sediment the Binckley sampler is raised to the surface, opened and emptied into the elutriator, thus separating the sand and the silt/clay fractions of the sample.

Instantaneous suspended sediment point samples are collected at each alternate vertical assigned for flow velocity measurements. Samples are taken at one point at a relative depth 0.6, if the local water depth is less than 1 meter and at two point, at relative depths 0.2 and 0.8, if the local depth is more. At relatively high flow velocities a special method was earlier developed in order to avoid a large drag angle of the sampler. A drifting technique was employed whereby the gauging craft was taken to a point a short distance upstream of the transect line, the engine stopped and the instrument lowered to the required depth. The craft was then allowed to drift slowly backwards across the transit line when the sampler was closed. In this way the drag angle of the sampler was reduced substantially. However, it was observed that this method was not followed during the joint measurement of the BWDB and RSP in 1995 and also not during another visit of the RSP to BWDB in 1993.

The bed load transport has not been measured regularly due to the difficulties to measure it and its presumed relative low importance.

Since 1966 bed material samples are also collected from the river bed for grain size analysis. It was decided to take five or six samples from each station and a few more in the Bahadurabad transect which crosses several channels during low flow. After 1977 the BWDB probably did not collect bed material samples on a regular basis.

A sample of the riverbed was collected with a Kolb bed sampler. This is essentially made up of two spring-operated jaws which when lowered to the bed are closed by suspension cable, which releases the tension on the spring, allowing the jaws to snap shut and at the same time picking up a sample of bed material. The samples are stored in a plastic bag and sent to the River Research Institute.

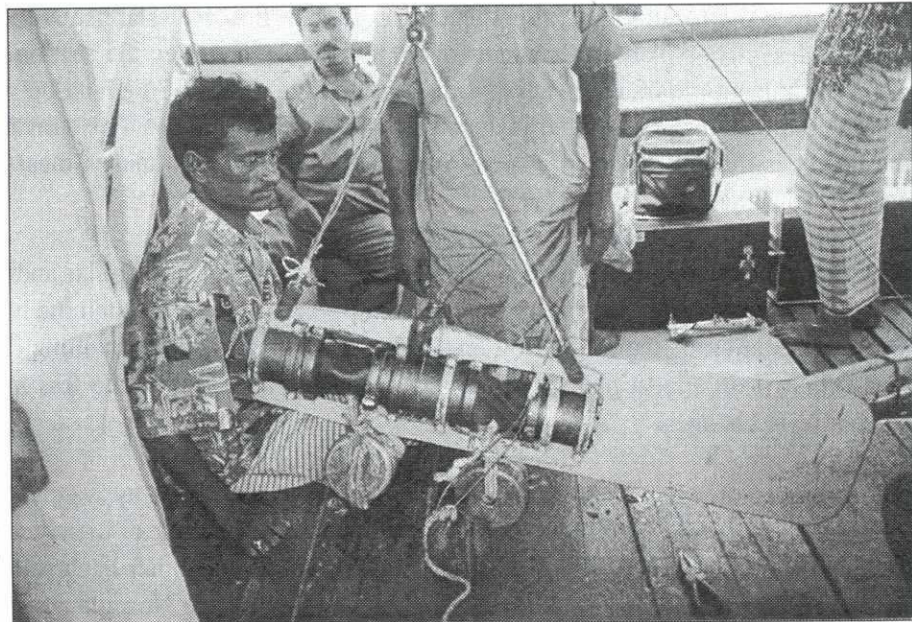


Figure 3.3 The Binckley Sampler

3.2.6 Cross-sectional surveys

The Morphology and Research Circle of BWDB surveys standard cross-sections in the lean season: from November to May. Their survey of a cross-section comprises two parts as: land part survey and wet part survey. The aim of these surveys is to characterize the morphological changes in a river over time. The survey methodology and the instruments used in these surveys are discussed in the following.

Instruments

In the land part of the survey BWDB uses measuring tape, pegs, theodolite, level, level staff, iron flat etc. for measuring distance and corresponding ground elevation. In the river part of the survey the water depth is measured by an echo sounder on a survey vessel. Sometimes a sounding lead is utilized instead of an echo sounder depending on the river and the water depth. For fixing the position in a river, generally a theodolite or sextant and land markers are used. In the water part, to identify the survey line, two flags mounted on two bamboo poles of different height are used.

Methodology

BWDB standard cross-sections are generally defined by three to five monuments or pillars. Monuments are made of concrete (0.25 m * 0.25 m) generally elevated 0.15 to 0.20 m above the ground, and mounted on a 0.60 m * 0.60 m size concrete base. Pillars are 0.1 * 0.1 m in size, and also made of grounded concrete with an elevation of 0.10 to 0.15 m above the ground level. The alignment of a cross-section is fixed by a bearing with respect to Magnetic North. Once the location and alignment of a cross-section are established they remain the same, unless major planform changes make it difficult to survey the section. The location of the monument/pillars are generally identified by the owner of the land on which they are placed, and with the plot number in a mouza map. A nail is fixed on a monument/pillar which the height is determined with respect to a PWD reference level and is measured from the nearest benchmark.

The BWDB fixes the alignment of a cross-section at a monument or pillar and then proceeds towards the river by measuring the distance along the alignment. Often the BWDB measures also the elevation of the ground by level. The interspacing of the levelling depends on the land relief, if on almost plain land the interspacing is about 60 m and less in case of more sudden level changes.

After arriving at a river bank where the land survey is hampered by water, the BWDB fixes with a theodolite a point on their line of survey to the other bank of the river and the water level is measured. A survey vessel starts the survey from the other bank sailing on the line of survey towards the bank where the land survey has ended. Nowadays a country boat is used as a survey boat. Often an echo sounder is mounted on this type of boat to measure the water depth. The position of the survey boat in the river is fixed with a theodolite or a sextant. After completion of the survey of the water part, the level of the survey is transferred to the other bank by assuming the same water level at both banks. For more details refer to RSP Special Report 20.

The field survey is recorded in field and level books and these data are worked out and processed in the office. Presently, the final document of the survey of a cross-section is presented in a tabular form, in which elevation of land is mentioned with respect to the PWD reference level with corresponding distances. The BWDB also presents the survey data graphically. In a sheet three to four years of surveys of a cross-sections are generally presented by superimposing the surveys. The monuments/pillars, special features such as levee, embankment and channels are noted for reference. The accuracy of the surveys is discussed in Chapter 8.

3.2.7 BIWTA bathymetric surveys

The Bangladesh Inland Water Transport Authority (BIWTA) performs hydrographic (bathymetric) surveys regularly in the rivers of Bangladesh. In a BIWTA bathymetric survey chart, soundings are presented in respect to "average lowest low-water level" (ALLW). In addition a few contour lines, submerged and exposed char lines, bank lines and some permanent features on the river banks are shown in a chart. The purposes of their surveys is to monitor the least available depth for the inland navigational routes. The coverage of the survey depends on the particular purpose, say for example to have an overall impression of the navigability of a river, to monitor the least available depth in a certain stretch of the river, to monitor the dredging or the bandalling works etc. The surveyed areas vary from a few square kilometres to almost the whole river stretch. However, the instruments used and methodology followed by the BIWTA during the bathymetric surveys are independent of the size of the survey and they are briefly described as follows.

Instruments

The BIWTA uses a 'work boat' type of vessel for their surveys. This boat has a length of 10 m, a width of 3 m and the minimum draught is about 1 m. With these vessels they can cover the shallow areas in the rivers also. During the survey a mother vessel supports for the accommodation of the surveyors, and facilitate the on-line processing of the data after survey works. Generally two surveyors are on board during the survey. The survey vessels are generally stationed at different key points, such as at Chandpur, Barisal, Dhaka, Aricha, Sirajganj. The depth of water is measured by an echo sounder mounted on the vessel, which is often calibrated by a steel plate submerged at a fixed depth. The Decca Chain positioning system is used by BIWTA during their soundings in the river. The accuracy of the system varies from about 20 to about 100 m depending on the location (or the oblique of the angles between the connecting lines of the beacons), weather and time (say for instance the morning or evening). There are five Decca Chain reference stations all over Bangladesh, to cover the classified inland navigation routes.

Method of survey

The methodology of the survey, especially the scale and the interspacing of the transects in the river depend on the purposes of the survey. The BIWTA has printed Decca Chain charts at different scales for the different locations. On these charts arcs are shown based on the different Decca Chain reference stations. Generally for a location arcs based on the three closest reference stations are intersected in a chart and indeed the spacing of the arcs depends on the scale of the survey. During the survey the survey vessel prefers to follow an arc which is perpendicular or nearly perpendicular to a river. The position in a transect line is fixed

by using the signal from a reference station, which arc intersects the previous arc with comparatively higher incidence angle. The fixes are marked on the echo sounding sheet with certain interval, although sudden depth changes are also fixed.

In a BIWTA survey, the depths are charted in respect to ALLW level, which is determined either by using the BIWTA or BWDB water level gauges. For a survey more than one water level gauge is generally used for the charted depth. The charted depths are linearly interpolated for an area located in between the two water level gauges. For a non-tidal area two water level readings per day are used for the average reduction from ALLW level and in a tidal area hourly gauge readings are generally used for reduction.

The BIWTA generally processes their data in the field so that if some major discrepancies are observed, the surveyor can verify the data in the field. Bathymetric charts are made on tracing paper in the office.

3.3 Existing data sets on main rivers

3.3.1 Introduction

RSP has made an inventory of existing data sets for river studies of the major river system in Bangladesh. The information provided here is based on collected reports, databases, and verbal information received from several agencies and organizations. Detailed information on this inventory together with the areas on maps or satellite images and extensive data tables are found in Annex 3 (Hydrology) and for the morphological data in Annexes 4 and 5, and also in Study Report 3, River Survey Project, May 1994. This inventory of data is not complete, because an important part of the data is difficult to identify and to retrieve. Maximum effort was given to collect as far as possible all information useful for river studies. The following sub-sections focus on the type of data and its source. The results of computer simulations or physical model tests relevant for hydrological and morphological studies are not included.

The inventory is grouped in hydrological, sedimentological, cross-sectional, bathymetrical and planform data.

3.3.2 Hydrological data

The need for surveys and investigations in the field of water resources in order to develop a strong hydrological data base was assessed by the Krug Mission, visiting Bangladesh in 1957 after two consecutive devastating floods of 1954 and 1955. The Master Plan which was prepared by IECO in 1964 emphatically recommended a systematic and scientific hydrological data collection and processing system (Shamsul Hoque, 1993). The available hydrological data from before 1964 are sparse, consisting mainly of water-level stages measured in a few main stations such as Hardinge Bridge and Bahadurabad.

The major source of hydrological data is the Directorate of Surface Water Hydrology-II of the BWDB.

Water-level time series

The BWDB operates 47 water level gauging stations in the main rivers in Bangladesh. For river studies water-level time series of stations upstream of the Bangladesh border would be useful, but unfortunately these data cannot be obtained from India. For almost all the stations in Bangladesh the available series cover the period 1964-95, with an interruption during the Liberation War in 1971. Daily time series from 50 water level stations including selected main stations in major rivers are available for a period of 25 years (1964 - 1989) in the computerised database prepared by the Flood Modelling and Management Project (1992 and 1993). The main stations along the Jamuna, Ganges and Padma rivers are listed in Table 3.1. These stations form a rather dense network along these rivers. The water levels measured in some of these stations are affected by a seasonal backwater effect, which means that no unambiguous stage-discharge relation can be established for these stations, see Annex 3. In the smaller distributaries the water level stations are far from the offtake, with exception of the station near the Gorai Railway Bridge.

Jamuna River	Ganges River	Padma River
Chilmari	Hardinge Bridge	Baruria
Bahadurabad	Sengram	Goalundo Transit
Sirajganj	Mahendrapur	Bhagyakul
Kazipur		Mawa
Porabari		Tarpasha
Mathura		Sureshwar

Table 3.1 Main water-level gauging stations along the major rivers

Stage-discharge data

Regular field surveys are carried out by SWH-I to determine the discharges in the main rivers. The discharge is calculated from depth, width and flow velocity measurements in a transect. Available processed stage-discharge measurements for the main rivers and distributaries cover in general the period from 1964/65 till now with some gaps, particularly for Gorai Railway Bridge, Bhairab Bazar, Mymensingh and Chowdhury Char. The annual rating curves are available from 1965/66 to 1995 with an interruption in 1971 for the discharge stations on the main rivers.

For three stations: Bahadurabad, Hardinge Bridge and Baruria the Flood Modelling and Management Project (FAP25, 1992 and 1993) established new annual rating curves for the period 1965-1989. They applied the same procedure as the BWDB, and these new rating curves do not differ much from the BWDB rating curves.

Discharge time series

Daily discharges have been determined by discharge rating curves and the observed daily water levels. When calculating the mean daily discharge from observed water levels the BWDB regularly corrects for shifts. This series covers the period from 1965/66 to 1995 for the main

stations on the major rivers. The Flood Modelling and Management Project (FAP25) also calculated discharge time series (1965 - 1989) for the stations Bahadurabad, Hardinge Bridge and Baruria on the basis of the corrected water level time series and the new rating curves. They found the BWDB correction procedure for shifting control questionable and did not apply any shift correction (Annex 3).

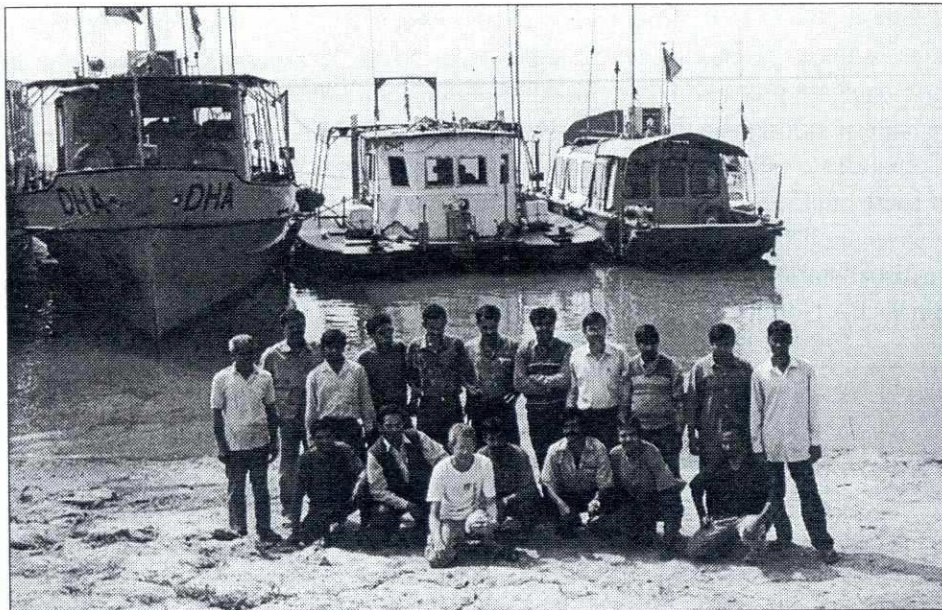


Figure 3.4 Three RSP survey vessels and their crews

3.3.3 Sedimentological data

The sediment data at the major gauging stations are actually available in reports with Surface Water Hydrology-II (SWH-II), BWDB, since 1956. But the old data from the period 1956-1966 are confusing as these data do not distinguish between suspended coarse and fine sediment (the coarse fraction is defined as the sand fraction and the fine fraction is the silt and clay fraction).

In the sixties the Food and Agriculture Organization of the United Nations funded a Hydrological Survey Team, which started an extensive sediment transport investigation in the main rivers (FAO-UNSF, 1969). This investigation was concentrated on suspended sediment, and the bed-load transport was not measured regularly. Ten gauging stations were selected along the main rivers. During the period 1966 and 1967, the sediment data collection was carried out weekly from the beginning of April to the end of November. The data collection continued until March 1970. The BWDB continued those sediment measurements after 1970 all over Bangladesh. In these ten main stations (see Table 3.2) the measurements were made on a weekly basis during the monsoon.

Some sediment data measured in the first years after the Liberation War could not be traced in the government offices, see the data availability in Table 3.2. During the Liberation War in 1971 no gauging was carried out. The fine sediment data have been analyzed by the River Research Institute.

Riverbed samples of the main rivers were collected by various organizations in the course of time, see Table 3.3. The BWDB collected more than 1,800 samples during the periods 1966-1970 and 1974-1977. These data have been stored with SWII-II. Not only government organizations were engaged in the sediment transport data collection, but also projects carried out by consultants. A few examples of such projects are NEDECO (1967), and the River Training Studies of the Brahmaputra River (Halcrow, 1992) which project took about 100 samples in July and November 1990 from the river bed in a test area south of Sirajganj. In the frame-work of the Meghna River Bank Protection Project about 100 bed material samples were taken in the Upper Meghna River and in Padma River. Bed material samples were also collected by the South West Area Water Resources Management Study (FAP 4) (Halcrow, 1992-1993) from the Gorai mouth and at the Kamarkhali bridge. These examples show that many samples had been collected in the past, however, they do not cover systematically all main rivers.

Name of station	River	Hydrological Period	
		Coarse sediment	Fine sediment
Bahadurabad 46.9L	Jamuna	1966-1969 & 1976-1993	1966-1969 & 1972-1988
Hardinge Bridge 90	Ganges	1966-1969 & 1976-1993	1967-1969 & 1973-1988
Baruria 91.9L	Padma	1966-1969 & 1976-1993	1968-1969, 1972-1978 & 1983-1986
Goalunda 91.9R	Padma	1966-1969, 1976-1978 & 1980-1982	1966-1969, 1977-1979 & 1981-1982
Mawa 93.5l	Padma	1966-1970, 1976 & 1980-1993	1966-1970 & 1974-1978
Gorai Rail Bridge 99	Gorai	1966-1969, 1989-1992	1967-1969
Mymensingh 228.3	Old Brahmaputra	1966-1969 & 1988-1991	1966-1967
Taraghat 137a	Kaliganga	1967-1970 & 1972-1993	1967
Jagir 68.5	Dhaleswari	1967-1969	1967
Bhairab Bazar 273	Upper Meghna	Nil	1959-1963 & 1972-1988 Except 1976, 1977, 1982

Table 3.2: Suspended coarse and fine sediment data available with SWII-II

Organization	Jamuna	Ganges	Padma	Meghna	Gorai	OldBrahmaputra	Dhaleswari	Arialkhan	Kaliganga
BWDB	1345	341	1	125	5	2			
SWMC				13	1	5	6	10	11
Others	139	12	6	31	32			7	
Total	1484	353	7	169	38	7	6	17	11

Table 3.3: Inventory of traced bed material samples collected by different organizations.

3.3.4 Cross-sectional data

The main river system of Bangladesh is covered by a network of standard cross-sections which have been surveyed by BWDB regularly during the past 25 years. In addition some soundings have been made near bridges and river training structures, but not on a regular basis.

BWDB surveys

The BWDB survey network comprises a total of 607 standard cross-sections at an interval of about 4 miles (6,436 m). In total 144 cross-sections are surveyed every year in the main rivers. In the medium and minor rivers 119 cross-sections are surveyed once in two years and 344 cross-sections once in three years. In each cross-section the water part and the land part have been surveyed, often including the floodplain over a distance of a few kilometres. This impressive network of standard cross-sections in the main rivers is shown in Figure 3.3. An inventory of the more than 3,000 available cross-sections is listed in Table 3.4.

River	Total length (miles)	Number of standard cross-sections	Cross-sections surveyed 1964-1992	Remarks
Jamuna	163	34	884	Few missing years
Ganges	82	18	256	Since 1985, inventory incomplete
Padma	65	15	307	Since 1989, inventory incomplete
Meghna	158	45	639	Missing period: 64-67 (partly), 66-71, 75-76, 81-85, 87-89, 92-93.
Old Brahmaputra	124	36	287	Data from 8 years are available
Dhaleswari	90	23	173	Data from 13 years are available (not for all cross-sections)
Gorai	124	32	194	Data from 13 years are available (not for all cross-sections)
Arial Khan	72	32	284	Data from 10 years are available
Total	878	235	3024	

Table 3.4: An inventory of standard cross-sections surveyed by the BWDB

In the Jamuna River, the oldest cross-sections were measured in 1964-1965 at an interval of about 8 miles for a study of a barrage near Bahadurabad. Since 1965-1966 this interval was reduced to about 4 miles by inserting additional cross-sections. Sequential cross-sections show very significant changes even at an interval of 4 miles. The variation in time is illustrated by cross-section J13-1 in Figure 3.5. In a very few cross-section surveys this distance is reduced to only 1 mile. Out of a total of approximately 1,000 cross-sections surveyed in the Jamuna River from 1964 to 1991, the River Training Study of the Brahmaputra Right Embankment (FAP1) could locate 700 which were stored in a database. Only 24 cross-sections of the remaining 300 cross-sections, dating from the period 1970-1976, could be traced (FAP1, 1993).

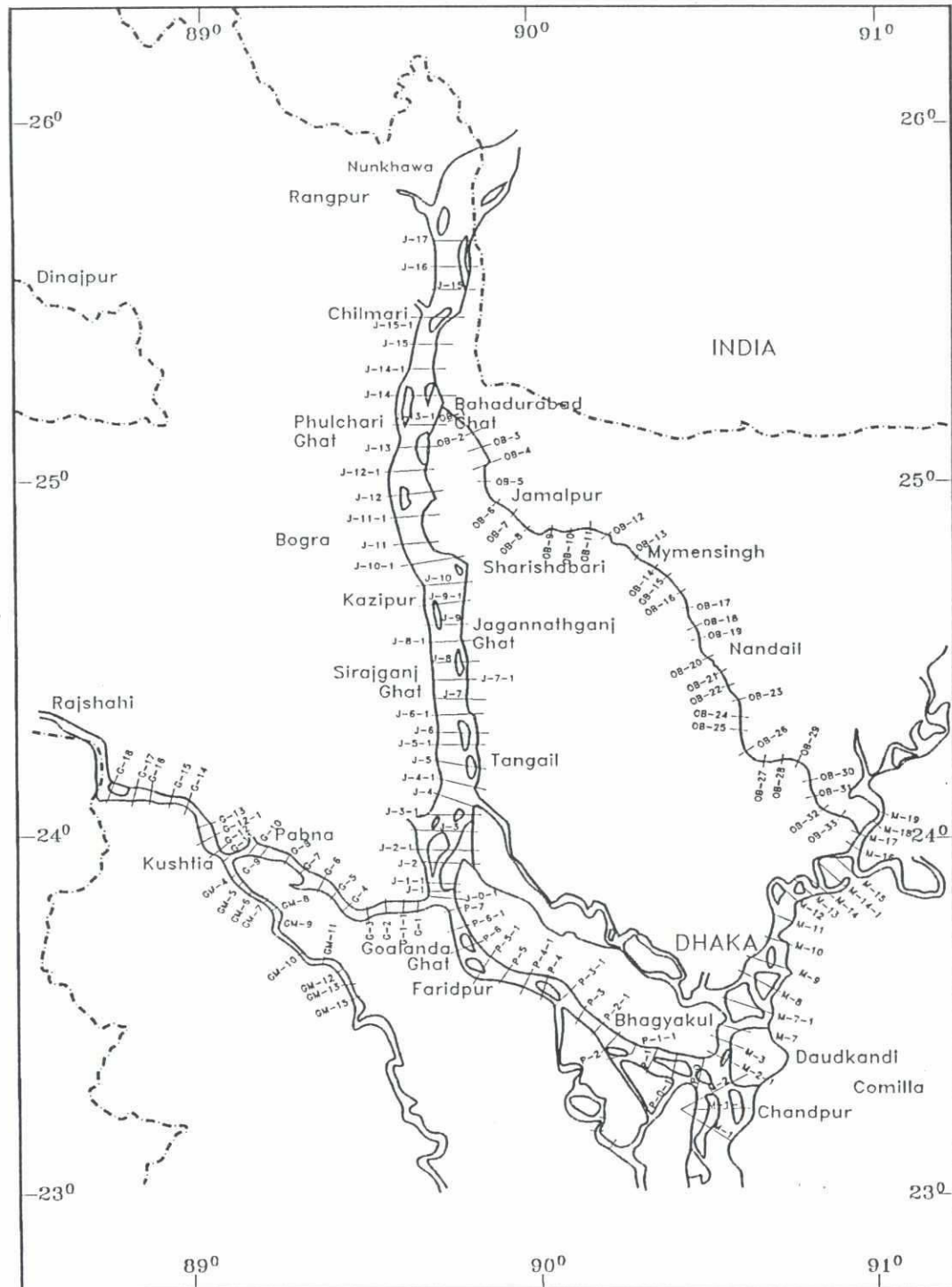


Figure 3.4 Standard BWDB cross-sections in the main river system (SR 3, Figure 3.13)

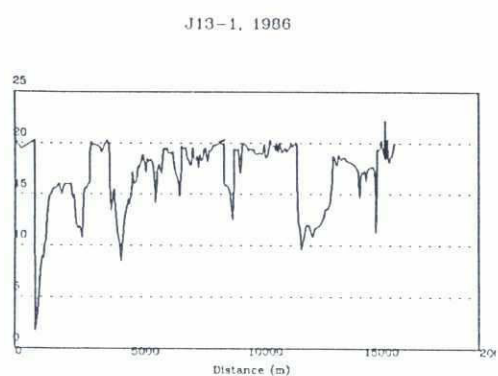
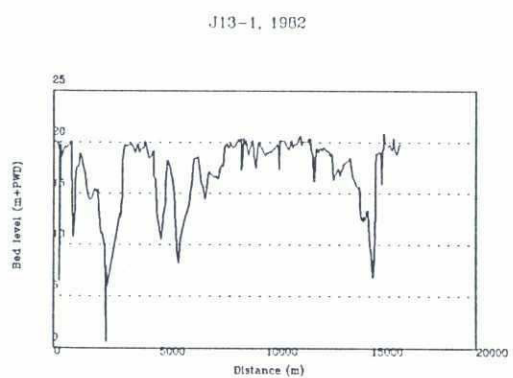
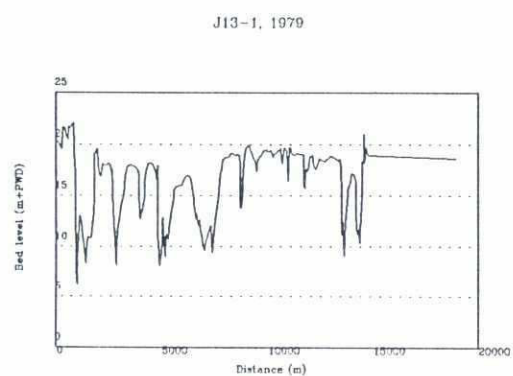
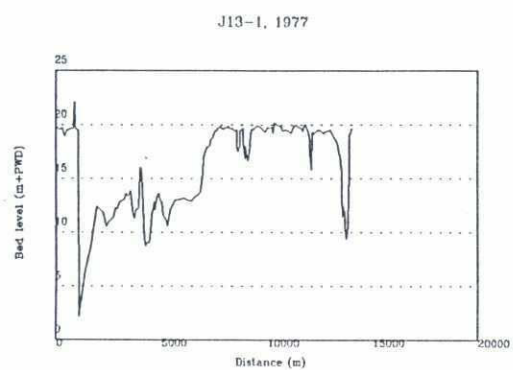


Figure 3.5 Cross-section J13-1 of the Jamuna River and its variation in time



In the Ganges, Padma and Meghna rivers the standard cross-sections were measured yearly from the sixties onwards with some short interruptions of only a few years. In the smaller rivers like the Dhaleswari, Gorai, Arial Khan and Old Brahmaputra rivers the cross sections were surveyed less regularly and systematically than in the main rivers. But the morphological changes in the cross-sections in those smaller rivers are also less dynamic than in the main rivers.

Railway Department

The Railway Department surveys the river bed near Hardinge Bridge, Bhairab Bazar Railway Bridge and Gorai Railway Bridge as part of the monitoring of scour holes and bed protections around the piers. The routes of the railway ferries crossing the Jamuna River between Bahadurabad and Fulchari and between Jagannathganj and Sirajganj are also sounded more or less regularly to monitor the least available depth for the ferries. The oldest sounding map dates back to 1946, but most of the available maps were prepared in the nineteeneighties and very few in the nineties.

Other projects

In recent years, several feasibility and design studies have been performed by consultants for projects often concentrated on a specific stretch of a river. In the framework of these studies some special cross-section surveys of the project area were made. A few examples of such surveys are given.

At the site of the Jamuna Multipurpose Bridge, several bathymetric survey campaigns were executed by BWDB's Morphology Division, Jamalpur in 1990 and 1991. The survey covered a stretch of the Jamuna River with a length of about 5 km. In this stretch nine cross-sections were taken at an interval of 500 m. A number of additional bathymetric surveys with more dense survey lines were carried out later in this area, for instance SWMC (1995).

For the design of the Road and Highways Bridge over the Upper Meghna River, 15 cross-sections were surveyed in the period 1989–1992. These cross-sections cover a stretch of the river of about 11 km. South West Area Water Resources Management Study (FAP 4) surveyed the Gorai River from the mouth to the Kamarkhali Bridge and the mouth of the Arial Khan with eight cross-sections in the Padma river near the offtake in the period 1992–1993. These examples illustrate the type of cross-section surveys done for special projects.

3.3.5 Bathymetrical data

The *Bangladesh Inland Water Transport Authority* (BIWTA) prepares bathymetric maps for monitoring of the least available depth in inland navigation routes. In general, these soundings cover a short stretch of the river and often not the full width of the channel, while also the adjoining chars are not surveyed.

The BIWTA started to make bathymetric surveys in 1967. From 1975 onwards almost every year one and often more soundings have been made in the ferry route from Aricha to Nagarbari. In the ferry routes from Sirajganj to Bhuapur and from Bahadurabad to Fulchari the frequency of the soundings is less. In the Ganges-Padma River (mostly from Goalundo to Mawa) soundings have been made since 1969. Soundings in the Meghna River have been made from 1964 onwards at more or less regular intervals. The contour lines relative to SLW or ALLW are drawn on maps at scales ranging from 1:5,000 to 1:50,000.

In the Old Brahmaputra, Dhaleswari and Arial Khan rivers only very few (one to five) soundings were made.

The BWDB did not make regular bathymetrical soundings in the main rivers.

Other projects

For special projects related to the construction of bridges, bank protection structures etc. some special bathymetric surveys of the project area were made. A few examples of these surveys are given.

Within the frame-work of the Meghna River Bank Protection project (FAP9B) a bathymetric survey was made from Mawa on the Padma to Haimchar on the Lower Meghna River in February-March 1991 and from the confluence of the Padma and Upper Meghna Rivers (Eklashpur) to Haimchar in August 1991. The distance between the survey lines varied from 100 m and 500 m to 2,000 m. After the completion of the Meghna Roads and Highway Bridge in 1990, the consultant conducted a detailed survey in an area near the bridge site. Maps were prepared with depth contour lines at a scale of 1:3,000. The River Training Studies of the Brahmaputra River (FAP1) defined two test areas in the Jamuna river. Three bathymetric surveys were carried out in test area 1 at Sirajganj in 1990 and two surveys in test area 2 near Kazipur in 1991. The Bank Protection and River Training (AFPM) Pilot project surveyed selected test-areas along the Jamuna River in the period 1992 to 1996. These test areas were located near Kamarjani (north of Manos Regulator) and downstream of Bahadurabad ghat. Some of these surveys included a topographic survey of the adjacent floodplain over a width of 1,500 m. The river channel was not surveyed over its entire width. Contour maps were prepared at a scale of 1:5,000.

These examples of bathymetric surveys for special projects are especially important for river studies, if they cover a larger area with different morphological features and if they are repeated so that these maps can be used to determine difference maps to study the morphological changes over time.

3.3.6 Planform data

A main source of data on the planform of the rivers are topographic maps. Since the sixties aerial photographs are sometimes used for planform studies. In the last decade the use of satellite images for this type of studies has developed rapidly.

Topographic maps

The oldest maps of the main river system are James Rennell's maps made between 1764 and 1776. These maps were the basis for the famous Bengal Atlas, which was the standard map for the East India Company for many years. A detail of a map made by engraver John Lodge and printed in the Political Magazine in 1785, shows the Brahmaputra River and the Teesta River following their old courses, see Figure 3.6. Since then a number of historical maps were produced by different organizations, of which some famous ones are: B.N.J Wilcox, 1828; British Admiralty, 1840; maps of the districts Jessore, Faridpur and Dhaka showing the rivers Ganges, Padma and the Gorai, 1855-1860, and Indian Atlas by J. Walker, 1866. Col. S.G. Burrard of the Survey of India issued 3 detailed maps of the complete Jamuna River in 1914. These are the old maps which have been traced in libraries and offices. The geographical coordinates on those historical maps are sometimes missing, and if they are indicated on the map they are less accurate. Often the location of old towns can be used for geo-referencing these maps.

The Survey of Bangladesh (SoB) prepares standard topographic maps covering Bangladesh at a scale 1:50,000. An inventory (*RSP, Study Report 3, 1993*) identified 198 of these maps. Some maps are printed in a small scale (1:250,000). The first version of those maps had been prepared in the fifties. In total 72 of the maps were revised in 1990/1991 on the basis of information obtained from aerial photographs of 1983. Each standard topographic (1:50,000) map covers an area of about 15 x 15 km² divided in 9 standard sub-areas of which detailed maps with contour lines were prepared, see Figure 3.6 in which the numbering system of these maps is indicated.

In addition to these standard topographic maps, different organizations made topographic maps of small areas for special purposes. For example the BWDB prepared topographic maps of some areas east of Meghna River and of an area around Dhaka (FPCO, 1992). In February 1992 FINNMAP/BIWTA prepared maps at a scale 1:10,000 and 1:20,000 of some areas near Jamalpur, Sirajganj, Tangail and the Coastal Zone.

Aerial photographs

According to the FAP ATLAS (FPCO, 1992), the Survey of Bangladesh has aerial photographs of the entire Bangladesh from 1975 at a scale 1:30,000 and from 1983 at a scale 1:50,000. In December 1990 FINNMAP/BIWTA made aerial photographs of the whole Jamuna river. This project prepared black and white photographic prints at scales 1:20,000 and 1:50,000 of a wide strip covering both sides of the Jamuna River. Each photograph covers an area of about 4.3 x 4.3 km². These prints show many details such as the dune pattern on bars which become dry during the lean season. As examples of what can be seen on aerial photographs he (Coleman 1969) showed upwellings seen on the water surface and crevasse-splay deposits on the banks of a Jamuna channel. The South West Area Water Resources Management Study (FAP 4) studied aerial photographs of the Ganges, the Padma and the Gorai Rivers.

The feasibility study of the Jamuna Bridge (JICA, 1976) used the aerial photographs of the Jamuna River taken in 1963.

Satellite images

Satellite images can be obtained from SPARRSO (Space Research Remote Sensing Organization), WARPO (previously FPCO) and from the EGIS project. LANDSAT images of Bangladesh have been made since 1973 and these images are the oldest available series of satellite images (*RSP, Study Report 3, May 1993*). The EGIS project cannot only process the computer compatible tapes (CCTs) of satellite images, but it can also analyze these images by using powerful GIS techniques. Furthermore, EGIS acquired the more recent images from the Thematic Mapper (TM) on-board the LANDSAT 4 and 5 satellites and a few images by the Marine Observation Satellite, MOS-1, during 1992 and 1993. WARPO possesses prints of recent images from the French operated SPOT (Systems Probatoire d'Observation de la Terre). This series consists of two images per year from 1989 to 1995. These images are more detailed than the Landsat images.

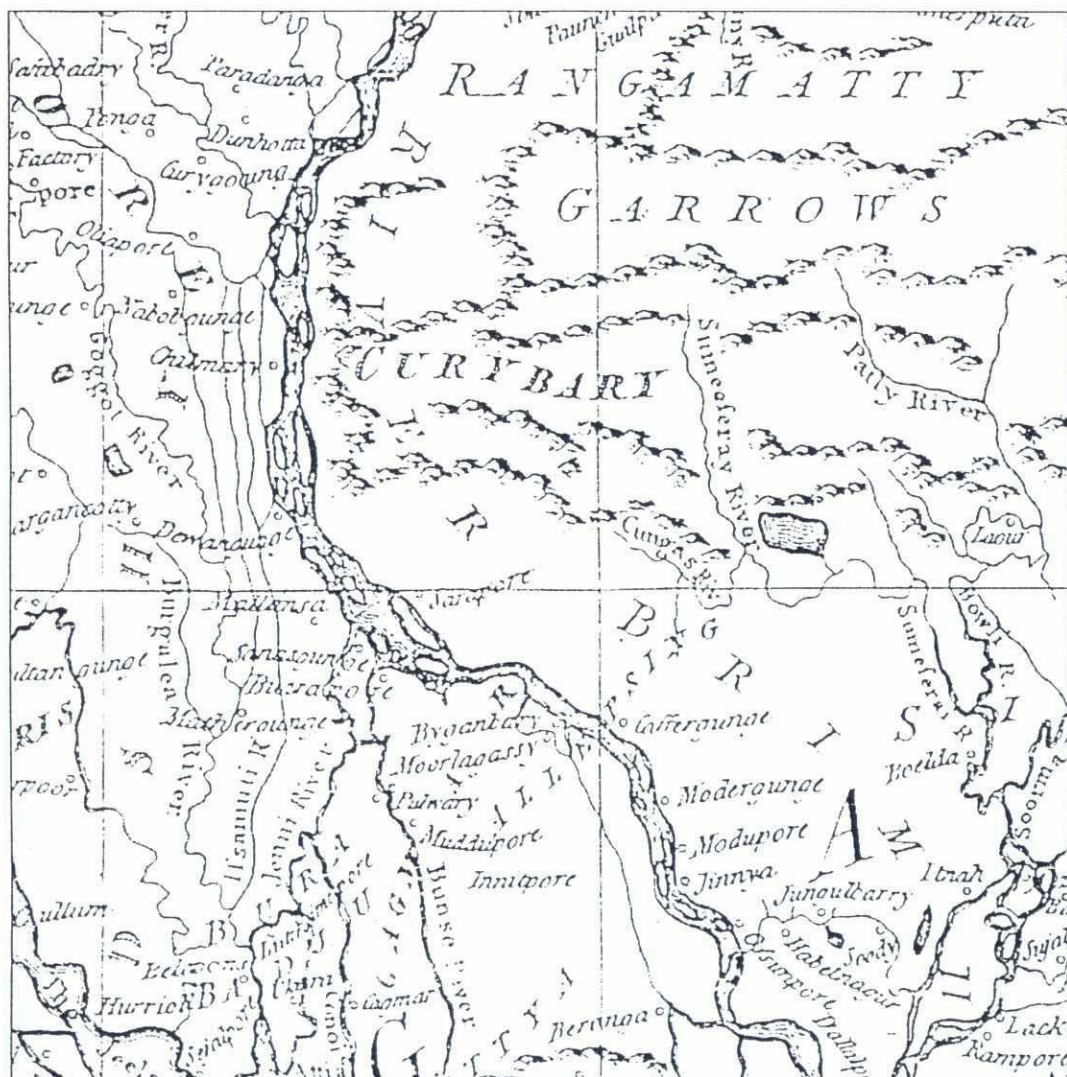


Figure 3.6 Detail of a historic map of the Brahmaputra River, drawn up by James Rennel (1765)

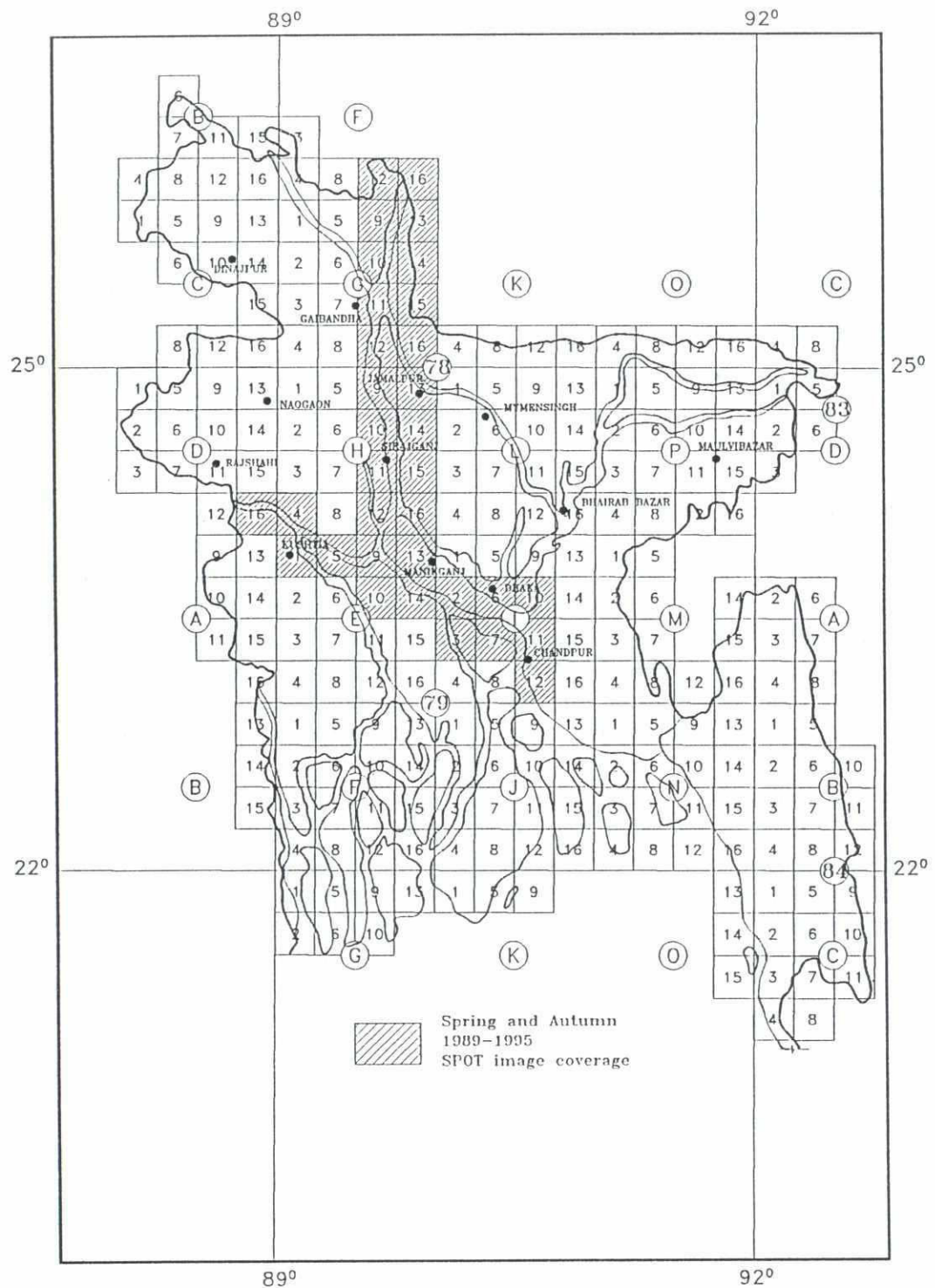


Figure 3.7 Numbering system of the maps with the geographic co-ordinate system

3.4 Data accessibility

Long term hydrological, morphological and sedimentological data are essential for water resources development projects, assessment of the navigability of the rivers, fisheries and the planning, design and implementation of river training works, bridges and other river crossings. Therefore, a large group of users in private organizations, non-governmental organizations and consulting firms need easy access to existing data.

Traditionally, data relevant for river studies have been stored in reports, booklets, maps and drawings, which are available in the libraries of different government offices, most of them in Dhaka. During the last decade data are also stored in electronic databases and on computer compatible tapes. Most of the data collected by RSP are published data as RSP had very limited access to unpublished data. Data which were published and stored in databases or in archives are discussed here.

3.4.1 Published data

The Hydrology Organization of the BWDB, SWH-II, is one of the pioneers in water-related data collection and storage. They collected reasonably long series of hydrological data (Hoque, Shamsul, 1993). All the original field sheets are stored in the office of SWH-II. Until 1977 a hydrological year book for hydrological data was produced regularly by SWH-II. Recently, SWH-II has stored water levels, daily discharge data etc. starting from the beginning of the sixties in a computerized data base. Users can purchase hard copies of the data.

The River Morphology and Research Circle of BWDB takes care of the cross-sectional data for all the rivers of Bangladesh. After processing, a copy of the processed data can be purchased. For the period 1960-1984 data are available as a drafted cross-section profile. Since 1984, the said Circle started to publish the cross-sectional data in book form. They started with the data of the Jamuna River. Since 1988 the data are published as "Morphological Survey Data Book of the River....." on regular basis for all the major rivers in Bangladesh. The time for processing and validation of the hydraulic data has been reduced to about a half year and for sediment data to about one year.

Historic maps of Bengal, which were published during the period 1765-1950, were collected among others by the Geology Department and the EGIS project. Copies of these maps can be obtained in the respective offices.

The FPCO, now WARPO, received prints of recent SPOT images of the main rivers for the period 1989-1995 both for autumn and spring. The Survey of Bangladesh has aerial photographs of the entire Bangladesh in 1975 at a scale 1:30,000 and for 1983 at a scale 1:50,000. The Survey of Bangladesh has a good library, where many maps can be found.

As mentioned earlier BWDB is the only organization which is carrying out systematically sediment transport measurements in the rivers all over Bangladesh. The historical sediment transport data for the period 1957 till 1965 for the major rivers were published by the Hydraulic Research Laboratory as sediment report "Report No. Sed - (year)". All these reports are available in the library of SWH-II. Suspended sediment transport data for both fine and coarse sediment fractions as well as results of grain-size analyses of riverbed materials, for ten gauging stations for the period 1966 and 1970, were published in a report, which

is one of the oldest available reports on sediment transport measurements in the main rivers (BWDB, 1969 and 1972). After 1970 the Hydraulic Research Laboratory produced regular reports on the suspended fine sediment concentration data. In the eighties the Hydraulic Research Laboratory was converted into River Research Institute and transferred from Dhaka to Faridpur. The field sheets of suspended coarse sediment data are stored in bound book form. The grain size distribution of samples of the river bed were published by the Hydraulic Research Laboratory for the period 1966-1977.

All these data have been collected by SWII-II and they are stored in a computerized database or in their library. Hard copies can be purchased. Some sediment transport data have been collected also by MPO and SWMC.

Some important publications on sediment transport data and morphological processes have been made by different consultants in their reports, for example International Engineering Company (1980) and various FAP projects. All the reports of the FAP projects are available in the library of WARPO. But the reports of other projects are often very difficult to find. It is recommended to establish a specialized library for the water sector, where all the reports prepared by consultants and experts can be borrowed by the users.

3.4.2 Databases

The storage of data in computer data bases is a rather recent development which requires coordination between the involved organizations and agencies.

The hydrological and sedimentological data for all the gauging stations in Bangladesh were collected and stored by SWII-II, BWDB. The mean daily water level data at Hardinge Bridge available since 1910 and for most of the other main stations since 1960. The field sheets for hydrological data for each station have been computerized until 1994 and were stored in a database called "MSACCESS DATABASE" ORACLE/RDBM.

Most of the data since 1966 have been computerized and stored in a computer database under the above mentioned name. The fine sediment transport data which were published by the River Research Institute were also incorporated in the database. However, the data on grain-size distributions of bed material samples are not yet stored in the database.

Recently, under the consultancy of the UNDP, the River Morphology and Research Circle, BWDB, started storing cross-sectional data in a computer database. The data entry is at an initial stage. At this moment the database contains data for the period 1993-1994 for a few rivers only. The cross-sectional profile data until 1995 are available.

The *Surface Water Modelling Centre* (SWMC) has, during its ten years of operation, assembled a large volume of data needed for its modelling activities. The databases of SWMC include hydrometeorological, hydrometric, bathymetric/topographic data (SWMC, 1993) and recently also sediment transport data. Data used in modelling have been through quality checking procedures. A smaller part of the data were collected by SWMC in their own measurements, the remaining were collected from other organisations or handed over from completed FAP projects or other development projects.

The current EGIS project aims to establish GIS databases of different kinds of maps. The map resources of EGIS, besides other maps, include remote sensing data like infra-red as well as black and white aerial photographs, LANDSAT TM and MSS, and radar satellite images like ERS-1, MOS-1 and Radarsat (in the process of acquisition). These data are stored in computer compatible tapes (CCTs).

The planform information of rivers from SPOT sheets of 1:50,000 scale, topographic information from BWDB maps of 1:7,920 and 1:15,840 scale, locations of the hydrometric stations from BWDB, and information on many other geographic features are stored in the EGIS National Database.

The LANDSAT images for the period 1972-1991 were collected by SPARRSO as a beginning of a database on satellite images.

3.4.3 Data in archives

For a long time, data for river studies have been stored in various archives. Some of them are described here.

The old field sheets on suspended coarse sediment transport data are missing at SWII-II. The field sheets of data measured since 1976 were bound together in books which are available for most of the stations. Recently, SWII-II decided to store all the historical data in their database for water levels, discharge and sediment transport in archives as backup files.

The bathymetric charts until 1994, showing contours of all the inland navigation routes in Bangladesh, are in an archive with BIWTA.

SWMC has a library of maps and satellite imageries, some of which were inherited from FAP25 after the information and expertise of this project was transferred to SWMC in 1994/95.

The Environment and GIS Support Project of Water Sector Planning (EGIS) has inherited a stock of maps from FAP 19 and other organizations. That project collected maps of different organizations, for example topographic maps of the Survey of Bangladesh (SoB), contour maps of the Bangladesh Water Development Board (BWDB), maps prepared by the Bangladesh Space Research and Remote Sensing Organization (SPARRSO), the Local Government Engineering Department (LGED), the Geological Survey of Bangladesh (GSB), the Bangladesh Inland Water Transport Authority (BIWTA), and other organizations and development projects.

In general, a long-term strategy for the selection of data to be stored in archives and computer databases should be established after consultation of users and the different organizations and agencies involved in data collection. The data collection, storage and retrieval demand a regular updating with the new developments in technology in the field of storage and retrieval methods.

Part B

Project Activities Studies and Training

4 Project activities

4.1 Introduction

The RSP began operation on June 9, 1992, and continued for a period of four years. Some milestones of the Project are listed in Table 4.1.

Phase 1 (June 9 1992 - December 31 1993)	
Award of contract, start of procurement	May 22, 1992
Team Leader's arrival, official project start	June 9, 1992
Arrival of equipment (1st consignment)	August 4, 1992
First survey (at Bahadurabad, by BWDB's 'Anwesha')	September 6-20, 1992
Performance tests at Bahadurabad	October 21 - 28, 1992
First routine flow and sediment transport gauging at Bahadurabad	January 14-16, 1993
Installation of two AWLRs at Bahadurabad and Gabgachi	June 1-2, 1993
Test gauging, comparing the 'reference method' and the 'recommended method'	August 16-22, 1993
International Workshop in Dhaka	November 6-9, 1993
Technical and administrative finalisation of scope of Phase 2 river surveys	December, 1993
Phase 2 (January 1, 1994 - June 8, 1996)	
First Phase 2 flow and sediment transport gauging (at Bahadurabad)	January 29 - February 1, 1994
Last routine gauging (at Hardinge Bridge)	March 2, 1996
Completion of the vessel survey programme (bathymetry at Gorai Off-take)	April 6, 1996
Completion of AWLR gauging	May 31, 1996
Project completion	June 8, 1996

Table 4.1 Chronology of the Project

	SURVEY COMPONENT	STUDY COMPONENT	TRAINING COMPONENT
Phase 1 (June 92 - December 93)	Mobilisation; pilot surveys of flow, sediment transport and bathymetry; bench mark validation programme; water level gauging at Bahadurabad; test gauging of field techniques; routine flow and sediment transport gauging at Bahadurabad; bathymetric surveys; planning of the Phase 2 programme	Phase 1 studies: Hydrology, sediment transport, morphology, physical impact of FAP implementation; FPCO International Workshop on 'Morphological characteristics of alluvial rivers'; preparation of Phase 2 study programme	In-house on-the-job training in survey techniques and data processing; dedicated training programmes for BWDB staff; preparation of Phase 2 training programme
Phase 2 (January 94 - June 96):	Phase 2 mobilisation; water-level recordings and routine flow and sediment transport gauging over the entire project area; bathymetric surveys; special surveys	Phase 2 studies: Hydrology, sediment transport, morphology, survey techniques	Continued in-house on-the-job training; dedicated training programmes for BWDB staff; external workshop on use of RSP databases

Table 4.2 Execution of the RSP

The project was divided into two phases, as shown in Table 4.2. As compared with the ToR, Phase 1 was extended by half a year because of the late project start relative to the 1992 flood season, and in order to accommodate delays during the initial mobilisation. A location map of the project area is shown in Figure 4.1.

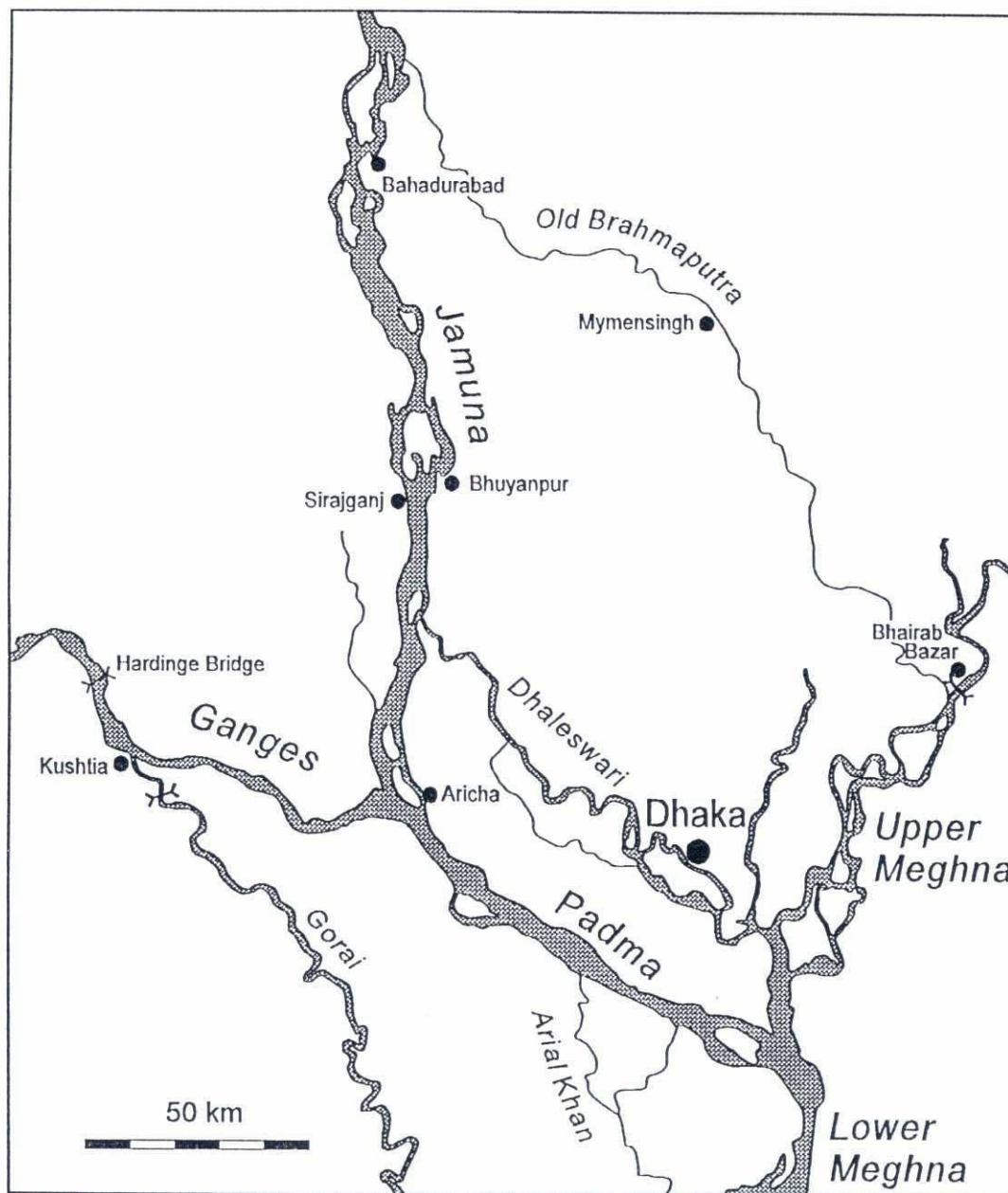


Figure 4.1 Location map

4.2 Surveys

The objective of the RSP field survey component is 'to collect reliable all-season hydrological, morphological and hydrographic data at key locations on the country's main river systems with emphasis given to collection of data during the monsoon season, introducing improved or new technology where appropriate' (ToR Section 3.1).

The RSP river survey component is illustrated in Figure 4.2. It comprised the following activities:

- mobilisation and test gauging;
- zero level validation of 47 BWDB staff gauges;
- water level gauging (12 AWLR stations and 15 additional staff gauge stations);
- routine gauging of flow and sediment transport at 11 cross-sections;
- special surveys for different specific purposes;
- bathymetric monitoring of seven areas; and
- topographic (land) surveys.

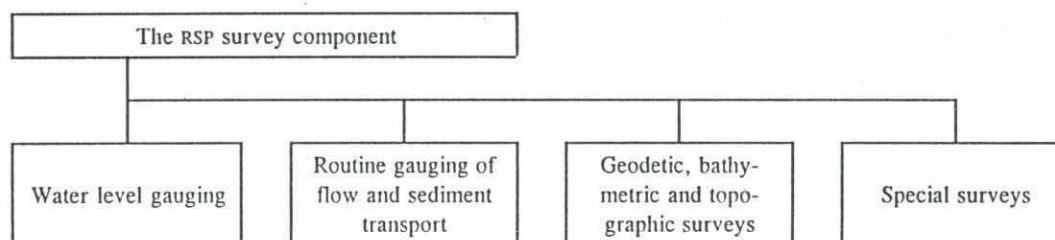


Figure 4.2 The RSP survey component

Within each phase, the work was divided into a monsoon season programme (June through October) and a lean season programme (November through May). The hydrological year in Bangladesh proceeds from April through March. A short outline of the implementation of the survey programme is given on the bar chart in Figure 4.3.

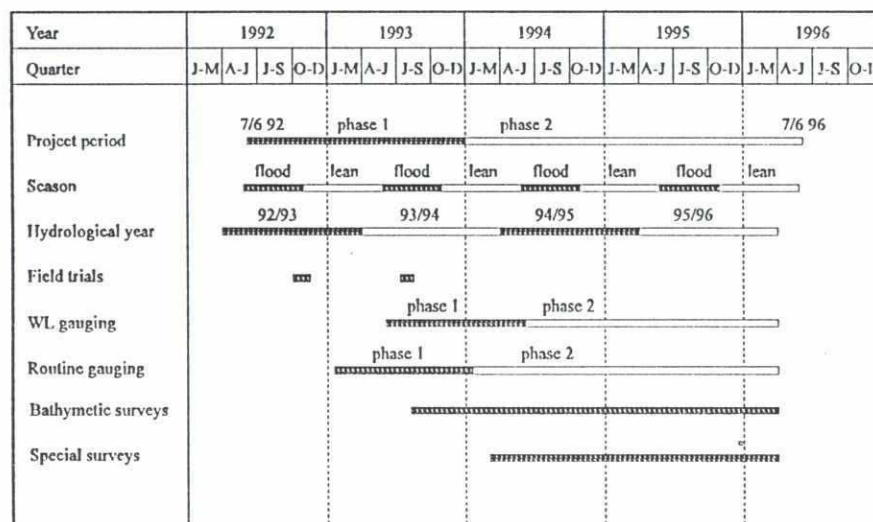


Figure 4.3 Bar chart of survey activities

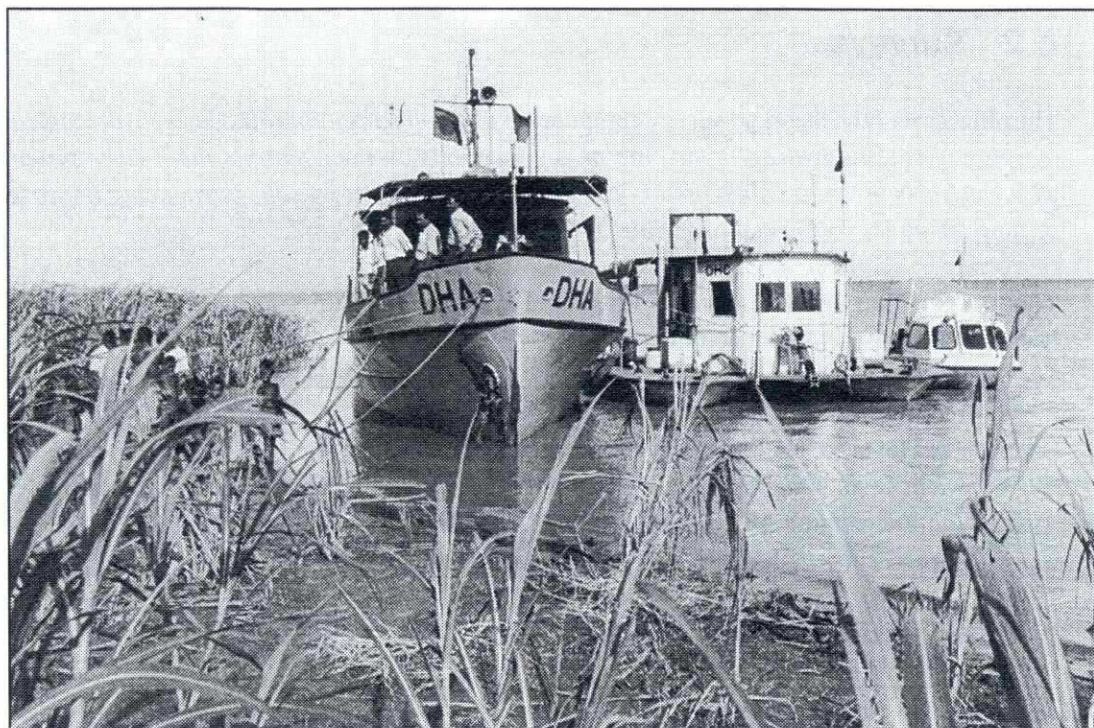


Figure 4.4 Some of the RSP survey vessels

4.3 Studies

The objective of the RSP study component was *'to undertake special studies of the behaviour of the river systems based on the new data that will be collected, existing data and through supplementary surveys The river studies would address aspects of the main river system that are essential for the planning of projects under the Flood Action Plan. ... The studies will be undertaken in response both to the demands of ongoing FAP studies and to the possible effects of planned Flood Action Plan projects on river regimes'* (ToR, clauses 3.1 and 3.4).

A tentative outline of the study activities was presented in RSP Study Report 1. The programme was discussed in connection with an International Workshop arranged by FPCO in Dhaka in November, 1993, and has subsequently been elaborated and amended in a dialogue with PA/RSPMU. Proceedings of the Phase 1 study activities were presented in *RSP Study Report 2: 'Hydrology'* and *RSP Study Report 3: 'Morphology'*.

The study programme for Phase 2 was presented in *RSP Final Report Phase 1*, and, in more detail, in a special report on the Study programme'. Progress of the work, and recommendations on adjustments of scope and time schedule, have been presented in the *RSP Interim Reports* and have been discussed with the PA throughout the project.

The initial programme was structured into a set of subjects, each subject covering a number of topics, as summarised in Table 4.3. The emphasis put on individual topics varied according to assigned priorities, available resources, etc. The study programme was regularly adjusted in close coordination with the PA/RSPMU. In the course of the project, results were reported in *RSP Working Papers* and *RSP Study Reports*, which at the end of the project were "replaced" by *Special Reports*.

The study programme was undertaken partly by a team of Bangladeshi professionals who were full-time attached to the Project, partly by a number of expatriate specialists, and partly by external institutions in Bangladesh and abroad, such as:

- Bangladesh University of Engineering and Technology (BUET)
- Virginia Institute of Marine Sciences and Wood's Hole Oceanographic Institute
- University of Nottingham
- University of Leeds

SUBJECT	TOPIC
Hydrology	Improved discharges and rating curves
	Improved historic discharge time series
	Water balances and overland flow
	Water level profiles and slopes
Sediment transport and river aggradation and degradation	Rating curves and balances
	Sediment transport predictors
	Long-term development of distributaries
	Flood plain subsidence
	High sediment concentrations
Planform characteristics and channel dimensions	Fine sediments
	Planform classification
	Channel dimensions (regime equations)
	Bank erosion rates
	Channel cut-offs
	Local slopes and their importance for planform changes
	Prediction of medium-term planform changes
Off-takes, bifurcations, confluences	Long-term changes of river locations
	Discharges and sediment distribution
	Influence of bars
Sand bars	Confluences
	Dimensions and dynamics of bars
Bed forms	Time dependency of bars
	Occurrence, dimensions, and dynamics
	Time dependency of bed forms
	3-dimensionality of bed forms
Measuring techniques	Roughness and bed forms
	Selection of measurement sites
	Optimization of hydraulic measurements
	Optimization of sediment measurements
	Bathymetry and radar imagery
	Sustainable survey techniques

Table 4.3 Study subjects

4.4 Training

The training activities of the project can be divided into:

- In-house training of project team members;
- in-house training of external specialists; and
- external training and professional relations.

The activities within each category are listed in Tables 4.4, 4.5 and 4.6.

As a part of the basis for the training, the RSP produced a series of '*RSP Lecture Notes*' and a series of '*RSP Workshop Contributions*'.

In 1994, an engineer of the project team was granted a one-year fellowship at IHE, The Netherlands.

- On-the-job training
- navigation and vessel operation
- survey techniques
- sediment analyses
- two-dimensional hydrodynamic and morphological modelling (SWMC)

Dedicated training courses

- basic hydraulics
- basic hydrology
- river dynamics
- hydrodynamic modelling
- presentation techniques
- use of PSD24
- use of C-programming
- use of HYMOS software package
- use of Autocad
- use of Fortran 77

Internal lectures

- coastal dynamics
- rainfall-runoff modelling

Table 4.4

In-house training of project team members

- Survey techniques (BWDB) (1993-95)
- Data administration (BWDB) (1993-95)
- Data processing and database administration (SWMC) (1996)

Table 4.5

In-house training of external specialists

January 93:	Training course on sediment transport and hydraulic roughness (BWDB, BIWTA)
May 93:	Training course on river dynamics (BWDB, BIWTA)
June 93:	Lecture on GPS/DGPS positioning (Hydroland, BIWTA)
May 94:	Joint BWDB/FAP24 workshop about river survey techniques (Bhagyalakul, 11/5 94)
July 94:	RSP participation in SWII internal workshop (Bhagyalakul 5/7 94)
April 95:	MSc student from BUET attached to the Project
May 95:	Lecture at BUET (by Dr. Phil Ashworth)
November 95:	Lecture about 'Geological controls of Bangladeshi rivers' (by Mr. Kurshid Alam, Director of Geological Survey of Bangladesh)
November 95:	Participation in the 4th FAP Conference in Dhaka 30/11 - 1/12 95
May 96:	Training workshop on data processing and RSP databases (WARPO, BWDB, BIWTA, SWMC)
May 96:	Lecture at BUET (by Prof. Colin Thorne)

Table 4.6 External training and professional relations

4.5 Assistance to other (FAP) projects

The direct relations between the RSP and other projects with respect to joint data production, data analysis or studies are summarised in Table 4.7. Not mentioned in this table is the upcoming '*Morphological Impact Assessment study*' (FAP27), which is expected to benefit much from the RSP surveys and studies.

WRIS ¹⁾	Liaison about data administration, routine gauging, tidal surveys
FAP1, FAP3, FAP4, FAP5	Liaison about data requirements
FAP16	Liaison about flood plain sedimentation studies, bathymetric surveying and data analysis
FAP18, FAP19, FAP21/22	Liaison about geodetic positioning
FAP20	Supply of data from Jamuna River
FAP21/22	Execution of dedicated surveys at Karmarjani (of bathymetry and flow pattern)
FAP19/EGIS	Collaboration on morphological monitoring and studies
1) Water Resources Information System, a UNDP/BWDB development project	

Table 4.7 Relations between RSP and other projects

4.6 Reporting and other outputs

4.6.1 Reporting

The RSP produced the following series of reports:

- Final Report, summarising the findings of the project and the induced recommendations (the present Main Volume and five Annex Volumes);
- Special Reports, covering a range of specific topics (24 titles);
- Survey and Study Reports, covering a range of specific topics (ten titles);
- Survey Notes, mainly working papers and internal guidelines with information about the survey work, (eleven titles);
- Various Reports, mainly internal guidelines, working papers, or interim findings (ten titles);
- Contributions to the FPCO Workshop 6-8 November 1993 (6 titles);
- Lecture Notes, as a basis for internal and external training courses (5 titles).

The progress reporting comprised an Inception Report, a Phase 1 Final Report, three Interim Reports (one for Phase 1 and two for Phase 2), and a series of 15 Quarterly Progress Reports. See also Appendices A and B attached to this report.

4.6.2 Databases

The data produced by the RSP are stored in three databases:

- The HYMOS database (with water-level data);
- the PSD24 database (with results of vessel surveys: routine gauging, special surveys, and bathymetric surveys); and
- the RSP sediment database (with sediment analyses).

Each database is structured in order to facilitate identification and retrieval of the many different data files. The data are listed in *RSP Special Report 22: 'Data Book 1993/95'* and *RSP Special Report 23: 'Data Book 1995/96'*.

5 Applied survey techniques

5.1 Introduction

The objective of the RSP field survey component was *'to collect reliable all-season hydrological, morphological and hydrographic data at key locations on the country's main river systems with emphasis given to collection of data during the monsoon season, introducing improved or new technology where appropriate'* (ToR Section 3.1).

The RSP field measurements comprised

- operation of a network of water level gauges in the main river system;
- a routine gauging programme of flow and sediment transport measurements;
- a programme of repeated bathymetric surveys of selected areas; and
- a programme of non-routine surveys for specific purposes related to the study component of the Project.

The present chapter gives an outline of the survey techniques implemented by the RSP. The techniques were initially identified in connection with the Consultant's proposal preparation. They were comprehensively developed during the contract negotiations, mobilisation, and the Phase 1 test gauging, which took place in a close dialogue with the PA. Based on experience from Phase 1, certain adjustments were made in connection with the Phase 2 mobilisation.

The results of the surveys are summarised in the following Chapter 6.

Please refer to *RSP Final Report Annex 1: 'Surveys'* and *Annex 2: 'Sustainable survey techniques'* for a more detailed description of the survey component and the experience gained in connection with its execution.

5.2 Measuring methods and instruments

5.2.1 Survey vessels

Three survey vessels – DHA, DHC and DIID – were mobilised for Phase 1 of the project, and two additional ones, DIIB and DHE, were added for Phase 2. Specifications for the vessels are given in Table 5.1 below. In addition to these vessels, the Project applied another motor vessel, the DHF, for auxiliary purposes and for dry season bathymetric surveys. The installed survey equipment is listed in Table 5.2.

Name	DHA	DHB	DHC	DHD	DHE
Length overall	20.2 m	11.2 m	8.7 m	4.9 m	5.2 m
Beam	4.7 m	3.2 m	6.3 m	1.9 m	2.2 m
Draft	1.2 m	0.9 m	0.8 m	0.8 m	0.8 m
Operational speed	12 knots	15 knots	12 knots	12 knots	20 knots

Table 5.1 Survey vessels

Equipment	DHA	DHB	DHC	DHD	DHE
DGPS positioning system	X	X	X	X	X
Echo sounder	X	X	X	X	X
ADCP current profiler	X	X			
EMF flow meter (for horizontal profiling)	X	X	X		
S4 electromagnetic current meter	X		X	X	
Propeller current meter (Ott or Valeport)	X			X	X
Pump sediment sampler	X		X	X	
Depth-integrated sediment sampler	X	X			
MEX turbidity meter	X				
Helley-Smith trap sampler	X	X	X	X	
Delft Bottle	X				
Van Veen grab sampler	X		X		
USBM-54 sampler	X				
Drag sampler				X	X
Side scan sonar (EG&G)	X				
SAFECOM satellite telex link	X	X			
VHF radio	X	X	X	X	X
Walkie talkie	X	X	X	X	X

Table 5.2 Instrumentation of the survey vessels

5.2.2 Positioning

The RSP used the Global Positioning System (GPS), which yielded a *horizontal* accuracy of ± 50 -100 m in its non-differential (GPS) mode, around ± 0.1 m in its stationary, differential (DGPS) mode, and around ± 3 -5 m in its dynamic, differential mode. The modes applied for different survey categories are listed in Table 5.3.

