GOVERNMENT OF THE PEOPLE'S REPUBLIC OF BANGLADESH

Flood Plan Coordination Organisation

FAP-25

FLOOD MODELLING AND MANAGEMENT

Flood Hydrology Study

Main Report

June 1992

Krüger Consult
in association with
BCEOM

Governments of
Denmark, France,
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FLOOD HYDROLOGY STUDY

MAIN REPORT

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LIST OF ABBREVIATIONS

BWDB	Bangladesh Water Development Board
CAT	Coordination Advisory Team.
DANIDA	Danish International Development Assistance
EPWAPDA	East Pakistan Water Development and Power Authority
FAP	Flood Action Plan
FAPMCC	FAP Modelling Coordination Committee
FEC	French Engineering Consortium
FHS	Flood Hydrology Study
FPCO	Flood Plan Coordination Organisation (under MIWD&FC)
FMM	Flood Management Model
GEV	General Extreme Value
GM	General Model
GOB	Government of Bangladesh
GPS	Global Positioning System
HYMOS	Software Package for Hydrometeorological Data Base Management and Processing System
IECO	International Engineering Company, Inc.
MIWD&FC	Ministry of Irrigation Water Development & Flood Control.
MIKE 11	Software Package for One Dimensional River Modelling
MPO	Master Plan Organisation (under MIWD&FC), now WARPO
NAM	Rainfall Runoff Model (Danish Abbreviation)
NCRM	North Central Regional Model
NWP	National Water Plan (under MPO)
RMC	Resident Model Coordinator
SWH	Surface Water Hydrology Directorate (under BWDB)
SWMC	Surface Water Modelling Centre (under MPO)
UK	United Kingdom
UNDP	United Nations Development Programme
WARPO	Water Resources Planning Organisation

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FLOOD HYDROLOGY STUDY

EXECUTIVE SUMMARY

Component 25 of the Bangladesh Flood Action Plan, **Flood Modelling and Management,** consists of three components one of which - **the Flood Hydrology Study** - has been drawn up with the objective of establishing the hydrological basis for defining unified engineering design criteria along the major rivers.

In addition, the Flood Hydrology Study(FHS) should recommend a unified methodology for establishing similar criteria along the secondary river network as required, notably, by the regional FAP studies, FAP 2-6.

The present report contains the main findings and recommendations of the Flood Hydrology Study.

Methodology

An approach, proposed in the Terms of Reference, for achieving the objectives of the FHS is to carry out a joint probability analysis of the various flood causing factors in Bangladesh. However, as the physical system of rivers, flood plains and embankments is determining, for each location, the interaction of these causes, a joint probability analysis can only be undertaken once various combinations of events with the same impact on flood levels are known.

It might be possible, with considerable difficulties, to carry out such analysis for the main river system, in its present conditions, based on historic water level and flow data. However, it has been concluded that such detailed analysis is impracticable, in particular in view of the need to derive design hydrographs for potential future flood protection scenarios, which may induce significant changes in the probability distributions of water levels and flows, and even in the joint probabilities of various flood causing factors.

The only practical and feasible approach, and the one on which the FHS is based, is to use the General Model (GM) of the Surface Water Modelling Centre (SWMC) to simulate long series of historical or possible future hydrographs in the main river system, on the basis of which hydrological design conditions can be derived. A similar reasoning holds for the establishment of design conditions along the secondary rivers, where the regional models of the SWMC may be applied.

Consequently, the adopted methodology for the FHS consists of three main activities:

- base line statistical and correlation analysis of historic water level and flow data with the aim to 1) assess the quality of available data and establish reliable boundary and validation data for the GM, 2) determine the statistical representativeness of the period

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1965-1989 for the full century, 3) recommendations on suitable probability distributions for various hydrological variables and 4) carry out frequency analysis on observed data as basis for comparison with simulated data;

a validation of the GM for the full period 1965-89, statistical analysis of model output including design statistics, proposal for associated safety margins, supply of regional model boundary conditions to the regional consultants, and outline of a methodology for deriving design statistics at a regional level as well as for comparison of alternative protections schemes;

runs with the GM for the period 1985-1989 for alternative future country-wide flood protection schemes and for the full 25-year period (1965-89) for the most likely future protection scheme, including the analysis of results and supply of boundary conditions to regional consultants.

Data Collection and Review

Hydrological data have been collected from eight different sources, the Directorate of Surface Water Hydrology-II of BWDB being the primary source of data. The hydrometric data (water level and discharge) relate to the major rivers and the most important tributaries and distributaries only, while hydrometeorological data (rainfall and evaporation) covers the whole country, for rainfall even the entire catchment of the three major rivers. A search was made in London for historic discharge data from India for the Brahmaputra and the Ganges, however, without any positive result.

In the initial stage, the data collection was hampered due to the lack of a proper data directory at BWDB. An effort has been made, as part of the FHS, to develop such a directory based on data collected from BWDB, data available with WARPO and other sources. The directory is contained in Appendix 2 of this report and includes information on station name, code and length of records.

The review of rainfall data has included i) 27 Bangladeshi stations, spread over the entire country, for the period 1902-89, ii) 18 Indian stations, 6 in the Brahmaputra and Meghna basins and 12 in the Ganges basin, for the period 1891-1950 and iii) one Nepalese station, Kathmandu, for the period 1921-86. The analyses have consisted of basic statistical analysis, double mass analysis and statistical tests for long-term trends. Generally, rainfall data have been concluded to be reliable with the exception of five stations in Bangladesh (Dewanganj, Kishoreganj, Netrokona, Patuakhali and Comilla) and Kathmandu, where rainfall prior to 1945 seems significantly lower than after 1945.

Water level data from 28 stations (for the period 1965-89) have been used as boundary and comparison stations for the GM. Though a detailed review of data from all 28 stations was desirable, it was not possible within the resources of the FHS and not least because such review and corrections normally are based on correlation methods and thus only possible if correlations exist. In practice, the review focused on water levels in the Jamuna and the Ganges. Also downstream water level boundary stations have been scrutinized, notably Daulatkhan in the Lower Meghna.

Information on observation methodology has been collected from BWDB and field visits have been undertaken to a few selected stations. The review process has identified several types of observation errors, including missing data, erroneous data for periods from one day up to a year or more resulting from the frequent shift of gauges and possibly unreliable bench marks. Unfortunately, it has not been possible to deal with all the different type of errors in the FHS. Misssing data for short periods have been filled by interpolation and erroneous data for a day or a few days have been identified and corrected from time series hydrographs and relation curve analysis with neighbouring stations. Correction of other error types (data shifted for weeks, months or even years) is believed to be highly subjective and under all circumstances not possible within the scope of the FHS. Under FAP 24 - the River Survey Programme - further data correction may eventually be possible considering also the results from FAP 18 - Topographic Mapping - with respect to datum differences between eastern and western part of Bangladesh and checked/revised datum levels for BWDB temporary bench marks. Water level data corrected by FHS is contained in Appendix 3 of this report.

Discharge data from 12 stations (for the period 1965-89) have been used as boundary and comparison stations for the GM. Of these, three stations have been reviewed in detail, namely Bahadurabad, Hardinge Bridge and Baruria, the two former being the main upstream boundary stations of the GM and the latter the main comparison station. No detailed assessment has been possible on the accuracy of the discharge measurements and the data have been used directly. The observation methodology applied in combination with the difficult physical environment, especially during floods, leave, however, little doubt, that sometimes discharge measurements may involve significant errors, of both random as well as systematic character.

The FHS has reviewed available rating curves and equations developed by BWDB for the three above mentioned key stations. As rating equations are not available for all years and with a view to developing rating curves with consistent extrapolation characteristics, it was decided to develop a new set of rating curves for those stations, one for each year. In general, the new rating curves are not much different from BWDB rating curves. The magnitude of shifts of the annual rating curves have been analysed by computing water levels corresponding to a particular discharge. The results for the three stations are quite similar. The total range of shifts for the 25-year period is 0.8-1 m with a standard deviation of around 25 cm. Changes from one year to the next may be quite substantial and reach up to 40 cm. The exact reasons for these shifts have not been analysed but they may likely be caused by morphological changes, systematic errors in discharge measurements and long term shifts in gauge locations.

The revised rating curves and water level time series have been applied to calculate new discharge time series for the period 1965-89. In this process, the FHS has not applied shift corrections as done by BWDB. Usually, shift correction is applied when the stage-discharge relation changes with time due to change in cross section characteristics along the control section. A shift is a correction which is applied to the stage of a discharge measurement to bring the measurement in accordance with the derived mean rating curve. The procedure inherently assumes that the discharge measurements are true, without error. If this is not the case, application of shift correction may introduce new errors. Several examples of such errors have been found by plotting BWDB mean daily discharges and corresponding water levels.

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Statistical Analysis of Observed Data

A frequency analysis of observed data for the period 1965-89 has been carried out for annual peak water levels (22 stations), annual maximum discharges (5 stations), average seasonal discharge (May to October) and total annual rainfall (27 Bangladeshi stations). The probability distribution function applied for each hydrological variable has been selected on the basis of the findings from a comparison of six common distributions (Gumbel, GEV 2, GEV 3, Log-Normal, Pearson III and Log-Pearson III. The results of the analysis are:

- the 3-parameter Log-Normal distribution is appropriate for the statistical analysis of annual maximum water levels and average annual, seasonal and sub-seasonal discharges (flood volumes);

- the 3-parameter GEV-2 and the 2-parameter Gumbel distribution are appropriate for the analysis of annual extreme discharges;

- the 3-parameter log-normal distribution is appropriate for the analysis of annual, seasonal and sub-seasonal rainfall data.

The above recommendations should not be applied rigidly, without precaution. Probability analysis is too much a matter of judgement to justify application of such recommendations as if they would represent the only truth. They may be considered no more and no less than guidelines. In this context it is noted that the choice of a particular distribution function is hardly relevant for a design period of say less than 50 years, where most theoretical distributions produce more or less identical design values. Nevertheless, it is necessary that all FAPs choose their design criteria in the same manner. The detailed results of the frequency analysis is found in Chapter 6 and Appendix 6.

The National Water Plan (NWP) has used different probability distribution functions, namely Pearson III for peak water levels and Log-Pearson III for peak discharges. A comparison of the results of using the two different sets of probability distributions is shown in Tables 6.4 and 6.5 for peak water levels and peak discharges respectively. The common data period is 1965-89. For water levels there is a perfect agreement except for Hardinge Bridge. The deviation at this location is because left censoring techniques have been applied in the FHS to account for the special flow conditions here. This is not possible with the Pearson III distribution used in the NWP. With respect to peak discharges, slightly higher values result from using the NWP distribution (except for Bahadurabad). This tendency gets more pronounced with increasing return periods (especially beyond 100 years) and is, together with the comparatively easiness of applying the FHS distributions, the justification for the recommendations made in section 6.2.

The statistical representativeness of the period 1965-89 for the whole century has been assessed based on long term records of hydrological variable, including monthly rainfall data from 16 stations for the period 1902-89, daily water levels at Hardinge Bridge (1910-89) and daily discharges at Hardinge Bridge(1933-89) and Bahadurabad (1956-89). Although the data basis for such purpose is appreciated to be limited in the absence of historical water level and discharge data from India, it could yet be concluded that the hydrometeorological conditions in Bangladesh during the last 25 years are fairly representative for the longer term. In general, one may consider the 1965-89 period as a slightly conservative basis for design, when compared to the last 50-100 years.

General Model(GM) Validation

The implementation of the FHS methodology required a dedicated version of the GM to be developed, including all boundary stations of the Regional Models and allowing a large computational time step to arrive at an acceptable running time. This dedicated model, FAP 25-GM, has been derived from the original GM, mainly by extending the Ganges schematization up to the Indian border at Pankha, and by cutting out the Teesta introducing its discharge directly as a lateral inflow to the Jamuna at Kaunia.

The validation of the model has been based on the comparison of computed and observed water levels at 22 stations along the major rivers, their main tributaries and distributaries. Discharges have been compared at 5 stations to check the flow distribution in the major river network. A comprehensive error analysis has been carried out, including determination of average and standard deviation of differences between observed and simulated values (peaks, seasonal and subseasonal), preparation of error frequency curves, frequency analysis and comparison of simulated and observed values for various return periods.

The average difference (the so-called model bias) may to a certain extent be reduced through recalibration but may also be due to errors in gauge datum and chainage. The standard deviation (the so-called model scatter) can not be reduced through recalibration and mainly stems from random morphological changes, which are not taken into account in the "fixed-bed" GM, and from random observation errors. With respect to water levels the average difference along the major rivers is generally less than 20 cm with standard deviations of the order of 20-30 cm. This is considered satisfactory taking into account that uncertainties in gauge levels and chainage can generate errors of the same magnitude in observations. For some stations (Serajganj, Mathura and Sengram) results may be further improved and this should be one of the aims in the updating of the GM, to be undertaken by SWMC towards the end of 1992.

The comparison of discharges at Baruria, the main comparison station, shows an average deviation of only 3% within a range of approximately +/- 15%, well within acceptable limits considering potential errors in discharge observations.

Overall model errors are less than 0.2 m in about 45% of the time and less than 0.4 m in about 75% of the time.

One of the main objectives of the model application is to provide designers with a model system exhibiting the same hydrodynamic and statistical characteristics as the real system. A comparison of observed and simulated data (peak and mean seasonal water level) shows satisfactory model performance in the four major rivers for the whole range of return periods. The secondary rivers are not yielding equally good results, one reason being that accurate calibration here has not been a priority at the SWMC. Improvements of model performance in these secondary rivers should be another aim in the next update though it is stressed that less satisfactory results here only have insignificant effects on the model performance in the major river network.

Hydrological Design Criteria

In general, the hydrological design criteria in the major rivers resulting from the Flood Hydrology Study should for the sake of consistency be applied by all other FAPs. However, this should not exclude the use of other results based on more detailed analysis serving specific purposes. It should also be stressed that the FHS results are not static and should be updated as and when improved information becomes available (FAP 18, FAP 24, SWMC etc) or when schemes affecting water levels and discharges in the major rivers are finally decided for implementation (e.g. Jamuna Left Embankment or Jamuna Bridge).

Based on the successful validation of the FAP 25-GM, the recommended design water levels and discharges at key locations in the four major rivers and Old Brahmaputra are shown in Tables 1 and 2. Design levels and discharges at other locations in the major rivers can be derived on the basis of the 25-year model output and applying the probability distributions recommended by FHS. Other FAPs may collect model output from FAP 25 office. where model output from run 6 is available.

The differences between observed and simulated water levels (in the present and any future situation) may be explained by the effects of random morphological changes (also causing the annual shifts in rating curves), errors in boundary conditions or observed water levels or model errors (schematization effects). It has been recommended to take these effects into account by adding a safety margin to the design water levels, as they appear in Table 1, derived directly from model output. The recommended safety margins, based on an analysis of the individual errors, are 40, 30, 25 and 20 cm for return periods of 100, 50, 20 and 10 years respectively. These margins have to be considered within the overall safety requirements including freeboard. FPCO is recoommended to take decision on this safety margin issue at short notice to ensure a unified approach in all FAPs for the assessment of design criteria.

Methodologies for Regional FAP Studies

A similar methodology, as adopted in the FHS for establishing hydrological design conditions along the main rivers in Bangladesh, should be followed by the regional FAPs and other relevant FAPs to obtain design levels at regional levels. The implementation of the methodology by other FAPs would include:

- the development of dedicated versions of the regional models, allowing larger time steps to be used and enhancing the feasibility of this approach;

- the preparation of boundary conditions required to run such dedicated regional models for the period 1965-1989;

- running of the models for the full 25 years period, at least once for the present (baseline) conditions and once for the ultimately adopted regional flood alleviation scheme(s). Combination of various options to reach the final plan may be studied on the basis of simulations for only a few selected flood seasons;

- sensitivity analysis of ultimately adopted regional scheme considering changed boundary conditions in the major rivers due to proposed schemes outside the region;

- statistical analysis of the results, aimed at assigning return periods to historical peak, seasonal or sub-seasonal values of selected design variables.

In view of the large effort involved in running the regional models for a period of 25 years, such activity should only be undertaken once the development and calibration of these models has an acceptable degree of accurracy.

In the planning and conceptual design stage the main aim of using the regional model will be to assess the hydraulic efficiency of alternative flood alleviation schemes or components. For this purpose it will be quite sufficient to run the regional model only for some 3 historical flood seasons, for example 1987, 1988 and another year. The need to follow a practical approach in this is evident.

For the implementation of the methodology FAP 25 has provided or is in the process of providing relevant FAPs with 25 years of boundary conditions for the regional models, both for the present situation and for possible future situations, taking into account the impacts of projects designed throughout the delta (country-wide protection schemes).

It is recommended that the results from the existing situation (run 6 of the FAP 25-GM) are used by all the regional FAPs as the basic boundary conditions for the "future without" and "future with" project analysis on a regional level. By doing so, it will allow determination of the real benefits of a proposed scheme(A) within the region, the results not being distorted by changed hydrological conditions due to a proposed scheme(B) outside the region. Additional sensitivity analysis may be undertaken for the final, preferred development scheme with external water levels taken from the 5-year simulations done under stage 3 of the FHS for alternative country-wide protection schemes.

In addition, the FHS has established guidelines for selection of probability distribution for various hydrological variables, for review and correction of regional model boundary and validation data, for determination of safety margins for design along the regional river network, for development of straightforward design events for situations where local flooding is only caused by local events, in particular rainfall and for taking into account the effects of possible long term morphological development on design water levels;

Alternative Country-wide Flood Protection Schemes

The effects of a future left embankment along the Jamuna has been analysed for the 1988 flood, considering only the effects on water level. Long term morphological effects have not been included and the results may thus be different from the the recent China-Bangladesh study and other studies where morphology has been included. To the extent that design life of the structure is much shorter than the time scale of long term morphological changes this simplification may be acceptable for deriving design water levels. The assumed alignment , as proposed by FAP 3, is from the offtake of the Old Brahmaputra down to the Dhaleswari offtake from where it follows the left banks of Dhaleswari and Kaliganga to the Dhaleswari-Kaliganga junction at Kalatia. The model simulation shows that for the 1988 flood the main increase in water levels is found in Dhaleswari (1.3 m) and Jamuna (0.54 m at Serajganj but only 0.07 m at Bahadurabad). In Padma, the increase is around 0.20 m and at Chandpur in the Lower Meghna only 0.05 m. More comprehensive analysis of 7 alternative flood protection schemes will be carried out in stage 3 of the Flood Hydrology Study and reported in August 1992 as **Annex 2** to the present report. Morphology will still not be considered but comparison with other studies will be done.

Table 1: Peak Design Water Levels (m PWD) at Key Stations along the Major Rivers and Old Brahmaputra (Jamalpur and Nilukhirchar).