The applied coordinate system was the Bangladesh Transverse Mercator (BTM). This is a transverse Mercator projection that is centred around the 90° meridian, which runs some 40 km west of Dhaka, and some 30 km east of Bahadurabad.

Coordinate shifts from latitude/longitude or from the WGS84 system were made by procedures established for the purpose of the Project in consultation with FAP18. Please refer to *RSP Final Report, Annex 1: 'Surveys'* for details.

Water level recorders	GPS
Reference stations	DGPS or traditional land surveying
Routine gauging of flow and sediment transport	DGPS
Special surveys	GPS or DGPS
Bathymetric surveys	DGPS

Table 5.3 Applied positioning techniques

5.2.3 Water level gauging

The RSP operated twelve AWLRs and eleven additional staff gauges. Another six staff gauges were installed for shorter periods for slope measurements at Bahadurabad and at Gorai Off-take.

The AWLRs were either acoustic or vented pressure cell types. The former were installed on fixed structures (bridges), while the latter were mounted on platforms that were established for the purpose in the rivers. The vented pressure cells registered the pressure difference between the air and the water, so that subsequent compensation for atmospheric pressure variations was not required. One station (Galgachi) was supplied with both types of sensors for the sake of comparison. Each AWLR was supplemented by a set of two staff gauges that were read every 3 hours during daytime (five times per day). These staff gauge readings were applied during the data validation, and had the additional purpose of serving as a stand-by during malfunctioning of the AWLR. In this way, complete records were obtained from all AWLR stations.

Information about the water level gauging programme is given in *RSP Special Report 2: 'Water level gauging'*.

5.2.4 Discharge measurements

Wherever possible, considering the water depth, discharge measurements were made by the Acoustic Doppler Current Profiler developed by RD Instruments. This instrument measures the vertical current profile by the Doppler shift of a transmitted sound wave that is reflected by small particles in the water. A total of four sound beams are used for registration of the three orthogonal components of the current velocity vector relative to the instrument, and hereby relative to the survey vessel. At the same time, the movement of the vessel over the riverbed is registered by the ADCP (and also by the DGPS positioning system), and the orientation of the vessel is registered by a gyro compass. On this basis, the current velocity vector components are transformed into a fixed coordinate system (see Figure 5.1).

Apart from measuring the current, the ADCP registers the water depth, in the same way as an echo sounder, but with a comparatively poor resolution. Therefore, a separate echo sounder was applied for depth registration. Also, the ADCP registers the movement of the vessel over the riverbed, by so-called bottom tracking, which is based on the Doppler shift

of the part of the sound wave that is reflected by the riverbed. Under conditions where the surface of the riverbed is stagnant, the bottom tracking provides a highly accurate means of relative positioning. Under conditions where the riverbed surface is moving, due to a high bed load during strong currents, the bottom tracking cannot supply any meaningful positioning control, so instead, under such conditions, the positioning was made by DGPS.

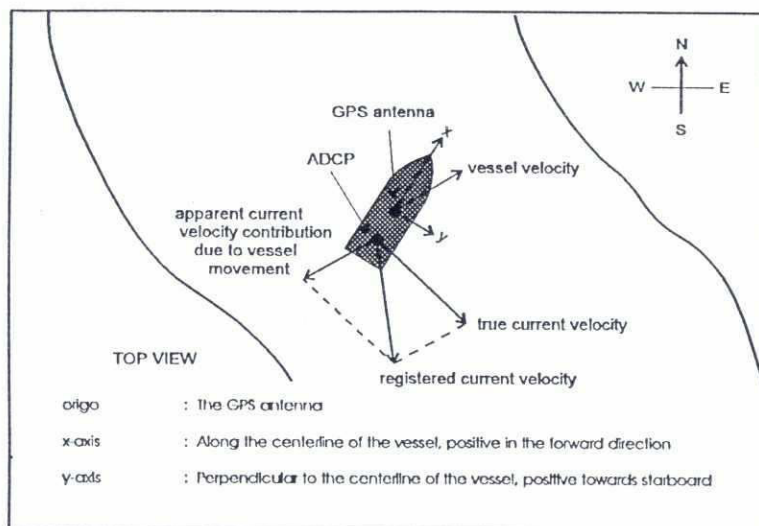


Figure 5.1
Coordinate transformation
of the ADCP
current-registration

The ADCP registration depends on its sound wave frequency (which, for a given instrument, cannot be changed). A higher frequency gives a better resolution, at the cost of a reduced penetration in silt-laden waters. The RSP selected a 300 kHz instrument for Phase 1, hereby giving priority to the data coverage (which indicated a good penetration). The instrument performed well, and no indications of poor penetration were encountered, so a higher frequency (600 kHz) instrument was selected for the Phase 2 capacity extension. Also this instrument performed according to expectations, although the limited penetration was felt occasionally.

The data coverage of the ADCP moving boat method is illustrated in Figure 5.2. The ADCP itself leaves two unmeasured layers: one surface layer, which was covered by an additional EMF instrument mounted on the survey vessel, and one bottom layer, which was not covered by measurements, but where the flow was estimated by a power curve fit. The vertical and horizontal resolution of the current profile can be selected (within certain limits). With the operation mode and survey procedure applied by the Project, the vertical resolution was 0.5 m. The horizontal resolution was determined by the sampling interval, which was one second, by the speed of the vessel, which was 2-4 knots, and by the selected averaging period, which was six seconds. This gave a horizontal resolution of 6-12 m for the purpose of routine gauging. The data flow on board the survey vessel is shown in Figure 5.3.

Field tests proved that the method gives highly consistent flow data. The deviation between successive gaugings or between simultaneous gaugings with different survey vessels indicated a standard deviation (with respect to total flow through the cross-section) of around 3 percent. A wide channel would require several vessels or several days for a flow gauging by the traditional velocity-area method, but could be covered by one vessel in a matter of hours by the ADCP moving boat method.

Please refer to *RSP Special Report 11: 'Optimization of hydraulic measurements'* for a detailed description of the method and a comparison with other flow gauging techniques.

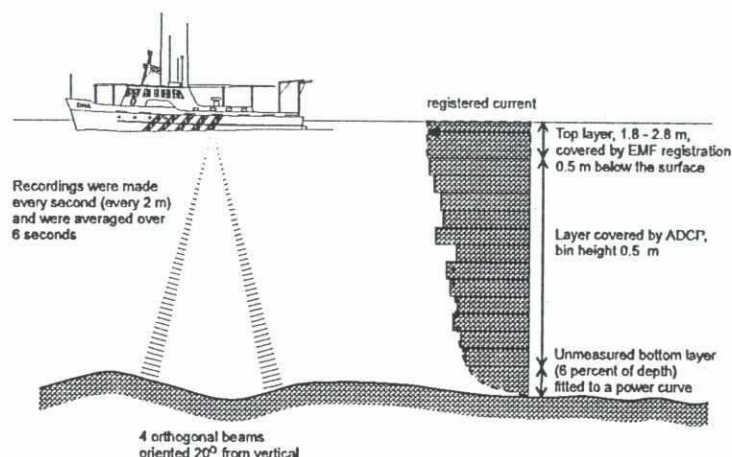


Figure 5.2
The ADCP moving boat method

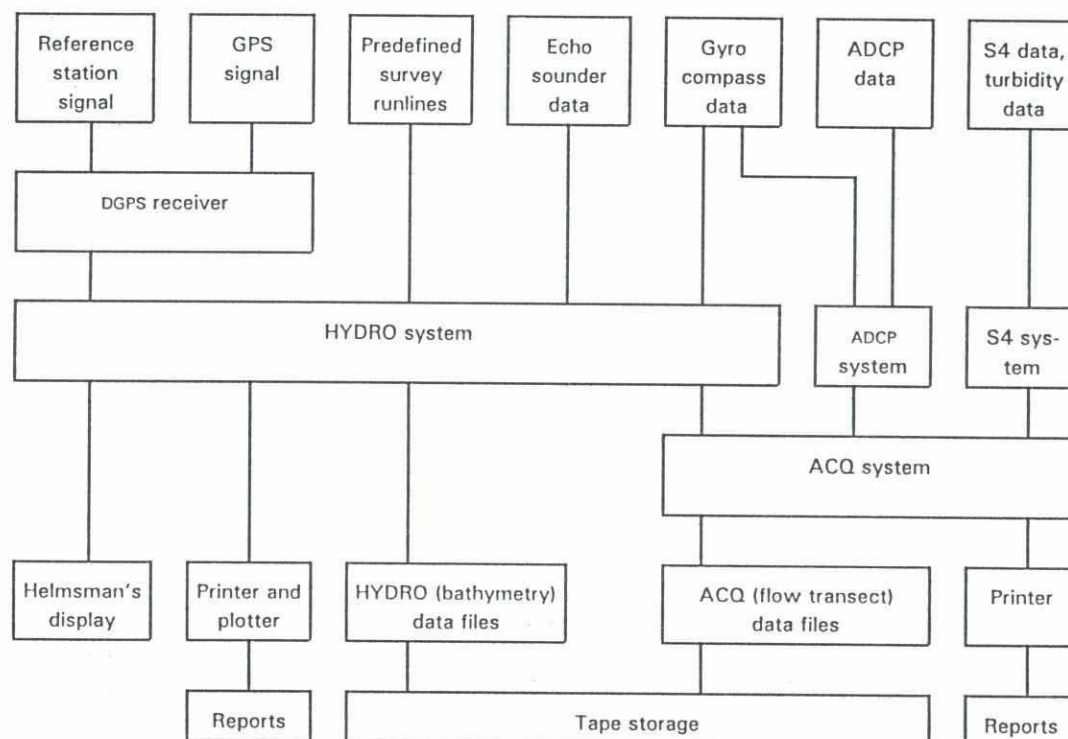


Figure 5.3 On-line data flow for RSP routine flow gauging

In smaller channels the traditional velocity area method was applied.

5.2.5 Sediment transport and other sedimentological measurements

Measurements of sediment transport and sediment characteristics were an integrated part of the RSP routine gauging.

The suspended sediment transport was measured by a velocity-area procedure, based on discrete vertical S4 or ADCP current profiles. The vessel was anchored during sampling of suspended sediment and the simultaneous velocity profile measurements.

The main components of the gauging procedure are given in Table 5.4. In the main channels (with a width above 500 m), the verticals were located on the basis of the ADCP mapping of the flow and sediment distribution, and 8-12 verticals were made. Small channels (with a width below 500 m) were covered by 4 verticals. The vertical was described by 6 points if the depth was above 5 m, and three points if the depth was below 5m.

The bed load and near-bed transport was measured by a Helley-Smith sampler and/or by a Delft Bottle, which give the sediment transport rate directly.

- 1 Longitudinal echo sounder reconnaissance of riverbed features
 - 2 Initial transects in each direction by ADCP, EMF, and echo sounder
 - 3 Vertical profiles:
 - (a) Current by ADCP and/or S4
 - (b) Suspended sediment concentration by pump bottle, and/or turbidity meter, and/or integrated bottle, and/or collapsible bag
 - (c) Pump bottle sampling for settling velocity analysis
 - 4 Bed load and near-bed transport:
 - (a) Helley-Smith sampler, and/or
 - (b) Delft Bottle
 - 5 Bed material by USBM-54 sampler and/or Van Veen sampler
(Since June, 1995, a drag sampler was applied from the smallest RSP vessels and from country boats)
 - 6 Concluding transects in each direction by ADCP, EMF, and echo sounder and/or ADCP backscatter intensity
- Note: As indicated, not all components were applied at all surveys. Please refer to the *RSP 'Data Books'* for a description of the actual programme of each survey.

Table 5.4 Components of the RSP procedure for routine flow and sediment transport gauging

Please refer to *RSP Special Report 12: 'Optimization of sediment measurements'* for a description and evaluation of the different techniques.

5.2.6 Bathymetric measurements

The morphological development of selected areas was monitored by a programme of repeated bathymetric surveys of 7 reaches within the project area. The line spacing was either 100 m or 200 m, depending on the area. To the extent possible, the survey lines were retained from one survey to another, in order to facilitate the analysis of erosion and accretion.

Along the survey lines, soundings and DGPS position fixes were made every 2 m. An A3 track plotter was used to record the vessel's progress on paper charts in scale 1:10,000 with the survey lines pre-plotted.

The on-line data flow was similar to the one applied for the flow gauging (Figure 5.3), except that the ACQ system (serving the ADCP and S4 registrations) was not active.

Dual and single frequency echo sounders were used to record analogue and digital depths. In any case, the resolution of the instruments was better than 1 cm. The beam widths varied from 7° to 24°. The draught of the transducers was regularly measured in calm conditions. Regular checking of the draught of the survey vessels was also made, as well as occasional bar checks. Only small differences of a few cm were recorded.

Results were referred to Standard Low Water (SLW) datum, which is, roughly, the water level that is exceeded in 95 percent of the time. The datum reduction was made by water level gauging at a reference station where the SLW datum is defined relative to PWD.

5.2.7 Drogue measurements

A programme of drogue (float) tracking was implemented in connection with the bathymetric surveys as from July, 1995. Generally, shallow-draft vessels were employed for the purpose, equipped with DGPS for positioning and Hydro software for the logging of positions.

The drogues had a draft of 2 m. Two drogues were deployed at the same time. They were re-positioned when they drifted too far away from each other, or when grounded. Fixing of their positions was done at an inter-distance of about half the width of the river or earlier, depending on how fast the drogues could be reached by the vessel.

5.2.8 Topographic measurements

A programme of topographic surveys was carried out to serve as a supplement to the bathymetric surveys. The topographic surveys determined spot elevations along survey lines that were aligned with the bathymetric survey runlines, in the direction across the river. The line spacing was 500 m. The point increment along the lines was 100-200 m for regular surfaces and less in case of irregularities. The survey lines extended from the river bank (or banks), and the water level was determined as well as the ground elevation. The location of the lines, and the two first points of each line, were established by DGPS. From this basis, the horizontal and vertical coordinates of the points along the line were determined by a Topcon total station. With the procedures applied in the field, the accuracy is estimated at 3 m (horizontally) and 2-3 cm (vertically). The range of the total station was around 1,200m.

The surveys included a mapping of topographic features, with the twin objective of providing supplementary information to the bathymetric contour maps and as a support to interpretation of satellite imagery (for a study jointly undertaken by EGIS and RSP, see *RSP Special Report 17: 'Spatial representation and analysis of hydraulic and morphological data'*). For this purpose, features were classified as indicated in Table 5.5.

- | |
|--|
| <ul style="list-style-type: none"> • Crop type: Paddy (species), wheat, jute, sugar cane, firewood (species), tobacco, spices (species), pulse, mustard, others • Crop height (cm) and area • Soil type: Silt or sand, dry or moist • Structures: Buildings, roads, dikes, ditches, embankments, etc. • Scour holes |
|--|

Table 5.5 Feature classification

5.3 Data elaboration

5.3.1 Water level gauging

Processing of the water level recordings comprised the following activities:

- Downloading of AWLR data and collection of staff gauge data, with on-site inspection of data coverage and data quality (spikes, steps, drifts);
- digitising of staff gauge readings and conversion of AWLR readings;
- zero level conversion to PWD;
- data validation;
- editing of data files; and
- storage in the HYMOS database.

5.3.2 Routine gauging of flow and sediment transport

As shown in Figure 5.4, the data processing for the routine gauging was divided into an on-line part and an off-line part. The on-line data processing comprised generation of composite data files, containing data from the different sensors, labelling of data files for identification, and monitoring of data coverage and consistency. The off-line processing comprised editing, validation, storage, and reporting.

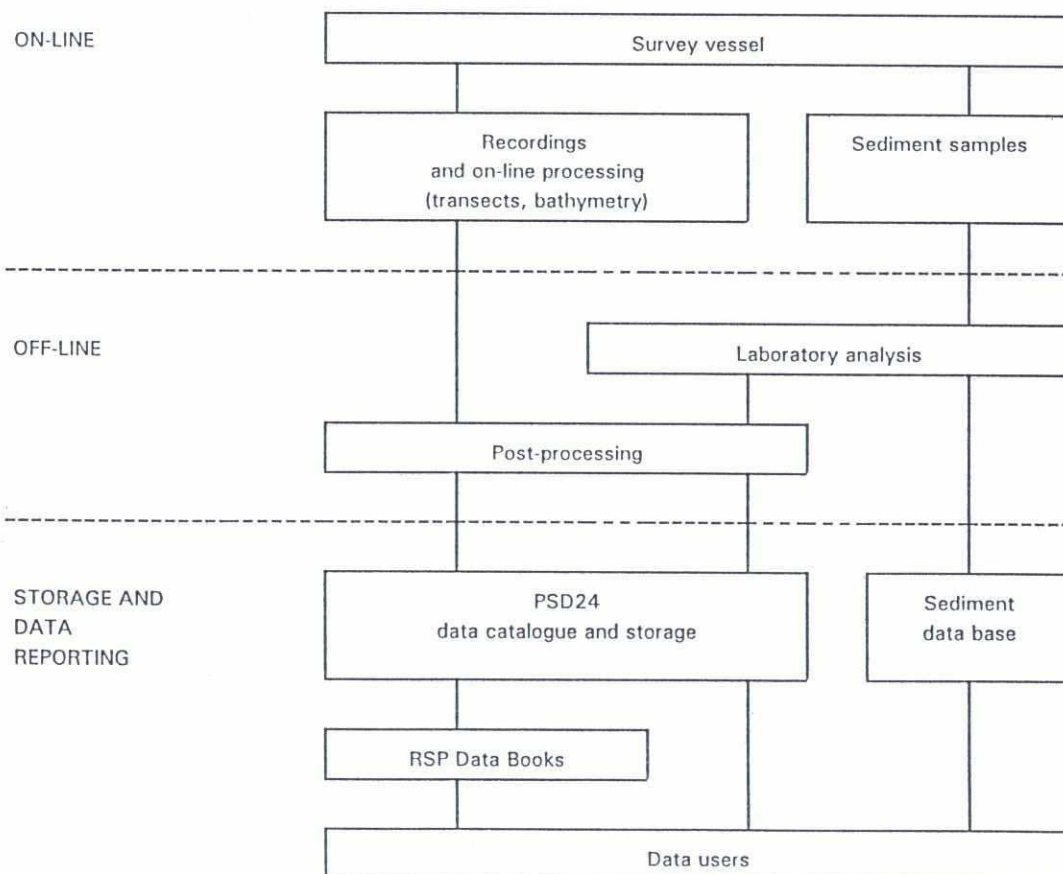


Figure 5.4 Data flow summary for the RSP routine gauging of flow and sediment transport

For each survey, a Survey Report was prepared in the field. It was used for internal purposes in connection with data processing, validation, and data reporting, as well as a support for adjustment of field procedures and work programmes. It contained:

- a chronology of activities;
- an outline of the data collection: Where and when which measurements were made;
- data logging sheets and sediment sample collection sheets; and
- any other observations or information of interest in connection with the field work, such as performance of instruments and adequacy of applied procedures.

5.3.3 Sediment analyses

In addition to the flow recordings, the routine gauging comprised determination of suspended sediment transport and bed load transport, as well as sediment grain-size distributions, and vertical distributions of sediment concentration and grain-size/settling velocity distribution. The analyses included in the routine monitoring are listed in Table 5.6.

Sampling	Method	Analysis			
		Silt concentration	Sand concentration	Grain-size/ settling velocity distribution	Transport rate
Suspended sediment	Collapsible bag, integrated bottle	+	+		
	Pump sampling	+	+	A	
	Delft bottle				+
Near-bed sediments	Pump sampling	+	+	S	
	Delft bottle			S	+
	Helley-Smith			S	+
Bed material sampling	USBM 54, Van Veen grab, drag sampler			S	.
A: Andreasen tube determination of settling velocity distribution (particles below 0.063 mm) and by dry sieving (particles above 0.063 mm). This analysis is made for selected samples only S: By dry sieving (or wet sieving for cohesive sediments)					

Table 5.6 Sediment analyses for routine gauging

The various types of samples were analyzed in the RSP sediment laboratory, which had facilities for the following standard analyses:

- concentration of suspended sediment (by micro-filtering);
- grain-size/settling velocity distribution of suspended sediments and riverbed sediments (by Andreasen settling tube);
- grain-size distribution of suspended sediments and riverbed sediments (by dry or wet sieving, mesh widths 1-0.5-0.25-0.125-0.063 mm);
- pipette analysis of grain-size distribution of small samples (used for non-routine purposes only).

In the course of the project, more than 16,000 analyses were made of concentration or grain size distribution.

Mineralogical composition and physical properties were analyzed for some 200 riverbed and flood plain sediment samples. These analyses are specified in Table 5.7. They were made at the laboratories of the Geology and Soil Science Departments, Dhaka University (except for the grain size distribution analyses, which were made in-house by the RSP).

Physical properties	Method of analysis	Full analyses	Limited analyses
Mineralogy			
– Sand-size minerals	Optical microscope	+	+
– Silt-size minerals	Optical microscope		+
– Silt-size minerals	XRD	+	
– Clay-size minerals	XRD	+	
– Trace minerals	Optical microscope	+	+
– Rock fragments	Optical microscope	+	+
Shape variables			
– Angularity	Microscope + shape chart	+	+
– Sphericity	Microscope + shape chart	+	
– Shape factor	Microscope	+	
Density	Pycnometer	+	+
Grain size	Sieving/settling tube	+	+

Table 5.7 Analysis of mineralogical composition and physical properties of sediments

5.3.4 Bathymetric surveys

Similarly to the routine gauging of flow and sediment transport, the processing of the bathymetric data was divided into

- an on-line component, producing composite x-y-z-t files for sets of runlines; and
- an off-line component, resulting in converted x-y-z files and finite grid depth tables, in both cases relative to the applied (SLW) datum.

5.4 Quality checking

The quality of the produced data was checked by different routines for the various types of measurements: (1) water level gauging, (2) routine gauging of flow and sediment transport, (3) bathymetric surveys, and (4) special surveys.

Origin of data	On-line control	Off-line control	User control
Water level gauging		+	+
Routine gauging of flow and sediment transport	+	+	+
Bathymetric surveys	+	+	+
Special surveys	(+)	(+)	+

Table 5.8 Categories of data quality control

In successive stages, various types of errors and deficiencies were monitored, according to the increased aggregation of information from different periods of time or from different sources.

The on-line control was an integrated part of the vessel survey procedure. It comprised the survey documentation, the basic data coverage, the immediate data consistency, and obvious measurement errors. Errors and deficiencies to be detected included for example improper performance of instruments or of the on-line data processing system; inconsistent recordings, such as for example instantaneous position shifts; or identification of unusual recordings, such as steps or spikes, or values beyond an expected range. The on-line control resulted in reporting of actual or potential deviations, and could prompt an immediate decision to repeat a suspect measurement.

The off-line control was an in-depth examination of the results, which normally involved examination of a graphic presentation of data from one or more sources. Inter-station comparison was a common tool, where it was checked for example whether some unusual stage fluctuation occurred at one station only, or whether the pattern appeared in several independent records.

The validation of water level data is summarised in Table 5.9 and is described in *RSP Special Report 2: 'Water level gauging'*.

Field check:	• Placement and state of staff gauges • General functioning of AWLRs, incl. clock • Zero level control (staff gauges and AWLRs) • Data coverage • Spikes, steps
Post-processing:	• Time and range check • Staff gauge/AWLR consistency (spikes, steps, trends)
Consistency:	• Inspection and inter-station comparison of hydrographs • Drafting and inspection of stage-discharge rating curves

Table 5.9 Validation of water level data

The final validation of data from the routine gauging of flow and sediment transport took place during the associated activities of preparation of the Survey Bulletins and the PSD24 data files. Here, the contents of the data files and their labelling and documentation were checked for consistency and completeness, against the Survey Reports prepared in the field, and against SPOT images and previous surveys at the same location. An outline of this validation is shown in Table 5.10.

Survey Bulletins, general:	• Completeness; missing pages, x- and y-axes of graphs, captions • Consistency of filenames • Consistency of cross-section areas, water levels, flow, suspended sediment transport, bed load transport • Total number of measurements indicated in Summary Table • $D_{35} < D_{50} < D_{65}$
Location map:	• Date of map versus date of survey • Scale bar • RSP and BWDB staff gauge locations • Position of all transects • Width(s) of transect(s)
Cross-sections:	• Width(s) of transect(s) • Depths (as compared with echo sounder plots in Survey Reports) • Consistency of depth indications • Left bank < > right bank
Key figures:	• Check extent against field sheets • Check water levels
Horizontal distributions:	• Transect azimuth/definition sketch • Whole graph reversed? • Left bank and right bank distances • General flow direction, versus (1) river planform, (2) definition sketch, (3) echo sounder plots from Survey Report • Consistency with (1) SPOT image, (2) previous survey at same location • Spikes • Unmeasured parts (versus PSD24 information) • General sediment transport pattern versus general flow pattern • Whether high sediment catches are reflected? • $S_{total} = S_{wash\ load} + S_{suspended\ bed\ load} + S_{bed\ load}?$ • Measurement locations versus vertical locations • Consistency of D_{50} values
ADCP/iso-velocity plots:	• Readability of contours and numbers • Contours touching the bottom or crossing each other • Unmeasured parts • Consistency with (1) SPOT image, (2) previous survey at same location
Sediment data:	• Sampling times and depths (against field sheets)
ADCP transects:	• Selection and indication of transect for PSD24 • Times and file names (against field sheets) • Miscellaneous notes under each table
PSD24 file list:	• Completeness • File type

Table 5.10 Validation of routine gauging data for Survey Bulletins and PSD24

The data validation for the special surveys took place in the same way as for the routine gauging for those surveys that comprised components of the routine gauging. For the non-routine parts of the special surveys, the data were validated by the (internal) users during the analyses.

5.5 Data storage

The data produced by the RSP are stored in three databases:

- The HYMOS system, which is an integrated software package (developed by Delft Hydraulics) for storage, analysis and presentation of water level data;
- PSD24 (Processed survey data of FAP24), which contains a (Paradox) data catalogue, and processed data from the routine gaugings and special surveys (in QuattroPro spreadsheet format); and
- The RSP sediment database, which contains results of all sediment analyses carried out by the RSP sediment laboratory (in QuattroPro spreadsheet format).

The databases are described in *RSP Special Report 21: 'Guide to RSP databases'*.

The amounts of data stored are shown in Table 5.11. The information stored in the PSD24 is described in Table 5.12. See also Appendix C (PSD24 Overview) attached to this report.

Database	Contents	Size
HYMOS	RSP water level time series	2 Mb
	BWDB flow and water level data	5 Mb
PSD24	PSD24 files (see Table 5.12)	500 Mb
	Bathymetry files	5 Gb
	Selected raw data files	7 Gb
Sediment database	Sediment analyses	180 Mb

Table 5.11 The RSP databases

Data from routine gauging and special surveys • ADCP/S4/EMF transects • Echo sounder transects • Sediment transport data • Longitudinal profile data • Vertical velocity profiles • Vertical sediment concentration and transport profiles • Suspended sediment grain size • Bed load transport analyses • Bed material analyses • Cross-sectional distributions of flow and sediment transport • Cross-sectional iso-velocity contours (UNIX files) Data from bathymetric surveys • Fixed grid (50 m by 50 m) bathymetry data (UNIX files)

Table 5.12 PSD24 data files

5.6 Data presentation and publication

The internal and external data documentation and reporting took place as shown in Figure 5.5. For each survey, a Survey Report was prepared in the field. It served as the internal documentation of the data collection and was sent to the RSP data processing office in Dhaka together with the data tapes, field notes and miscellaneous prints and plots from the on-line data processing. As a part of the post-processing, a *Survey Bulletin* was prepared for each survey. These Survey Bulletins describe the data collection and give a condensed summary of the results.

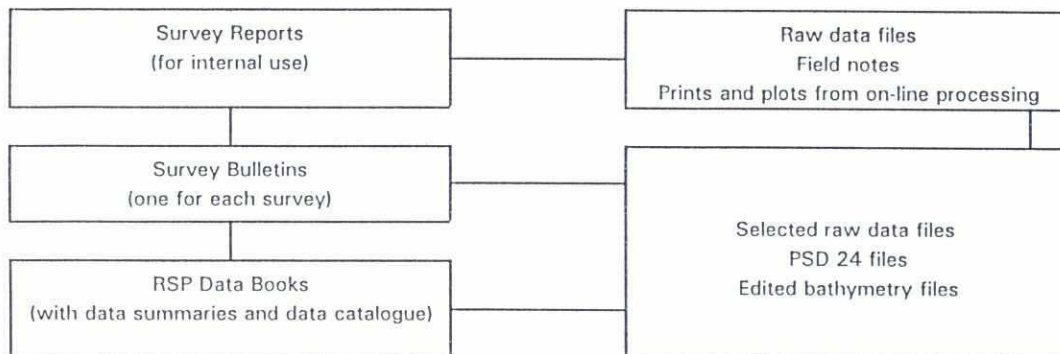


Figure 5.5 Data reporting

The results of the routine gauging and of the special surveys are presented in the *RSP Data Books (RSP Special Reports 22 and 23)*, one covering the period June 1993 to March 1995, and one covering the hydrological year from April 1995 to March 1996.

Each Data Book contains a text volume with summaries of the data collection, chronologically and by station, together with hydrographs and rating curves for flow and sediment transport (wash load, suspended bed material load and bed load). Separate volumes present, for each location, the surveys one by one, as reported in the Survey Bulletins: where and when the data were collected, data summaries, and a complete catalogue of all data files.

Results of the water level gauging are presented in *RSP Special Report 2: 'Water level gauging'*. The bathymetric surveys are described in *RSP Special Report 3: Bathymetric surveys*, and the results are presented on a set of 145 sounding plans and 145 contour maps in A0 format and scale 1:10,000 or 1:20,000.

6 Overview of survey results

6.1 Introduction

The extent of the data collection was largely defined in the Terms of Reference of the Project. The programme was executed with certain adjustments, as deemed advisable on the basis of the detailed planning and the experience gained in the early stage of the work, and as agreed with the Client, the RSPMU and the funding agency. Funds were for example reallocated to special surveys for the collection of data for specific studies undertaken under RSP. The modifications are listed in *RSP Final Report Annex 1: 'Surveys'*.

The present chapter gives a summary of the results of the surveys. Please refer to the *RSP Data Books* for a complete inventory of the data collection and for key findings of each survey.

6.2 Water-level gauging

The water-level gauging of RSP began in Phase 1 of the project with establishment of a staff gauge at Gobindi (near Bahadurabad) in November 1992. AWLRs at Bahadurabad and Gabgachi were established in June/July 1993, together with a network of additional staff gauges in the same area for measurements of local water-level slopes.

Another ten AWLRs were set up in May/August 1994, distributed over the entire project area. The station network is shown in Figure 6.1. Most of the stations were located near a BWDB gauge, from where long-term data are available. In addition to the AWLR stations, several separate staff gauges were deployed on a short-term basis for registration of backwater effects or local water-level slopes at Bahadurabad and at Gorai Offtake.

The placement of the AWLRs was quite difficult. The primary concern was a suitable hydraulic regime, where local irregularities do not influence the registration significantly, so that the data have a good validity in relation to the general hydrodynamics of the river section. AWLRs cannot easily be shifted on a routine basis during the year, so the location must cover the entire flood season hydrograph and, wherever possible, the entire annual water-level range. The planform stability and the extent of local erosion or sedimentation were considered, and also the logistical requirement that the station be accessible for inspection, data downloading, servicing, and repairs.

The AWLR stations were demobilised in May 1996. Between them, they were in operation for 303 station-months (Table 6.1).

The data series were partly validated in early 1995 and the remainder after completion of the programme, as described in Section 5.4. The water-level gauging programme and the related data validation are described in *RSP Special Report 2: 'Water-level gauging'*. Summary presentations of the results are given in the *RSP Data Books*, and all results are stored in the IYMOS database.

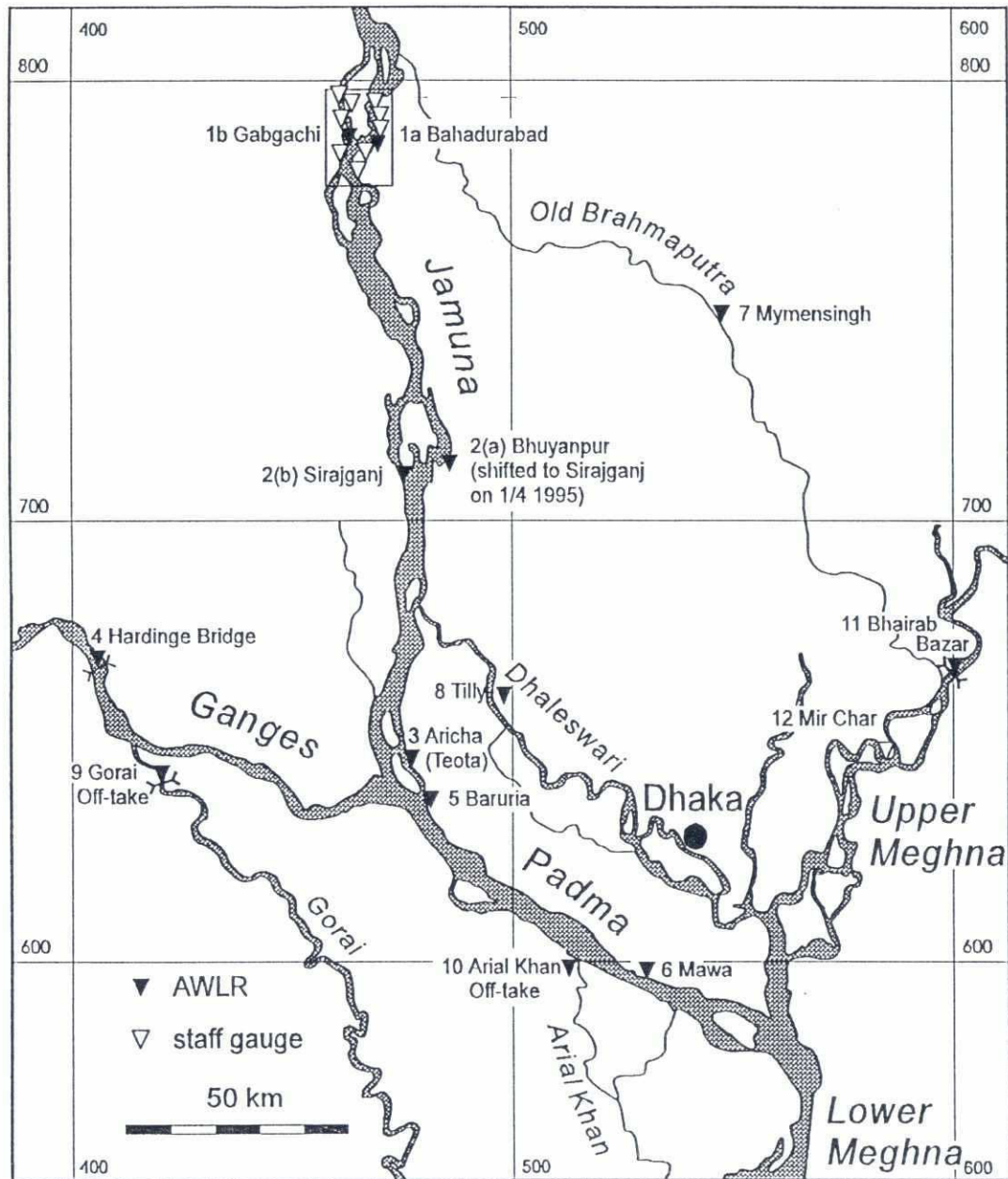


Figure 6.1 Water-level gauging stations

Station	River	Operation period	Station-months
1L Bahadurabad	Jamuna	6/6/93 - 31/5/96	34.3
1R Gabgachi		15/7/93 - 31/5/96	33.5
2 Bhuyanpur/ Sirajganj		29/5/94 - 30/4/95 1/4 95 - 26/5 96	11.0 + 13.9
3 Aricha (Teota)		13/5/94 - 23/5/96	24.4
4 Hardinge Bridge	Ganges	21/7/94 - 31/5/96	22.3
5 Baruria	Padma	28/5/94 - 24/5/96	23.9
6 Mawa		10/5/94 - 30/5/96	24.7
7 Mymensingh	Old Brahmaputra	29/6/94 - 24/5/96	22.8
8 Tilly	Dhaleswhari	28/5/94 - 23/5/96	23.8
9 Gorai	Gorai	22/7/94 - 31/5/96	22.3
10 Arial Khan	Arial Khan	3/6/94 - 31/5/96	23.9
11 Bhairab Bazar	Upper Meghna	24/7/94 - 28/5/96	22.1
		Total	302.9

Table 6.1 Summary of data collection, water-level gauging

6.3 Routine gauging of flow and sediment transport

6.3.1 Basic programme

The objective of the RSP routine gauging was to produce detailed and accurate information about the flow and sediment transport through a cross-section of a river, including the cross-sectional distributions.

The locations of the RSP transects for routine gauging were defined in the ToR. Several of them are also covered by BWDB's routine gauging programme. Their exact location was selected on the basis of a field reconnaissance, which considered to the extent possible the flow regime, the regularity of the channel, and its morphological stability. In general, however, ideal gauging transects are rare in the river system of the project area, and the basic demand of data production imposes a need of compromising. In many cases, the geometry changed considerably in the span of one single flood season (see for example Figure 6.5), so continuous adjustments of the cross-section locations were necessitated. The flow pattern could, from case to case, be influenced by adjacent cross-section shifts, shifting channels, bedforms, and other depth irregularities. The transect locations are shown in Figure 6.2.

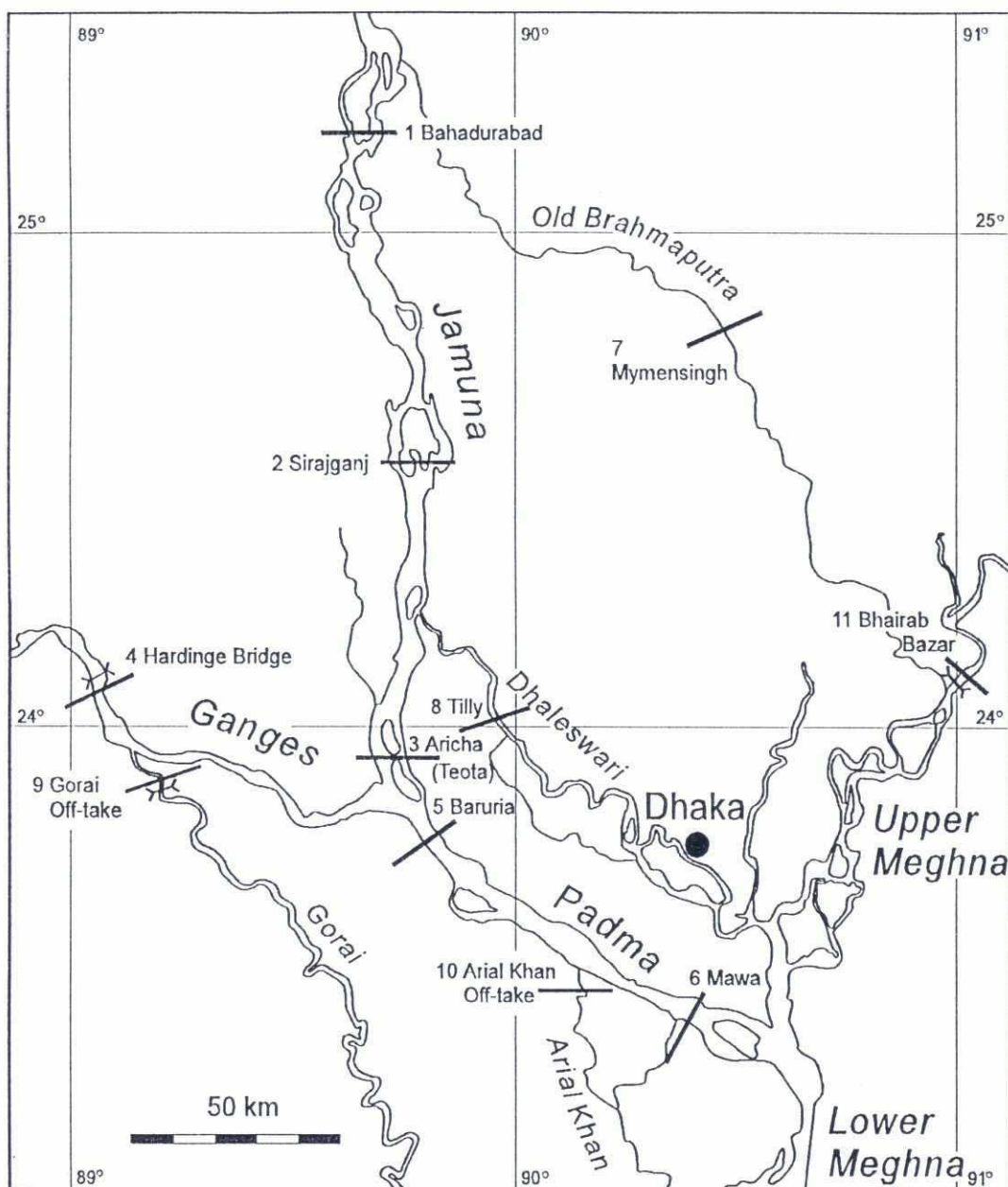


Figure 6.2 Transects for RSP routine gauging of flow and sediment transport

The first routine gauging survey took place in January 1993, and the last one was made in March 1996. The survey routine is briefly described in Section 5.2, and is elaborated in *RSP Final Report Annex I: 'Surveys'*. The extent of the programme is summarised in Table 6.2, which shows that the RSP completed a total of 252 routine gauging surveys at 11 transects. Summaries of results of each survey are presented in the *RSP Data Books*, together with a description of the exact place and time of each measurement, and a complete listing of the raw data files and processed data files. The detailed results are stored in the PSD24 database.

The flood surveys in 1995 deserve extra attention as river stages were far higher than encounters during the others monsoons within the project period. Especially the peak flow measurements in June, July and August 1995 are worth mentioning.

Year	93		94		95		96	Total
Season	lean	flood	lean	flood	lean	flood	lean	
1 Bahadurabad	3	4	6	7	6	9	8	43
2 Sirajganj		3	5	6	7	7	6	34
3 Aricha		1		2	0	4	0	7
4 Hardinge Bridge		1	5	7	6	7	5	31
5 Baruria		4	5	7	6	7	5	34
6 Mawa		1		2	1	3	2	9
7 Mymensingh			3	4	3	5	3	18
8 Tilly		1	3	4	3	5	3	19
9 Gorai Off-take		1	3	4	3	6	3	20
10 Arial Khan Off-take		1	3	4	3	5	2	18
11 Bhairab Bazar	1	1	3	3	4	4	3	19
Total	4	18	36	50	42	62	39	252

Table 6.2 Summary of data collection, routine flow and sediment transport gauging

6.3.2 Tidal surveys

In the dry season, the astronomical tide can extend up to several of the RSP standard transects: Baruria, Arial Khan Off-take, and Mawa in the Padma River, and Bhairab Bazar Railway Bridge in the Upper Meghna.

A number of extended surveys of tidal-influenced flow was carried out by the Project, as listed in Table 6.3. During these surveys, the flow was monitored over periods of 13 or 26 hours. Specific procedures were implemented that aimed at describing the time and space distribution of the flow in more detail than it was done during the routine flow gauging.

The surveys aimed at providing an appropriate time resolution of the tidal flow and, at the same time, a reasonably detailed resolution of the cross-sectional distribution of flow and sediment transport. Two or three vessels were deployed for the purpose. One vessel was repeatedly shifting its position during the survey, doing regular (hourly) flow and depth contour measurements along and across the river, while one or two vessels were anchored doing continuous single point (EMF) current-recordings, and regular (hourly) single vertical

current-profiles by ADCP/EMF and S4. Also, the near-bed sediment transport was measured every hour by the anchored vessels, with Helley-Smith and Delft Bottle.

The tidal measurements at Mawa in early 1996 were compared with simultaneous measurements by BWDB. The standard tidal survey routine of BWDB comprises 15-hours measurements every two weeks.

Bhairab Bazar (Upper Meghna)	26-28/4 1993 10-12/2 1994 18-19/3 1995
Baruria (Padma)	21/3 1994
Arial Khan Off-take (Padma)	18-19/4 1994
Mawa (Padma)	17-18/2 1995 30-31/1 1996 7-8/2 1996

Table 6.3 Dedicated tidal surveys

6.3.3 Overland flow and floodplain sedimentation

As a supplement to the routine gauging, a separate programme of overland flow and floodplain sedimentation measurements was carried out during the 1995 flood season, which was the only flood season with flow and stages above median (flood conditions) within the flood seasons covered by the RSP field programme.

The measurements were made on the left bank of Jamuna, southeast of Bahadurabad. The study built on previous work in the same area by FAP19 (the Geographic Information System Project). The study area covered part of the Active and Young Jamuna Floodplains and part of the Older Jamuna Floodplain.

The measurements and the results are summarised in *RSP Final Report Annex 5: 'Morphology'*, and are elaborated in *RSP Special Report 15: 'Overland flow and floodplain sedimentation'*.

6.4 Geodetic, bathymetric and topographic surveys

6.4.1 Validation of BWDB bench marks

One of the tasks of RSP was to verify the zero levels of 47 selected BWDB water-level gauges by second order levelling. The stations are shown in Figure 6.3. The work was executed in early 1993. It included a level crossing of Jamuna River at Bahadurabad, which was done by traditional land surveying during an extremely low stage in the dry season of 1992/93. The results are reported in *RSP Special Report 1: 'Validation of staff gauge bench marks'*. This report compares the applied zero levels of the gauges with the levelling results of the RSP, as well as certain deviations that were identified between the BWDB and the FINMAP bench mark networks.

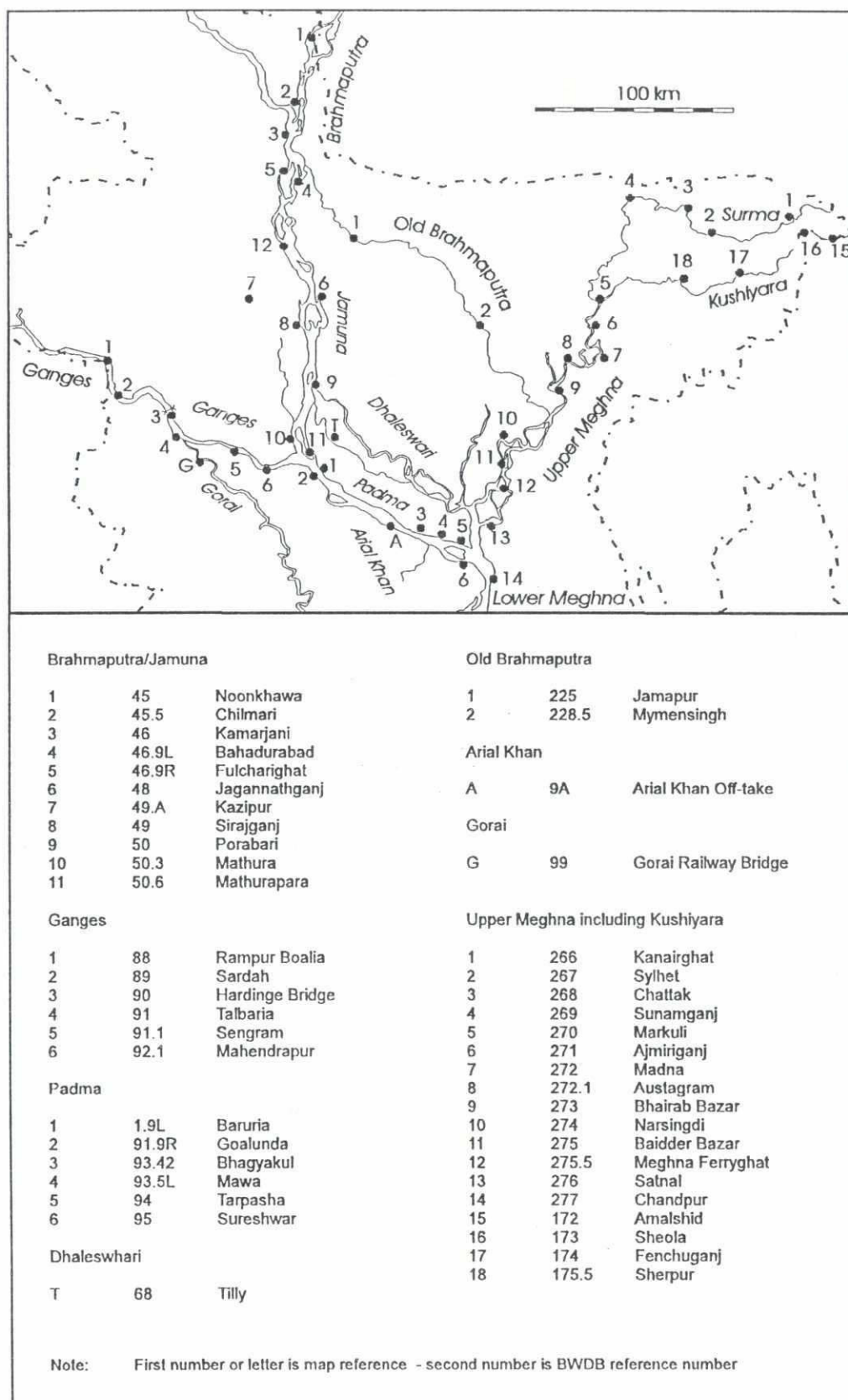


Figure 6.3 Location of BWDB water-level gauges selected for zero level validation

6.4.2 Bathymetric surveys

The bathymetric survey programme comprised repeated mappings of 7 areas. The original extent, as described in the ToR, was to carry out the surveys before and after each monsoon season. In the course of the project, however, a demand was felt of more detailed information about the morphological processes, so the RSPMU recommended to supplement the programme with certain flood season surveys, which improved the time resolution of such processes. The bathymetric survey areas are shown in Figure 6.4 and are described in Table 6.4. The work programme is summarised in Table 6.5. Results of these surveys were presented on A0 sounding plans and contour maps. The data collection and processing are described in *RSP Special Report 3: 'Bathymetric surveys'*.

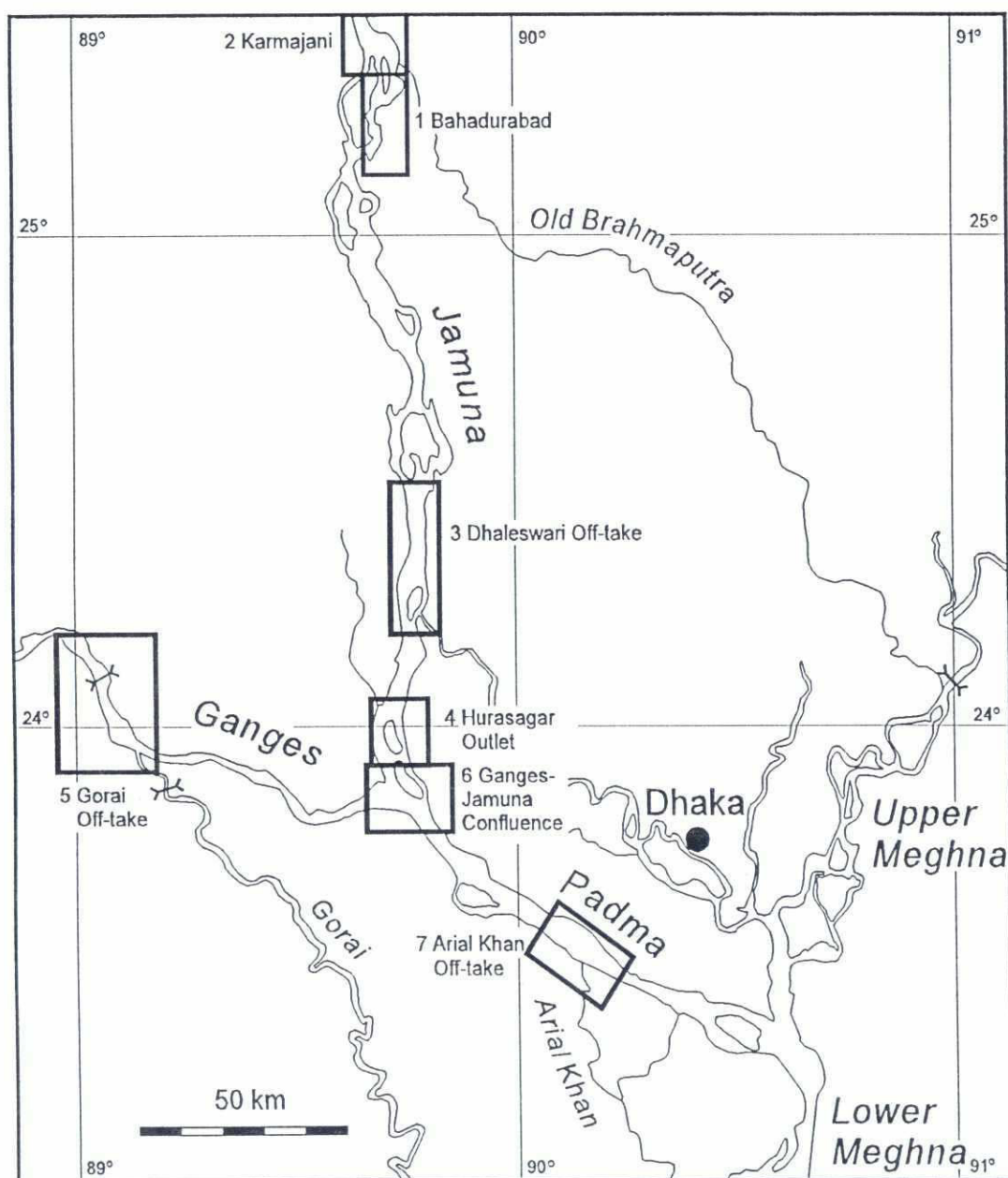


Figure 6.4 Bathymetric survey areas

River	Location	Area 1)	Line spacing
Jamuna	1 Bahadurabad	29 - 91 km ²	100 m
Jamuna	2 Karmajani	50 - 160 km ²	100 m or 200 m
Jamuna	3 Dhaleswari Off-take	60 - 85 km ²	200 m
Jamuna	4 Hurasagar Outlet	15 - 21 km ²	200 m
Ganges	5 Gorai Off-take	4 - 107 km ²	200 m
Jamuna/Ganges	6 Confluence	73 - 107 km ²	200 m
Padma	7 Arial Khan Off-take	79 - 99 km ²	200 m
1): The actual net area varies from one survey to another			

Table 6.4 Description of bathymetric survey areas

Year	93		94		95		96	Total
Season	lean	flood	lean	flood	lean	flood	lean	
1 Bahadurabad		2	1		2	1	2	8
2 Karmajani				1	2	1	1	5
3 Dhaleswari Off-take					2		1	3
4 Hurasagar Outlet			1		2		1	4
5 Gorai Off-take				1	2		1	4
6 Jamuna/Ganges Confluence		1	1		2	4	1	9
7 Arial Khan Off-take			1		2		2	5
Total		3	4	2	14	6	9	38

Table 6.5 Bathymetric surveys carried out by RSP

6.4.3 Char topography

A char topography programme was carried out in the final stage of the project. These surveys included a mapping of topographic features, are described in Chapter 5. An outline of this programme is given in Table 6.6. The extent of the data collection and presentations of the results are given in *RSP Special Report 3: 'Bathymetric Surveys'*, and the findings are elaborated in *RSP Special Report 17: 'Spatial representation and analysis of hydraulic and morphological data'*.

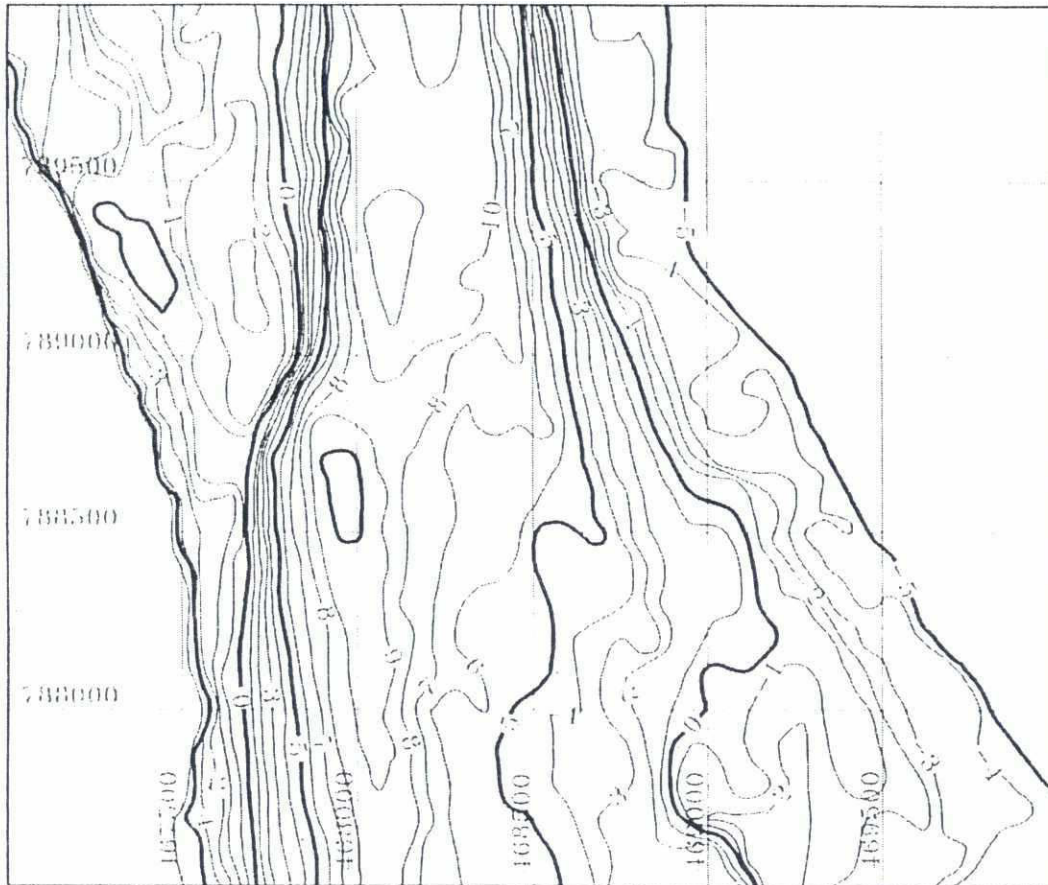


Figure 6.5 Examples of bathymetric surveys, Bahadurabad, left channel

Location	Start date	End date	Survey
Gorai Off-take	15-Jan-95	14-Feb-95	9044
Bahadurabad	25-Nov-95	20-Dec-95	8032 F)
Bahadurabad	25-Dec-95	06-Jan-96	8032 F)
Bahadurabad	09-Mar-96	14-Mar-96	8032 F)
Kamarjani	07-Jan-96	16-Jan-96	8034 F)
Kamarjani	15-Mar-96	18-Mar-96	8034 F)
Ganges/Jamuna Confluence	22-Mar-96	31-Mar-96	8037 F)

F): Feature classification was included in this survey

Table 6.6 Topographic mapping of chars

6.5 Special surveys

The extent of the special surveys were not specified in the ToR of the project, which only mentioned '... some supplementary surveys'. The special surveys programme was recommended on and approved by the RSPMU. These surveys served a variety of demands of specific river data that were identified in connection with the study activities. They can be divided into three categories:

- Additional flow measurements at Bahadurabad (carried out on 28 occasions);
- a so-called bedform inventory programme, comprising repeated recordings of longitudinal depth contour profiles (carried out on 28 occasions); and
- a variety of other purposes (carried out on 43 occasions).

Many of the special surveys supported several study activities at the same time, while most of the study activities in turn were based not only on the special surveys, but also on the results of the routine gauging programme (and also to a high extent on data produced by BWDB).

Results of the special surveys are reported in the 9000-series of Survey Bulletins and are included in the *RSP Data Books* and in the PSD24 database.

6.5.1 Flow measurements at Bahadurabad

The objective of the additional flow measurements at Bahadurabad was to improve the data coverage of the routine flow gauging, for several good reasons, one being to allow for a detailed inter-calibration and a mutual validation of the BWDB and the RSP rating curves at that key location.

These flow recordings were made by the same procedure as that of the routine gauging, except that sediment transport measurements were omitted. The surveys were scheduled so that they, together with the routine gauging, provided a good coverage of the hydrograph.

The extent of these recordings is indicated in Table 6.7. Please refer to *RSP Final Report Annex 1: 'Surveys'* for a complete inventory.

Year	94		95		96	Total
Season	flood	lean	flood	lean		
Number of surveys	16	7	5			28

Table 6.7 Additional flow measurements at Bahadurabad

6.5.2 Bedform inventory programme

The bedform inventory programme supplied data to the studies of bars and bedforms. Like the other special surveys, this activity was not included in the ToR, but was recommended by the PA. It comprised repeated recordings of longitudinal depth contour profiles in the Jamuna River between Aricha, Sirajganj, and Bahadurabad. Hereby, a supplement was provided to the information about the time and space variation of bedforms produced by a number of special surveys at Bahadurabad. As compared to these surveys, the bedform inventory programme covered the entire downstream reach from Bahadurabad to Aricha, hereby highly extending the spatial coverage of the detailed measurements at Bahadurabad with respect to frequency of occurrence, spatial variability and geometry of bars and dunes.

The measurements were more frequent than the ones at Bahadurabad, but only one longitudinal line was recorded, and the positioning (by ordinary, or 'non-differential' GPS) was less accurate than for the bathymetric surveys. Therefore, and also due to the shifting positions of channel and bars, the transect direction was not always aligned with the main bar and dune axes, and the transects were not the same during successive mappings. The recordings were made while transferring between routine gauging transects.

An outline of the data collection is given in Table 6.8, and a complete inventory is included in *RSP Final Report Annex I: 'Surveys'*. Results of the programme are presented in the related RSP study reports and special reports, and particularly in *RSP Special Report 9: 'Bars and dunes in Jamuna River'*.

Year	94		95		96	Total
Season	flood	lean	flood	lean		
Number of surveys	11	10	7			28

Table 6.8 Bedform inventory programme

6.5.3 Other special surveys

These surveys were targeted at specific analyses and were in many cases carried out by adaptation of elements of the routine procedures. In other cases, measurements were carried out by methods that were selected for the purpose. For example, geological investigations of river deposits were made by vibro-coring, seismic surveying, and by ground penetrating radar. The equipment for this work was supplied and applied by the research institutions involved in the study component of the project. The scope of this category of non-routine surveys covered a variety of subjects, such as for example:

- surface slope mapping;
- flow dynamics at constrictions, off-takes, bifurcations, and confluences;
- hydrodynamic effects of planforms and bedforms;
- examination of survey techniques (hydraulics and sediment transport);
- bed material characteristics;
- comparative measurements with BWDB (hydrology and morphology);
- length and time scales of flow and sediment transport;
- geological mapping of river deposits.

The extent of this activity is indicated in Table 6.9. Please refer to *RSP Final Report Annex 1: 'Surveys'* for a complete inventory. Results of the programme are presented in the series of RSP Special Reports. The comparative measurements with BWDB are elaborated in the following Section 6.6.

Year	94		95		96	Total
Season	flood	lean	flood	lean		
Number of surveys	15	6	16	6		43

Table 6.9 Other special surveys

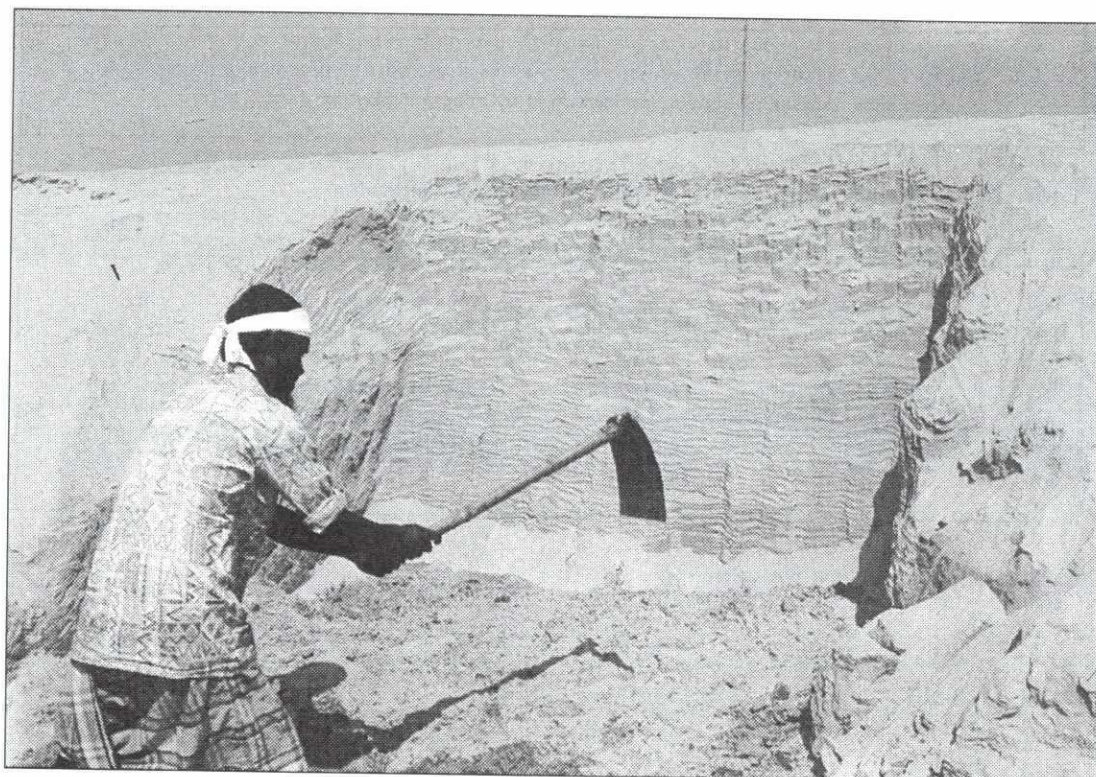


Figure 6.6 Profile wall for geological dating of chars (Special Survey no. 9097, Bahadurabad, February 1996)

6.6 Comparative measurements with BWDB

6.6.1 Flow and sediment transport

In 1993, a comparison between BWDB and RSP flow gaugings at Bahadurabad indicated a systematic difference, RSP measuring lower discharges than BWDB during high stages. A *'Committee on Shift in the Rating Curve at Bahadurabad'* was established to examine the matter, with representatives from BWDB (Surface Water Hydrology I & II), FPCO, BUET, and RSP. One recommendation of this committee was to carry out a series of comparative BWDB and RSP measurements, in order to investigate such possible systematic deviations that could be related to the different instrumentation or the different procedures applied by BWDB and RSP.

As shown in Table 6.10, the techniques applied by the two programmes were based on rather different principles, and they were therefore well suited for examining the performance of each other. As BWDB's monitoring is permanent, while the RSP survey component was a fixed term project, the comparison was intended mainly for the purpose of BWDB, and the work was planned and reported accordingly. The programme of joint measurements is shown in Table 6.11.

BWDB:	Positioning by sextant, depth registration by wire length, 2-point current measurements by propeller type (non-directional) current meter, no anchoring, suspended sediment sampling by Binckley trap sampler
RSP:	DGPS positioning, registration of measuring/sampling depth by pressure cell, water depth registration by echo sounder, flow gauging by ADCP moving boat method or by 6-point measurements by S4 electromagnetic current meter, vessel anchored during vertical profiling, suspended sediment sampling by pump system or by integrating bottle

Table 6.10 Inter-comparison of BWDB and FAP24 instruments and methods

107	Bahadurabad	17-23/10 94	routine gauging
134	Mawa	17-18/2 95	routine gauging (tidal)
139	Bhairab Bazar	17-20/3 95	routine gauging (tidal)
9070	Bahadurabad	16-20/7 95	special comparative survey
9086	Hardinge Bridge	3/10 95	special comparative survey
9089	Mawa	19-22/10 95	special comparative survey
9092	Bahadurabad	7-8/11 95	special comparative survey

Table 6.11 Joint BWDB/RSP measurements

The results are presented in *RSP Special Report 19: 'Joint discharge measurements'*, where the following aspects are evaluated:

- Anchoring and positioning;
- depth control of instruments and sediment samplers;
- determination of cross-section profile geometry;
- accuracy of current velocity measurements;
- significance of the flow direction;
- the horizontal and vertical resolution; and
- the sediment sampling procedure.

Further, the report contains observations and suggestions in relation to the techniques applied in the BWDB routine gauging.



Figure 6.7 The catamaran used by BWDB for flow gauging

6.6.2 Morphology

Similarly, on one occasion, a comparative survey was made between BWDB, Morphology and Research Circle, and RSP. This survey took place in the period March 24-26, 1995, at the BWDB standard cross-section at Bahadurabad (cross-section J#13_1). The joint activities comprised both the field measurements and the data processing.

The RSP did not carry out morphological monitoring in a way that was directly comparable with the BWDB procedure. The RSP did repeated surveys of a few selected areas, as described in Section 6.4, whereas BWDB undertakes long-term monitoring of a large number of cross-sections. Therefore, a special RSP survey was made for the purpose of evaluating the techniques applied by BWDB. This was done by comparison with the corresponding RSP routines for positioning on land and on the river, for topographic and bathymetric surveys, and for data processing.

The study is described in *RSP Special Report 20: 'Joint measurements, morphology'*. The data analysis for the joint survey comprised (1) a comparison between the BWDB and the RSP results, (2) a comparison between both surveys and SPOT imagery from March 24, 1995, and (3) a comparison with BWDB surveys from 1993 and 1994. The following aspects were examined:

- The horizontal and vertical control;
- positioning on land and on the river;
- procedures for measuring the dry part of a cross-section;
- procedures for sounding of the water part of a cross-section;
- the data documentation and processing routines applied by BWDB.

On the basis of the analyses, recommendations were made on adjustments of the field and data processing procedures applied by BWDB.

7 Main findings from surveys and studies

7.1 Introduction

During the River Survey Project extensive surveys were carried out on all the main rivers of Bangladesh during a period of more than three years. These surveys were divided into routine surveys and special surveys. The latter were done in relation to studies of the main river system. In addition, studies were carried out on the basis of data collected in the past. During both the routine and the special surveys and during the studies many interesting results surfaced which improved the understanding of the main river system considerably. In this Chapter a summary is given of the main findings of the River Survey Project.

It is not an easy task to summarize these results. The main reason is that all aspects are very much interlinked. It is not possible to discuss some aspects of e.g. observed morphological processes without keeping in mind the possibilities and limitations of the measuring techniques and methods used, while there is also a close link between hydrology, hydraulics, sediment transport and river morphology. Nevertheless, it is necessary to structure this Chapter to some extent. The following sections deal with measuring methods and techniques (Section 7.2), hydrology (Section 7.3), sedimentology (Section 7.4) and river morphology (Section 7.5), respectively. It is stressed that here only a summary can be given. Much more detail is available in the Annexes and the Special Reports. An overview of these Special Reports is given in Appendix B of this report.

Of course the present study did not start from scratch: it builds on results and data that became available over the last decades, in the first place the data collected by the BWDB in a painstakingly tedious and time-consuming effort under very difficult climatic and institutional conditions over more than three decades and covering an impressive network. More recently the data becoming available via satellite imagery (used in a.o. the Jamuna Bridge Study, FAP19 and FAP21/22) prove to be invaluable for improving the understanding of these major rivers.

Benchmark studies on the main river system of Bangladesh are the NEDECO (1968) study and the Coleman (1969) paper. Substantial progress in the understanding of the main rivers in Bangladesh was made under the Jamuna Bridge Study and a number of projects under FAP (FAP1, FAP4, FAP6, FAP9B, FAP19, FAP21/22 and FAP25). In the present Chapter the findings of the RSP study are discussed against the background of the results of these earlier studies, but using at the same time the improved understanding of the different phenomena that was obtained during theoretical and empirical studies in other parts of the world over the last decades.



7.2 Measuring techniques

7.2.1 General

The planning and execution of the RSP field survey programme was based on a considerable knowledge about river survey operation in Bangladesh, as relayed by the BWDB. As compared to the BWDB routine gauging, however, the RSP survey programme involved several pilot applications of new technology. The project took place in a period of rapid general technological development of positioning and flow gauging techniques. A substantial experience was gained in the process, and a part of this experience may be of interest also in a wider context. The following section gives a summary of observations on measuring routines and techniques made during the RSP river surveys.

7.2.2 Positioning

The RSP did most of its positioning by differential GPS (DGPS). This technique performed fully according to expectations. Also, it is noted that there are no practical alternatives available in Bangladesh, where the original Decca system covers a part of the river system only, and suffers from regular and extended downtime. Non-differential GPS gives an accuracy which is about the same as the Decca system, but at a much lower cost, and the accuracy of differential GPS is much better (although at a higher cost). The technology has been, or is being implemented for high-accuracy positioning by several national agencies (SoB, SWII of the BWDB, SWMC), and can be regarded as an example of a step-wise and irreversible technological development.

Within the project, the horizontal control suffered from the absence of a well-defined, operational geodetic grid. At the start of the project, it was expected that a new BTM grid established at that time by FAP18 would be implemented in general within the FAP programme. As official information about this grid had not been released, and in order to facilitate the data exchange within the FAP programme, the RSP re-constructed the required ellipsoid transformation and datum shift parameters from field surveys of fixed points with known coordinates.

Since then, however, another BTM grid, the 'Geodetic Control Network in Bangladesh' has been developed by Survey of Bangladesh and Japan International Cooperation Agency. The grid is well-defined and operational, and it is expected that it will be commonly used in the future. If so, it should be implemented for all national routine monitoring, as this will highly facilitate the exchange of data between the many different data producers and data users in Bangladesh. The grid is established in the field by a network of 141 geodetic control points that covers most of Bangladesh. Elevations have been established relative to an estimated mean sea level in Chittagong. Well-defined routines exist for conversion between this grid and WGS84, which is the basic GPS coordinate system.

The vertical control during the bathymetric surveys of the RSP was done in the traditional way: The actual, instantaneous water depth was recorded from a moving vessel using an echo sounder, and the simultaneous water level was recorded relative to the datum by staff gauges and/or AWLRs (with a known zero level) at certain locations within the survey area. The bed level relative to the datum was calculated as a part of the post-processing.

This procedure requires that the water-level difference between the gauge location and the vessel is known, for example from interpolation of the water level between adjacent gauges. In some cases, however, the vertical control was affected by surface slope irregularities. For example, between Bahadurabad and Baruria, the average surface slope is some 7 cm/km, but as has been demonstrated by RSP measurements, the slope can vary considerably with time and space around this average value. Among the bathymetric survey areas of the RSP, problems in this regard were particularly felt at Bahadurabad (due to braided channels), and at the Jamuna/Ganges confluence, where backwater occurs during peak flow in the Ganges.

A good vertical control requires a fine grid network of water-level gauges, so that the survey vessel remains within, say, 2-3 km from the nearest gauge, and so that the water level is always gauged in the channel where the soundings are made. Within this grid, water levels should be interpolated (rather than extrapolated, except over short distances).

However, this is not free of hassles. The data processing becomes more intricate, and, maybe more significant, the transparency of the results is reduced, because the datum cannot be easily traced to bench marks in the field, so that there is a risk that the data become contaminated with inherent benchmark datum irregularities. For morphological monitoring, a part of this uncertainty can be countered by using the same benchmarks (and the same DGPS reference stations) for successive surveys.

A recent technological accomplishment offers an alternative way of maintaining the vertical control during this type of work, as the DGPS positioning has been developed to serve the purpose of accurate vertical positioning of a moving boat. This system, the so-called RTK (real-time kinetic) DGPS, seems particularly attractive for bathymetric surveying in areas with a significant, irregular, and, perhaps, not fully known surface slope. This is because the river bed level is mapped directly relative to the selected (satellite-based) coordinate system, and not indirectly via datum transfer by a water level. The RTK-DGPS tool was not available until late in the project period and was for that reason not applied by the RSP.

7.2.3 Water-level gauging

The staff gauge measurements of the RSP were implemented in a way similar to the technique applied by BWDB, and the Project has little to add to the long-term experience of that organisation. In most cases, the staff gauges functioned well. Occasionally errors occurred for example in connection with stage shifts and gauge relocations. A proper bench mark reference is crucial, as well as regular verification of the staff gauge datum level and occasional validation of the bench mark level. Any shifts, for whatever reason, must be recorded.

A well-known consideration, which was encountered in connection with the analysis of BWDB data, is the placement of the gauging stations in a river that continuously shifts its course and flow domain. Several BWDB stations are located at places that would not have been selected today, but are retained for the good purpose of preserving the continuity of the long-term records. Here, a compromise must be pursued between the conflicting requirements of long-term consistency and short-term validity. Please refer to *RSP Final Report, Annex 2: 'Sustainable survey techniques'* for a discussion of this subject.

At locations with a pronounced tidal effect, staff gauge readings made during daytime only are not adequate, and, at some locations and some periods of the year, staff gauge readings make little sense at all, unless combined with a dense programme of flow recordings. Where fixed structures are available use of an AWLR with an acoustic sensor is recommendable.

The experience with the AWLRs operated by the Project is somewhat conditional. First, it is noted that an AWLR is much more expensive than a staff gauge with respect to procurement and installation, whereas the operation costs are of the same order of magnitude. Secondly, it was learned that identification of a good location for installation was difficult, and sometimes impossible. Problems encountered were (1) river erosion or siltation, (2) impact of ship collision, and (3) drying up of the river. In order to meet these difficulties, a strategy was conceived of applying the AWLRs for recording during high stages only, when they can be installed in 'safe' places. If so, the measurements at the same location during low stages must be done using staff gauges. In this connection it is noted that tidal effects are most pronounced at low stages.

Irrespective of whether a suitable location could be identified, a set of two adjacent staff gauges was installed and operated for the reasons of quality checking and data collection security. It is concluded that such a support procedure is essential.

The experience of the project does not justify a general use of AWLRs for routine monitoring in the area covered. This is not only due to the higher costs, as compared to staff gauges, but also because of the difficulties with finding a good permanent location for installation. Subject to proper organisation and execution, the two methods can provide an equal data quality (although the time resolution of the staff gauges is less than that of the AWLRs). Within the main part of the river system, where tidal effects are insignificant, staff gauge readings remain a cost-effective method with a suitable potential performance.

In the future, however, AWLRs may be required in Bangladesh for real-time monitoring for operational flood forecasting purposes and at tidal stations. It may be speculated that an increasing demand of minimum flow data at such stations will be induced by a need of an extended basis for water resources planning and environmental monitoring.

7.2.4 Selection of survey vessels

A survey vessel is a mobile platform from where instruments can be handled and samples taken. The characteristics of a 'good' survey vessel depend on (1) its application, and (2) the physical environment in its operation area.

The DHA vessel was the main survey vessel of the Project. It was mobilised for Phase 1 and performed well during the entire programme. Its stability was adequate for river navigation, and it had a suitable size for all types of measurements that were included in the RSP programme. Also, for many purposes, it served as a self-supporting operation unit, because the survey staff could be accommodated onboard. Its draft (of 1.2 m) was suitable for this size of a vessel, but still part of the operation (during ADCP transect gauging and bathymetric surveys) was limited by the draft. It was able to anchor for stationary work (vertical profiling and sediment sampling), also in a strong current. Its speed (of 12 knots) was fully adequate for survey work, and, depending on the schedule, transfer from one station to another seldom required more than one day. It could operate in most weather conditions encountered on the

ivers. The vessel did not have unscheduled down time worth mentioning, which, apart from the qualities of the vessel, may be taken as a proof of the skill and diligence of its skipper and crew.

The DIIB vessel was mobilised for Phase 2 of the project. It was intended for routine gauging, but without facilities for the most heavy operation (side scan sonar and pump sampling). It had a smaller draft (0.9 m) and a higher speed (15 knots) as compared with the DIIA. It performed according to expectations, although its operation was sometimes hampered by waves. The DHC catamaran was custom-built during the Phase 1 mobilisation. It was a light vessel with a small load capacity and proved less well suited for the type of operation it was intended for. Its inboard/outboard propulsion system with so-called z-drives was sensitive and broke down occasionally.

During the initial planning, it was tentatively considered to mobilise a Hovercraft vessel for the purpose of the project. Such vessels have been used occasionally elsewhere for river surveys, although not that much experience is available on their performance, and particularly not under comparable physical operating conditions. The idea was abandoned due to the unknown operational risk. The main potential advantage of a Hovercraft is its high cruising speed and its ability to cross shallow banks and flats in braided river sections, whereby cross-sections in such sections can be covered in less time. The operation and maintenance are more intricate and more costly than for traditional vessels.

The design of survey vessels for routine gauging in an environment like the one of the RSP survey area should consider aspects as listed in Table 7.1. It is noted that the various required qualities listed in the table partly oppose each other.

Navigation:	• Stability • Manoeuvrability, including ability to maintain position in a strong current • Draft • Speed • Ability to anchor in a strong current and a moving river bed, and stationarity while anchored • Low vulnerability to impact of grounding • Navigation control system (positioning, radar support, orientation, route tracking, Helmsman's display of runlines) • Dynamic monitoring for data correction (draft, heave, sway)
Survey work:	• Space for survey work • Room for data processing, computers and electronics (with airconditioning) • Power supply • Facilities (davits and (power) winches) for instrument handling and sample collection
Operation:	• Communication (general and data transmission) • Reliability of propulsion system • Storage room (samples, consumables, supplies, spare parts) • Bunkering capacity • Accommodation for crew and survey staff

Table 7.1 Quality characteristics of a survey vessel (excluding safety aspects)

Another quality aspect that relates to the survey vessel is the navigational safety. Even where *prudent procedures and appropriate precautions* are by far the most important safety elements, the vessel itself will influence the safety and the associated preventive weather down time. For example, the stability of the vessel is a basic safety characteristic. The sensitivity of the propulsion system to damage by fishing nets is of a considerable practical interest when operating on large rivers. The risk of collision with other vessels can be reduced (but certainly not eliminated) by a radar system, and by good lanterns. Radar reflectors are of less value in Bangladesh, where few vessels use radar. The hull of the vessel should be so strong that it is not very sensitive to occasional grounding. It is self-evident that the vessel should be supplied with adequate safety equipment.

- Grounding (particularly at falling stage)
- Propeller or propeller shafts damaged by fishing nets
- Collision with other vessels
- Falling overboard (particularly at night, or in strong currents while anchored, or during bad weather)
- Capsizing, for example during storms

Table 7.2: Safety risks in Bangladeshi rivers

7.2.5 Flow gauging by ADCP

A particular feature of the RSP was the application of the combined DGPS positioning and flow recording by ADCP, which made it possible to measure flow distribution and integrated flow rates over a cross-section with a better accuracy and in a much shorter time (and hence with a better validity) as compared to traditional velocity-area methods. To do a standard velocity-area flow gauging in one of the large rivers requires several days, which is a long time as compared to the time scale of flow fluctuations, not only at the tidal-influenced sections but also in the upstream reaches.

Further, the DGPS-ADCP approach does not require anchoring of the vessel while doing the measurements. The method is instead intended for flow recordings while transversing the river. This is a particular advantage in the large Bangladeshi rivers, where anchoring in the main flow channels is not only risky from a safety point of view, but can also be unpractical, because the anchor can sometimes be buried so deep in the river bed that it cannot be retrieved. For example, during the initial pilot survey with the '*Anwesha*', anchoring in the main flow channels at Bahadurabad was not practical. Also, the BWDB routine flow gauging at that location (by the velocity-area method using propeller current-meters) has, by necessity, to be made without anchoring.

For these reasons, it can be concluded that the DGPS-ADCP technique has distinct advantages, both with respect to quality and capacity, also for the Bangladeshi river environment, as compared to velocity-area flow gauging by propeller instruments.

As pointed out by the Project Advisor, a potential remains for further development of the technique and for improving the understanding of its performance. This involves further studies of the accuracy of the single current profile as well as of the entire flow gauging, and also for optimization of deployment and of the entire flow gauging procedure.

Due to the high instrument procurement and maintenance costs, and the need of a fully computerised data processing, the DGPS-ADCP technique is initially best suited for dedicated, fixed-term applications. In the course of time, the technology (in its future state of development) will most likely be implemented for routine monitoring purposes in Bangladesh and elsewhere.

The ADCP gauging requires an accurate relative positioning to reach its full performance. Under normal operating conditions, this is provided by 'bottom tracking', where the instrument itself (in addition the flow) registers the movement of the vessel relative to the riverbed. Sometimes, however, bottom tracking is not possible. This is the case (1) if the river bed cannot be detected during extremely high suspended loads, or (2) if the surface of the river bed is moving at high flows. During the planning of the RSP, the former difficulty was envisaged (and provided for in the design of the survey spread), while the latter was not. As it turned out, the latter was the main problem, but the effect was the same, and could be mitigated in the same way, namely by substituting the bottom track by the DGPS position.

The penetration of the ADCP depends on its frequency, the penetration being better for low frequencies, but at the cost of a somewhat reduced vertical resolution. Initially, the RSP mobilised a 300 kHz instrument for the DHA vessel, in view of the lack of experience with the instrument under extreme sediment loads. Subsequently, a 600 kHz instrument was selected for Phase 2 for the DHB. Both instruments performed well under the conditions encountered. The 600 kHz one gave the best resolution, i.e. 0.25 m as compared to 0.5 m for the 300 kHz instrument, but the latter was fully adequate in this respect. Occasional penetration limitations were encountered with the 600 kHz instrument. Inevitably, both were equally affected by a moving river bed, when occurring.

The Project had quite some difficulties with respect to the processing of ADCP data, which is obviously much more complex than for the area-velocity gauging. These difficulties were caused by the lack of experience with this new technology, and it is believed that in the near future, the computerised data processing of ADCP transects will become a matter of routine.

The advantages of the DGPS-ADCP method are less evident when combined with sediment sampling, where the superior flow recording capacity cannot be fully used. Yet, for sediment transport gauging, a good description of the flow field is crucial for obtaining good results.

7.2.6 Sediment transport

The physical environment for suspended sediment sampling in the large Bangladeshi rivers is extreme with respect to high, and highly varying current velocities (ranging up to around 4 m/s), and with respect to high, and highly varying sediment concentrations (ranging up to around 5 g/l). This affects not only the sampling routine and analysis procedure, but also the design of the sampling device, and its handling and operation.

The method originally recommended by the Consultant for the RSP was sampling by a traditional pumping system, or a depth integrating bottle. The applied pump sampler was designed for the purpose of the Project, as it was reasonably expected that samplers developed for application elsewhere could not function under the given physical operating conditions. The sampler consisted of a combination of a submerged pump with a variable capacity and an EMF, carried by an umbilical (a single string cable for suspension, flow tube, and power supply). Also, a turbidity meter was attached. Initially, this device did not perform according to expectations. It is evaluated, however, that the initial inadequacies of the pumping system were related to the specific design (rather than inherent shortcomings of the technique as such), and after implementing a number of modifications, the performance of the system became acceptable. Please refer to *RSP Final Report Annex 1: 'Surveys'* for details.

In the course of the project the instrumentation for suspended sediment gauging was extended. Another type of depth-integrating sampler, notably the collapsible bag, was added to overcome the depth limitations of the depth integrating bottle. At the initiative of the PA the Delft Bottle was added (especially for near-bed transport measurements, see hereafter) but certainly also useful for suspended load measurements). The ADCP backscatter intensity data used qualitatively for selection of measuring verticals in a cross-section became quantitatively more important when acceptable correlations were found between these data and the concentration of suspended coarse sediments. Further developments of the use of the ADCP technique in the near future is expected. Please refer to *RSP Special Report 12, "Optimization of sediment measurements"*.

The suspended sediment sampling technique will inevitably remain a compromise between given aims and some rather visible limitations. If possible, the method should be targeted towards the specific application of the data (provided that the application is known beforehand). For general purposes, a well designed pumping system is believed to be the most accurate and also versatile, although its implementation for routine monitoring can have significant practical limitations with respect to costs, as well as handling of the instrument itself and of the samples.

Practical and useful alternatives exist, such as the integrating bottle applied by the Project, such as the Binckley sampler applied by the BWDB, but these are characterised by certain constraints with respect to time resolution, space resolution and grain-size resolution and validity.

7.2.7 Bed-load and near-bed transport measurements

During the initial planning, it was envisaged to measure the bed-load transport by sand dune tracking: Repeated fine-grid depth soundings of a suitable area, followed by a calculation of the transport as represented by the propagating sand dunes.

Pilot surveys in 1992 and 1993 indicated that this procedure was not well suited. Sometimes, sand dunes did not exist at the appropriate location, or their propagation could not be resolved in a practical way. This impression was confirmed later on in the Project (e.g. at the tidal surveys in 1995). Even when good field data are produced, their interpretation is subject to inherent uncertainties about uni-directionality of the transport and about the depth of the moving layer. Hence, for the purpose of routine gauging, dune tracking is a time-consuming exercise with an outcome that is not reliable. Thus, for the purpose of routine gauging, the dune tracking was omitted. Instead, the near-bed transport was measured by a Helley-Smith

sampler. With this sampler good results were obtained in mid-flow conditions. During low flows the near-bed sand transport is too low to be of interest. In the high flows the drag is considerable, the risk of scooping is higher and the measuring time is difficult to determine.

As an alternative, at the initiative of the PA, a Delft Bottle was applied on a pilot basis, and it was later included in the routine gauging programme. It was found that certain design adjustments of its frame would be needed before this sampler was fully applicable for this purpose in the Bangladeshi rivers, particularly in strong currents (where also the bed-load transport is at its highest).

7.2.8 Sediment analyses and sediment transport calculations

Analysis of suspended sediments and river bed sediments took place in the in-house sediment laboratory of the project. Within the routine programme, the analyses were confined to traditional property characteristics (concentration, grain-size distribution, and settling velocity distribution), and were carried out by proven techniques (micro-filtering, settling tube tests, and sieving). Supplementary, extended analyses were carried out by the laboratories of the Geology and Soil Science Departments, Dhaka University (see *RSP Special Report 14: 'Mineralogical and physical properties of river sediments'*).

The sediment laboratory emerged as an entirely problem-free zone within the project. The data produced reflect the advantage of routine application of proven technology, namely a good data consistency and data transparency.

The information obtained by the standard methods was adequate for a gross description of transport rates and processes. The uncertainties with respect to transport rates and settling velocities were mainly related to the collection of the samples in the field, rather than to the quality of the analysis, whereas the quality of the grain-size distributions of river bed sediments mainly was related to the validity of the collected samples, rather than to the analysis.

Some open questions arose in connection with the processing and routine presentation of the sediment transport rates. Calculated transport rates represent a compound of many different data, which can be processed and presented in many different degrees of synthesis: single point or depth increment or vertical profile or length increment or entire cross-section; instantaneous or daily mean or long-term net transport; total transport or different grain-size categories. When the purpose of the data compilation is general rather than specific, the choice is in principle open within such a multi-dimensional array of options.

Following an examination of the immediate demands of the internal data users of the project, and after consultations with BWDB and the RSPMU, the project selected the standard presentations included in the *RSP Data Books*. These comprised (1) horizontal distributions across the river of instantaneous, vertically averaged transport of wash load, suspended bed material load, near-bed load, and total transport; (2) horizontal distributions across the river of D_{50} , of instantaneous, vertically averaged transport of wash load, suspended bed material load, and near-bed load; (3) summaries of single (depth-specific) suspended material grain size analyses: Weight percent above and below 0.063 mm, and D_{10} , D_{50} and D_{90} ; and (4) summaries of single bed material grain-size analyses: Weight percent above and below 0.063 mm, and D_{35} , D_{50} and D_{65} .

These presentations aimed at two objectives, one being a documentation of the physical conditions (with respect to flow and sediment transport) prevailing during the specific data collection, and one being a condensed extract of the data, suited for example for gross sediment transport rating curves. Experience indicated that alternative post-processing was required for the purpose of the different analyses and studies. This demand could be met, because all individual analyses were stored for this purpose. Still, a more versatile presentation could be conceived, perhaps a computer-based interactive data catalogue that could extract the desired information.

7.2.9 Tidal effects and backwater effects

It is expected that in the years to come, the demand of flow data for tidal-influenced reaches will increase in Bangladesh in connection with the enhanced utilisation of the lean season water volume and because such data are important in connection with environmental studies. One example would be impact monitoring of the reduced lean season flow in the Ganges.

Within the RSP project area, tidal effects only occur at the most downstream cross-sections, and only in the lean season. Here, the Project executed a programme of dedicated tidal flow and sediment transport gaugings.

Gauging of tidal-influenced reaches is more complicated than elsewhere:

- The water level must be registered continuously, and with a time increment that can resolve the (around 12 hours) tidal wave, for instance 30 minutes. This requires either AWLR registration, with the implications mentioned above, or round-the-clock staff gauge readings;
- the flow (and/or the surface slope) must be registered separately in addition to the stage;
- the data analysis and data interpretation are more complex, and can best be made by hydrodynamic modelling;
- real-time flow monitoring is considerably more complex (whereas real-time water-level monitoring at tidal stations does not differ from real-time monitoring at non-tidal stations).

It is noted that for analyses based on hydrodynamic modelling, water-level monitoring at such stations is of a pronounced practical interest, even in the absence of simultaneous flow monitoring. The tidal stations are located in the downstream end of the river systems, and data from such stations are therefore of a particular value as boundary values for regional river models, as applied for example by SWMC. In cases when routine monitoring of the flow is not practical, a series of dedicated fixed-term tidal surveys can provide a substantial amount of valuable information.

The traditional way to avoid backwater effects is simply to locate the gauging station outside the affected area, but in the complex river system of Bangladesh this would be a serious trade-off due to the extent of such areas.

Within the RSP routine gauging programme, backwater was encountered at Aricha during peak flow in the Ganges, and at Bhairab Bazar during peak flow in the Lower Meghna. The effect was examined on the basis of water-level slopes along the rivers, and one new water-level

gauging station (at Mir Char, 20 km downstream of Bhairab Bazar, on the Upper Meghna) was established by the Project for the purpose.

Effective flow monitoring during backwater can be made by a combination of measurements and hydrodynamic modelling, either by traditional hindcast simulations, or by an off-line or real-time data assimilation procedure. This, however, was not pursued within the framework of the RSP.

7.2.10 Routine gauging schedule

The scheduling of the routine flow and sediment transport gauging was a matter of concern throughout the Project, and was continuously reviewed between the project and the RSPMU. Two main impressions were:

- The measurement programme should address the time scale of stage-discharge variations (rather than the time scale of the flow variation itself);
- for the same reason, the measurement programme should provide an effective coverage of peak flow events.

This is because even detailed and accurate measurements of the instantaneous flow rate remain examples, with a low validity, unless supported by related long-term data. The desired knowledge about the flow is inevitably produced on the basis of some type of stage-discharge relationship. The quality of the information about the flow depends not only on the quality of the flow gauging itself, but also on the quality of the water-level monitoring and of the relationship between them. The significance of the scheduling is enhanced when using a gauging routine like the one of the Project, which was based on a few high-cost survey units, instead of a larger number of lower-cost units, as applied by BWDB. Please refer to *RSP Special Report 11: 'Optimization of hydraulic measurements'* for a discussion of this issue.

7.2.11 Topographic and bathymetric surveys

The land surveys of the RSP were largely carried out by traditional means, with occasional DGPS support. The bathymetric surveys were carried out by traditional echo sounding and with DGPS positioning. This first-time application in Bangladesh has, in the course of the project period, become an established practice for this type of work.

Within the Project, relative emphasis was given to the bathymetric surveys as compared to the land surveys, both with respect to capacity and time spent. With the benefit of hindsight, it is concluded that the resource distribution may have been less than optimal. Due to the stage variation, the effects of the morphological processes can materialise both below the river surface and on chars and banks that are dry land during parts of the year. The mapping of land contours and river bed contours are complementary, and the data coverage should be harmonized, as pointed out by the PA. The experience indicates a need for a higher capacity and resource allocation for topographical surveying, if necessary at the cost of a reduced resource allocation for bathymetric surveys. A new land survey technique (based on three-dimensional RTK-DGPS positioning) has recently been developed and is available in Bangladesh (at SWMC). The technique is powerful with respect to capacity and accuracy, and may well have a large potential for future monitoring of morphological processes.

The RSP surveys were not only made before and after the monsoon, but also during high flows, when the morphological processes were in rapid progress, in order to examine details of these processes. It appeared that the data analysis of such high-flow surveys was particularly intricate, because not only the stage, but also the bed levels varied during the work. For example, if the measurements for some reason had to be discontinued for a few days, a discontinuity would appear in the recordings, because the bed level had changed in the mean time. The same was the case at the boundary between data from two channels that were surveyed successively. Even when the measurements were made continuously from one end of the survey area to the other, so that no discontinuities appeared, the interpretation was difficult, because the data would not yield an instantaneous (and thereby fully consistent) image of the bed forms: The data represented a complex combination of time variations and space variations. (This aspect somewhat resembles the implications of measuring flow by a traditional velocity-area method over a large cross-section over several days, where the flow can change significantly during the work).

7.2.12 Data administration

Whilst the data collection of the RSP was partly based on the most recent technology, the data processing, although fully computerised, was largely carried out by proven methods, such as separate time and space integration procedures for data reduction, and separate analysis and storage of data that describe time and space variations.

It is tentatively believed that there is a potential, and perhaps a big potential, for enhancing the quality and the validity of the river data by implementation of new data processing technology, notably by data assimilation into numerical hydrodynamic and morphological models. A circumstance to keep in mind in this context is that field measurements are expensive compared to numerical modelling, and particularly so when compared to the operating costs of a model once it has been established.

A suitable combination of field measurements and numerical modelling is particularly powerful for description of complex processes, such as flow in backwater and tidal areas, and overland flow phenomena. Here, the modelling can serve two purposes: (1) an integral processing of aggregate information on a well-defined (although simplified) basis, and (2) an extension of the validity of short-term registrations.

Hydrodynamic models are well implemented in Bangladesh, for example at the SWMC, and at BWDB's Flood Forecasting and Warning Centre. Data assimilation techniques exist, but can today hardly be characterised as well-proven, particularly not with respect to sediment transport and morphological processes. Still, there is reason to believe that attempts to improve the accuracy and validity of knowledge about the river processes should consider an upgrading of the data processing. This is particularly the case when keeping the overall cost-effectiveness in mind.

An observation made at an early stage of the survey programme concerned the volume of data that could be produced in the field by the high-capacity survey instrument spreads. Initially, the field measurements produced more data than could be processed with any reasonable effort. This high production rate of field data reflected a considerable duplication of measurements for consistency validation and data security, which was not justified once some experience had been developed with the routine gauging. Therefore, in the first half

of 1994, the gauging procedures were streamlined, and the data collection and data processing routines and capacities were harmonised, so that in the final year of the survey programme, the routine gauging truly became 'routine'.

The processing and presentation of the bathymetric mapping were more difficult and time-consuming than anticipated, considering that these tasks are traditional standard operations. The software originally selected for the purpose did not perform as expected, and had to be replaced, and also the procedures for preparation of the final sounding and contour maps required successive adjustments until a late stage of the Project. The RSPMU extended a valuable support also in this respect. For future applications, the software and hardware for data processing should be supplemented by high-capacity presentation software for final editing and finishing of the maps (which were done by hand during the Project). To the extent that the bathymetric surveys will be used for navigation, the data should be processed and disseminated in the shortest possible time, because of the dynamic behaviour of the river system.

7.3 Hydrological characteristics

7.3.1 Water-level slopes

Water-level slopes provide important information about the hydraulic and morphological behaviour of rivers. Under the RSP both far-field and near-field investigations of water-level slopes have been carried out. Longitudinal water-level profiles have been determined for the main rivers for different flow conditions (Figure 7.1). In the upstream reach of the two main rivers in Bangladesh, the overall slopes appear to be fairly constant: 7.6 cm and 5.5 cm per km for the Jamuna and Ganges rivers respectively. Farther downstream, the slopes vary considerably with river discharge. In the Padma River the slope is about 4 cm per km during the flood season and almost nil during the lean season. The slopes in the Meghna River are even less: 2.2 cm/km to about zero for flood and lean-season flow conditions respectively. Apart from providing relevant information for backwater and sediment transport computations, the longitudinal profiles give clear indications of possible errors in the gauge zeros. The result of the overall slope analysis has been the trigger of a full-scale re-levelling of gauge zeros and benchmarks, see Sub-section 5.2.1 of Annex 3.

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

The potential use of local water-level slopes for the assessment of morphological developments was studied by means of the left Jamuna channel records of 1995. From satellite images of the left channel configuration prior to, during, and after the 1995 flood, it can be deduced that for some time the channel was partly blocked near Jim's bar: during the flood the channel west of the bar silted up. From the images of the area after the flood period one can observe that the river responded to the temporary blockage by expanding the channel east of the bar. The development of this process in time can be read from the Bahadurabad hydrograph in combination with the water-level differences/local slopes between Bahadurabad and upstream and downstream stations; please refer to Annex 3 and Figures 7.2 and 7.3.

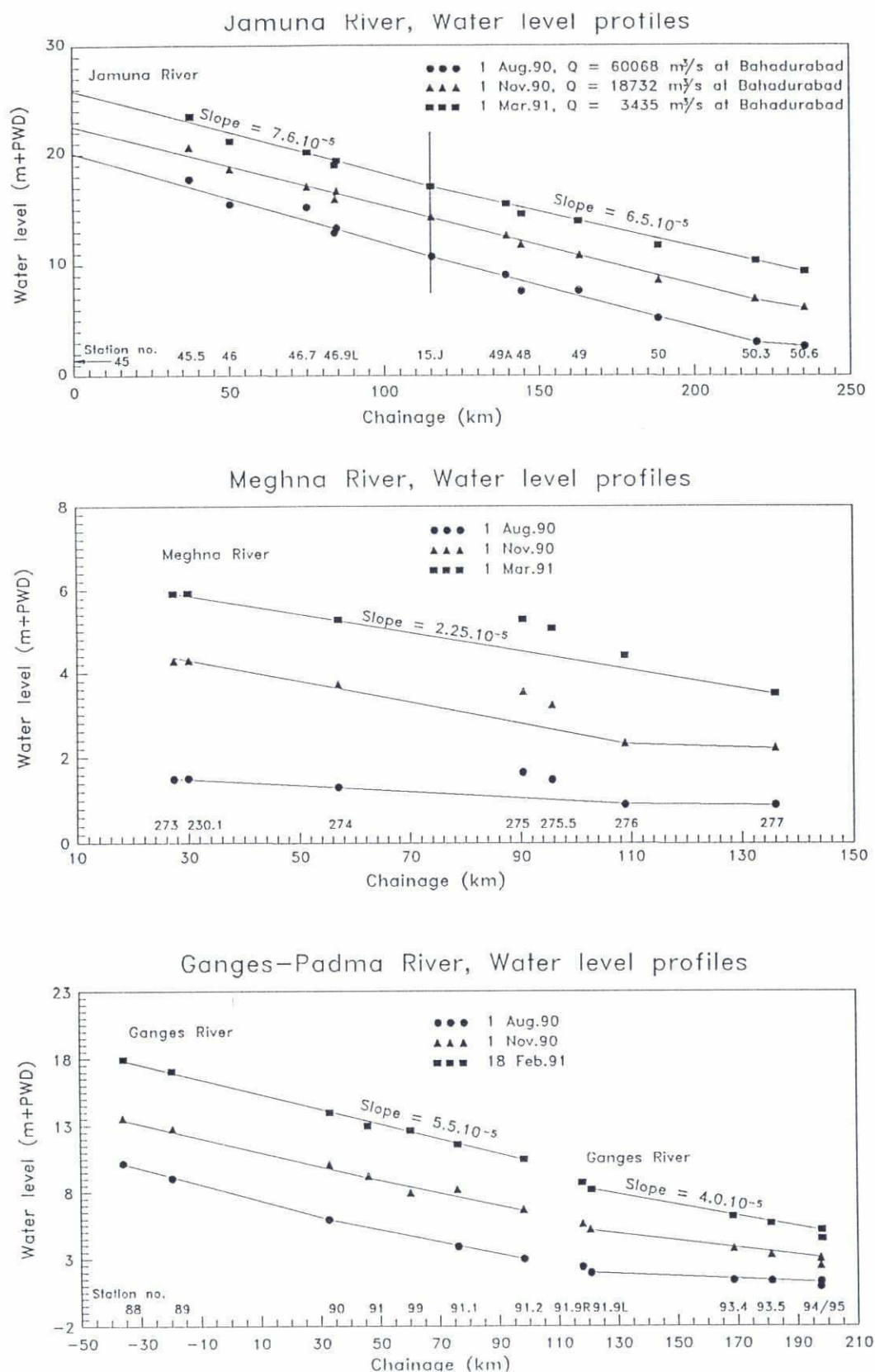


Figure 7.1 Water-level profiles

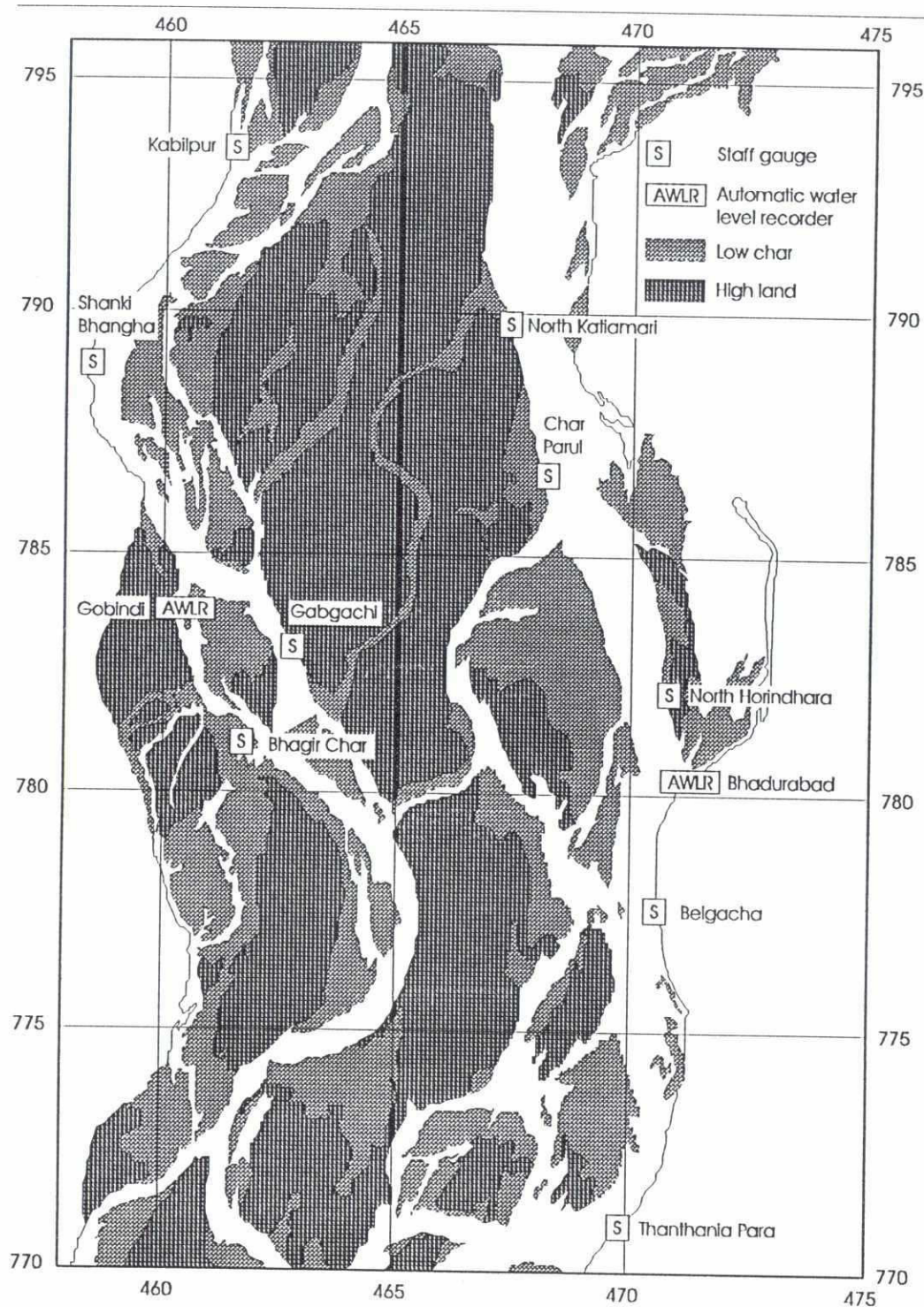


Figure 7.2 Location of RSP water-level gauging sites at Bahadurabad

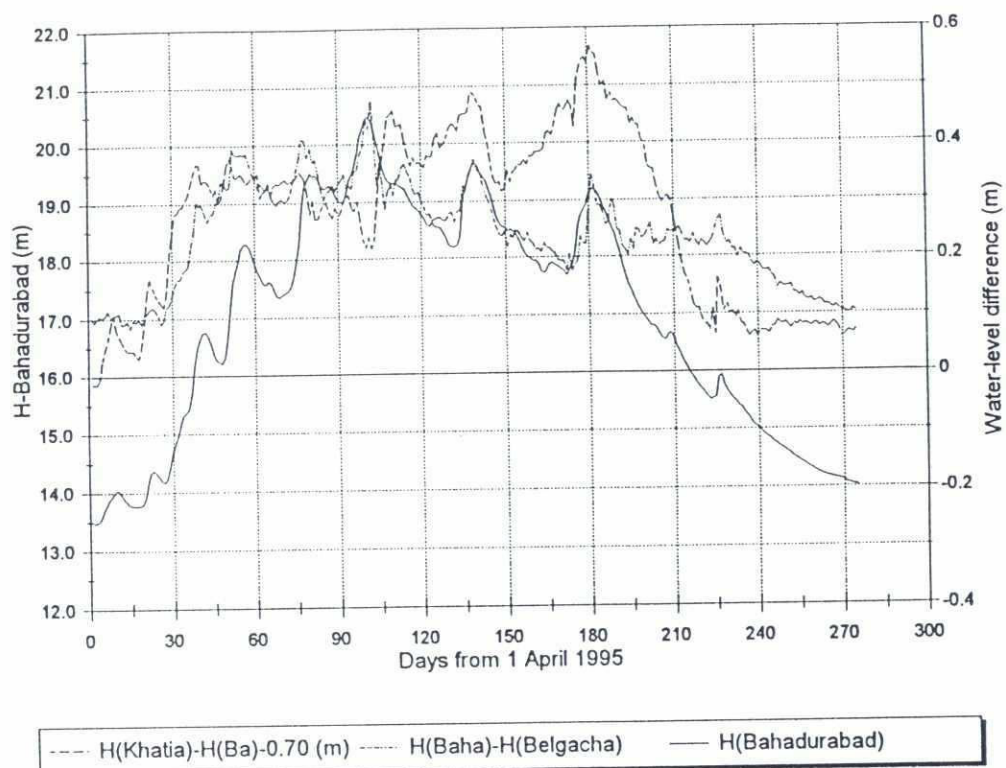


Figure 7.3 1995-hydrograph of the Jamuna river at Bahadurabad and water level differences upstream and downstream of the Bahadurabad flow measuring transect

7.3.2 Discharge observation

Test measurements carried out by the RSP at Bahadurabad in the Jamuna River revealed that the ADCP-EMF moving boat method gives very reproducible results; crossing the river and back gave differences within a few percent. Discharges measured by the ADCP-EMF moving boat method are on average less than those measured by conventional velocity-area method using propeller type current-meters. Analysis of joint discharge measurements by the BWDB and RSP revealed that, on average, the BWDB measured a higher discharge than RSP varying from -3% to 13%. The year to year variation in the stage-discharge data is less in the RSP than that in the BWDB.

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

7.3.3 Stage-discharge relation

The existing method used in Bangladesh to establish a h-Q rating curve is to fit straight lines for each segment, assuming that the offset value (the level at which the discharge is zero) estimated for the first segment is also the value for the remaining segments. This makes it impossible to obtain a good non-biased fit to the points of the upper segments. The unrealistic offset values for the upper segments applied by BWDB/FAP25 also lead to unrealistic exponents b in the rating curve equation $Q = c(h+a)^b$. For example, for the third segment of the 1988 rating curve for Hardinge Bridge, FAP25 estimated an exponent $b = 6.629$ (and $a = -2$ m), whereas the RSP's estimate is $b = 2.002$ ($a = -10$ m). In general, the exponents b should be in the range 1.3-3.5 depending on the type of river. Exponents higher than 3.5 are highly suspect and non-physical. Too high b values lead to overestimation of the discharge if used for extrapolation.

Because of the inadequate rating-curve method currently applied in Bangladesh, RSP developed new rating curves for the main stations of the major rivers, for each hydrological year with enough data available; see e.g. Figure 7.4. The procedure in developing the rating curve includes a segmentation of the rating curve, where the segment boundaries coincide with changes in the cross-sectional geometry. For each segment the data are fitted by power type equation. Essential to the RSP procedure is that the value for the power remains within physical limits and that the offset applied to stage is unique for each segment. By selecting a unique offset for each segment the fit to the data has been improved.

Possible improvements by applying separate rating curves for the left and for the right channel at Bahadurabad were investigated, as an alternative to the single relation. Neither the BWDB data nor the results based on RSP data show significant improvement of the stage-discharge relation. However, channel-wise development of the stage-discharge relationship was a better approach since the hydraulic and morphological conditions in the right channel were different from those in the left channel (Special Report 4, RSP, 1996). The highest discharge in the right channel at Bahadurabad during 1994 and 1995 were about 25% of the total flow, and its share decreased substantially with the fall in stage.

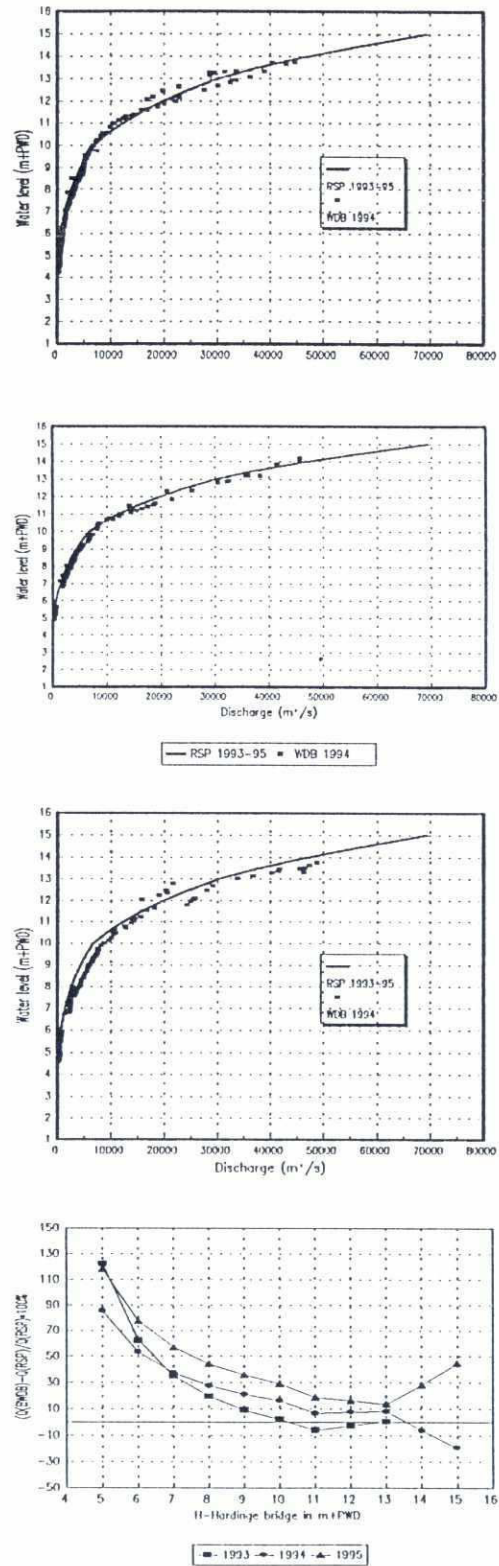


Figure 7.4

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

Stage-discharge data of the RSP and the historical stage-discharge data measured by the BWDB at Bhairab Bazar show a large scatter. Correction of backwater effects by the constant-fall-method improves the stage-discharge relation considerably (Figure 7.5).

The stage-discharge relation has to be extrapolated often beyond the measured range. Extensive investigations were carried out by the RSP into the most adequate extrapolation procedure (Special Report 4, RSP, 1996). The following procedures were considered:

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

The conveyance-slope method with horizontal segmentation of the river cross-section is recommended to arrive at reliable extrapolations of the stage-discharge relation at Bahadurabad.

The trends and magnitudes of shift of the annual rating curves have been illustrated by plots of the variation of water-level for selected particular discharges (specific gauge analysis). At the stations in the major rivers there are no consistent long-term trends in the water-levels for particular discharges, but variations from year to year are considerable due to morphological changes in the physical system. This indicates that the major rivers (Jamuna, Ganges and Padma) are in dynamic equilibrium. For the Gorai River the analysis, however, clearly shows an increasing trend indicating that the Gorai is aggrading due to the deposition of sediments.

7.3.4 Discharge time series

Using the h-Q rating curves of RSP derived from stage-discharge data of BWDB, discharge data were generated (1966-95) for five stations on the main rivers. Various hydrological analyses revealed that BWDB's discharge measurements at Bahadurabad for medium to high flows are too high since the major 1988-flood and resulting discharge time series based on these data are inconsistent with the discharge at Baruria (corrected for the Ganges). Application of the discharge rating curve, based on early pre-1988 stage-discharge data, produces consistent discharge series for that period.

The discharge series for Baruria prior to 1972 give low values and should be excluded from the historical records for any statistical analysis.

7.3.5 Statistical analyses

The corrected and updated long time series of mean daily water-levels and discharges for the five discharge stations analyzed provide an adequate basis for various frequency analyses of the time series. The three-parameter log-normal distribution fits well to the annual maximum water-levels as well as discharges (Figure 7.6). Generally, poor fits were found with the Extreme Value Type I or Gumbel distribution for the annual maximum discharge.

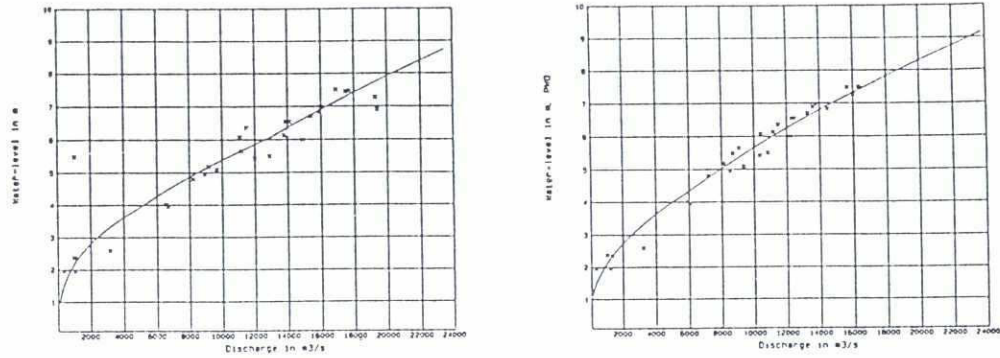


Figure 7.5 1988 rating curves for Bhairab Bazar, (a) without and (b) with correction based on constant fall

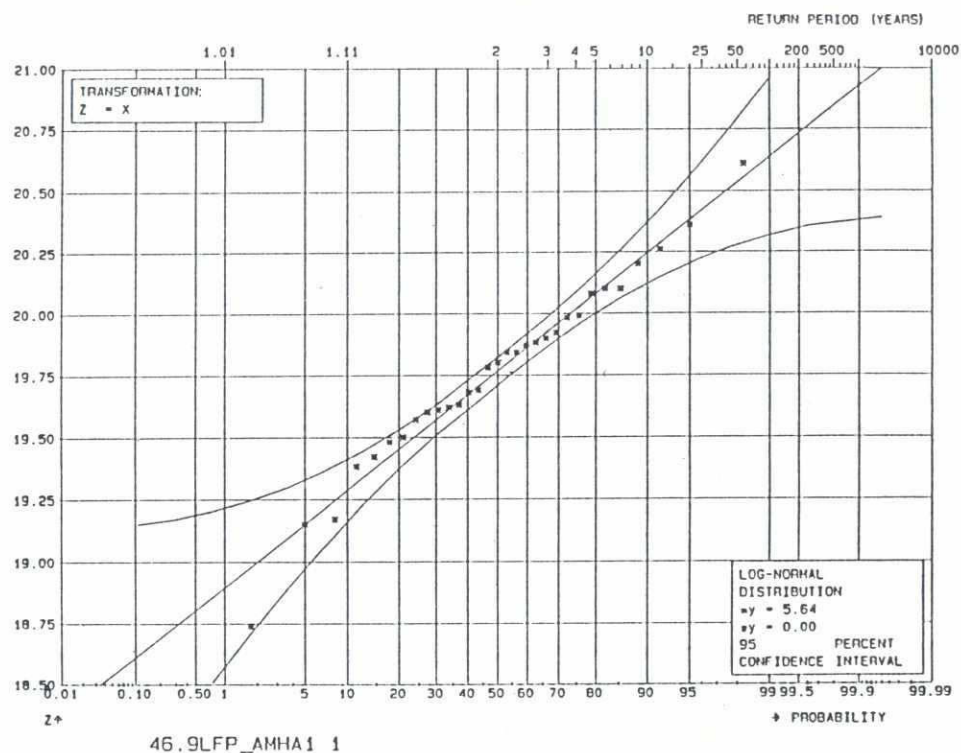


Figure 7.6a Fit of log-normal distribution to annual maximum water levels at Bahdurabad

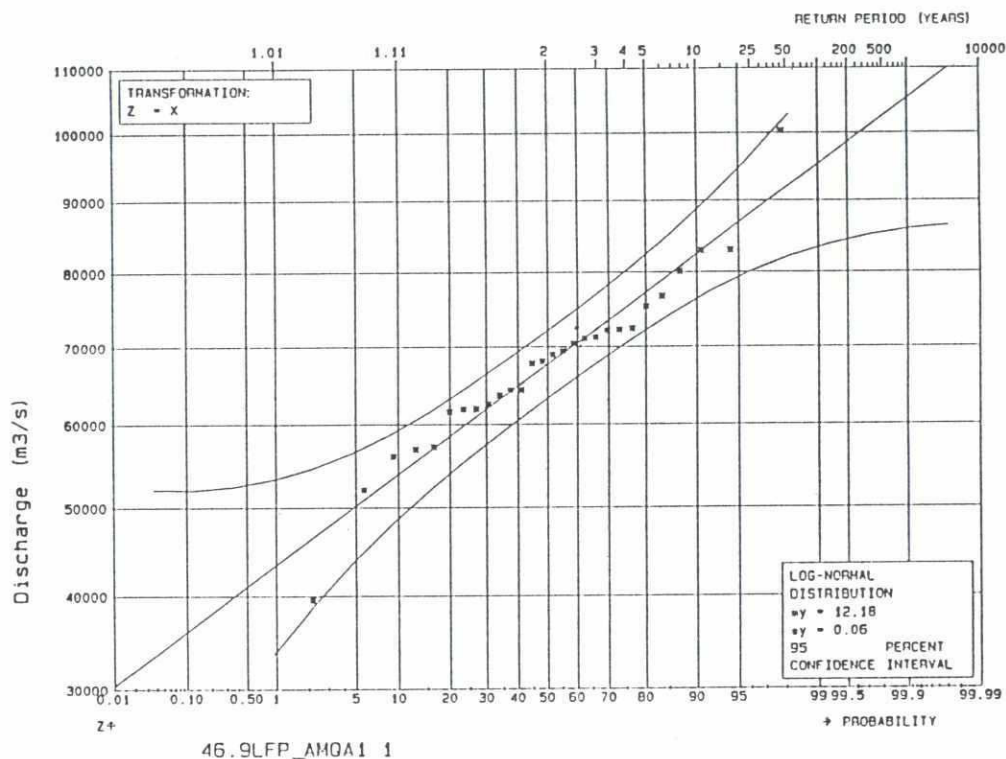


Figure 7.6b Fit of log-normal distribution to annual maximum discharges at Bahdurabad

7.3.5 Recommendations

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

- 1 – The setting up of a Hydrological Information System is proposed according to the guidelines and processing procedures as outlined in Annex 3. The proposed procedure is recommended to be applied to the historical water-level and stage-discharge data of all stations in the hydrological network.
- 2 – An AWLR-station downstream of Bhairab Bazar is recommended to be established to correct the stage-discharge relation for Bhairab Bazar for variation in slope.
- 3 – It is recommended to investigate the additional benefit of the execution of discharge measurements at Mawa relative to flow measurements at Baruria and at the Arial Khan offtake.
- 4 – Studies are recommended on the extent of backwater effects on the stages at Hardinge Bridge to investigate possible reduction in the scatter of the stage-discharge data. At the same time a relocation of the gauging site is recommended to minimize morphological effects on the gauge readings appearing as seasonal variation in the velocity head for equal discharges.
- 5 – The application of the conveyance-slope method for the extrapolation of the stage-discharge relation beyond the measured range is strongly recommended.
- 6 – To support studies on the dynamic behaviour of the main river system and to be able to explain the variation in the stage-discharge relations at the various sites, the use of an one-dimensional mathematical hydraulic/morphological model of the main river system is imperative.

7.4 Sedimentological characteristics

When discussing the sedimentological characteristics of the main rivers of Bangladesh, typically the following aspects are addressed: bed and bank material, bedforms, resistance to flow, sediment transport, sediment transport formulae, sediment rating curves, sediment loads and sediment balances, and floodplain sedimentation. In this Section also some remarks are made as to the EIA of FAP as far as the response of the main river system is concerned on measures proposed under FAP.

7.4.1 Bed and bank material

Already in the FAO (1967) and NEDECO (1968) studies data on the bed material of the main rivers are given. These data however were based on a limited number of samples only and hence they cannot be considered as representative. What was interesting though, was that the samples showed a substantial variation in particle size ranging from fine sand up to 0.5 mm down to silt of a few micrometers only. Under the River Survey Project a special study was carried out to make an inventory of the variation of particle sizes, using a part of the Ganges River as pilot reach. It was observed that roughly speaking the samples are made up of two subsets of materials, one of fine sand and the other of silt. Further study elucidated that silts are found only at certain places. These are either places in the lee side of morphological features and in local depressions (e.g. abandoned channels) or near eroding banks. These banks act as a source of fine silts as the upper layers of the floodplains consist of fine sand with on the average 25 % of silts. The present understanding is that the overall morphology of the river is determined by the fine sands, and that settling of silt takes place at places where the overall morphology and local hydraulic conditions allows for settling of fine material. Often these are places where the water is almost stagnant. Consolidation of these fine silts may take place, but due to the virtual absence of clay particles in the Brahmaputra River the resistance to erosion of these slightly consolidated silt deposits is very low. Recent silt deposits have only a marginal influence on the river behaviour.

There are however some places along the major rivers where the river banks are more resistant. Also Coleman (1969) indicates some more stable reaches in the Jamuna River, but some of these reaches (e.g. the nodes which have been cited by many authors as being stable) may not be so stable after all. The major erosion at the location of the Jamuna Bridge under construction during the floods of 1988 and later demonstrates that these nodal points may be temporary features only. Other banks are more stable. Typical examples of the latter are Sara along the Ganges River and Mawa along the Padma River. It is possible to link these to recent information of the surface geology of Bangladesh, and this supports the possible presence of older, more resistant deposits. For more details see *Section 7.5, Annex 5* and *RSP Special Report 7*.

Considering the "real" bed material (i.e. the sand fraction) of the main rivers a more complete picture is now available, owing to some additional sampling (see *RSP Special Report 8*). The bed material is fine sand, the D_{50} ranging in the Jamuna River from around 0.25 mm at the Indian border (0.18 mm for the Ganges River) to less than 0.10 mm near Chandpur. The σ_g ranges between 1.4 and 1.8 only, hence it is fairly uniform bed material. The reduction in D_{50} along the rivers is substantial and probably may be explained by the combined effect of abrasion and longitudinal sorting, the latter in combination with aggradation in combination with subsidence. The bed material composition of the distributaries is comparable with the

composition of the main rivers at the reach where they take off, though for the Gorai the bed material is on average a little coarser than for the Ganges River. Probably the bed material size of the distributaries decreases in downstream direction as well. An inconsistency was observed in the Old Brahmaputra River, where the bed material size near Mymensingh is larger than at the offtake. Here the effect of the input of local tributaries might be important (see *RSP Special Report 8*).

An exploring study was carried out into the mineralogical characteristics of the sediments (see *RSP Special Report 14* and *Annex 4, Chapter 2*). It was found that the bed material of all major rivers have specific mineralogical characteristics and that they vary in the relative contributions of heavy minerals, quartz and mica. In particular the high mica contents of the Jamuna sands is interesting because of its geotechnical relevance. In Bangladesh the main source of mica is the Teesta River. The percentage of mica seems to decrease quickly along the Jamuna River probably because mica is very vulnerable to abrasion. Another special feature is the relatively large contribution of heavy minerals. The large differences in densities and – to a lesser extent – also the particle form of the different minerals will affect their settling behaviour and may play an important role in local sorting.

Local sorting was observed in the main rivers during different surveys. The D_{50} of bed samples may vary by a factor 4. Armouring however does not take place, as the shear stresses are almost always quite in excess of the critical value (Jansen, 1979). In view of this, probably also the effect of local sorting on the river morphology is limited. There is no pronounced influence of the season on the composition of the bed material (see also Klaassen et al, 1988).

7.4.2 Bedforms

In many rivers bedforms occur at the interface between the water and the bed. By now it is fairly well accepted that there exists a variety of bedforms which in rivers are often superimposed; see e.g. van Rijn (1993). Already Coleman (1969) discussed the occurrence of bedforms in the Jamuna River extensively. He identified three types of bedforms, notably:

- ripples;
- dunes, both two- and threedimensional;
- mega ripples.

Klaassen et al (1988) studied bedform dimensions in the Jamuna River within the framework of the JMB study, and proposed empirical predictors for dune heights. In the present study the observations by both Coleman (1969) and Klaassen et al (1988) were confirmed, but due to the larger data base improved predictors could be developed. Some special surveys were done to identify and quantify bedforms and their dimensions. In addition thalweg soundings were used. Finally the side-looking sonar was extremely helpful in identifying the variation of bedform occurrence in a 2-d space.

In much of the older literature it is stated that during high stages bedforms vanish. As shown by Julien & Klaassen (1995) this is often not correct for large alluvial rivers like the main rivers in Bangladesh, because here large Shields-values are combined with low Froude-numbers. This statement was confirmed by the findings of this study: dunes are ubiquitous in the main channels for all flow stages. There are however also some reaches (about 5%

of all reaches considered) where temporarily no bedforms are present. The occurrence of bedforms is very much dependent on 3-d hydraulic conditions, and on underloading. Hence the occurrence of bedforms at specific places is difficult to predict.

In line with the relations found by Klaassen et al (1988) the dune dimensions were linked to the flow conditions. Dune heights scale with the water depths. Usually average dune heights are about 15% of the water depth. Also in this study no bedforms larger than about 8 m were observed. It has to be concluded that the figure of 15 m presented by Coleman (1969) did not relate to dunes or mega-ripples, but are most probably related to a confluence. An interesting feature is the slope of the leeside of the dunes: this slope varies between the angle of natural repose and very gentle slopes (less than 10°). This has serious implications for the form roughness (see hereafter, but also Annex 4, Chapter 3). This gentle lee slope is probably caused by the sediment in suspension that is entering into the wake downstream of the dune crests. Probably the influence of the suspended load is more pronounced during higher stages.

During some special surveys dune migration rates were measured as well. The available measuring techniques (in particular the echo sounder in combination with the DGPS) allow for a good accuracy. It was found that the migration rates vary between 1 to 17m/h. From these values, in combination with the dune heights, it is possible to get an upper estimate of the bedload transport. As shown by Fredsoe & Tjerry some of the suspended material enters into the wake downstream of dunes, causing that some of the suspended load contributes to the advance of the dune front as well. See hereafter and *RSP Special Report no. 12*. A correction for the influence of suspended load is needed in these rivers, where the suspended load is dominant.

Also the bedform response to changes in flow stage was studied. In some publications (e.g. Julien and Klaassen, 1995) it is shown that the bedform dimensions may lag behind changes in flow stage for several days. This is not the case in the rivers in Bangladesh. In these rivers the adaptation is very fast. This is probably due to the much larger sediment transport rates in these rivers.

Finally, the flow over large dunes was studied. Also for this type of studies the available equipment, in particular the ADCP, is unique. The observed flow pattern is similar to the pattern observed in flume studies by e.g. Mierlo and de Ruiter (1988), see also Van der Knaap (1990) and by Bennet and Best (1995). The large boils often observed in the Jamuna (Coleman, 1969) and other main rivers are linked to the dune crests.

7.4.3 Resistance to flow

There were two major questions to solve regarding the resistance to flow of the main rivers in Bangladesh. Firstly, very low values for the resistance to flow of the main rivers in Bangladesh had to be used during various studies in the past (FAP1, FAP9B, FAP21/22), notably Chézy C-values in the order of 80 to 100 $\text{m}^{1/2}/\text{s}$ and more. Otherwise it was not possible to reproduce observed or extrapolated stages with known discharges. An explanation for this is needed. Secondly, for low flow conditions a much larger resistance to flow (C-values in the order 50 $\text{m}^{1/2}/\text{s}$) is observed (see Klaassen et al, 1988). Also this should be explained.

An overall expression for the resistance to flow in the Jamuna River was tested recently in the 2-D morphological modelling for the Jamuna Bridge (DIII, 1996). To reproduce the overall resistance to flow correctly and to prevent a too smooth bathymetry over the chars, the following expression was used:

$$C = 60 \cdot \left(\frac{h}{h_{\text{mean}}} \right)^{0.50}$$

which by using $h_{\text{mean}} = 5.8 \text{ m}$ can be transformed to:

$$C = 24.8 h^{0.50}$$

Some support for this expression can be found by using the at-a-station relations for the Jamuna River (Klaassen & Vermeer, 1988). By combining these with the continuity equation and the Chézy equation it can be shown for any of that (see *Annex 4, Chapter 3*).

$$\bar{C} = 22 \bar{h}^{0.61} \approx 27 \bar{h}^{0.5}$$

Traditionally resistance to flow in alluvial flow is ascribed to a combination of particle roughness and form roughness. As was stressed by e.g. Peters (1993), there are additional contributions to resistance to flow in these main rivers. These contributions are due to irregularities of the river bed and banks, in particular pronounced in braided rivers both during floods and during lower flow stages. Typical contributions can be:

- the effect of bends;
- additional energy losses due to lateral momentum transfer;
- expansion (Carnot) losses due to decelerating flow caused by the non-uniformity of the cross-sections.

In smaller rivers, in particular the distributaries being used for agriculture during the low-flow season, energy losses due to vegetation might also be considerable in some periods.

To study resistance to flow detailed slope measurements were carried out in a river reach near Bahadurabad during the years 1993, 1994 and 1995 (See *Annex 3*) and *RSP Special Report 4*. In particular the surveys in 1995 were important when in addition to bathymetric soundings and discharge measurements, also float tracking was done. A detailed analysis was carried out, from which it was concluded that the Chézy-values were in the order of $70 \text{ m}^{1/2}/\text{s}$ and that these could be explained fully from grain roughness and bedform roughness. It was required to correct for the gentle lee-side of the bedforms, making the contribution of the bedform roughness almost negligible. During high stages there may still be bedforms (see before), but due to their gentle lee-sides they hardly contribute to the resistance to flow. Exploring computations show that the effect of lateral diffusion on the overall resistance to flow is negligible for these wide rivers. Estimates of the other contributions could not be assessed, but in view of the measured C-value of about $70 \text{ m}^{1/2}/\text{s}$ (to be compared with 80 to 100 mentioned before) their contribution can only be significant in exceptional cases (depending on the bathymetry).

During low flow, when the resistance to flow increases the effect of the non-uniformity of the cross-sections, the effect of bars and the form roughness (steeper lee-sides?) may be larger. The influence of lateral momentum transfer remains very small. An important contribution to the overall increase in roughness over a stretch is the increased sinuosity of the flow. Bars that have emerged in the second order channel force the flow into a more curved pattern, and this increase in length leads to an (apparent) increase in resistance to flow, which may partly explain the observed behaviour.

7.4.4 Sediment transport patterns

Sediment transport patterns in large and wide, untrained alluvial rivers like the Jamuna and the Ganges Rivers are quite different from conditions in more narrow and trained rivers. The main difference is the occurrence of bars (morphological features as they are referred to by Peters, 1993), the irregularity of the cross-sections, the distribution of the bedforms and the mobility of the bed (and banks) even during low flow conditions. Local slopes can be several times the overall slopes (see *Annex 3*) and can be quite different from the overall slope direction. The implication is that the flow magnitude and direction may vary considerably. The sediment transport of the bed material (BWDB nomenclature "coarse sand") is often simplified to:

$$s \propto u^n \quad (7.1)$$

where s = sediment transport per unit width (m^2/s), u = flow velocity (m/s) and n = power (in large sandbed rivers n is about 4). This implies that there are huge differences in transport capacities.

The most important consequence is that the (alluvial) river is continuously reworking its own deposits both in the main channels and in the floodplain. A bar that is deposited during previous flow conditions may be eroded again in a subsequent phase of the hydrograph. Quantities of sediment generated by bank erosion and by erosion of bars can be quite considerable and are locally overloading the river. This implies that over short distances sediment may be eroded, of which the coarse fraction is deposited more downstream. This gives rise to sand-arrows (Peters, 1977 and 1993), and demonstrates the importance of the coarse fraction for morphological changes.

Some interesting examples of overloading and re-working are given in Annexes 4 and 5. As an example Figure (7.7) is given.

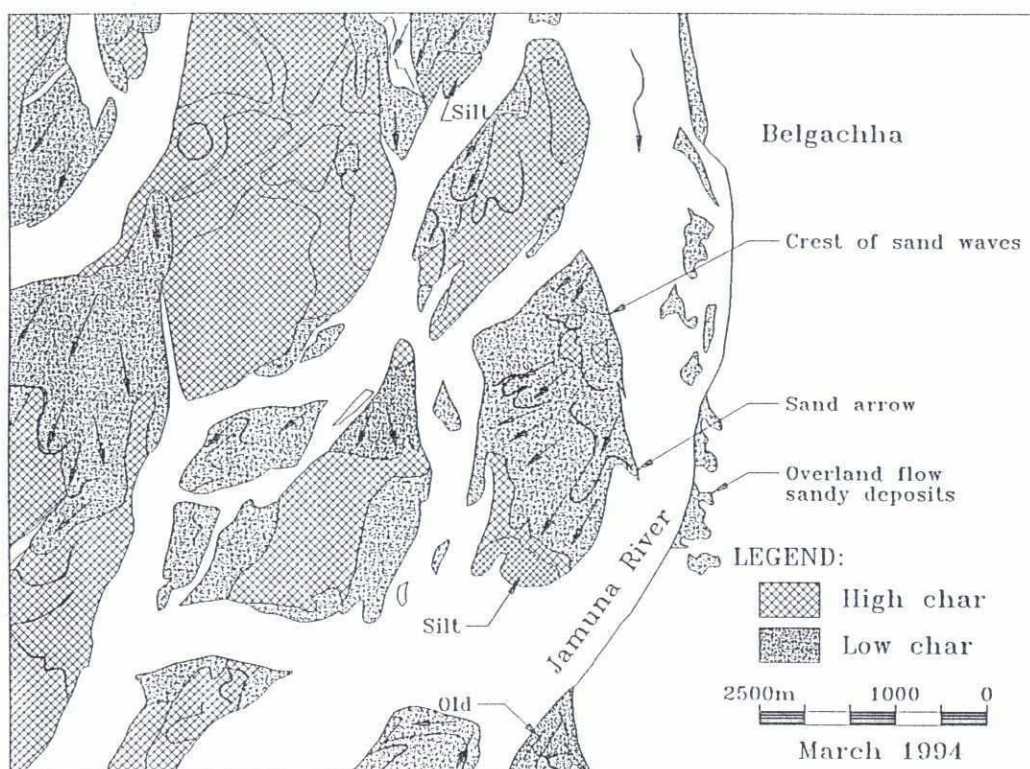


Figure 7.7 Example of sand arrow

The extreme variability of sediment transport, of local slopes and of velocities make the interpretation of sediment transport measurements quite complicated. The sediment transport is not completely determined by the local conditions, but is the resultant of complicated 2-dimensional upstream phenomena including overloading. Typical adaptation lengths of (over or underloaded) suspended load verticals are - depending as they are on size, density and shape of the sediment particles - in the order of 0.2 to 5 km; see Annex 4.

A very interesting development is the use of the ADCP for studying the variability of the flow field and the sediment transport. Assuming that the sediment concentration is given by

$$c = \frac{s}{h \cdot u} \propto \frac{u^{n-1}}{h} \quad (7.2)$$

where c = concentration (mg/l) and h = water depth (m), over- and underloading can be identified. This is shown in Figure 7.8, where on the left side the measured bed topography and the measured bed material transport (from the backscatter of the ADCP) is presented, and on the right part of the right side the computed sediment transport using the above equation in combination with a sediment transport predictor (for s), derived especially for the main rivers in Bangladesh (see hereafter). By subtracting the computed sediment transport concentrations from the measured ones an indication of the overloading is obtained. This is presented in the middle part of Figure 7.8. For easy interpretation the bed topography (as contours) was added to this latter graph. It can be seen that overloading - defined here as excess sediment transport (up to 500 mg/l!) - is observed on an eroding slope next to a scour hole. By linking this to morphological features and the flow pattern, a much better understanding of the complicated re-moulding of the river bed is obtained. This very interesting and unique development within the RSP opens the door to possibilities for better surveys and studies and to increased understanding of the morphological behaviour of large alluvial rivers.

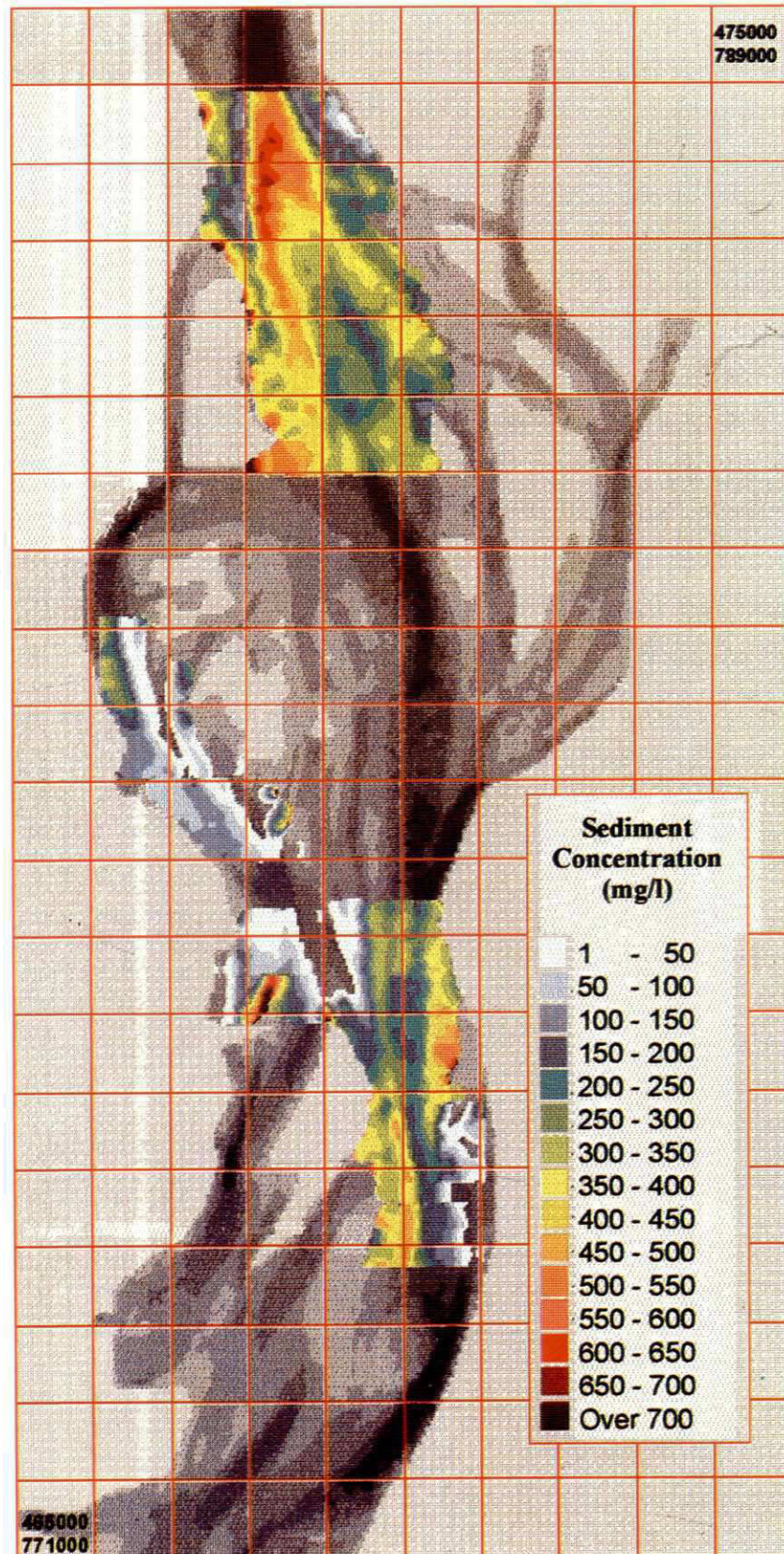


Figure 7.8 Identification of overloading from ADCP backscatter

Another important conclusion derived from detailed RSP surveys with Delft Bottles, introduced on the initiation of the PA, is the importance of near-bed load, the sediment transport in the lower decimeters of the transport verticals where the coarse particles are transported. Often the transport in this layer is not measured due to measuring problems and assessments are made on the basis of theoretical assessments (like Einstein, 1950; van Rijn, 1984). Different from what was assumed in previous studies (e.g. Klaassen et al, 1988 and the FAPI report) the contribution of this near-bed load was found not to be marginal. During low flow conditions up to 50% of the load can be transported in this layer; during floods, when most of the sediment is transported, the contribution reduces to the average of some 10 % of the total bed material load.