STATIONS	RETURN PERIODS					
	2	5	10	25	50	100
CHILMARI	23.85	24.23	24.45	24.70	24.88	25.04
BAHADURABAD	19.83	20.16	20.36	20.60	20.77	20.94
KAZIPUR	15.69	16.05	16.26	16.50	16.67	16.82
SERAJGANJ	14.26	14.62	14.82	15.05	15.20	15.35
PORABARI	12.10	12.45	12.66	12.91	13.08	13.24
MATHURA	9.77	10.12	10.36	10.67	10.91	11.15
HARDINGE BRIDGE	14.68	14.79	14.86	14.96	15.02	15.09
SENGRAM	11.93	12.31	12.52	12.75	12.90	13.05
MAHENDRAPUR	10.68	10.99	11.16	11.36	11.49	11.61
BARURIA	8.32	8.63	8.86	9.16	9.39	9.63
MAWA	5.92	6.20	6.41	6.68	6.90	7.13
BHAIRAB BAZAR	6.43	6.76	6.96	7.20	7.37	7.53
CHANDPUR	4.38	4.63	4.80	5.02	5.18	5.35
JAMALPUR	16.64	16.98	17.16	17.37	17.51	17.64
NILUKHIRCHAR	11.91	12.24	12.47	12.76	12.98	13.21

Notes : Log Normal distribution & the data for the period of 1965-89 is considered for all the stations except for Hardinge Bridge where Gumbel is applied with left censoring for the period of data of 1910-89.

Table 2 Peak and Mean Seasonal (May to October) Design Discharges (m3/s) along the Major Rivers and Old Brahmaputra (Nilukhirchar)

a): Peak Design Discharges

STATIONS	RETURN PERIODS					
	2	5	10	25	50	100
BAHADURABAD	67700	78500	85600	94600	101200	107900
HARDINGE BRIDGE	48800	59600	66800	75800	82500	89200
BARURIA	89600	102000	112400	128500	143100	160300
BHAIRAB BAZAR	13400	15700	17300	19300	20800	22300
NILUKHIRCHAR	3130	3810	4260	4830	5250	5660

Notes : Gumbel distribution is applied for all the stations exept for Bhairab Bazar where GEV II is applied. Period of data is 1965-89.

b): Mean Seasonal Design Discharges

STATIONS	RETURN PERIODS					
	2	5	10	25	50	100
BAHADURABAD	34000	37700	39900	42500	44300	46000
HARDINGE BRIDGE	19000	21900	23400	25000	26100	27100
BARURIA	47700	51500	53600	55900	57400	58800
BHAIRAB BAZAR	7500	8600	8500	10600	11500	12500
NILUKHIRCHAR	920	1140	1280	1460	1590	1720

Notes : Log Normal distribution & the data for the period of 1965-89 is applied for all the stations.

1. INTRODUCTION

1.1 General

Component 25 of the Bangladesh Flood Action Plan (FAP 25), **Flood Modelling and Management,** consists of the following three sub-components:

- A Coordination Advisory Team (CAT);

- A Flood Hydrology Study (FHS);

- A Flood Management Model (FMM).

The project is executed by the Flood Plan Coordination Organisation (FPCO) with the Danish Ministry of Foreign Affairs (DANIDA) as the lead donor. The donor agencies of France, the Netherlands and United Kingdom also contribute to the project.

The first two of these project components, CAT and FHS, are ongoing since January 1991. The implementation of the last component, FMM, is expected to start from mid 1992.

The present report contains the main findings and recommendations of the Flood Hydrology Study. The time schedule and implementation of the Flood Hydrology Study is, however, such that even after submitting this report additional analyses will be carried out. Those results will be reported in Annex 2 to this main report.

1.2 Objectives and Scope of the Flood Hydrology Study

The objectives of the Flood Hydrology Study may be summarized as follows:

- to establish the hydrological basis for engineering design criteria along the major; rivers;

- to recommend a unified methodology for establishing such basis along regional rivers, to be implemented by the regional FAP studies.

From the onset of the Flood Action Plan it was appreciated that though valuable preparatory work had been undertaken on flood statistics in Bangladesh, e.g. within the National Water Plan, Ref. 9, and in the FEC "Prefeasibility Study for Flood Control", Ref. 6, there was a need to carry out a more refined analysis with a view to establishing sound, regionally distributed hydrological design events supporting the selection of unified engineering design criteria.

The Flood Hydrology Study was originally intended to have a duration of six months but was extended on the basis of the recommendations in the report of the second CAT mission in May 1991, see Ref. 17. Thus, the actual implementation of the project has taken place in the following stages:

- **Stage 1**, activities carried out in the period up to April 1991 and reported in the Stage 1 Interim Report, Ref. 19, containing the results of the preliminary frequency analyses of inundated areas, water levels, discharges and rainfall and also discussing possible approaches to establishing the hydrological basis for engineering design criteria;

- **Bridging Period,** being the period from May 1991 to August 1991, in which the feasibility of the revised methodology, as outlined in the report of the second CAT mission and summarized in Chapter 2, was proven;

- **Stage 2,** being the period from September 1991 to January 1992, in which the revised methodology was implemented;

- **Stage 3,** being the period from February 1992 to July 1992, in which a more comprehensive analysis of country-wide flood protection schemes is carried out

The present report contains the results and recommendations obtained during the Bridging Period and Stage 2 and may be considered the main report of the Flood Hydrology Study. The main activities undertaken are:

- a validation of the General Model (GM) of the Surface Water Modelling Centre (SWMC) for the period 1965-1989;

- frequency analysis of model results with the aim of producing required design statistics and determining the representativeness of the period 1965-1989 for the whole century and to provide standard errors of estimate for specific design criteria;

- provision of boundary conditions for regional models based on output from the GM, to be used by the regional and other relevant FAPs;

- development of a methodology to be applied by the regional FAPs for establishing hydrological design criteria on a regional basis;

- simulation of one country-wide protection scheme with the GM in order to establish possible effects of such measures, details of which should be studied in stage 3 of the FHS, based on the findings of other FAPs, in particular FAP 1 - FAP 6.

1.3 Contents of the Report

The present report consists of two volumes, the first volume referred to as the **Main Report** and the second volume, referred to as **Annex 1**. A third volume, **Annex 2** will be prepared by the end of stage 3.

The present volume, the **Main Report**, starts with an Executive Summary and the present introductory chapter. Chapter 2 describes the general methodology applied in the Flood Hydrology Study and its justification, while Chapter 3 provides a short description of the study area and the genesis of floods in Bangladesh. In Chapter 4, an overview of the data collection carried out by FAP 25 is given. Chapter 5 details the comprehensive review and correction of hydrological data and an in-depth analysis of rating curves for some key stations in the hydrological observation network. Chapter 6 describes the results of the statistical analysis of the corrected data, including assessment of suitable probability distributions, a joint probability analysis of flood causing factors and an analysis of the representativeness of the period 1965-1989 for the century.

The results of the 25-years simulation with the GM (the socalled run 6) is described in Chapter 7, including details on the FAP 25 dedicated version of the GM (FAP 25-GM), model validation, recommendations with respect to updating of the model, statistical analysis of model results and comparison with observations, and recommendations on safety margins to be applied for design purposes. Finally, likely hydrological effects of a Brahmaputra Left Embankment has been roughly assessed, while detailed analyses of various (combinations of) flood protection schemes will be undertaken in stage 3.

Chapter 8 contains the recommended methodology to be applied by the regional FAP studies for analysis of the overall regional effects of alternative flood alleviation measures and to arrive at suitable hydrological design criteria at feasibility and detailed design level. The programme for stage 3 of the FHS is outlined in Chapter 9. The results of this stage is contained in **Annex 2**.

The second volume, **Annex 1**, comprises a number of appendices giving more detailed information (methodology, results and graphical presentations) on the comprehensive data analysis, which has been carried out in the Flood Hydrology Study.

Tables and figures are numbered continuously within each chapter, the tables being placed within the text of each chapter and the figures in the back of the Main Report.

1.4 Acknowledgement

The FHS has been carried out in close cooperation with the SWMC under the Water Resources Planning Organisation (WARPO - previous MPO). The assistance and active support from SWMC throughout the study is highly appreciated.

2. METHODOLOGY

2.1 General Methodology

In the Terms of Reference of the Flood Hydrology Study(FHS), it is stated that the FHS should "provide the hydrological basis for establishing unified engineering design events for the FAP". This should be achieved by "analyzing in depth the characteristics of flood hydrology in Bangladesh by taking into consideration, among other things, the joint probability of the simultaneous occurrence of the individual main causes of floods".

The main problem in a theoretical joint probability analysis of various causes of floods is to incorporate the interaction of the physical system with these causes. For example, a certain water level in a backwater zone can be produced by various combinations of tail water levels and rainfall dependant upstream inflows. The physical system of rivers, flood plains and embankments determines for each particular location the interaction of the various causes of flooding. Joint probability analysis can only be undertaken once various combinations of events with the same impact on flood levels are known.

It may, eventually, be possible to carry out such analysis for the main system in its present conditions, based on historical water level and flow data. However, such data generally do not exist for most part of the regions, outside the main system. Moreover, results of such analysis for the main river system are also not applicable for potential future situations upon completion of a country-wide flood protection scheme. Embankments along all major rivers may change the pattern and amount of overbank spills substantially, and consequently induce significant changes in the probability distributions of water levels and flows, and even in the joint probabilities of various flood causing factors.

The conclusion is that a theoretical joint probability analysis is extremely difficult and impracticable, in particular in view of the need to derive design hydrographs for potential future situations with anticipated changes in the conditions of the main river system. Hence, the only practical and feasible option is to use the GM of the SWMC extensively to simulate long series of historical or possible future hydrographs in the main river system, on the basis of which hydrological design conditions can be derived. A similar reasoning holds for the establishment of design conditions along the secondary rivers, where the regional models of the SWMC may be applied.

Consequently, the adopted methodology for the FHS consists of three main activities:

- base line statistical and correlation analysis of historic water level and flow data with the aim to 1) assess the quality of available data and establish reliable boundary and validation data for the GM, 2) determine the statistical representativeness of the period 1965-1989 for the full century, 3) recommendations on suitable probability distributions for various hydrological variables and 4) carry out frequency analysis on observed data as basis for comparison with simulated data;

- a validation of the GM for the full period 1965-89, statistical analysis of model

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output including design statistics, and supply of the regional model boundary conditions to the regional consultants;

- runs with the GM for the full period 1965-1989 for potential future situations after the implementation of alternative country-wide flood protection schemes including the analysis of results and supply of boundary conditions to the regional consultants.

The detailed methodology is described in Appendix 1. It has been defined essentially in the report of the second CAT mission in May 1991 and reviewed during subsequent CAT missions.

It is stressed that the FHS does not pretend to be a general study of flood hydrology in Bangladesh. Issues which may be important for flooding in regional rivers only, having none or little effects on flooding conditions in the major rivers, are either not addressed or may be embedded in the methodology of the FHS. Examples on this include:

- flash floods generated by short duration (hourly or less) intensive rainfall, especially in the North East, but with no effects on flooding in the major rivers;

- tide, monsoon setup and cyclone generated storm surges in the Bay of Bengal which affect flooding conditions in the coastal areas of South West and South East and in the Lower Meghna. While not being studied in detail, these phenomona are taken into account in the methodology of the FHS through their influence on downstream water level boundaries in the GM.

The detailed analyses of above flood causing factors will be the responsibility of the relevant FAPs, i.e. in the first case FAP 6 and in the second case FAP 4, FAP 5, and FAP 7.

2.2 Summary of Activities.

The detailed activity schedule of the FHS has included:

- Collection and review of hydrological data from BWDB. Prudent procedures have been applied to check and correct these data with a view to establishing a set of quality data for key stations along the major rivers (see Chapter 4 and 5);

- establishment of a unified methodology for statistical analysis including :

    * statistical procedures for fitting of probability distributions, see section 6.1;

    * selection of suitable probability distribution function(s) for various hydrological variables, see section 6.2;

- frequency analyses on observed hydrological data, see section 6.3;

- study of joint probabilities of main streamflows and rainfall inside Bangladesh, see section 6.4;

- assessment of the representativeness of the simulation period for the whole century through collection and statistical analysis of historic data for the Ganges and Brahmaputra basins in Bangladesh and India (water level, discharge, rainfall). The search for historic water level and discharge data from India was unsuccessful, but rainfall data was collected, see section 6.5;

- validation of the FAP 25-GM for the period 1965-89 and determination of hydrological design conditions (water levels, discharges and flood volumes) along the major rivers, see sections 7.1 - 7.5;

- recommendations on hydrological design criteria, see section 7.6;

- recommendations on associated safety margins to be applied for different return periods to account for uncertainty due to shortness of available records, effects of random morphological changes, observation errors, possible errors in model calibration etc, see section 7.7;

- establishment of a methodology for considering effects of long-term morphological changes on design conditions , see section 7.8;

- supply of 25-year boundary conditions (water levels and discharges) for the regional models to the regional FAP's, and other FAP's as required, see section 7.9;

- running of the FAP 25-GM for country-wide protection scenarios, see section 7.10, Chapter 9 and Annex 2;

- establishment of a methodology to be followed in regional studies for establishing hydrological design conditions in regional rivers, see Chapter 8.

3. STUDY AREA

Prior to getting into details of the flood hydrology of one of the world's largest and most complex hydraulic systems, this chapter is aimed at giving an outlook of the project area and describing the monsoon cycle that governs all life in this region.

3.1 Description of the Study Area.

The study area covers the three basins of of the rivers Ganges, Brahmaputra and Meghna, situated inside the territory of Bangladesh and referred to hereinafter as the Bangladeshi Delta. It covers an area of 120,400 sq.km out of the 144,000 sq.km of Bangladesh, i.e. 84% of the country's territory, cf. Figure 3.1.

Compared to other major deltas in the world, this is the most densely populated and it is among the first for its surface area and peak flows.

The Bangladeshi Delta is very complex. Its main structure may be described as follows:

- entering the Delta from the North, the Brahmaputra, changing its name to Jamuna at the offtake of the Old Brahmaputra;
- the Jamuna meets the Ganges entering from the West at Aricha. Downstream of the confluence the river flows south-east under the name of Padma, up to its confluence with the Upper Meghna;
- downstream of this confluence, the river flows south to the Bay of Bengal under the name of Lower Meghna.

Branched to these main rivers, the delta network includes:

- tributaries such as the Atrai, Teesta, Dharla and Dudkumar rivers in the North West draining to the Jamuna or the rivers draining the Upper Meghna watershed;
- looping branches between the rivers such as the Old Brahmaputra and the Dhaleswari;
- distributaries between the main rivers and the sea such as the Gorai and the Arial Khan.

The average slope of the rivers in the delta is very low, about 0.00006, (6 cm/km).

When dealing with the flood hydrology of the Bangladeshi Delta it should be appreciated that about 93% of the catchment area of the three main rivers is situated in India, China, Nepal and Bhutan, cf. Figure 3.2 . The distribution of the catchment areas of the three rivers on the riparian countries is shown in Table 3.1.

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Table 3.1: Distribution of Catchment Areas (Sq km and %) on River Basin and Riparian Countries, from Ref.11.

	Ganges		Brahmaputra		Meghna	
	Sq.km	%	Sq.km	%	Sq.km	%
Bangladesh	46,300	4	39,100	7	35,000	43
India	860,000	79	195,000	35	47,000	57
China	33,520	3	270,900	49	-	-
Nepal	147,480	14	-	-	-	-
Bhutan	-	-	47,000	9	-	-
Total	1,087,300	100	552,000	100	82,000	100

The **Ganges** originates from the Gangotri glacier in the Himalayas at an elevation of about 7,010 m near the Indo-China border. The length of the main river is about 2,550 km. It enters Bangladesh near Pankha after draining the south side of the Himalayas and the major part of northern India.

The **Brahmaputra** originates from the Tibetan Himalayas at an elevation of 5,150 m near the Nepal-Chinese border. It first drains the dry northern side of the Himalayas, flowing eastwards under the Chinese name of Tsangpo through a succession of rapids. Then turning southwards, it enters India taking the name Brahmaputra . Turning westwards, it drains the very humid Assam Valley. It turns once more southwards round the Garo Hills and enters Bangladesh near Noonkhawa, where it takes the name Jamuna.

The **Meghna** river is a combination of smaller rivers draining the south slopes of Meghalaya and the south eastern slopes of Assam, where world records of rainfall have been observed.

3.2 Genesis of Floods

The monsoon cycle is the major climatic phenomenon governing the runoff from the entire catchment.

Figures 3.3 and 3.4 show the distribution of mean annual rainfall in Bangladesh and over the total catchment respectively. The genesis of floods in Bangladesh is briefly described hereafter and illustrated on Figures 3.5 to 3.8, showing hydrographs at various locations for 1986. This year has been selected, because it allows the illustration of most of the phenomena described in the following. For description of the major floods in 1987 and 1988 reference is made to the numerous reports on those floods, e.g. Ref. 4 and Ref. 6.

In time, the monsoon cycle can be roughly schematised as a succession of a dry season (from November to April) and a wet season (from May to October). At the turn of these seasons (May and November) short periods of meteorologically greater instabilities favour the occurrence of violent cyclones in the Bay of Bengal.

Due to the cyclonic origin of storms in the monsoon season, rainfall is very irregular as it can be observed in Figure 3.5. Heavy rainfall of short duration (few days) alternates with almost dry spells of identical duration.

In the midst of the monsoon, a short dry period may occur, known as the the monsoon break. Depending on the length of this period (up to 20 days), the monsoon break may or may not be observed in the river flows.

The timing and the intensity of the monsoon vary widely from place to place over the whole catchment. Its duration decreases from east to west. In western India, the monsoon normally begins in June and ends in October and is thus about two months shorter than in the eastern part of Bangladesh. This results in shorter duration floods in the Ganges at Hardinge Bridge than in the Jamuna at Bahadurabad. This is illustrated in Figure 3.6.

Similarly, the rainfall depth decreases from east to west but is mainly dependent on the relief (altitude and orientation) as can be seen on Figures 3.3 and 3.4. Assam receives the highest rainfalls, culminating at Cherapunji, where annual depths over 11 m have been observed. The southern Himalayan slopes of Nepal receive annual depths ranging from 1,500 to 3,000 mm, while on the western Indian plateau, annual rainfall depths are below 1,000 mm. Intermediate depths are observed in the eastern Ganges valley. With the Himalayas acting as a barrier of the monsoon, the lowest depths (about 500 mm or less) are observed on the Tibetan northern slopes of the upper Brahmaputra catchment. River flows follow the monsoon cycle with alternating flood seasons and low flows.

Typical monsoon hydrographs in the main rivers, cf. Figure 3.6, comprise two components:

- A base flow from June to October on the Jamuna and from July to October on the Ganges;

- Superimposed the baseflow are fluctuations with a characteristic period of half to one month, generating various peaks in the Jamuna and the Ganges hydrographs. The first flood peaks in the Jamuna are mainly due to snowmelt runoff from the Himalayas.