Under the RSP the transport of wash load was also studied. In many handbooks (e.g. Jansen et al, 1979) it is implicitly assumed that wash load, defined as the finest sediments not present in the river bed, is distributed uniformly over the cross-section. Results obtained under this study suggest that for the large alluvial rivers under study this concept had to be revised. The wash load of the Jamuna and Ganges Rivers consists mainly of silt particles with a small percentage of clay (*RSP Special Report 14*). Sources of fine material are - in addition to the upstream catchment - also to be found in eroding banks, anabranches with almost stagnant water and bartails (see before), while flow over floodplains and possibly also flow over vegetated bars induce settling of fine sediments and act as sinks. This makes that also the transport and exchange of fine sediments is much more complex than previously visualised.

7.4.5 Sediment transport formulae

An improved suspended load predictor, in particular applicable to the conditions in the main rivers of Bangladesh, was developed. This formula reads:

$$s = \frac{0.165}{1 - \epsilon} \sqrt{g \cdot \Delta \cdot D_{50}^3} \left\{ \frac{h \cdot i}{\Delta \cdot D} \right\}^{1.82} \cdot \frac{C^2}{g} \quad (7.3)$$

where s = suspended sediment transport per unit width (m^2/s), ϵ = porosity (-), g = acceleration of gravity (m/s^2), D_{50} = characteristic particle size, i = slope (-), C = Chézy-coefficient ($m^{1/2}/s$), and Δ = relative density, defined via:

$$\Delta = \frac{\rho_s - \rho}{\rho} \quad (7.4)$$

with ρ_s = density of sediment (kg/m^3) and ρ = density of water (kg/m^3).

The development of this formula was not an easy task for a number of reasons:

- as indicated before the conditions in these large alluvial rivers are extremely time-and space-dependent;
- the sediment transport and water depth is measured locally; of the slope only the overall value is known;
- as an alternative the measured velocity u is used, allowing to obtain the value of $h \cdot i$ via the Chézy equation; an estimate of the value of C has to be used instead which again introduces inaccuracies;
- the dependence on C cannot be determined independently (see Annex 4) and was assumed to be the same as in the Engelund-Hansen (1967)-formula;

- there is a major difference between the sediment transport rates measured by the RSP (and measured by the BWDB in the sixties) and the measurements by the BWDB since 1971 (see Annex 4).

For the derivation of an appropriate sediment transport predictor RSP data were used. These did fairly coincide with the BWDB-data from the sixties. In particular the RSP data collected in Bahadurabad and in the different distributaries proved to be valuable. Most of the other stations proved to be affected by their location: either in a constricted section or downstream of the Jamuna-Ganges confluence. As shown via the use of a 1-d model, both location types demonstrate significantly biased data through the difference between local and overall slope.

In the derivation of an appropriate sediment transport predictor the approach was aimed at correctly estimating the value of n in Equation (7.1). The power n is very important for many morphological processes and a good estimate of n is imperative for a good reproduction of the morphological characteristics of rivers in 1-d and 2-d morphological models.

Equation (7.3) still has to be extended to include the effect of near-bed transport. For the time being this was achieved by introducing a correction factor.

The derived sediment transport predictor for Bangladesh's main rivers corresponds to a n value of about 4. This indicates that the type of predictor is rather a Van Rijn (Bagnold)-type of predictor (with n about 4) than an Engelund-Hansen predictor (with $n = 5$). Also for the Zaire River, a similar sand-bed river, the Bagnold predictor (1963) turned out to be good (Peters, 1977). It is stressed that the use of 1-d but also 2-d models was very instrumental in obtaining insight in sediment transport processes in Bangladesh's main rivers.

7.4.6 Sediment transport rating curves

A sediment rating curve is the relation between the sediment transport rate S (m^3/s) and the discharge Q (m^3/s). Sediment rating curves are subject to considerable spurious correlation and they should be used only for interpolation and for making balances. In no way they are a substitute for a sediment transport equation. Sediment rating curves are prepared for both bed material transport and for wash load (in the terminology of the BWDB "coarse" and "fine" sand).

A general expression for a sediment rating curve is:

$$S = A Q^B$$

where A and B are empirical coefficients. For unconstricted, rather stable river reaches away from confluences etcetera, the value of A for sediment rating curves for bed material is about 1.5. As shown by Galapatti (1993) a much larger value for A is found for constricted reaches like Hardinge Bridge. In Baruria, downstream of the confluence, plotting S versus Q yields a figure with enormous scatter. Both for the Hardinge Bridge and for Baruria it could be shown, using a 1-d morphological model (see RSP Special Report 13), that this is due to the specific morphological changes over time in a constriction and near a confluence.

7.4.7 Sediment loads and sediment balances

Sediment rating curves can be used to determine the yearly amounts of sediments being transported by a river. This yearly volume is varying through the years: during years with high floods much more sediment is transported than in years with minor floods only. To get a reliable estimate of the average yearly volume transported by a river, one has to average over a sufficiently long period. This excludes the use of RSP data as they are covering a too short period.

Sediment transport data for the period 1965-1970 were used for determining average yearly sediment loads. This period was selected as the data were found sufficiently accurate, also after comparing them with RSP data. Table 7.3 gives the computed yearly volumes in Mtons for the main stations in Bangladesh, where sediment transport is being measured by the BWDB in the period 1965-1970. The accuracy of these data are in the order of 10%. (see *RSP Special Report 18*).

River	Station	Yearly volume (Mtons)		
		Coarse	Fine	Total
Jamuna	Bahadurabad	202	388	590
Ganges	Hardinge Bridge	196	352	548
Old Brahmaputra	Mymensingh	2	?	?
Dhaleswari	Tilly/	3	16	19
Gorai	Railway Bridge	18	29	47
Padma	Baruria	366	520	886
Upper Meghna	Bhairab Bazar	1	?	?

Table 7.3 Yearly load (BWDB data period 1965-1970)

According to the BWDB data for later periods, it appears as if there is a reduction of the sediment loads in the rivers in time.

This was already observed earlier (e.g. in the Jamuna Bridge Study, see RPT et al, 1986 and the FAPI Final Report). Joint (RSP and BWDB) measurements showed that the old FAO-instruction of using the Binckley sampler while floating with the current still gives the best results.

Using the data presented in Table 7.3 a balance was made for both the local bed material and the wash load (sand and silt/clay, respectively). A comparison was made between what is entering the system (Jamuna + Ganges) with what is leaving the system (Old Brahmaputra + Dhaleswari + Gorai + Padma).

The results are presented in Figure 7.9, both for the bed material load and for the wash load. It can be observed that in the considered period (1965-1970) the incoming and leaving bed material load is almost the same. Possibly some bed material is stored but this cannot be proven statistically.

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SUSPENDED COARSE SEDIMENT BALANCE Rating curve (1966–1970)

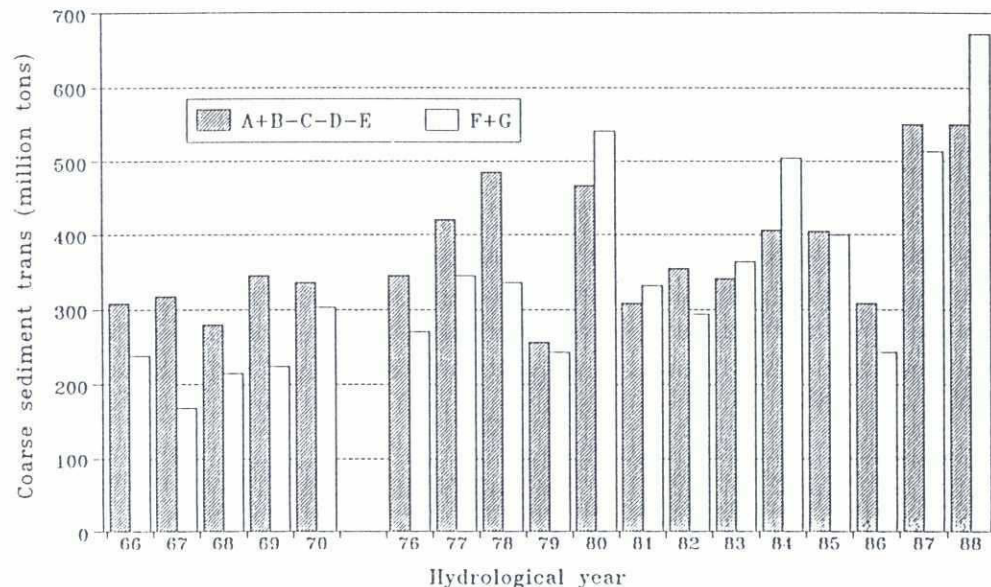


Figure 7.9 Sediment balance for the main rivers (BWDB data period 1965-1970)

The above may suggest that the system of main rivers is fairly well in equilibrium. An analysis of FAP1 showed that over the past decades the Jamuna River is slowly widening, but the overall cross-section is not increasing. Based on an analysis of cross-sections measured by the BWDB, Klaassen & Vermeer (1988) stated that the Jamuna River is neither degrading or aggrading. This does not necessarily imply that the smaller rivers (Old Brahmaputra, Dhaleswari, Gorai and Upper Meghna) may not be adapting and may experience net storage or loss, but their contribution to the overall balance is too small to identify this.

A slightly different picture emerges when the yearly volumes of wash load are studied. Statistically significantly smaller quantities of wash load is leaving the system compared to what is entering. This may indicate that some of the wash load is stored in the river system. Assuming that this is not in the riverbed itself, it must be in the floodplains and/or on the chars.

7.4.8 Flood plain sedimentation

A special study was carried out to study the mechanism of flood plain sedimentation in relation to overland flow (RSP SPR 15). This study was done as a continuation of the work started by FAP19. The measurements were carried out during the monsoon of 1995, with a 1:20 year peak discharge in the Jamuna, hence a major flood. The maximum depth and the duration of flooding varied between 1.8 and 2.8 m and 40 to 100 days, respectively. The floodplain selected is located along the left bank of the Jamuna south of Jamalpur.

Flood plain sedimentation was measured in six locations in different ways: with special sediment traps, on permeable mats (pieces of cloth) and on layers of brick dust. Deposition of sediment was measured after the flood had receded. It consisted of (i) sands deposited as crevasse splays along the minor rivers (spills), already described by Coleman (1969), and (ii) clay deposits in areas further away from these rivers. Two sample locations were near spilling rivers and here sand deposits of about 0.2 m formed. Clay deposits at the other locations had a depth of 1–3 mm.

In addition the sediment concentrations in the overland flow was measured. The maximum values measured during the peak of the flood are shown in Figure 7.10. Sediment entering into the Jamuna flood plain is mainly by convection (in line with Narinesingh, 1995). The concentration of sediment in the water decreases with distance from the river along the path of the water. Diffusion plays probably a smaller role.

It is tempting to generalize these results to get an estimate of the floodplain sedimentation along the Jamuna River. However, the amount of data available is very limited.

In addition to the RSP results and Bristow (1987), there are some estimates based on oral information from farmers (ISPAN, 1995), while also some results of ^{137}C dating of vibro-core samples taken in 1995 in the study area are available.

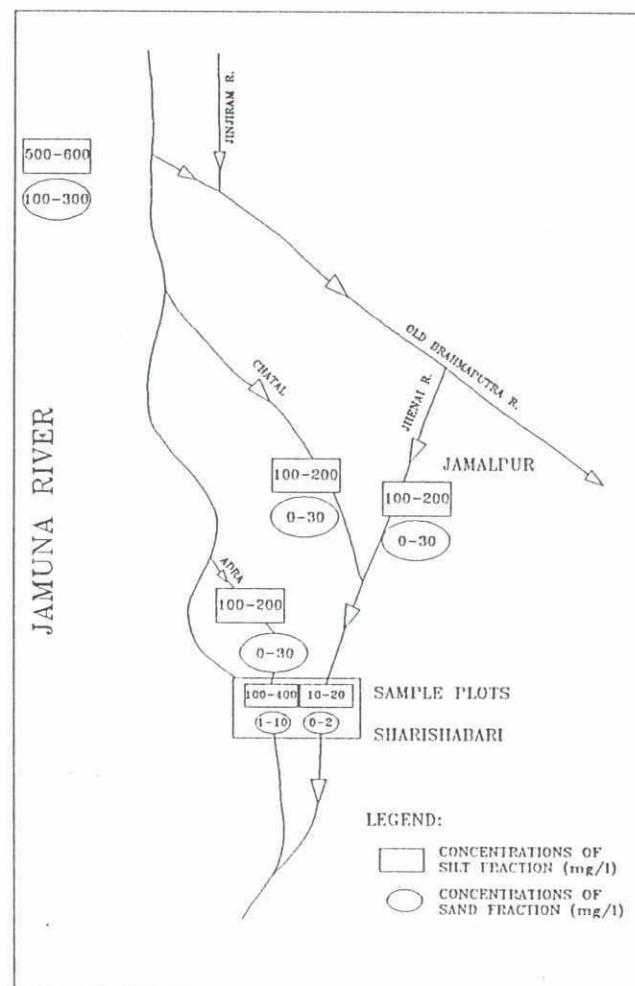


Figure 7.10
Maximum sediment concentrations in flood plain during the peak of the flood in 1995

First estimates of the floodplain sedimentation rate in the study area, averaged over a longer period (considering the spatial distribution of the sampling places and the fact that 1995 corresponded to a fairly high flood), are between 1 and 4 mm/year. Assuming the Jamuna flood plains and permanent char land to have an area of some 2,000 km², this corresponds to deposition of about 2 to 8 Mt/year for the Jamuna alone (based on $\rho_s = 2650 \text{ kg/m}^3$ and $\epsilon = 0.4$). For more details see RSP Special Report 15.

Continued sedimentation would cause the flood plains to rise, though at a decreasing rate due to reduction in flooding due to the increasing flood plain levels. There are no statistically significant indications, however, that the flood plains of the Jamuna are rising (see RSP Special Report 6). Two compensating mechanisms can be visualised: (i) regular erosion by river channels which mobilize the floodplain sediments again, and (ii) subsidence of the whole river. Subsidence is known to be important in the area, and it probably consists of both neotectonics and consolidation of the very deep (20 km) layers of alluvial sediments underlying Bangladesh. Subsidence would be compensated by increased sedimentation. It is interesting to note that along the Upper Meghna River, where subsidence is known to be substantial and where most of the sediment carried to the river is depositing in the Sylhet region, the floodplain levels are relatively low (see Haskoning et al, 1992). Also this is an indication that subsidence is substantial. Although the RSP studies have added to an improved understanding, more studies are needed to better clarify the intricate relationship between subsidence, river erosion and flood plain sedimentation along the main rivers in Bangladesh.

7.4.9 Integrated view

In the project not only the different main rivers and distributaries were studied in isolation, but their characteristics were compared and their mutual linkages were studied. This provides an integrated view of the main river system and allowed also for making a first assessment of the (morphological) impact of some scenario's for implementation of FAP (see hereafter). The basis for the mutual comparison was an extended form of Lane's balance, which expresses the balance between the sediment that has to be transported by the river and its transport capacity which is a function of its discharges. In its simple form as proposed by Lane (1955) it reads:

$$S.D :: Q.i$$

and it allows to assess the response of a river to changes in its imposed variables, via the change of the river slope i owing to changes in (yearly volume of bed material load) V , (characteristic particle size of the bed material) D and (discharge) Q . The extended form, developed in a theoretical way under certain assumptions (Klaassen, 1995), reads:

$$k \cdot \frac{n-3}{6} V \cdot D^p :: \alpha_Q \cdot \bar{Q}^{\frac{n+3}{6}} \cdot i_e^{\frac{n}{3}}$$

where k = number of channels (-), α_Q = coefficient characterising the variability of the discharge through the year (-), see Klaassen (1995), n and p = powers of the velocity and the particle size in the following simplified sediment transport equation:

$$s = m_1 \cdot D^{-p} \cdot u^n$$

and i_e = "equilibrium slope" according to the improved Lane's balance (-).

The above equation can also be written as:

$$i_e = K \sqrt{\frac{\frac{n}{3} \left(\frac{k^{\frac{n-3}{6}} V \cdot D^p}{\alpha_Q \cdot \bar{Q}^{\frac{n+3}{6}}} \right)}{}} \quad (10-8)$$

where K = coefficient in which e.g. the effect of the Chézy coefficient and the proportionality coefficient in the regime equation for the width are incorporated. For the time being it is assumed that K is constant for the different rivers in Bangladesh once they have reached "equilibrium" conditions (or in other words once they are in regime).

By using the different data on the main rivers their equilibrium slope can be estimated. Comparing this with the actual (water-level) slope provides at the same time better insight in the consistency of the data and it allows to draw some conclusions as to the state of the different rivers.

The most relevant data on the main rivers are summarized in Table 7.4 and in Figure 7.11. These were used to prepare Figure 7.12, which is a key figure in the present discussion.

Most of the main rivers of Bangladesh plot on one line, which is to be expected when they are in regime and the data in Table 7.4 are representative. Two rivers are not in line with the others, notably the Upper Meghna and the Gorai Rivers. The Upper Meghna is typically "out-of-regime", due to previously having carried the Brahmaputra discharge and sediment load and due to major subsidence in its basin. The latter retards the adaptation of the river to its new conditions as it receives hardly any sediment from its upstream "feeders", the Kushiara and the Surma Rivers. The Gorai River might not be in equilibrium either, its larger equilibrium slope possibly indicating that the river is receiving more sediment and/or less water than previously.

River	$\bar{Q}$ (m ³ /s)	α_Q (-)	V (10 ⁶ tons)	D ₅₀ (mm)	k (-)
Jamuna River	20,400	1.2	200	0.21	3
Ganges River	10,600	1.2	190	0.12	1
Padma River	28,400	1.15	370	0.09	1
Upper Meghna	4,500	1.3	1	0.14	1
Old Brahmaputra	550	1.3	2	0.15	1
Dhaleswari River	1,000	1.3	3	0.16	1
Gorai River	1,200	1.3	17	0.15	1
Arial Khan River	2,570	1.3	?	0.15	1

Table 7.4 Summarized data of the various rivers in Bangladesh

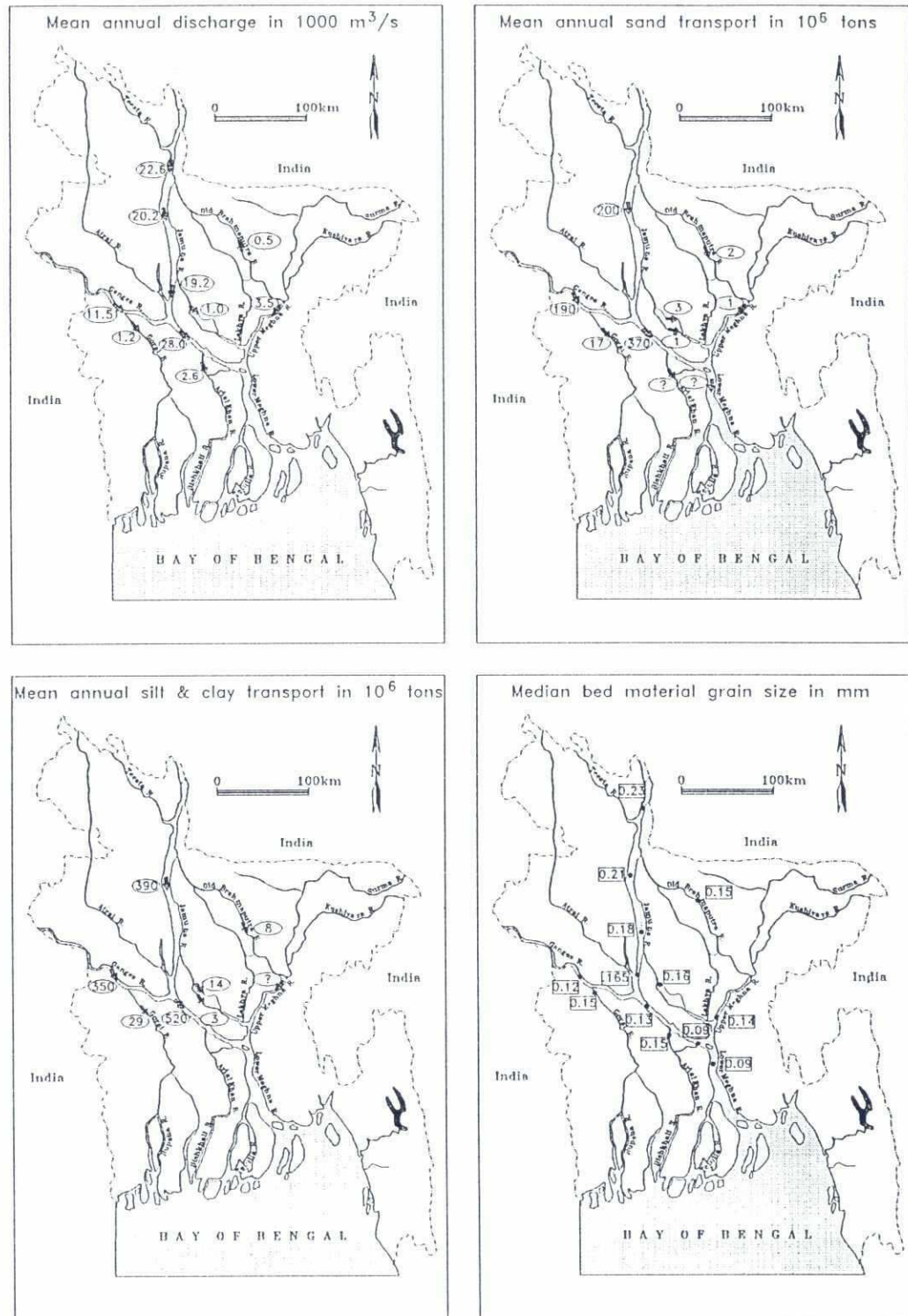


Figure 7.11 Summary of available data on discharges, sediment loads and bed material composition

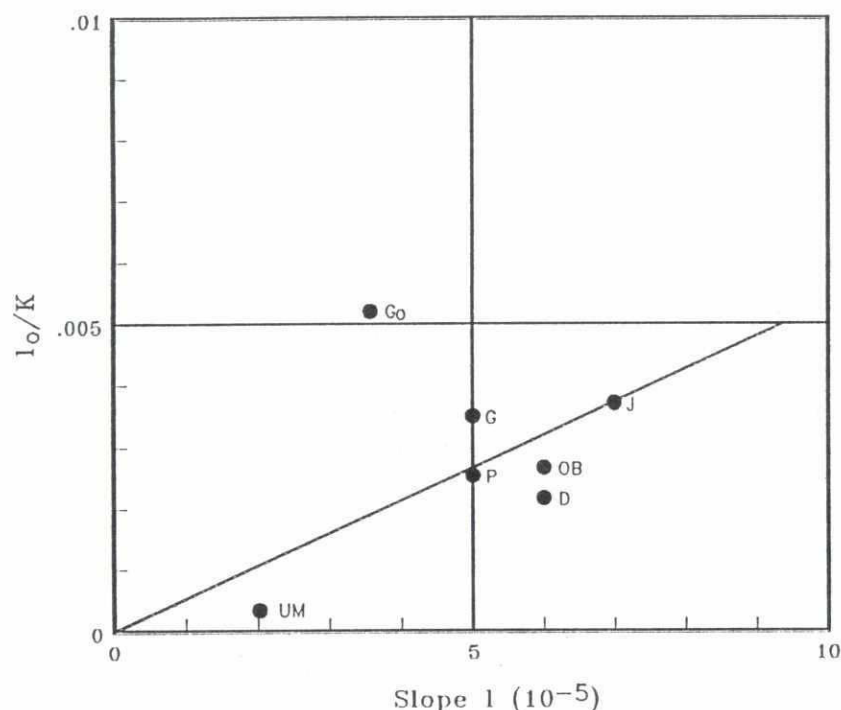


Figure 7.12 Plot of i_e/K versus the actual slope i (J = Jamuna, G = Ganges, P = Padma, UM = Upper Meghna, OB = Old Brahmaputra, GO = Gorai)

Other checks on the consistency of the data were made as well. This was done by considering the continuity at confluences and by studying the distribution of sediment at offtakes. In particular the particle sizes and the mineralogical compositions were used as "tracers". The results obtained in RSP Special Report 14 indicate that the data used are fairly consistent, hence the overall data as presented in Table 7.4, are the best estimates of the characteristics of the main rivers in Bangladesh at this moment.

One reservation has to be made regarding the distributaries. Some of the distributaries (definitely the Old Brahmaputra, and possibly the Dhaleswari and the Gorai) are experiencing changes in the discharges and possibly also in the sediment load entering via the offtake. Rapid deterioration may take place (see further Section 7.5 and Chapter 9 of Annex 5).

7.4.10 Morphological impact of FAP implementation

Implementation of some of the measures proposed by some of the FAP projects, will change the balance between yearly sediment load and sediment carrying capacity. In Phase 1 of the project the morphological impact was assessed. For this only a 1-d approach was used, not taking into account any changes in planform, meandering characteristics etc.

As these morphological changes usually take a long time to fully materialize (centuries), a distinction was made between the ultimate changes and intermediate changes between the moment of implementation and the final conditions. For the ultimate conditions the improved Lane's balance (see above) was used (giving the final conditions), for the initial changes some analytical considerations were given.

The assessment was mainly based on a scenario for which a long term model simulation (1965-1989) was undertaken for the establishment of hydrological design criteria along the major rivers. This scenario was at that time considered as one of the most likely future protection scenario's (FAP 25, 1993). Some results of the present analysis are presented in Table 7.5 and Figure 7.13. Ultimately the stages in the rivers will fall, as more water is directed through the main rivers. A first estimate of this reduction in stages is given in Table 7.5. Lowering of water levels will have a positive effect on drainage possibilities, but might affect groundwater levels. Another adverse effect may be reduced siltation due to less flooding of the floodplains. These effects however may only materialize after a long time. Figure 7.13 gives a qualitative assessment of the intermediate conditions. Slightly higher stages should be expected due to mainly the hydraulic effect of the simulated implementation of measures. For more details on the method of analysis, the scenario used and initial hydraulic impacts, see Annex 4, Chapter 10 and RSP Special Report 5.

It is obvious that this assessment should be refined in the future. First of all the development of a National Water Management Plan, as foreseen for the coming years, will probably lead to different scenario's.

Station	River	River(s) downstream	Lowering of water stages		
			Effect of slope change in river (m)	Effect of downstream rivers (m)	Total lowering (m)
Bahadurabad	Jamuna River	Jamuna River-Padma River-Lower Meghna River	0.0	1.0	1.0
Sirajganj	Jamuna River	Jamuna River-Padma River-Lower Meghna River	0.6	0.4	1.0
Hardinge Bridge	Ganges River	Padma River-Lower Meghna River	0.0	0.4	0.4
Baruria	Padma River	Lower Meghna River	0.4	0.0	0.4
Bhairab Bazar	Upper Meghna River	Lower Meghna River	0.0	0.0	0.0
Chandpur	Lower Meghna River	None	0.0	—	0.0

Table 7.5 Preliminary estimates of lowering of stages for ultimate conditions for scenario used

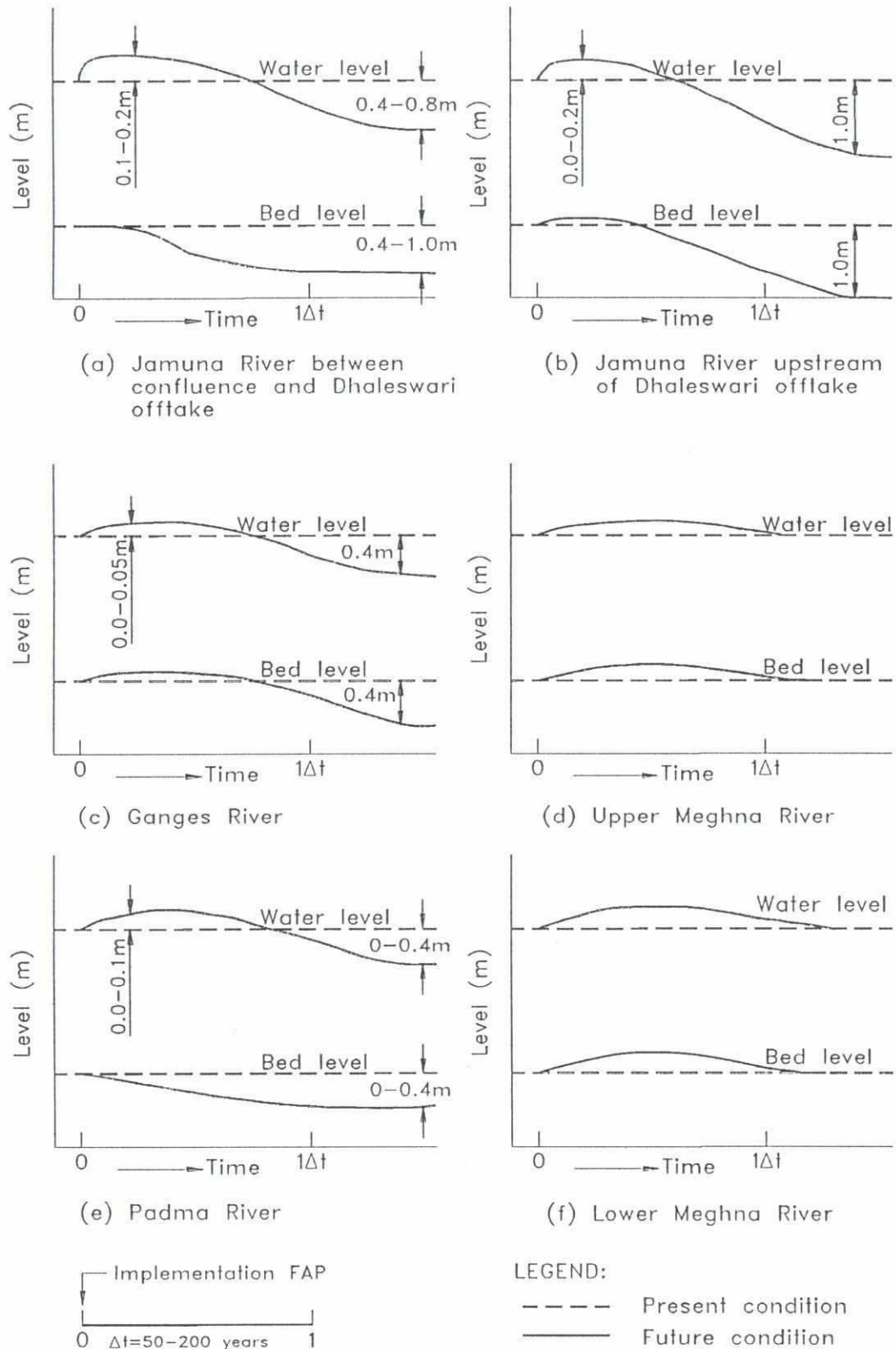


Figure 7.13 Qualitative change of bed levels in the main rivers due to one scenario for implementation of proposed measures

Secondly, it is important to extend the assessment to include also the changes in planform and other morphological parameters, including the effect on the floodplains (and floodplain sedimentation) and on the offtakes. Thirdly, the increasing insight in the morphology of the main rivers will lead to better methods to predict the hydraulic and morphological response of these main rivers.

It is stressed here that the ultimate development of the river system will be affected by the natural development of the system and by other anthropogenic factors, like the (partial) flow diversion from the Ganges at Farakka. The natural development includes also neotectonics and is reflected in the changes that are experienced in the offtakes. In this very active environment with rivers that adjust rapidly to changes imposed, predictions of future behaviour will always be subject to large uncertainties.

7.5 River morphological characteristics

River morphology deals with the "form" of the river, and comprises the study of river characteristics like slope, cross-sectional area and shape, planform (single or multiple channels, braiding index, sinuosity, meander wave length, etcetera), bars, scour, and form changes like bank erosion (and accretion), cutoffs and avulsions. Bangladesh's main rivers are all alluvial rivers, i.e. rivers that are flowing in alluvial deposits and hence that are free to shape themselves within these movable boundaries. Understanding river morphological characteristics of the main river system is important for the prediction of its future behaviour, for the assessment of its response to human interference and to determine design boundary conditions for river training works.

Modern approaches to river morphology consider the river as a system, that responds (via assuming certain values of these characteristics) to inputs. These inputs (discharges, sediment loads and sediment calibre) are ultimately governed by climate and geology in the river catchment and are changing along the river. Controls exist along the river as a result of the previous history of the river system (determinative for the composition of the floodplain and the occurrence of "hard points"), local effects (neotectonics, vegetation) and, more recently and not so much for Bangladesh's main river system, anthropogenic factors (the influence of human activities). A full understanding of this intricate interrelationship is still missing, but in the last decades quite some progress has been made in scientific approaches to river morphology. In *Annex 5* the river morphological characteristics of Bangladesh's main river system are discussed, by combining this improved understanding with features observed during some of the routine and many of the special surveys. In this Section the most important findings are summarized.

7.5.1 General aspects

Before entering into more detailed descriptions of various interesting findings, it is appropriate to discuss some salient aspects of Bangladesh's main rivers. By far the most important aspect is the extremely dynamic behaviour of the morphological system. As already discussed by Coleman (1969), major changes can take place in one flood season. This has major implications for surveying: the bed topography changes rapidly, and hence the representativity of sediment transport measurements and of measured cross-sections is fairly limited. A few weeks of flood may change the conditions significantly. Hence variability (in space and time)

is the rule. The reason for it is obvious: according to a study by Hickin & Nanson (1984) bank erosion is fastest for fine sand as bank material with a diameter of about 0.2 mm, and this is exactly the type of material abundantly present all over Bangladesh.

This has major implications e.g. for measured cross-sections: they are only one realisation of a stochastic process. In a few weeks the cross-sections may be quite different. Moreover, slightly different boundary conditions may cause a completely different development in time. This type of non-linear processes, very sensitive to small changes in boundary conditions and to small internal disturbances, are usually indicated as chaotic systems. In particular the Jamuna River is very much chaotic in its behaviour. This limits its predictability very much (Klaassen et al, 1993).

Under the River Survey Project repeated bathymetric soundings during one monsoon, as initiated by the PA, proved to be very useful. It provided insight into the rapid changes taking place. Figure 7.14, based on three bathymetric soundings during 1993, shows the rapid changes in cross-sections taking place during one flood only.

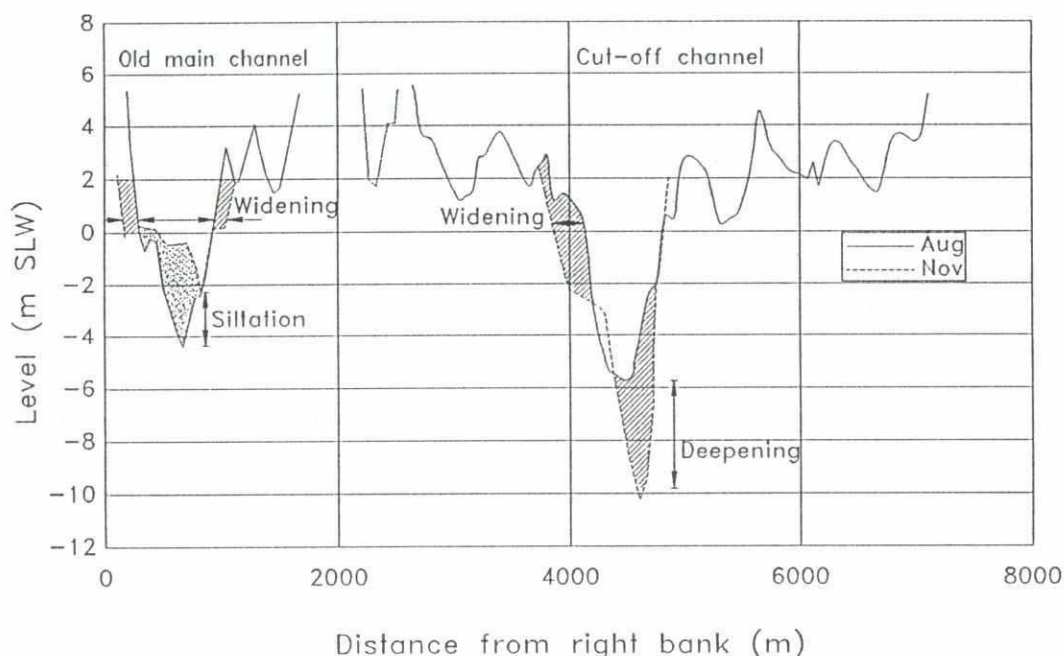


Figure 7.14 Changes in cross-sections near Bahadurabad during 1993 flood season

Moreover, in braided rivers substantial changes in planform are taking place over the flood season due to the variation of the discharge itself. During low flow the river is usually confined to one or two main channels with some islands and most of the other channels are not taking part in the discharge. During floods most of the islands are flooded and many channels are active in conveying water. Hence, many more bifurcations and in particular confluences are present. This is schematically indicated in Figure 7.15, presenting two river planforms surveyed at Bahadurabad during flood (August) and at the end of the fall (November). The implication is that features which are due to e.g. a confluence existing during flood conditions (e.g. a confluence scour hole) may remain present in the low flow season as a remnant of its previous generation.

Another important issue is the fact that the rivers are active in all stages. Also during periods of low flow the rivers are transporting sediment and hence adjusting their bed to the changed hydraulic conditions. Areas with higher velocities are eroding and deposition of the eroded material is taking place at places with lower velocities. Hence the rivers are constantly "re-working" (Peters, 1993b) their beds, as a response to the variation in discharge.

As discussed in more detail in Annex 5, Chapter 2, the river characteristics are dependent variables, given the inputs to the system and the controls. These river characteristics can be divided in primary dependent variables and secondary dependent variables, depending on the level of detail one is considering the river. Primary dependent variables determine the overall characteristics of the river, notably its overall slope, planform, braiding index (number of channels), sinuosity, bankfull depth and width, and overall width of the system.

In *RSP Study Report 1* a partly theoretical and partly empirical approach to find the relation between the inputs and controls on the one hand and the river characteristics as system outputs, developed under FAP21/22, was proposed.

The secondary characteristics are rather related to "internal" phenomena: bars, scour, bank erosion and cutoffs. In the project the emphasis was on the secondary characteristics and on the linkages between the different rivers, in particular offtakes and to a lesser extent confluences.

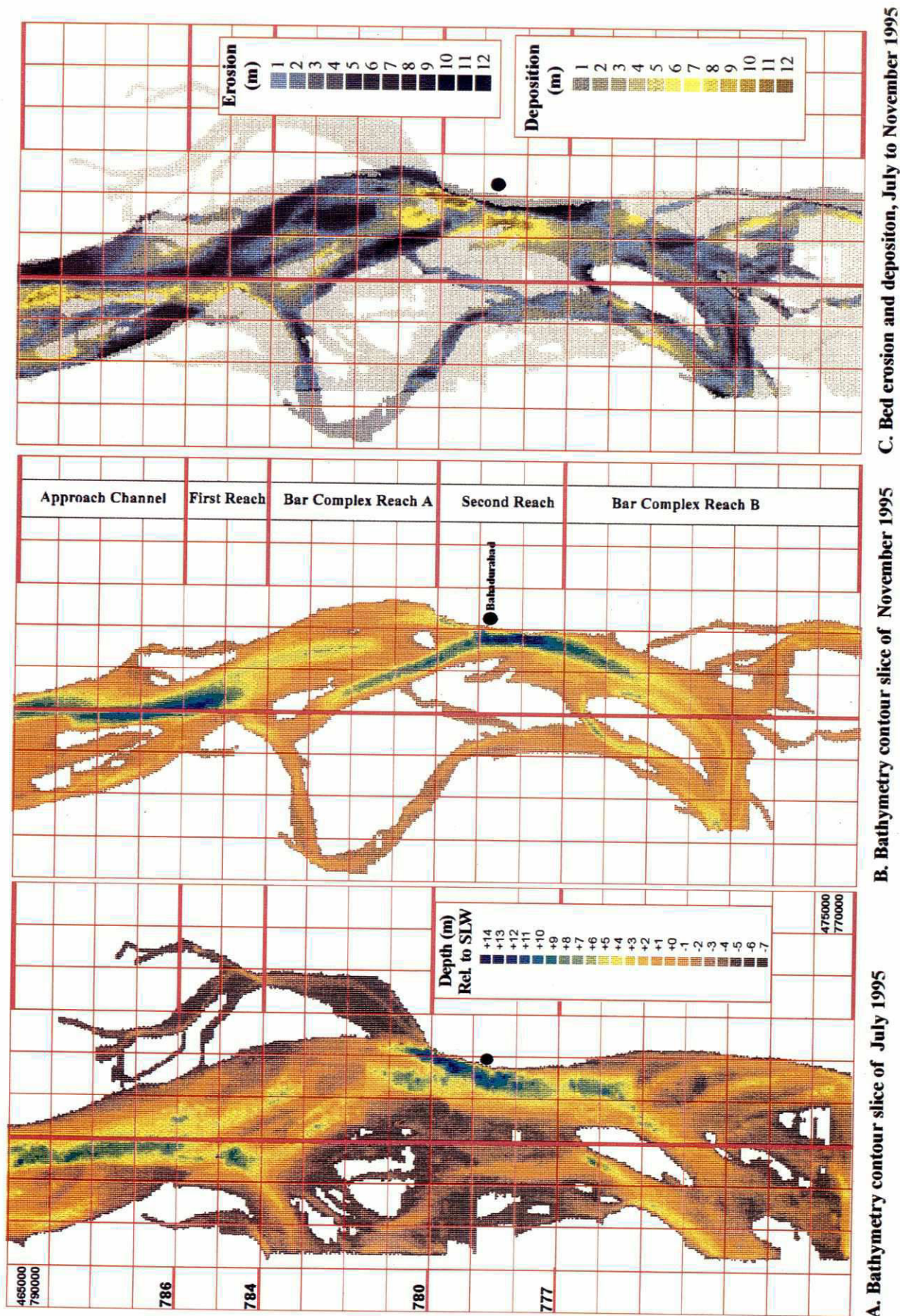


Figure 7.15 Changes in planform at Bahadurabad (mainly) due to changes in discharge

7.5.2 Controls

As explained earlier a river can be considered as a system, its characteristics being determined by inputs and controls. The inputs (discharges, yearly sediment loads and the sediment calibre) basically are known, and were already discussed in Phase 1 in RSP Study Report 3. The most recent information on discharges in the different rivers is provided in Annex 3. Sediment loads were summarized in the previous Section; more information can be found in RSP Special Report 18. Data on bed material size of the different major rivers is provided in RSP Study Report 3 and RSP Special Report 8.

Controls on the rivers are notably the flood plain composition, possibly locally limiting the lateral extension of the river, and the local geology. The effect of other possible controls, notably vegetation (on the bank erosion) and human influence (the anthropogenic factor) on the rivers, is in general still limited. Locally, however, some town bank protection works have a major influence on the planform development of the river. Major bank protection works are present at Sirajganj (Jamuna), Rajshahi (Ganges) and Chandpur (Lower Meghna River).

Figure 7.16 shows how the planform of the Lower Meghna River is affected by the town protection of Chandpur. Without protection works the river would have shifted much more in Eastern direction. Also infrastructural works have and are creating "hard points" (railway bridges at Hardinge Bridge and Bhairab Bazar and the Meghna bridges on the Upper Meghna, and the future Jamuna Bridge on the Jamuna River).

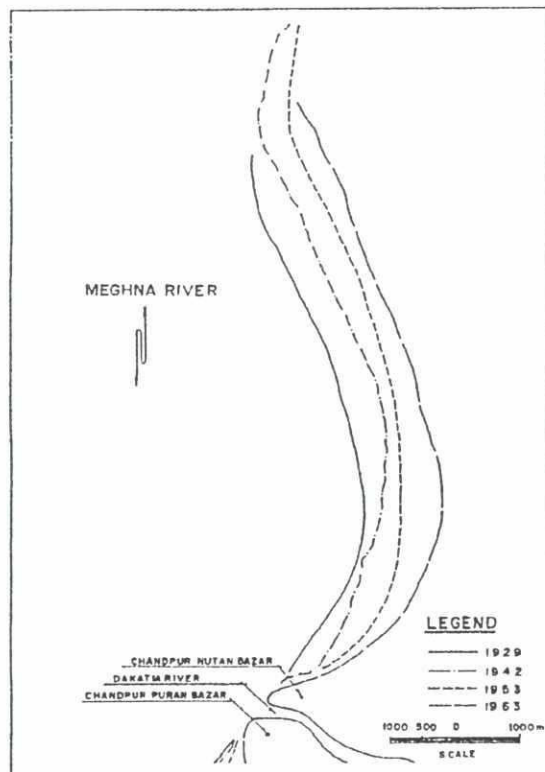


Figure 7.16 Influence of town protection works at Chandpur on Lower Meghna River

Geology has a very important effect on Bangladesh's main river system. The alignment of the main rivers can be explained on a geological time scale from the subsurface geology (see Haroun er Rashid, 1977). Morgan and McIntyre (1959) gives a very good overview of the complicated geological history of the delta of Bangladesh and its alluvial rivers. In the past many avulsions have taken place, the last one being the shift of the Brahmaputra River to its present Jamuna course. Figure 7.17 (MPO, 1985) shows the development of the Ganges Brahmaputra delta in geological times. The main rivers in Bangladesh, although being alluvial, are in older deposits of other rivers as well.

Geology is probably also of importance in the present time. In Section 7.4 the possible effect of subsidence is already mentioned. Differences in subsidence may lead to variations of the valley slope and cross-valley tilting, a possible explanation for the West-ward shift of the Jamuna River North of Sirajganj. Mosselman et al (1994) propose that even in the present braided pattern of the Brahmaputra/Jamuna River the effect of lineaments (with possibly differential subsidence rates at both sides) can be observed.

Also the composition of the flood plain does probably act as a control on the rivers. This composition is a reflection of the history of the system. In Section 7.4 Sara (upstream of the Hardinge Bridge) and Mawa along the Padma are mentioned as "hard points".

The planform developments at Bahadurabad (see Annex 5, Chapter 13) and of the right bank of the Ganges River upstream of the Gorai offtake (see Annex 5, Chapter 9) suggest that more resistant layers are present. These controls (probably clay layers) appear to be of a temporary nature as also at these locations bank erosion is eminent, though at a lower rate and intermittently due to the specific characteristics of these rivers, where periods with active bank erosion alternate with periods without bank erosion. This is illustrated in Figure 7.18, where the locations of the bank line near Bahadurabad is shown over the years 1973-1993.

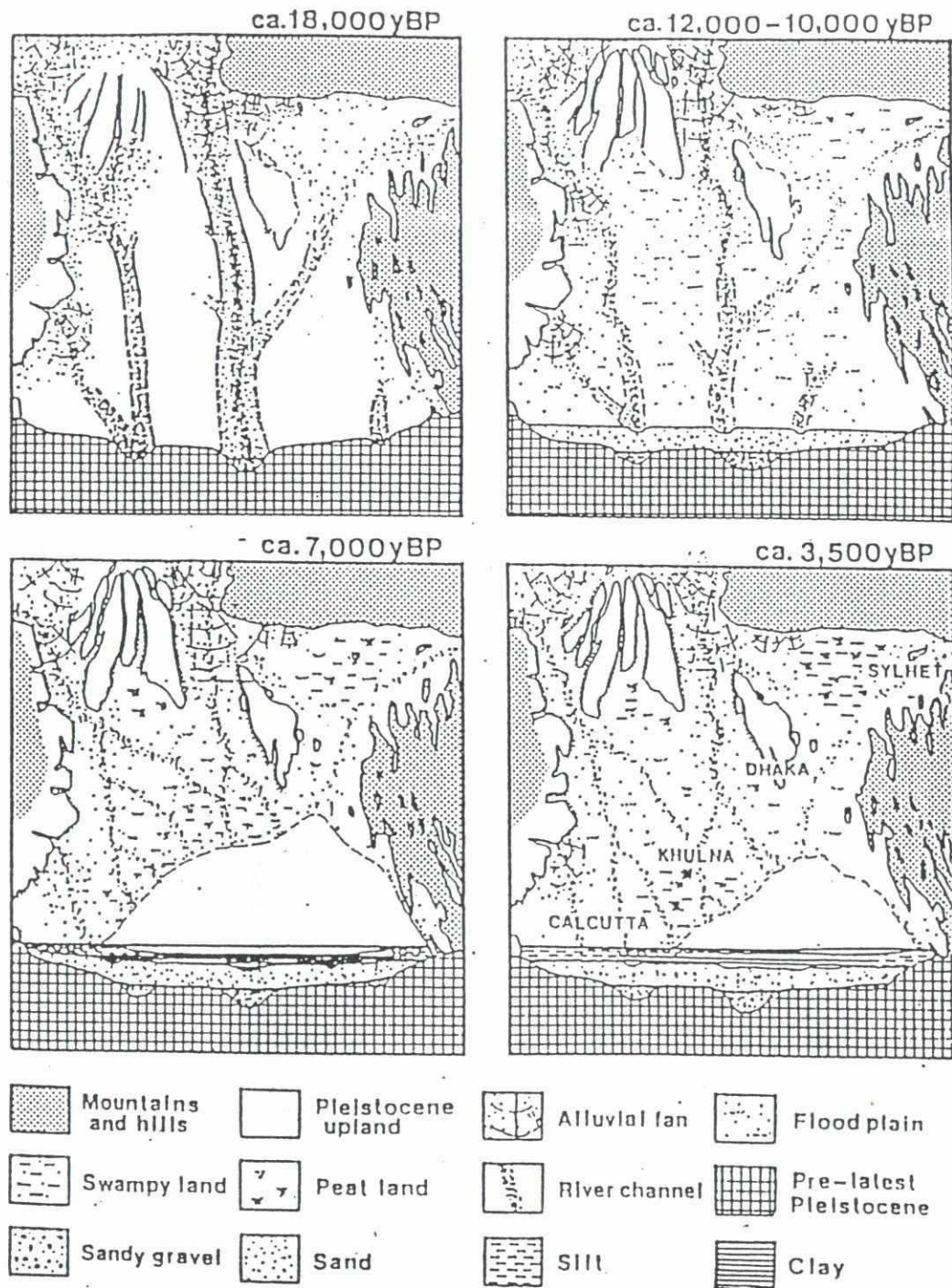


Figure 7.17 Development of the Ganges-Brahmaputra delta (yBP = Years Before Present)

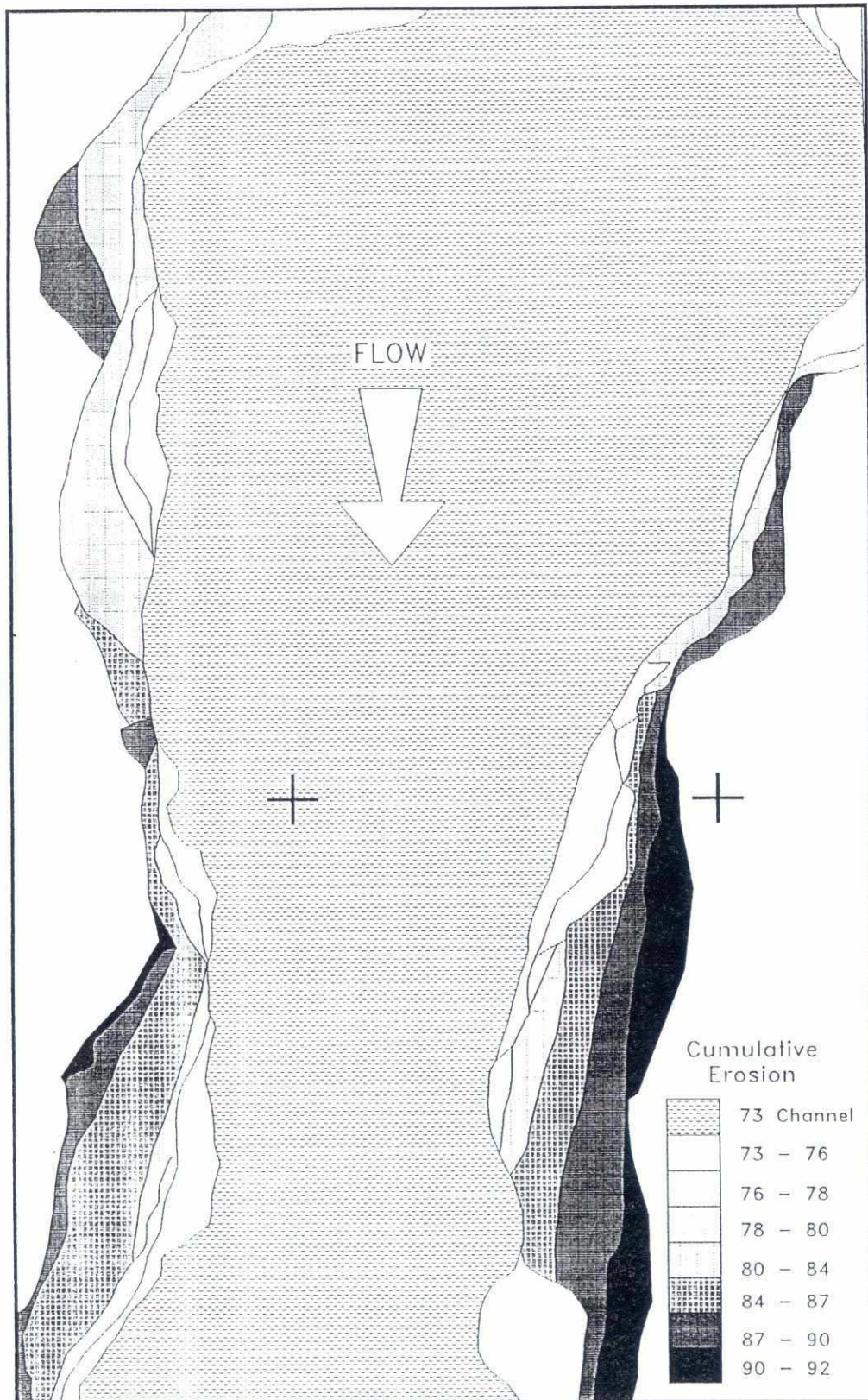


Figure 7.18 Bank line locations at Bahadurabad over the period 1973-1993

7.5.3 Overall slopes, planform characteristics and channel dimensions

Overall slopes of the main rivers are given in Annex 3. The slopes of the different rivers decrease in downstream direction. In line with the improved Lane's balance:

$$k^{\frac{n-3}{6}} V \cdot D^p :: \alpha_Q \cdot Q^{\frac{n+3}{6}} \cdot i^{\frac{n}{3}}$$

this is caused by two factors: the reduction in particle size and the decrease in braiding.

Only in an early stage of the project some studies into the planform characteristics of the main rivers in Bangladesh were carried out. Especially the difference between the Ganges and the Brahmaputra Rivers was addressed: both rivers have approximately the same inputs (discharges, sediment loads and sediment calibre), but their planforms are quite different: the Brahmaputra is braided with low sinuosity, whereas the Ganges has the overall appearance of a meandering river with a sinuosity of about 1.7 and demonstrates a sequence of slightly braided and single channel reaches. Although a full explanation is still missing, geological controls may play a role, possibly linked to the lower percentage of clays in the washload of the Jamuna River. Also the recent avulsion of the Jamuna may be important: possibly the river did not have sufficient time to create its own hard points.

During the study channel dimensions were often measured. It was noted that both channel depths and channel widths are extremely variable characteristics. In fact it is impossible to determine e.g. one characteristic channel width, but rather a range of widths does exist. This holds almost by definition for the braided Jamuna channels, but also the Ganges River exhibits quite some variability. During some bathymetric surveys at Bahadurabad the development of a cutoff channel could be monitored. It was observed that initially the cutoff channel was deepening very rapidly even leading to some over-deepening, width adjustments taking place as well but at a delayed pace (see RSP Special Report 24).

Channel dimensions are often linked to bankfull discharge. In the recent past different values for the bankfull discharge of the Jamuna River have been proposed: Klaassen et al (1988) 44,000 m³/s and Thorne et al (1993) 60,000 m³/s. A study of floodplain levels on the basis of BWDB cross-sections (RSP Special Report 6) showed that there is quite some variability in the floodplain levels (1.5 to 2 m along the Jamuna River). The different figures for the bankfull discharges could be explained by different definitions of bankfull level. A value of 48,000 m³/s corresponds to about 50% flooded, which might be a definition to be used for bankfull discharge.

Regime equations were developed for the Ganges as well. Existing ones for the Jamuna were refined (RSP Special Report 7). Both regime equations and at-a-station relationships, though empirical and too simple in their concept of one single relationship between discharge and channel dimensions, are attractive for first assessments of river behaviour and response.

7.5.4 Offtakes

Offtakes are important elements in the network of main rivers. The distributaries that begin at these offtakes have an important role in a.o. the supply of water to the interior of Bangladesh. The conditions at the offtake, in particular during the flood season, determine the inflow of water in the low flow season. In the fall of the hydrograph the offtake is scoured

again. It is a race versus time between this so-called retarded scour and the fall of the water level in the main river. Has too much sediment entered in the offtake during the flood, then the offtake may be blocked early in the fall of the flood hydrograph.

One of the important findings from Phase 1 was that the discharge entering the offtakes along the Brahmaputra/Jamuna River (for Old Brahmaputra and Dhaleswari Rivers, respectively) during flood decreased significantly over the last decades, indicating a significant deterioration of these offtakes (see RSP Study Report 1, Section 3.5).

The Gorai offtake was selected amongst the main distributaries for a detailed study in Phase 2. The total isolation of the Gorai at the offtake from the Ganges every dry season during recent years is a matter of great concern. The development of the Gorai offtake is particularly worrying because of its importance for the fresh water inflow to the Southwest Region. Apart from possible effects of the operation of the Farakka Barrage, also the planform changes in the Ganges and developments in the Gorai may be causing the lack of dry season flow to the Gorai.

The Gorai offtake study had three main elements:

- analysis of historical data to understand how the hydraulic conditions at the offtake have changed over the last 30 years;
- collection and analysis of detailed data in special surveys of the RSP. The data are used to set up and calibrate a two-dimensional morphological model of the area;
- two-dimensional morphological modelling to improve the understanding of the morphological developments at the offtake and thereby of factors that are important for maintaining a dry season flow to the Gorai.

The analysis of historical flow and water-level data focused on the developments in bed levels at Gorai mouth because any rising trends would cause earlier disconnection of the Gorai from the Ganges at the end of the monsoon. It was concluded that although bed levels at the Gorai mouth had been going up and down in a cyclic manner over the last decades it appeared that in particular the major floods in 1987 and 1988 had caused considerable rises in the level which were never really recovered in the following years. It was also found that the post-monsoon drop in water level in the Ganges had become considerably faster in the last 10 years than it used to be, also for the water-level range which is critical for the development of a dry season offtake channel to the Gorai.

Mathematical modelling was introduced as a tool to interpret the information provided by the field data in an integrated way. The mathematical model makes it possible to explore the governing river processes in detail and to investigate the effects of various measures to improve the conditions for flow into the Gorai river. The two-dimensional morphological modelling system (MIKE21C) was used. MIKE21C has already been applied extensively in relation with model studies in Bangladesh (FAP1, Jamuna Bridge, Paksey Bridge). It comprises computational modules to describe flow hydrodynamics including helical flows (secondary currents), sediment transport on plane and sloping bed including the effect of time/space lag on suspended sediment load. The model is fully morphological with feedback from calculated changes of bed levels and bank lines to the hydrodynamic simulation.

The model simulations carried out for the 1995 monsoon period addressed the following aspects:

- the development of the offtake channel
- the development of the bar in front of the offtake and effects of changes of it
- the effect of the flow distribution in the Ganges
- the effect of the flow resistance of the Gorai
- the effect of narrowing the Gorai mouth
- the effect of a different angle of the offtake channel near the mouth

Figure 7.19 shows the measured and simulated bathymetry at the end of the 1995 monsoon. The model simulations of the morphology of the Ganges were less realistic, because the model area covers only part of a large bend. If the objective had been to study the morphological developments in the Ganges the model area should have been much larger. Repeated bathymetric surveys of the Gorai offtake clearly illustrated the deposition in Gorai mouth during the monsoon making the offtake channel wider, and the subsequent erosion of a more narrow offtake channel during falling water level in the Ganges. This development was reproduced in the 2D model. Figures 7.20 show a measured sequence of bathymetries locally at the offtake and the corresponding simulated ones.

One-dimensional models have a severe disadvantage in simulating conditions at offtakes and bifurcations: They are unable to simulate the distribution of sediment transport between the two branches. This distribution will have to be assumed or supplied by a two-dimensional model. Well designed and calibrated two-dimensional models are able to provide the distribution of sediment, but are unable to predict developments much more than one year ahead. Combined use of one-dimensional and two-dimensional modelling is, therefore, necessary to predict long term developments.

Model simulations were repeated with small changes in bed resistance in the Gorai representing possible changes in the Gorai river. The flow resistance in the Gorai was found to be very important for the morphology at the offtake and for the development of dry season flow to the Gorai.

The 1987 flood was used in a two-dimensional model simulation of a high flood. It was found that a higher flood results in more deposition in front of the offtake during the monsoon compared to the more average 1995 monsoon. During falling stage in the Ganges the bed levels are again decreasing but do not fully recover, i.e. the result at the end of the monsoon is a higher bed level due to the higher flood.

In another application it was tested how a significant increase of the bed level at the Gorai mouth (a bar) would affect the performance of the offtake. The simulation showed that the bar would start to erode during the monsoon but also that the critical cross section would again deposit at the end of the monsoon to near the same level as it started. Full recovery of bed levels, if it would ever happen, would therefore require at last one more monsoon.

Figure 7.21 shows time series of discharge and sediment transport to the Ganges and the Gorai during the 1995 monsoon as simulated by the two-dimensional model. Figure 7.22 shows the relative distribution of sediment transport between the two rivers as a function of their sharing of the discharge, for some of the applications as well as the base run.

The morphological model of the Gorai offtake has provided important information about the morphological nature of offtakes. The modelling tool is able to simulate the behaviour of the offtake, the morphology as well as the hydrodynamics, but for long-term predictions the 2D-modelling has to be combined with 1D morphological modelling. The two-dimensional modelling of the RSP has contributed to a scientific explanation for the closure of the Gorai river. Local engineers have received initial training in the handling of this advanced modelling tool. It is recommended to use two-dimensional modelling in future studies of offtakes and bifurcations, with close guidance by the model developers and preferably in combination with one-dimensional modelling.

Another study - though smaller - into offtakes in which the RSP project could participate was related to the offtake of the Dhaleswari River. As part of the construction of the Jamuna Bridge the Northern offtake of the Dhaleswari was closed off in the low flow season 1994-1995. During the next flood in 1995 a new spill channel developed directly downstream from the working harbour. The location of the new channel and some results from the field observations of the channel are given in Figure 7.23. Also in this case the channel first developed mainly by deepening and only later it started to widen: this appears to be a general rule. Simulations with a 1-d morphological model (SOBEK), assuming certain distributions of the sediment at the offtake were used to hindcast the morphological development of the new spill channel and proved to be very useful for better understanding the development of the spill channel. The most interesting aspect of this study was the quick development of the spill channel: in less than 1 month after a connection was established a substantial channel had scoured. This depends very much on the relative water levels between parent and offtake river. In the case of the Dhaleswari River the water level was about 1 m lower than in the Jamuna River at a distance of 2 km. Due to the very high slope a spill channel developed rapidly. This result is similar to what was found in the 2-d model of the Gorai offtake after lowering the water level downstream in the Gorai.

The deterioration of the conditions in the offtake of the Old Brahmaputra River probably can be attributed to a general shoaling of the offtake area, resulting in a smaller relative water-level difference.

This is probably the clue to the future behaviour of the offtakes: river engineering measures can be devised aiming at increasing the slope in the offtake, which will increase the flow into the distributaries considerably. On a longer time scale it is possible that in due time always distributaries, as part of an alluvial fan, may deteriorate due to sedimentation and only when the parent river has silted up enough in its new alignment it could start to function again.

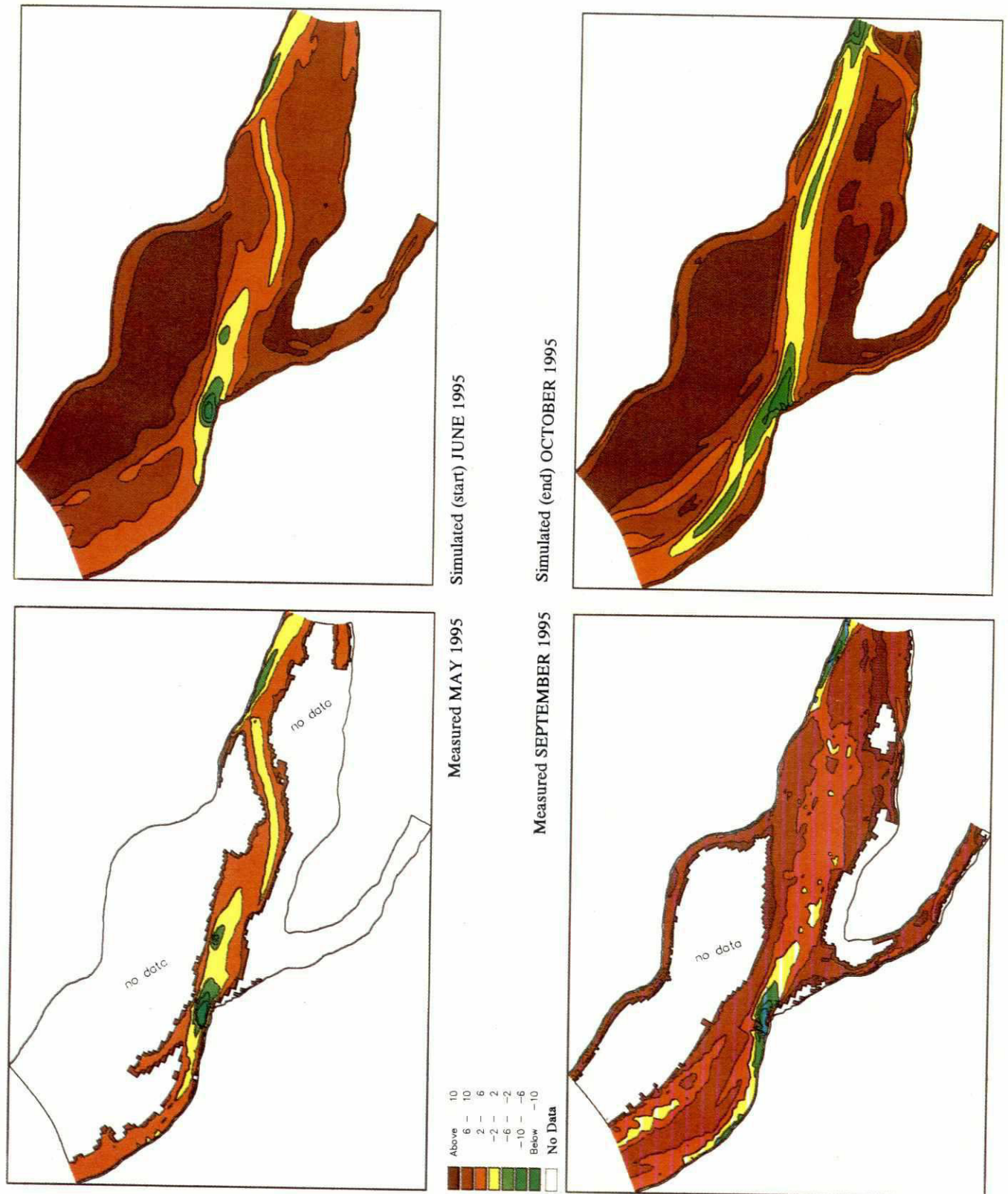


Figure 7.19 Measured and simulated bathymetry, end of 1995 monsoon

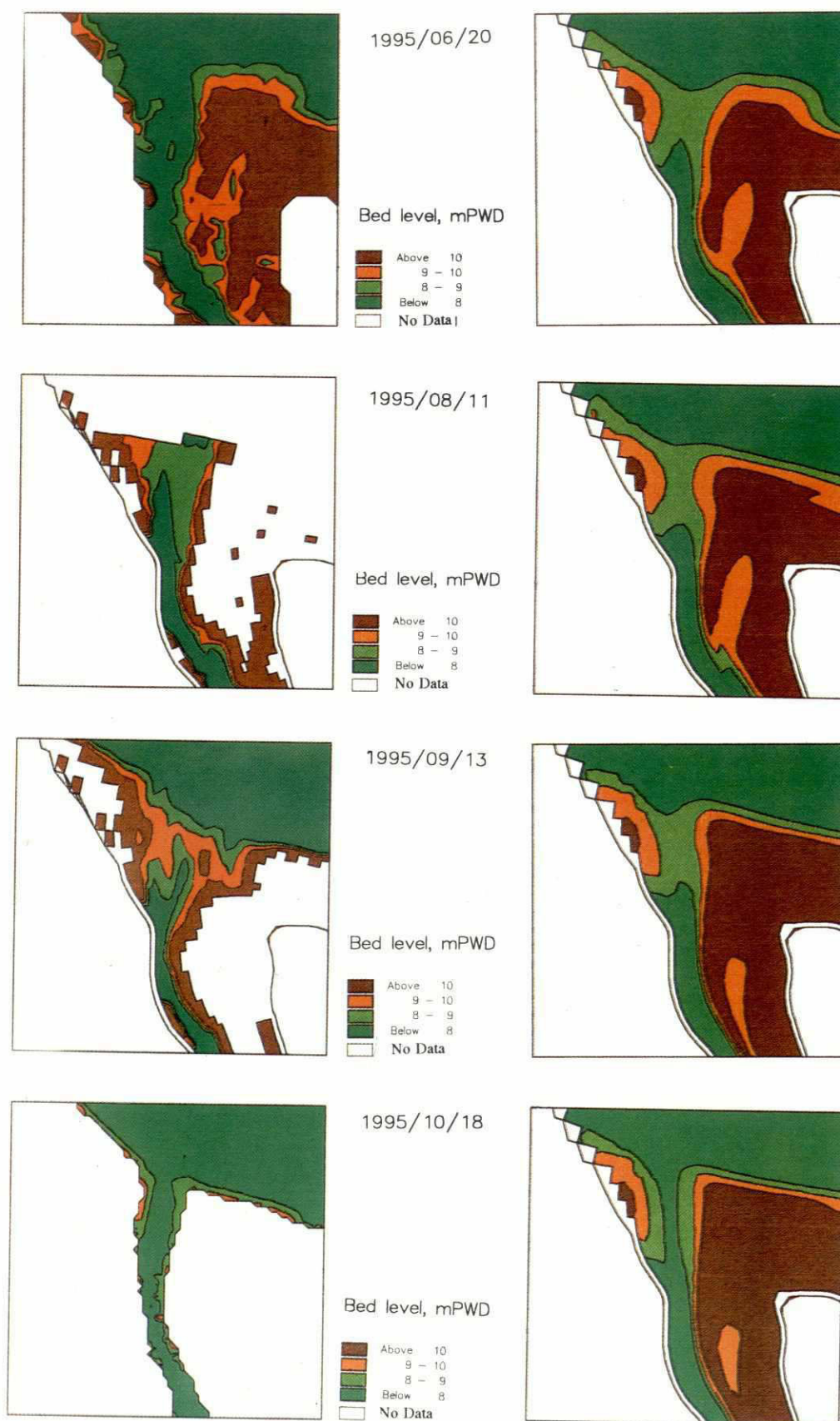


Figure 7.20 Morphological verification of Mike21 simulation of behaviour of Gorai offtake. Measured sequence of bathymetries locally at the offtake and the corresponding simulated ones.