The Ganges and Jamuna hydrographs combine at Baruria to produce hydrographs of similar pattern. It is observed that in 1986 neither the highest peak in the Jamuna nor in the Ganges produced the highest peak in the Padma at Baruria. Moreover, the influence of the monsoon break in August 1986 may be observed on Figure 3.6.

In the Upper Meghna catchment, cf. Figure 3.7, where the rivers respond immediately to the rainfall, erratic hydrographs are observed such as the one at Sheola. These kinds of rivers with smaller catchments are known as "flashy rivers" in Bangladesh. The Teesta river in the northwest of Bangladesh also falls in this category. At Bhairab Bazar, the confluence of the contributing rivers, the combination of local rainfall and catchment integration lead to a more regular hydrograph with a significant baseflow, cf. Figure 3.7.

In the Lower Meghna, cf. Figure 3.8, at Chandpur, peaks are indistinct due to the flood attenuation in combination with the influence of backwater and the tide. The tidal fluctuations at Galachipa in the Bay of Bengal can also be observed at Chandpur.

The influence of cyclones is also illustrated on the same figure. The cyclone, raising the level in the Bay by about 1 m in the first half of November 1986, causes a raise in level of about 0.5 m at Chandpur.

The mechanisms described above explain the simple flooding process along the major rivers. In areas away from the major rivers, flooding may stem from various independent or combined causes:

- local rainfall;
- overflow from regional rivers;
- flash floods from smaller rivers;
- tides (mainly in the SW region);
- cyclone generated backwater;
- drainage congestion.

The actual magnitude and duration of floods at a particular location depends on the degree of synchronisation of the various flood causing factors, which may be expressed through their joint probabilities of occurrence. As explained in Chapter 2 such analysis is extremely difficult. However, the ultimate effect of the combined occurrence of these factors are accounted for in the methodology applied in the FHS.

One recent example of the aggravating effect of synchronisation of various flood causing factors is the 1988 flood. The magnitude and extent of this flood was caused by the simultaneous peaking of flood in the Jamuna and the Ganges. The duration of the flood was aggravated as a result of impeded drainage caused by the simultaneous occurrence of spring tide in the Bay of Bengal. This is due to second order effects of tidal wave propagation resulting in mean daily water level being up to several decimeters higher during spring tide than during neap tide, the actual difference depending on the particular location.

3.3 Previous Flood Hydrology Studies

Obviously, numerous studies on flood hydrology have been undertaken in Bangladesh, some of more general character others relating to the floods in specific years. It is not intended to provide a complete overview of these studies in the present report, however three studies may be worthwhile recalling here. The first is the IECO Master Plan Study from 1964, see Ref. 21, the second is the National Water Plan from 1987, see Ref. 9 and the third the "Prefeasibility Study on Flood Control" from 1989, see Ref. 6.

The IECO Master Plan Study undertook a comprehensive analysis of climate, surface water and groundwater data. Especially the rainfall analysis was very comprehensive and included preparation of annual and monthly isohyatal maps, intensity-duration relationships (1 - 72 hours) for seven stations, and development of methods for deriving intensity-duration-frequency as well as depth-area-time relationships. The quality of the rainfall data was not discussed.

With respect to water level observations the report notes that interpretation of water level recordings before 1960 is difficult due to lack of knowledge of exact datum. A program was initiated prescribing at least annual check of datum with nearest bench mark. When establishing new stations (including temporary stations as a result of gauge shift) levelling should be done as soon as possible.

Concerning discharge observations the report recommends that data before mid-1960 be used with caution, because of the observation method (few surface floats in each cross section). The data analysis for several hydrometric stations include preparation of flood duration curves and flood frequency analysis on water level as well as discharge. There is no indication of probability distributions used.

In the National Water Plan, a comprehensive analysis of flood data was carried out, including discharges and water levels for several hundred stations and determination of flood depths under existing conditions (flood phases). The frequency analysis was done using the Log-Pearson III for discharges and Pearson III for water levels. The report shows a good fit to these distributions though it does not provide any justification for selection of these particular distributions.

Attempts were made to derive regional flood frequency curves for different regions. This turned out to be not very successful not least in areas where floods are mainly caused by spill received through distributaries of the main rivers.

A limited analysis of the effect of cyclone generated storm surges on water levels in the coastal areas was carried out based on empirical relationships between wind speed, pressure drop and maximum storm surge height.

In the "Prefeasibility Study on Flood Control" the lag time between flood peaks in the Jamuna and the Ganges was analysed. It was shown that the simultaneousness of flood peaks in these two rivers, one of the main reasons of the disastrous flood of 1988, may be a more frequent event than previously anticipated. Out of a sample of 32 years it appeared that in 8 years the Jamuna peak occured late within +/- 12 days of the Ganges peak (normally in early September). The FEC study also did some analysis of hydrograph shapes and selection of reference floods, which was considered in developing the final methodology of the FHS.

3.4 Observation Network.

The meteorological and hydrometrical observation network includes about 250 rainfall stations and about 300 water level stations, of which 22 stations on the major river network are regularly rated. The complete list of these stations is given in Appendix 2.

Daily rainfall data are available for most of the rainfall stations from 1961, with the exception of a few missing years. About 100 of these stations have monthly data available as far back as from 1902.

Most of the numerous existing water level stations listed in Appendix 2 have only short series of observation.

4. DATA COLLECTION

The nature of the FHS is such that all analyses are based on existing secondary data. Collection of primary data in the field has been outside the scope of the study.

Secondary data have been collected :

- for all parameters relevant to the FHS: rainfall, water levels, discharge, rating curves, and evaporation;
- for the longest period possible to optimise statistical analysis;
- including information allowing fair assessment of data quality.

Due to the scatter of information and administrative procedures, data collection has been very time consuming and required a lot of efforts before a comprehensive and consistent data base could be set up.

This chapter summarizes the sources of data, the type of data that has been collected and the data bases which have been developed.

4.1 Data Sources

Various agencies have been approached to obtain basic hydrological data including :

- Directorate of Surface Water Hydrology-II (SWH-II) of Bangladesh Water Development Board (BWDB);
- Surface Water Modelling Centre (SWMC);
- Water Resources Planning Organisation (WARPO), previous Master Plan Organisation (MPO);
- Indian and Oriental Office of the British Library in London;
- Joint Rivers Commission (JRC), Bangladesh;
- North West Hydraulic Consultants;
- Brahmaputra River Training Studies (FAP 1);
- Department of Irrigation,Hydrology and Meteorology, Nepal.

The major source of hydrological data is the Directorate of Surface Water Hydrology-II of BWDB. In the initial stage, the data collection was hampered due to the lack of a proper data availability directory at BWDB. Efforts have been made by FAP 25 to develop such a hydrological data directory based on data collected from BWDB, present data available with WARPO and other sources.

Further efforts would be necessary by BWDB to correct, modify and update the present directory in order to arrive at a final version of a hydrological data directory for future use. The present available directory is given in Appendix 2.

4.2 Collected Data

Rainfall Data

The collection of rainfall data was highly facilitated by the availability of the rainfall data base from North West Hydraulics Consultants. This data base contains daily rainfall volumes for the period 1954 to 1989 for all the observation stations in Bangladesh, see Appendix 2.

Furthermore, monthly rainfall volumes have been collected from BWDB publications for 27 selected stations in Bangladesh for the period 1902 to 1959, see Ref. 14 and 15.

Table 4.1 : Annual Rainfall Data Available for India

Years	Bombay	Nagpur	Jabalpur	Calcutta	All other stations
1817-1825	X				
1826-1828	X	X			
1829-1832	X	X		X	
1833-1844	X			X	
1845-1854	X		X	X	
1855-1876	X	X	X	X	
1881-1936	X	X	X	X	X
1939-1950	X	X	X	X	X
No. of Yrs	118	87	90	106	58

Historical rainfall data (prior to 1950) for the Indian catchments of the Ganges and the Brahmaputra rivers have been collected from the Indian and Oriental Office of the British Library in London (U.K). The time series are indicated in Table 4.1 and include 22 stations, viz: Goalpara, Gaohati, Dibrughar, Darjeeling, Jorhat, Silchar in Eastern India, (Brahmaputra and Meghna basins), Rajmahal, Monghyr, Patna, Allahabad, Benares, Bareilly, Agra, Kanpur, Delhi, Jaipur, Bhopal and Kotah in the Ganges basin and Bombay, Nagpur, Jabalpur and Calcutta close to but outside the Ganges basin.The four last stations have been chosen for their exceptional length of records.

Finally, hydrological yearbooks have been obtained from the Department of Irrigation, Hydrology and Meteorology in Kathmandu, Nepal. The rainfall series for Kathmandu from 1921 to 1986 has been utilized.

Water Level Data

Mean daily water levels for non-tidal stations and daily extreme water levels for tidal stations were collected from BWDB, WARPO and SWMC. Emphasis has been given to the gauging stations located on the main river system. Where long periods of data are available along the major tributaries and distributaries such data have also been collected. Data provided by BWDB were in the form of printed tables (hard copies), while WARPO and SWMC provided data on diskette. For the tidal stations, the diskettes also contained mean daily water levels calculated as the average of minimum and maximum water levels. From FAP 1, mean daily water level data were collected for the period 1965-89, for Bahadurabad and Serajganj on diskette and from Mathura and Mahendrapur as hard copies. An updated list of the data available with FAP 25 is given in Appendix 2.

From JRC, mean daily water level data from India have been collected for the Ganges at Farakka and the Brahmaputra at Pandu for the period 1966-71 (June to October only).

Discharge Data

Mean daily discharge data were collected from BWDB, WARPO and SWMC. Data received from BWDB were in the form of printed tables, while WARPO and SWMC data were on diskettes. An updated list of data available with FAP 25 is given in Appendix 2.

From JRC, 10-day mean discharge data (June-October) from India have been collected for the Ganges at Farakka and the Brahmaputra at Pandu for the period 1948-85 and 1955-75 respectively. Mean daily discharge data have been collected for the period 1966-71. Finally, for the Brahmaputra at Pandu, monthly average dicscharge data have been collected for the period 1974-84.

A search for Indian discharge data in UK, at the Indian and Oriental Office of the British Library, was without results as later also confirmed by FAP 6.

Stage-Discharge Data

Results from discharge measurements including stage, measured velocity, derived discharge, width and area have been provided by BWDB in printed form for a few selected stations. Available rating curves for the important stations were also procured. An updated list of data available with FAP 25 is given in Appendix 2.

Evaporation Data

Evaporation data has also been collected from BWDB from 13 stations spread over Bangladesh for a period of about 6 years, see Appendix 2. Mean monthly values have been computed for use in the NAM model.

4.3 FAP 25 Data Bases.

The data collected from the sources, as referred in section 4.1, were available in various formats ranging from hard copies to compatible diskettes. They have been stored in a computer data base. Initially, Lotus 1-2-3 spreadsheet package was selected for this purpose. Very often, FAP 25 had to create boundary and validation data set in ascii-format as input to FAP 25-GM. On completion of the GM model run at SWMC, the output was statistically analysed and the results were released to various FAPs as and when required. Most of the FAPs also use the Lotus 1-2-3 spreadsheat package.

However, because of the need of more sophisticated hydrological analyses FAP 25 decided to acquire HYMOS, a hydro-meteorological data management and processing package developed by DELFT HYDRAULICS. HYMOS has been used extensively for data validation, flow measurement analysis, stage-discharge analysis and statistical frequency analysis since September 1991. The data used for stage 2 of the FHS are also stored in the HYMOS data base.

HYMOS is being transferred to the Surface Water Hydrology Directorate of BWDB and a two-day workshop has been held for 12 GOB officials, with a view to demonstrating the possible uses of the package.

From the experience gained with procurement of data from various GOB agencies FAP 25 would like to recommend that GOB takes the necessary action to establish a commonly agreed format for data base, data updating and processing software thereby facilitating the sharing of a common data set among a large number of users. This will curtail huge time requirement and avoid duplication of analysis by various agencies. It is noted that similar recommendations are available in the "Inter Agency Committe Report on Data Improvement" of the MIWD&FC. The recently started UNDP-assisted support programme for BWDB Hydrology may also be of benefit in this connection.

5. DATA REVIEW

Although hydrological observations are often a matter of routine work, numerous errors may be introduced at the different stages of observation, measurement, processing, and storage.For fairly straightforward observations such as rainfall, the data review may be a simple one using standard procedures. For water level and discharge observations involving comprehensive processing, data review may be more difficult including the need of sound judgement along with hydrological techniques for data checking.

The complex river system of Bangladesh makes hydrological observations second to none in terms of complexity and resource requirement. A detailed review of key station data has been a prerequisite in the FHS, with priority to those used in the GM at boundary and comparison points.

Attempts have been made to locate possible sources of error through interviews and inspection in the field. Subsequently, standard correlation techniques have been applied to correct data.

5.1 Review of Rainfall Data

Rainfall data is used as boundary conditions in the NAM rainfall-runoff model of the GM. They have also been used in the analysis of the representativeness of the period 1965-89 for the whole century.

A consistency analysis has been carried out on annual rainfall depths for four groups of rainfall stations:

- **1st group:** 27 Bangladeshi stations spread all over the country, including the 26 stations used in the General Model and Chittagong, cf. Figure 5.1. The period considered is 1902-89;

- **2nd group:** 6 Indian stations located in Eastern India in the Brahmaputra and Meghna basins, cf. Figure 5.2, for the period 1891-1950;

- **3rd group**: 12 Indian stations spread over the Ganges basin, cf. Figure 5.2, also for the period 1891-1950;

- **4th group:** The Nepalese station of Kathmandu, the only station with more than 20 years of observation (1921 to 1986).

For each group the analysis has consisted of:

- the computation of annual mean depth, standard deviation, coefficient of variation, minimum and maximum values for two or three consecutive periods and the total observation period. These values are listed in Tables 5.1 and 5.2. Mean values and standard deviations are plotted in Figures 5.3 a) and b) respectively for comparison of Bangladeshi stations;

Table 5.1 : Basic Statistical Analysis for 27 Bangladeshi Rainfall Stations

STATIONS	PERIOD : 1902 to 1989						PERIOD : 1902 to 1932						PERIOD : 1933 to 1964						PERIOD : 1965 to 1989					
	YRS	MAX	MIN	AVG	STD	CV	YRS	MAX	MIN	AVG	STD	CV	YRS	MAX	MIN	AVG	STD	CV	YRS	MAX	MIN	AVG	STD	CV
006 BOGRA	74	2740	1034	1773	377	0.213	26	2445	1168	1740	351	0.202	24	2516	1034	1721	365	0.212	24	2740	1215	1860	401	0.215
009 DHAKA	71	3028	1197	1962	326	0.166	22	2633	1403	1898	305	0.161	24	2566	1197	1906	306	0.161	25	3028	1556	2071	333	0.161
025 PABNA	69	2220	1019	1536	276	0.179	27	1946	1055	1503	227	0.151	19	2220	1066	1562	314	0.201	23	2105	1019	1554	289	0.186
027 PHULBARI	26	2881	1564	2116	365	0.173	0						2	2571	2063	2317	254	0.110	24	2881	1564	2100	368	0.175
062 DEWANGANJ	71	4225	938	2207	600	0.272	29	4225	938	2371	729	0.308	20	2587	1242	1906	343	0.180	22	3258	1563	2264	483	0.213
063 DURGAPUR	71	5304	2235	3599	625	0.174	28	5304	2235	3535	739	0.209	18	4293	2511	3685	497	0.135	25	5136	2720	3610	557	0.154
071 KISHOREGAN	74	3930	1458	2370	543	0.229	29	3511	1546	2368	485	0.205	20	3930	1458	2440	672	0.276	25	3568	1616	2315	480	0.207
073 MYMENSING	77	3374	1306	2350	420	0.179	27	2993	1630	2328	382	0.164	27	3268	1306	2241	462	0.206	23	3374	1919	2504	360	0.144
104 CHANDBAG	53	4346	2018	2983	551	0.185	6	3801	2357	3034	538	0.177	23	3670	2018	2772	469	0.169	24	4346	2073	3173	554	0.175
105 CHANDPUR	70	2906	1680	2322	336	0.145	23	2877	1701	2320	357	0.154	23	2827	1855	2319	297	0.128	24	2906	1680	2327	349	0.150
110 HABIGANJ	61	4153	1520	2548	496	0.195	20	3377	1800	2597	458	0.176	16	3331	1941	2530	439	0.173	25	4153	1520	2521	553	0.219
111 ITAKHOLA	57	3040	1529	2164	341	0.158	7	2841	1566	1984	435	0.219	26	2634	1529	2149	313	0.146	24	3040	1588	2234	317	0.142
116 LALLAKHAL	70	7506	3873	5697	878	0.154	22	7090	3991	5373	850	0.158	25	7354	3873	5803	925	0.159	23	7506	4330	5893	758	0.129
122 MOULVIBAZA	59	3933	2008	2798	526	0.188	22	3859	2074	2803	521	0.186	14	3933	2008	2976	621	0.209	23	3484	2091	2684	427	0.159
123 NETROKONA	75	4327	595	2855	615	0.215	29	3788	2084	2954	473	0.160	23	4169	595	2621	725	0.277	23	4327	1900	2964	588	0.199
127 SUNAMGANJ	65	8720	2526	5428	1058	0.195	21	6398	3786	5329	685	0.129	19	7544	3128	5291	1180	0.223	25	8720	2526	5615	1183	0.211
128 SYLHET	68	6146	2879	4069	706	0.173	21	4750	2879	3902	571	0.146	23	6136	2989	4008	779	0.194	24	6146	2922	4273	689	0.161
205 RAJSHAHI	72	2118	784	1436	343	0.239	25	2118	866	1436	331	0.230	25	2011	784	1395	387	0.278	22	1881	1009	1483	293	0.197
206 RANGPUR	75	3389	1277	2191	471	0.215	26	2909	1358	2110	394	0.187	26	3055	1313	2184	453	0.207	23	3389	1277	2290	547	0.239
224 CHUADANGA	69	2469	571	1507	314	0.208	26	2370	1027	1522	259	0.170	19	2085	571	1460	324	0.222	24	2469	988	1529	354	0.232
258 BARISAL	74	3163	1460	2173	386	0.178	28	3132	1460	2153	364	0.169	24	3040	1547	2152	386	0.179	22	3163	1613	2221	409	0.184
266 PATUAKHALI	74	6206	1648	2927	803	0.274	29	6206	1975	3091	905	0.293	21	4785	1917	3107	847	0.272	24	3481	1648	2573	429	0.167
306 CHITTAGONG	75	4204	1701	2869	494	0.172	27	3896	1701	2875	530	0.184	26	3497	1851	2750	419	0.152	22	4204	1981	3004	496	0.165
354 CHANDPUR	67	2683	1022	1989	363	0.183	29	2606	1409	1953	350	0.179	16	2483	1164	1973	329	0.167	22	2683	1022	2048	396	0.193
356 COMILLA	73	4690	1692	2529	625	0.247	26	4608	1784	2582	642	0.249	25	4690	1712	2640	693	0.262	22	3642	1692	2341	461	0.197
409 HARIDASPUR	66	2589	1011	1676	305	0.182	22	2182	1011	1650	290	0.176	21	2163	1044	1598	259	0.162	23	2589	1283	1773	331	0.187
510 KHULNA	77	2689	1204	1741	307	0.176	25	2134	1204	1651	262	0.159	29	2689	1252	1701	309	0.182	23	2426	1320	1891	297	0.157
BANGLADESH	76	3286	1738	2447	298	0.122	28	3126	1738	2378	311	0.131	23	2899	2073	2394	246	0.103	25	3286	2161	2573	287	0.112