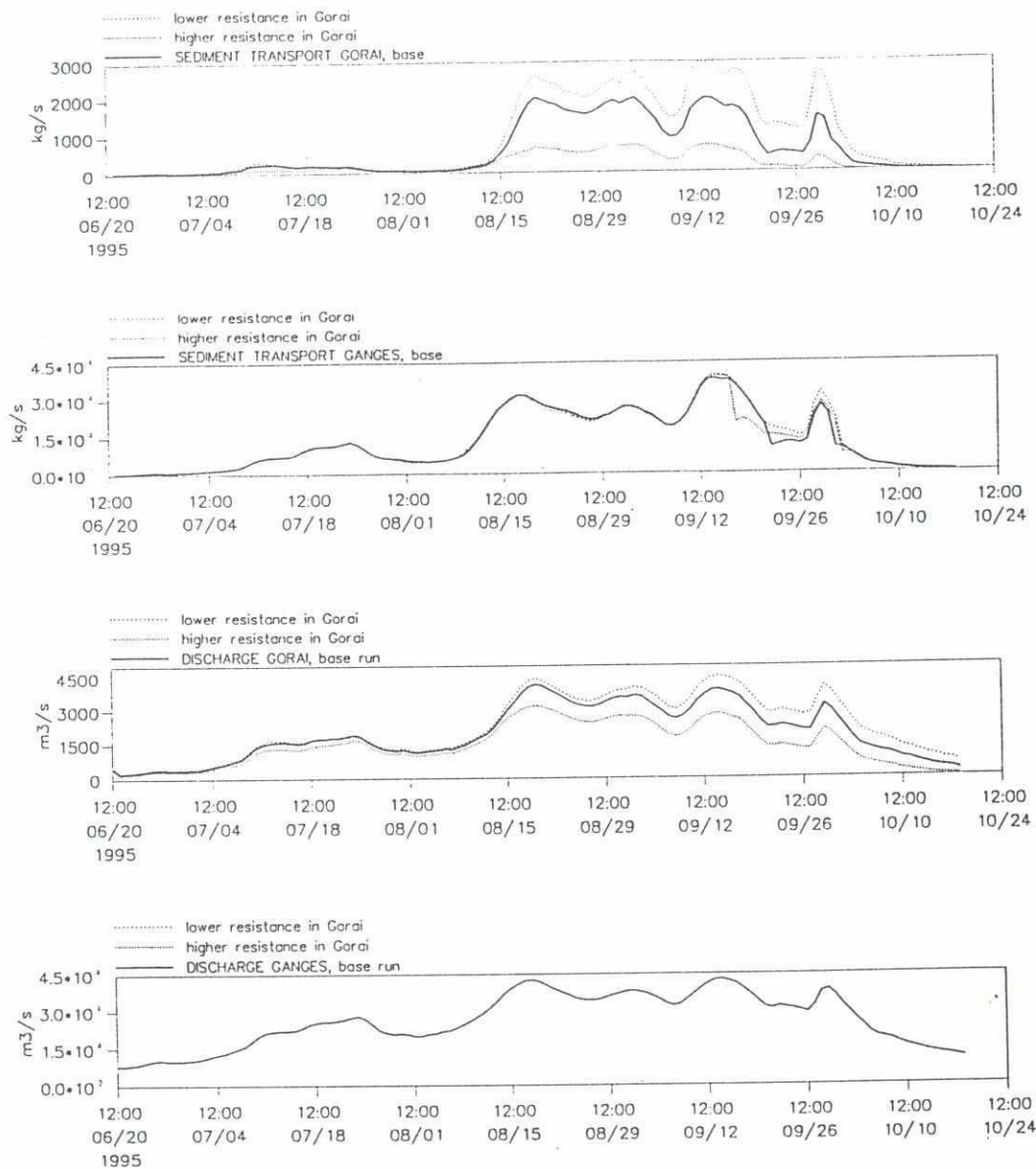
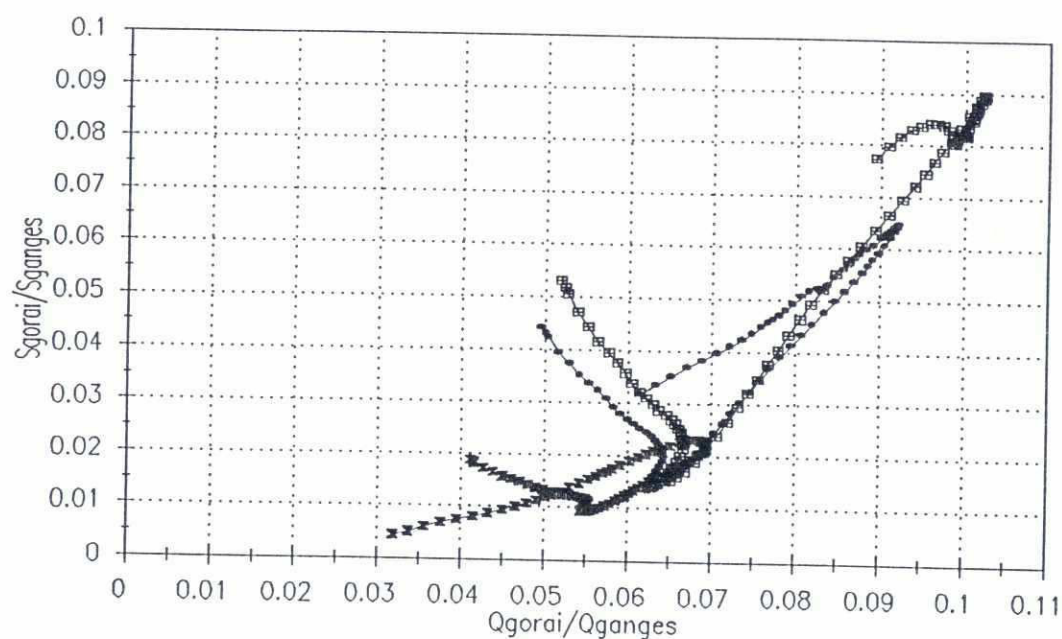
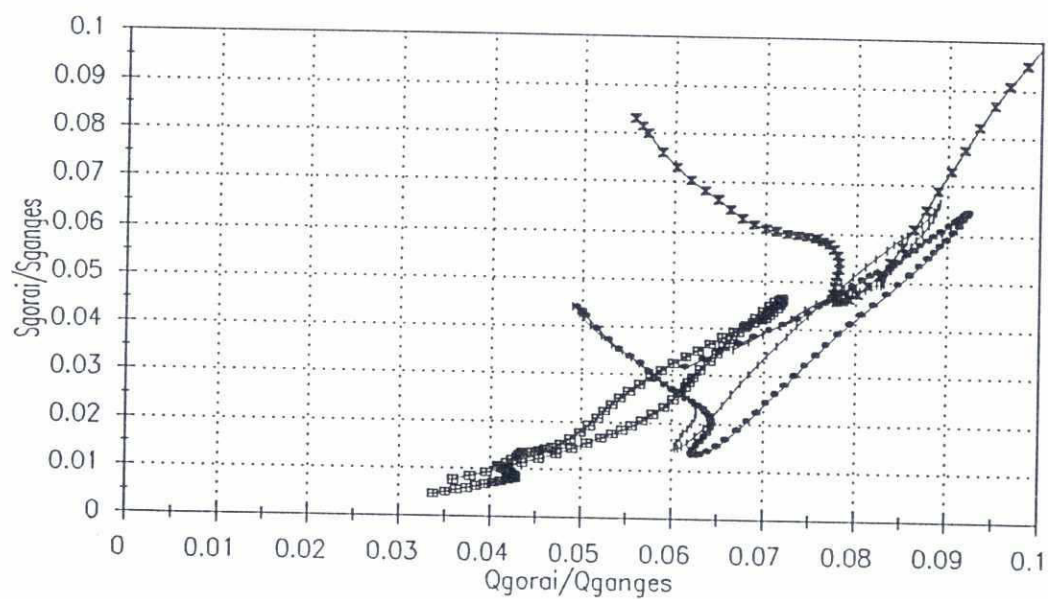


Figure 7.21 Time series of discharge and sediment transport to the Ganges and the Gorai during the 1995 monsoon as simulated by the two-dimensional model.



—•— base run -x- high resistance -□- low resistance



—•— base run -x- lowering d/s water level
-□- bar in front -+- narrowing mouth

Figure 7.22 Distribution of Sediment transport between Ganges and Gorai, 1995, as simulated by the two-dimensional model

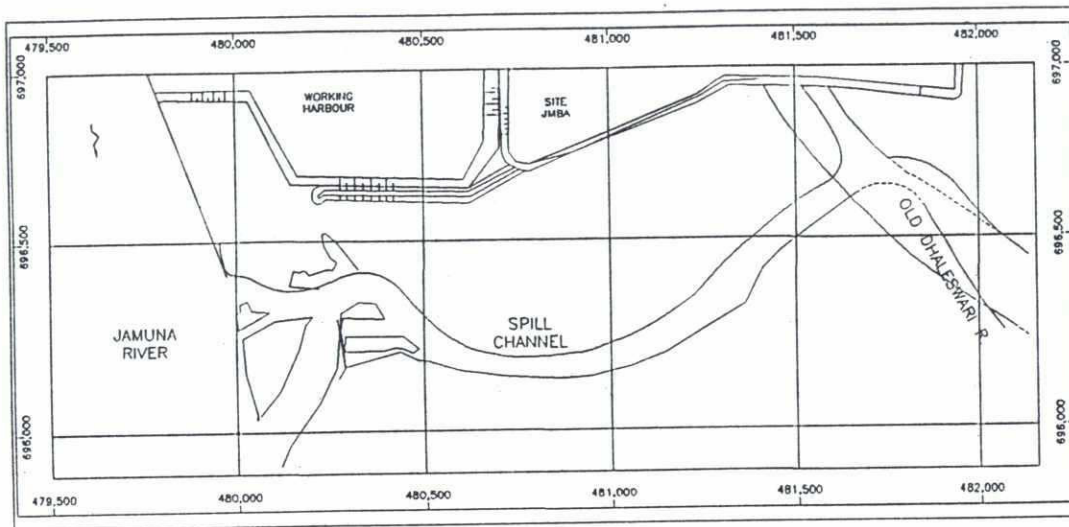


Figure 7.23 Development of new channel between Jamuna and Dhaleswari Rivers

In the study of offtake behaviour mathematical models were used to increase the understanding of the morphological behaviour. The application of mathematical models has contributed to elucidating some aspects of the morphological behaviour of offtakes a lot.

7.5.5 Confluences

Within the RSP no special surveys and studies were done on the morphological behaviour of confluences, not being considered a priority item. However, in accordance with the ToR, bathymetric soundings of the confluence of the Jamuna and the Ganges Rivers were made during five periods (after the flood of 1993, and before and after the floods in 1994 and 1995). These bathymetric maps, although not extensively analyzed, allow for some conclusions to be drawn. Moreover, some results were available of simulations carried out with a one-dimensional morphological model (SOBEK) to study variations in sediment transport near confluences, which assisted in improving the understanding of the morphological phenomena occurring at confluences.

Two aspects are of importance:

- a) the hydrographs of the Jamuna and the Ganges Rivers are always about 1 month out of phase (see Figure 7.24), causing strongly non-uniform flow (backwater effects and drawdown effects) during both flood season and fall (see Annex 5);
- b) the very low flows in the Ganges ($< 500 \text{ m}^3/\text{s}$) with the Jamuna still carrying discharges larger than $4,000 \text{ m}^3/\text{s}$ during the low flow season, whereby the confluence almost ceases to exist.

Jamuna River erosion did take place. In Figure 7.26 also the changes between December 1994 and April 1995 are presented. Changes over this shorter period later in the low flow season after the next flood are only very minor. This observed behaviour confirms the qualitative description predicted in *RSP Study Report 1* and results obtained (in *RSP Special Report 13*) via mathematical simulations.

Apart from this degradation and aggradation the changes in the low flow season are minor. In the Jamuna River some retarded scour of bends can be observed in the period October 1993 till April 1994. Interesting is the fact that the confluence scour hole is filling in and moving in downstream direction during the low flow period. Major changes did take place in the flood season of 1994 between April 1994 and December 1994 (see Figure 7.25): small changes in the direction of the flow in the Jamuna and the Ganges River, possibly connected to planform changes, cause the location of the confluence to shift: the deepest point is now about 1.5 km more downstream.

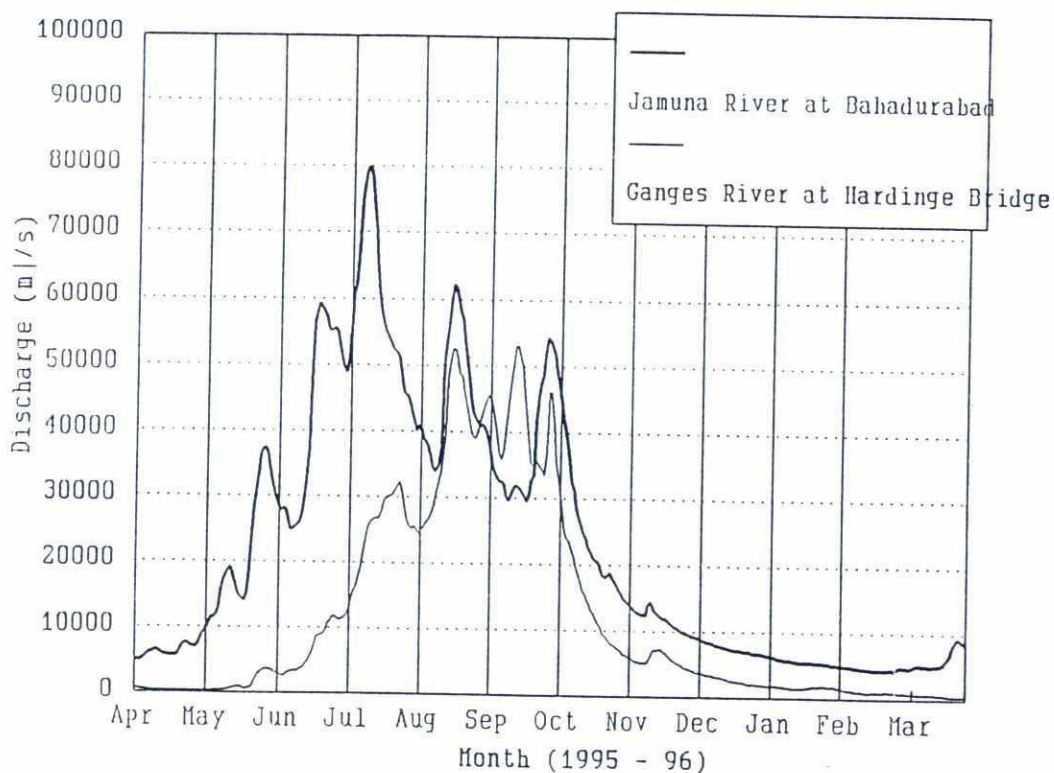


Figure 7.24 Discharge hydrographs of Jamuna and Ganges rivers in 1995

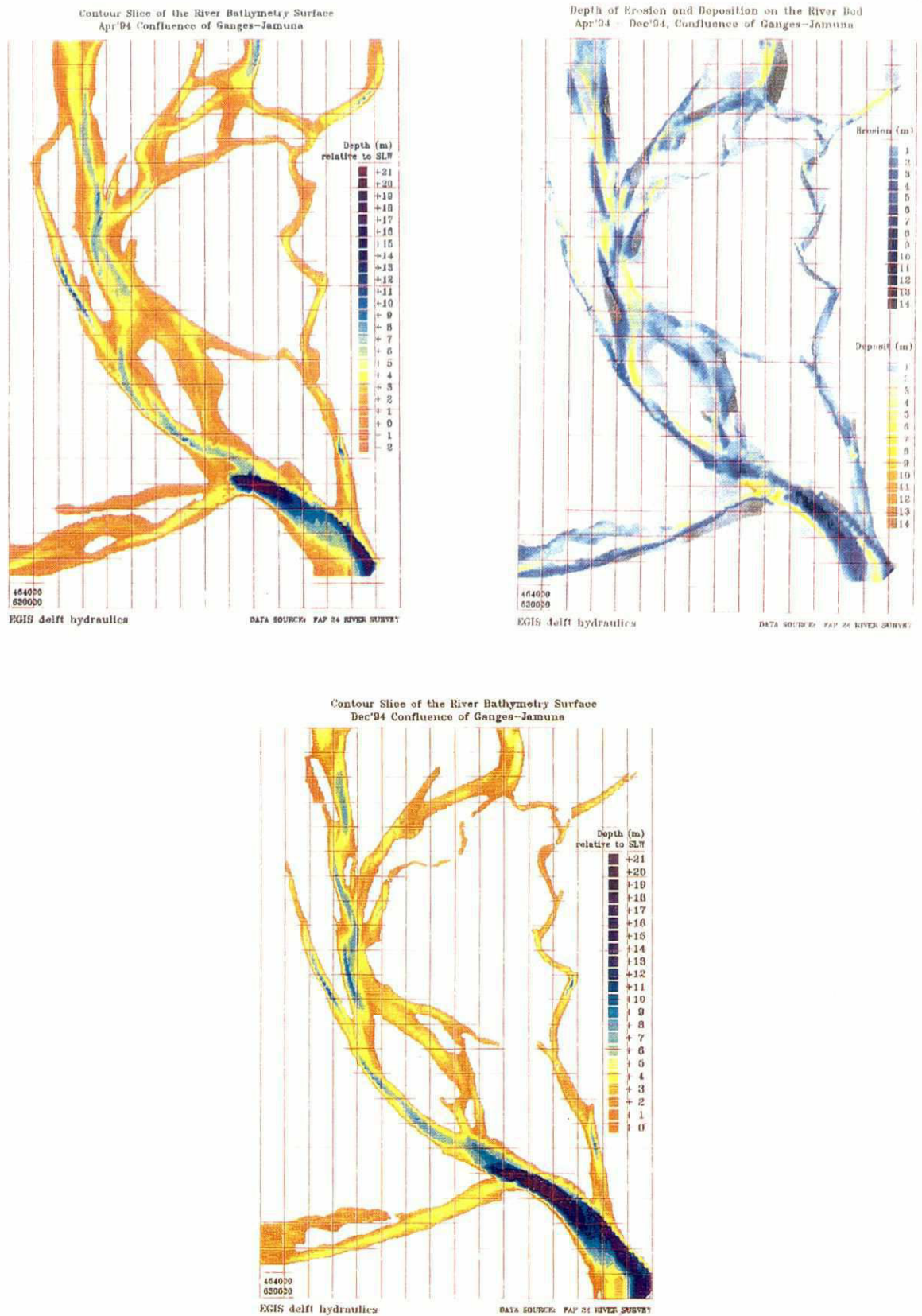


Figure 7.25 Jamuna-Ganges confluence before 1994 flood, after 1994 flood and changes.
Above left: April 94, Above right: December 1994, Below: Changes Apr-Dec 1994

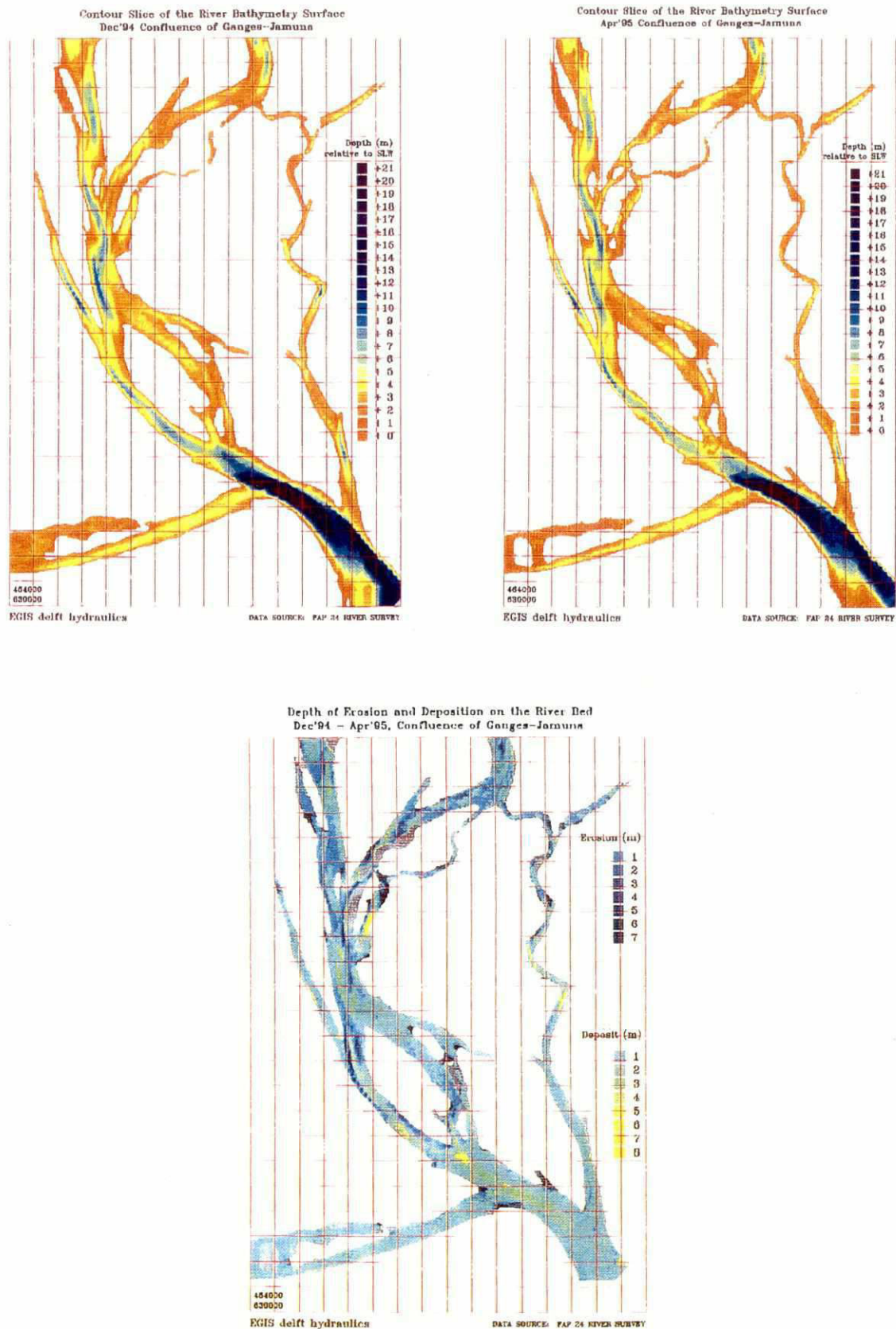


Figure 7.26 Jamuna-Ganges confluence after 1994 flood, before 1995 flood and changes.

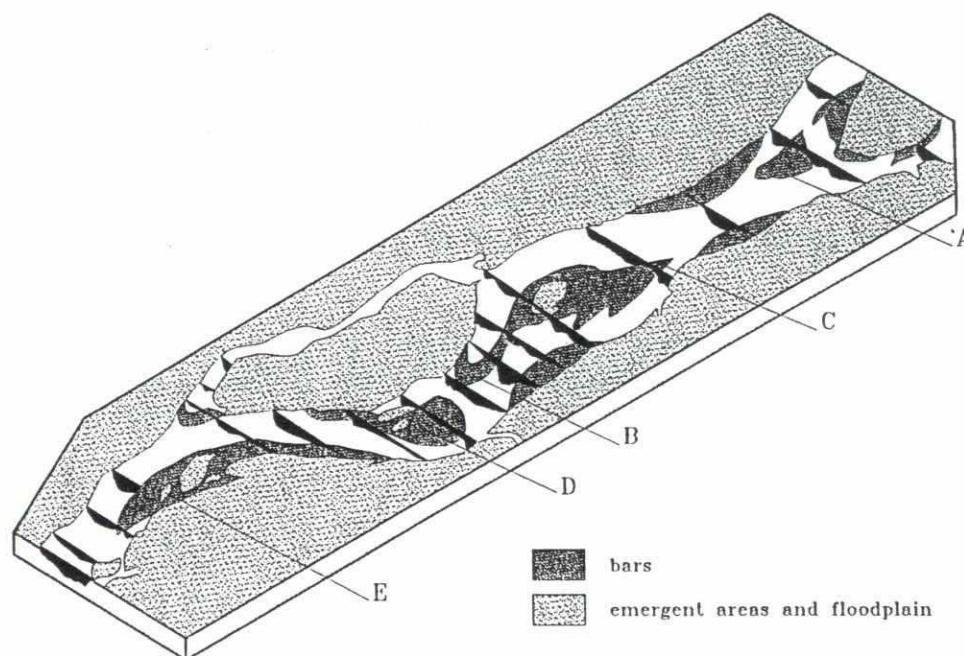
Above left: December 1994, Above right: April 1995, Below: Dec 94-Apr 95.

Confluence scour depths observed are generally larger than would be obtained with the prediction method developed for sand-bed rivers by Klaassen & Vermeer (1988). It can be shown that this is caused by time-lag effects: in the analysis the momentary water depths in the Ganges River were used, while during the formative stage of the confluence scour hole the depths were much smaller. The size of the scour hole is so large (order of 10^6 m^3) that it is filling in only slowly during the low flow season.

7.5.6 Bars and bifurcations

Bars are abundant in most of the major rivers in Bangladesh. Via their migration through the system they play a pivotal role in bank erosion processes (Klaassen & Masselink, 1992) and offtake performance (FAP4B, Vol. 3). Different types of bars can be distinguished (see Figure 7.27): point bars in meandering rivers, alternate bars in straight river reaches, attached bars and mid-channel bars in braided rivers.

Two special studies were carried out, one (with the University of Leeds, UK) to study the initial growth of a mid-channel bar, considered to be the fundamental building blocks of braided rivers, and the other to study the flow field - in particular the secondary flow - around a "mature" bar (together with the University of Nottingham, UK). Both studies included the upstream bifurcation as the flow and sediment transport at the bifurcation determine the conditions in the downstream anabranches. The results of these studies are summarized here; they are discussed in more detail in Chapter 6 of Annex 5, while detailed results are presented in the RSP Special Reports 9 and 16, respectively.



A first-order tributary bar, B second-order tributary bar, C first-order medial bar, D and E first-order point bars with subsidiary scroll bars and chute channels

Figure 7.27 Types of bars in the main rivers of Bangladesh

The study of the mid-channel bars was quite relevant, as it is one of the most common bar types in the braided Jamuna River. Sand bars often form downstream of a zone of flow convergence and are initially deposited as a central symmetrical bar cone, aligned parallel to the primary flow direction. Mid-channel bars grow through lateral accretion induced by secondary flow in the anabranches, vertical aggradation by successive stacking of dunes and downbar migration of an accretionary dune field front. The basic planform morphology of a mid-channel bar is rhomboidal with two protruding bartail limbs that provide a sheltered zone for accumulation of fines. Bar growth and reworking are strongly stage dependent, with rapid rates of bar aggradation and anabranch scour during peak flow and minor reworking at low flow.

At a later stage of development one of the anabranches scoured substantially initiating bank retreat on the adjacent permanent char. The enlargement and migration of this anabranch was primarily due to an increase in sinuosity of the main channel thalweg immediately upstream of the bar. The enlargement and realignment of the west anabranch led to rapid bank retreat at the opposite east bank at Bahadurabad ghat. Such a process is typical for later stages of mid-channel development, and it is often part of the overall channel shifting or channel outflanking.

The study on the pattern around a mature bar revealed that there exists a close association between zones of upwelling or downwelling and variations in suspended load concentration which indicate the importance of secondary currents in affecting sediment transport pathways. The pattern of helical flow around a bar is more complicated than was previously thought.

Measurements suggest that in the left anabranch clockwise secondary circulation just downstream of the point of bifurcation leads to scour and bank erosion at the bar head. About one third of the way along the bar the main flow crosses to the outer bank and counter-clockwise secondaries generate at the outer bank scour and sedimentation on the flank of the bar at the inner bank. The main flow crosses back to the inner bank about two thirds of the way along the bar, generating clockwise secondary circulation and tending to sculpt into a rhomboidal shape. Flow patterns in the right anabranch are broadly a mirror image of those in the left channel.

These flow patterns can explain most of the observed trends of planform change for the studied bar during the period of observation. However, other features can only be understood when viewed in the wider context of large-scale, longer-term planform evolution.

Both the study of the further development of the two anabranches around the bar (University of Leeds) and a study of historical channel planform (University of Nottingham) demonstrate that short-term, local bar development is driven by changes in approach flow orientation that in turn occurs in response to longer-term, larger-scale planform changes. This underlines the conclusions on the importance of the upstream angle as found in a study using satellite imagery under FAP21/22 (Mosselman et al, 1994).

Finally reference should be made to some studies carried out under the EGIS project (formerly FAP19) in cooperation with the RSP. This was an extension of the char land studies (FAP19, 1994). Based on a study of LANDSAT satellite imagery covering the period 1973-1994 it was possible to get insight into the age of char land, which with some care can be interpreted also towards the age of chars. Most chars have disappeared after six years. Only a few percent

of the chars remain present for decades. This seems an additional support for the statement that the sedimentation of fines in the tail of the bars does not lead to the formation of hard points. For more details see RSP Special Report 17.

7.5.7 Scour holes

Scour relates to deeper parts of the river caused by specific flow patterns, most of the time imposed by the planform of the river. In past studies of the main rivers of Bangladesh the following types of scour have been identified:

- constriction scour;
- bend scour;
- confluence scour;
- protrusion scour.

In addition general scour and local scour have been identified, but these are not considered here. Figure 7.28 gives a schematic outline of the four types of scour listed above. Often the different types occur in combinations.

It is known that deep scour holes have been observed in the system, with maxima of 62 m-SLW at Mawa (in a natural constriction of the river, probably linked to a hard point) and 55 m - SLW upstream and downstream of Chandpur (at a protrusion and local scour near the town protection).

The studies on scour carried out under the project were mostly interpretations of the bathymetric maps. No special survey was carried out apart from Jamuna River at Kamarjani together with FAP 21/22, where the specific interest was to determine the maximum scour depth present and to study its cause. In the project the following maximum scour depths were measured:

- 15.5 m below SWL in a bend near Kamarjani in November 1994 and August 1995
- 17 m below SWL at a protrusion near Bahadurabad;
- 26 m below SWL at the Jamuna-Ganges confluence in December 1994 (has probably been deeper during the peak of the flood);
- 45 m below SLW at a protrusion slightly upstream of the Gorai offtake in the Ganges River in October 1994.

Some other interesting observations regarding scour holes are summarized below:

- In some cases confluence scour does occur in an eroding outer bend, making the scour holes much more serious;
- in some of the scour holes bedforms could be identified clearly, different from what is sometimes assumed

Because deep scour holes were found during some of the bathymetric soundings, it was possible to follow their time-wise development. As an example the scour holes observed in Bahadurabad in 1993 are discussed (see Figures 7.29 and 7.30). Both confluence scour and protrusion scour are linked to the changes in planform. When the discharge changes also some confluences vanish and the amount of protrusion reduces as well. As a consequence the cause of formation of some of the scour holes has disappeared. Hence they remain as a remnant

of their previous formation and start to wander through the river system. In Figure 7.29 their change in location is indicated. Also the change in shape of one of these scour holes was studied, see Figure 7.31.

As can be observed these scour holes start to wander through the river system, changing their alignment and filling in while they travel through the system. This behaviour was never before observed and is possibly unique for braided sand-bed rivers. It may have serious implications as to the maximum scour to which e.g. bridge piers may be subjected. The downstream slope of the scour holes is about 1:40 (see Figure 7.31), which is substantially more gentle than the slope of scour holes downstream of structures.

Usually constriction scour is linked to reductions in width due to e.g. groynes, hence man-made constructions. An example of such a man-made constriction is reduced width in between the guide bunds upstream of the Hardinge Bridge over the Ganges River. These constrictions can give rise to spectacular variations of the bed level over the flood hydrograph, degradation during the flood and infilling during the lean season. A recent study at the SWMC demonstrated that within the guide bunds the bed level may fluctuate over 6 to 7 m due to the natural constriction (DIII/SWMC 1996). Interestingly, natural constrictions may occur as a consequence of non-uniformities in the river width due to retarded bank erosion at some places or differences in accretion in others. These demonstrate similar behaviour: scour during the flood and deposition during low flow, and serious influences on the sediment transport (see Chapter 7 of Annex 4, and for more details RSP Special Report 13). In November 1993 and November 1994 a clear constriction could be observed near Bahadurabad.

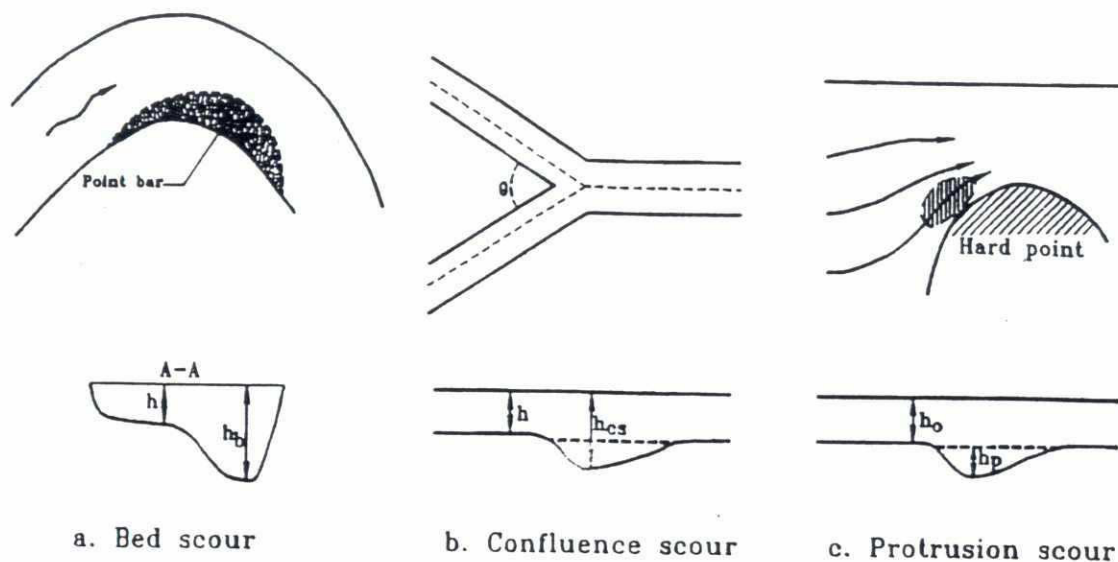


Figure 7.28 Different types of scour in the main rivers in Bangladesh

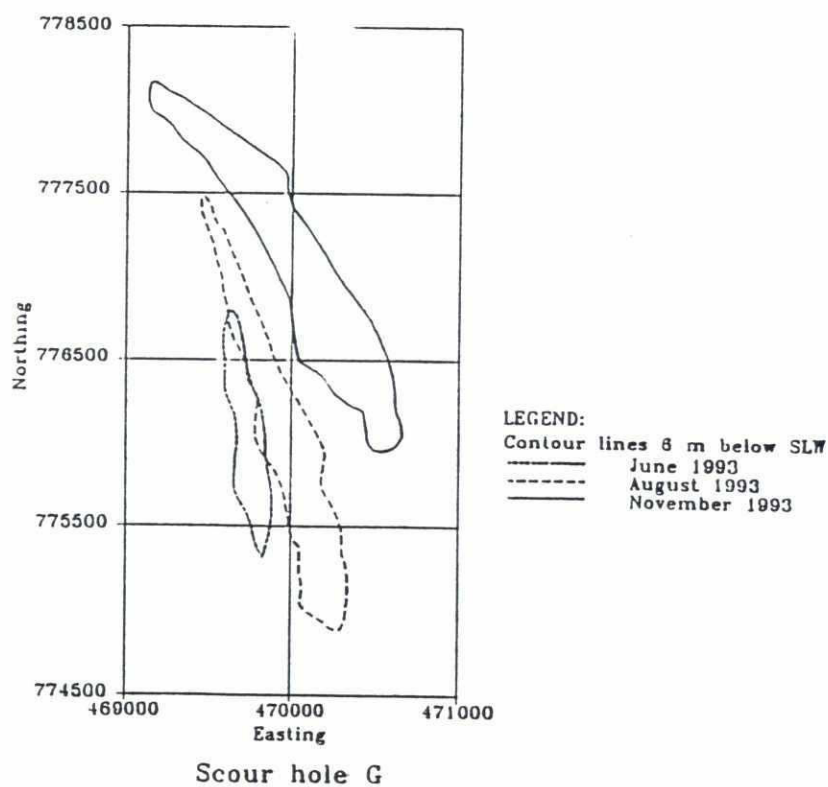


Figure 7.29 Change in location of scour hole in time

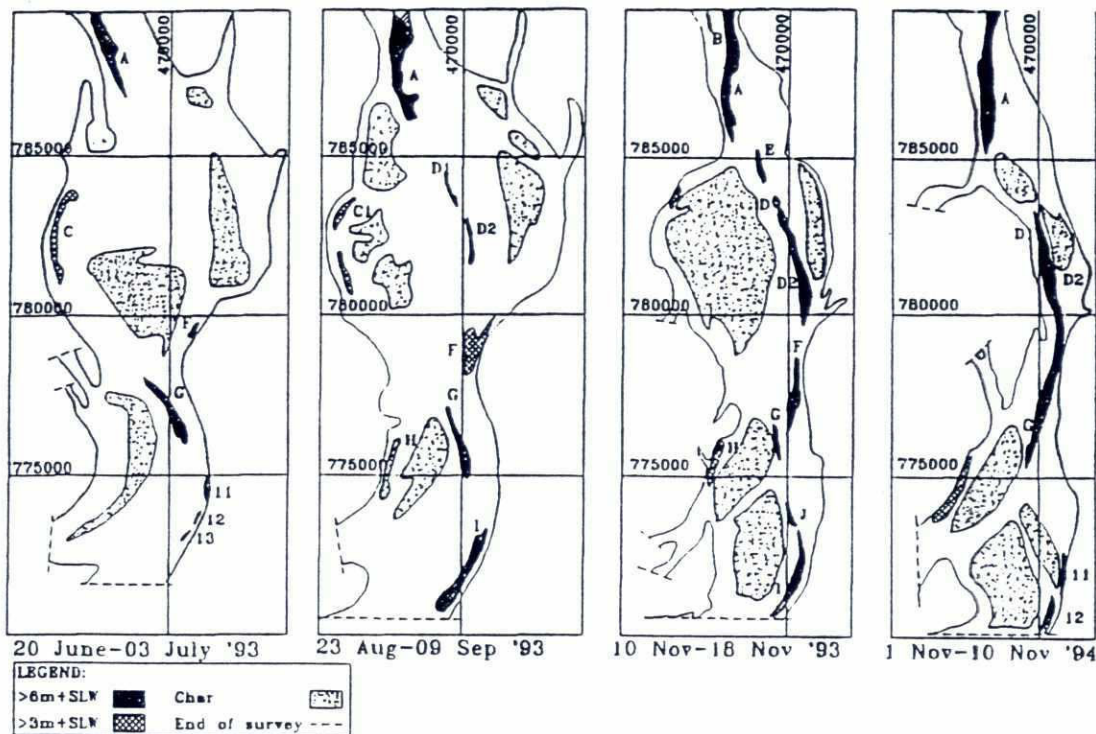


Figure 7.30 Location of scour holes near Bahadurabad in 1993

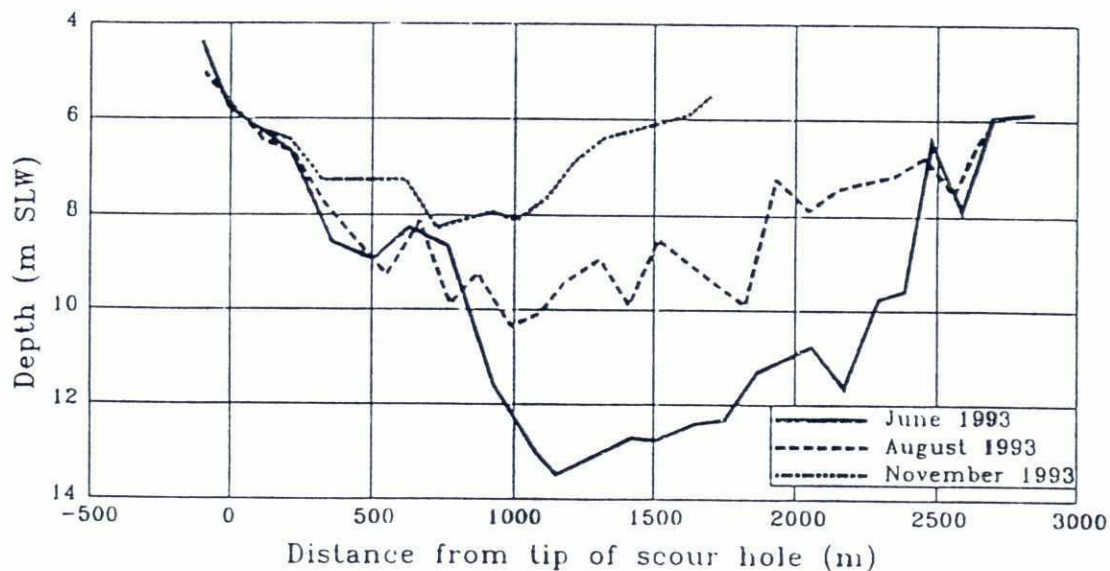


Figure 7.31 Change in shape of scour hole in time

7.5.8 Bank erosion and cutoffs

Bank erosion (and the corresponding bank accretion) and cutoffs (or more generally by the formation of new channels, plus the reversed phenomenon of sedimentation of channels) are the mechanisms by which the planforms of rivers change. Bank erosion along the different main rivers in Bangladesh was studied in different projects over the last decade. Bank erosion

rates along the Jamuna River were studied by Klaassen and Masselink (1992) on the basis of LANDSAT imagery with one year intervals, resulting in empirical relations for bank erosion comparable to the ones derived by Hickin & Nanson (1984). Additional studies were done under FAP 1, a.o. on the occurrence of bends that produce high rates of bank erosion over a number of years (Halcrow et al, 1992).

Two RSP studies gave additional insight into the mechanisms involved in bank erosion, notably one (together with the University of Nottingham) on the flow field in an eroding bend, and another on locations of bank erosion on the basis of the bathymetric soundings at Bahadurabad. The first study, meant to identify secondary flow cells in a bend downstream of Bahadurabad, demonstrated that the flow field in an anabranch of a braided river is much more complicated than in a bend of a meandering river (see also before under *Bars and bifurcations*).

The other study allowed to link changes in the location of bank erosion at Bahadurabad to changes in bed topography. Reference is made to Figure 7.32, where measured bed topographies in 1993 are compared with the location of the bank erosion. The change in the location of bank erosion is due to the formation of a char immediately downstream of Bahadurabad during the flood. Due to this char the bank erosion moves in downstream direction. The reason for the formation of the char can be linked back to the major cutoff that took place upstream of Bahadurabad. More details on this aspect can be found in RSP Special Report 24, where the development of the planform and the bed topography at Bahadurabad are discussed extensively. See also Peters (1993).

As part of the two-dimensional morphological modelling for the Jamuna Bridge a bank erosion formula relating the bank erosion to the near-bank water depth and sediment transport was calibrated against observations and applied in predictions of additional bank erosion one monsoon ahead due to the presence of guide bund structures (DHI 1996 a,b,c).

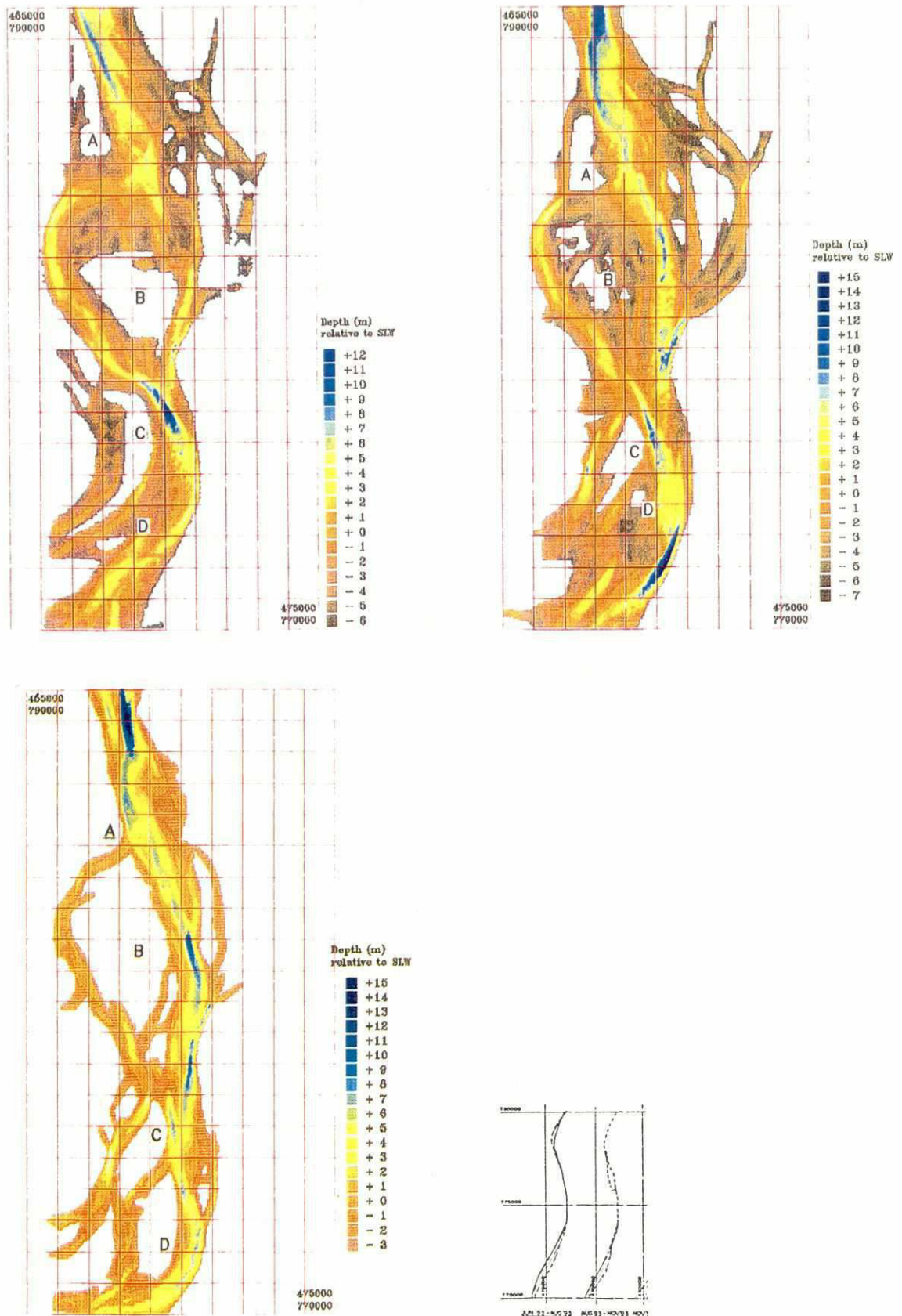


Figure 7.32 Change in location of bank erosion near Bahadurabad in 1993 due to change in bed topography and in planform

Another very interesting phenomenon that could be studied closely using the bathymetric charts of 1993 and subsequent years was the development of the cutoff which took place upstream of Bahadurabad. The potential for such a cutoff was already present in view of the large cutoff ratio (see Klaassen & van Zanten, 1989) and the existence of some channels connecting the river upstream with the river near Bahadurabad. The cutoff was probably caused by excessive erosion of a char and bank upstream of the bifurcation. From the deposits it can be observed that major deposition of sediment was taking place in 1993. This changed the angle at the bifurcation and led to excessive quantities of sediment entering into the right channel. This resulted in blocking of the right channel and erosion of the cutoff-channel. This happened in a few months only. Initially the cutoff channel over-deepened and later started to widen. The next year a mid-channel bar developed in this cutoff channel. The detailed study carried out (see RSP Special Report 24) resulted in interesting results and improved understanding of the (relatively) small causes which trigger such a major event.

Finally, it is interesting to note that the two cutoff channels, that had initially developed (see Figure 7.32) in previous years, were both directed at the deep protrusion scour hole that developed upstream of Bahadurabad during flood due to the inflow from the eastern ana-branch. One can speculate that most of the time cutoff channels are attracted by such deep scour holes. If found generally true, this would be quite interesting to include for any predictions of planform changes of these braided rivers.

7.5.9 Flow fields and maximum velocities

It may initially be amazing to find some findings on flow fields and maximum velocities in a section on morphology. Flow fields in the main rivers, however, are very much determined by the bed topography, which is determined by morphological processes.

Velocities in the Jamuna River were studied by Halcrow et al (1993), see also West et al. (1992). The latter give a probability density function for velocities in the Jamuna River. Average velocities in the Jamuna can be evaluated using at-a-station relationships (see e.g. Klaassen & Vermeer, 1988), resulting in:

$$\bar{u} = 0.095 Q^{0.26}$$

For a discharge of the previously used bankfull discharge of 44,000 m³/s this results in an average velocity of about 1.5 m/s. A similar approach for the Ganges on the basis of the at-a-station relations for the Ganges River derived in RSP Special Report 7 leads for the braided reaches of the Ganges River to:

$$\bar{u} = 0.36 Q^{0.15}$$

For a bankfull discharge of 44,000 m³/s this corresponds to an average velocity of about 1.8 m/s. The higher maximum velocities for the Ganges can probably be linked to the larger influence of controls, limiting the width of the Ganges river.

Locally the velocities may be much higher due to 2- and 3-dimensional effects. Maximum velocities measured were:

- 3.2 m/s in an eroding outer bend in the Jamuna near Kamarjani;
- 3.7 m/s near a protrusion in the Jamuna River near Bahadurabad;
- 4.0 m/s near a protrusion in the Ganges River, upstream of the Gorai offtake.

Note that also here the maximum velocities for the Ganges are higher. Typically these maximum velocities were observed some tens of meters outside the bank. These maximum velocities were measured during slightly below bankfull discharges; whether higher stages lead to higher velocities is not yet known. Most of the time the maximum velocities occurred at the surface; in some special cases (primarily accelerating flows) maximum velocities lower in the vertical were even higher.

Maximum flow velocities are linked to typical specific conditions, like protrusions of the bank into the main flow. Both in the case of Bahadurabad and the Ganges River near the Gorai, it is possible or in the case of the Ganges even probable that here a (temporary) hard point is present. For analyses of RSP measurements of velocities, see Annex 5, Chapter 11.

7.5.10 Exchange of sediments

Sediment transport in a river takes place intermittently. Sediment is temporarily stored in sedimentation areas (chars and scour holes that are being filled in) and later mobilized again upon erosion. This takes place in two ways. One way is storage and re-mobilization in and from the river bed. The second way is storage (via flood plain sedimentation) in the flood plain and in more permanent chars of the river and re-mobilization (mainly via bank erosion). Main differences between the two are:

- in the former case the storage of fine sediment (silt and clays) is negligible, while in the floodplain also deposition (and erosion) of fine sediments is significant;
- both ways operate at different time scales, remobilization from the river bed usually occurring within a few years, while for permanent chars and the flood plain the remobilization may take place only after decades.

Thorne et al (1993) have studied for one reach in the Jamuna River the storage of sand and silt in the chars and supply of sand to the river via bank erosion. For a reach with a length of some 100 km they propose that the silt input from the banks is only about 3% of the silt carried through the reach, but the sand yield from bank erosion is about 25% of the sand load supplied from upstream. According to their findings there is an overall widening of the river and they demonstrate that the sand eroded from the banks is closely related to the storage of sand in char growth.

Via the application of GIS on the bathymetric maps it was possible to get some insight in the variation of the sand load in longitudinal direction. It was found by comparison of bathymetric maps from Bahadurabad between August and November 1993 that the (temporal) storage of bed material in bed topography changes is in the order of 30% of the total bed material load in the river (see Figure 7.33). Hence very substantial amounts of the sediment are temporarily stored in the river and only eroded in subsequent periods. In terms of total sediment transport this figure of 30% is a substantial amount and it indicated that for making balances long-yearly averages are needed.

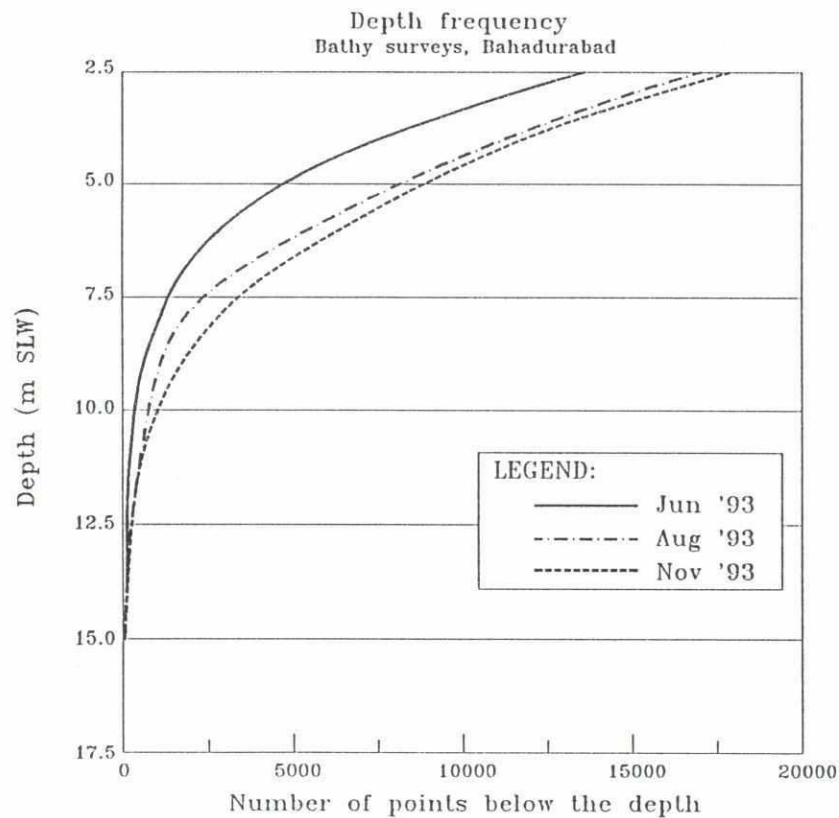
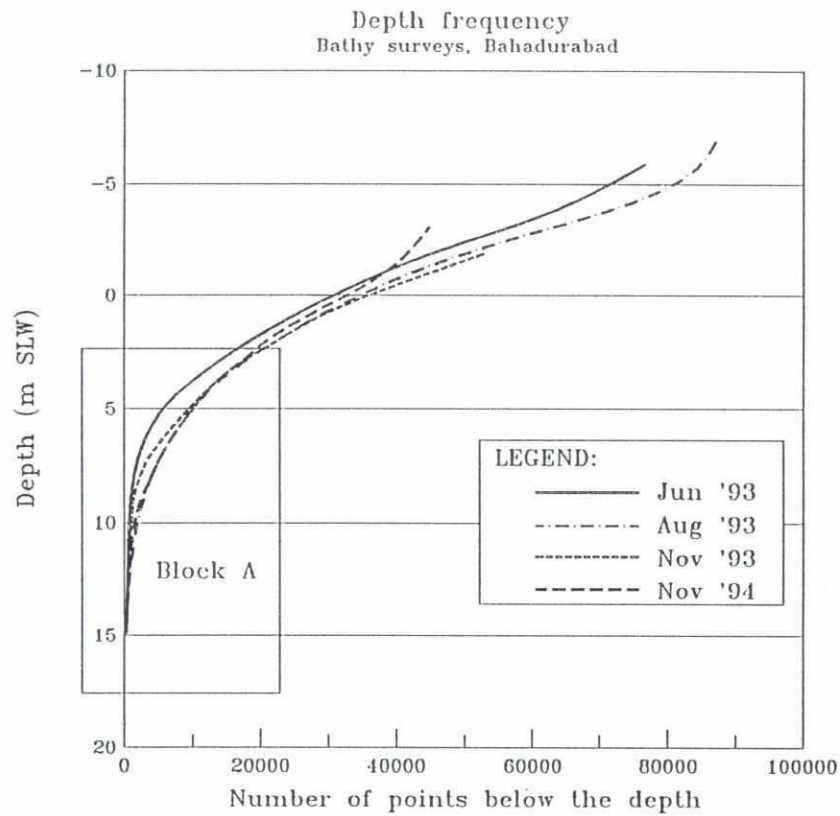


Figure 7.33 Example from analysis of balance for Bahadurabad

7.5.11 Planform development

Using the series of bathymetric maps obtained in the project in combination with satellite imagery it was possible to explain the planform development at Bahadurabad over the period 1993-1995. This analysis showed that sometimes planform changes take place very rapidly, and that they often are explained by developments upstream, often quite far away (tens of kms). These upstream causes are often only local phenomena like bank erosion over a few kms, but they trigger a chain of events in time and space. It clearly demonstrates that deterministic long-term predictions of the river behaviour is not possible, and that the longer the period for which the prediction is wanted, the larger the inherent uncertainty will be.

For a more extensive discussion on predictability of planform changes (and implicitly also on predictions of the bed topography) see Klaassen et al (1993). More detailed information on the analysis of the morphological developments near Bahadurabad is given in Chapter 13 of *Annex 5* and *RSP Special Report 24*.

7.5.12 Prediction methods

Prediction methods can be used for different purposes. In this project mathematical models were used for study purposes. Using the models concepts were tested (1-d modelling for interpretation of sediment transport data and sediment rating curves) and the sensitivity of the functioning of offtakes to changes was investigated (2-d morphological modelling for the Gorai offtake).

Prediction methods can be distinguished according to the duration over which the prediction is made. The following models can be identified:

- short-term models, for several months ahead;
- medium-term models for some years;
- long-term models, for e.g. the engineering life-time of a project.

As discussed by Klaassen et al (1993) different factors influence the accuracy of the predictions, and determine whether deterministic, stochastic or statistical modelling is more appropriate.

It is obvious that for short-term prediction to be relevant the total cycle of data collection - analysis - model building - simulation - reporting - taking of action - should be fairly short. Two types of short-term predictions can be visualised. One type are predictions of changes that will take place during the fall and the low flow season, e.g. which of two anabranches will scour. This type of prediction is important for guiding dredging activities and for the planning of AFPM measures. Unless quicker ways of data collection and processing are found, the use of 2-d morphological models for short term predictions does not seem appropriate. Studies under this project, guided by the experience of the Project-Adviser (Peters, 1988) on the Zaire River, have shown that also for rivers like the Jamuna prediction methods can be developed that, based on measurement of some key parameters (slopes, depths, velocities, bedforms, sediment transport patterns) in the different anabranches, can be used for prediction of short-term developments (e.g. during the fall of a flood). For a more extensive discussion see *RSP Special Report 24*.

Another type of short-term predictions are predictions where the data collection would be done during one monsoon period and immediately thereafter. The results will have to be ready early enough to allow action (e.g. the implementation of bank protection works) to be taken before the next monsoon. The ongoing two-dimensional morphological modelling for the Jamuna Bridge (DIII, 1996), has demonstrated that this has now become possible due to the more and more powerful computers in combination with advanced user-friendly software. For this study the above cycle of data collection – analysis – model building – simulation – reporting (started in June 1995) and was finished in February 1996, leaving 3-4 months for action to be taken before the monsoon period. It is foreseen that the near future will see an increasing number of applications of such advanced modelling techniques side by side with the previously mentioned technique meant to still benefit from the "force" of the water.

Medium term prediction (for a few years ahead) of changes in bed topography can use the same 2-d morphological models as presently applied to guide the construction of the Jamuna Bridge as discussed before. Furthermore, a model is under development (see Klaassen et al, 1993) for medium-term planform changes. These models are sensitive to initial and boundary conditions and to model formulation and change in character from mostly deterministic to mostly stochastic, the longer the simulation period is extended.

Long-term morphological models are only appropriate for 1-d approaches, where the rivers are considered as a sediment conveying network. For the specific case of Bangladesh the functioning of the offtakes will, unless much more insight in their behaviour is obtained, always have an important effect, causing these models to be stochastic models as well. For long-term 2-d problems a statistical approach is more appropriate, in which maximum velocities, minimum bed levels, etc. are expressed in terms of exceedance frequencies.

In conclusion it can be stated that mathematical modelling under this project has been very useful for a better understanding of the morphological behaviour of Bangladesh's main river system.

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8 Validation of previously collected data and RSP data

8.1 Introduction

After the collection of the survey data in the field, they have to be processed and stored in the office. Before using the data in studies it is important to validate them. The validation is to assess the reliability and accuracy of the data in the light of the objectives of the data collection. To some extent the expectations of the users of the data should be considered in the validation process. In practice, the common survey strategies aim at the collection of the most accurate data with the available instruments and the applied methodology. The need for improvement of the data validation is illustrated by the preliminary results of a response study with the users of data collected by government agencies (Hoque, Shamsul, 1993). These results show that in 1990 only 30 to 40% of the users are of the opinion that the data are adequate and reliable. Since the data of the Hydrology organization form an important part of all the data collected by government agencies, it is expected that these results are also more or less valid for the hydrological data collection. In the mean time improvement has been achieved with the establishment of linkages with SWMC and FAP studies and the assistance provided by a UNDP project to the hydrology organization.

In this chapter an overview is given of the results of validation activities done by the project or others of the different types of hydrological and morphological data.

8.2 Water-level gauging

8.2.1 BWDB measurements

The BWDB measures the water levels in a network of staff gauges and automatic water recorders. Data from staff gauges are read and recorded by gauge readers, who are members of the regular establishment of the BWDB, Hydrology organization. The monthly recorded data are routed through the sub-divisions to the processing unit of SWII-2. In that office the data are stored after checking and processing. Similarly, data of automatic gauge recorders are also transferred to the processing unit in graph sheets or data logger cassette (Hoque, Shamsul, 1993).

The RSP checked the quality of the data and validated it, using HYMOS software. In this software the validation is done by examining the data in several steps, called screening, time-series graphs, relation curves, double-mass analysis and series homogeneity tests. In the screening of data series, some statistical parameters were computed and the outliers were detected. In the time-series tests, residuals, residual mass curves and moving averages were computed so as to detect errors. Relation curves between the two series of data were used to detect random and systematic errors. Other facilities of the software, such as double mass analysis technique and the series homogeneity tests, were not used.

Some typical inaccuracies found in water levels measured by staff gauges are described in the following: Sometimes frequent raising and lowering of the staff gauges is necessary to follow quick changes in the water level. This is likely to introduce errors, particularly if several shifts take place between two check-levellings. In principle, a shift of the gauge should

immediately be followed by a relevening. The Flood Modelling and Management Project (FAP25) stressed the importance of frequent check-levellings of staff gauges.

Near an eroding bank it might be necessary to shift the gauge to a new location at some distance from the previous one. Average water-level slopes in the main rivers are about 5 to 8 cm per km. Hence, shifting the gauge over distances as far as one kilometres may introduce significant differences in simultaneous water-level readings. This should be described in detail in the relevant documents.

Some gauges have been located near bridge piers or bridge abutments, where high velocities are experienced during floods. In general, at those locations the riverbed will erode during floods and silt up during the lean season. This implies that the velocity head for equal discharges can be different, depending on the season and hence a time varying stage-discharge relation results. Furthermore, it is recommended to correct the measured water level for the varying velocity head.

8.2.2 RSP measurements

Validation of RSP water-level data was directed at obtaining the correct data from simultaneous AWLR and staff gauge readings. It was performed in two principal ways; in the field while offloading the AWLR data, and later in the office. Upon retrieval of data in the field, the data are visualized in a graphical representation of the readings versus time. Distinct errors such as sensor over-range, recording of error codes, and spikes in the data can then be recognized by visual inspection.

In-office data validation is done by examining the data on some criteria. These are physical limits of the recorded data, time-window, and consistency and difference check between the simultaneous records.

Physical limits

Firstly, the data have to be within a certain limiting range reflecting certain physical limitations. For the AWLR, the limits are -0.50 and $+0.50$ m and for the staff gauge 0.0 and 2.0 m. The associated reference levels which are set in the reference file, must also fall within the fixed limits. This also allows the operator to enable or disable the use of a certain data source.

Time window

When the recorded data pass the physical tests, they are subjected to a time test. During processing, the program advances through the data files. At each processing step, the time is increased to the time associated with the next valid sample in either AWLR or the staff gauge file, or both in case of coinciding sample times. The sample time stamp must fall within a window of -1.5 and $+1.5$ minutes around the processing time. In other words, only data for which the time stamp differs less than 1.5 minutes from the current data processing time are accepted for further use. Due to the mechanism of advancing through the files, always at least one sample coincides with the processing time.

Difference

If samples of both data sources pass the physical and time tests, they are subjected to the difference test. If the difference falls within the margin as set in the reference file, the AWLR level is regarded as valid, otherwise the staff gauge level is adopted. If both AWLR and staff gauge level pass the test, the AWLR level will be used. The data collection interval of the AWLR is 30 minutes, whereas that of the staff gauge is 180 minutes. Hence, only one out of six AWLR samples can be tested according to the time criterion as described before, which could result in a wastage of data. To overcome this problem, a linear interpolation procedure is applied to the staff gauge data, provided that these data passed the time and range tests. For each AWLR sample time, the AWLR level is compared with the associated interpolated staff gauge level. If the difference falls within the margin that has been set in the reference file, then the AWLR value is regarded as valid.

In this way consistent and validated time series of daily water levels were prepared for eleven stations by the project.

8.3 Discharge measurements

Discharge measurement data were validated in two principal ways. One is done by plotting the h (water level) and Q (discharge) and visually identifying the outliers. From a cluster of data, if some data deviate from the trend shown by the majority, they were detected. The detected data are examined for possible mistakes in data-punching from field sheets, field recording and possible physical reasoning. If no explanation is found from these tests, the detected data are considered as unacceptable measurement errors and discarded.

Secondly, the discharge data are examined for consistency with hydraulic geometric properties of the transect. These were done by plotting cross-sectional area as function of water level, velocity versus water level, discharge versus cross-sectional area and discharge versus average flow velocity. Again visual checks were applied to detect outliers. In the anabranching Jamuna River, the consistency check was also applied between the individual channels.

8.4 Sediment transport and other sedimentological measurements

The collection of suspended sediment transport data began in the fifties at Bhadurabad, Hardinge Bridge, Gorai Railway Bridge and Bhairab Bazar. These data were not analyzed by the RSP because some confusion exists on these data, whether the samples include only the coarse fraction, only the fine fraction or both. This illustrates the importance of complete documentation and storage of old survey data.

The sampling of the suspended sediment transport and the bed-material sampling were extended considerably since 1966. However, the bed-material sampling stopped somewhere in late seventies but the suspended sediment transport measurements were continued. The RSP has done sediment transport measurements at the major gauging stations for about three years, 1993 until the end of 1995. A BWDB and RSP joint sediment transport measurement was carried out in the Jamuna River near Bahadurabad. In this section, main focus is pointed at

the validation of the BWDB suspended sediment transport data for the major stations and the results of the joint measurements by BWDB and RSP.

8.4.1 Methods

A simple validation method is checking for consistency of sediment transport data series taken in one station and using the same sampling method. This can be done with a trend analysis with data covering a period of many years. One of the criteria, which has been selected initially for validation of the sediment transport data, is the discrepancy ratio i.e. deviation of each measured point from the rating curve. A relative measure as discrepancy ratio should be used in combination with an absolute measure for the deviation of the observed value from the average trend.

Another validation method is to compare the measurements with measurements by other instruments or measurements done within the framework of other gauging strategies but taken at the same location and in the same period.

8.4.2 Results

The results of the validation of sediment transport data are discussed per main station: Bahadurabad, Hardinge Bridge and Baruria.

Bahadurabad

All the available suspended coarse sediment data from Bahadurabad gauging station for the period 1966-1993 are plotted against discharge in Figure 8.1. The discrepancy ratio for all the data of Bahadurabad station is presented in Figure 8.2. The maximum value of this ratio is 22 for low to moderate discharges and it falls below the range 4-5 for moderate to high discharges. Therefore, the data are relatively more scattered at low to moderate discharges than at moderate to high discharges. This trend does not hold for the absolute differences, which are rather constant. This scatterness in the 1966 to 1993 data set might be caused by physical phenomena and does not necessarily indicate erroneous data.

However, this scatterness reduces if the data are split in separate periods of a few consecutive years. The data for the period 1989-1991 are very scattered, partly because the accuracy of the measured discharges had fallen below the normal level during that period. Therefore, the data of this period were removed from the analysis.

Furthermore, the data shows a decreasing trend in sediment transport over the period 1966-1993. An explanation for this decreasing trend could be a change in measurement technique. A joint measurement of the BWDB and the RSP was carried out at Bahadurabad in July 1995. Between these two measurements, a good agreement in sediment transport of the silt and clay fraction (fine fraction) was found, but the sediment transport of the sand or coarse fraction differed significantly in channels with high flow velocities (exceeding 2 m/s). Under those conditions the BWDB measured significantly less sediment transport than the RSP did. Next a comparison was made with the routine gauging sediment samples from the RSP and the BWDB for the period 1994-1995. The result shows that during the monsoon the sediment transport measured by the BWDB was up to ten times less than the sediment transport

measured by the RSP. In the lean period, the BWDB measured the same sediment transport of sand fraction as the RSP. This confirmed the result of the joint sediment transport measurements. The most probable explanation for the underestimation of the sediment transport during the monsoon period is the large deflection angle of the Binckley silt sampler supporting cable in high flow velocities, if the survey vessel maintains position by dynamic positioning. Without a correction for this deflection angle the sample was taken in a higher position in the vertical than the required depth. During the joint measurement it was observed that the technique which was recommended by the survey team sent by the United Nations in 1966 for avoiding a large deflection angle, was not followed up (Special Report 19, RSP, June 1996). This means that the underestimation of sediment measurement could have been existing for a longer period. Another comparison was made between the BWDB data 1966-1970 and RSP data 1994-1995 and it shows no significant decreasing trend in sediment transport particularly at high discharges (Figure 8.3). In that figure the RSP data at low discharges concave downward maybe due to the natural scour hole present in the left channel at Bahadurabad. The conclusion is that the coarse sediment fraction was not measured sufficiently accurate during the high flow velocities and during a long period between 1974 and 1995. The measurements of the fine sediment fraction were not much affected by this change in field technique.

At Bahadurabad, the exponent to the flow velocity of the sediment rating curve is within the normal range 3-5. This indicates that the measuring site at Bahadurabad is good if no deep scour hole is present in the measuring transect.

Station	Sediment Rating Curve Data Period	Mean	Percentage of data in the range		Standard deviation	No of data
			0.50-1.50	0.10-1.90		
Bahadurabad	1966-1993	1.81	59	78	2.59	661
	1966-1970	1.01	87	98	0.34	126
	1976-1982	1.01	93	99	0.31	216
	1983-1988	0.98	99	100	0.20	178
	1993	0.78	100	100	0.26	35

Table 8.1: Some statistical parameters of coarse sediment transport data measured by BWDB in Bahadurabad

Hardinge Bridge

All the available coarse sediment transport data for Hardinge Bridge station are plotted in Figure 8.1. The trend in the data is slightly concave downward at low discharges. That graph shows that the scatterness of the data is constant for various discharges and also constant for sub-sets of data covering different periods 1966-1970, 1976-1982 and 1983-1988. This indicates that the scatterness of the data is homogenously distributed in time.

The scatter in sediment transport data is possibly due to the location of the Hardinge Bridge gauging station in an artificially constricted reach of the Ganges river. In general, a scour hole develops in a constricted reach. At low to moderate discharges such a scour hole functions as a sediment trap, and at high discharges the deposited sediment is washed away (Special Report 18, RSP, 1995). This phenomenon give rises to an increased variability in the sediment transport. The sediment transport curve at a constriction has its largest slope at low discharges and its smallest slope at the highest discharge, so that the curve is concave downward.

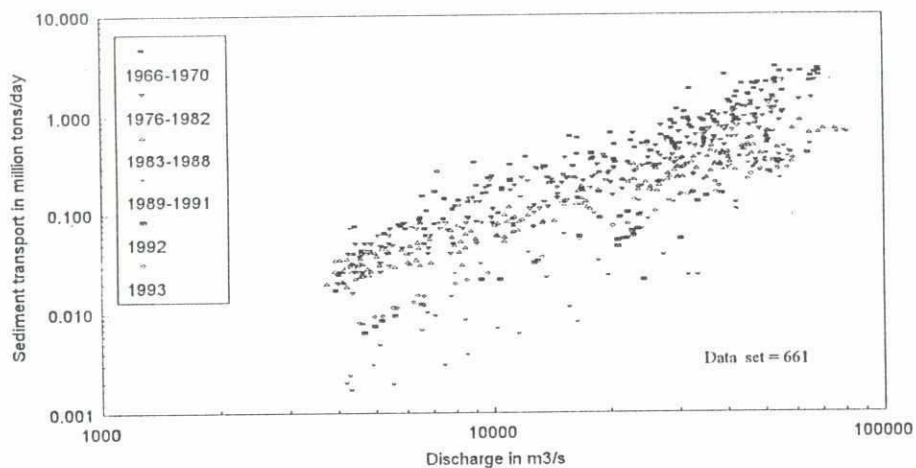
The conclusion is that these coarse sediment transport data are sufficiently accurate and internally consistent, but that in an analysis of these data this scour hole effect should be taken into account. In this sense the location of the measuring transect is not optimal.

Baruria

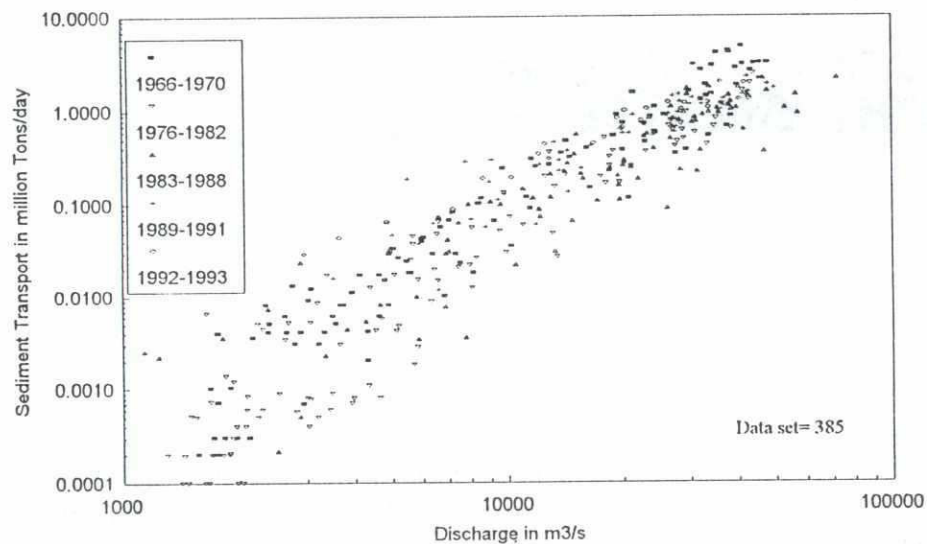
The available coarse sediment transport data for Baruria station are plotted in Figure 8.1. The data are very scattered and the trend in the data is concave downward at low discharges. This scatterness did not improve when the data were separated in different periods. In Figure 8.2, the discrepancy ratio is high up to 16 at low discharges. The Baruria gauging station is located downstream of the confluence of the Jamuna and the Ganges rivers. The 1-D model results (Special Report 18, RSP, 1995) show that at the confluence the sediment transport is highly variable, while further downstream, the variability reduces. That model calculated also a concave downward trend in the sediment rating curve. At the confluence of the Ganges and the Jamuna River one or two big scour holes are present most of the time. The same effect as described for Hardinge Bridge, occurs also in the sediment data of Baruria.

The 1-D model also shows that the reaches upstream of a confluence are continuously adjusting, fluctuating around an average bed level, and hence the system is in a dynamic equilibrium. At the rising stage, the riverbed is degrading at the confluence, whereas during falling stage it is aggrading. The late flood in the Ganges River causes a backwater effect in the Jamuna River. This effect causes some seasonal aggradation of the riverbed. It can be seen from the model that also downstream of the confluence, alternating aggradation and degradation of the riverbed occurs. These changes of bed levels in different branches near the confluence are the main reason of the variability in the coarse sediment transport data measured at the Baruria transect.

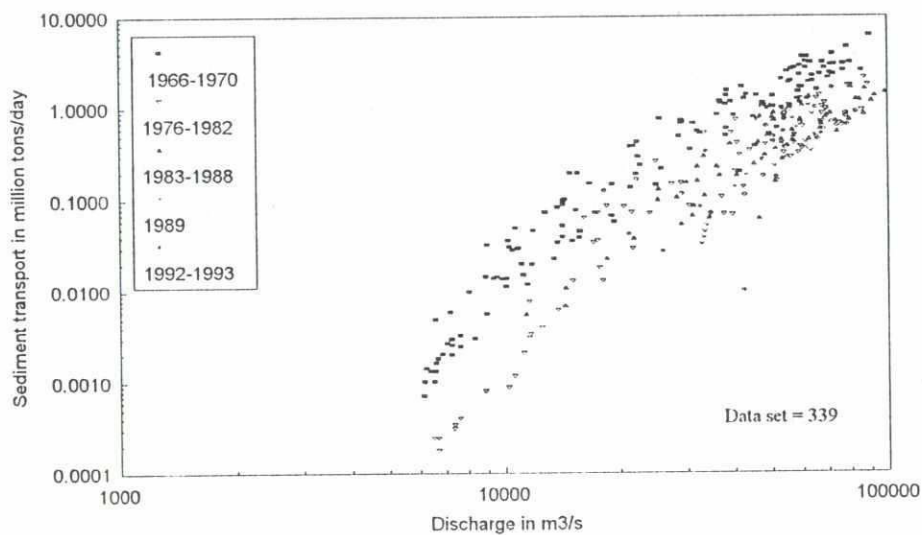
The conclusion is that these coarse sediment transport data are sufficiently accurate and internally consistent, but that in an analysis of these data scour hole effects as well as the seasonal aggradation and degradation of the riverbed should be taken into account. In this sense the location of the measuring transect is not optimal.



a) Jamuna River at Bahadurabad



b) Ganges River at Hardinge Bridge



c) Padma River at Baruria

Figure 8.1 Suspended coarse sediment data measured in Bahadurabad, Hardinge Bridge and Baruria

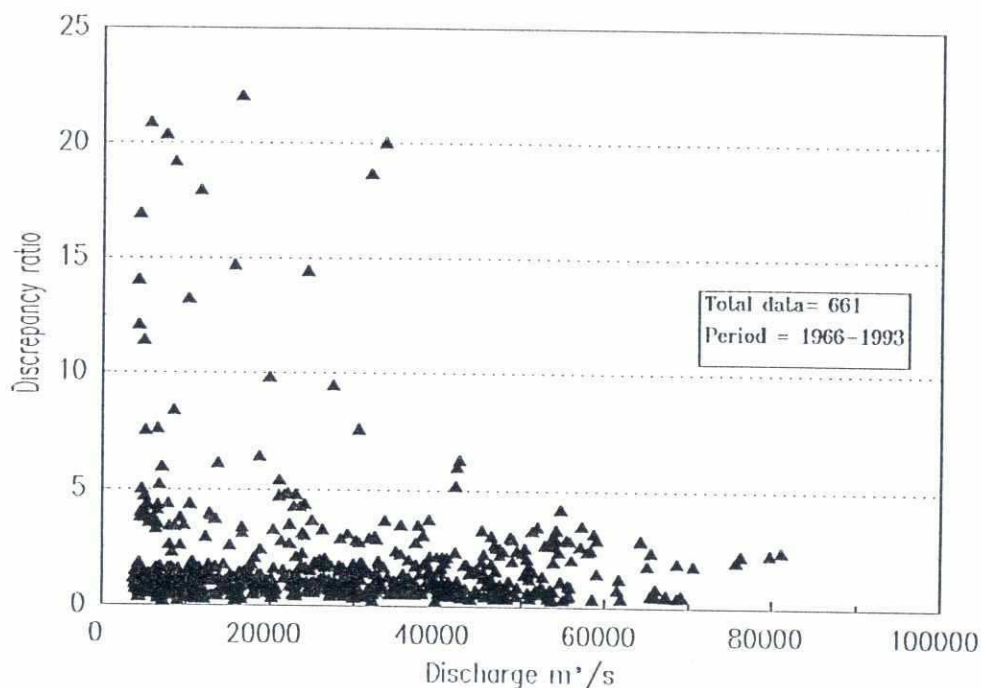


Figure 8.2 Discrepancy ratio of suspended coarse sediment data (Bahadurabad).

Bed material

Bed material samples were taken since 1965 from the main rivers. A simple method to validate the data is to check on coarse outliers and on the general trend in the data taken from different places along the river.

Some samples taken with the Van Veen sampler at locations with deep water and high flow are less reliable, because part of the fine fraction of the sample can have been washed out during hoisting of the sample. In general, other samples were found reliable, especially the samples taken by the USBM.

The bed-material samples are taken to determine the grain-size distribution of the bed material. The variability in the grain-size distributions of different samples is large if some samples with a high percentage of silt are included. It is recommended to separate the samples in samples with less than 40% silt and in samples with more than 40% silt.

In the past sometimes only a few samples of the riverbed were taken and analyzed. Because of the variability in the grain-size distributions of the samples it is recommended to take at least ten samples to determine a reliable average grain-size distribution.

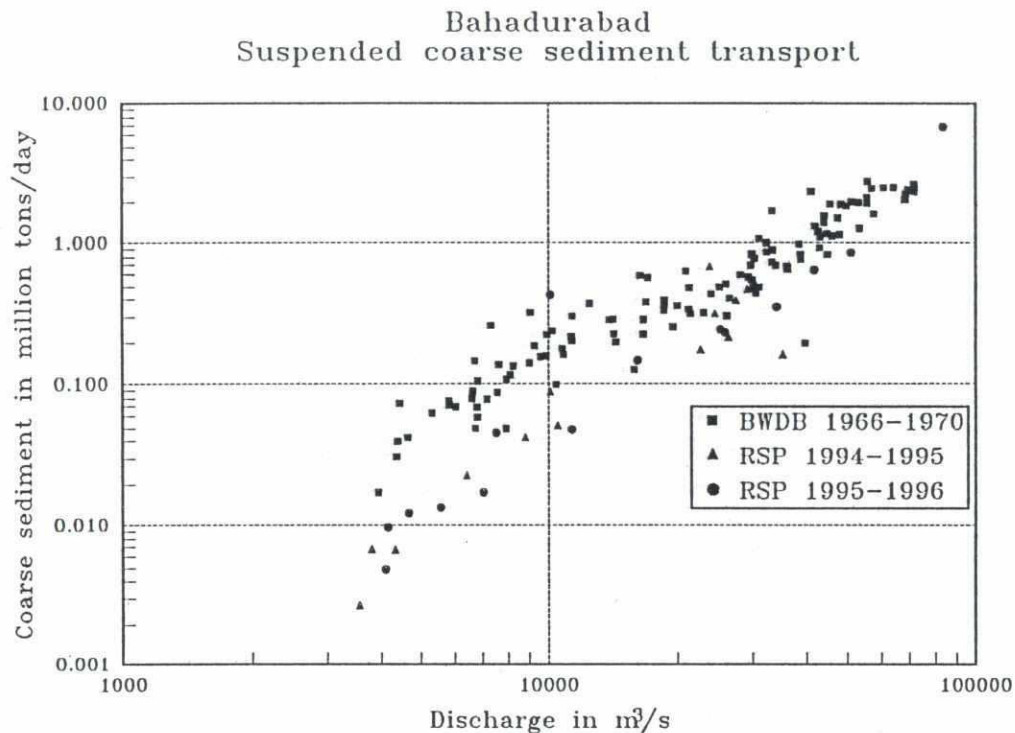


Figure 8.3 Comparison of BWDB and RSP sediment transport measurements in verticals of transects

8.5 Cross-sectional data (BWDB)

Since the sixties the BWDB had measured cross-sections in a large network covering the main rivers and also the smaller rivers with only a few interruptions. These data were used in many studies. Various users of these data had checked their quality often in a non-systematic way and by visual inspection of graphs with a strong distortion of the vertical scale. During the study of the Jamuna Bridge, after checking the history of the benchmarks of the cross-sections a selection of validated cross-sections were used for their study (Klaassen and Vermeer, 1988). A few years ago FAPI digitized all available BWDB cross-sections of the Jamuna River and stored this information in a database. They assessed the quality of those data (Halcrow, 1993) but could not improve the quality by removing inconsistencies in these data. In general, the previous users of the data tend to conclude that their accuracy is not sufficient for detailed engineering studies. At this moment still no database with accurate and validated cross-sections measured by BWDB is available.

The RSP attempted to estimate the inaccuracies in BWDB cross-sectional data by checking them against satellite images, against soundings from other organizations and by intercomparison of BWDB standard cross-sections surveyed in consecutive periods (see RSP, 1994, 1996a and 1996b). In 1995, the RSP participated in a joint cross-sectional survey with the BWDB Morphological Circle in the Jamuna River to get an impression of the applied methodology and, if necessary, to recommend on measures for improving the quality of these measurements (see RSP, 1996c).

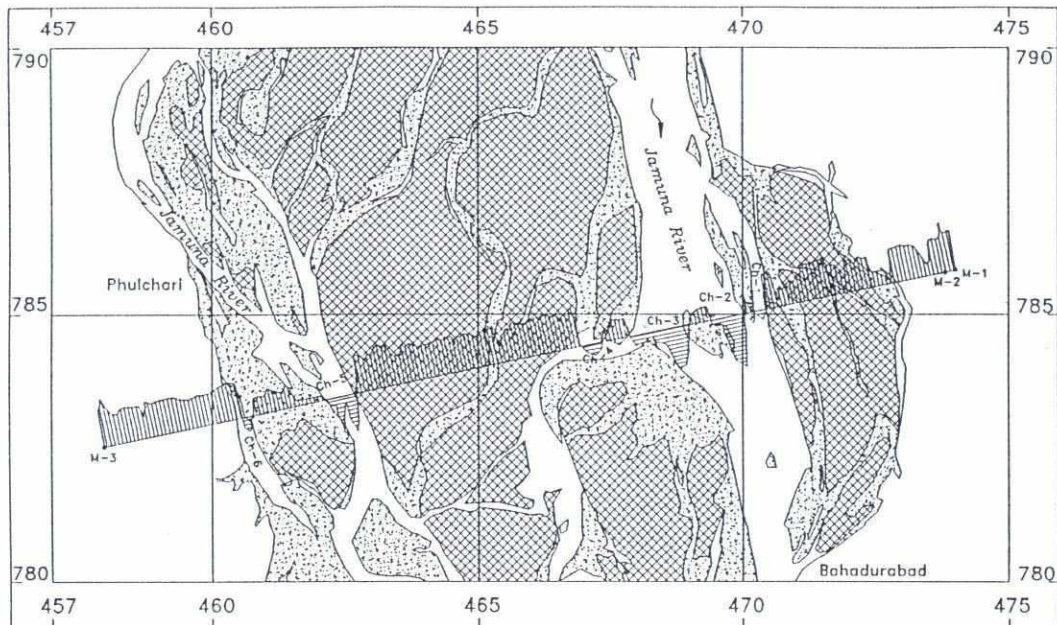


Figure 8.4 Location of the entire BWDB cross-section J#13_1 in the planform as seen on a SPOT image

Data validation methods

Two main aspects of validation methods for cross-sections are the positioning (alignment, bearing, start of the cross-section line) and the vertical levels of the cross-section.

Geographic location of cross-sections

Cross-sections have been compared with the planform of the river on satellite images. This comparison is a very powerful tool for validation of the positioning of cross-sections, see for example Figure 8.4 with cross-section J#13_1 projected on the planform as seen on a SPOT sheet. Preferably, images taken during the lean season and shot a short time before or after the cross-section survey, should be selected for this comparison. LANDSAT images are available without a geo-referenced coordinate system and, therefore, these are less suited for this purpose. The SPOT sheets show more details while also having a coordinate system.

The graph of the cross-section can be projected on the satellite image, if the horizontal scale of the cross-section graph is the same as the scale of the image sheet. The water level at the day the image was made can be drawn in the cross-section graph. The validation method consists of checking the water line in the cross-section with the land/water lines on the satellite image. This can be done visually by shifting and rotating the cross-section graph.

The validation of the geographic location of cross-sections will be a far less effort if a DGPS system is used for positioning.

Vertical levels

The benchmarks in the field should be checked to eliminate possible inaccuracies in the common reference plane, often PWD. In general, the RSP checked all the benchmarks for the water-level gauges, but this checking did not include specific benchmarks for the standard cross-sections.

The vertical levels can be checked by comparing the same cross-section measured in different years. If the geographic position of the cross-section was not changed then the height of the embankments or of a part of the flood plain has probably not changed either. The comparison of the floodplain level and the height of the embankments can indicate an erroneous shift in vertical direction. For this comparison a part of the adjacent floodplain should be measured; fortunately this is often the case, see example of a Jamuna River cross-section J#13_1 in Figure 8.5. Also a sudden constant shift of the level of a char indicates an error. In the example the floodplain has been measured probably along the same alignment in 1993 and 1994 and it might have been shifted in 1995. A common error is a spike, which means an error in a individual measurements. Spikes are also found by visual inspection of a graph.

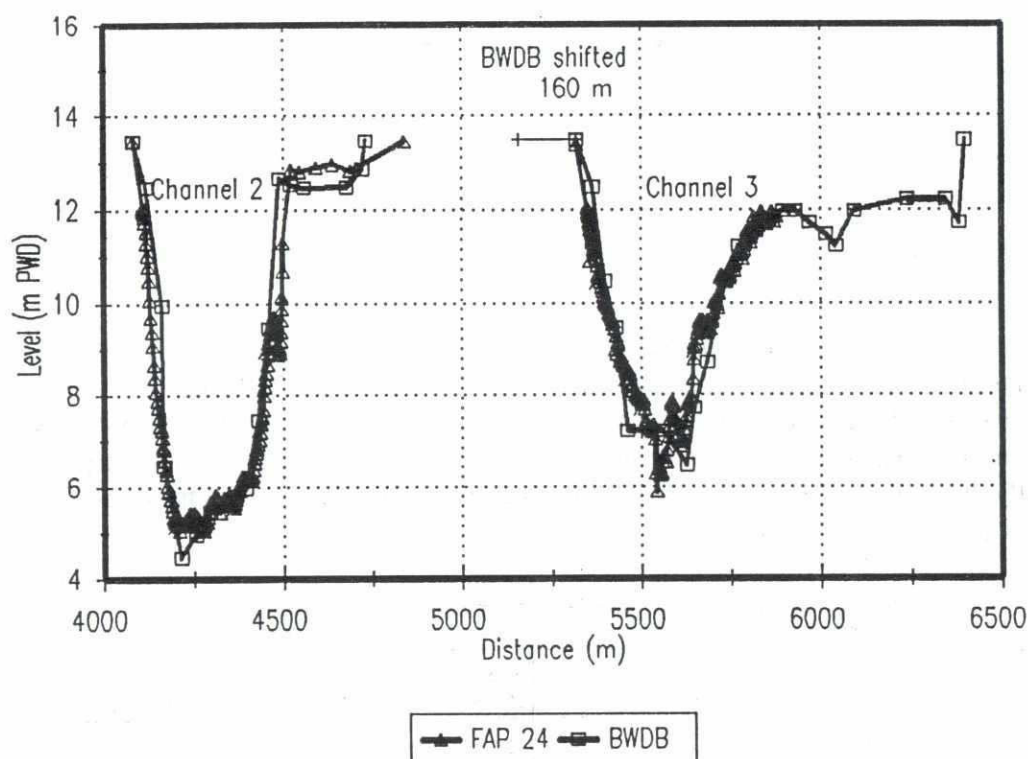


Figure 8.5 Comparison between the RSP survey and a part of a BWDB crossion survey in J#13_1

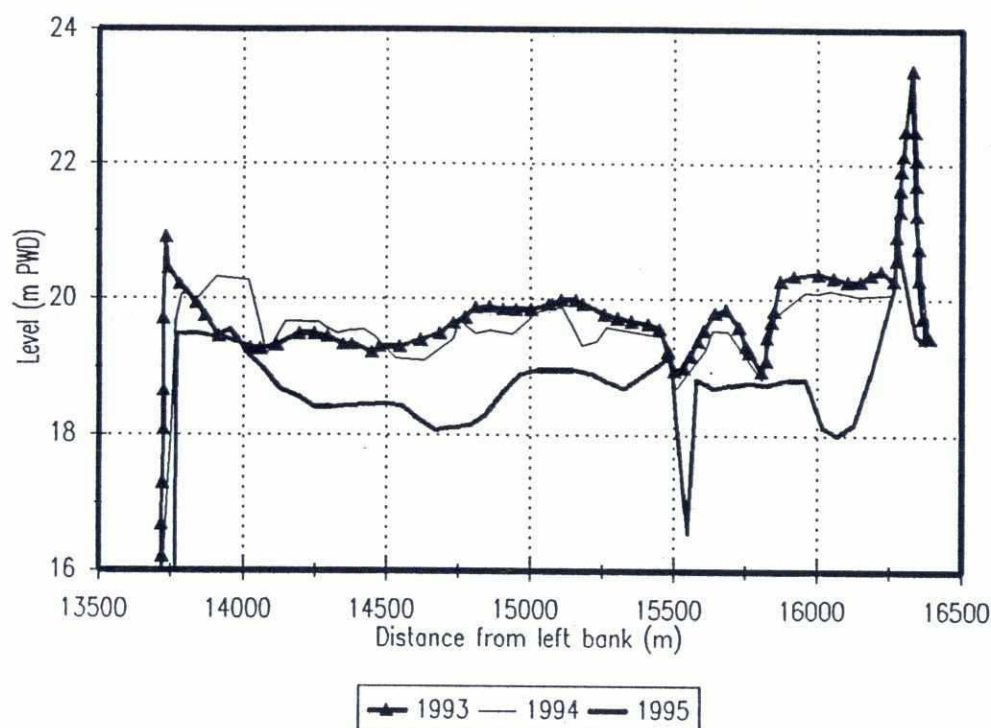


Figure 8.5a (For explanation, see text in previous page)

Results

The RSP checked the inconsistencies in a number of selected cross-sections of the Jamuna, Ganges and Padma rivers, see Special Report on 'Floodplain level and bankfull discharge of the Jamuna, Ganges, and Padma Rivers'. The results of an earlier validation of some cross-sections in the Jamuna river downstream of Sirajganj were presented in RSP, Study Report 3. Finally, this validation of the Jamuna river cross-sections was extended by EGIS project using GIS techniques.

River	Number of standard cross-sections	not available	not consistent	vertically consistent	total
Jamuna	16	183 (39%)	104 (22%)	177 (38%)	464 (100%)
Ganges	14	174 (43%)	25 (6%)	207 (51%)	406 (100%)
Padma	11	100 (31%)	34 (11%)	185 (58%)	319 (100%)

Table 8.2 Some results of the validation of cross-section measurements by BWDB.

The overall conclusion of these validation exercises was that the consistency of the cross-sections of the Ganges river is comparatively better than the consistency of the cross-sections in the Padma and the Jamuna rivers. In the Jamuna river the cross-sections are longer than in the other rivers, the number of channels in a cross-section is higher. Furthermore, the morphological changes in the Jamuna River are faster than in other rivers. Rapid migration of

the river banks has washed away monuments or pillars of several cross-section in the last decades. It seems likely that these circumstances are responsible for a reduced accuracy of these cross-section surveys.

These exercises have also shown that after detection of an inconsistency in a cross-section it is often uncertain how to remove an inconsistency (except spikes). This makes correction of cross-section data cumbersome and often impossible.

In recent years an UNDP aided project has been proceeding in improving the survey techniques and modernisation of survey equipments of the BWDB Morphological Circle. It can be expected that in the near future the quality of BWDB cross-section survey will be improved. From experiences in the BWDB cross-section validation of the main rivers, and from the experiences in the joint measurement, a few recommendations can be made:

- The validation of the cross-sections should include an assessment of the accuracy of the data, because the required accuracy is not constant, but depends on the purposes of the study.
- All cross-sections, especially the monuments of the cross-sections, should be defined by geographic coordinates or by any other projection. The height of the monuments/pillars should be reconnected to the newly established network of bench marks. Both the new and old values should be published for the user of BWDB cross-sections.
- Introduction of an adequate data validation system using GIS in BWDB could improve the quality of the survey data.

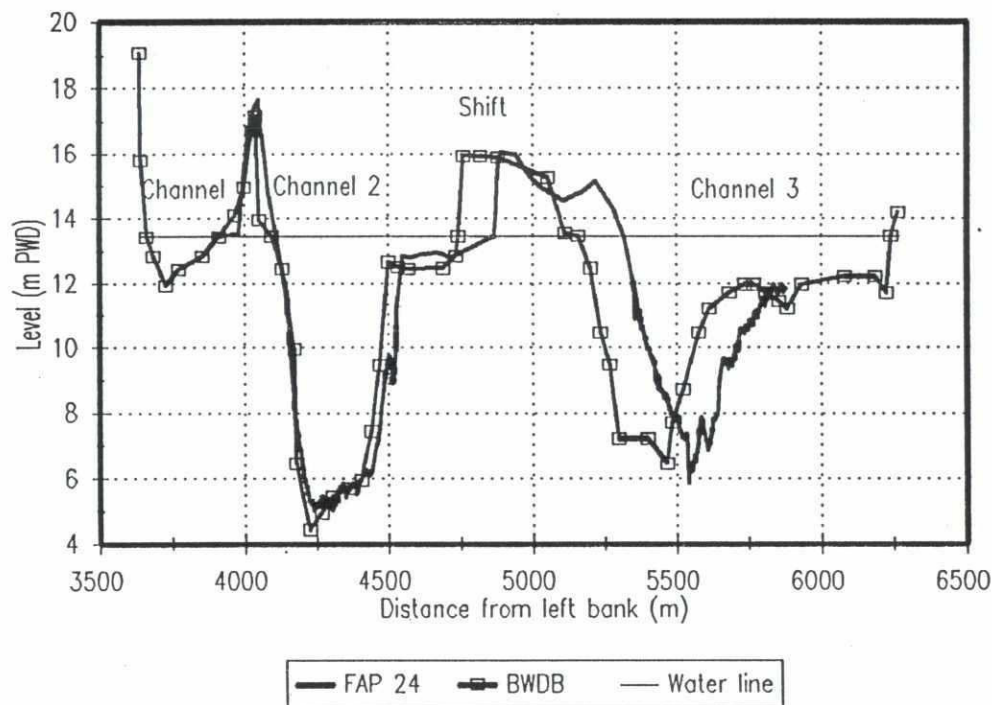


Figure 8.6 Example of shift in the landsurvey over a char, joint measurement BWDB and RSP

8.6 Bathymetric maps

Bathymetric maps of selected reaches of the main rivers were prepared by the BIWTA and also by RSP. The main purpose of the bathymetric surveys done by BIWTA is to monitor the least available depth in inland navigation routes. The RSP bathymetric surveys cover certain stretches of a river which are aimed at the study of morphological processes and planform studies. The quality of these surveys depends on the quality demands for the purposes it is prepared. The BIWTA bathymetric surveys are for monitoring navigational routes but they can also be used in the study of morphological processes of a river (Klaassen et al 1988; Klaassen and Vermeer, 1988b, Haskoning et al, 1990 etc.).

8.6.1 Data validation methods

The validation of the planform of the bathymetric map can be done by checking some known distances between special features in the map. A more thorough method is to project the bathymetric map onto a satellite image of the same area, and shot nearly at the same time as the time of survey. If the water levels are the same, then the pattern of bank lines should be the same in the bathymetric map and in the satellite image. Differences can occur because of a different projection. This type of differences are often easily recognizable in maps of a sufficiently large area.

At this moment no thorough methods are available for the validation of the measured depths and the reduction to a common datum. An easy method is to check for internal consistency of the data in a bathymetric map: outliers can be detected visually and be removed. If a standard cross-section measured by BWDB is located in the area of the bathymetric survey then that cross-section can be compared with a cross-section along the same transect line and derived from the bathymetric map.

8.6.2 Results

The RSP compared only six cross-sections picked up from BIWTA bathymetric charts surveyed in 1990 in the Jamuna River downstream of Sirajganj, with the BWDB cross-sections (see RSP, Study Report 3, 1994). These BIWTA cross-sections were plotted together with the BWDB cross-sections in the same plot, for an accurate comparison. The BIWTA surveys were done in January 1990 and the comparison with the BWDB surveys of April and May 1990 showed considerable differences, mainly because of the morphological changes in the river. For validation and checking of the bathymetric surveys it is recommended to make such comparisons with the BWDB cross-sections if both surveys were done in the lean season and the time lapse between the surveys is less than two months.

The RSP projected the BIWTA bathymetric chart surveyed in January 1990 onto the SPOT image of 16 March 1990 of the Jamuna River downstream of Sirajganj, see RSP, Study Report 3 1994. It was observed that BIWTA surveys are rather accurate and consistent with the SPOT images if the coordinates are shifted over a small distance because of the different projections used by SPOT and BIWTA, see for example Figure 8.9.

The BIWTA bathymetric survey plots are presented with respect to average lowest low water level (ALLW), which is determined by averaging of 3 to 5 years records from the adjacent water level gauges of BIWTA and BWDB. As mentioned for the case of BWDB cross-sections,

the errors related to the bench marks and water-level gauges is also applicable to the BIWTA bathymetric surveys. The accuracy of the Decca Chain system used in BIWTA survey is on average about ± 30 m, but it may increase up to ± 100 m depending on the location of the river (and the angles between the connecting lines of the beacons). The depth is measured by echo sounder. The interspacing between two survey lines varies from 50 to 500 m and the spacing of the charted depth varies from 25 to 250 m along a survey line depending on the scale of the survey. Hence a BIWTA survey map presents smooth contour lines. The BIWTA is mainly interested in areas with shallow depths, i.e. in the case of bed forms the water depth at the crest of a bedform is considered for plotting in the chart only (Figure 8.8). Therefore, the BIWTA bathymetric charts results always show shallower depth than the actual river depths, the magnitude depending on the presence of bed forms and their heights.

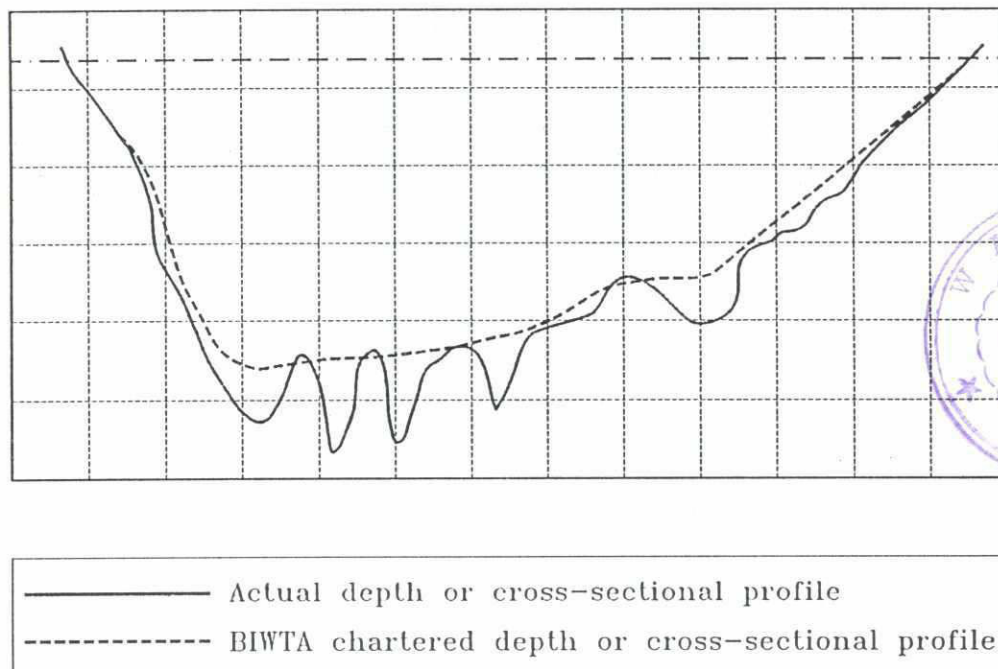


Figure 8.7 BIWTA-charted depth in comparison to actual depth

The accuracy of the DGPS positioning system used in RSP bathymetric survey is about ± 5 m. For vertical controls, the bench marks and zero value of the water-level gauges used were reconnected from the recently established geodetic bench marks network for some locations where available, otherwise old SoB bench marks were used for reconnection. The interspacing of survey lines vary from 100 to 200 m depending on the location of the survey and the spacing along each survey line is about 2 to 5 m only. The resolution of an echo sounder is about 0.02 m, but the nature of the riverbed (hard, soft, moving or not) may affect the result and enhance the uncertainty of the result. This, however, is more a physical uncertainty as regards the position of the bed than an uncertainty related to the instrument. The bank lines in the bathymetric maps of lean season surveys follow the bank lines on SPOT images sufficiently accurate for morphological studies.

The accuracy of the riverbed relative to the PWD reference plane varies from a few centimetres to a few decimeters because of the variation of local water-level slope. The magnitude of this variation depends on the distance of the survey area to the water-level gauge considered and the difference between the local water-level slope and the estimated slope.

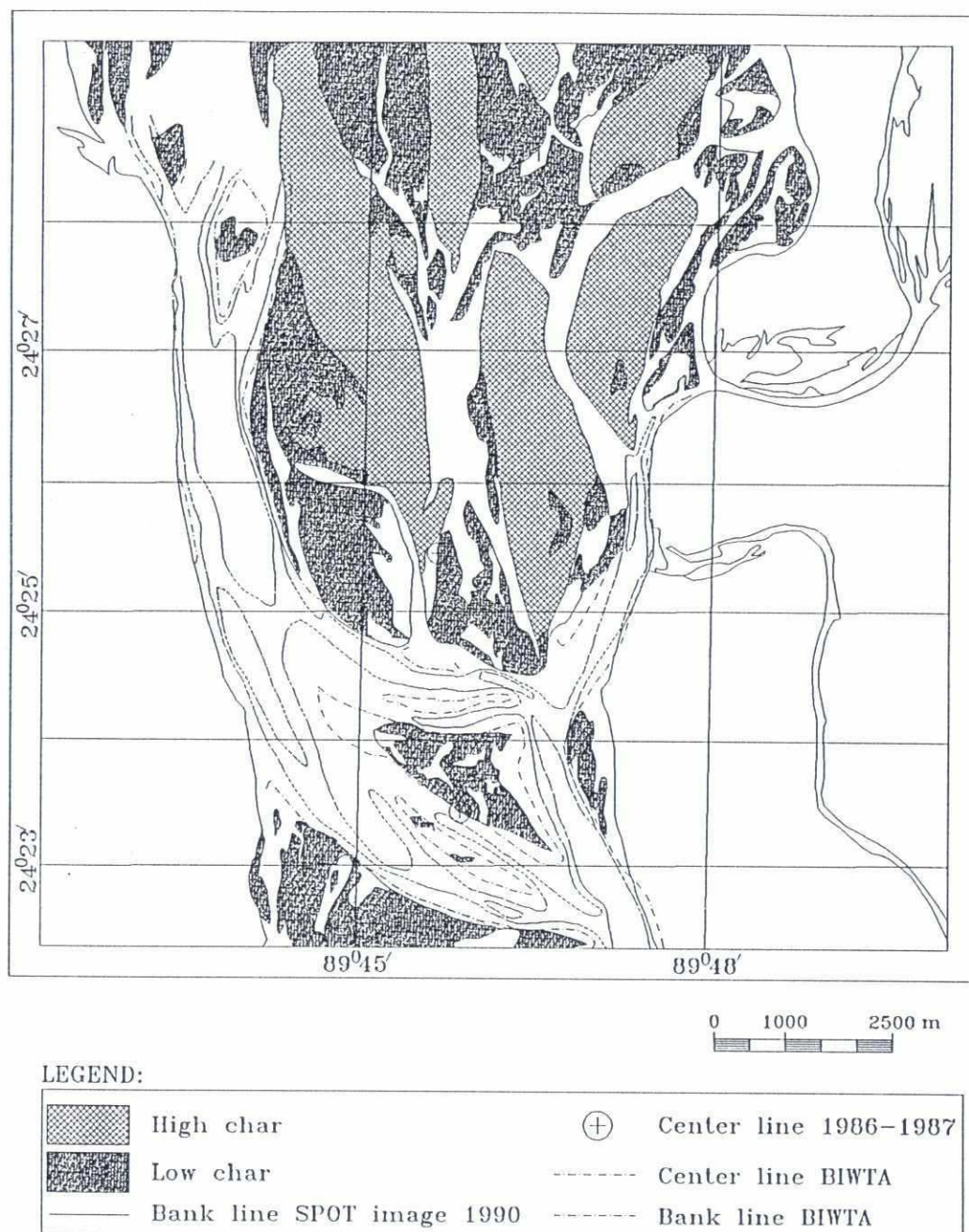


Figure 8.8 BIWTA bathymetric chart (1990) and SPOT images (1990)

9 Transfer of data bases and training

9.1 Transfer of data bases

The RSP has collected a vast volume of river related data at substantial cost. Consequently, the adequate transfer of raw and processed data to the Government of Bangladesh was essential in view of safeguarding the investment under the project. Processed data as stored in the PSD24 and HYMOS data bases contain only a fraction of all data collected under the project, but are of direct interest to engineers and others. These data bases were handed over to several government agencies on CD-ROM, including WARPO, SWH-II of BWDB, BIWTA and SWMC. Data files related to the bathymetric surveys were handed over on CD-ROM to SWMC and BIWTA.

The full data sets may in the future be of interest for detailed river studies by specialist studies which may require re-processing of the original data collected under the project. Therefore, the Client decided to store all the original data sets with the SWMC, likely the only government body equipped and in a position to store, handle and process the vast amount of original data. Therefore, the following information and data were handed over to SWMC (digital information on CD-ROM):

- Two sets of tapes with raw field data, some 27 Gb of information
- original field sheets and survey reports
- field records of staff gauge readings
- hard copies of results of sediment analyses
- all intermediate and final data files of the processing of routine gaugings, special surveys and bathymetric surveys, about 12 Gb of information
- PSD24 data files and related script and other files, about 500 Mb
- the HYMOS data base, including all validated water level data collected under the project and about 30 years of hydrological data collected from BWDB and other sources for the hydrological studies
- the sediment data base with all details of the sediment analyses
- validated water level data
- all software used for data processing in RSP, from data screening through various calculations to PSD24 related software

9.2 Training

Training is according to the ToR one of the objectives of RSP. On the one hand the ToR considered strengthening of particularly BWDB through training of its professional staff important. On the other hand no formal budget for training was provided, and any training programme should not hamper the survey activities. Moreover, BWDB was not appointed as counterpart organization to the project, and was therefore not formally involved in the project. This particular institutional setting of the project in conjunction with paucity of funds for training caused the training component difficult to implement properly. Consequently, training consisted in Phase 1 mainly of on-the-job training and in-house courses on river engineering, while a comprehensive training programme was developed for Phase 2. Though revised time and again during 1994 this programme never materialized for several reasons, one being the

lack of funds and late availability of appropriate trainees. Therefore, also during Phase-II only limited (mainly) on-the-job training could be performed.

In summary training activities carried out during the project included inter alia:

- training of vessel crew in ship handling, including the use of the computerized auto pilot and communication systems
- extensive training of national surveyors in all advanced survey techniques and equipments introduced by RSP, including also the DGPS positioning system, bathymetric surveys and modern equipment for land surveys
- joint flow and sediment transport measurements with SWH-I of BWDB and with the Morphology Directorate of BWDB
- installation, operation and maintenance of AWLR stations
- in-house training in data processing and general purpose software
- in-house refresher courses on subjects as hydrology, sediment transport and river morphology; staff from other organizations were invited to participate
- a short training programme for BWDB staff, at the Bhagyalakul training centre
- invited lectures at BUET University, Dhaka
- participation for about one year of a BWDB Exec. Eng. in several RSP project activities
- training of the local monitoring expert of FAP21/22
- training of some BWDB surveyors on-board of the RSP survey vessels
- training of one BWDB staff (SWH-II) in data processing as applied under RSP
- Training of seven staff members of WARPO, BWDB, SWMC and BIWTA on topics relevant for the transfer of RSP data bases to these organizations, including principles of measurement procedures and instruments, principles of the PSD24 data base and related data processing and practical exercises demonstrating the potential use of the data contained in the PSD24
- training of SWMC in two-dimensional hydrodynamic and morphological modelling.
- training of SWMC staff in all aspects of RSP data processing, as part of the transfer of all RSP data and information to SWMC.

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Part C

**Recommendations
for further action**

10 Data collection on main rivers using sustainable techniques

10.1 Introduction

A survey technique is a combination of a set of tools and a procedure for their application for a given purpose. Hereby, a survey technique is one element of a survey technology which, in addition to the technique, comprises the knowledge required for its intended application, both theoretical skills and practical experience, and also the organizational framework.

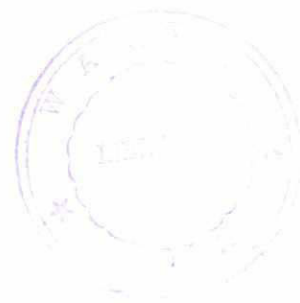
For the present purpose, a sustainable technique can be characterized by (1) being suited for a given purpose, and (2) being suited for implementation and consolidation in a given context. An optimal technique can be defined as the best choice among available options, considering a number of quality criteria. These criteria can be purely technical, but can also include general operational aspects, capability requirements and costs.

A sustainable technique may not necessarily be optimal, for example, if the context for its consolidation is in conflict with wider optimization criteria. However, an optimal technique is sustainable only if it is suited for implementation and consolidation, and not otherwise. Several sustainable techniques can be conceived as true alternatives, or depending on the time horizon for implementation and consolidation. Also, there can exist critical constraints other than the purely technical ones, such as capacity requirements, or the compatibility with established skills and practices. Whenever pursuing an optimal solution, it must be kept in mind that 'the best can be the enemy of the good'.

10.2 Objectives

The objective of a dedicated river survey is well known, because such surveys are carried out for a specific purpose. The objectives of a routine gauging programme are wider and less clear, because they cover a broad range of known and unknown applications and data users.

Without some assumptions about the objective, however, a survey technique (or a survey programme) cannot be optimized, because the objective is the reference against which alternatives can be compared. A summary of objectives, in general terms, is given in Table 10.1, which considers routine gauging in Bangladesh. The general objectives can be broken down into more detailed and more operational objectives, outlining targets for different quality aspects, such as accuracy, data coverage, etc., which in turn can serve as a basis for selection of survey techniques. One example of a basic quality criterion is that the accuracy of the value to be measured is acceptable as compared with the intended use of the data.



Hydrology:	• Overall water balance for general water resources planning and management • Flood monitoring and flood forecasting • Lean season water balance (irrigation demand and supply) • Basis for water quality monitoring (related to household water supply, irrigation, industrial supply) • Operation of regulators and dams • Hydraulic design basis for bank protection, regulation, and planning and management of physical infrastructural facilities (ferry ghats, bridges, embankments, etc.) • General land use planning and management (land erosion and accretion)
Sediment transport and morphology:	• Navigational depths of waterways • Morphological design basis for bank protection, regulation, and planning and management of physical infrastructural facilities (ferry ghats, bridges, embankments, etc.)

Table 10.1: Objectives of routine gauging

The objectives of a routine gauging programme can vary with time, and important future objectives can well be obscure at present. As one example, the important flood forecasting presently undertaken by BWDB's Flood Forecasting and Warning Centre requires real-time water-level and rainfall data, a need which was hitherto not foreseen. While the measurements as such were also suited for this new purpose, an adaption of the data flow was required. Another example of a new objective of an existing routine gauging programme is the enhanced need of water quality monitoring, which is induced by the increasing utilisation of the lean season water resource.

The objectives can be compatible, complementary, or even in conflict with each other, and can indicate widely different techniques. For example, monitoring of lean season water resources and water quality can necessitate tidal surveys in downstream reaches, but may, on the other hand, require less heavy gear as compared with flood season streamflow gauging.

10.2.1 Context

The sustainability of a survey technique relates to a specific context, which comprises two categories of aspects (J.J.Peters, personal communication):

- the physical environment; and
- all other aspects, such as infrastructure, institutional capacity and capability, relative costs (of equipment, fuel, skilled labour, unskilled labour, etc.), and the global level of technological development.

For practical purposes, the former category can be taken as a given, while all other aspects will inevitably vary in time, gradually or stepwise. A technological achievement (such as for example the GPS satellite positioning system) can render a previous technique (Decca positioning) obsolete within a period of a few years, if the new option is accessible, better and cheaper at the same time. Similarly, a financial constraint can be removed instantaneously

by some budget re-allocation within a government system, or temporarily by a foreign development grant. Infrastructural constraints and relative costs are also bound to change. Therefore, what is sustainable today may not be sustainable in the future.

If the characteristics of the river system be considered as the primary basis for a selection of survey techniques, another part of the same basis is the range of techniques that are available. In this respect, the RSP has gained a particular experience, in accordance with one of its objectives, namely *'introducing improved or new technology where appropriate'* (TOR Section 3.1). The third part of the basis is the set of implicit or explicit constraints that relate to the preservation of existing techniques, as well as to the possible implementation of new ones. These constraints will not be discussed in depth in the present report, because the specific experience of RSP in this regard does not relate to a sustainable permanent routine gauging programme. The rationale is illustrated in Figure 10.1.

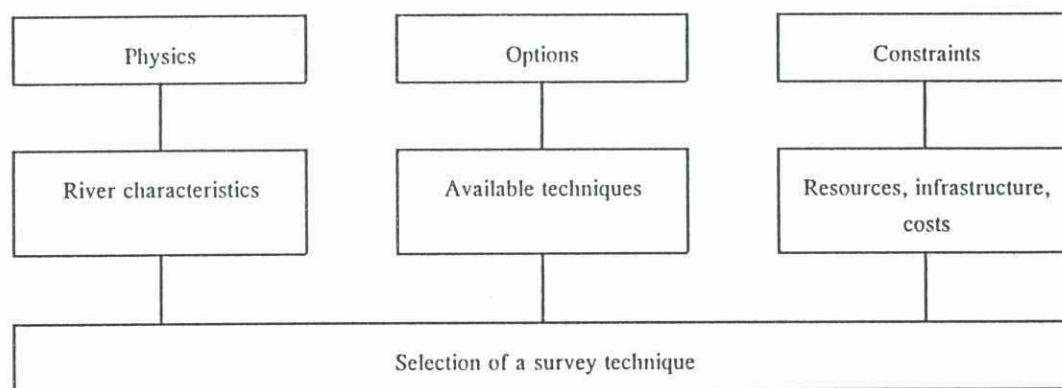


Figure 10.1: Basis for selection of a survey technique

10.3 Routine measurements and special surveys

10.3.1 Survey operation in general

Survey operation in large alluvial rivers is affected by the physical environment, and to do measurements in an appropriate way in the dry season imposes requirements that deviate from the ones in the flood season. The related data quality implication is that procedures must either adapt to the flow regime, or, if fully standardised, must be selected as some sort of a compromise between partly deviating aims.

For example, a sediment sampler that is otherwise a good choice may be less suited under extreme current-velocities. Another example is relative positioning by ADCP bottom tracking, which normally provides a good accuracy, but which is not possible in case of a strong current over a fine sandy riverbed. This shortcoming should not prevent the use of bottom tracking whenever possible, but necessitates the availability of an alternative (DGPS positioning) when not.

Techniques and routines can be changed for several other good reasons, one trivial example being that some equipment is worn down and needs to be replaced. Sometimes, a new technique becomes available in the course of the general technological development, such as RTK-DGPS positioning, which can provide vertical control at the same time (and for the

same cost) as the horizontal control provided by the DGPS positioning, or an improved knowledge about the performance of sediment concentration registration by the ADCP backscatter technique.

Whenever changing a technique, the consistency and the transparency of the field work methodology should be observed as separate, important data quality characteristics. Shifting between different survey techniques can improve the data quality, but there is always a consistency cost involved. Not only the techniques, but also the rules for the choice between them should be defined and described, and the origin of the produced data should be communicated to the data user.

Logistical aspects of survey operation comprise access to the station, staff transport and accommodation, handling of samples, data transmission, supply of fuel and other consumables, and communication. Such aspects are highly cost-related, and could in theory be fully countered, if abundant resources were available; for example by using helicopter transport between stations, or simply by the availability of ample staff and survey facilities. In practice, however, logistical constraints can be decisive to the data quality, for example if they interfere with a desired time and space coverage of the survey programme.

10.3.2 Routine gauging

A summary of objectives of general routine gauging of rivers in Bangladesh was given in Table 10.1 above. The related quality characteristics are as follows:

- Data accuracy and validity to comply with implicit or explicit standards, and avoiding significant or unnecessary systematic deviations;
- consistency, inter-programme and long-term;
- time and space coverage being adequate for a reasonable description of main processes and developments within the river system;
- transparency of the entire data production, comprising aspects such as traceable zero levels and positions, field routines, and data validation and processing; and
- a timely dissemination of results.

These quality aspects deviate from the aims of special surveys or other short-term surveys with specific purposes, and they also deviate partly from the quality goals of the RSP. The long-term consistency is an important consideration in connection with BWDB's monitoring, where the criterion plays a visible role, for example when maintaining gauging stations or standard cross-sections at locations that would not have been selected today, but which are retained for the good purpose of producing long, uninterrupted data series. The decision on whether and when to shift a station or a procedure is more difficult within a general monitoring programme, where possible benefits with respect to accuracy and validity are obtained at the cost of a reduced consistency.

The transparency criterion indicates a demand of standardisation wherever applicable, documentation of gauging routines and data processing procedures, and a reporting to the data users of any shifts of gauging stations, techniques, instruments, or data processing procedures.

10.3.3 Special surveys

As compared with a routine gauging programme, a special survey is characterised by a finite duration, a much more confined scope, and a better knowledge about the purpose, the data users, and the quality requirements. At least from this point of view, it is much easier to select a suitable approach for a special survey than it is the case for a routine gauging programme.

A special survey will often aim at describing a specific state or a specific process within the river system, rather than a general monitoring of selected system indicators. The quality requirements of a special survey depend on the context, but will appear as a sub-set of the routine gauging requirements listed above. Sometimes, the consistency and transparency considerations are less critical for special surveys, whereas the accuracy requirements can be more strict. Therefore, techniques and routines can and must be selected and shifted more freely.

Such diversification with respect to survey techniques requires in itself technological capabilities and survey capacities that deviate from the requirements of routine gauging, for example with respect to outlook.

10.4 Routine measuring network and frequency

10.4.1 Measuring network

The design of the measuring network should in principle address (1) the river system itself, and (2) the objectives of the gauging programme. The former is "given", and is "known", whereas the latter can vary in time and is only partly known (in the case of long term general gauging programmes). Therefore, it makes sense to address the former part of the decision-basis, while considering the objectives in less specific, but still reasonably operational terms: Description of the time and space variation in the river system of the water level, flow, sediment transport, and morphology.

Different requirements are imposed by different categories of data applications. An adequate coverage of the flood season stage and discharge is necessary for purposes related to floods, hydraulic design, and hydraulic and morphological impact studies. Applications within water resources planning, and environmental monitoring and impact assessment, are more dependent on lean season flow data. Stations that are suitably located for gauging of high stages and high flow are not necessarily ideal for lean season gauging, and vice versa.

A basic quality of a routine gauging network is to accommodate a broad range of national data requirements. Therefore, for any conceivable resource allocation, the network will inherently appear as a compromise between the conflicting aims of coverage and density.

This is one reason why different, coordinated networks are usually applied for different gauging activities, such as staff gauges, AWLRs, flow gauging, sediment transport gauging, waterways monitoring, morphological monitoring, and environmental monitoring. The general quality of the entire gauging programme can be observed by combining the different gauging programmes in such a way that they support each other. As an example, a combined network

can comprise a large number of staff gauges, a few AWLRs, a fair number of standard cross-sections for flow and sediment transport gauging, and an even coarser network of cross-sections for morphological monitoring.

Another network design aspect is whether the monitoring programme appears as a predominantly empirical (field data oriented) approach, or a predominantly deterministic (process description oriented) approach. This is not only a matter of taste and tradition, but depends highly on both the river system itself and on the use of the data. A simple system, where processes are well understood and well described, will tend to favour a deterministic monitoring programme, which could be based on a few stations with a large spacing. A complex system, where different processes interact, will enhance the data demand, so that a higher network density is required for a similar level of knowledge. From the point of view of the use of the data, planning and design applications can well be accommodated by a fully empirical data basis, while impact assessment, flood forecasting, and any other applications that involve real-time operation or prediction will indicate a process-oriented description.

In connection with a deterministic description of a river system, it is noted that if lateral inflows and outflows between (flow gauging) transects are higher than the uncertainty of the flow recording at the gauging transect, the system is empirically underspecified (with respect to flow measurements); otherwise, the system is overspecified. Overspecification increases the general data quality and provides a means for identification (and, possibly, correction) of inconsistencies. The costs, however, will increase.

10.4.2 Measuring frequency

Similarly, the measuring frequency must be considered with a combined background of the dynamics of the river system and the intended use of the data produced. In addition to natural seasonal and short-term variations, the frequency can be selected with a view to possible regulation within the river system. An adequate quality is often related to:

- the resolution of the general time variation (e.g. for calculation of monthly discharge volumes); and
- an appropriate description of extreme stages and peak flows (e. g. for design purposes, and also in general in order to reduce the need of extrapolating the observations made).

This, in turn, requires an appropriate overall resource allocation between the different components of the gauging programme.

The time resolution of the gauging programme as such is jointly determined by the gauging frequencies of the different components, such as staff gauge readings (maybe several times per day) and flow and sediment transport gauging (maybe with an interval of 1-2 weeks).

The peak flow gauging is critical with respect to time resolution. This is because the predominant peak flow processes partly differ qualitatively from the ones prevailing during low and medium flow. The peak flow regime can involve overbank flow, different routing of the discharge, backwater effects, and an active interaction between hydrodynamic and morphological processes causing abrupt stage shifts. Therefore, statistical extrapolation or deterministic prediction are often unreliable and always unproven if based on low and medium flow data.

Also, the time scale of flow and stage variation will be smaller during high flows, which will affect the data accuracy even if medium and high flow conditions are consistent.

An adequate quality requires a small time increment of the flood season routine gauging, or possibly even a targeted programme that adjusts to the actual flow conditions. In Bangladesh, the basis for such targeting could be the real-time monitoring of water levels which is undertaken by BWDB/FFWC in the flood season.

Tidal effects and salinity effects, occurring in the lean season, are other examples that the relative significance of the processes can deviate from one season to another.

For a more thorough discussion of measuring networks and frequencies, please refer to *RSP Final Report Annex 2: 'Sustainable survey techniques'*.

10.5 Recommended measuring methods and instruments

10.5.1 General

The quality of a river survey technique is basically related to the quality of the produced data, since data production is the only reason for executing the survey. The data quality may be divided into:

- Accuracy;
- validity; and
- consistency.

The criteria are related, because the consistency, in a wider sense, reflects the time variation of validity and accuracy deficiencies. For long-term gauging programmes, the data consistency is a particularly important quality characteristic, because the long-term consistency is seldom self-evident for long-term programmes, but is a prerequisite for inter-comparison of long time series. An example of a risk of a consistency deficiency would be if a mechanical instrument was replaced by an electronic one, or if a standard cross-section was relocated.

Each of the listed quality characteristics are, to a varying extent, determined by the following determinants:

- Instrument performance; and
- Procedures (survey and data processing).

This can be illustrated by a matrix, as shown in Figure 10.2.

	Accuracy	Validity	Consistency
Instruments	(error contribution)	(error contribution)	(error contribution)
Procedures	(error contribution)	(error contribution)	(error contribution)

Figure 10.2: Quality determinants of survey data

The instrument performance comprises:

- Accuracy;
- range;
- resolution (time, space, the value itself);
- data collection capacity; and
- other aspects, such as operation and maintenance, risk of breakdown or malfunctioning, costs, etc.

From another point of view, the consistency criterion can be extended by an aim of 'inter-programme compatibility', which can be looked upon as a separate quality aspect. This criterion reflects that instruments and procedures should, as far as possible,

- be standardised within the programme;
- be harmonised (with respect to accuracy, data coverage, resolution, etc.); and
- be retained in the course of time, unless a change is evidently preferable, and, if so, appropriate consideration should be given to consequences of the change.

As one example, a high-capacity current-velocity instrument (like an ADCP) should be applied together with a positioning system with an equally high capacity (like a dynamic DGPS system). The criterion is already inherently covered by the quality aspects mentioned above, but may be emphasised separately, because of its particular significance in connection with long-term routine gauging.

10.5.2 Positioning

The systems in use in Bangladesh for horizontal control of moving platforms (location of vessels) are the Decca navigation system and triangulation by sextant or theodolite (subsection 3.2.2). As the Decca system is becoming obsolete and new systems are considered but not yet operational (1996) the main system for the Bangladesh organisations is the triangulation system. Sometimes temporary positioning systems are used in Bangladesh by projects such as the Jamuna Bridge project, the Meghna Estuary Studies and the RSP. They all use a kind of DGPS system. The RSP applied a the GPS/DGPS system with short range portable reference stations (subsection 5.2.2). This system performed fully according to expectations (Subsection 7.2.2). The most vulnerable component of the system appeared to be the power supply of the portable reference stations. If the country (for instance, BIWTA) decides to install a nationwide network with a few mid- or long range reference stations, this problem is solved. And with prices of transceivers going further down, it may be expected that the near future the sustainable technique is not any more the sextant but the DGPS.

10.5.3 Water level

From a practical point of view, considering the normal gauge performance and typical data applications, the critical quality requirements of a water-level recording are:

- 1 the absolute vertical level; and
- 2 the time resolution.

An accurate vertical level reflects the combined demands of inter-station consistency, for example for slope calculations, and of long-term consistency, for any type of time series analysis. The adequacy of the time resolution can be considered (1) for the gauging programme in general, and (2) for periods of flow measurements at the gauging station, intended for stage-discharge correlation.

In comparison with these requirements, the accuracy of the water level registration itself is less critical, with the possible exemption of special scientific purposes. The water level of a large alluvial river is influenced by effects such as local wind stress and atmospheric pressure fluctuations, which can contribute by decimeters of water level, and density variations due to temperature variations and sediment load, which in the Bangladeshi rivers can contribute by centimetres of water level. To the extent that such effects are not recorded and included in the system description, they will appear as noise in the registration; it would not make sense, for example, to pursue an accuracy of 1 cm without measuring the local wind at the site of the gauging station.

For operational monitoring purposes, real-time water level registration is desired. In the years up to the early 1990s, BWDB (Surface Water Hydrology-II) gradually developed a real-time monitoring network which now comprises around fifty stations, covering a large part of Bangladesh. Recently, in addition to this, a telemetric system with 9 new and 5 old stations has been established with automatic water level registration. A further extension of this network is presently under advisement.

Relevant aspects with respect to site selection for water level gauging are:

Hydrological validity: The main objective of a water level station is to collect stage information, which is often used either to establish stage-discharge rating curves, to measure water level slopes, or to reduce bathymetric soundings to a reference datum. Therefore, stations should be located close to the discharge transect when a stage-discharge relationship is desired, and preferably at the centre of a bathymetric sounding area if depth reduction is desired.

Availability of a fixed structure: If a stable fixed structure exists near deep water, it is an attractive location. The structure can be for example a bridge pier, a jetty, or support for a tension line. At such places, however, the risk of local flow disturbances caused by the structure must be noted.

Riverbed stability: A stable riverbed is required for several reasons. First, the stability of the platform depends on the stability of the riverbed on which its foundation is laid. Therefore, the riverbed should not experience excessive erosion, and it should not be so soft as to allow sinking of the platform. Second, the morphological developments should not be such that the water course changes its location and the sensor becomes isolated in stagnant water. Third, moving bed dunes (if any) should not be so high that they can bury an AWLR sensor.

Flow field intensity: The site should be away from intensive flow fields for two reasons. First, the structural stability can be threatened by an excessive current force. Second, when a pressure sensor is installed, the flow velocity generates an extra pressure adding an error to the recorded pressure head.

Accessibility: The accessibility of the site is especially important in view of the operation and maintenance activities.

Security: The site should be secure against possible theft of equipment, and against impact of vessels caused by anchoring. Hence, it should be located in a secure place away from the navigational fairway. Also, the structure should be protected against impact and loading caused by floating debris.

The time resolution must be adequate for describing commonly occurring stage variations. Hereby, it is noted that the extreme (or at least the high) stage variations are of a particular interest in relation to many data applications, and are also decisive for the required time resolution of the registration.

One consideration in this connection is whether staff gauges read during the daytime only can provide data of an adequate quality. If a time resolution finer than twelve hours is required, this may render traditional staff gauges unpractical, whereby large additional costs may be incurred.

The relationship between stage and discharge is non-linear, with an exponent of between two and three (at Bahadurabad, see *RSP Special Report 4: 'Stage-discharge relationship for the Jamuna River at Bahadurabad'*). Therefore, inaccuracies incurred by interpolation of the water level are amplified when the data are used for flow estimates by rating curves. Also, this aspect calls for a reasonable time resolution, and particularly so during the execution of a flow gauging.

A distinction can be made between non-tidal and tidal stations. As an example of the former category, at Bahadurabad, a stage rise of 0.6 m/day occurs once every second year, and a rise of 0.9 m/day was observed once in 29 years. The maximum fall is about half of the maximum rise. For details, please refer to *RSP Special Report 4: 'Stage-discharge relationship for the Jamuna River at Bahadurabad'*. More abrupt rises occur at stations that are exposed to flash floods.

At tidal stations, a suitable resolution can be related to the predominant tidal period. The tide in the Bay of Bengal (and the Lower Meghna and the Ganges Delta) is predominantly half-daily, with a main period of 12.4 hours. This tide requires registrations at least every 30 minutes for a reasonable resolution, suitable for example for harmonic analysis.

A different aim of a suitable time resolution is to provide for a certain over-specification, for the purpose of identification of erroneous readings.

Staff gauging will remain the core of the water-level measurements, often as stand-alone stations, sometimes supplementing ALWR stations (Subsection 3.2.3). Besides staff gauges the RSP operated twelve ALWRs with either acoustic or pressure cell type transducers (Subsection 5.2.3). Main problem with the ALWR is to find safe places for the platforms (Subsection 7.2.3). Therefore, as much as possible existing structures were used. The ALWR applications will therefore be limited to for instance main tidal stations and stations for flood forecasting. The use of the acoustic sensor is recommendable as the sensor is installed above the water surface, thus avoiding problems of sedimentation. In case of malfunctioning the sensor can be repaired/replaced also during high flows, thus limiting down time.

10.5.4 Water depth and bed level

The water depth is in most cases measured by an echo sounder. Also, an ADCP can register the depth (by basically the same technique, but much less accurately). There are three objectives of this type of measurement:

- Mapping of depths, for navigation charts;
- mapping of overall river geometry, for integrated process descriptions, such as hydrodynamic modelling; and
- mapping of bed elevations, for morphological monitoring.

The typical depth resolution of a good echo sounder is less than 1 cm, while the aggregate instrument error, when used from a vessel, is somewhat higher. Error contributions comprise small, uncontrolled movements of the vessel, including unregistered heave, draft variations depending on speed and loading, and uncertainties regarding the sound velocity.

The velocity of sound in water depends on the pressure, temperature, and salinity. In rivers, the pressure effect is insignificant (because all depths are moderate). In shallow freshwater, the sound velocity increases by 0.6 percent (or 6 cm per 10 m sound wave migration) if the temperature increases from 25°C to 30°C.

The horizontal resolution along the runline equals the speed of the survey vessel divided by the registration frequency. If, for example, measurements are made every second, and the operational speed is 4 knots, one registration will be made for every 2 m of runline. The horizontal resolution perpendicular to the runline depends on the selected line spacing, with a lower limit determined by the positioning accuracy.

A consistency consideration gives as a practical quality criterion that the survey should be able to describe typical true depth variations over the selected length increment (1) along the runline and (2) between adjacent runlines.

This criterion indicates the relation between instrument performance, operational speed, and line spacing. However, the criterion is only fully operational if the bed level variation is known. Alternatively, the desired quality can be expressed in terms of runline length increment, line spacing and depth resolution, and the acceptable uncertainties for positioning and depth registration.

For both cross-sectional profiles and bathymetric surveys (subsections 3.2.6. and 3.2.7) use of echo sounders is recommended. In the RSP, two types of echosounders were used with a dual frequency (30/210 kHz) or a single frequency (200 kHz), see subsection 5.2.6. In the project area no important advantages of the dual frequency system were found (e.g. no major mud layers on the riverbed). Hence, the single frequency echosounder (of about 200 kHz) is recommended.

10.5.5 Flow

Flow registration is a main operation of any routine river gauging programme, because flow data are required for a variety of important practical purposes. Flow data are applied as time-averaged values, such as mean daily flow, for planning and design purposes, and as 'instantaneous' values for deterministic system descriptions, including calibration of hydrodynamic models.

Flow registration can be made by (1) a velocity-area method, (2) a traditional moving boat method, and (3) an ADCP-based moving boat method, like the one applied by the RSP. In any case, the main quality aspect is the accuracy of the registration. This accuracy, in turn, is determined by:

- The relative positioning accuracy;
- the vessel orientation and the instrument alignment (for ADCP, and other instruments that measure velocity components relative to the vessel);
- the accuracy of the depth registration; and
- the accuracy and validity of the current-velocity registration.

As compared with these contributions, the significance of the absolute positioning and the time registration is negligible.

The accuracy of the current-velocity registration is related to the instrument performance and the measurement procedure, for example the applied registration period. At non-tidal stations, the validity of the registration depends on the cross-sectional flow distribution and time variation, the number of vertical profiles in the cross-section, and the number of points in the vertical profile. At tidal stations, an additional validity aspect is the time resolution and the time coverage. These aspects are discussed in detail in *RSP Final Report Annex 2: 'Sustainable survey techniques'*.

In large alluvial rivers, an additional, secondary quality characteristic is the duration of the flow gauging. A flow registration by a traditional velocity-area method can require a long time. If the water level and the flow change significantly during the gauging, the data processing will become more complex, and additional uncertainties will be introduced by the required combined time and space normalisation of the data. Hereby, measurements at non-tidal stations will become affected by some of the data processing implications that are inherent at tidal stations, but which can be disregarded at non-tidal stations, provided that the duration of the flow registration is short, as compared with the time scale of flow variations. For the same reason, each channel of a braided river should be surveyed separately. The processes may well differ between the channels, for example as reflected by different stage-discharge relationships, but also purely practical reasons apply, such as the time required for making a whole cross-section (as compared with the time required for making each channel), and the time required for transferring from one channel to another. For example, if one channel is measured Tuesday and the next Wednesday, the flow and the stage can shift so much overnight that grouping the data will adversely affect their quality.

Another secondary quality aspect of some practical significance is the need of anchoring. In case of a strong current and a mobile riverbed, anchoring can be risky, or even impossible. Normally, anchoring is recommended in connection with velocity-area gauging.

The flow gauging of the BWDB is based on the velocity-area method for which Ott or SEBA propeller current-meters are used (subsection 3.2.4). The RSP used as much as possible the ADCP moving boat technique (Subsection 5.2.4) and otherwise the velocity-area method using mostly the S4 electromagnetic current-meter. From the experience it was learned that the ADCP performed excellently especially in high flows in the main channels, while it is also a powerful tool in tidal areas (subsection 7.2.5). The velocity-area method is especially attractive in smaller channels and shallow parts of the cross-section, where instead of the S4 better smaller EMFs or propeller current-meters can be used.

For the time being the sustainable technique is the velocity-area method as applied by BWDB. For tidal areas a moving boat system with one current-meter is probably the best choice. In the near future this system can be developed in combination with the nation-wide positioning system (a similar combination was tested in 1994 in the context of a UNDP project but was never made operational). The ADCP should be used for special measurements, for instance to calibrate the other two techniques.

10.5.6 Suspended sediment transport

Measurement of suspended sediment transport is another traditional routine gauging activity. A variety of methods exists, with widely different characteristics, qualities and shortcomings, as elaborated in *RSP Special Report 12: 'Optimization of sediment measurements'*. A common characteristic for the proven methods is that they involve sampling of a portion of suspended sediments, either in connection with a concentration-velocity method (pumping system, integrating bottle, or Binckley sampler), or a transport method, where the mass of the sediment sample is empirically related to the transport rate (Delft Bottle). In all cases, the total transport through the cross-section is calculated by an area integration of point or line measurements of the transport rate.

As with flow measurements, the main quality criterion of suspended sediment sampling is the accuracy, which comprises:

- The relative positioning accuracy (spacing between verticals);
- the accuracy of the depth registration; and
- the validity of the sampling, relative to a range of grain sizes or settling velocities.

As compared with these quality characteristics, the absolute positioning, the time registration, and the laboratory analysis of collected samples are of secondary significance, because of the relatively good performance of available techniques.

Secondary quality aspects are (1) the time required for covering a full cross-section, and (2) whether anchoring is required or not. For velocity-concentration methods, the quality of the velocity measurement is of equal significance as the quality of the sediment sampling.

Sediment transport gauging at tidal stations is particularly difficult. Here, the validity criterion is extended to comprise not only the instantaneous transport, but also the net transport, and a special need is required for an adequate time resolution.

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A new, not yet fully proven technique is mapping of the cross-sectional distribution of suspended sediments by ADCP backscatter. The technique was applied by the RSP as a supplementary method. The quality determinants of this technique deviate from the sampling techniques. The validity criterion is particularly important, because the backscatter signal is an under-specified function of grain size and concentration. Another inherent quality characteristic is the depth range, which imposes a practical restriction, since the method cannot cover the lowest 6% of the water column (where a large part of the sediment transport takes place). The performance of the ADCP backscatter registration is complementary to the performance of the techniques that involve sediment sampling, and the two methods can possibly prove to be a powerful combination. Please refer to *RSP Special Report 24: 'Morphological developments at Bahadurabad'* for a description of the method and a discussion of its performance.

For sustainability considerations regarding suspended load gauging the objectives and, consequently, the desired accuracy play a major role. The Binckley Sampler as used by the BWDB (subsection 3.2.5) is a very reliable instrument. However, instantaneous sampling to obtain time-averaged values is causing substantial errors. So this sampler should then only be used for time series, which is not an appropriate method for routine gaugings. When no details are needed in the vertical the depth-integrating samplers of the collapsible bag type are the best choice. When the shape of the sediment vertical is important, the Delft Bottle can be used although the sampler catches the coarser fractions only. For all sediment fractions the pump system is recommended. Possibly the Delft Bottle but certainly the pump system and the ADCP technique are considered for special measurements only.

10.5.7 Near-bed transport

The near-bed transport of suspended material represents a substantial part of the bed material transport through a cross-section, and is, apart from that, of a particular morphological significance. At the same time, it is difficult to gauge, be it by direct methods, involving collection of samples, or by indirect methods based on monitoring of the progression of bed forms.

Near the riverbed, both the transport rate and the sediment properties can deviate from what can be predicted from distributions higher in the water column. Both velocity gradients and concentration gradients are steep, and often the flow and the lateral concentration distribution are irregular.

Such irregularities affect the validity of the measurements, for example when relating sediment concentrations to flow velocities for calculating the transport rate by a concentration-velocity method. Due to the finite (and deviating) time and space resolution of instruments and samplers, the sediment particles can appear as if they were moving with a velocity that is different from the current-velocity. A different implication is that the flow irregularities impede the handling and the position control of instruments and samplers. Samplers that are suspended can dig into the riverbed, and samplers that rest on the riverbed can be exposed to scour. Also, the anchor of the survey vessel can cause an artificial resuspension of river bed material that can contaminate the sampling. ADCP backscatter registration does not cover the lowermost part of the water column.

The critical quality aspects are:

- The accuracy of the depth registration relative to the riverbed;
- the validity of the sampling itself; and
- the consistency (time, height above the riverbed, space resolution, averaging period) between the sediment sampling and the associated flow velocity registration (in case of velocity-concentration measurements).

The validity relates to a specific range of grain sizes or settling velocities, but also, in particular, to the registered transport relative to its near-bed distribution. The quality aspects are highly influenced by the performance of the instrument or sampling device.

The validity of the sampling is critically related to the vertical sampling coverage and resolution relative to the riverbed. Even if the sampling level above the riverbed can be controlled accurately, for example at 5 cm or 15 cm, this is no safeguard that the data describe the near-bed transport with the desired general validity, due to patchiness of the near-bed transport, resulting in steep gradients or even stepwise changes in time and space, caused by bed forms or related to sediment plumes. For this reason, and at the present level of understanding of predominant physical processes, a valid description of near-bed sediment transport in large alluvial rivers requires a dense data coverage in space and time.

For concentration-velocity methods, the quality of the velocity registration is equally decisive as the quality of the sediment concentration determination. Here, the important aspect is the consistency between the two measurements (rather than the accuracy of the current-velocity registration). The consistency can be supported by (1) applying different methods that supplement each other, partly compensating specific shortcomings, and (2) applying an appropriate averaging (over time and space), which filters out a part of the small-scale irregularities.