Table 5.2 : Basic Statistical Analysis for 18 Indian Rainfall Stations

STATIONS	PERIOD : 1891-1920						PERIOD : 1921-50						PERIOD : 1891-1950					
	YRS	MAX	MIN	AVG	STD	CV	YRS	MAX	MIN	AVG	STD	CV	YRS	MAX	MIN	AVG	STD	CV
Stations in Brahmaputra Basin																		
Goalpara	30	2833	1590	2339	345	0.148	28	3813	1657	2495	535	0.215	58	3813	1590	2414	454	0.188
Gaohati	30	2031	1201	1652	227	0.138	27	2083	1048	1576	283	0.179	57	2083	1048	1616	258	0.159
Dibrugarh	30	3661	2048	2777	410	0.148	28	5004	2210	2876	584	0.203	58	5004	2048	2825	504	0.178
Darjeeling	30	4256	2271	3116	506	0.162	28	3792	2325	2889	346	0.120	58	4256	2271	3006	450	0.150
Jorhat	30	4227	1681	2188	462	0.211	27	2864	1053	2162	343	0.159	57	4227	1053	2175	410	0.189
Silchar	30	4489	1939	3197	612	0.192	28	5599	2389	3454	600	0.174	58	5599	1939	3321	620	0.187
Stations in Ganges Basin																		
Rajmahal	30	2270	729	1383	352	0.254	28	1903	832	1303	244	0.187	58	2270	729	1345	307	0.229
Monghyr	30	1762	624	1228	273	0.222	27	1762	421	1121	259	0.231	57	1762	421	1177	272	0.231
Patna	30	1959	642	1254	339	0.271	27	2081	787	1115	298	0.268	57	2081	642	1188	328	0.276
Allahabad	30	1935	516	1000	291	0.291	28	1578	578	990	236	0.239	58	1935	516	995	266	0.268
Benares	30	1591	708	1042	242	0.232	28	2108	741	1107	292	0.264	58	2108	708	1073	269	0.251
Bareilly	30	1588	492	1023	282	0.276	28	1666	558	1113	308	0.276	58	1666	492	1066	298	0.280
Agra	30	1148	277	636	204	0.321	28	1071	284	720	198	0.274	58	1148	277	677	205	0.304
Kanpur	30	1604	370	906	330	0.364	28	1450	490	865	244	0.282	58	1604	370	886	292	0.330
Delhi	30	1078	167	650	235	0.361	28	1059	281	644	194	0.301	58	1078	167	647	216	0.334
Jaipur	30	1455	120	587	281	0.479	28	1284	230	637	223	0.350	58	1455	120	611	256	0.419
Bhopal	30	1610	595	993	254	0.255	28	1779	675	1176	277	0.235	58	1779	595	1082	280	0.259
Kotah	30	1600	171	722	279	0.386	27	1375	382	840	298	0.355	57	1600	171	778	294	0.378

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- statistical tests for difference in these mean annual values and standard deviations for two or three successive periods, using Student's t-test and Fisher F-test;

- the sequential plotting of annual depths, the 5 - year moving average and the mass residue (accumulated deviation from the mean value), see Appendix 3 (upper graphs);

- double mass analysis of each station against the mean of the stations of each group (see Appendix 3, lower graphs). For the Bangladeshi stations, only 16 of the stations have been considered for calculation of the mean, i.e. only reliable stations with a long series of observation. The annual rainfall at Kathmandu has been plotted against the Bangladeshi mean depth;

Figure 5.3 b) shows inconsistency in the standard deviation plot for the stations 266 and 356 during the period 1965-89.

The double mass analysis in Appendix 3 shows abnormalities for several stations, mainly for:

- Station 062 (Dewanganj), where high values have been observed between 1920 and 1930. From 1964, the series appears to be acceptable;

- Station 071 (Kishoreganj), where high values have been observed between 1930 and 1940. Since 1964, the standard deviation appears to be abnormally high;

- Station 123 (Netrokona), where low values have been observed between 1948 and 1953. After 1964 the series appears acceptable;

- Station 266 (Patuakhali), where the double mass curve suggests inconsistency of the data for the period 1964-1989;

- Station 356 (Comilla), where a lot of abnormalities may be observed: numerous missing years, high series around year 1950 and low values in years 1987 to 1989.

As a general conclusion, these stations should not be considered reliable, with the exception of stations 062 and 123 for the period 1964-1989.

Some minor deviations are observed in the double mass curves for Indian stations, but considering these stations being widely spaced, it is concluded that the discrepancies are not very significant.

The reliability of Kathmandu rainfall station is questionable. Rainfall depths prior to 1945 appear to be significantly lower than after 1945.

5.2 Review of Water Level Data

Water level data are used in the GM:

- as basic data for the generation of upstream boundary discharges;
- as downstream boundary condition;
- for comparison of observed and simulated water levels.

The review of the water level data is thus a prerequisite for a proper validation of the GM and for the generation of reliable boundary conditions.

5.2.1 Selection of Water Level Stations

28 water level stations have been selected as boundary or comparison stations for the GM, see Table 5.3. A detailed review of the water level observations at these 28 stations was desirable. However, as data review is mainly based on correlation methods, it was possible only in rivers where such correlation may exist. Thus, the review focused on the Jamuna and the Ganges with the exception of Mathura and Mahendrapur, which were collected at a later stage in the study.

Downstream water level boundary stations have also been scrutinized, with particular priority given to Daulatkhan on the Lower Meghna.

5.2.2 Observation Methodology

The observation methodology followed by BWDB in collecting field data has been investigated by FAP 25 through meetings with BWDB and field visits.

Bahadurabad, Fulchari, Nilukhirchar and Baruria have been visited and discharge measurements have been observed in detail at Baruria in August 1991. Information on measurements procedures has been collected from BWDB local teams, from SWMC and also from FAP 1, who has investigated the Jamuna sites in detail. Moreover, one member of the FAP 25 team, who has acted as a field hydrologist at BWDB in the past, has a sound knowledge of the procedures used at Hardinge Bridge.

The main comments on the methodology with specific details of observation, as detailed below and in section 5.3.1, relate to the hydrological station at Bahadurabad.

Gauge Location

The staff gauge at Bahadurabad is located at a convenient position, on the discharge measurement transit line, which is situated about 750 m upstream of the present

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Table 5.3 : List of Water Level Boundary and Validation Stations for General Model (GM).

RIVERS	STATIONS	CODES	CHAINAGES	STATUS
JAMUNA	Chilmari	45.5	37.1	C
	Bahadurabad	46.9L	84.7	C
	Kazipur	49/A	139	C
	Serajganj	49	162.35	C
	Porabari	50	188.2	C
	Mathura	50.3	220	C
GANGES	Hardinge Bridge	90	32.5	C
	Sengram	91.1	71.5	C
	Mahendrapur	91.2	97.5	C
PADMA	Baruria Transit	91.9L	14.5	C
	Mawa	93.5L	60	C
UPPER MEGHNA	Bhairab Bazar	273	20	C
	Meghna Ferry Ghat	25.5	80	C
LOWER MEGHNA	Chandpur	277	19.167	C
	Daulat-Khan	278		B
OLD BRAHMAPUTRA	Jamalpur	225	36	C
	Nilukhirchar	228.5	108	C
	Toke	229	162	C
LAKHYA	Demra	7.5	70	C
KALIGANGA	Taraghat	137A	22.5	C
GORAI	Gorai	99	7	C
	Kamarkhali	101.5	73	C
ARIAL-KHAN	Madaripur	5	36	C
TENTULIA	Dashmunia	290		B
LOHALIA	Galachipa	185		B
BISKHALI	Pathergata	39		B
MADHUMATI	Rayenda	107.2		B
RUPSA	Mongla	244		B

Note : STATUS B for boundary conditions
STATUS C for comparison point

Bahadurabad railway yard; the water level is measured in the main channel of the Jamuna (Bahadurabad Channel) but no information seems available allowing determination of since when the gauge has been located at this position. Often, within in a year, the position of the gauge may be shifted upstream/downstream over a stretch of about one km.

At high stages, when the site is not accessible, water level is measured on a gauge situated on the railway bank 300 m away from the main flow. It is situated close to the railway dyke, which may induce two-dimensional currents, affecting the local water level. Significant differences in water level may be expected when shifting from one gauge to the other.

The water level is measured five times a day, at 6.00, 9.00, 12.00, 15.00 and 18.00 hrs. The measurement is done on wooden gauges, fixed in the water by bamboo sticks. They are deeply pushed in the ground to ensure a good stability, but no protection against the frequent fluvial traffic has been provided at this site.

Gauge Shifts

When the top of the gauge is to be raised, or the bottom to be lowered, a new gauge is fixed close to the previous one and the relation between data of the two gauges is determined through simultaneous reading. In principle, this method may have a precision less than one centimeter. But this operation is done frequently, two or three times in a month during the flood and two or three times during the dry season, due to the large range of water levels at this station (around 7 to 8 meters at Bahadurabad). These frequent moves may ultimately generate shifts in the observations, which are very difficult to correct, in particular when several shifts of the gauge occur between two check levellings from the bench mark.

Check Levellings to Bench Marks

In principle, the datum of the gauge should be checked weekly or fortnightly by levelling from a temporary bench mark, situated close to the railway, about one km away. This distance is not convenient for such a frequent checking.

During the 70'es, these check levellings often generated corrections of around 0.10 to 0.50 feet, whereas all the checks in the last 10 years have shown systematically an error of 0 cm. These checks have been noted to occur weekly or fortnightly but for 1991, no record was found from June to September, where gauge shifts are known to have taken place. This raises serious doubts as to which extent the check levellings have actually been carried out for the last years.

Water level corrections resulting from check levelling with the bench mark are carried out at field office level before the mean daily water level is computed and transmitted to Dhaka.

5.2.3 Types of Observation Errors

Several types of observation errors have been detected in the review process. These types are described hereafter and illustrated on Figure 5.4.

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Type 1: Missing Data

The gaps can be filled up simply by correlation with the nearest station or by interpolation when very few data are missing. Sometimes it is seen that a few daily data not available at BWDB in Dhaka, however may exist in historical hard copy format in the field offices of BWDB Hydrology.

Type 2: Daily Erroneous Data

If data for a day is divergent errors can be eliminated by plotting annual hydrographs. Most of the time, it results from errors in data coding and often only one decimal is erroneous.

Type 3: Shifted Data for a Few Days

Sometimes a constant shift is observed for a few days. This may result from a gauge reading error or from a gauge disorder. A few days may pass before it is realised that the data is erroneous and appropiate action is taken. Sometimes, the erroneous data is simply left, sometimes approximate corrections are made by the gauge reader himself. In that case the right correction may be difficult.

Type 4: Shifted Data for a Few Weeks

During flood, gauges are sometimes shifted to follow the rising water level. If the datum of the gauge is not properly connected with the bench mark, such shift may result in erroneous gauging until the next connection with the bench mark is done.

This type of error is believed to be the single most important for correct determination of high stage water level and peak values. The only possible way to detect them would be through a very detailed correlation analysis with neighbouring stations and even then there is no guarantee that reliable correlations can be applied. Such analyses have not been possible within the present resources of the FHS. This type of error may not affect rating curves for the lower water levels.

Type 5: Shifted Data for Long Periods

Some shifts are observed for long periods (one year or even more). This is due to an upstream/downstream shift in gauge location which is also reported to take place without proper indication of such new location. With a typical slope in the Jamuna of 7 cm/km, a two km shift corresponds to a water level difference of 15 cm. Furthermore, a different temporary bench mark may be used, which is not consistent with the previous one.

Type 6: Inconsistent Trends

Trends are sometimes inconsistent as compared to the general trend of surrounding stations. There is a simple physical explanation to this kind of error. It can result from erroneous interpolation used to replace missing data or to a progressive move of the gauge itself due to erosion.

Type 7: Static Water Level

Static or almost static water levels are observed for the last few years at Kholabarichar and Kazipur in the dry season. During the field visit, it finally appeared that Kholabarichar station was no longer situated on the Jamuna but on the Old Brahmaputra which is completely disconnected from the Jamuna during the dry season. This is not an observation error, but a dislocation of the station itself.

Type 8: Reliability of Bench Marks

The reliability of bench marks is also an issue. It is, however, outside the scope of the FHS. Results from FAP 18, as and when they become available, may be of great benefit in this context.

5.2.4 Peak Water Levels.

As the accuracy of peak water levels is essential for the FHS, particular attention was paid to error detection in peak levels. For that purpose, annual peak water levels have been plotted against time for the Jamuna on Figure 5.5. Some obvious errors can be identified :

- a reduction of the slope between Noonkhawa and Bahadurabad from about 1983 due to a drop of about 1.5 m in observations at Noonkhawa;

- an increase of the slope between Kholabarichar and Bahadurabad in 1965 and 1966 due to an increase of about 0.8 m in observations at Kholabarichar;

- an obvious error at Kholabarichar in 1972 where the slope with Bahadurabad is inverted;

- an obvious error at Kazipur in 1982 where the peak level seems to be overestimated by about 0.5 m.

Besides obvious errors, other likely inconsistencies may be observed for which any definite conclusions may be difficult.

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5.2.5 Systematic Checking

Unfortunately, all errors can not be dealt with in the FHS. In general, it has been possible to correct for error types 1-3. Correcting other errors would be highly subjective and even then not possible within the present scope and resources of the FHS. Such more detailed corrections may be considered under two other projects, i.e. FAP 24, the River Survey Programme, and the UNDP-assisted strengthening of BWDB Hydrology.

Corrections in the present study have been made using correlations between stations. Systematic checking has been carried out by plotting water levels against each other for various stations on the Jamuna and Ganges rivers. Distances between stations appear from Table 5.3.

For each year, water level relation curves have been plotted at:

- the stations of Chilmari, Kholabarichar, Kazipur, Serajganj and Porabari against water levels at Bahadurabad, cf. Figure 5.6.

- the stations Sengram on the Ganges and Gorai and Kamarkhali on the Gorai against water levels at Hardinge Bridge, cf. Figure 5.7.

Although numerous graphs have been produced, only a few examples are shown and commented in the following.

For the Jamuna stations water level relation curves are plotted with respect to Bahadurabad for the years 1970, 1976 and 1983 in Figure 5.6. The left set of graphs is constructed with BWDB data and the corrected graphs based on correlation findings are shown in the right side. It can be seen that the correlations in general do not fall on a straight line. Within a year the variations may remain most of time within a range of 40 cm, if the stations are close enough and within 70 cm if they are distant though there is no definite correlation between range of variations and distance between stations. In some cases the range of variation may be even greater than 1 m. From one year to another the mean position of the relation curve may be shifted in the order of 40 cm.

These annual shifts are also observed in rating curves, as described in section 5.3.2.

Several causes may explain such variations. It is clear that the dynamics of flow explain part of the variations and, in particular, the loop effect induced by backwater. For neighboring stations, local two-dimensional effects and the changes in these effects due to changes in the bed morphology may also be responsible for significant variations and, in particular, the yearly shift. These two-dimensional effects are a consequence of the composite feature of the cross section in which transverse water level may be far from horizontal as the one dimensional hypothesis suggests. Analyses carried out by FAP 1, see Ref. 13, indicates that local bends in the braided channels, islands, narrowing branches and various baffles may induce local deviations from the mean transverse level. Due to the possible high velocities and low depth/width ratio, these deviations can reach tenths of a meter.

The regular shift of the gauges is probably responsible for most of the remaining uncertainties. Some gauge reading errors can also be detected as during the year 1966. If the error appears only once, it is to be searched at the related station; if it appears in all four graphs, it is to be searched at Bahadurabad station. These errors, when obvious, have been corrected one by one.

Similar analysis is shown on the graphs of Figure 5.7 for the Ganges stations in the years 1965, 1976 and 1981. Obvious errors can be observed in year 1965 for example. These errors have been corrected by interpolation. It can also be observed that a rather better correlation is observed at Gorai than at Sengram. This may be explained by the influence of the backwater from the Jamuna up to Sengram.

Corrections made are listed in Appendix 4.

5.2.6 Downstream Tidal Water Level

The consistency of water levels at downstream boundary stations has been checked by plotting superimposed hydrographs of mean daily data at nearby stations. The corrections are not easy due to the tidal status of these stations. Nevertheless, obvious deviation from the reference level (by checking mean water level for dry season) have been corrected.

Special attention has been given to Daulatkhan, which is a key downstream station for the FAP 25-GM. A constant correction of + 75 cm has been applied to the water level, according to SWMC analysis, see Ref.3.

For the other coastal stations, it appears that water level variations during the flood are not correlated to the water level in the major rivers, so missing years have been filled up by the values of adjacent years. Corrections are presented in Appendix 4.

5.3 Review of Discharge Data

Discharge data are available from 109 stations in the delta for varying periods. About 22 stations on the major river network have long time series of data of which 12 stations have been considered in the FHS, see Table 5.4. These 12 stations are used in the GM as upstream boundary stations and for model validation purposes.

The cross-border flows in the main rivers (Ganges and Jamuna) represent the most significant causes of floods in Bangladesh. As a consequence, a special effort has been made to review the data at Bahadurabad and Hardinge Bridge. The objective has been to determine, as accurate as possible, the discharge at these stations for the period 1965-89, as they are used as upstream boundary stations in the GM. Also some key stations, such as Baruria, used as discharge comparison points have been examined in detail.

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Table 5.4 : List of Discharge Boundary and Validation Stations for General Model (GM).

RIVERS	STATIONS	CODES	CHAINAGES	STATUS
JAMUNA	Bahadurabad	46.9L	79.075	B
GANGES	Hardinge Bridge	90	35.75	B
KANGHSA	Jaria Jhanjail	36	0	B
SURMA	Kanairghat	266	0	B
KUSHIYARA	Sheola	173	0	B
TEESTA	Kaunia	294	80	B
ATRAI	Mohadevpur	145	0	B
PADMA	Baruria Transit	91.9L	11.125	C
UPPER MEGHNA	Bhairab Bazar	273	15	C
OLD BRAHMAPUTR	Nilukhirchar	228.5	114	C
GORAI	Gorai	99	3.5	C
	Kamarkhali	101.5	75.5	C

Note : STATUS B for boundary conditions
STATUS C for comparison point

5.3.1 Observation Methodology

The mean daily discharge data data supplied by BWDB are generated from water level observations and established rating curves. These rating curves are developed from actually measured discharges. Often, observations around peak floods are missing causing extrapolation of rating curves to estimate peak discharges. The following points normally effect the discharge measurements:

- Erosion and aggradation processes are responsible for substantial changes in the rated cross-sections.