Indirect determination of near-bed transport can be done by tracking of sand dunes, although the 'true' transport rate determined in this way is different from the one determined by sampling on or above the riverbed. Critical quality aspects are (1) the time and space resolution, which should be adequate for describing the dimensions and the progression of the sand waves; and (2) the accuracy of the transport calculation, which is subject to a number of assumptions, such as the net transport being strictly uni-directional (to the extent that this is not true, the system becomes underspecified).

Although the near-bed sediment transport is an important part of the total transport, measuring the near-bed transport is not recommended during routine gauging. The best approach is to execute special measurements to determine the near-bed transport/total transport ratio for varying river stages and various locations as far as feasible. For these special measurements the Delft Bottle is the best choice. Other transport samplers like the BTMA and the Helley-Smith sampler should only be used up to midflow conditions. If the transport of both the fine and coarse sediments are sought, rather than the Delft Bottle a pump system (in a frame on the riverbed) is to be considered.

10.5.8 Bed material sampling

From the three types of instruments considered the sustainability scores were not much different. The KSBM 54 scoop sampler is recommended for special measurements because of its better method of sampling (less distributed samples). Moreover, the instrument is used from an anchored vessel enabling accurate positioning. The use of the other samplers, the Van Veen grab sampler and the drag sampler from a floating craft is easy. As the grab sampler is heavier and sometimes fails to close, the drag sampler is preferred for the more routine type of measurements.

10.5.9 Sediment properties

A distinction can be made between:

- Grain size and settling velocity characteristics;
- other physical properties; and
- mineralogical properties.

The first category is a traditional gauging activity, which was part of the RSP routine gauging programme. A variety of techniques exist for the sampling, and procedures for the laboratory tests are standardised and well proven. The main quality criterion is the validity of the sample, relative to the general characteristics of suspended or bed sediments as they occur in the survey area, and as they vary in time and space. For suspended sediments, another key aspect is the validity in relation to the sediment transport, whether this be determined by a velocity-concentration method or by a direct transport method. This is because, for practical reasons, the grain size distribution of a collected sample can very well deviate from the true distribution. The accuracy of the laboratory analysis is a separate quality aspect, which, although secondary (with respect to influencing the overall quality) may be of some practical significance, particularly for settling velocity analyses.

A pilot study conducted by RSP indicates both a considerable scientific interest and a high practical significance of further information about sediment properties (in addition to the grain size or settling velocity characteristics), such as mineralogical composition, density, and shape. The study is reported in *RSP Special Report 14: 'Mineralogical and physical properties of river sediments'*.

No operational quality criteria can be suggested for this gauging activity, which has so far not been executed on a routine basis. Rather, the general objective applies, that the data quality should be acceptable as compared with the intended use of the data. It may be speculated, though, that the validity of the sample location is of particular significance because variations may occur over small distances, depending on flow pattern and river bed geometry. Another quality aspect to be kept in mind is the consistency and the transparency of the laboratory analyses, because mineralogical and certain physical properties (for example the particle shape) can be determined by a variety of methods that are not fully standardized, and the performance of which is not always proven or understood in every detail.

10.6 Data processing and quality checking

10.6.1 Water-level gauging

Processing of the RSP water level recordings comprised the following activities:

- downloading of AWLR data and collection of staff gauge data, with on-site inspection of data coverage and data quality (spikes, steps, drifts);
- digitising of staff gauge readings and conversion of AWLR readings;
- zero level conversion to PWD;
- data validation;
- editing of data files; and
- storage in the HYMOS database.

The validation of water level data is described in *RSP Special Report 2: 'Water level gauging'*. After storage, the data were available to different types of analysis and presentation, as exemplified in *RSP Final Report Annex 3: 'Hydrology'*.

The validated data files are few (one for each gauging station and each year), and not too big. Being simple time series, they can be easily converted into different file formats, and, once available, they can be distributed to the end users without any practical problems.

One difficulty experienced by the RSP was the duration of the data flow, from the measurements which were taken to the final storage of validated data, which could in some cases take up to one year, even if data was downloaded at least monthly. This was mainly due to capacity constraints. Many applications of water level data require that the validated data are available within a much shorter time.

Real-time transmission of water-level data was not implemented by the Project, but is now widely used by BWDB. Real-time data transmission has several advantages, both with respect to the use of the data, and with respect to quality control and immediate mitigation of detected data quality deficiencies. Obviously, both the capital costs and the operational costs are higher than for off-line registration.

10.6.2 Routine gauging of flow and sediment transport

The data processing for the RSP routine gauging was divided into an on-line part and an off-line part. The on-line data processing comprised generating composite data files, containing data from the different sensors, labelling of data files for identification, and monitoring of data coverage and consistency. The off-line processing comprised editing, validation, storage, and reporting.

In the future, it may be speculated that the on-line data processing component could be extended to a nearly complete, and fully automated production of data files and survey reports. This could involve preparation of key plans and file catalogue entries onboard the survey vessel, as well as a larger part of the data file conversion. This is the practice today within modern marine bathymetric surveying, carried out from vessels with powerful facilities, but should, in view of the well-known rapid development within information technology, also now be within reach on small vessels. The advantages would include more strictly struc-

tered data processing and a much shorter production time. The data file validation can by necessity not be completed until after the field programme, because it involves inter-survey and inter-station comparisons.

10.6.3 Bathymetric surveys

The processing of bathymetric data by the RSP was divided into

- an on-line component, producing composite x-y-z-t files for sets of runlines; and
- an off-line component, resulting in converted x-y-z files and finite grid depth tables, in both cases relative to the applied (SLW) datum.

Final data presentations were made on large-sized A0 hardcopies.

Several problems were encountered in the process. Initially, the off-line data processing took much too long time, particularly in connection with debugging and datum conversion. Also, selection and implementation of suitable software for the contour plots required more attention than foreseen. The hardcopy maps required many resources, one reason being that the work was not completely automated. This, in turn, extended the production time. In the future, it may prove more expedient to submit data as A4 key plans together with the data files. Hereby, the storage is facilitated, and the different users can edit and present the data in their own environment and in accordance with their own different purposes.

10.6.4 Quality control

With the large data volumes produced by modern computerised survey equipment, a high degree of automation is a necessity in connection with the quality control. Even if production time were of no consequence, and resources were abundant, a fully manual quality control would inevitably suffer from lack of consistency and transparency.

On the other hand, as it is well known, the errors are neither consistent nor transparent. While 'an error' can be clearly defined, for example as 'an unacceptable deviation between a measured value and a true value', it cannot be described in unambiguous operational terms. Consider for example a single peak of 1 m in a depth registration along a runline; such a peak may well be an error, but it is not completely certain that this is the case, even if the peak did not appear in adjacent runlines. As another example, a peak in a hydrograph may have been overlooked in the registration, but still, the hydrograph, appearing as a smooth curve, looks completely un-suspect, and the peak, if observed at one adjacent station only, will probably (wrongly) be judged as an error. Such risks of accepting erroneous data and discarding correct data exist both for manual and automatic validation and are not related to the data volume.

The RSP applied a stagewise data quality control:

- On-line control (where applicable), based on graphic (computer screen or plot) presentations, comprising monitoring of data coverage, and obvious inconsistencies, such as range checks, spikes, and stepwise changes in the data series;
- off-line validation, based on graphic presentations, comprising consistency checks (for example staff gauges readings versus AWLR recordings, stage-discharge relations, consistency of bathymetric contour plots, and inter-station comparisons); and
- control of survey bulletins, comprising consistency and completeness.

The operational (or on-line) quality control takes place while the measurements are made, with the objective of identifying obviously erroneous or missing measurements, so that they can be replaced immediately. A consistent positioning can be verified by graphical route tracking, manual or (preferably) computer-based, which will clearly highlight the inevitable occasional abrupt off-sets, and which can (partly) verify the data coverage during bathymetric surveys. Electronic data signals can be checked on-line by automatic routines that label and report out-of-range values, stepwise shifts, repeated constant values, and other doubtful or obviously wrong registrations. Measurements that do not involve electronic data registration can be checked manually, for example by plotting a vertical current velocity profile.

The off-line validation comprised consistency checks (of hydrographs, current-profiles, and cross-section distributions of flow and sediment transport), stage-discharge comparisons (of flow, sediment transport and water levels), inter-station comparisons (of water levels), and comparisons between adjacent runlines of bathymetric surveys. Survey Bulletins were checked for consistency and completeness against the Survey Reports and against SPOT images and previous surveys at the same location, as described in *RSP Final Report Annex 1: 'Surveys'*.

The RSP experience clearly confirmed that quality control is a process that continues for as long as the data are being used. Certain errors will not emerge until a late stage in the analysis, such as inter-station comparisons, comparisons of data from different sources, or using the data in connection with numerical modelling. For example, this is the case with flow and water-level data being used for rating curves, where outliers and loops can be true reflections of correct measurements, or can be caused by different types of measurement errors or other data inconsistencies. Another example is absolute zero level deviations, which will appear clearly if water level data are used for hydrodynamic modelling, but which can be literally impossible to detect otherwise (even if the zero levels have been carefully validated and are fully correct relative to the selected reference bench mark). Still another example is errors that are detected during comparisons of successive bathymetric mappings for analysis of erosion and accretion areas and rates.

Therefore, a stage of the quality control may be complete, once a number of check procedures have been carried out; but the process as such continues, because there is an inherent element of quality control in any type of downstream data analysis. It is likely that institutions such as BUET, SWMC, FFWC, and others, regularly identify inconsistencies in hydrological data, also from measurements that were made years ago. This fact has an important implication in connection with routine gauging. It is annoying when quality defects are detected at a late stage, for example after the Hydrological Yearbook has been published, or the CD-ROMS have been distributed. Still, a provision should be made for subsequent reporting of defects and inconsistencies, once they have been detected, and no matter the time involved.

10.6.5 Evaluation

An important quality aspect in connection with data processing is its transparency. This is particularly the case with complex data flows like the ones implemented by the RSP for the flow and sediment transport gauging and also for the bathymetric surveys. These data flows are not covered by established data processing standards. Their transparency requires visible and well documented procedures for data conversion, checking, averaging, miscellaneous calculations (of flow, sediment transport, etc.), and contour delineation on bathymetric maps. Such procedures are not that difficult to develop, and many are available beforehand; but at the start of the RSP, their applicability in the new DGPS-ADCP context was not fully proven, and operational specifications for their performance were not available.

In the course of the Project, two successive data flow frameworks were developed: One entirely within the UNIX environment (in Phase 1), and another within a combined UNIX and DOS environment (in Phase 2). The former was oriented towards the FIELDMAN catalogue system, and the latter towards the PSD24 database and standard DOS software (mainly the *QuattroPro* Spreadsheet). Specifications were established and modified in the process, and continued updates were required of check lists, guidelines and manuals. These developments contributed to an improved overall quality, and facilitated the data dissemination, but at the inevitable cost of a reduced transparency until a late stage in the project.

The Project pursued a high degree of automation within its data processing. This was required due to the size of the data flow, but an additional benefit (that did not fully materialize within the Project) was to reduce the time lag from when the measurements are made and until the data are available to the data user. This aspect is obviously critical in connection with real-time monitoring (of floods or flow), but is also of a high practical interest in connection with general routine gauging.

10.7 Data storage including databases

10.7.1 General

Storage of river data should be as simple as possible, given the volume and the complexity of the generated data. Within the RSP, the water-level data represented a small volume of simple data files, whereas the routine gauging of flow and sediment transport, and the bathymetric surveys, produced large and complex data files.

To illustrate the implications, it can be mentioned that the water level data produced by the RSP, some 500 station-months, can be stored on two ordinary floppy diskettes. The results of the 252 routine gaugings of flow and sediment transport, the 38 bathymetric surveys, and the almost one hundred special surveys require around 40 CD ROMs for a complete storage.

10.7.2 Simple data files

Simple data files are for example recordings from a water level gauging station, which appear as a single parameter time series. Once generated and validated, these data files are easy to catalogue, store, disseminate, identify, and retrieve.

The RSP used the HYMOS software package for this purpose. This software system can both store the data and can perform a range of hydrological analyses and data presentations. The entire system, processing software and data, can easily be installed on one PC.

10.7.3 Complex data files

Complex data files can be multi-dimensional arrays, or time series of such arrays, often with a varying structure (for example number, location and depth of verticals in a cross-section). They can even be aggregate arrays, such as time series of current velocity vector components grouped into a single vertical profile or an entire cross-section.

The RSP developed the PSD24 database for the purpose of storing complex river data files. It was formed around a Paradox data catalogue. The data files were generated by routines that were largely developed for the purpose within the framework of the Project.

The database was designed in a dialogue with RSPMU, and after consultations with BWDB and SWMC. A main challenge was imposed by the need for a drastic reduction of the raw data volume, which was necessitated simply in order to access the data, not to speak of the possibility to compare data from different surveys. Another challenge was the aim of a comprehensive automation of the processing, which was desired both to reduce the time lag between data production and data availability, and to ensure transparency and avoid errors related to manual procedures.

The development took place in a particularly dynamic interaction between the data using and the data producing groups within the Project. Specifications for synthesisation, presentation, and storage were drafted, tested, reconsidered and revised, and numerous iterations were required to arrive at a result which was acceptable to the users without imposing prohibitive requirements on the processing. The result, the PSD24 with its contents, is unique beyond any doubt. It is evaluated by the consultant as a good and readily accessible source of highly valuable results of the surveys. The PSD24 was developed to accommodate complex data files with a variety of file structures. The raw data comprised the following types:

- time series (of water levels);
- x-y-z-t arrays (of cross-sectional depth contours);
- x-y-z-t arrays of time series (of current-velocity in vertical profiles);
- x-y-t arrays of current-profile (x-y-t) arrays (of flow across transects); and
- x-y-z arrays of sediment concentrations and grain-size distributions (from the sediment laboratory).

During the data processing, all these files were condensed and transformed into x-y arrays. The file format was selected as the one of the *QuattroPro* spreadsheet, from where the files can be converted to ASCII format. Many analyses and presentations can be made directly in the spreadsheet.

While using the PSD24 should be straightforward, this is not the case with its operation. On the contrary, the operator must possess an in-depth knowledge of the underlying software, both in the DOS and the UNIX environment, in order to generate and add new data files, not to speak of changing the structure of the database, if this should for some reason be desired.

10.7.4 Evaluation

The overall data administration framework of the RSP is not very well suited as a model for future applications. For historical reasons, the processing involved several shifts between the UNIX and the DOS environment. At the start of the Project, the capacity of the DOS system was not adequate for handling big data volumes, so a UNIX system was selected. Soon after, however, the data users within the project organisation expressed a preference for undertaking the final analysis in the DOS environment, where a variety of standard software (spreadsheets and graphic software) was available as attractive tools.

If the system had been designed today, it would obviously have been implemented entirely within one operating system. Today, both the DOS and the UNIX systems (as well as others) are adequate for this purpose, and both seem to become more powerful every year.

A suitable standard software package for similar purposes would be ArcView, which has been implemented by such organisations as EGIS, BWDB/FFWC, and SWMC.

The RSP did not accomplish a full integration between data processing and data reporting. Due to time and capacity constraints, the production of Survey Bulletins and the preparation of PSD24 files was done by separate teams within the project organisations. This incurred a certain duplication of work that could be prevented by a streamlining of the internal procedures.

10.8 Data presentation and publication

For each RSP routine gauging survey, a *Survey Report* was prepared on-site and for each survey, an RSP Survey Bulletin was prepared after completion of the data processing and storage.

The Survey Reports were used for internal purposes in connection with data processing, validation, and data reporting, as well as a support for adjustment of field procedures and work programmes. The Survey Bulletins were prepared on the basis of the Survey Reports. They described the measuring locations, listed the produced data, and presented an extract of the results. Please refer to Appendix 1 of the present report for an overview. The Survey Bulletins were directly compiled to form the data volumes of the RSP Data Books.

No specifications were available beforehand for the format of the Survey Bulletins and the Data Books. Therefore, their contents and appearance were developed in a collaboration with the PA, the RSPMU, representatives from BWDB and SWMC, and the internal data users. The selected format was implemented as a compromise between various priorities, such as coverage and volume. Here the RSP gave priority to a full description of (1) where and when the measurements were made, (2) the hydraulic conditions prevailing during the measurements, and (3) where the results are stored. Other formats than the one selected may be equally or even more useful, for example with respect to the contents of the data summaries. However, to the reader it is obvious that their volume should not be extended.

Possibly, in the future, the 'Data Books' may be replaced by 'Data CDs'. Preferably, one CD (or a few) should cover one (hydrological) year of measurements. This requires that the books be structured in a different way, as a small separate catalogue system with maps in a suitably compressed format. Quite some work would be required to structure this presentation, but once it had been done, the dissemination of results would be facilitated, and at the same time speeded up.

10.9 Special surveys

Improved knowledge of the behaviour of the main river system of Bangladesh, its natural development and its possible response to different development scenarios is of utmost importance. Although over the past ten years this knowledge has increased considerably, also owing to the results obtained in this project (see Chapter 7), still some important issues are not yet understood sufficiently. There is an urgent need for addressing these issues. This should be done by a number of studies combined with and supported by special surveys, using up-to-date measuring techniques.

It is appropriate to discuss in this Chapter, on the basis of the experience gained during the RSP project, the type of surveys to be carried out, the specifications for survey vessel, survey equipment, data processing, data storage and data presentation and to indicate additional conditions to be fulfilled in order to allow for a smooth operation of the special surveys. In formulating these requirements, the starting point was the future studies that are proposed in Chapter 11 and Appendix 4.

10.9.1 Type of surveys

In view of the requirements coming from the special studies to be performed in future (see Chapter 11 and Annex 4), the special surveys will be mostly:

- discharge and sediment transport measurements;
- repeated bathymetric soundings, combined with accurate slope measurements (possibly by RTK-DGPS) and identification of flow patterns and sediment transport patterns (ADCP).

10.9.2 Survey vessels

It is impossible to combine in one vessel the capability to do detailed sediment sampling and bathymetric soundings. Hence it is preferable to have at least two boats, a large one with all the equipment and extensive sleeping facilities and a smaller one especially for bathymetric surveys and with ADCP as well.

The large survey vessel should comply with the following specifications:

- allow for a prolonged stay on board (2 weeks) for a crew of about 6 to 8 persons;
- air-conditioned;
- sufficiently large for handling the equipment at ease;
- draft of maximum 1.0 m;

In view of these requirements it is estimated that the vessel should be about 20 m long.

For the smaller vessel the following specifications are given:

- no sleeping facilities other than for the crew
- air-conditioned;
- draft 0.5 m.

10.9.3 Survey equipment

The following equipment would be needed on board both the large and the small vessels for carrying out the special surveys, proposed in Chapter 11 and Appendix 4:

- DGPS for positioning with one wall stations but different possibilities to mount the wall station;
- echo-sounder;
- ADCP for both flow measurements and sediment monitoring using backscatter as indicator;
- electronic current meters.

For the large vessel instead of a DGPS it can be considered to use a RTK-DGPS, which can be used for accurate slope measurements as well. The different instruments should be connected to a computer driven survey system like HYDRO. For data collection via DGPS (or possibly the RTK-DGPS), echo-sounder, electronic current-meter and the ADCP, a number of PCs and a printer are needed.

In addition, the following equipment is required for the large vessel:

- pump samplers;
- Delft bottles (and possibly Helley-Smith sampler) for near-bed transport;
- Helley-Smith sampler for bed load transport;
- bed material sampler.

10.9.4 Data processing

For the data processing both hardware and software is required. As hardware:

- 2 Pentium PCs with 1.6 Gb hard disc, 40 Mb RAM and CD-ROM drive;
- 1 A0 plotter;
- 1 A4 colour printer and 1 A3 laser printer (monochrome);
- 1 A3 digitizing table;
- 2 tape drives;
- 1 CD storage unit;

and as software:

- MIKE 21 pre-or postprocessing modules (or any other package for presenting bathymetric data)
- spreadsheet programs. e.g. Quatro Pro
- file conversion software

The above are the present (1996) ideas. In view of the fast developments in both hardware and software, an update will be needed when such a study/survey unit is established.

In addition, a small sediment laboratory is required (sieving, settling tube, etcetera).

10.9.5 Data storage

Data can be stored in two data bases:

- in HYMOS for discharge and water-level data;
- in a data base comparable to the PSD24 (or in the PSD24 itself).

10.9.6 Data presentation

Data presentation will be in the form of Survey Bulletins. In addition GIS can be used to present the results of bathymetric sounding and to superimpose measured flow lines, sediment transport rates etc. The GIS can also be used for manipulating the data.

Hence for data presentation the following software is needed:

- HYMOS
- GIS e.g. ARC/INFO, possibly combined with ERDAS for processing of satellite imagery
- Corel Draw

10.9.7 Additional conditions

Moreover, the following conditions should be fulfilled:

- on-line quality control on board the vessels is a must;
- electronic workshop with sufficient spare-parts (note that for a similar set-up the Consultants used only a minimum of spare parts over the period of 3.5 years they were doing surveys);
- transport for crew, spare parts and supplies.



11 Future studies on survey techniques and river behaviour

11.1 Introduction

During the *River Survey Project* (FAP24) quite a number of studies were carried out into measuring techniques for the large alluvial rivers in Bangladesh, on the one hand, and into the behaviour of these rivers, on the other hand. Although very interesting results were obtained (an overview of main findings being given in Chapter 7), still many unsolved questions are left. Not so much as to sustainable measuring techniques, as the special surveys and the different studies carried out during the project were quite sufficient to draw definitive recommendations on these (see Chapter 10). Rather the unresolved questions relate to:

- (1) promising measuring techniques for special studies, where advanced techniques might be required, and
- (2) the behaviour of Bangladesh's main river system, in terms of its hydrology, its sedimentology and its morphology.

The first type of questions is obvious and is linked to experiences gained during the surveys and to developments in measuring techniques (including remote sensing) over the past years. These are addressed in Section 11.2.

The second type of questions – those related to the behaviour of the river system – are dealt with in the subsequent Sections of this Chapter. Obviously, preparing a list of study topics to be addressed in the future could be done on the basis of earlier considerations on key issues. In particular in Study Report 1, prepared at the end of Phase 1 of the RSP, key problems were identified, and these were analysed in some detail to identify possible study topics which could be taken up in Phase 2 of the project. Use was made of a systems approach to rivers as morphological systems, schematically shown in Figure 11.1, in which the present state of the river system is considered as a continuum between the past and the future.

The future state of the river system, determining future socio-economic aspects like its use for agriculture and navigation but also flooding, is affected by developments in the past and the subsequent autonomous development, natural changes (in independent variables controlling the river system) and changes induced by human activities (like implementation of flood control measures).

Based on this conceptual view, the following problems were identified in *Study Report 1*:

- limited data on the present state of the river system;
- future performance of the offtakes;
- prediction of bank erosion 2 or 3 years ahead;
- design conditions for groynes and revetments;
- effect of narrowing/bank protection works/AFPM (Active Flood Protection Measures) measures.

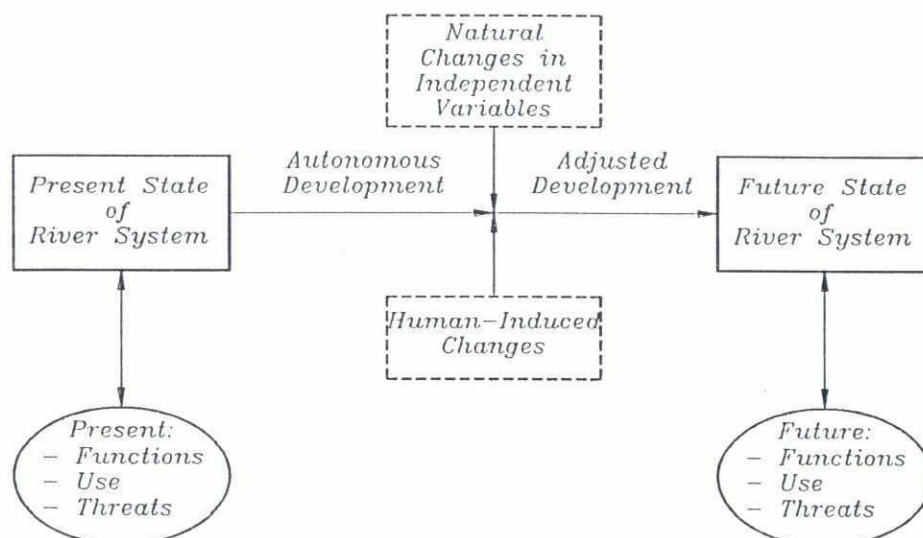


Figure 11.1 Influences on the development of a river system

Note that initially also the morphological impact assessment of implementation of FAP was considered as a key problem to be taken up by RSP in Phase 2, but after Phase 1 – during the International Workshop on Morphological Behaviour of Major Rivers in Bangladesh in Dhaka in November 1993 – it was decided to develop a separate project. For this project (Morphological Impact Assessment or FAP27) a TAPP has been prepared in the mean time.

On the basis of a further analysis of these key problems a number of study topics were identified. Quite a number were taken up in Phase 2, and quite some progress was made. Study topics for the after-RSP era consist of:

- study topics taken up in Phase 2, but still needing continued study;
- study topics not tackled during Phase 2, and still relevant; and
- new topics that have emerged on the basis of the results obtained under the RSP activities and new ideas generated elsewhere.

In this Chapter a listing and a short description is given of the most important study topics, which should be addressed by special studies in the future. As will be elaborated upon in more detail in the next Chapter (dealing with implementation of the recommendations coming from this study), it is proposed to establish both a special study unit and, linked to it, a special survey unit. These two units should together address the various study topics via a combination of studies and surveys. Hence the remaining part of this Chapter can be read as a first task description of these units, which hopefully will materialize within the framework of the future Morphological Impact Assessment project (FAP27).

The structure of this Chapter is in line with some of the previous Chapters. Subsequently studies are listed in the following fields:

- survey techniques (Section 11.2);
- hydrological characteristics (Section 11.3);
- sedimentological characteristics (Section 11.4);
- river morphological characteristics (Section 11.5).

In a separate Section (Section 11.6) also the morphological impact assessment is discussed. For more details on the proposed studies reference is made to the relevant chapters in the Annexes 2, 3, 4 (Chapter 12) and 5 (Chapter 15), respectively, and to Study Report 1 where for most topics a description, an approach and required study tools and expected results is given.

Study Report 1 also provides an extensive discussion on the relation between present and future problems experienced with Bangladesh main river system and the key problems. As indicated earlier, this Chapter draws partly on this report. However, as the understanding of the system has improved considerably, the perspective is slightly different. Nevertheless, Study Report no. 1 is recommended for better appreciation of the relevance of the proposed studies for future planning of integrated flood control and water resources projects.

11.2 Studies on survey techniques

11.2.1 Water levels

Often bridge piers or other structures are selected as the location for a water-level gauge, because it is easy accessible, and it is a permanent location which is not likely to erode in the future. The disadvantage is that the water level is affected by the increased velocity head. Methods should be developed to correct the measured water level for the increased velocity head.

The technical development of different types of water-level sensors should be followed, especially the advantages and disadvantages of an acoustic versus a radar sensor should be evaluated.

11.2.2 Velocities

The acoustic velocity measurements by ADCP might be affected by high concentrations of coarse sediments also differences between water velocities and the speed of the coarse sediment particles may play a role (Peter 1994). If this effect cannot be neglected, then the measured velocities should be corrected for it.

The traditional moving boat technique with one current meter can be optimized by applying ADCP-calibrations. In this optimization study special attention should be given to surveys in tidal conditions. Different instruments give different shapes of the velocity vertical especially near the bed, which affects the shear-stress velocities. The reason of these differences need further investigation.

11.2.3 Suspended load

The ADCP backscatter seems to be a very useful measure for the concentration of the sand fraction. At this moment calibration curves are available for Bahadurabad and Mawa only. The relation between the backscatter, the particle diameter and possible other parameters (such as the effect of depth and concentration variations on the backscatter intensity) should be investigated more in detail to establish a more general relation between backscatter intensity and suspended sediment transport.

The American type of collapsible bag sampler for suspended sediment transport measurements as used by the RSP has a high flow resistance due to its poorly streamlined shape and is not very stable in high flows. This can be improved by an integrated collapsible bag as sketched in the figure below. The following aspects of an integrated collapsible bag should be optimized: a minimum thickness of the unmeasured zone versus a maximum content of the bag, and a minimum drag of the sampler versus a minimum weight of the sampler. The sampler should have different nozzle sizes in order to apply it efficiently under different hydraulic conditions. Further it should be stable in high flow velocities and it should be easy to operate the sampler, especially to change bags. Examples of a few of these samplers in use in China and Germany are given in SPR 12.

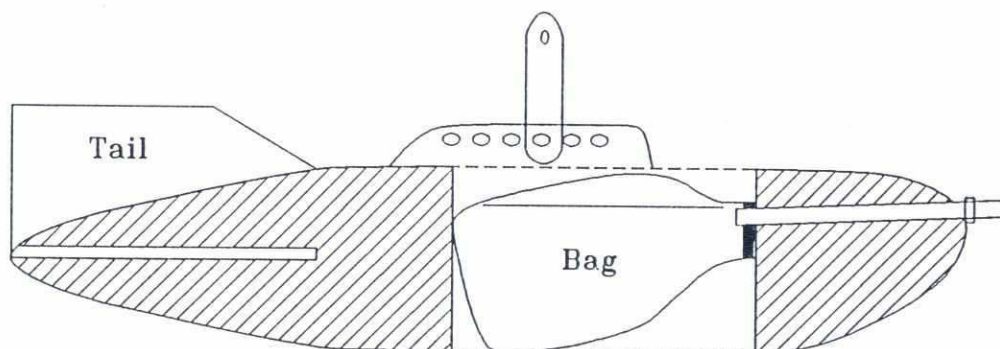


Figure 11.2 Integrated collapsible bag sampler (principle sketch)

11.2.4 Near-bed sediment transport

To measure the near-bed sediment transport a special sampler should be developed. This sampler should have a stable orientation in low flows, and a minimum drag by a thin umbilical and streamlined shape of the sampler. Further, it should induce minimum scouring of the river bed around the sampler and it should be tested in high flow conditions. After the design of the sampler has been optimized with regard to these aspects, the sampler can be extended with more advanced options, such as remote control vertical position of intake nozzle and velocity meter and also of the frame by using a short-range echosounder.

Further investigations are needed to define the thickness of the near-bed layers in varying flows and at various locations.

The Delft Bottle catches only a part of the sediment transport with diameters in the range 0.063 - 0.125 mm. This partial catch depends on the sediment concentration and the flow conditions and it should be investigated in more detail.

The applicability of ultra-sonic sensors to measure the near-bed sediment transport should be investigated.

11.2.5 Remote sensing

River studies and river management can be benefitted by a faster delivery time of satellite images. It seems that quick looks prepared by SPOT can be delivered within three weeks! The contrasts in the rivers on SPOT images can be optimized by filtering techniques. Probably these contrasts are a measure for the sediment concentrations in the river (near the water surface). At the day the SPOT image is shot, simultaneous field checks are needed to establish a relation between the color of the water surface and the sediment concentration.

The accuracy of the geographic coordinates printed on SPOT sheets need improvement. Normally Landsat images are printed without a coordinate system. Planform studies will be facilitated with an accurate coordinate system on the images.

Radar images have a potential for the study of morphological developments especially during the monsoon, mapping of the flood extent, planning of AFPM activities and determination of the river bathymetry. In pilot projects these potentials would be tested and elaborated.

Topic		Proposed studies
Survey techniques	Water levels and slopes	• Slope measurements with RTK-DGPS
	Velocities	• Combining moving boat with ADCP calibration
Satellite imagery	SPOT	• Applicability of quick looks for operational applications
	Radar	• Use of radar for mapping flood extent • Use of radar for planning AFPM activities

Table 11.1 Proposed priority study topics on survey techniques inclusive use of satellite imagery (for more details see text; for background information see Annexes 1 and 2)

11.3 Hydrological studies

- relation between rating-curve changes and river morphology
- optimization of network? offtakes? also in view of measuring sediment transport
- extension of network in d/s direction?
- selection of new sites (Mawa versus Baruria and Arial Khan)
- detailed local slope measurements
- overland flow
- flow over chars and in and out of floodplain

Topic	Proposed studies
Special studies on network	• Study of potential new sites in view of hydrological and morphological characteristics • Comparison discharge measurements Mawa versus Baruria and Arial Khan

Table 11.2 Proposed priority study topics on hydrology (for more details see text; for background information see Annex 3 and Study Report 1)

11.4 Sedimentological studies

The sedimentological studies to be done in the future can roughly be divided into:

- *additional measurements* aiming at completing the data base on the main rivers in Bangladesh;
- *special studies* aiming at improving the understanding of the river behaviour, using this data base and doing special studies.

An overview of the additional measurements to be done and the special studies to be taken up on a priority basis is given in Appendix D, Table A4.3. A concise description of topic and the reason why it is proposed to be taken up on a priority basis is given below.

Topic		Proposed studies
Additional measurements		• Geological controls
Special studies	Resistance to flow	• Contributions to resistance to flow • Low resistance during floods
	Floodplain sedimentation	• Rates of floodplain sedimentation

Table 11.3 Proposed priority study topics on sedimentological characteristics (for more details see Appendix 4; for background information see Annex 4 and Study Report 1)

(a) *Geological controls*

By now it is clear that along Bangladesh's rivers some less erodible controls are present. These might be very important for the stability of the river system as they, in combination with properly sited river training works, can reduce the bank erosion. In order to better understand the presence of these controls and their role, it is proposed to sample some of the known or expected geological controls: Bahadurabad and Bhuapur along the Jamuna River, Sara and the control upstream of the Gorai intake along the Ganges River, and Mawa along the Padma River. The samples should be tested to determine their characteristics (e.g. clay content, consolidation characteristics, shear strength) in view of their erodibility and their relation to the possible development of hard points along the Jamuna River (see Section 7.5).

(b) *Contributions to resistance to flow*

Resistance to flow is caused by the combination of a number of contributions, notably: grain roughness, bedform roughness, non-uniformity of cross-sections, bars, vegetation and possibly even other contributions. There is only very limited insight into the relative importance of these contributions. Furthermore it has been found that 2-D mathematical models are very sensitive to how the resistance to flow varies over the river depth. It is proposed to assess the different contributions and their variation over the depth. Such a study should include local slope measurements (either with RTK-DGPS or AWLR or both) and flow measurements. Also it is advantageous to use 2-d flow models to integrate the results and to test assumptions regarding the contributions and distribution of resistance to flow.

(c) *Low resistance to flow during floods*

Special study into the cause of the extremely low resistance to flow observed in e.g. the Padma River during floods. Very high Chézy values have been found but mainly from mathematical modelling. There is an urgent need, also in view of the relevance of the topic for flow modelling, to verify and clarify this unusual phenomenon. As one possible explanation is that the very low resistance to flow is linked to boundary layer phenomena, detailed velocity profile measurements might be appropriate. Hence an essential part of this study is detailed field measurements of flow fields, slopes, bedform characteristics and velocity profiles.

(d) *Floodplain sedimentation*

Continuation of studies into floodplain sedimentation, analogous to the studies carried out by the RSP (see SPR-15). Purpose of proposed continuation is to better understand the intricate relationship between subsidence, sediment balances and floodplain sedimentation. Roughly, two types of field investigations is proposed: one where the yearly sedimentation during floods is measured at selected places, another where vibra-coring with dating is used to get an integrated picture of floodplain sedimentation over the past decades. Selection of sites will be based on satellite imagery and possibly 2-D modelling will be used to determine sediment routes into the floodplain and allow for later generalization.

11.5 Morphological studies

The morphological studies to be done in the future can roughly be divided into:

- *additional measurements* aiming at completing the data base on the main rivers in Bangladesh;
- *special studies* aiming at improving the understanding of the river behaviour, using this data base and doing special studies.

An overview of the additional measurements to be done and the special studies to be taken up on a priority basis is given in Appendix D, Table A4.4. A concise description of topic and the reason why it is proposed to be taken up on a priority basis is given below.

Topic		Proposed studies
Additional measurements	On regular basis	• Water and sediment distribution at offtakes • Scour holes
Special studies	Offtakes	• Historic development of offtakes • Water- and sediment distribution at offtakes
	Scour holes	• Natural scour: types, occurrence of natural scour, depths of scour, combination of scour types • Scour near bank-protection works (Jamuna Bridge, etc.)
	Prediction methods	• Prediction of short-term planform changes (quick assessment) • Prediction of short-term planform changes (using 2-d morphological models) • Probabilistic approach to mid-term planform prediction

Table 11.4 Proposed priority of study topics on river morphological characteristics (for more details see Appendix 4; for background information see Annex 5 and Study Report 1)

(a) *Water and sediment distribution at offtakes*

In view of the importance of the offtakes for the interior of Bangladesh it is proposed to collect on a routine basis the water and sediment transport distribution at some of the four important offtakes (Dhaleswari and Gorai and possibly the Old Brahmaputra). These measurements should be done on a regular basis (weekly?) during the flood season. In view of its importance the Gorai offtake should be measured together with the sediment transport in the Ganges upstream of the offtake throughout all years. For the Old Brahmaputra and the Dhaleswari it may suffice to rotate, hence concentrate on the Old Brahmaputra one year and on the Dhaleswari the next year. A plan for these measurements has to be developed, comprising which branch of the parent river and where in the distributary has to be measured, etcetera. Satellite imagery will be used during the interpretation of the results.

(b) *Scour holes*

Near bank protection works, around bridge piers and along guide bunds scour hole depths should be measured (and probably are). This should be done on a yearly basis during the flood season including the rise and fall. Probably these data are collected for a number of structures, but they are not stored centrally. It is proposed to make an inventory of any measurements carried out, to develop a programme for future measurements and to create a data base. This data base should include satellite imagery for interpretation as scour holes near river training/protection structures are in Bangladesh very much linked to the planform of the river.

(c) *Historic development of offtakes*

Study using available data (maps, cross-sectional soundings, satellite imagery, routine gauging, RSP results and any other, if relevant) together with geomorphological analyses on offtake behaviour to assess in an integrated way the historic changes of the various offtakes and to identify the possible cause of changes in offtake performance.

(d) *Water and sediment distribution at offtakes*

Field study of the water and sediment distribution at offtakes, in particular during the flood season and the subsequent fall. Concentrating on relative sediment intake. Interpretation in relation to the planform of the parent river, in particular the offtake angle, the presence of bars, and the water-level differences between parent river and distributary. Interpretation using among others existing knowledge on bifurcations and mathematical models, see (h).

(e) *Natural scour: types, occurrence of natural scour, depths of scour, combination of scour types*

In the main rivers of Bangladesh different types of scour have been observed: bend scour, confluence scour, (natural) constriction scour, and protrusion scour. For each prediction methods have been proposed, but these have to be verified and, if appropriate, improved. In particular prediction methods of scour depth in the case of combinations of different types of scour still have to be developed further. This can be done by a combination of field measurements and 2-D morphological modelling. In addition, the development in time of scour holes should be studied both in the field and in mathematical models.

(f) *Scour near bank-protection works (Jamuna Bridge, etc.)*

Increasingly, bank protections are being built along the main rivers in Bangladesh. Repeated measurements should be done at locations where heavy attack is occurring to determine the related local scour. This should be tested against predicted local scour during the design. For the interpretation also satellite imagery may be needed to identify the overall flow field on the basis of the observed bed topography.

(g) *Prediction short-term planform changes (quick assessment)*

There is a need for a quick assessment method to be used during the flood to predict changes that will take place during the fall. Promising attempts have been made on the basis of ADCP measurements (see e.g. Chapter 14 of Annex 5), and there is a need for further testing and inclusion of additional parameters like slope.

(h) *Prediction of short-term planform changes (using 2-D morphological models)*

Predictions of the bed topography after the next flood can be made using the bed topography measured at the beginning of the dry season. For this purpose 2-d morphological models can be used. Improvements of model performance should be based on a comparison of simulations with the models with developments in prototype, and possibly testing of the different modules to identify possibilities for improvement of the models.

(i) *Probabilistic approach to mid-term planform prediction*

The understanding of causes, effects and magnitude of bank erosion in braided rivers is still fairly limited. In line with existing planform models for meandering rivers, there is a need for prediction of planform changes of braided rivers. This should be done along the lines indicated by Klaassen et al (1993), hence a probabilistic approach. Such a model will be extremely useful in the planning of bank protection works.

11.6 Morphological impact assessment

Different from the previous chapters, here a separate section is included that deals with morphological impact assessment. The reason for it is that probably in the short term a project will start that will tackle this aspect. As a matter of fact, this morphological impact assessment addresses an aspect that was supposed to be covered by the River Survey Project when it was developed. After Phase 1 it was decided to have this aspect handled by a different project.

The future impact assessment of the new FAP27 (MIA - Morphological Impact Assessment) can build on what has already been done in FAP25 and in the River Survey Project. In FAP25 the hydraulic impact of some possible implementation scenarios was investigated. Under the River Survey Project this was extended by assessing the ultimate morphological impact of one - at that time - probable scenario. Furthermore, the intermediate conditions were indicated, though the time scale of these intermediate effects could be addressed only roughly. Another simplification was that the rivers were only considered as a sediment conveying network that can only change its slope. Alluvial rivers like the Jamuna and the Ganges, however, change also their other morphological characteristics. Hence the future MIA project has to

concentrate on intermediate conditions on the one hand and changes in other morphological characteristics on the other hand. This leads to two first priority projects (d and e hereafter). However, to be able to do that there are some studies which have to be carried out first. These studies are proposed to be carried out as first priority projects as well, as they are essential for performing the tasks d and e. These are:

- response of Old Brahmaputra and Upper Meghna morphology to historical changes in flow, as an example of how Bangladeshi rivers respond to changes in imposed variables;
- future development of offtakes, as input for 1-D modelling and modelling of river morphological changes;
- Computational frame-work for river morphodynamics.

These special studies, to be detailed hereafter, have to be carried out first before the formal morphological impact assessment can be done.

(a) *Response of Old Brahmaputra and Upper Meghna morphology to historic changes in flow*

After the avulsion of the Brahmaputra to its present Jamuna course, the Old Brahmaputra and the Upper Meghna have begun to adapt to the new imposed discharges and sediment loads. An impact study on the basis of historical data may yield quite interesting results which can be used in future morphological impact studies. Use can be made of (old) maps, satellite imagery, historical data in combination with mathematical models for testing of assumptions on river adjustment.

Topic	Proposed studies
Special studies	• Integrated morphodynamic frame-work • Future development of offtakes
	• Response of Old Brahmaputra and Upper Meghna morphology to historic changes in flow
Morphological impact assessment	• Impact assessment of implementation FAP/NWMP implementation (one-dimensional)
	• Impact assessment of implementation FAP/NWMP implementation (including planform changes and future offtake behaviour)

Table 11.3 Proposed priority study topics related to morphological impact assessment (for more details see Appendix 4; for background information see Annex 4 and 5 and Special Report 5)

(b) *Future development of offtakes*

Based on the results of the studies under (6), (7) and (8), development of possible scenarios for the future performance of the different offtakes along the different main rivers.

(c) *Computational frame-work for river morphodynamics*

Extension of the computational framework used in FAP21/22 (see Annexure 1 of Study Report no 1) using (1) RSP results, (2) results of some of the special studies proposed here and (3) developments elsewhere, to arrive at an integrated computational frame-work for river morphodynamics, allowing e.g. the morphological impact assessment of FAP/NWMP implementation. See also (31).

(d) *Morphological impact assessment implementation FAP/NWMP implementation (1-dimensional)*

Extension of morphological impact assessment carried out under this project (see Section 7.4). Use of a one-dimensional morphological model for intermediate conditions using existing data on the main rivers.

(e) *Morphological impact assessment FAP/NWMP implementation (including planform changes and future offtake behaviour)*

Extension of morphological impact assessment carried out under the RSP and study (14) proposed in Section A4.4, but now extended to include changes in braiding and/or meandering pattern and in cross-sections. Also offtakes should be included, including their future performance as well. The latter implies that also here a stochastic approach has to be used, as different assumptions about the development in time of the offtakes have to be included. This study will build upon many results obtained in special studies proposed above, but in particular on the topics (5) *Computational frame-work for river morphodynamics* and

(g) *Future development of offtakes, and preferably the results from (32) Response of Old Brahmaputra and Upper Meghna morphology to historical changes in flow as well.*

12 Recommended actions

12.1 Introduction

Several proposals on sustainable survey techniques, river behaviour studies and special studies were recommended for the future and discussed in previous Chapters. How best to take action on these recommendations? What should be the institutional measures and how are the capabilities developed of those institutions for handling these actions? These are some of the relevant questions one must address while an action is proposed. The latter is more an issue for addressing by the River Survey Project Adviser (PA). We concentrate on addressing the first question based on our experience while working on surveys and studies of the main rivers in Bangladesh. According to the Terms of Reference, the River Survey Programme *"will constitute the first phase of a longer term effort aimed at expanding and strengthening the collection of hydrological and morphological data and further developing understanding of the behaviour of the main rivers in Bangladesh"*. Although it is not yet clear how and when the next phase (expansion of data collection and further developing of the understanding) of this longer term effort will start, it is appropriate and in the spirit of this Terms of Reference to discuss in a last Chapter of this report steps to be taken for an implementation of the recommendations given in the previous Chapters.

In view of the uncertainty as regards to available external resources and institutional developments for data collection and study it is not possible to propose a precise programme for implementation of the different recommendations. Rather a list of required activities is given here. At a later stage this has to be converted into an Action Plan. Data collection on the main rivers in Bangladesh over the last decades has been an enormous effort and much of the present understanding could only be derived on the basis of the large data set which has been assembled. There is, however, an urgent need for certain re-arrangements in the data collection as modern instruments and methodologies, including remote sensing (not necessarily limited to satellite imagery), are creating new opportunities for more optimal data collection. At the same time, the increased understanding of the behaviour of the main rivers, substantially improved over the past ten years due to some projects and studies, should in Consultants view be anchored within Bangladesh. This is the real challenge for the coming decade: to optimize the data collection in Bangladesh under conditions of quickly improving measuring techniques and changing needs within the society, and to make sure that this data collection is beneficial for the sustainable development of Bangladesh.

The most appropriate possible actions outlined in Table 12.1 are discussed according to the following subjects:

- survey techniques,
- studies and,
- institutional aspects.

Measures for Implementation	RECOMMENDED ACTION		Type of Action	Actors/ Agencies	SPECIFIC ACTIONS	Time frame and frequency
	Description	No				
Measures re measuring platforms and techniques	Improvements measuring vessels	M.1	Project	BWDB-Hydr	1 refurbishing large vessels; 2 improvements catamarans	Ongoing and afterwards when need arises
	Improved positioning: introduction DGPS and training	M.2	Project	BWDB-Hydr/-Morph	1 purchase DGPS systems; 2 installations wall station for Hydr and Morph; 3 development new procedures; 4 training	Ongoing
	Other (minor) improvements in hydraulic and sediment transport measurements	M.3	Project?	BWDB-Hydr	1 purchase echo-sounders plus batteries; 2 installation on catamarans; 3 development new procedures; 4 training	Once (briefly)
	Improved cross-sectional measurements	M.4	Instruction	BWDB-Morph	1 new instruction for levelling; 2 adaptation programmes; 3 use of satellite imagery for positioning in field	Once (briefly)
	Introduction ADCP and other advanced equipment and training in the use	M.5	Project	SSU (see below)	1 establishment requirements; 2 selection of type of platform and techniques; 3 purchase of platforms and instruments; 4 training	Together with establishment SSU
	Improved quality control	M.6	Instructions	BWDB-Hydr/-Morph/SWMC/-EGIS	1 implementation RSP recommendations	Once (immediately)
Measures re data storage and presentation	Extension of data bases	D.1	Project?	BWDB-Hydr/Morph	1 selection or design of data bases for bed material, sediment transport, etc.; 2 data entry	Immediately and continuous
	Publishing of data books	D.1	Project?	BWDB-Hydr/-Morph?	1 contents data books and link with data bases; 2 design data books; 3 preparation data books	Within five years and continuous
Institutional measures	Regular review of measuring activities	I.1	Policy/Project	BWDB-Hydr/-Morph/BIWTA/-others	1 identification of interest groups (users); 2 advice in view of use and effort required; 3 meeting for taking decisions on changes	Every five years
	Institutional measures for quality control	I.2	Policy/Project	BWDB-Hydr/-Morph	1 advice on institutional changes to allow for improved quality control; 2 implementation	Once (in three years) and continuous
	Improved maintenance	I.3	Project	BWDB Hydrology (assistance BUET?)	1 improvement equipment workshop; 2 establishment electronical capability	Once (workshop) and rest linked with SSU
	Establishment Study Group Large Rivers (SG-LR)	I.4	Project (combined with FAP27-MIA?)	To be decided: BWDBHydr/-Morph/SWMC/WARPO	1 decision on institutional setting; 2 establishment interest group; 3 (rolling) work programme; 4 capacity building; 5 development linkages with other institutions (also from abroad)	Once (within three years)
	Set-up Special Survey Unit (SSU)	I.5	Project	BWDB Hydr/SWMC	1 decision on institutional setting; 2 establishment interest group; 3 (rolling) work programme; 4 capacity building; 5 development linkages with other institutions (also from abroad)	Once (within three years)
	National storage of "water" (river/coast) databases	I.6	Project	To be decided: BWDBHydr/-Morph/SWMC/WARPO/-EGIS	1 decision on institutional setting; 2 establishment interest group; 3 (rolling) work programme; 4 capacity building; 5 development linkages with other institutions (also from abroad)	Once (immediately)

Table 12.1 Proposed actions for implementation

12.2 Survey techniques

In the earlier Chapters equipment and methods are recommended for a future gauging strategy for Bangladesh based on RSP experience as reported in RSP special reports 11 and 12. What is the best way to implement these recommendations for pursuing a sustainable gauging strategy? One may group the whole array of hydraulic surveying practices in some disciplines and the available options for the best implementation of the recommendations are discussed as follows:

12.2.1 Establishment of dependable survey facilities

- As far as possible, the selected vessels within different relevant organizations should be renovated and upgraded or perhaps replaced in order to be able to handle advanced equipment and ensure all-season work.
- In most existing survey vessels, instrument handling accessories such as davit, winches, etc. are not at an adequate operational level. They need upgrading as well.
- Existing vessels do not have any radio communication systems with the survey operation manager stationed at the office. This is a vital link necessary during survey and should be established.
- Most existing survey practices are dependent on inaccurate positioning systems such as Decca Navigation system, sextants and theodolites. More advanced and accurate DGPS system should be established at a national level as a multi-user system.
- As will be discussed later, the above facilities should be available within institutions which has the experience, expertise and relevant resources.
- It is proposed to establish a special survey unit to conduct special dedicated surveys. This unit is probably required because it is not sustainable to install advanced facilities required for such surveys in vessels engaged in routine operations. Initially, external resources would be required to establish such a unit. However, the future market for such establishment should be explored before any initiative is taken.

In Table 12.1 some action types are indicated against relevant existing institutions in Bangladesh. With the existing government agencies such as BWDB Hydrology and Morphology Directorates, and BIWTA, the survey facilities are at the marginal level. They need further improvement, if all-season survey has to be pursued. The facilities of BWDB catamarans are inadequate for handling new types of equipment.

12.2.3 Instrumentation

- With most government institutions, the existing measuring instruments are at their marginal level. They need replacement with improved ones.
- On bed-profile measurements, the existing devices should be replaced by single frequency echosounders.
- For velocity and discharge measurements, the non-directional propeller current meters should be replaced with directional ones. Preferably advanced electronic sensors should be used.
- The instantaneous Binckley sampler used for suspended sediment sampling by BWDB should be replaced by time-integrating devices.
- As part of a special survey unit proposed earlier, advanced instruments should be installed in order to ensure a detailed and accurate survey of different parameters.

12.2.4 Efficient and accurate measurements

Measurements can be divided into routine measurements and special measurements (see also Section 10.3). The results obtained by the River Survey Project demonstrate that well-devised special measurements can be decisive in improving the understanding of the behaviour of the main rivers. The consultants feel that there is a need for the continuation of this type of special surveys, though on a smaller scale. Already in Section 10.9 an overview is given of the measuring methods and instruments which should be used during these surveys.

For a Special Survey Unit, special vessels should be used, their design being based on the experience obtained by the RSP over the four years of the project. The studies should be carried out by specialised personnel, supported by staff that is involved in the analysis of the data. Also here a linkage with a foreign institute specializing in river surveys is a prerequisite for the first period of functioning of the special survey group. The staff of the group should be trained abroad in carrying out these surveys, and in the elaboration of the results. They should have a good understanding of the inaccuracies involved in measuring in these major alluvial rivers in view of the extreme temporal and spatial variation of the different relevant phenomena.

An efficient and accurate measurement is possible only if:

- required survey facilities and instrumentation exist as per objectives,
- an efficient and trained survey crew is available who understands the operational mechanism and accuracy of instruments, the methodology of gauging, and have some knowledge of the river behaviour,
- an effective link is established with the operational manager of surveys for necessary backstopping and advice.

For efficient and accurate measurements, an optimal measuring method should be followed. For example, although a velocity-area-method of discharge estimation has a universal applicability, a moving boat method with ADCP can prove to be efficient and accurate in these large rivers.

12.2.5 Data storage, elaboration, quality control and dissemination

Data elaboration is an integral part of the survey, its efficient management is necessary in order to ensure an accurate data processing. As it is well known, data validation and quality control should go hand in hand together with data elaboration activities. In addition, an effective mechanism should be developed to ensure proper dissemination of the collected information.

Storage of data in easily accessible data bases is a large advantage for quality control, for the use of data in studies and for the supply of data to third parties. Part of the data on the main rivers of Bangladesh has been entered into the data-bases (see Section 3.4) by different organizations and the RSP. Also most of the River Survey Project data is available in the form of data-bases. The overall status can be summarized as follows:

- hydrological data from the BWDB and from the RSP available in the HYMOS data storage and retrieval system;
- BWDB sediment transport data are available in spread sheets made by the RSP;

- cross-sectional data of BWDB Morphology are only partly digitized and stored in spreadsheet;
- RSP routine gauging data and other RSP data are available in the PSD24 data base;
- RSP bathymetric soundings have been stored as MIKE 21 files and in ARC/INFO GIS system together with some other data;
- LANDSAT (and some other) satellite imagery (1973-now) available via ERDAS.

There is an urgent need for consolidating and harmonizing the various data-bases. At present a Morphological Database is being set up with EGIS which can be used advantageously for morphological studies. A separate study should be carried out into the need for the further development of databases. Which organisation should be responsible for their maintenance, how can they be interlinked and be made available to other parties? Furthermore there is an urgent need for training of staff from Bangladesh institutes in the development, maintenance and use of databases.

12.3 Studies

There is a need for the establishment of a study unit specializing in studies of the hydrology and the morphological behaviour of the main rivers in Bangladesh. The group should consist of a well-balanced combination of well-trained scientists and people with more practical experience in monitoring closely the behaviour of the main rivers of Bangladesh. Right from the beginning this group should be entrusted with studies aiming at practical results like predictions of short- and medium term of river behaviour. Furthermore, they should initiate special surveys to study certain aspects of river behaviour. It is probably advisable to entrust to this study unit at a later stage also studies on water quality and fisheries. Linkages with leading foreign institutes should be encouraged, as this may be very important for training of staff, for attaining a sufficient standard and for quality control. In view of the importance of rivers in Bangladesh and the future use of the expertise of foreign institutes, external resources should be made available.

An important aspect of studies should cover the hydro-morphological impact assessments of engineering and other interventions.

12.4 Institutional aspects

12.4.1 Introduction

How best to institutionalize the recommended actions? What are the relevant institutions? How are their resource-base developed? These are some of the relevant questions we tried to address in this section.

In view of a statement in the Terms of Reference regarding the duties of the PA *"To advise FPCO on possible institutional development need for an extended programme and intensified surveys and studies of the river system of the country"*, the observations on institutional aspects in this Chapter can be limited. It is preferred to indicate some boundary conditions which in the view of Consultants have to be fulfilled to make sure that the collection of hydrological and morphological data is useful for the further development of the resources of the country. Figure 12.1 shows a schematic diagram indicating the possible institutionalization of the recommended actions.

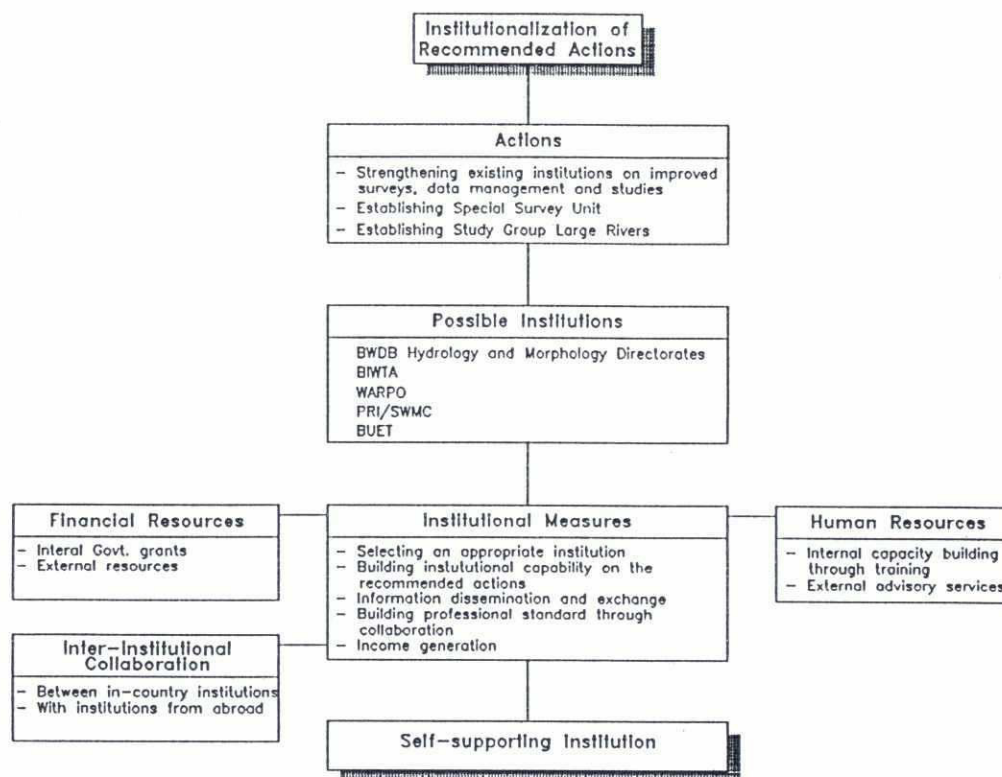


Figure 12.1

12.4.2 Institutional measures

A first requirement is that there should be an institutionalized, regular review of measuring activities versus the need for data inside Bangladesh, improved measuring techniques and budgetary limitations. The different institutions that are involved in data collection (BWDB, BIWTA, Railways, etc) in Bangladesh should take part in this regular assessment to allow for proper coordination. Such a review should be done considering the data need of the different users of the data. Finally it may be needed to establish in due time a small group that keeps track of modern developments in the field of data collection to regularly advise the review meeting on better and/or more optimal ways of data collection, and data storage and retrieval. This is needed particularly in Bangladesh as the task of data collection is enormous due to the many rivers playing a role in the whole network, their dimensions and their extreme movability. As long as up-to-date expertise on measuring techniques is not available in-country it may be necessary to use external advisory services on a regular basis, but doing this it should be ensured that consolidation of know-how is taking place to make this type of services superfluous in due time.

Another important matter is institutionalized quality control. The institutional arrangements must be such that quality control is ensured. One way to reach this is to let staff, working in field data collection, also be involved in (i) the elaboration of the data and in (ii) quality control via comparison with similar or complementary measurements. Another way is to use the collected data in an early stage in studies of the behaviour of the rivers. This allows for early identification of outliers and at the same time it will challenge the staff to test develop-

ing concepts on river behaviour. The publishing of yearbooks with validated data on river stages, sediment transport, cross-sections, etc. should be encouraged. Budgetary changes should be implemented (or institutional changes be made) to allow for improved maintenance of instruments including quick import of spare-parts while the staff of the data collection unit should be strengthened with electro-technical capabilities and a well-equipped workshop. An upgrading of the Morphology Department of BWDB is urgently needed, together with budgetary possibilities for purchase of satellite imagery plus introduction of GIS and other software. This will allow for improved quality control e.g. via quality checks of cross-sections using satellite imagery.

There is a need for the establishment of a study unit on hydrology and morphology of the main rivers of Bangladesh. Aspects to be considered are:

- where such a unit should be established (potential candidates for housing such a unit are BWDB Hydrology/Morphology, WARPO, RRI/SWMC);
- need for special measuring unit for study purposes;
- links with other activities (combined with operational tasks like floodplain management or flood management? link with EGIS?).

The future Morphological Impact Assessment project can form a nucleus for the development of such a study unit.

In addition to its bathymetric survey programme, BIWTA is most actively involved in small-scale temporary works in the main rivers, via both maintenance dredging and via bandalling. In view of the rapidly developing understanding of the behaviour of the main rivers, it seems appropriate to upgrade the morphological knowledge within BIWTA with the establishment of a small group which should specialize in making short- and medium term predictions of morphological changes. The alternative is to let these predictions be made by the study unit proposed in the previous section. An obvious disadvantage of having a group outside BIWTA involved, is that the important aspect of "learning by doing" is not ensured in this way.

A last aspect to consider is whether institutions responsible for data collection and/or the proposed study unit should be part of a public institution or should be privatised. Important aspects are possibilities for income generation via selling of data, carrying out of studies and/or assisting in projects. Initially funding would be needed from donors for setting up a privatised organisation in view of the institutional changes required.

12.4.3 Financial resources

The scope of income-generation by the relevant institutions engaged in basic data-base development in hydro-morphology is very limited. The practice of income-generation by selling the collected data is not adequate to meet the entire expenses. The organizations, instead are heavily dependent on government grants and external resources. Experience shows that government grants for such activities are far from adequate affecting the quality and quantity of works of such institutions. It seems practical that until government capabilities are enhanced, external resources should be sought from the development partners. Such resources should be used in such a way that the concerned institution becomes self-sufficient in due course.

Some cases where such external resources can be sought are the following:

- Improvement and/or replacement of survey facilities such as vessels, instrument handling accessories, communication equipment, positioning systems, etc. The relevant organizations are the BWDB Hydrology and Morphology Directorates.
- On several sectors of instrumentation such as procuring echosounders, velocity measuring devices, suspended sediment samplers, etc. external resources would be required. The relevant organization in this regard is also BWDB.
- External resources are also required for establishing the Special Survey Unit. The best possible institution to administer such an unit should be determined. The BWDB is a possible option. As indicated earlier, other institutional options should also be considered.
- Advisory/consultancy services would be required on data elaboration and quality control activities and establishment of a Study Group Large Rivers.

12.4.4 Human resources

A skilled and properly trained human resource is a must for an effective functioning of an institution. Inadequacy of such work force is obvious in many relevant institutions. This inadequacy can be interpreted both in terms of required skill and the number of such personnel. The policy of human resources development can be pursued in the following way:

- A good development of human skills on different aspects can be obtained through on-the-job training in the externally aided projects.
- Secondly, people should be trained abroad on the relevant field with a clear indication that such training has an application.
- An important aspect of human resources development is that such people should have a scope of career development.
- Measures should be taken to retain and consolidate the generated expertise and practical experience.

12.4.5 Inter-institutional collaboration

Inter-institutional collaboration between in-country institutions within Bangladesh and between Bangladesh and institutions from abroad is very helpful for enhancing professional standard.

- The in-country collaboration is required for a healthy exchange of views and information for mutual benefit of participating institutes. This will prevent duplication of works and raise professional standard. The relevant collaborating agencies can be the government agencies, service institutes, consultancy firms and university research institutes.
- Collaboration with institutes from abroad is helpful in a similar way. Scientists from abroad can learn from Bangladesh rivers while Bangladesh professionals can benefit from the research experience of the overseas scientists.

Glossary

Terms or explanations marked with an asterix (*) relate specifically to the RSP (River Survey Project). Cross-references are printed in *italics*.

Absolute accuracy: The *accuracy* of a value when compared with a general standard. The absolute accuracy is important when comparing data from different contexts, such as different projects or survey programmes. To be distinguished from *relative accuracy*.

Accuracy (of a survey instrument): The compliance between a *true* and a measured value, expressed in the physical unit of the value, and often expressed as the (estimated) standard deviation. For a given instrument, the accuracy is normally related both to the instrument itself and to the actual procedure for its application, notably including the applied *calibration* procedure. The accuracy can often be improved by repeating a measurement several times.

*** ADCP moving boat method (or ADCP-DGPS method, or ADCP-EMF method):**
The same as *recommended method*.

Analysis (of river data): Processing, involving a sometimes comprehensive transformation, in order to arrive at the intended information that was the objective of the measurements. Data analysis is often carried out stage-wise and in different contexts. In general, data analysis involves both hidden and explicit assumptions about the relation between primary data and final results. (As one example, a flow rate can be calculated assuming that a set of current measurements were made simultaneously, even if it took a whole day). Such assumptions can affect both the *accuracy* and the *validity* of the results. A suitable *quality* is supported by an adequate *transparency* of the analysis.

Andreasen settling tube test: A standard method for determination of settling velocity distribution of suspended sediments, by successive bottom withdrawal of small sub-samples from a large-volume (25 l) sample of suspension. The sub-samples are taken after a fixed schedule that can extend over several days. For each sub-sample, the sediment concentration is determined (by micro-filtering), whereafter the settling velocity distribution can be calculated. Also, the grain-size distribution can be calculated by a relation between the settling velocity and the grain size.

Backscatter registration (by an ADCP): Registration of the intensity of the reflected signal, which is related to the grain-size distribution and the concentration of suspended material of the water column. For a given grain-size distribution, a well-defined relationship can be established between the backscatter registration and the sediment concentration. The method is new and is not yet fully proven, but can potentially provide details about the sediment transport. * Its viability in the rivers of Bangladesh was examined during the RSP.

Bathymetric survey: Mapping of riverbed or seabed elevations (normally by water depth measurements by echo sounding).

Bed material: Sediment (fine or coarse) deposited by the river and composing the riverbed. To be distinguished from suspended bed material, which is coarse suspended sediment (* with a grain size above 0.063 mm).

Bedforms (of a river): Morphological features of the riverbed, for example sand dunes.

Bed load: *Bed material* transported immediately above the riverbed, and in almost continuous contact with it, carried forward by rolling, sliding or hopping.

Bin (of an ADCP instrument): The volume over which each velocity *sample* is averaged. The ADCP measurements cover a conical water column, that is divided into segments (bins) of equal heights. The bin height depends on the selected mode of operation (within the limits of the depth *resolution* of the instrument, which is in turn related to its *frequency*).

Bottom tracking (of an ADCP instrument): Just like the instrument can measure the movement of the water relative to the vessel, it can also measure the apparent movement of the riverbed relative to the vessel. This is called bottom tracking. Bottom tracking gives an accurate description of the vessels trajectory across the river during the flow gauging. * During high flows, RSP experienced that the riverbed was 'moving' (due to a high bed load); under such conditions, bottom tracking was not possible, so the relative positioning had to be carried out by DGPS instead.

BTM (Bangladesh Transverse Mercator) grid: A geodetic projection of the Mercator type, which features a true projection of angles and a slightly distorted projection of distances. The grid is aligned with the 90° east meridian. The scale distortion is small, and the grid coordinates, *eastings* and *northings*, are approximately orthogonal. They are given in m or km from a defined point of origin located southwest of Bangladesh (whereby all coordinates within Bangladesh become positive).

Calibration (of a survey instrument): Measurement of a set of values that are, at the same time, also measured by other, more accurate means, in order to determine a systematic *error* of the instrument (for subsequent compensation).

Concentration (of sediments in a sample): Mass or volume of sediments in a *sample* relative to the mass or volume of the entire *sample*. Can be expressed for example as weight percentage, volume percentage, or kg/m³.

* **Concentration method (for sediment transport gauging):** Calculation of the sediment transport by multiplying a *concentration* with a *flow* rate, which have been measured simultaneously, but independently. To be distinguished from the *transport method*.

Consistency (of survey data): Compliance between the *quality* of different data sets, produced by different methods, or at different places, or at different times.

Current velocity: The rate of movement of the water (in m/s). The velocity is a vector, which is either described by a speed and a direction, or by 2 or 3 orthogonal components.

Data assimilation: Statistically optimized estimation of the state of a system that is over-specified by a combination of time series of measured state variables and (physical) relations between them. Data assimilation can be done by integration of field measurements and model simulations, with the objective of improving their joint *quality*.

Datum: A defined vertical reference level (for water levels, bed levels, or land elevations), for example *SLW* or *PWD*.

Density: (1) mass per unit volume (for example given in kg/m^3), (2) number of measurements per unit area or unit distance (opposite of spacing).

Depth reduction (of bathymetric soundings): Conversion of depth measurements to the applied *datum*. * RSP measured depths by echo sounding relative to the survey vessel (or relative to the surface of the river). The depth reduction (to *SLW datum*) was made by gauging of the water level at a place where *SLW* was defined, specifying the actual water-level *slope* during the measurements and assuming that this slope represented the slope of the *SLW* between the water-level gauge and the survey vessel.

* **Discharge:** (1) integrated net *flow* through a fixed cross-section of a river, (2) net sediment transport through a fixed cross-section of a river.

* **Easting:** East coordinate in the BTM grid, given in m (6 digits) or km (3 digits). Easting = 500 km + the distance (positive towards east) from the 90° east meridian. Hence, per definition, the 90° east meridian has an easting of 500. For example, the easting of Gulshan (at the SoB primary bench mark) is 542.

Error (of a survey instrument, a survey procedure, or a calculation method): The difference between a *true* and a measured value, or between a desired and an actual value. Errors are inversely related to *accuracy* and *validity*. They can be random (stochastic) or systematic.

* **Feature mapping:** Mapping of land surface characteristics (embankments, structures, vegetation, etc.), for example for interpretation of satellite imagery.

Flow (in a river): Volume transport per time unit, expressed in m^3/s , either locally (at a point), or over a cross-section.

Frequency (1) (of data logging): Number of units (for example *samples*) per time interval. (2) (of an echosounder or an ADCP): The frequency of the transmitted and reflected sound wave. * RSP used 210 kHz and 30/210 kHz echo sounders, and 300 kHz and 600 kHz ADCPs.

Gauge: A device for measuring water level or pressure.

Gauging: Measurement at a fixed point.

* **Geodetic survey:** Mapping of geodetic coordinates (of bench marks, reference stations, etc.)

Hydrograph: A time series of water levels at a fixed location (either measured or calculated by a model).

Hydrostatic levelling: Datum transfer by means of a still fluid (water) in a long tube, for example across a river. Provided (i) that the air pressure is the same at both ends of the tube, and (ii) that the fluid has a homogenous density (unaffected by e.g. temperature gradients), the fluid surface at each end will adjust to the static pressure, as determined by the gravity field along the tube, so that the two surface levels adjust to a horizontal surface.

* The method was not applied by RSP.

Length scale: A distance that is characteristic for a specific phenomenon (for example a wave or a sand dune). In order to describe the phenomenon, a fair number of measurements must be done within one length scale.

Mapping: Measurements covering a certain area. To be distinguished from *gauging*.

Morphology (of a river): (1) its shape, (2) the study of states, processes and effects related to the shape of a river.

Moving boat method: Flow gauging by a continuous single-point current *record*, measured from a vessel crossing the river from one bank to another, first in one direction, and afterwards in the opposite direction.

* **Near-bed sediment transport:** Sediment transport in the lowest part of the water column, where the concentration of *bed material* is usually highest, but where sediment sampling and flow measurements are for practical reasons particularly difficult.

* **Northing:** North coordinate in the BTM grid, given in m (6 digits) or km (3 digits). The northing = the distance to equator minus 2000 km. For example, the northing of Gulshan (at the SoB primary bench mark) is 631.

Off-line processing (or post-processing) (of survey data): Data processing carried out after completion of the field work.

On-line processing (of survey data): Real-time data processing onboard the survey vessel, one objective being to monitor the data *quality* and data coverage, so that measurements can be repeated immediately, if needed. * RSP applied on-line processing of position, current, flow and depth data.

Procedure (for a river survey): The combination of instruments, software and practices applied for arriving from one point in the data flow to a subsequent point, for example for different types of field measurements, collection of *samples*, laboratory analysis, and data analysis.