- Migrating chars in the major rivers may induce transverse velocities affecting the discharge measurement and often survey lines may not be perpendicular to the general flow direction.

- Due to the size of the rivers, discharge measurements are extremely difficult. Compromises must be made between the number of velocity profiles, the time devoted to measurement in each profile, and thus for the whole section, considering the general flow situation, (whether water level is changing slowly or quickly etc).

- Velocity measurements are made from boats which have not a perfectly fixed position.

- The use of non-directional current meters may introduce over estimation of discharges, see Ref. 12. Angle correction is applied but not always based on float trackings of the particular day.

- Depths are measured with the current meter instead of with an echosounder, which may lead to an overestimation of depths, in particular during high currents.

Discharge measurements are made with a frequency varying from one to several weeks depending on the location and time of the year. Within the scope of the FHS it has not been possible to check the raw data, i.e. velocity and cross section data, and the BWDB discharge data calculated from the velocity measurements have been used directly.

No detailed assessment has been possible of the accuracy of the discharge measurements. Some of the issues above may introduce random errors, others give rise to systematic errors (overestimation). FAP 1 has carried out a detailed assessment of potential errors involved in discharge measurements in Jamuna, cf. Ref. 12. There are examples indicating that some times errors of some 20-30% or even more may occur.

5.3.2 Rating Curves

Plotting of all actual discharge measurements carried out from 1966 to 1989 at Bahadurabad and Hardinge Bridge leads to the rating curves of Figure 5.8, where a considerable scatter is observed. This scatter may be partly due to changes in the physical system (erosion, aggradation and moving bedforms) and may partly result from random or systematic errors in discharge measurements as explained above. Loop effects due to varying water surface slopes during rising and receding parts of the flood are not significant.

For each discharge station, BWDB normally develop each year a new rating curve based on the total number of discharge measurements at each station in the hydrologic year and also including some values from the previous and the following year for consistency purposes.

The FHS has initially reviewed rating curves and equations developed by BWDB for the three key stations at Bahadurabad, Hardinge Bridge and Baruria. As rating equations are not available for all years and with a view to developing rating curves with consistent extrapolation characteristics, it was decided to develop a set of new rating curves for these three stations. Each annual rating curve has been fitted to a two- or three-step power function. For Hardinge Bridge the extrapolation is easy most of the time, because the highest discharge observation is close to the highest observed water level in a particular year. For the other two stations this is not the case and extrapolation has been done considering rating curve slopes in other years. Examples of new rating curves are shown on Figures 5.9 a), b) and c) for Bahadurabad, Hardinge Bridge and Baruria respectively for the last five years. In general, the new rating curves are not much different from the BWDB derived rating curves.

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Table 5.5 : Analysis of Shifts of Annual Rating Curves at Bahadurabad, Hardinge Bridge and Baruria.

a) :

STATION : Bahadurabad
RIVER : Jamuna

Discharges (in Cumecs)	**20000**	**30000**	**40000**	**50000**	**60000**
FAP25 GM Stage (m)	16.43	17.42	18.22	18.89	19.45
Mean observed Stage (m)	16.74	17.85	18.62	19.16	19.54
Maximum (m)	17.38	18.33	19.00	19.55	19.81
Minimum (m)	16.10	17.11	17.92	18.58	19.10
Standard Deviation (m)	0.27	0.27	0.24	0.24	0.22

The standard deviation of the rating curve shift at Bahadurabad is 25 cm

b) :

STATION : Hardinge Bridge
RIVER : Ganges

Discharges (in Cumecs)	**20000**	**25000**	**30000**	**35000**	**40000**
FAP25 GM Stage (m)	12.21	12.88	13.22	13.50	13.74
Mean observed Stage (m)	12.15	12.69	13.10	13.46	13.78
Maximum (m)	12.62	13.12	13.54	13.91	14.25
Minimum (m)	11.80	12.36	12.83	13.17	13.47
Standard Deviation (m)	0.22	0.20	0.19	0.17	0.17

The standard deviation of the rating curve shift at Hardinge Bridge is 19 cm

c) :

STATION : Baruria
RIVER : Padma

Discharges (in Cumecs)	30000	40000	50000	60000	70000
FAP25 GM Stage (m)	6.16	6.64	7.05	7.50	7.93
Mean observed Stage (m)	5.73	6.41	6.93	7.36	7.72
Maximum (m)	6.27	6.90	7.40	7.85	8.24
Minimum (m)	5.40	6.07	6.54	6.95	7.32
Standard Deviation (m)	0.22	0.22	0.24	0.27	0.30

The standard deviation of the rating curve shift at Baruria is 25 cm

The magnitude of shifts of the annual rating curves have been analysed by computing water levels corresponding to a particular discharge. The results of this analysis for Bahadurabad, Hardinge Bridge and Baruria are given in Tables 5.5 a), b) and c) respectively. It can be observed that

- at Bahadurabad, there is around 1 m between the upper and lower envelope of the rating curves, with a standard deviation of around 25 cm.

- at Hardinge Bridge, the difference between the upper and lower envelope is 0.80 m and the standard deviation is 20 cm.

- at Baruria, the difference between the upper and lower envelope is about 0.90 m and the standard deviation is of 25 cm.

Substantial annual shifts in mean rating curves are observed, the standard deviation of which is about 25 cm. In fact these changes may reach up to 40 cm from one year to the next, cf. Figure 5.9.

Such shift may be due to :

- morphological changes caused by erosion and sedimentation implying either changes in the cross section area or changes in the bedforms resulting in changes in the friction factor;

- amplification of the morphological changes due to two-dimensional currents, as discussed in section 5.2.5;

- systematic errors in discharge measurements and long term shifts in gauge locations, see section 5.2.3.

It is not within the scope of the FHS to further analyse the causes of such shifts. It is expected that FAP 24 may contribute information on the subject.

Other upstream discharge stations, used in the GM are:

- Jariajhanjail on the Kanghsa;

- Kanairghat on the Surma;

- Sheola on the Kushiyara;

- Mohadevpur on the Atrai;

- Kaunia on the Teesta.

Discharges at all these stations are relatively low, and the influence on the results of the GM is minor. Therefore, discharge data provided by the BWDB have been used directly. Rating curves have been developed from gauged data only when daily discharges were not directly available.

The parameters of the computed rating curves are presented in Tables 5.6 a) to c) for the major rivers and in Table 5.6 d) for the secondary rivers.

Table 5.6 a) : Rating Parameters at Bahadurabad, Code: 46.9L

YEARS	INTERVAL-1				INTERVAL-2				INTERVAL-3		
	a	b	c	Limit-1	a	b	c	Limit-2	a	b	c
1965	Gauged data not available										
1966	-9	2.163	230.337	15.00	-9	2.888	64.042	18.92	-9	4.590	1.288
1967	-9	3.095	40.735	18.27	-9	4.729	1.070				
1968	-9	2.960	44.008	18.37	-9	4.478	1.473				
1969	-9	2.253	163.820	15.08	-9	2.878	53.026	19.17	-9	4.797	0.618
1970	-9	2.806	68.481	19.31	-9	5.427	0.151				
1972	-9	2.751	63.702	16.32	-9	3.378	18.284	17.77	-9	3.753	8.113
1973	-9	2.918	44.326	18.46	-9	5.592	0.109				
1974	-9	3.006	33.604	17.38	-9	4.470	1.497	19.59	-9	6.454	0.014
1975	-9	2.261	170.904	15.00	-9	2.817	65.095	18.72	-9	3.759	7.645
1976	-9	2.132	223.145	15.90	-9	3.015	40.574	18.73	-9	4.767	0.753
1977	-9	2.133	228.634	15.87	-9	3.037	40.026	19.49	-9	5.876	0.051
1978	-9	2.453	128.454	15.99	-9	2.831	61.556	17.80	-9	3.770	7.994
1979	Gauged data not available										
1980	-9	2.402	130.379	16.56	-9	3.236	24.116	18.28	-9	4.476	1.522
1981	-9	2.885	54.504	16.37	-9	2.656	85.968	18.19	-9	4.179	2.937
1982	-9	2.380	132.559	15.00	-9	2.861	56.662	17.51	-9	4.474	1.789
1983	-9	2.327	143.899	15.00	-9	2.855	56.754	18.57	-9	4.219	2.604
1984	-9	2.948	46.632	18.53	-9	4.920	0.548				
1985	-9	2.291	150.439	15.53	-9	3.227	25.974	18.37	-9	4.710	0.941
1986	-9	2.689	79.453	17.48	-9	3.609	11.102				
1987	-9	2.830	61.926	17.00	-9	3.478	16.089	18.49	-9	4.724	0.975
1988	-9	2.884	62.009	16.95	-9	3.130	36.7398	18.57	-9	4.31	2.533
1989	-9	3.035	52.270	18.50	-9	3.420	21.983				

Note :
1. Limit-1 is the Upper limit water level for interval-1.
2. Limit-2 is the Lower limit water level for interval-3.
3. Rating equation : $Q = c(WL + a)^b$
4. When gauged data were not available, rating curve is estimated according to the previous and next years values.

Table 5.6 b) : Rating Parameters at Hardinge Bridge, Code: 90

YEARS	INTERVAL-1			Limit-1	INTERVAL-2			Limit-2	INTERVAL-3			REMARKS
	a	b	c		a	b	c		a	b	c	
1965	Gauged data not available											
1966	-2	2.687	22.447	10.00	-2	4.109	1.211	12.52	-2	4.847	0.213	
1967	-2	3.119	10.639	11.42	-2	5.096	0.126	13.30	-2	5.415	0.058	
1968	-2	2.777	22.637	10.21	-2	4.329	0.863	13.00	-2	4.584	0.482	
1969	-2	2.638	34.712	10.00	-2	3.785	3.349	12.45	-2	4.378	0.832	
1970	-2	2.479	42.417	10.00	-2	4.150	1.317	12.97	-2	4.445	0.650	
1972	-2	2.593	40.977	10.00	-2	3.495	6.614	12.41	-2	4.437	0.727	
1973	-2	2.674	34.865	11.26	-2	4.677	0.403					
1974	-2	2.840	25.491	11.34	-2	4.653	0.443					
1975	-2	2.685	31.904	10.00	-2	4.067	1.858	13.00	-2	3.940	2.548	
1976	-2	3.641	4.110	11.27	-2	4.853	0.276	13.50	-2	4.764	0.344	
1977	-2	2.935	19.124	11.00	-2	4.108	1.498	12.99	-2	5.406	0.067	
1978	-2	3.092	14.213	11.00	-2	4.077	1.641	12.77	-2	5.253	0.100	
1979	-2	3.011	15.609	11.44	-2	4.694	0.357	12.77	-2	5.219	0.102	
1980	-2	2.684	24.307	9.00	-2	3.929	2.269	12.63	-2	4.499	0.589	
1981	-2	2.684	24.307	9.00	-2	3.929	2.269	12.63	-2	4.521	0.589	No gauged data
1982	-2	3.092	14.213	12.00	-2	5.253	0.100					No gauged data
1983	-2	3.001	14.949	11.00	-2	3.452	5.887	12.64	-2	5.616	0.035	
1984	-2	3.120	12.173	11.71	-2	4.658	0.369	13.56	-2	6.511	0.004	
1985	-2	3.108	13.951	10.81	-2	4.206	1.282	13.68	-2	4.528	0.581	
1986	-2	3.075	15.535	10.66	-2	3.879	2.741	12.23	-2	4.965	0.219	
1987	-2	2.910	16.055	10.00	-2	4.611	0.469	14.14	-2	7.933	0.000117	
1988	-2	3.301	7.376	11.00	-2	4.333	0.786	12.86	-2	6.629	0.0032	
1989	-2	2.831	20.101	10.00	-2	4.123	1.403	12.74	-2	5.069	0.149	

Note :
1. Limit-1 is the Upper limit water level for interval-1.
2. Limit-2 is the Lower limit water level for interval-3.
3. Rating Equation : Q = c(WL + a) ^ b
4. When gauges data were not available, the rating curve is estimated according to the previous and next year values.

Table 5.6 c) : Rating Parameters at Baruria, Code: 91.9L

	INTERVAL-1				INTERVAL-2				INTERVAL-3		
YEARS	a	b	c	Limit-1	a	b	c	Limit-2	a	b	c
1965	Gauged data not available										
1966	-0.5	1.493	2264.192	4.80	-0.5	1.971	1127.926	6.84	-0.5	2.497	427.087
1967	-0.5	1.314	2503.261	5.00	-0.5	2.166	710.061	6.57	-0.5	2.864	201.874
1968	-0.5	1.186	2879.392	4.51	-0.5	1.913	1049.866	6.36	-0.5	2.941	170.268
1969	-0.5	1.106	3091.531	4.35	-0.5	2.299	619.823	7.56	-0.5	3.124	123.387
1970	-0.5	1.418	2282.407	4.81	-0.5	2.339	593.877	7.00	-0.5	2.536	411.184
1972	-0.5	1.277	2602.816	4.30	-0.5	2.413	571.182	6.00	-0.5	2.619	411.976
1973	-0.5	1.504	1953.326	5.00	-0.5	2.362	538.274	6.00	-0.5	2.934	211.163
1974	-0.5	1.572	1858.980	5.12	-0.5	2.858	259.678	6.68	-0.5	3.601	67.166
1975	-0.5	1.248	2763.213	4.35	-0.5	2.436	556.830	7.34	-0.5	3.939	30.905
1976	-0.5	1.057	3699.763	4.12	-0.5	2.025	1064.520	6.42	-0.5	3.230	125.020
1977	Gauged data not available										
1978	Gauged data not available										
1979	-0.5	1.060	4077.209	4.28	-0.5	1.519	2212.718	5.59	-0.5	3.278	126.633
1980	Gauged data not available										
1981	-0.5	1.101	3655.907	3.79	-0.5	1.844	1510.241	6.00	-0.5	2.951	232.377
1982	-0.5	0.846	5435.121	4.22	-0.5	1.896	1365.873	6.59	-0.5	3.529	71.624
1983	-0.5	1.215	3656.588	4.48	-0.5	2.057	1143.290	7.29	-0.5	3.424	83.256
1984	-0.5	1.087	4022.440	3.90	-0.5	1.853	1575.037	6.28	-0.5	2.880	259.698
1985	-0.5	1.195	3295.626	4.07	-0.5	2.110	1029.705	5.77	-0.5	2.770	343.450
1986	-0.5	1.383	2365.000	5.14	-0.5	3.000	198.000	7.47	-0.5	3.481	77.710
1987	-0.5	1.321	2594.325	4.36	-0.5	2.164	831.255	6.89	-0.5	3.081	151.763
1988	-0.5	1.336	2723.682	4.54	-0.5	2.185	832.480	6.52	-0.5	3.067	170.920
1989	-0.5	1.272	3127.429	4.93	-0.5	2.467	528.252	7.11	-0.5	2.971	204.113

Note :
1. Limit-1 is the Upper limit water level for interval-1.
2. Limit-2 is the Lower limit water level for interval-3.
3. Rating equation : Q = c * (WL + a) ** b
4. When gauged data were not available, rating curve is estimated according to the previous and next years values.

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Table 5.6 d) : Rating Parameters at Secondary River Stations

STATIONS	YEARS	RANGE OF WATER LEVEL MIN	RANGE OF WATER LEVEL MAX	PARAMETERS OF THE RATING CURVE a	b	c
KANAIRGHAT 266	65 to 68	3.00	8.90	-2.000	3.651	0.282
		8.90	16.00	-2.224	3.055	0.993
		FITTED ON 1970 DISCHARGES OBSERVATIONS				
	1989	3.00	7.33	-2.000	4.484	0.107
		7.33	16.00	-1.734	2.861	1.408
		FITTED ON 1989 DISCHARGES OBSERVATIONS				
JARIA JHANJAIL 36	1969	3.00	7.96	-2.000	2.581	2.795
		7.96	12.00	-2.320	2.608	3.077
		FITTED ON 1969 DISCHARGES OBSERVATIONS				
	1981	3.00	7.03	-3.000	1.965	17.002
		7.03	12.00	-1.860	2.147	7.730
		FITTED ON 1981 DISCHARGES OBSERVATIONS				
	1982	3.00	7.58	-3.000	1.976	13.820
		7.58	12.00	-1.710	2.792	1.992
		FITTED ON 1982 DISCHARGES OBSERVATIONS				
	1989	3.00	7.62	-3.000	2.075	10.459
		7.62	12.00	-0.486	4.254	0.059
		FITTED ON 1989 DISCHARGES OBSERVATIONS				
KAUNIA 294	1965	26.00	27.42	-25.000	2.988	10.892
	1967	27.42	31.00	-24.460	5.909	0.251
		FITTED ON 1969 DISCHARGES OBSERVATIONS				
	72 to 75	26.00	28.41	-26.000	4.448	8.519
		28.41	31.00	-27.190	3.083	230.575
		FITTED ON 1969 DISCHARGES OBSERVATIONS				
MOHADEVPUR 145	65 to 73 1975	One step function		-12.500	2.730	7.540
		FITTED ON 1974 DISCHARGES OBSERVATIONS				
	74 and 76 to 85	Data not available for the dry season Filled by interpolation				
	1965	Data not available from 1st to 14th Aug Filled by interpolation				
	1975	Data not available for the dry season Filled by interpolation				

5.3.3 Shift Corrections

When calculating mean daily discharge from observed water levels and derived rating curves BWDB today apply regular shift corrections. Before 1982, this was done manually and no strict method was applied. After 1982, with the introduction of computers in BWDB, shift corrections have been applied systematically. It has not been possible to obtain details on the actual computational procedure.

Usually, shift correction is applied when the stage-discharge relation changes with time due to change in cross section characteristics along the control section. A shift is a correction which is applied to the stage of a discharge measurement to bring the measurement in accordance with the derived mean rating curve. The procedure inherently assumes that the discharge measurements are true, without error. If this is not the case, application of shift correction may introduce new errors.

Examples of such errors are illustrated on Figure 5.10 a). This figure shows the relation between water level and mean daily discharge at selected locations. It appears that the scatter is much higher than what could reasonably be explained by back water effects etc., which may result in looped curves. Several of the derived mean daily discharges are likely to be in error due to the application of shift corrections.

Another example is shown on Figure 5.10 b) for Bahadurabad in 1982, where the rated point A is about one meter above the mean curve. This cannot be reasonably explained by changes in the stage discharge relation, rather be regarded as an error and thus ignored. The rigid application of the shift correction resulted in a calculated peak discharge much lower than what could be expected from the observed peak water level on September 21st, 1982, at Bahadurabad.

It has been concluded that the magnitude of possible errors involved in discharge measurements makes the application of shift correction questionable. In the FHS it has been decided to calculate discharges directly from observed water levels and mean annual rating curves derived as described above. Examples of such recomputed discharge hydrographs are given in Figure 5.11. Some deviations from BWDB hydrographs are observed.

5.3.4 Correlations at Bahadurabad and Hardinge Bridge

Given the importance of accurate flow data at Bahadurabad and Hardinge Bridge, some advantage was taken of the few flow data available for the neighbouring Indian stations of Pandu on the Brahmaputra and Farakka on the Ganges to further check data consistency through correlation analysis. Superimposed plotting of monthly discharge series at the two pairs of stations was carried out.

Brahmaputra flow data are available since 1955 at Pandu and 1956 at Bahadurabad. The catchment between the two stations, 96,000 Sq.km or about 19% of the entire catchment area, is an area of very high rainfall and is expected to contribute substantially more than 19% of the total flow at Bahadurabad. Between the two stations about 4% of the flow is diverted through the Old Brahmaputra. As a result, a close correlation cannot be expected between the two stations. Although significant discrepancies appear during the dry season from 1975 and onwards, a broad consistency between the two stations has been found in the wet season flows.

Ganges discharge data (10-daily mean) are available since 1948 at Farakka. The catchment areas at at Hardinge Bridge and Farakka are about 1,066,000 sq.km and 1,011,000 sq.km respectively, a difference of only 5%. A good agreement has been found between Hardinge Bridge and Farakka.

5.4 Concluding Remarks

As it appears from above the FHS has spent considerable effort on reviewing of water level and discharge data in the major rivers. While this review process has lead to the conclusion that for the purpose of the FHS the data quality in broad terms may be characterized as satisfactory, it has also identified a scope for improvement both in observation methods as well as in the data processing. A number of other FAPs have reached similar conclusions. In this context the widespread use of mathematical river models has offered a new and excellent opportunity to check geographical consistency of data to an extent which has not previously been possible.

It is believed that relatively limited resources available for hydrological survey combined with the complex physical environment for such surveys in Bangladesh are the major reasons for this situation. The ongoing or soon to start strengthening of BWDB Hydrology (DANIDA support to data collection in 1991 and 1992 monsoon season through SWMC, UNDP assisted support programme, and FAP 24 -River Survey Programme) together with the results from FAP 18 - Topographic Mapping, would be major contributions to the continued improvement of the hydrological data base.

6. STATISTICAL ANALYSIS

The need and objectives of various statistical analyses as part of the FHS have been outlined in Chapter 2. Some of these analyses are concerned with data checking as described in the previous chapter. This chapter discusses:

- the selection of suitable theoretical probability distributions for various hydrological variables, section 6.1 and 6.2 with details in Appendix 5;

- results of the frequency analyses using observed data, based on the recommended probability distributions, section 6.3 and Appendix 6;

- a joint probability analysis with respect to various flood causing factors in Bangladesh, section 6.4;

- an assessment of the representativeness of the period 1965 - 1989 for the century, section 6.5.

6.1 Selection of Probability Distributions

Prior to the systematic frequency analysis of water level, discharge and rainfall data, tests have been performed for the selection of the most appropriate probability distributions for use in Bangladesh.

For water levels and discharges focus has been on gauging stations along the main rivers. Even in these rivers particular statistical behaviour, induced by local hydraulic processes, may occur as observed for example for water levels at Hardinge Bridge, where the selected standard distribution is not applicable . In such cases, specific distribution studies should be undertaken, following the methodology outlined in this section.

Rainfall probability distributions are generally not affected by particular local conditions and the distribution recommended by the FHS may be applied countrywide.

The methodology used in this study for the selection of probability distributions is also recommended for application by other FAPs for feasibility studies and detailed design, at project specific locations. The methodology includes:

- selection of possible probability distributions among the most widely used ones:

  * Gumbel (or GEV type I)
  * GEV type II
  * GEV type III
  * Log Normal
  * Pearson III
  * Log-Pearson III

- selection of representative and reliable key-stations, well distributed over the study area (in the present study 5 stations);

- fitting of the various probability distributions for the selected key-stations, using the Maximum Likelihood method or another method of similar quality, and plotting of the results for visual inspection. Special attention should be given to eventual outliers or the eventual need for left censoring;

- application of goodness-of-fit tests, e.g. Chi-square test;

- comparison of the extrapolation properties of the tested probability distributions;

- selection of (an) appropriate distribution(s) for application in the project area.

For comparison of the extrapolation properties of various distributions, extrapolated values have been plotted for the fitted distributions up to the 1,000-year return period. It is acknowledged that such an extrapolation is certainly not needed for the FAP, and has little value as such, considering the available short observation periods (only 24 years). However, probability distributions used to estimate 100-year design events or levels, should preferably produce also realistic 1,000-year events. If the latter appears not to be realistic (for example a 1,000-year maximum water level of more than 2 m above the 1988 maximum water level), there is no guarantee that extrapolations towards the 100-year events can be relied upon.

The above methodology has been applied for the following hydrological variables:

- annual maximum water levels;

- annual maximum discharges;

- average seasonal discharges;

- total annual rainfall.

6.2 Suitable Probability Distributions

This section summarizes the results of the systematic analysis of suitable probability distributions for frequency analysis of hydrological variables in Bangladesh. Details are given in Appendix 5. The recommendations, in particular for the main river system, are as follows:

- the 3-parameter log-normal distribution is appropriate for the statistical analysis of annual maximum water levels and average annual, seasonal and sub-seasonal discharges (flood volumes);

- the 3-parameter GEV-2 and the 2-parameter Gumbel distribution are appropriate for the analysis of annual extreme discharges. The GEV-3 distribution may be considered, but it should be noted that this member of the GEV-family has an upper threshold, which may not be very realistic for the considered variable;

- the 3-parameter log-normal distribution is appropriate for the analysis of annual, seasonal and sub-seasonal rainfall. It has been outside the scope of the FHS to determine the most appropriate distribution for short term maximum rainfall data (hourly or daily).

The Log-Pearson III distribution, as applied for annual maximum discharges in the National Water Plan (NWP), see Ref. 9, gives similar results as the GEV for low to medium return periods. For higher return periods (more than 100 years) the distribution gives higher peak discharges than any other tested distribution and is thus probably somewhat conservative. It has the additional disadvantage that it has four parameters, the estimation of which is doubtful based on such short records as are available in Bangladesh.

The Pearson III, as applied for annual maximum water level in the NWP, usually yields the same results as the log-normal distribution. The latter is preferred for its easiness in application.

It is stressed that the above recommendations should not be applied rigidly, without precaution. Probability analysis is too much a matter of judgement to justify application of such recommendations as if they would represent the only truth. They may be considered no more and no less than guidelines.

Nevertheless, it is recommended that all FAPs choose their design criteria in the same manner. For example, design levels for the Right and Left Embankments of the Jamuna should be established in the same way.

It is noted that the choice of a particular distribution function is hardly relevant for a design period of say less than 50 years. Most theoretical distributions produce more or less the same design values. However, the actual choice of a distribution may substantially affect the 100-years design events.

In some cases, in particular when local conditions induce a particular statistical behaviour other than observed in the main river system of Bangladesh, it may be necessary to repeat the full analysis for the complete set of potentially appropriate distributions for some key-stations in an area, along the lines indicated in Section 6.1.

Hence, it is recommended that other FAPs, who are not working along the major rivers and require design level for the higher return periods, perform a similar analysis for their project area in the feasibility and detailed design stage, to confirm the validity of the above results for each particular region and secondary river system.

6.3 Results of Frequency Analyses on Observed Data

Based on the recommendations in section 6.2, frequency analyses have been carried out on observed peak water levels (20 stations), observed peak discharges (5 stations) and observed seasonal (May to October) discharges (5 stations). Details are provided in Appendix 6, while summary of the results are given in Table 6.1, 6.2 and 6.3 respectively.

It appears from Table 6.1 that differences in peak water level between the average flood and the 100-year flood are in the order of 1-1.5 m for most locations. The particular flow conditions at Hardinge Bridge, however, result in a difference of only 30 cm at that location. Table 6.2 shows that the 100-year peak discharges are typically 60-80% higher than the average peak discharge.

It is observed from Appendix 6 (see p. A.6.2 - A.6.4, and A.6.15) that for a particular year peak discharge and peak water level at a specific station may have different return periods. This is due to the observed shifts in rating curves, as described in section 5.3.2, and for which reason there is no unique relationship between discharge and water level.

Comparison with other studies, e.g the National Water Plan, Ref. 9, and the FEC study, Ref. 6, shows that a flood in a particular year may have estimated return periods different from the FHS. There may be several reasons for this including difference in data period considered, difference in actual data because of difference in revision, and application of different probability distribution. Estimated differences in return periods may be several tens of years, but is should be recalled that the estimation of return period is very sensitive to small variations in water levels and discharges, cf. Tables 6.1 to 6.4.

It is stressed that the methodology of the FHS is based on the use of simulated data for establishing hydrological design criteria in the major rivers. Hence the results in Tables 6.1, 6.2 and 6.3 are not supposed to constitute recommended design water levels and discharges. They have been prepared only for the purpose of comparison with simulated values as presented in Chapter 7.

For example, in the National Water Plan (NWP) the probability distribution functions applied are different from the FHS, namely Pearson III for peak water levels and Log-Pearson III for peak discharges. A comparison of the results of using the two different sets of probability distributions is shown in Tables 6.4 and 6.5 for peak water levels and peak discharges respectively. The common data period is 1965-89. For water levels there is a perfect agreement except for Hardinge Bridge. The deviation at this location is because left censoring techniques have been applied in the FHS to account for the special flow conditions here. This is not possible with the Pearson III distribution used in the NWP. With respect to peak discharges, slightly higher values result from using the NWP distribution (except for Bahadurabad). This tendency gets more pronounced with increasing return periods (especially beyond 100 years) and is, together with the comparatively easiness of applying the FHS distributions, the justification for the recommendations made in section 6.2.

Table 6.1 : Calculated Peak Water Level for Selected Return Periods Based on Observed Data.

STATIONS NAME	CODES	2	5	10	25	50	100
CHILMARI	45.5	23.98	24.31	24.51	24.75	24.92	25.08
BAHADURABAD	46.9L	19.78	20.04	20.21	20.42	20.57	20.73
KAZIPUR	49A	15.59	15.94	16.16	16.42	16.60	16.77
SERAJGANJ	49	13.91	14.26	14.51	14.84	15.10	15.36
PORABARI	50	12.25	12.61	12.80	13.00	13.14	13.26
MATHURA	50.3	10.01	10.46	10.76	11.14	11.42	11.69
HARDINGE BRIDGE	90	14.72	14.80	14.85	14.92	14.97	15.02
SENGRAM	91.1	11.66	12.06	12.28	12.52	12.69	12.84
MAHENDRAPUR	91.2	10.70	11.09	11.32	11.60	11.80	11.99
GORAI R. B.	99	12.91	13.30	13.51	13.73	13.88	14.01
KAMARKHALI	101	8.86	9.10	9.23	9.37	9.46	9.54
MADARIPUR	5	4.23	4.65	4.94	5.31	5.59	5.87
BARURIA	91.9L	8.14	8.51	8.76	9.08	9.32	9.57
MAWA	93.5L	5.91	6.22	6.44	6.76	7.01	7.27
MEGHNA F. G.	275.5	5.54	5.93	6.17	6.45	6.65	6.84
BHAIRAB BAZAR	273	6.57	6.96	7.20	7.49	7.69	7.89
CHANDPUR	277	4.50	4.72	4.84	4.96	5.04	5.12
JAMALPUR	225	17.03	17.38	17.56	17.76	17.89	18.00
NILUKHIRCHAR	228.5	12.36	12.82	13.08	13.39	13.59	13.79
TOKE	229	8.52	9.08	9.39	9.74	9.97	10.19
DEMRA	7.5	5.79	6.19	6.43	6.73	6.95	7.15
TARAGHAT	137A	8.81	9.34	9.65	10.00	10.24	10.47

Notes : A Log Normal distribution is applied for all the stations except for Hardinge Bridge where Gumbel is applied with left censoring.

Table 6.2 : Calculated Peak Discharges (m3/s) for Selected Return Period Based on Observed Data.

STATIONS NAME	NO.	2	5	10	25	50	100
BAHADURABAD	46.9L	67000	78000	85000	94000	100500	107000
HARDINGE BRIDGE	90	49000	59500	66500	76000	82500	89000
BARURIA	91.9L	86000	101000	110500	123000	132500	141500
BHAIRAB BAZAR	273	13700	15800	17200	19000	20300	21600
NILUKHIRCHAR	228.5	3000	3600	4000	4600	5000	5400

Notes : A GEV II distribution is used for Bhairab Bazar.
Gumbel is used for all the others stations.

Table 6.3 : Calculated Seasonal (May to October) Mean Discharges (m3/s) for Selected Return Period Based on Observed Data.

STATIONS NAME	NO.	2	5	10	25	50	100
BAHADURABAD	46.9L	33000	37000	39000	41500	43500	45500
HARDINGE BRIDGE	90	19000	21500	23000	25000	26000	27000
BARURIA	91.9L	46500	52000	55000	58500	61000	63000
BHAIRAB BAZAR	273	7800	9400	10500	11900	13000	14200
NILUKHIRCHAR	228.5	1300	1500	1600	1800	1900	2000

Notes : A Log Normal distribution is used for all the stations

Table 6.4 : Comparison of NWP and FHS Figures for Annual Peak Water Levels(m) for 2-, 10- and 100-Year Return Periods.

Stations	2 years		10 years		50 years		100 years	
	NWP	FHS	NWP	FHS	NWP	FHS	NWP	FHS
Bahadurabad	19.78	19.78	20.22	20.21	20.58	20.57	20.73	20.73
Hardinge Bridge	14.26	14.72	14.87	14.85	15.27	14.97	15.42	15.02
Bhairab Bazar	6.56	6.57	7.22	7.20	7.73	7.69	7.93	7.89
Baruria	8.14	8.14	8.78	8.76	9.32	9.32	9.55	9.57

Table 6.5.: Comparison of NWP and FHS Figures for Annual Peak Discharges (m3/s) for 2-, 10- and 100-Year Return Periods.

Stations	2 years		10 years		50 years		100 years	
	NWP	FHS	NWP	FHS	NWP	FHS	NWP	FHS
Bahadurabad	67000	67000	84500	85000	100000	100500	107000	107000
Hardinge Bridge	48500	49000	67500	66500	86500	82500	95000	89000
Bhairab Bazar	13300	13700	18100	17200	24900	20300	28600	21600
Baruria	85000	86000	114000	110500	146500	132500	162000	141500

6.4 Joint Probability Analysis

6.4.1 Past Studies

The Terms of Reference of the FHS calls for an analysis of joint probabilities of various flood causing factors in Bangladesh. This issue has already been addressed to some extent in previous studies and it is worthwhile recalling some of the earlier findings.

A comprehensive study of historical rainfall data and flood information was published by P.C. Mahalanobis, see Ref. 20, in 1927. It goes as far back as 1870 and covers North Bengal, including the North West Region of present Bangladesh and adjacent territories in India. Several conclusions related to the general features of the monsoon climate in this region may well be applicable to a much wider region.

One of the conclusion is that the temporal variability of rainfall diminishes rapidly as the period under consideration is increased. For seasonal and sub-seasonal periods, the indicated coefficients of variation are about 17% on a one year basis and of the order of 25 to 30% on a three-monthly basis, showing a fairly steady regime. Rainfall is very heavy in the northern hills, where the lowest coefficients of variations are found. On a one-week basis, the coefficient of variation is of the order of 85%, and on a daily basis of the order of 165%.

The above shows the monsoon characteristics of rainfall in Bangladesh. The observed low inter-annual variability of rainfalls is also demonstrated by the low variability of annual flow volumes in the main rivers at Bahadurabad and Hardinge Bridge.

Furthermore, within one year, see Ref. 20, verbatim:

"monsoon rainfalls are pulsatory in character and heavy falls are almost invariably brought about by cyclonic storms from the Bay. The tracks of these storms vary very considerably and the actual region of the heaviest precipitation along any particular track also varies largely".

" The actual site of heaviest precipitation fluctuates very irregularly during any particular season, and it is a matter of great uncertainty where the greatest rainfall would occur during the advance of a storm from the Bay".

" Such fluctuations are, however, perfectly random, and the rainfall records do not reveal the existence of particular regions which are more likely to receive heavier falls than other regions".

"Sudden and torrential downpours caused by cyclonic storms from the Bay constitute the most important direct cause of floods in North Bengal and have brought about all the great floods during the last 50 years (1880-1922)".

In the more recent 1989 "Pre-feasibility Study for Flood Control in Bangladesh", see Ref.6, the issue of joint probabilities and correlations was also addressed. On a monthly basis, it was found that a significant correlation exists between Brahmaputra and Meghna flows and rainfall over Bangladesh. However, this merely shows the regularity of the monsoon cycle, at least in the east of the catchments.

To analyze the joint probability of flood peaks in the Ganges and the Jamuna, the distribution of time lags between annual flood peaks in these two rivers was also studied in Ref.6. It was found that simultaneous peaking is not a rare event and that in 19% of the cases, the time lag is less than 10 days. This analysis would be sound if each contributing river had only one peak in a year. However, as explained in Section 3.2, each river may have several peaks and often the highest peak in the Padma does not result from the highest peaks in the Ganges and the Jamuna.

Information available to the FHS has allowed only a limited number of correlation analyses between various flood causing factors. These analyses are presented in the following sections.

6.4.2 Correlations on an Annual Basis

Ganges Watershed Annual Water Balance

Rainfall data have been collected for fairly regularly distributed stations in the Indian Ganges basin, see Chapter 5. The mean annual rainfall depth of all stations has been plotted against the mean annual discharge at Hardinge Bridge in the Ganges for the period 1934 to 1950, when overlapping records for rainfall data in India and flow data for Hardinge Bridge are available, see Figure 6.1. The correlation coefficient is only 0.68 and not very significant.

Annual Rainfall over Bangladesh

The work of Mahalanobis demonstrates the highly temporal and spatial variability of heavy cyclonic storms over Bangladesh. Correlations in annual rainfall over Bangladesh have been established for five rainfall stations, approximately aligned across Bangladesh from North East to South West. The distance between the five selected stations are listed in Table 6.6.

Table 6.6: Distance(km) Between Selected Rainfall Stations

Station	R116 Lallakhal	R128 Sylhet	R110 Habiganj	R009 Dhaka	R510 Khulna
R116	0	32	109	235	365
R128		0	77	204	332
R110			0	132	256
R009				0	131
R510					0

Correlation coefficients between annual rainfall of individual pairs of stations are plotted against distance on Figure 6.2 a). The graph gives an indication of the spatial homogeneity of the monsoon season, which is in the order of 100 or 200 km. On an annual basis, it shows no homogeneity at the scale of the country. Hence, northern Bangladesh may well experience a wet year, while at the same time the southern part of the country experiences a dry year.