PWD = Public Works Department datum: A horizontal datum applied by PWD, BWDB and others. It is defined by a network of SoB and BWDB benchmarks with a specified elevation above PWD. Its zero level is located 0.46 m below the Mean Sea Level defined in 1909.

QUALITY: The compliance between a desired and an actual property (or set of properties). Within river surveys, quality characteristics can comprise *accuracy*, *consistency*, *resolution*, *transparency*, *validity*, costs, and several other aspects.

Range (of a survey instrument): The interval between the lowest and the highest value it can register.

Rating curve: A specific *stage-discharge* relation for a given cross-section and a given *gauge* location, used for calculating time series of flow or sediment transport on the basis of time series of water level and discrete measurements of flow and/or sediment transport.

* **Recommended method = ADCP moving boat method:** Flow gauging from a moving boat by ADCP, supplemented by an EMF deployed near the surface, with DGPS positioning.

Record: Set of related data, either a time series (for example of water level), or an array (for example of position, depth, and current velocity), or a time series of arrays.

* **Reference method:** Flow gauging by single point measurements from a moored vessel in a number of verticals across the river (e.g. by an S4 electromagnetic current-meter and/or by an Ott propeller-type current-meter). The flow is calculated by a velocity-area method.

* **Registration:** Same as measurement and same as recording, is sometimes distinguished from observation (which involves some elements of arbitrary judgement).

Relative accuracy: The *accuracy* of two values when compared with a common, but not necessarily general standard, for example two recordings by the same instrument with an unknown, systematic error. The relative accuracy is important when comparing different values, for example when determining the distance between two vertical profiles by subtracting their positions, or when determining a riverbed erosion by subtracting two successive bed level measurements. The relative accuracy of many measuring methods is better than (and is always at least equal with) the *absolute accuracy*.

Resolution (of a survey instrument): The smallest increment of the *true value* that can be registered. The variation can be in time, space, or with respect to the measured value (current speed, water level, etc). The resolution is not related to the *accuracy*. For a given instrument, the resolution is normally related to the procedure for its application. A distinction can be made between nominal and actual resolution, the latter being affected by the deployment of the instrument and by the physical environment. For example, an S4 current meter (in its standard *range*) has a resolution of 0.2 cm/s if mounted on a fixed frame, but less if suspended by a cable. As another example, the actual resolution of a staff gauge is affected by waves. The resolution of most propeller-type current meters represents one revolution of the propeller.

* **Retarded scour:** The term is usually applied to indicate riverbed scour during the falling river stage in the shallow crossings between two meander beds.

* **Routine gauging:** Repeated measurements by RSP of flow and sediment transport (by the *recommended method*) at eleven cross-sections on the main rivers of Bangladesh.

Runline: A well-defined line along which measurements are carried out. It is good practice to retain runlines for successive surveys, in order to improve the *validity* of comparisons between the results.

Sample (1) (of water, suspended sediments, or riverbed sediments): A portion of water, suspension, or the riverbed collected for laboratory analysis, (2) (by an electromagnetic instrument): A single-pulse registration. Such samples are often averaged over some period of time in order to improve the *accuracy* of the registration. Often, this averaging is done by the instrument itself, so that only the average value is stored. For many such instruments, the sampling *frequency* and the averaging period can be selected by the user within certain intervals, depending on the purpose and the physical environment.

*** Sand dune tracking:** A method for determination of *bed load*. The progression of sand dunes is measured by repeated mappings (by side scan sonar and/or echo sounder), and the associated volume transport is calculated, assuming (1) one-directional transport, and (2) no transport takes place below the base level of the dunes.

Settling velocity: The (downward) velocity of a sediment particle in still water. The settling velocity depends on the grain size, density, and shape of the particle, and on the viscosity (or temperature) and density of the water. It can be measured (in a settling tube) or calculated (from the grain size, often assuming that the particles are spherical).

SLW = Standard Low Water datum: A datum representing the water level that is exceeded in 95 percent of the time. Hereby, the slope of the datum (approximately) follows the dry season *slope* of the river surface, inclining downwards towards the sea. The present SLW was defined at a number of gauge locations by BIWTA in 1990.

*** Special surveys:** Surveys executed by RSP for dedicated non-routine purposes, normally related to the study component of the Project.

Spheroid (for geodetic mapping): An assumed, simplified, but geometrically well-defined shape of the earth. An example is 'Everest 1830', which is applied by Survey of Bangladesh. Several variants of this spheroid exist and have been applied on different occasions.

*** Staff gauge levelling:** Transfer of *datum* across a channel by simultaneous staff gauge readings for a certain period of time at each bank. In the case of unknown or irregular *surface slopes*, the *validity* of this method is doubtful.

Stage: Water level at a given location, e.g. at a *gauging* station.

Surface slope: The (local or general) inclination of the river surface, relative to a horizontal plane, and positive in the downstream direction. For a given cross-section (with a given roughness and a given hydraulic radius), the slope is related to the flow in a well-defined way. * Typical average slopes of the rivers of the RSP survey area are between 2 cm/km (Upper Meghna) and 8 cm/km (Jamuna).

*** Survey:** A specific programme of (related or unrelated) field measurements.

*** Survey spread:** A set of facilities (instruments, software and hardware for data registration, position control, communication, data administration, power supply, etc.) installed onboard a vessel.

Threshold value (of a survey instrument): The smallest deviation from zero (of the *true value*) that can be registered.

Time scale: A time interval that is characteristic for a specific phenomenon (for example a turbulence pattern or a tidal variation). A description of the phenomenon requires a fair number of measurements within one time scale. By averaging a *data record* over several time scales, the phenomenon will become concealed.

Topographic survey: Mapping of land elevations.

Transparency (of a survey or data analysis procedure): The insight conveyed to the data user about how the data were produced, for example for assessing the *validity* of the data for a given, possibly unforeseen, purpose. An acceptable transparency is obtained by documentation and can be supported by using standard methods.

*** Transport method (for sediment transport gauging):** Direct registration of the sediment transport by a sampling device (for example a Delft bottle) that has been designed and calibrated so that the mass or volume of a collected sample reflects the sediment transport. To be distinguished from the *concentration method*.

True value (of a physical characteristic within river hydraulics): An ideally correct value, determined without any errors whatsoever. A true value can be instantaneous or averaged over a certain period of time, and it can relate to an infinitesimal point or be averaged over a certain length, area or volume.

*** Umbilical:** Single-string suspension cable for an aggregate device for sediment sampling by pumping, current, depth and tilt measurements, and turbidity measurements. The umbilical consists of a tube (for flow), surrounded by conductors for power supply and transmitted signals. It replaces a number of separate tubes, cables etc. that could become entangled during deployment.

Validation (of survey data): Confirmation of the data *accuracy* by comparison with independent measurements of the same values. For example, an acoustic water-level recorder may be validated against staff gauge data. Validation can provide for elimination of systematic *errors* related to the survey procedure, and can, if carried out regularly, identify the time of occurrence of errors appearing as stepwise deviations between time series.

Validity (of survey data): The compliance between a desired value and an actual value. Even if both are *accurate*, the validity can be low, for example due to time and space variations (such as measuring current for determination of flow in a few points and over a few seconds only).

Wash load: Transport of suspended fines (* with a grain-size diameter below 0.063 mm)

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Appendix A

Overview of Survey Bulletins and Data Books

General

The data reporting of the RSP is done at three levels:

- (1) the *Survey Reports*, one for each survey, with descriptions of the data collection. These reports were for internal use and were used during post-processing and quality control;
- (2) the *RSP Survey Bulletins*, one for each survey. These reports contain descriptions of the time and place of the survey, a summary of the survey programme, an extract of the results, and a listing of data files; and
- (3) the *RSP Data Books*, covering (i) January 1993 - March 1995, and (ii) April 1995 - March 1996. These reports contain comprehensive extracts from the Survey Bulletins: The time and place of the survey, a summary of the survey programme, an extract of the results, and a listing of data files. In addition, the Data Books present hydrographs, and rating curves for flow and sediment transport.

The water level recordings are described in *RSP Special Report 2: Water level gauging*, and the data are stored in the HYMOS database. The bathymetric surveys are described in *RSP Special Report 3: 'Bathymetric Surveys'*, and the data, organised as x-y-x files and as finite grid tables, are stored in PSD24.

The structure of the data reporting is shown in Figure A1.1. For an inventory of all RSP surveys, together with their Survey Bulletin numbers, please refer to Appendix A of *RSP Final Report Annex 1: 'Surveys'*.

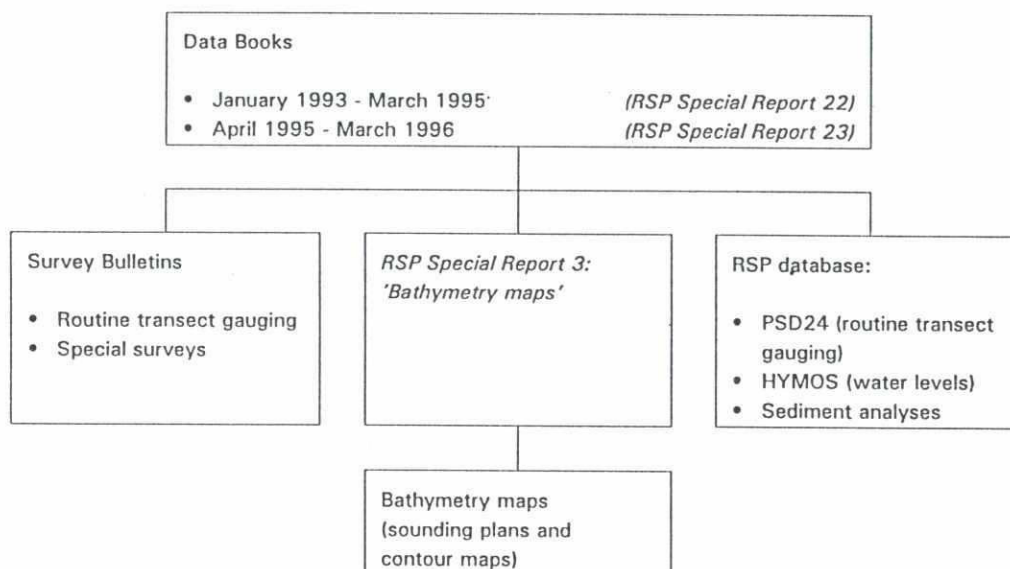


Figure A1.1 Data reporting of the RSP

Survey Bulletins

One Survey Bulletin was prepared for each routine gauging of flow and sediments and one for each special survey. The former are numbered from 1 and upwards, whereas the latter are numbered from 9000 and upwards.

The objective of the Survey Bulletins is to describe

- where, when and how each measurement was made;
- the hydraulic regime during the measurements; and
- the storage of the data.

In order to confine their volume, as a principle, the Survey Bulletins contain only information that is specific to each survey. General descriptions of instruments, procedures and data administration are reported elsewhere.

Each routine gauging Survey Bulletin is organised as shown in Table A1.1, while the ones for special surveys are adapted in accordance with their scope, whereby they become less standardized. The Survey Bulletins are incorporated as a part of the Data Books.

- | |
|---|
| <ul style="list-style-type: none"> • A location map, showing river planform, water level gauge(s), and the cross-section(s) where the measurements were made; • Cross-section geometry of each channel, showing location of the verticals; • Table of survey programme as made (by type, and number in each channel); • Summary table of results: Stage, flow, total suspended sediment transport, total bed load; • Presentations of horizontal distributions of flow and sediment transport (by channel): Depth; unit discharge; unit transport of wash load, suspended bed material load, bed load, and total sediment transport; and D_{50} of suspended load, bed material load and bed load; • Cross-sectional flow distribution (iso-velocity contours, by channel); • Grain size distribution tables (by channel, vertical profile, and sampling depth): Suspended load, near-bed suspended load, bed load, and bed material; • Data catalogue with file names: ADCP/EMF transects, vertical current/turbidity profiles, suspended sediment (profiles or depth-integrated), and bed load sampling; and • A summary table of PSD24 data files. |
|---|

Table A1.1 Contents of an RSP Survey Bulletin

Data Books

There are two RSP Data Books: One covering the data collection until end of March, 1995, and one covering the remaining part of the programme.

The aim of the Data Books is to give an outline of the data produced by RSP. Brief data summaries are presented, and catalogue entries are listed for the period covered by each Data Book. The Data Books are divided into:

- A text volume, which describes the data collection and coverage, and presents hydrographs, rating curves, and summary tables of water levels, flow and sediment transport;
- a data catalogue for the routine gauging, with details about the completed measurements, together with summary presentations of flow and sediment transport from the individual surveys. Also, this part contains a full catalogue listing of the collected data and their storage; and
- a data catalogue with similar information about the special surveys.

The data catalogues are identical with the sets of Survey Bulletins for the period covered.

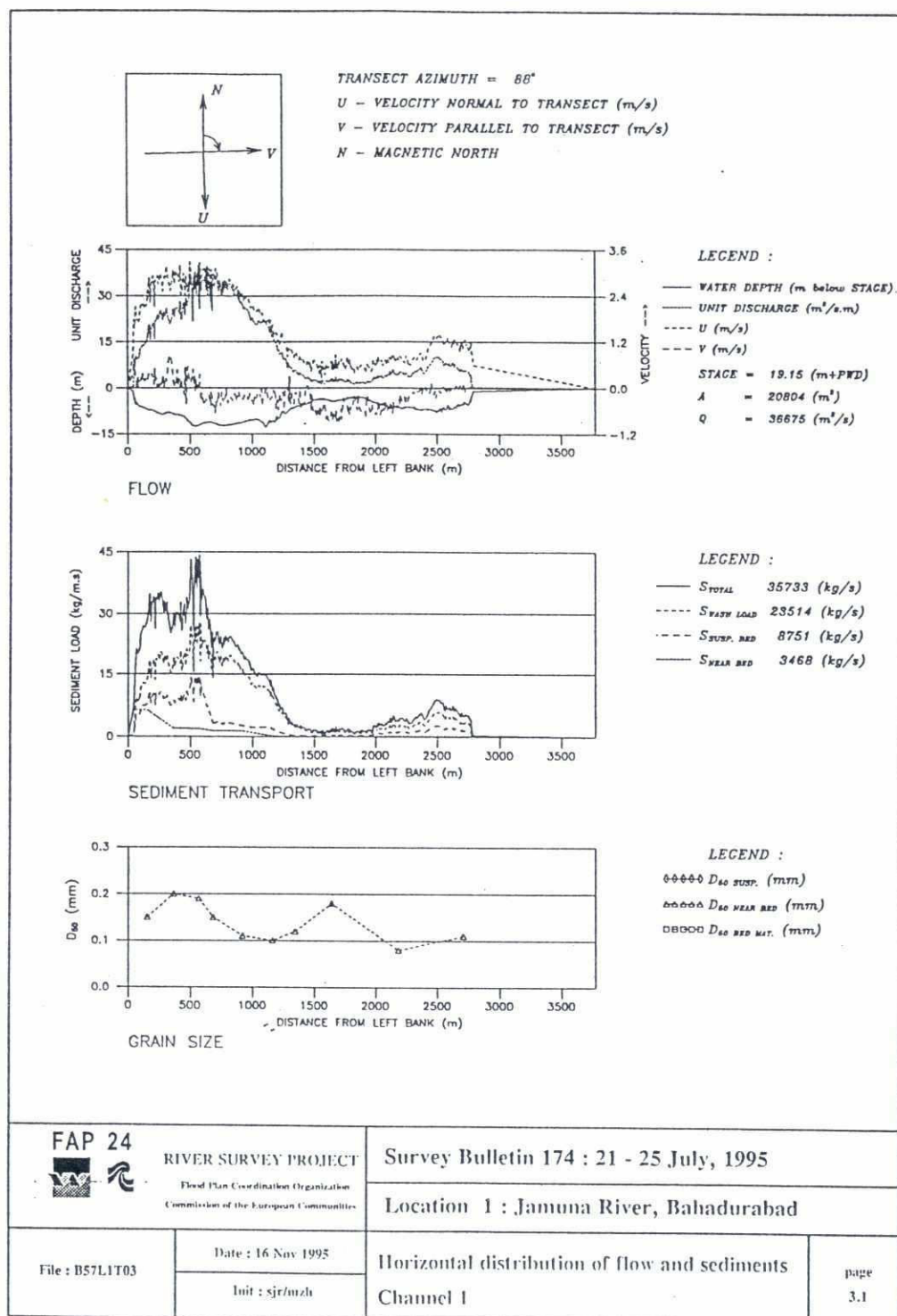


Figure A1.2 Presentation of horizontal distribution of flow and sediment transport
(example, from Survey Bulletin 174: 21-25 July 1995)

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Appendix B

Overview of Special Reports

Index of RSP Special Reports

- 1 : Validation of staff gauge bench marks
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RSP Special Report 1: 'Validation of staff gauge bench marks'

This report describes the validation of the bench marks of 47 BWDB staff gauges covering the main river system of Bangladesh. The work was executed in early 1993, and the results were reported to FPCO in June 1993 as *RSP Survey Report 2: 'Land survey, zero control water level stations'*.

The zero level of the gauges was determined by levelling the gauge to bench marks approved by FPCO. The checking comprised a comparison between the zero level obtained in this way and the one that was actually used by the gauge reader. The levelling was done relative to the BWDB network, and whenever possible the BWDB bench marks were connected to the FINMAP network of bench marks that was established under FAP18.

The work comprised site visits to each location check if the registered information about the bench marks corresponded with the situation in the field. If bench marks were found to be in accordance with the description supplied by FPCO and in a good condition, levelling between bench mark and gauge was carried out. If this was not the case, a proposal was sent to FPCO on how to improve the situation either by replacement, re-levelling or construction of new benchmarks.

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The report contains inspection reports and location maps of each gauging station, tables listing observed level differences, and specific recommendations on upgrading of certain bench marks.

RSP Special Report 2: 'Water level gauging stations'

This report describes the RSP water level gauging programme, which comprised a network of 11 automatic water level recorder (AWLR) gauging stations within the project area. The gauges were either based on acoustic sensors (which were often mounted on bridges) or vented pressure cells (which were mounted on platforms in the river). Each AWLR was supplemented by 2 staff gauges for validation.

The rivers of Bangladesh are unconfined and freely migrating with continuous modification of their banks and chars by erosion and siltation. This implies that any structure built for the purpose can either be scoured, eroded and collapsed or dried up during the low river stage. Erosion and scour hazards demand that the structure should have a deep and secured foundation. However, construction of such a foundation increases the cost to several times the purchasing cost of an AWLR. Moreover, the siltation problem may make a structure redundant anyway after some time. In case of free river migration, the life-time of a structure can be quite short, depending on the choice of the location.

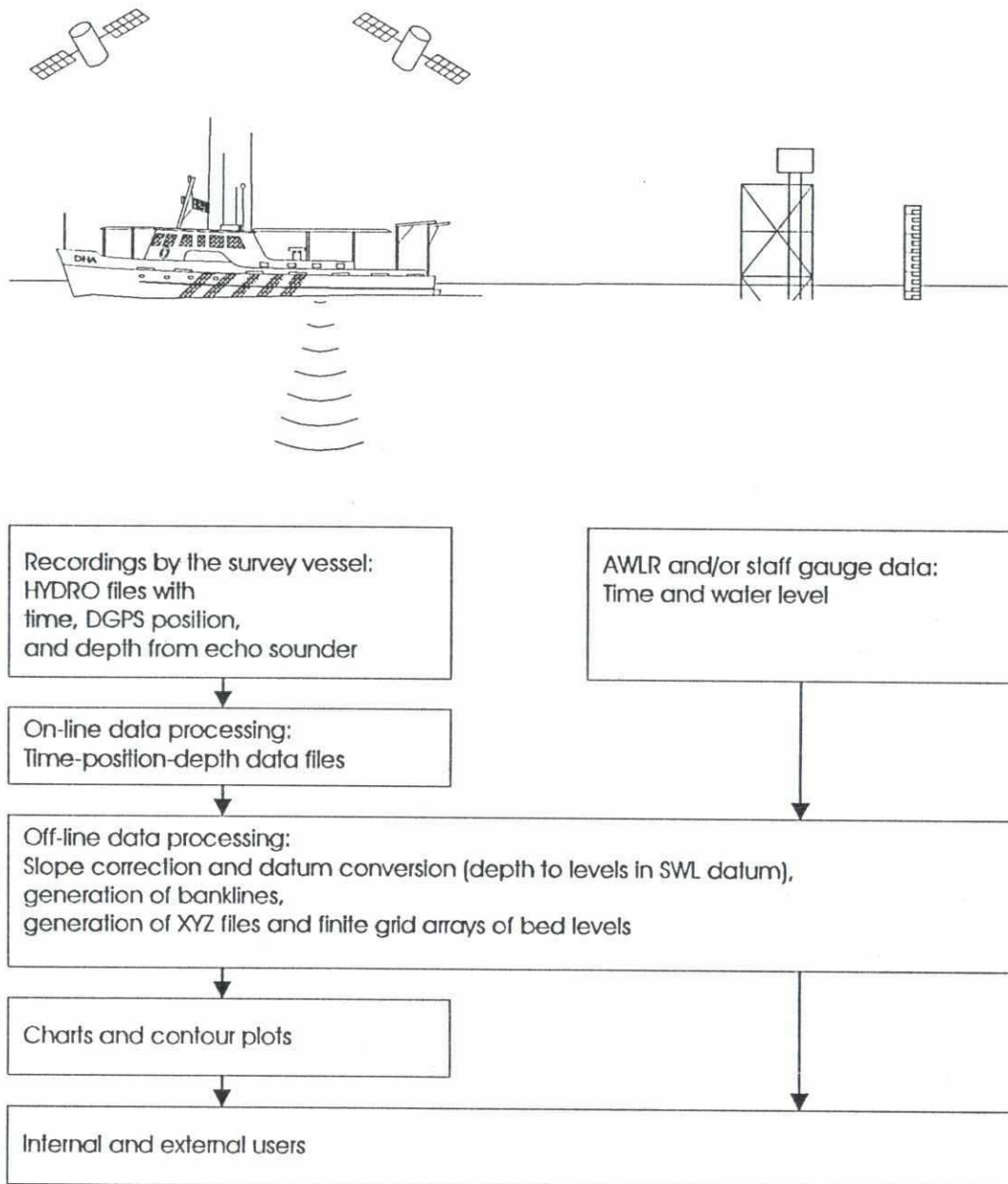
Because of the high seasonality of the rivers, the low-draft country boats change their navigation routes so as to follow the shortest possible way, often along the bank. This makes structures along the banks vulnerable to collision by vessels. This actually happened in some cases for RSP structures. The changing nature of the navigation routes makes it tricky to choose a location.

The report describes different water level gauging principles, guidelines for selection of gauging locations, gauging network design, construction of different types of platforms, instrument installation, and operation and maintenance procedures. Also, the data processing and validation is described. Specific observations are made on the operation of the RSP network, and recommendations are given on future national development of water level gauging.

RSP Special Report 3: 'Bathymetric surveys'

This report describes the RSP bathymetric survey programme: Extent of the data collection, horizontal control (relative to the BTM grid), vertical control (relative to Standard Low Water datum), positioning (by DGPS), instrumentation, survey routines, and procedures for data processing (including depth reduction) and data validation. Also, the topographical survey and feature mapping programme is described, as well as the mapping of flow lines by (drogues) as a supplement to the bathymetric surveys.

The water-level variation is described for each survey area, as well as stage-slope relationships. Further, the report contains index maps with runlines for each survey. The data have been submitted separately to WARPO as bathymetry charts (scale 1:10,000 or 1:20,000) and contour plots (scale 1:10,000 or 1:20,000 and 1:50,000). The data have been stored in two ways in the PSD24 data base for special or more detailed analyses: (1) edited sets of all recordings of position, depth, and time along the survey lines (so-called xyz-files), and averaged and interpolated depths and bank contours in a fixed (50 m by 50 m) grid covering the entire survey area.



Data flow for bathymetric surveys

RSP Special Report 4: 'Stage-discharge relationship for the Jamuna at Bahadurabad'

This report presents analyses of 103 pairs of stage-discharge data from the Jamuna River's left and right channels at Bahadurabad. The measurements for these 103 pairs of data were taken by the Hydrology Directorate of BWDB from 1 April to 15 November 1995; another 15 pairs of data were measured by RSP from April 1995 to January 1996. During 1995 there was much flooding. Daily water level data were collected for 1 April to 31 December 1995 from 6 staff gauges located at 5 to 9 km intervals along the two channels. This study is the continuation of an earlier study based on the data for the hydrologic year 1994-95 during which there was little flooding. This earlier study was published in July 1995. The measured data have been used to study the relationships of local water surface fall, discharge, cross-sectional area, mean velocity, water surface width, hydraulic depth, conveyance factor, slope-roughness factor, and flow distribution with stages for the two channels.

Relationships among geometric and hydraulic parameters show that the flow regimes during the falling stage, flood season, and rising stage were different. The differences were due to changes in the shape of cross-sectional geometry and bedform roughness caused by the morphological process. It was found that two segments for the rising stage, one segment for the flood season, and another two segments for the falling stage were appropriate for the stage-discharge relationships for 1995-96. Selection of segment limits was linked to the shape of the cross-section. Standard error analysis indicated that this approach can improve the accuracy of the fitted annual stage-discharge relationship. Recommendations were made on how to select the segments when the number of stage-discharge data are limited.

Channel-wise development of the stage-discharge relationship was a better approach since the hydraulic and morphological conditions in the right channel were different from those in the left channel. This approach reduced the uncertainty caused by the large measurement time required to complete the discharge measurements in two channels. However, standard error analysis indicated that the gain in accuracy achieved by this approach was not significant when compared with the approach of fitting a single relationship with the combined discharges of the left and right channels. This is because the small discharge of the right channel can not substantially influence the standard error based on total discharge.

Two methods for the extrapolation of discharges at stages beyond the range of measured discharges have been compared. Based on accuracy performances and practical considerations, these two methods were selected from five methods studied in the earlier report. Verification against measured discharges showed that the accuracy of the conveyance-slope method was better than the direct extrapolation of the fitted stage-discharge relation which is presently practised by BWDB.

The highest discharges in the right channel at Bahadurabad during 1994 and 1995 were approximately 25% of the total flow, and its share decreased substantially with the fall in stage. The distribution of flow between the left and right channels was not proportional to their conveyance factors. The Froude number of flow in the right channel was much smaller than in the left channel. Analysis of local water surface fall data indicated that the right channel was aggrading. From 1994 to 1995, there was an upward shift in the stage-discharge curve in the right channel and a slight downward shift in the stage-discharge curve in the left channel.

It is recommended that frequent discharge measurements should be taken during the first half of the hydrological year. If there are cost considerations, the frequency can be reduced during the second half of the year. A consistency check of discharge measurement data for a hydrological year should be performed channel-wise. This can be done by plotting stage and discharge against cross-sectional area and cross-section averaged velocity for left and right channels.

The study was made in a collaboration between RSP and professor Jahir Uddin Chowdhury, Institute of Flood Control and Drainage Research, BUET, who also prepared the report.

RSP Special Report 5: 'Qualitative impact assessment of FAP implementation'

In this report a quantitative assessment is made of the impact of the implementation of the Flood Action Plan on the main river system. The assessment is limited to the hydraulic and morphological impact. Whether or not a certain development is acceptable or even preferable from environmental or socio-economic point of view is not studied here.

The assessment is done on the basis of knowledge of the main river system as laid down in *RSP Survey and Study Report 2: 'Selection of study topics for Phase 2'* and *RSP Survey and Study Report 10: 'Morphological Studies Phase 1'*, and on the results of the hydraulic simulations carried out by FAP25, in particular Annex 2 of the *FAP25 Main Report: 'Analysis of country-wide protection schemes'*.

The assessment was done in some subsequent stages. Firstly the results presented by FAP25 were analyzed as far as changes in discharges in the main rivers were concerned. Then the so-called Lane's balance was applied to assess the ultimate conditions in the main rivers. Next the intermediate conditions were assessed in a qualitative way. Finally, the impact on the distributaries was estimated, together with the possible feedback on the main rivers.

The results demonstrate that the initial increase in stages in some rivers (in particular the Padma, Jamuna and Ganges Rivers) will in due time probably change to a reduction in stages. Rough estimates indicate degradation and lowering of stages of more than 0.6 m, for most of the main rivers apart from the Upper and Lower Meghna Rivers. This degradation will only materialize fully after 50 to 100 years or more. An important finding is that the assessment for the distributaries cannot be fully done in a deterministic way. The development of the distributaries is at least partly determined by phenomena which are varying in time, hence the period and sequence of implementation of the various projects may be important. The assessment supports the selection of study topics proposed by RSP at the end of Phase 1, and underlines the need to improve the understanding of the behaviour of off-takes.

Finally it is remarked that the present assessment is a very preliminary one only. It should be followed by more detailed assessments in due time, in which also the sequence of projects and possible adaptations should be studied as part of the development of a well-balanced Flood Action Plan.

RSP Special Report 6: 'Flood plain levels and bankfull discharges'

Natural rivers are generally characterised by a wide variation of discharges and sediment load. The channel formation is determined by the continuous changes of the discharge and the sediment load. In order to determine the channel dimension and the planform characteristics with the help of a single discharge value, the bankfull discharge is often being used. The bankfull discharge is defined by Richards (1980) as *'the flow which just fills the range of the section of the alluvial channel without overtopping the banks'*. He continues that it *'has often been... treated as dominant or formative events controlling channel form'*.

For rivers with multiple braided channels, like the Jamuna, Ganges and Padma, the flow filling up to the banks and above is playing an important role in forming and shaping secondary channels. The flow below the banks and braided bars and chars may not be representative for the channel formation. One of the important parameters for the river training and bank and flood protection work is the bank-full width of a river, and this bank-full width can only be related to the bankfull discharge.

After overtopping the banks of a river, the flow extends over the adjacent land along the river, which can be defined as the floodplain. Due to the relatively shallow depth and the vegetate surface of the floodplain, the flow often loses its sediment carrying capacity, and as a result, sedimentation occurs over the floodplain. In the course of time, such sedimentation can raise the flood plain as well as the bank of the river. Not only the floodplain sedimentation, but also other phenomena: Bank erosion and flood spills with a sediment deficit, are the determining factors for the floodplain level adjacent to the river bank. Also, tectonic effects can play a role, but these are beyond the scope of this study.

The floodplain level is related with the bankfull discharge, which is utilised as a parameter for the prediction of channel dimensions and plan-form characteristics of the major rivers.

BWDB data from 1966-93 (cross-section geometries, water level, and flow) have been applied, together with flow data produced by RSP. The report describes the variability of the floodplain level during the last few decades. The bankfull discharge of the Jamuna River is estimated at about 48,000 m³/s, of the Ganges River at about 43,000 m³/s, and of the Padma River at about 75,000 m³/s. In the report, these findings are related to different definitions of the bank level, and are discussed on the basis of different predictors reported in literature for other rivers.

RSP Special Report 7: 'Channel dimensions and geomorphological controls'

A river responds to a number of independent variables as can be expressed by a number of dependent variables. The roles of the variables depend on the time scale, which determine whether a variable plays the role as an independent or a dependent variable. In an engineering time scale, the independent variables are the time dependent discharge, the yearly average sediment discharge, the grain size, the valley slope, bed and bank material characteristics, etc. The dependent variables are the bank-full discharge, the bank-full width, the depth, the flow velocity, the sinuosity, the slope, the total width, etc.

In a separate RSP study, these questions have been examined on the basis of BWDB cross-section survey data along the three rivers from 1966 to 1993, supplemented by results of several previous studies, LANDSAT and SPOT images, and RSP data.

As wandering rivers, the Ganges and Padma have different characteristics with respect to channel geometry, as shown in the following table:

River	Planform	Width (m)	Average depth (m)	Average velocity (m/s)	Roughness ($m^{0.5}/s$)	Slope (cm/km)
Ganges	Braided	3718	6.50	1.78	93	5.6
	Constricted	2476	6.90	2.51	144	4.4
Padma	Braided	5200	7.78	1.93	100	4.9
	Constricted	3867	8.00	2.42	134	4.1

Variation of different parameters with the changing of characteristics of the river stretches

In general, the channel dimensions can be described by the different dependent variables. In the present study, emphasis is given to the bank-full width and depth, which can serve as key parameters of the channel dimensions. First, an attempt is made to derive a regime type of relation to determine these two parameters as a function of the bank-full discharge, which is another dependent variable. Next, the result is examined and verified against the geomorphological conditions of the rivers. The regime type of relations can of course be applied only if the river is in an equilibrium.

The regime relations hide the influence of the other independent variables, although their role in determining the channel dimensions is well recognised. For the main rivers, Jamuna, Ganges and Padma, the magnitude of the yearly average sediment discharge, the grain size and the valley slope differ from each other, within a range of a factor of two.

Another factor, the bed and bank material characteristics, is a function of the geology of the basin. Geological factors control the morphology of a channel to a certain extent. For example, a highly erosion-resistant bank can control the planform characteristics, also within a graded or engineering time-scale. Therefore, when studying the channel dimensions, especially the geomorphological controls, the equilibrium aspect of the channels is a subject of particular attention.

The report outlines the relevant key factors of the geology of the Bengal Basin. The morphology of the main rivers is discussed briefly. The data analysis is summarised, as a basis for a discussion of the significance of different parameters to the channel dimensions. Finally, conclusions are drawn on the channel dimensions of the Jamuna, Ganges and Padma Rivers, their relation to the discharge (as expressed by regime equations), and the significance of geomorphological controls.

RSP Special Report 8:**'Bed material sampling in Ganges, Padma, Old Brahmaputra and Jamuna'**

The characteristics of the river bed materials are important in studying the morphological processes of a river. For example for studies of planform development, bank erosion, scour hole development, or formation and movement of bars, it is required to know the characteristics of the bed material. Moreover, the characteristic sizes of bed material are used for roughness and sediment predictors.

The sediments that pass through the main rivers have grain sizes of fine sand to silt and clay. The average ratio of sand to silt is approximately 1:2 in the Ganges and Jamuna Rivers (see *RSP Special Report 18: 'Sediment rating curves and balances'*). In the river bed samples, however, the ratio of sand to silt depends on the position and hydraulic environment of the river bed during the bed material sampling. Moreover, the characteristic sizes of the bed materials also vary from point to point.

This report describes a study of the bed material characteristics, grain sizes, gradation, and grain sorting processes that are relevant for morphological studies such as roughness and sediment transport prediction and modelling.

The study was based on 317 samples collected by RSP in Ganges, Old Brahmaputra, and Jamuna Rivers. These samples were analyzed by the RSP sediment laboratory. In addition, results of almost 400 previous sample analyses were available from NEDECO (1967) and (1983), Jamuna Bridge Appraisal Study (1987), and Brahmaputra Right Embankment Project (1990). Bathymetric surveys and SPOT images were used for assessing the channel shape and river planform.

The median grain size D_{50} , the geometric standard deviation, and the downstream fining rate of the bed material samples of the Ganges, Old Brahmaputra and Jamuna Rivers are compared in the table below. In the table, the geometric standard deviation has been calculated according to Van Rijn as $0.5 \cdot (D_{50}/D_{16} + D_{84}/D_{50})$.

In the report, the grain size of the bed material is related to the hydraulic regime, the sediment budget, and the river planform, and the time and space variation is examined and discussed.

River		D_{50} (mm)	Geometric standard deviation	Downstream fining rate (mm/100 km)
Ganges		0.14	1.4	0.025
Old Brahmaputra		0.18	1.8	
Jamuna	Bahadurabad	0.19	1.52	0.01
	Sirajganj	0.20	1.55	

Grain sizes of bed material samples (with less than 40% silt and clay)

RSP Special Report 9: 'Bedforms and Bar dynamics in the main rivers of Bangladesh'

This report was prepared in co-operation with the University of Leeds, U.K. The main conclusions are summarized as follows:

Study of the evolution, morphology and flow dynamics associated with dunes and bars in the main rivers of Bangladesh shows that these bed features are ubiquitous within all the active channels. Dunes and bars largely control the rates and patterns of bedload transport and significantly influence the location and rate of bank erosion/bed scour. Use of both routine survey data and a series of special surveys between 1994 and 1996 has permitted assembly of an unrivalled database concerning dune and bar dynamics throughout the flood hydrograph. Principal conclusions from the study are:

- Dunes are the dominant bedform within all active channels and on bar margins/edges at all flow stages
- Dune height and wavelength range from 0.15-6.3 m and 4-350 m respectively
- Dune leeward angle ranges from 3-50° with a mean of 9°
- Dune superimposition is common although there are no clear morphological relationships between the size of primary and secondary dunes.
- Bedform response to flow stage is rapid with little lag effect but the variability in dune height and wavelength increase at higher flow stages
- Dunes create individual flow fields which control the local suspension of sediment, both over low and high angle leeward dunes
- Dunes are the dominant mode of bedload transport and therefore are of central importance in generating local bed morphology and initiating the formation of bars
- Mid-channel bars are the most common bar type in the Jamuna and exert considerable influence on the local flow structure, channel change and bank erosion
- Sand bars often form downstream of a zone of flow convergence and are initially deposited as a central symmetrical bar core, aligned sub-parallel to the primary flow direction
- The basic planform morphology of a mid-channel bar is rhomboidal with two protruding bartail limbs. This morphology is characteristic of all scales of mid-channel bars
- The bartail may be an important storage zone for fine sediment and can form highly cohesive 'plugs' which may be difficult to erode. Downstream migration of the barhead may preserve this plug and temporarily 'remove' the finest fractions from the channel and floodplain transport system
- Mid-channel bars grow through (i) flow divergence at the barhead and deposition at the bar margins, (ii) lateral accretion induced by secondary flows in the anabranches, (iii) vertical aggradation by successive stacking of dunes, and (iv) downbar migration of an accretionary dune field front. This front may only form during short-lived (days) fluctuations in discharge at the hydrograph peak
- Bar growth and channel change is not always accompanied by downstream migration of the bar nucleus
- Channel change and the rate of sediment erosion and deposition is strongly stage dependent with no lag behind the hydrograph peak. The mean erosion and deposition rates are in balance throughout the hydrograph suggesting no net aggradation or degradation of the braidbelt
- A six-stage model for mid-channel bar growth and morphological change in the study area is proposed which is consistent with observations in the literature and may be applied more widely in the Jamuna

RSP Special Report 10: 'Morphology of Gorai Off-take'

The distribution of discharge and sediment transport at river offtakes is a key factor for the long term morphological development of the distributaries of the main rivers. The offtake of the Gorai was selected for a detailed study, one reason being its importance for the fresh water inflow to the Southwest Region. The total isolation of the Gorai at the offtake from the Ganges every dry season during the latest years is a matter of great concern. The study had three main elements:

- Analysis of historical data to understand how the hydraulic conditions at Gorai Offtake have changed over the last 30 years;
- collection and analysis of detailed data in special surveys of the RSP. The data are used to set up and calibrate a two-dimensional morphological model of the area; and
- two-dimensional morphological modelling to improve the understanding of the morphological developments at the offtake and thereby of factors that are important for maintaining a dry season flow to the Gorai.

The model simulation of a monsoon period has addressed the development of the offtake channel, the development of the bar in front of the offtake, and the effect of changes of the bar. The simulations reproduced a main feature of the Gorai Mouth: The deposition in front of it during the monsoon and subsequent development of a deeper channel during decreasing Ganges stage. The flow resistance in the Gorai was found to be important for the morphology at the offtake and thereby for the development of dry season flow to the Gorai.

The study has provided important information about the morphological nature of offtakes, and has contributed to a scientific explanation for the closure of the Gorai River.

RSP Special Report 11: 'Optimization of hydraulic measurements'

This report considers hydraulic measurements for routine gauging of velocity, depth, water level, and width, taken to obtain discharge information, stage-discharge relationships, and to produce bathymetric maps. The optimization of such measurements covers four basic, but inter-related, activities: (1) optimization of measurement networks, (2) optimization of measurement frequencies, (3) optimization of equipment and methods, and (4) optimization of survey operations.

A multi-criteria optimization analysis technique was developed and applied for screening these activities. The criteria determined that the equipment and methods used in this study should allow for high data quality at low procurement and operational and maintenance costs. In addition, the equipment and methods should be easy to operate, take minimal measurement time, require little maintenance, and should well represent the hydraulic parameters.

Since this report covers the final evaluation of hydraulic measurements, different activities were further screened on a multi-criteria sustainability analysis technique. The applied criteria were:

- The affordability of investment and operational and maintenance costs;
- operational and maintenance institutional capabilities;
- technological compatibility;
- optimal technique and survey results;
- justifying results against incurred expenses; and
- environmental suitability.

The findings and recommendations are based on the routine gauging of water level and flow, as well as several programmes of special surveys that were made in order to account for equipment and method accuracy within the RSP. Also, the results were considered of the comparative BWDB/RSP measurements that are described in *RSP Special Report 19: 'Joint BWDB/RSP measurements, hydrology'*.

The report contains separate annexes on (A): Turbulent structure and optimal measuring time, (B): Some aspects of turbulent flow structure in large alluvial rivers, and (C): Optimal vertical and horizontal distribution of velocity measurements in discharge estimation.

RSP Special Report 12: 'Optimization of sediment measurements'

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

Measurements of various sediment transport parameters are important for sedimentological and morphological studies of rivers. Unless such parameters are known, a river management plan can not be executed. In Bangladesh, sediment transport data have been collected for over three decades. The FAO started to systematize the hydraulic data collection activities in 1965, and published its findings in 1969. Since then, BWDB has been collecting suspended sediment data at approximately 25 transects across different rivers.

As a supplement to these measurements, the RSP started in 1992 as a supporting project for the different Flood Action Plan projects. The survey techniques applied by RSP were developed as a stagewise process, which involved the pre-selection of instruments before the mobilization phase, evaluation of the performance of instruments during the test gauging phase, and subsequent selection and mobilization of the project during Phase 2. Hereby, the experience from Phase 1 of the project (1992-1994) served as a basis for adjustments of methodology and equipment used during Phase 2 (1994-1996).

The objective of this report is to make a final evaluation of the sediment measuring equipment and methods that were implemented by RSP, so that the experience gained can be included in the basis for future developments of the sediment measurements. Also, the report presents a wider discussion and recommendations on:

- optimization of equipment and methods;
- optimization of spatial density or measurement network;
- optimization of temporal density or frequency of measurements; and
- optimization of survey operation.

The report contains separate annexes on (A) Sediment measuring instruments; (B) Computation of total sediment transport; (C) Near-bed sand transport measurements by Delft Bottle and Helley-Smith samplers; (D) Estimation of suspended sand concentration from ADCP backscatter; and (E) Fine sediments, their hydraulic behaviour and importance for Bangladesh rivers.

RSP Special Report 13: 'Sediment transport predictors'

A proper quantification of the extent of erosion, deposition, and changes in channel form of alluvial river courses has been a subject of considerable research, and still is. In the water development sector, for planning and design, it is required to predict future changes of the river morphology. Hereby, the sediment transport is a main feature. Therefore, a systematic knowledge about river flow and sediment transport is of utmost importance from the standpoint of improved planning and design of water development projects, and knowledge is essential about the factors that determine the sediment transport in a given flow.

This report deals with prediction of sediment transport for the major alluvial rivers in Bangladesh. A new equation is presented. It is compared with well known sediment transport prediction formulae against the same data. These analyses were carried out for the Jamuna, the Ganges and the Padma Rivers. Hereby, certain inconsistencies were noticed in the basic material of sediment transport data. The inconsistencies were examined by 1-dimensional modelling.

Additionally, a theoretical investigation has been carried out in order to examine the magnitude of the exponent 'n' of the flow velocity in sediment transport prediction formulae applicable for alluvial rivers.

Data for the study were taken from the field sheets on sediment and discharge measurements carried out by BWDB, Surface Water Hydrology II at Bahadurabad, Hardinge Bridge, and Baruria gauging stations, on the Jamuna, Ganges and Padma Rivers, respectively.

RSP Special Report 14: 'Mineralogical and physical properties of river sediments'

Knowledge about the physical properties of river-borne sediments is important in understanding the geologic characteristics of watersheds, the geomorphological response of rivers, and the engineering properties.

The objective of this study was to prepare a data base for the physical properties of sediments found in the major rivers of Bangladesh. More specifically, the objectives were:

- To understand the mineralogical and physical properties of river sediment in relation to the different environments of the river, notably river bed sediments, near bed sediments, and suspended sediments;
- to correlate the relationship between grain size distribution and mineralogical properties of river sediments;
- to determine the role of physical and mineralogical properties of river sediments on river morphological behaviour;
- to estimate the variation in river mineralogical properties in relation to geographical occurrence; and
- to study the mineralogical characteristics of floodplain sediment, and to estimate the variation from river sediment.

The study area included the major rivers of Bangladesh and one floodplain site along the left bank of the Jamuna River. Samples were collected from the river bed, from the water column, from the river bank, and on the floodplain. A total of 386 samples were analyzed for mineralogical composition, while 193 samples were analyzed for physical properties.

The report describes the sampling and the analyses, and gives a characterisation of the general mineralogical and physical composition of the sediments of the major rivers. The following aspects are discussed on the basis of the collected data:

- The linkages between physical and mineralogical properties;
- the relationship between mica and heavy minerals;
- the seasonal variation of physical properties in the rivers;
- the spatial variation of the sand fraction mineralogical properties of river sediment (between different locations, along the river, and vertically);
- the contribution of individual channels downstream of a confluence;
- the correlation between river and floodplain sediment;
- the topographical variation of physical properties in floodplain sediment; and
- the variation of mineralogical properties within river bank profiles.

The following annexes are included in the report: (I) Short description of minerals of river sediments of Bangladesh, (II) Results of laboratory analyses of river and floodplain sediment samples, and (III) Glossary.

RSP Special Report 15: 'Overland flow and flood plain sedimentation'

The report presents results of a study of overland flow and floodplain sedimentation processes in a selected area of the Jamuna floodplain. The general objective of the study was to assess the importance of this type of flow, as well as spill flow over the river banks, sediment transport, and sedimentation processes on the floodplain. These results will improve the understanding of:

- Water and sediment balances along river stretches;
- overland flow patterns in view of impact assessment of man-made changes on the development of rivers and floodplains; and
- processes of floodplain sedimentation.

A comprehensive study of these subjects requires a large-scale research effort that is beyond the lifespan and financial resources of the RSP. Therefore a regional pilot study was undertaken to monitor floodplain sedimentation during the 1995 wet season. The floodplain along the left bank of the Jamuna River was selected for the study, because it is one of the most extensive floodplains in Bangladesh. The overland flow and sediment flux were measured mainly at distributary and man-made outtakes (i.e., culverts). Sedimentation rates were registered at a number of sampling plots with sediment traps and mats. The mineralogical and physical properties of a number of sediment samples from the study area were analyzed, as reported in *RSP Special Report 14: 'Mineralogical and physical properties of river sediments'*. Mr. S. Kuhl and Mr. S. Goodbred of Virginia Institute of Marine Science, VIMS, performed vibrocoreing in the study area and some of their results are included in this report.

The report contains separate annexes on (i) Overland flow surveys and (ii) Floodplain sedimentation measurements near Sharishabari.

RSP Special Report 16:

'Study of secondary currents and morphological evolution in a bifurcated channel'

In studies of flow structures on single-thread meandering rivers, secondary currents have been shown to have a large influence on the morphological development of meander bends.

Until this joint study between RSP and the University of Nottingham, UK, there had been few similar studies carried out on the influence of secondary currents on large braided rivers such as the Brahmaputra River. As a consequence of this lack of fieldwork, our understanding of braided river behaviour and the development of predictive tools have been impeded.

This document reports on a series of field surveys to investigate the flow distributions around a braid bar in the Brahmaputra River near Bahadurabad. Results demonstrate linkages between large scale secondary current cells and the pattern of primary flow and the pathways of concentrated suspended sediment around the bar. Patterns observed along the flanks of the braid bar curved anabranch are similar to those observed in single-thread meandering channel bends. Patterns observed at the flow bifurcation upstream of the bar demonstrate how the secondary currents influence the development of the bifurcation through their effect on the near bed primary flow pattern and sediment transport. The results further demonstrate that an ADCP is a powerful instrument, capable of investigating three-dimensional coherent flow structures in large rivers.

RSP Special Report 17:**'Spatial representation and analysis of hydraulic and morphological data'**

GIS and image processing are powerful tools for characterising and analysing the morphology of the major rivers in Bangladesh. The goal of this study was to visualise and analyse the large volumes of hydraulic and morphological data produced by the RSP, also in order to facilitate the access to the data for future users. The study comprised

- river bathymetry mapping and change analysis;
- analysis and presentation of fluvial data (flow and sediment transport) in combination with bathymetry;
- testing a method for short-term morphological prediction;
- development of a method to derive a land elevation map from satellite images; and
- a revised representation of the 50 percent conveyance line of the Jamuna River.

In addition to BWDB and BIWTA data, the study was based on 19 bathymetric surveys and 3 topographic surveys and feature mappings carried out by RSP, together with 13 LANDSAT images from the lean season in the period from 1973 to 1996.

The study has demonstrated a wide range of applications of spatial analysis tools, notably GIS and image processing, within river studies and river engineering applications. In the report, such applications are exemplified, and their implications are discussed. An analysis is presented of the medium term planform development of the Jamuna River (1978-94), and the short-term erosion and sedimentation processes are analysed quantitatively by a new predictor that has been developed from a method suggested by Peters (1988). This new predictor reads

$$\Delta z_b = \Delta t \cdot k_1 \cdot \left(1 - \frac{u}{k_2 \sqrt{h}} \right)$$

where Δz_b is the bed level change, Δt is the time, u is the flow velocity, h is the water depth, and k_1 and k_2 are coefficients to be derived from the data, k_2 in theory being the product of the Chézy coefficient and the square root of the river slope.

The report contains appendices with details about the applied data processing procedures.

The study was carried out and reported in a collaboration with Environment and GIS Support Project for Water Sector Planning (EGIS)

RSP Special Report 18: 'Sediment rating curves and balances'

The sediment transport is measured regularly at certain gauging stations along the main river system of Bangladesh by BWDB. Various studies have observed certain inconsistencies in these data, such as:

- scatter in the sediment transport data presented in linear or log graphs;
- steep rating curves expressed in a log-log graph; and
- a decreasing trend in sediment transport over the historical period 1966-1994.

In the report, the inconsistencies are related to the gauging technique, the measuring site (the morphology of the gauging station), seasonal effects, and/or natural events such as earthquakes in the catchment or extreme floods.

Following a review of the data, an attempt is made to produce suitable sediment rating curves for the stations located on the main river system. These relations, in turn, are used for estimates of sediment balances between the major stations by means of such sediment rating curves, in order to determine the long-term development trend of the river system. The findings are compared with results of previous studies.

Almost all the available BWDB sediment transport data for the period 1966-1994 were collected for the study, but, due to inconsistencies, data from certain periods and certain stations were excluded from the analysis.

Specific subjects are elaborated in three annexes: (1) Inventory of available suspended sediment data, (2) Sediment rating curve, and (3) Sediment balances.

River, station	Annual sediment transport in million tons per year							
	Coleman ¹	Holeman ¹	MPO ¹	FEC ¹	CBJET ¹	Hossain ²	BWDB ¹	RSP ¹
Jamuna at Bahadurabad	607	800	387	431	499	650	507	590
Ganges, at Hardinge Bridge	478	1600	212	338	196	480	448	548
Padma, at Mawa			563		581		694	
Padma, at Baruria				723	317		723	897
(1) Total suspended sediment transport								
(2) Total (bed and total suspended) sediment transport								

Comparison of sediment transport according to various authors and studies

RSP Special Report 19:

'Joint discharge measurements, RSP and BWDB, Surface Water Hydrology'

In the beginning of 1994, a '*Committee on Shift in the Rating Curve at Bahadurabad*' was established to examine certain systematic differences between flow data produced by BWDB and RSP. The Committee recommended that BWDB and RSP organise joint and simultaneous measurements in order to assess the quality of the applied survey procedures.

BWDB and RSP used different methods and equipment for their discharge measurements: Anchoring, positioning of the survey vessel, depth registration, positioning of the current meter, and the registration of the flow velocity and direction. Also, the data processing routines were different. A programme of joint measurements was executed in 1994 and 1995, and the following aspects were studied:

- The positioning of the transect and the verticals;
- the measurement of the cross-sectional profile, especially the width at the water surface and the depths in the verticals;
- the flow velocity measurements, the instrument characteristics and the positioning of an instrument in a vertical;
- the registration of flow angles; and
- the sediment transport measurements, especially the measurement of the sediment concentration or the sediment transport.

The report presents a comparative analysis of these questions, evaluates the applied survey routines, and gives suggestions on adjustments and future developments.

RSP Special Report 20: 'Joint measurements BWDB/RSP, morphology'

Since 1966, the Morphology and Research Circle of BWDB has executed cross-sectional profile measurements of some 34 transects along Jamuna River. The average length of the transects is 14 km. The data produced represent a unique source of knowledge about the behaviour of the river.

A joint cross-sectional profile survey was carried out in Jamuna River at Bahadurabad by the Morphology and Research Circle and RSP in March, 1995. The joint activities comprised (1) the field measurements and (2) the data processing.

The report describes and compares the procedures applied by BWDB and RSP with respect to identification of the cross-section, horizontal and vertical control, measuring the dry part of a cross-section, and sounding of the water part of a cross-section. Also, a discussion is given of the procedures for data processing and validation.

It is observed that the accomplishments of the Morphology Division of BWDB at Mymensingh are impressive, and even more so in view of the available resources. It is really a hard job to survey over land consisting of bare sand in hot weather, and to change the mode of survey (between land and water) frequently with the traditional procedures and instruments. A precise survey of a cross-section with a length of more than 16 km in 5 to 6 working days is nearly impossible with the present procedures and manpower allocation.

The recommended additional work for the BWDB survey team comprises: (i) always carrying a few spare pillars for replacement of lost ones; (ii) checking the position of intermediate pillars; (iii) daily data elaboration; (iv) re-surveying of parts of a cross-section, in case of errors beyond an acceptable range; (v) keeping record of closing errors and their distribution. These extra activities require more time for the field work.

Also, recommendations are made on strengthening the data validation and documentation, for example by comparing the survey data with Satellite imagery, and by comparing surveys of different years. Such additional work, which also includes acquisition of the satellite images, requires that additional resources are made available.

RSP Special Report 21: 'Guide to RSP databases'

The data produced by RSP (mainly water levels, flow data, sediment transport data and bathymetries) are stored in three databases:

- HYMOS: Water level data;
- PSD24 (= Processed Survey Data of FAP24): Results of the routine gauging and special surveys of flow and sediment transport, and bathymetry data files; and
- primary sediment analysis data.

Between them, the databases contain some 12 giga-bytes of data. The data files of all three databases are catalogued in the *RSP Data Books*.

In the course of the Project, the databases have been used in general for the various activities within the Project's study component. These activities have aimed at general and specific analyses of hydrological and sediment transport processes and morphological developments.

After completion of the project, the data stored in the databases may potentially serve a variety of purposes within national river planning, administration and engineering, as undertaken by WARPO, BWDB, and other national agencies. Also, the data may be useful for future FAP projects and other projects that require river data.

Also, it is believed that the data will be of interest for many scientific purposes.

The report describes the over-all data storage, and the catalogue system and structure of each database. Guidelines are given on how to identify and retrieve the data, which can be done directly, or, in case of the PSD24, via a query in its catalogue. Details are given about file name conventions, and about data file types and contents. Also, the report includes an enclosure with a description of the generation of the processed transect data files and cross-sectional aggregate files that are stored in the PSD24.

Please refer to Appendix C of the present report for a brief description of the PSD24.

RSP Special Report 22: 'River Data Book, June 1993 - March 1995'

The main categories of data produced by RSP are:

- Water level data;
- flow data;
- sediment and sediment transport data; and
- topographic and bathymetric data.

The data were collected by different types of surveys:

- a water level gauging programme;
- routine gauging of flow and sediment transport (pre-defined surveys at fixed locations);
- special surveys (defined by the RSP study team for the use in their studies); and
- topographic and bathymetric surveys (pre-defined surveys of fixed areas).

The water level gauging is described in *RSP Special Report 2*, and the bathymetric surveys in *RSP Special Report 3*. The *RSP Data Books* describe the results of the routine gauging programme and of the special surveys. They contain (1) a text volume with a short description of the survey programme and the applied routines, together with summary presentations of results of the measurements, and (2) additional volumes with a documentation of the data collection, selected findings, and a full catalogue of the data files.

Please refer to Appendix A of the present report for a brief introduction to the RSP data reporting and a listing of the contents of the Data Books.

RSP Special Report 23: 'River Data Book, April 1995 - May 1996'

This report resembles the previous one, except that it covers the period from April 1995 to the completion of the Project.

RSP Special Report 24: 'Morphological processes in the Jamuna River'

This study deals with the morphological processes in the Jamuna River, the lower reach of the Brahmaputra River in Bangladesh. Over the flood season major changes take place in the planform and bed topography of this large, braided sand-bed river, and the cause and effects of these changes were studied in an attempt to better understand the behaviour of this type of rivers.

The basic data available for this study are seven bathymetric surveys of the left part of the river near Bahadurabad. The area had a total length of 20 km and the data were collected during the period June 1993 through November 1995. In the area many additional data were collected in the same period: on a routine basis water levels at four to six locations, discharges, sediment transport rates and bed samples, while also at some selected places detailed bathymetric soundings and main flow and secondary flow measurements were done in 1994 as part of other studies. Also some bathymetric soundings from other reaches were used, though to a lesser extent as the data collection there was less complete. In the analysis of the data GIS was used, which proved to be a powerful tool for interpretation of (spatial) morphological data. Moreover, a method to interpret ADCP backscatter intensity data for quantitative analysis was developed and applied. This enabled insight into sediment transport patterns, which are quite peculiar in these large untrained sand-bed rivers, due to the constant reworking of the bed.

During the period that was covered in these sounding maps, a major cutoff took place, which caused very substantial changes in flow pattern, bed topography and bank erosion locations

and rate. In the report the results are analyzed to determine the interaction between bars, channels and flow and the constant re-working of the bed. This resulted in an improved understanding of cause and effects of the rapid changes taking place in this braided river system with fine sand as bed material. The results clearly demonstrate that small changes in flow and sediment distribution yield major changes in even the same flood season. It also shows that medium-term predictions can only be done with a limited accuracy, underlining the logic behind the probabilistic prediction technique proposed by Klaassen et al (1993).

Other analyses included (1) a detailed study of types, causes and dimensions of scour holes, (2) location and rate of bank erosion, including the testing of some predictors, and (3) the preparation of balances to study the exchange of sediments in these rivers. Based on the detailed analysis of the collected field data a prediction method for short-term development of the bed topography changes was developed and successfully tested.

All in all, the study showed that repeated soundings during the flood season, in combination with GIS for presentation and further study and interpretation, are a very promising method to increase the knowledge about these large, braided sand-bed rivers.

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Appendix C

PSD24 Overview

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Introduction

The PSD24 (Processed Survey Data of FAP24) was developed by the project as a vehicle for compilation and dissemination of the data produced during the routine gauging of flow and sediment transport. Also, PSD24 contains bathymetry data, as well as extracts of the water level data produced by the project (that are also stored in full in the HYMOS database).

In addition to the primary data files, the database contains a set of highly condensed and edited summary files that describe the cross-sectional distributions of flow and sediment transport.

In total, PSD24 contains more than 12 Gb of data.

The anticipated use of PSD24

In the course of the Project, PSD24 has been used for the various activities within the Project's study component. These activities have aimed at general and specific analyses of hydrological and sediment transport processes and morphological developments.

After completion of the project, it is hoped that the data can serve a variety of purposes within national river planning, administration and engineering, as undertaken by WARPO, BWDB, and other national agencies. Also, the data may be useful for future FAP projects and other projects that require river data.

Also, it is believed that the data will be of interest for many scientific purposes.

The anticipated user of PSD24

It has been assumed that the data user is familiar with the QuattroPro spreadsheet, and a large majority of the processed data files are formatted for this system. If not so, it is possible to convert the files to any other desired format. The QuattroPro spreadsheet is conveniently applied in the DOS/Windows environment.

Contour plots of bathymetries or cross-sectional distributions, and analysis of 2-dimensional distributions require application of the Mike21 Pre- and Postprocessing software package.

Some basic knowledge about accessing the Paradox catalogue system is an advantage, even though the data files can be identified and accessed directly, if so preferred.

Most users of data from the RSP routine flow and sediment transport gauging programme may benefit from consulting the *RSP Data Books (RSP Special Reports 22 and 23)* as a reference for the data coverage in time and space, for a catalogue listing, and for a description of the hydraulic regime of each gauging. For a description of the origin of the data, reference is made to *RSP Final Report Annex 1: 'Surveys'*.

The operator (but not the user) of PSD24 must be familiar with the UNIX environment, since some basic data file conversion operations are done in this operating system. Also, the

operator must be well familiar with the Paradox system, which is used for the catalogue component of the database.

The procedures applied for data transformation are described in *RSP Special Report 21: 'Guide to RSP Databases'*, which also provides the user with a basic introduction to the system.

Data categories

PSD24 contains the following file types:

- ADCP/S4/EMF transect data
- echosounder transect data
- sediment transport data
- longitudinal profile data
- stationary velocity profile data
- suspended sediment concentrations
- suspended sediment size
- bed load transport analyses
- bed material analyses
- flow and sediment transport distribution
- iso-velocity plot data
- fixed grid bathymetry data

File name conventions

File names for the transect survey data retain the same name structure as the RSP raw data files, except that the extension will be used to identify the different types of PSD24 files.

2.07

Example file name: b2a1t08.ech	
<i>b</i>	= Survey location
<i>2</i>	= 1992 (year)
<i>a</i>	= 10 or October (month)
<i>1</i>	= 21 (day)
<i>1</i>	= Vessel No. 1
<i>t</i>	= Transect (B = bathymetry)
<i>08</i>	= Sequence no.
Survey location	
<i>Aricha</i>	<i>a</i>
<i>Bahadurabad</i>	<i>b</i>
<i>Baruria</i>	<i>u</i>
<i>Bhairab-Bazar</i>	<i>z</i>
<i>BWDB</i>	<i>v</i>
<i>Hardinge Bridge</i>	<i>h</i>
<i>Kushtia</i>	<i>k</i>
<i>Mawa</i>	<i>m</i>
<i>Mymensingh</i>	<i>y</i>
<i>Offtake Arial Khan</i>	<i>o</i>
<i>Sirajganj</i>	<i>s</i>
<i>SWMC</i>	<i>w</i>
<i>Tilly</i>	<i>t</i>
File extension/ File type	
<i>.ase</i>	<i>ADCP/S4/EMF transect data (QPRO)</i>
<i>.ech</i>	<i>echosounder transect data (QPRO)</i>
<i>.sed</i>	<i>sediment transport data (QPRO)</i>
<i>.lng</i>	<i>longitudinal profile data (QPRO)</i>
<i>.prf</i>	<i>stationary profile data (QPRO)</i>
<i>.ssc</i>	<i>suspended sediment concentration analysis (QPRO)</i>
<i>.ssz</i>	<i>suspended sediment size analysis (QPRO)</i>
<i>.bdl</i>	<i>bed load sediment analysis (QPRO)</i>
<i>.bdm</i>	<i>bed material analysis (QPRO)</i>
<i>.trs</i>	<i>survey bulletin transect plot data (QPRO)</i>
<i>.dt2 & .ct2</i>	<i>iso-velocity plot data (MIKE 21)</i>

The file name conventions have been followed rigorously for the routine surveys and, as far as possible, also for the special surveys.

Directory structure

The files are stored in directories which are unique to the specific file category (transect, bathymetry or water level) and unique to the date of the survey and the survey location. To illustrate, consider the following directory tree:

<u>Home</u>	<u>Category</u>	<u>Year</u>	<u>Month</u>	<u>Location</u>	<u>Day</u>	<u>File name</u>
p:\psd24	\transect	1992				
		1993				
		1994	1 mar			
			1 apr	\baru		
				\baha	102	
					103	\b4431t02.ase
						\b4831t02.ech
						\b4831t02.ssz
						\b4831t02.sed
p:\psd24	\bathy	1992				
		1993				
		1994	1 may			
			1 jun	\aric		
				\baha	102	
					125	\b46y1.ct2
						\b46y1.dt2

The transect survey location names have been abbreviated as follows, together with identifications of occasional BWDB or SWMC data:

<i>aric</i>	=	<i>Aricha</i>
<i>baha</i>	=	<i>Bahadurabad</i>
<i>baru</i>	=	<i>Baruria</i>
<i>bbaz</i>	=	<i>Bhairab Bazar</i>
<i>bwdb</i>	=	<i>BWDB</i>
<i>hard</i>	=	<i>Hardinge Bridge</i>
<i>kush</i>	=	<i>Kushtia</i>
<i>mawa</i>	=	<i>Mawa</i>
<i>myme</i>	=	<i>Mymensingh</i>
<i>aria</i>	=	<i>Offtake Arial Khan</i>
<i>sira</i>	=	<i>Sirajganj</i>
<i>swmc</i>	=	<i>SWMC</i>
<i>till</i>	=	<i>Tilly</i>

The catalogue system

The data files can be retrieved by the following characteristics:

- Survey bulletin number
- File name
- Location
- Channel number
- River
- Survey type
- File contents
- File location
- Survey date
- File format
- Starting easting
- Starting northing
- Ending easting
- Ending northing

Appendix D

Future studies on survey techniques and river behaviour

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Introduction

Chapter 11 of this report provides a listing of the proposed future study topics, which could not be tackled in this project or which came up on the basis of results obtained, but only for the most important ones. These issues should be addressed by special studies in the future. This annex gives – in the form of some tables – a more complete listing of studies that are proposed to be carried out in the coming say decade. The studies relate to (i) promising measuring techniques for special studies, where advanced techniques might be required, and (ii) the behaviour of Bangladesh's main river system, in terms of its hydrology, its sedimentology and its morphology.

The structure of this Annex is in line with Chapter 11. Subsequently proposed studies are listed in the following fields:

- survey techniques;
- hydrological characteristics;
- sedimentological characteristics;
- river morphological characteristics.

The topics proposed are listed in Tables to follow. A tentative ranking is given, notably:

- 1 = Immediately to be taken up;
- 2 = To be taken up in a few years (by Special Study Unit);
- 3 = In due time, e.g. via collaboration with Universities and institutes

For background information on the topics for which studies are proposed, reference is made to the relevant chapters in the Annexes 1 and 2, 3, 4 and 5, respectively.

Survey techniques including use of satellite imagery

Topic		Proposed studies	Ranking
Survey techniques	Water levels and slopes	• Methods for correction for velocity heads • Comparison of acoustic versus radar sensors • Slope measurements with RTK-DGPS	3 2? 1
	Velocities	• Effect of coarse sediments on ADCP measurements • Combination moving boat with ADCP calibration	2? 1
	Suspended load	• Development integrated collapsible bag • Further development use of ADCP for "coarse" sediment	2 2
	Near-bed sediment transport	• Development of a special sampler for the Jamuna River • Study of performance of Delft Bottle with respect to "losses" • Development of ultra-sonic sensors for near-bed transport	2 2 3
Satellite imagery	SPOT	• Optimization contrast for better interpretation • Applicability of quick looks for operational applications	3 1
	Radar	• Use of radar for mapping flood extent • Use of radar for identification morphological development • Use of radar for planning AFPM activities • Use of radar for determining submerged bathymetry	1 2 1 2
Legend ranking: 1 = Immediately to be taken up; 2 = To be taken up in a few years (by Special Study Unit); 3 = In due time, e.g. via collaboration with Universities and institutes			

Table A4.1 Proposed study topics on survey techniques inclusive use of satellite imagery (for more details on those ranked 1 see Section 11.2; for background information see Annexes 1 and 2)

Hydrological studies

The hydrological studies to be done in future can roughly be divided into:

- *additional measurements* aiming at completing the data base on the main rivers in Bangladesh;
- *special studies* aiming at improving the understanding of the river behaviour, using this data base and doing special studies.

Topic		Proposed studies	Ranking
Additional measurements	?	?	
	?	?	
Special studies	Network	• Study of potential new sites in view of hydrological and morphological characteristics	1
		• Comparison discharge measurements Mawa versus Baruria and Arial Khan	1
		• Extension of hydrological network in downstream direction, possibilities and limitations	2
	Rating curves	• Changes in rating curves and morphological changes	2
	Overland flow	• Overland flow Jamuna River (1- and 2-d modelling, measurements) as basis for overall sedimentation assessment	2
		• Flow over chars (measurements; analysis resistance to flow)	3
	Slopes	• Detailed local slope measurements plus morphological interpretation	2
Legend ranking: 1 = Immediately to be taken up; 2 = To be taken up in a few years (by Special Study Unit); 3 = In due time, e.g. via collaboration with Universities and institutes			

Table A4.2 Proposed study topics on hydology (for more details on those ranked 1 see Section 11.3; for background information see Annex 5 and Study Report 1)

Sedimentology

The sedimentological studies to be done in future can roughly be divided into:

- *additional measurements* aiming at completing the data base on the main rivers in Bangladesh;
- *special studies* aiming at improving the understanding of the river behaviour, using this data base and doing special studies.

Topic		Proposed studies	Ranking
Additional measurements	On a regular basis	None	-
	Once	• Bed material sampling • Mineralogy of sediments • Composition of banks, floodplains and chars • Composition of subsoil of rivers • Geological controls	2 2 2 3 1
Special studies	Bed material	• Longitudinal sorting, abrasion and subsidence • Deposition of fine sediments • Formation of controls	3 2 3
	Resistance to flow	• Contributions to resistance to flow • Low resistance during floods	1 1
	Bedforms	• Occurrence of bedforms • Slope of lee-side of dunes	3 2
	Sediment transport patterns	• Areas with intense morphodynamic activity • Flow and sediment transport over dunes	2 3
	Floodplain sedimentation	• Rates of floodplain sedimentation • Overall floodplain sedimentation • Floodplain sedimentation and subsidence	1 2 2
	Morphological impact assessment	• Impact assessment implementation FAP/NWMP implementation (1-dimensional)	1
Legend ranking: 1 = Immediately to be taken up; 2 = To be taken up in a few years (by Special Study Unit); 3 = In due time, e.g. via collaboration with Universities and institutes			

Table A4.3 Proposed study topics on sedimentological characteristics (for more details on those ranked 1 see Section 11.4 and 11.6; for background information see Annex 4)

River morphology

The river morphological studies to be done in future can roughly be divided into:

- *additional measurements* aiming at completing the data base on the main rivers in Bangladesh;
- *special studies* aiming at improving the understanding of the river behaviour, using this data base and doing special studies.

Topic		Proposed studies	Ranking				
Additional measurements	On regular basis	- Water and sediment distribution at offtakes - Scour holes	1 1				
	Once	None	-				
Special studies	Slopes, planform and cross-sections	- Width and width adjustment of channels - Pointbar accretion due to bank erosion - At-a-station-relations - Meander dimensions and braiding indices - Integrated morphodynamic frame-work	2 3 3 2 2				
			Offtakes	- Historical development of offtakes - Water- and sediment distribution at offtakes - Modelling of offtakes (1-d, 2-d) - Future development of offtakes	1 1 2 2		
					Confluences	None?	-
					Bars and bifurcations	- Dimensions of bars (length, width, height) - Development of bars in time - Flow around bars and growth of bars - Water- and sediment distribution at bifurcations	3 3 3 2
							Scour holes
	Bank erosion and cutoffs	- Bank erosion concepts - Development of new channels - Study of major planform changes like cutoffs and abandonment of channels - Infilling of old channels and oxbow lakes	1 2 3 3				
	Flow pattern and maximum velocities		- Maximum flow velocities (probability of occurrence) - Location and moment of occurrence of maximum flow velocities	2 2			
	Exchange of sediments	- Exchange of sediments (sand and silt) between main rivers and floodplain - Scour and fill in the main rivers		2 2			
	Channel form changes and planform development		- Meandering of Dhaleswari River and other distributaries - Occurrence of hard points - Effect of neotectonics on planform - Importance of deep scour holes for planform development	2 2 2 2			
	Prediction methods	- Prediction short-term planform changes (quick assessment) - Prediction short-term planform changes (using 2-D morphological models) - Prediction medium term bed topography changes - Probabilistic approach to mid-term planform prediction		1 1 2 1			
			Morphological impact assessment	- Response of Old Brahmaputra and Upper Meghna morphology to historical changes in flow - Impact assessment implementation FAP/NWMP implementation (including planform changes and future offtake behaviour)	2 2		

Legend ranking:
1 = Immediately to be taken up;
2 = To be taken up in a few years (by Special Study Unit);
3 = In due time, e.g. via collaboration with Universities and institutes

Table A4.4 Proposed study topics on river morphological characteristics (for more details on those ranked 1 see Section 11.5 and 11.6; ; for background information see Annex 5)