Annual Ganges and Brahmaputra Runoff

Annual, two-monthly and 10-day mean discharges at Bahadurabad on the Jamuna and Hardinge Bridge on the Ganges are compared in Figure 6.3. The absence of even a significant correlation between the annual flood volumes on both rivers is evident. In other words, the rainfall volume of the monsoon in the Ganges catchment is independent from the one in the Jamuna watershed. This is consistent with the previous finding that over large distances no correlations between rainfall exists.

6.4.3 Correlation of Shorter Periods

As the monsoon phenomenon is actually the result of a combination of a great number of cyclonic rainfalls, each limited in time and space, correlations have been searched for shorter periods of rainfalls.

The analysis carried out on annual rainfall in section 6.4.2 was repeated using:

- 3 sub-seasonal periods (May/June, July/August and Sept/Oct);
- weekly rainfalls from July to September over the last 25 years;
- daily rainfall from July to September over the last 25 years.

For each case correlation matrices have been computed. Correlation coefficients are plotted against distance in Figures 6.2 b) to f). Exponential regression has been applied to the results.

The best correlation is observed for the 2-monthly period. However, the interstation correlation coefficient decreases rapidly with distance confirming the erratic character in space and time of cyclonic storms, as described by Mahalanobis, see Section 6.4.1.

6.4.4 Frequency Distribution of Tropical Cyclones

Since monsoon rainfalls, as well as cyclones, originate from the general cyclonic activity over the Bay of Bengal, it is worth examining possible correlation between the two phenomena.

For that purpose, the monthly distribution of tropical cyclones formed over the Bay of Bengal between 1948 and 1970 is plotted in Figure 6.4, from Ref. 7.

The cyclonic origin of the monsoon rainfall is evident. It shows also that the severity of the cyclones is inverse of the number. The probability of severe cyclones occurring during the time of maximum floods (viz. from July to September) is very low.

6.4.5 Conclusion

At the time scale of peak floods (one or two weeks), correlations between rainfall at various locations in Bangladesh and between rainfall and peak flows are very weak. The cyclonic storms behave as turbulent vortices and are random in nature. Nevertheless, they are responsible for the flood peaks on the major rivers. There is no distinct correlation between high floods in the rivers and disastrous cyclonic storms, which generally occur at the beginning and end of the wet season. Even correlations between annual flows on the Ganges and Brahmaputra rivers, and between annual rainfall in the Ganges basin and annual flows at Hardinge Bridge are all found to be weak. Hence, extreme floods on the main rivers, rainfall driven flash floods and rainfall over Bangladesh appear to have little correlation. It is considered highly unlikely that the existing data base can provide further information in this respect.

Consequently, there is little need to consider the issue of joint probabilities of various flood causing factors any further. Moreover, the actual (weak) correlation structure is embedded in the actual data series for the last 25 years, and is therefore well taken into account in the long term simulations with the General Model and the regional models.

6.5 Representativeness of 1965-1989 Period for the Century

6.5.1 Available Data

An appraisal of the statistical representativeness of the hydrological conditions during the last 25 years for the century can only be done, if long data series exist. Such series have mainly been available for rainfall stations in Bangladesh and the conclusions presented in the following should be viewed in that perspective. The following information was used for analysis:

- monthly rainfall data series for 16 stations in Bangladesh (see Table 5.1), for the period 1902 to 1989 (88 years);
- daily water levels at Hardinge Bridge, from 1910 to 1989 (80 years);
- daily discharges at Hardinge Bridge, from 1933 to 1989 (55 years);
- daily discharges at Bahadurabad from 1956 to 1989 (33 years).

6.5.2 Annual Rainfall

The consistency analysis of annual rainfall data, as discussed in Section 5.1 (see also Appendix 3), revealed that for most of the stations the annual rainfall for the 1964 - 1989 period is about 2% higher compared to the full sample (88 years).

The probability distributions of the mean annual rainfall for 16 stations in Bangladesh is shown in Figure 6.5, both for the last 25 years and for the full period. Compared to the long term, rainfall depths during the last 25 years are 4% higher for the 10 year return period and 8% higher for the 100 year return period.

The Student's t-test and Fisher F-test have been applied to analyse possible differences between the long and the short time series in mean and standard deviation respectively. The t- and F-tests statistic equal 1.88 and 0.93 respectively, as compared to the 5% critical values of 2.0 and 1.70 respectively.

The conclusion is that observed differences between the data for the two periods may be considered to fall within the range of possible deviations and are thus insignificant from a statistical point of view. Moreover, since for most stations average rainfalls and standard deviations are slightly higher in recent years compared to the earlier part of the century, designs based on statistics derived for the last period may be considered to be slightly conservative.

6.5.3 Long Term Water Levels at Hardinge Bridge

Long term records are available for water levels at Hardinge Bridge, i.e. 1910-89, see Figure 6.6, where annual peak water levels, average peak water level, five-year moving average and the mass residue curve are depicted. Though it is appreciated that the water level observations are affected by the special flow conditions at Hardinge Bridge (constricted flow) and may be affected by morphological changes in the Ganges the record has been tested for significant trends. The analysis has shown that peak water levels for Hardinge Bridges are random, without serial correlation and without long term trends. The mean peak water level for the period 1965-89 is not significantly different from the period 1910-64.

6.5.4 Discharges at Bahadurabad and Hardinge Bridge

Probability distributions of annual maximum discharges at Bahadurabad and Hardinge Bridge for the last 25 years are compared in Figures 6.7 a) and 6.7 b) with the distributions for the longer term. To facilitate comparison observed distributions were fitted with a Gumbel distribution. The analysis for Hardinge Bridge is of particular interest, given its rather long record of observations.

The probability distributions derived for the last 25 years produce slightly higher extreme discharges than the one for the long term, in the order of 5% for return periods ranging from 10 to 25 years.

The Student's t-test and Fisher F-test applied on the means and standard deviations gave the results shown in Table 6.7. These tests confirm that the two samples for each station are identical from a statistical point of view.

Table 6.7: Test Statistics for Comparison of 1965-89 Discharge Time Series with Total Length of Records at Hardinge Bridge and Bahadurabad.

Statistics	Bahadurabad	Hardinge Bridge
t	0.50	0.23
5% critical t	2.00	2.00
F	1.21	1.30
5% critical F	1.89	1.75

6.5.5 Conclusion

Although only few data are available for detailed analysis, the tentative conclusion is that the hydrometeorological conditions in Bangladesh during the last 25 years are fairly representative for the longer term. In general, one may consider the 1965-1989 period as a slightly conservative basis for design, when compared to the last 50 to 100 years, in particular because:

- maximum river flows for given return periods are slightly higher;

- annual rainfalls are marginally higher (2%);

- variation of annual rainfall is more pronounced.

Hence, the approach to use model simulation results for the period 1965-89 as a basis for an assessment of design criteria appears to be solid and justified.

7. GENERAL MODEL (GM) APPLICATION

7.1 General

The methodology described in Chapter 2 is based on an intensive use of the General Model (GM). The GM has been developed at the Surface Water Modelling Centre (SWMC) of the Water Resources Planning Organisation (WARPO, the previous MPO).

The GM is based on the MIKE 11 software package, including rainfall-runoff, hydrodynamic, morphological and transport-dispersion modules of which only the two former are used in the FHS. The MIKE 11 is developed by the Danish Hydraulic Institute.

As mentioned in Chapter 1 the FHS has been carried out in close cooperation with the SWMC, who has prepared a dedicated version of the GM for the purposes of the FHS and carried out all the runs with the GM. Preparation of input data and analysis of model output has been done by FAP 25. The model results have been discussed in detail with the SWMC and also FAP 1.

A number of simulations was carried out in which the model performance was gradually improved. Ultimately, a recalibration was done by the SWMC and the model results presented in this chapter is based on this recalibrated and updated version of the GM.

The implementation of the FHS methodology required a dedicated version of the GM to be developed, including all boundary stations of the Regional Models and allowing larger computational time step to arrive at acceptable running times. This dedicated model is derived from the original model, calibrated for the last years. The FAP 25-GM is described in section 7.2-7.4 and the model validation results and subsequent statistical analyses of model output in section 7.5. The model results are referred to as FAP 25-GM (run 6).

Recommended design water levels in the major rivers appear from section 7.6. Due to non corrected errors in observations, errors resulting from model schematization and the use of a fixed bed model to represent flows and water levels in an alluvial river, differences between observations and simulations are unavoidable. From the estimation of these differences, safety margins have been calculated for project design, see section 7.7.

A methodology for taking the effect of long-term morphological developments into account is described in section 7.8 and the supply of model results to other FAPs is shortly described in section 7.9.

The FHS methodology also includes the task to carry out 25-year runs with the GM for future flood protection scenarios of the delta and to perform the frequency analysis of the results. The reporting of these results will take place in August 1992 and included as Annex 2 of the present report. However, a provisional run with a future protection scenario has been carried out for the five-year period 1985-89, see section 7.10.

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7.2 Description of the FAP 25 General Model (FAP 25-GM).

The FAP 25-GM is a dedicated version of the General Model(GM) developed by the SWMC. For use in the Flood Hydrology Study three major constraints had to be complied with:

- The model should be run frequently for a long period, 1965-89. Therefore, it was necessary to increase the time step from 1 to 3 hours.
- All boundary locations for the regional models must be included in the FAP 25-GM. The list of the relevant stations is given in Appendix 10.
- Boundary conditions of the model should not be affected by any possible future protection scenario which may have to be modelled at some point in time.

The main differences between the FAP 25-GM and the GM are the following points:

- The Ganges schematization is extended up to the Indian border at Pankha, using cross sections available in the flood forecasting version of the GM, as used by FAP 10.
- The Teesta river is not included in the model, because a shorter time step would have been necessary for the computation of the flood in this flashy river. Instead,its discharge is introduced at Kaunia as a lateral inflow into the Jamuna.
- Low (artificial) base flows have been introduced in the Old Brahmaputra during the dry season, to avoid mathematical instabilities. These flows have been chosen low enough not to affect the results of the model.

The model area of this dedicated version of the GM is depicted in Figure 7.1. For a detailed description of the GM as such, reference is made to reports of SWMC, see Ref.2 and 3.

7.3 Boundary Conditions

The FAP 25-GM uses data from 13 stations as boundary conditions, 7 for upstream discharges and 6 for downstream water levels, see Table 7.1.

For all stations, the longest consistant time series available today runs from 1965 to 1989, with the exception of 1971, or a total of 24 years. Since the inception of the FHS also data from 1990-91 have become available. They are not used in the analyses but may be obtained from SWMC.

<u>Upstream Discharges</u>

Discharges on the Jamuna and Ganges and also at stations on the Upper Meghna are introduced far upstream, in order to ensure the independence of boundary conditions from the actual state of the model, under all possible future circumstances.

The Bahadurabad discharge is introduced near Kurigram at the outfall of the Dharla in the Brahmaputra with an 8 hour time lag. The Hardinge Bridge discharge is introduced at Pankha with a 16 hour time lag, while the Kaunia discharge is introduced as a lateral inflow to the Brahmaputra at the Teesta outfall.

Measured discharge data have been collected and revised annual rating curves computed for the reasons mentioned in Chapter 5. These revised rating curves have been applied to derive revised discharge time series from observed (and corrected) water levels for Bahadurabad and Hardinge Bridge, cf. section 5.3. The above recalculation of discharge boundary conditions proved to be a major step forward in the validation of the GM.

Table 7.1 : FAP 25-GM Boundary Stations.

RIVERS	STATIONS	CODE	STATUS
DISCHARGES			
JAMUNA	Bahadurabad	46.9L	New rating curves generated from measured discharges Discharges introduced at Kurigram
GANGES	Hardinge Bridge	90	New rating curves generated from measured discharges Discharges introduced at Pankha (Indian Border)
KANGHSA	Jaria Jhanjail	36	New discharges generated for 69/70, 81/82, 82/83 and 89/90 BWDB data for the other years
SURMA	Kanairghat	266	New discharges generated for 65/66 to 68/69 and 89/90 BWDB data for the other years
KUSHIYAR	Sheola	173	New discharges generated for 69/70 and 89/90 BWDB data for the other years
TEESTA	Kaunia	294	Discharges introduced as lateral inflow in the Jamuna New discharges generated for 65/66 Interpolated data used for missing days. BWDB data for the other years
ATRAI	Mohadevpur	145	New discharges generated from 65/66 to 73/74 and 75/76 Interpolated data used for missing days.
WATER LEVELS			
L. MEGHN	Daulat-Khan	278	For all these station :
TENTULIA	Dasmunia	290	65/66 to 67/68 data collected from the Hydrology Year Book
LOHALIA	Galachipa	185	15 days moving average values used for these years
BISKHALI	Pathergata	39	BWDB data (checked and completed by interpolations)
MADHUMA	Rayenda	107.2	for the other years
RUPSA	Mongla	244	A systematic correction of + 0.75 m is applied to Daulat Khan mean water level (correction suggested by the SWMC)

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Upstream boundary conditions for secondary rivers were based on the rating curves computed by BWDB. Eventual inaccuracies in these curves are of minor importance to the GM results.

Downstream Water Levels

Downstream boundary conditions are daily mean water levels at 6 tidal stations. All data have been scanned and data gaps filled, using relations with other coastal stations. Special attention was given to the downstream boundary station Daulat Khan on the Lower Meghna. A systematic correction of + 0.75 m (datum error) has been applied to this station to obtain correct water levels all along the Lower Meghna, see section 5.2.6.

For the period 1965/66 to 1967/68 only 15-days moving average values of water levels are available for these tidal stations.

Annual peak and mean water level at these tidal stations are poorly correlated to floods on the main rivers. Boundary conditions at these stations are therefore considered independent from upstream flows.

7.4 NAM Model and Rainfall

A total of 26 rainfall stations has been used as inputs for the NAM rainfall-runoff model providing internal boundary conditions for the GM. The first run with the FAP 25-GM showed that satisfactory results for the locally generated runoff could be achieved, even with a relatively limited number of rainfall stations. Hence, only approximately 3 stations have been selected for each region, plus 11 additional stations in the North East region to better represent the high rainfall gradient in that region. The selection has been done with consideration to expected reliability and available length of record. This has allowed the analysis of the representativeness of the simulation period for the century to be based on the same rainfall stations as used in the simulations, see section 5.1.

The selected rainfall stations are listed in Table 5.1 and their distribution within the delta can be seen on Figure 5.1

7.5 Validation of the Model.

During recalibration and updating of the GM, the SWMC has in general concentrated on model performance in the four major rivers, i.e. Jamuna, Ganges, Padma and Meghna, and to some extent Old Brahmaputra. In the hierachy of SWMC models, including the GM and six regional models, these major rivers are only included in the GM, which provides boundary conditions for the regional models. Accurate simulations for regional rivers represented in the GM (e.g. Dhaleswari, Lakhya, Arial Khan and Gorai) should be achieved with the respective regional models.

The validation of the model has been based on the comparison of computed and observed water levels at 22 stations along the major rivers, their main tributaries and distributaries. Discharges have also been compared to check the distribution of flow in the different branches of the system. Appendix 7 contains the complete water level hydrographs (observed and simulated) for the entire period 1965-89 for Baruria, Bhairab Bazar, Bahadurabad and Hardinge Bridge. Examples of hydrographs for the period 1987-89 are shown on Figures 7.2 a) and b).

A comprehensive error analysis, both for water levels and discharges, has been carried out. Variables considered are :

- annual peak values;
- daily values for 2-month subseasonal periods (May-June, July-August and September-October;
- daily values for the entire period May-October;

The term "error" is used for differences between observed and simulated variables.It is virtually impossible to obtain a perfect fit for all above variables at various stations in all years, mainly because of random morphological changes, errors in the observations and limitations in GM and its schematization of the flooding phenomena in Bangladesh.

The error analysis has included determination of average and standard deviation of errors based on daily differences as well as preparation of error frequency curves (distribution of errors) using sequential 10-day averages.

A frequency analysis of simulated variables has been carried out using the probability distributions recommended in section 6.2. Simulated values for different return periods have been compared with the values obtained from observed data, cf. section 6.3.

7.5.1 Analysis of Computed Water Levels.

For each year at any station the difference between observations and the model results has been computed for peak water level and daily water levels on a subseasonal basis. The average and the standard deviation of these differences are presented in Table 7.2. Figures 7.3 a) and 7.3 b) give a comprehensive view of the bias and the scatter of the results for peak levels and seasonal levels for selected stations along the major rivers. Error frequency curves for all comparison stations, except Meghna Ferry Ghat and Toke where records are short, are shown on Figures 7.4 a)-d). The complete analysis is presented in Appendix 7.

Model Bias

The average difference between observations and model results - the model bias - can result from:

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Table 7.2:
25 Years Model Validation Statistics on Water Level
(Errors (Obs-Sim) of 5-parameters are given)
Values are in cm

RIVER	STATION	PEAK		(MAY-JUN)		(JUL-AUG)		(SEP-OCT)		(MAY-OCT)	
		AVG	STD	AVG	STD	AVG	STD	AVG	STD	AVG	STD
JAMUNA	Chilmari	9	26	-22	38	8	25	-4	27	-6	27
	Bahadurabad	-2	27	11	22	20	25	24	22	18	21
	Kazipur	-6	26	-23	34	-14	21	-16	25	-18	23
	Serajganj	-29	26	-20	38	-20	23	-2	23	-13	24
	Porabari	13	27	2	35	8	41	24	34	11	30
	Mathura	25	27	7	42	30	30	31	31	23	29
GANGES	Hardinge Bridge	19	20	-15	21	19	19	19	22	8	19
	Sengram	-28	20	-35	33	-24	22	-42	31	-34	20
	Mahendrapur	6	26	14	22	8	23	-14	23	2	17
PADMA	Baruria	-18	19	6	23	-4	18	-3	23	0	18
	Mawa	2	20	29	23	8	19	13	25	20	24
MEGHNA	Bhairab Bazar	14	34	-25	17	14	25	36	29	8	20
	Meghna FG	19	19	1	10	17	17	28	22	15	14
	Chandpur	7	25	7	12	7	18	9	19	8	15
OLD BRAHMAPUTRA	Jamalpur	37	30	-16	54	34	43	25	44	14	45
	Nilukhirchar	41	31	30	63	40	41	48	45	39	44
	Toke	-38	41	-6	46	9	42	36	42	13	37
DHALESHWARI	Taraghat	-2	36	-40	61	18	35	36	41	4	43
LAKHYA	Demra	34	20	16	14	34	17	40	23	30	16
GORAI	Gorai RB	7	23	-10	49	6	30	-6	31	-4	30
	Kamarkhali	-24	28	29	58	-23	26	-36	28	-10	30
ARIAL KHAN	Madaripur	-53	29	18	13	-40	22	-51	22	-24	15

Note : (-)ive value of average indicates overestimation.

- erroneous gauge level (bench mark unreliability);
- error in the chainage (location) of a gauge in the model;
- non-random morphological changes during the last 25 years (evolution of the rating curve);
- errors in bottom roughness coefficients applied in the model.

The first item is being addressed by FAP 18 - Topographic Mapping, but useful results have not yet been released. The second item has been addressed by FAP 1 and SWMC. Recent up-to-date information from FAP 1 on the Jamuna chainage including gauge and cross section locations has been used in the updating of the GM. Further, SWMC has carried out GPS (Global Positioning System) surveys resulting in revision of chainage for some of the gauge locations. Uncertainties in levels and chainage can generate errors of a few decimeters.

The model performance in the major rivers is considered satisfactory, generally with errors less than 20 cm. For some stations results can be further improved (Serajganj, Mathura and Sengram)) by adjusting Manning-Strickler coefficients. The model performance in the Old Brahmaputra is possibly affected by the increased siltation in the offtake from Jamuna leading to undersimulation of peaks in the early part of the 25-year period.

In the regional rivers model performance may be improved, notably in the Lakhya (Demra) and Arial Khan (Madaripur). The less satisfactory results in these rivers has, however, not any significant effects on the major rivers.

Scatter of Results

The standard deviation of errors (over the 24 year period) results from annual variations of bed shape and roughness coefficients (due to changing bedforms), and from errors in water level and discharge measurements. Reducing the former variations could only be envisaged with a movable bed model, which could take into account the "random morphological changes" as they occured in the past. On the other hand, such "random morphological changes" will also occur in the future and they can never be predicted precisely, because they are likely to depend on the particular sequence of the floods, as they may occur in the future. Hence, they are proposed to be included in the safety margin, adopted for the protection of flood protection works. As this scatter is also due to observation errors and errors in the boundary conditions, it can never be completely eliminated.

The standard deviation of errors are remarkably similar in the entire model area, see Table 7.2. For peak water levels it is typically 20-30 cm, and for daily water levels 15-30 cm though with a wider range.The standard deviations of errors give a very good estimate of the model uncertainity due to random morphological changes and possible errors in measurement. These standard errors are further used in the computation of

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safety margins, cf. section 7.7.2.

Error Frequency Curves

The error frequency curves, Figures 7.4 a)-d), show that overall model errors are less than 0.2 m in about 45% of the time and less than 0.4 m in about 75% of the time. There is no significant seasonal variation in the errors though it seems slightly more difficult to simulate the receding floods (September-October) than the pre-monsoon and main monsoon periods, May-June and July-August respectively.

7.5.2 Analysis of Computed Discharges

An error analysis of computed discharges has also been carried out for Baruria station on the Padma and some other stations on secondary rivers. The results are summarized in Appendix 7, and examples given on Figures 7.3 c) and d).

For Baruria, the mean seasonal (May-October) difference for the last 25 years is only 3 %, ranging from -17 % in 1967 to + 10 % in 1974, due to possible errors in:

- discharges at Bahadurabad, Hardinge Bridge and Baruria, as derived from observed water levels and rating curves;
- annual runoff as computed by the NAM model;
- the distribution of discharges throughout the different branches of the model.

The differences between computed and observed discharges in Baruria are well within acceptable limits, considering that errors in discharge measurements and NAM model results is estimated to be at least of the order of 10%.

At Bhairab Bazar the average error is less than 2% excluding 1974, where water levels are suspected to be in error, probably due to a gauge shift. At Nilukhirchar, in Old Brahmaputra, errors are considerable, the model performance being affected by the increased siltation in the offtake from Jamuna as mentioned above. A comparison of BWDB and model rating curve extrapolation characteristics also shows that the latter is considerably more flat. This issue should be adressed in the next update of the GM.

7.5.3 Frequency Analysis of Results

One of the main objectives of the model application is to provide designers with a model system exhibiting the same hydrodynamic and statistical characteristics as the real system. A frequency analysis of simulated water levels and discharges using the probability distribution functions recommended in section 6.2 has been carried out and comparison made with the results based on the observed data, cf. section 6.3. Only stations along the four major rivers and Old Brahmaputra, where FAP 25 shall establish hydrological design criteria, have been considered.

Peak Water Levels

The results for peak water levels are shown in Table 7.3. It appears that along the four major rivers there is an excellent agreement between model results and observations, differences being less than 20 cm for the whole range of return periods. Exceptions are Mathura, Serajganj for the lower return periods and Mahendrapur for the higher reurn periods. It is noted that for Bhairab Bazar and Chandpur observed peak water levels for 1974 and 1965 have been omitted from the analysis as the are suspected to be in error.

In Old Brahmaputra levels based on observed data are very much higher than modelled, for the reasons explained above. For design purposes one should rely on the model results because they represent present conditions and degree of siltation in the offtake from Jamuna.

Mean Seasonal Water Levels

The results for mean sesonal water levels (May to October) are shown in Table 7.4. This variable does not serve any specific engineering purposes. The analysis has been done merely for model validation purposes. The results are considered satisfactory and quite similar to the results for peak water levels. Differences of more than 20 cm are observed only at Serajganj, Mathura, Sengram and Mawa along the major rivers and at Nilukhirchar on Old Brahmaputra.

Peak and Mean Seasonal Discharges

The results for peak and mean seasonal discharges are shown on Table 7.5 and 7.6 respectively. Discharge data, used as upstream boundary condition and introduced near the stations of Bahadurabad and Hardinge Bridge, are identical to observed data and therefore the statistical distributions of observed and computed discharges are obviously the same.

The results for Baruria are satisfactory, differences being generally less than 10%.
At Bhairab Bazar, the agreement is excellent for peak discharges. For mean sesonal discharges the results are also satisfactory.At Nilukhirchar, while the undersimulation of mean seasonal discharges is also reflected in mean seasonal water level this does not seems to be the case for peak discharges and water levels.

7.5.4 Conclusion

The overall performance of the FAP 25-GM is encouraging. With few exceptions results in the major rivers are satisfactory both in terms of water levels (peak and seasonal values) as well as discharges. Determination of hydrological design criteria for the four major rivers using the model results will be consistent and can be done with confidence.

Table 7.3: Comparison of Observed and Simulated Peak Water Levels for Selected Return Periods.

STATIONS		RETURN PERIODS					
		2	5	10	25	50	100
CHILMARI	BWDB	23.98	24.31	24.51	24.75	24.92	25.08
	MODEL	23.85	24.23	24.45	24.70	24.88	25.04
BAHADURABAD	BWDB	19.78	20.04	20.21	20.42	20.57	20.73
	MODEL	19.83	20.16	20.36	20.60	20.77	20.94
KAZIPUR	BWDB	15.59	15.94	16.16	16.42	16.60	16.77
	MODEL	15.69	16.05	16.26	16.50	16.67	16.82
SERAJGANJ	BWDB	13.91	14.26	14.51	14.84	15.10	15.36
	MODEL	14.26	14.62	14.82	15.05	15.20	15.35
PORABARI	BWDB	12.25	12.61	12.80	13.00	13.14	13.26
	MODEL	12.10	12.45	12.66	12.91	13.08	13.24
MATHURA	BWDB	10.01	10.46	10.76	11.14	11.42	11.69
	MODEL	9.77	10.12	10.36	10.67	10.91	11.15
HARDINGE BRIDGE	BWDB	14.72	14.8	14.85	14.92	14.97	15.02
	MODEL	14.68	14.79	14.86	14.96	15.02	15.09
SENGRAM	BWDB	11.66	12.06	12.28	12.52	12.69	12.84
	MODEL	11.93	12.31	12.52	12.75	12.90	13.05
MAHENDRAPUR	BWDB	10.70	11.09	11.32	11.60	11.80	11.99
	MODEL	10.68	10.99	11.16	11.36	11.49	11.61
BARURIA	BWDB	8.14	8.51	8.76	9.08	9.32	9.57
	MODEL	8.32	8.63	8.86	9.16	9.39	9.63
MAWA	BWDB	5.91	6.22	6.44	6.76	7.01	7.27
	MODEL	5.92	6.20	6.41	6.68	6.90	7.13
BHAIRAB BAZAR	BWDB	6.55	6.89	7.09	7.33	7.49	7.65
	MODEL	6.43	6.76	6.96	7.20	7.37	7.53
CHANDPUR	BWDB	4.48	4.68	4.82	4.97	5.09	5.20
	MODEL	4.38	4.63	4.80	5.02	5.18	5.35
JAMALPUR	BWDB	17.03	17.38	17.56	17.76	17.89	18.00
	MODEL	16.64	16.98	17.16	17.37	17.51	17.64
NILUKHIRCHAR	BWDB	12.36	12.82	13.08	13.39	13.59	13.79
	MODEL	11.91	12.24	12.47	12.76	12.98	13.21

Notes : Log Normal distribution & the data for the period of 1965-89 is considered for all the stations except for Hardinge Bridge where Gumbel is applied with left censoring for the period of data of 1910-89.

Table 7.4: Comparison of Observed and Simulated Mean Seasonal Water Levels for Selected Return Periods.

STATIONS		RETURN PERIODS					
		2	5	10	25	50	100
CHILMARI	BWDB	21.86	22.18	22.35	22.54	22.66	22.77
	MODEL	21.86	22.13	22.30	22.49	22.63	22.76
BAHADURABAD	BWDB	17.76	18.03	18.18	18.37	18.50	18.62
	MODEL	17.58	17.87	18.04	18.24	18.39	18.52
KAZIPUR	BWDB	13.57	13.88	14.04	14.22	14.33	14.43
	MODEL	13.71	13.99	14.16	14.37	14.51	14.65
SERAJGANJ	BWDB	11.97	12.22	12.35	12.49	12.58	12.67
	MODEL	12.07	12.38	12.57	12.80	12.96	13.11
PORABARI	BWDB	10.15	10.43	10.58	10.73	10.83	10.92
	MODEL	10.00	10.28	10.45	10.66	10.81	10.95
MATHURA	BWDB	7.97	8.30	8.48	8.66	8.78	8.89
	MODEL	7.71	7.93	8.06	8.22	8.33	8.43
HARDINGE BRIDGE	BWDB	10.82	11.06	11.19	11.34	11.44	11.53
	MODEL	10.71	11.05	11.22	11.41	11.53	11.64
SENGRAM	BWDB	8.70	9.03	9.21	9.39	9.52	9.62
	MODEL	9.02	9.30	9.46	9.62	9.72	9.82
MAHENDRAPUR	BWDB	8.21	8.48	8.62	8.78	8.87	8.96
	MODEL	8.22	8.47	8.59	8.73	8.82	8.90
BARURIA	BWDB	6.38	6.61	6.74	6.86	6.95	7.02
	MODEL	6.38	6.58	6.69	6.81	6.89	6.96
MAWA	BWDB	4.50	4.74	4.87	5.02	5.12	5.21
	MODEL	4.34	4.51	4.60	4.70	4.76	4.82
BHAIRAB BAZAR	BWDB	4.94	5.22	5.38	5.56	5.68	5.80
	MODEL	4.84	5.14	5.33	5.57	5.75	5.93
CHANDPUR	BWDB	3.32	3.48	3.56	3.65	3.71	3.76
	MODEL	3.23	3.36	3.44	3.53	3.59	3.65
JAMALPUR	BWDB	14.82	15.14	15.32	15.51	15.64	15.75
	MODEL	14.62	14.91	15.10	15.34	15.53	15.72
NILUKHIRCHAR	BWDB	9.99	10.33	10.55	10.82	11.01	11.20
	MODEL	9.59	9.99	10.24	10.55	10.76	10.98

Notes : Log Normal distribution & the data for the period of 1965-89 is considered for all the stations.

This does not mean that further refinement of model performance is not possible. The observed disagreement at three stations in the major rivers and in the secondary rivers may be addressed by the SWMC in the next update of the GM, planned for the end of 1992. Availability of the results from FAP 18 is considered very important for further model improvement.

Table 7.5 : Comparison of Observed and Simulated Peak Discharge (m3/s) for Selected Return Periods.

STATIONS		RETURN PERIODS					
		2	5	10	25	50	100
BAHADURABAD	BWDB	67000	77700	84800	93800	100400	107000
	MODEL	67700	78500	85600	94600	101200	107900
HARDINGE BRIDGE	BWDB	49000	59800	67000	76000	82700	89400
	MODEL	48800	59600	66800	75800	82500	89200
BARURIA	BWDB	86000	100900	110700	123100	132400	141500
	MODEL	89600	102000	112400	128500	143100	160300
BHAIRAB BAZAR	BWDB	13700	15800	17300	19000	20400	21700
	MODEL	13400	15700	17300	19300	20800	22300
NILUKHIRCHAR	BWDB	3000	3650	4070	4610	5010	5410
	MODEL	3130	3810	4260	4830	5250	5660

Notes : Gumbel distribution is applied for all the stations exept for Bhairab Bazar where GEV II is applied. Period of data is 1965-89.

Table 7.6 : Comparison of Observed and Simulated Mean Seasonal Discharges (m3/s) for Selected Return Periods.

STATIONS		RETURN PERIODS					
		2	5	10	25	50	100
BAHADURABAD	BWDB	33100	36800	39100	41700	43500	45300
	MODEL	34000	37700	39900	42500	44300	46000
HARDINGE BRIDGE	BWDB	19000	21900	23500	25100	26200	27100
	MODEL	19000	21900	23400	25000	26100	27100
BARURIA	BWDB	46600	51900	54900	58400	60800	63000
	MODEL	47700	51500	53600	55900	57400	58800
BHAIRAB BAZAR	BWDB	7900	9500	10600	12000	13000	14200
	MODEL	7500	8600	8500	10600	11500	12500
NILUKHIRCHAR	BWDB	1320	1550	1680	1840	1940	2040
	MODEL	920	1140	1280	1460	1590	1720

Notes : Log Normal distribution & the data for the period of 1965-89 is applied for all the stations

7.6 Hydrological Design Criteria

The FHS should establish hydrological design criteria along the major rivers. For consistency, all other FAPs should in general use the results of the FHS. However, this should not exclude the use of other results based on more detailed analysis serving specific purposes. It should also be stressed that the FHS results are not static and should be updated as and when improved information becomes available (FAP 18, FAP 24, SWMC etc) or when schemes affecting water levels and discharges in the major rivers are finally decided for implementation (e.g. Jamuna Left Embankment or Jamuna Bridge).

Based on the 25-year model simulation, the recommended design water levels and discharges in the major rivers are shown in Tables 7.3-7.6 ("Model") of the preceding section. Design levels and discharges at other locations in the major rivers can be derived on the basis of the 25-year model output and applying the probability distributions recommended in section 6.2. Appendix 8 provides a schematization and river setup used in the FAP 25-GM. Model results from run 6 are available for a total of approximately 400 water level points and 350 discharge points.

With respect to Old Brahmaputra, it is believed that model results provide the most reliable basis as long as the present geometry of the offtake from Jamuna is maintained. For secondary rivers represented in the FAP 25-GM design criteria should be established using the regional models and following the methodology presented in Chapter 8.

Design water levels on the country-side of possible embankments along the major rivers (for the purpose of establishing head differences for hydraulic structures design) can not be assessed with the FAP 25-GM but requires the application of the relevant regional models.

7.7 Safety Margins for Design Water Levels

7.7.1 General

As discussed in section 5.3.2, substantial shifts in rating curves from one year to the other are observed for various discharge stations. Such changes are likely caused by morphological processes, in particular gradual changes of bedforms and cross-sectional shapes. The mechanisms of these phenomena is not yet well understood, but the impression is that the last years flood may well have a distinct impact on the rating curve to be adopted for the next year. Hence, this phenomenon causes an additional variation of annual maximum flood levels above the variation related to the particular shape of each flood hydrograph, as would occur in a river with a 'fixed' bed.

The GM presumes indeed a 'fixed bed' of the river with a unique relation between levels and bottom roughness coefficients. This section therefore addresses the question to what extent design water levels, as calculated with the 'fixed bed' model, should be

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adjusted to take into account the effect of apparently more or less at random shifting rating curves.

7.7.2 Methodology for Assessment of Safety Margins

Variations in water levels for a fixed discharge, due to shifts in rating curves caused by morphological processes, can likely be represented by a normal distribution with zero mean and a standard deviation in the order of 25 cm (20 to 30 cm; see Table 5.5 in section 5.3.2). For future annual flood peaks such variations must be considered to be fully statistically independent from the actual floods itself. Hence, its randomness adds up to the standard deviation of the probability distribution of annual maximum water levels, as determined on the basis of simulations with a "fixed bed" GM. In other words, if an infinitely large number of flood events is simulated with a "movable bed" model, a larger variance of the annual maximum flood level would be found than it would be the case if the same events are simulated with a "fixed bed" model, the difference being the variance due to morphological processes.

The updating of the GM is likely to produce a close match of the probability distributions of simulated and observed annual maximum water levels for all key-stations. Even then, a substantial random error in individually simulated extremes may occur, with a close to zero mean and a standard deviation in the order of 25 cm (section 7.5.1, Table 7.2). It is impossible to determine to what extent such errors are affected by the above discussed morphological phenomena, and to what extent they are due to other errors, e.g. modelling errors, errors in boundary conditions or errors in observed water levels. It is therefore recommended to take the random effects of morphological phenomena separately into account, in addition to the standard errors as derived from simulated and observed maximum water levels (Table 7.2). As a consequence, the total safety margin to be added to design water levels consists of:

- a margin to account for the effects of random morphological processes, as displayed through annual shifts in rating curves;
- a margin to account for possible errors in model calibration, boundary conditions and observed water levels;
- a margin to account for probable underestimation of extreme events due to the shortness of the available record of observations;
- freeboard to account for wind set-up, wave run-up and other safety requirements.

The latter component is left to the judgement of design engineers. The others are discussed in detail in Appendix 9, while the summary of the results are given in the following section.

7.7.3 Recommended Safety Margins

The total safety margin, accounting for the effects of random morphological processes, for model errors, and the likely underestimation of extreme events, due to the shortness of available records of observations, should be added. For the latter component a margin dH, based on the difference between expected probability and exceedence probability (discussed in Appendix 9), is used.

The results are summarized in Table 7.7. The recommended total safety margins are denoted dHmax. In view of the representativeness of the last 25 years for the long term and the slight overestimation of the margin dXp (see Appendix 9), some reduction of the sum of dXp and dH has been applied.

The parameters in Table 7.7 are:

P : probability of non-exceedance
T : return period
dXp: safety margin to account for modelling errors and variations due to morphological changes
dH : Safety margin due to shortness of record

Table 7.7: Recommended Total Safety Margins (dHmax) for Different Return Periods.

P	T	dXp	dH	sum	dHmax
0.99	100	0.28	0.21	0.49	0.40
0.98	50	0.25	0.17	0.42	0.35
0.95	20	0.20	0.08	0.28	0.25
0.90	10	0.15	0.04	0.19	0.20

As stated above, the safety margin dHmax has to be considered within the overall safety requirements including freeboard.

It is recommended that FPCO takes a decision on this issue at short notice, considering the importance of a unified approach in all FAPs for the assessment of design criteria.

7.8 Long Term Morphological Developments.

The impacts of random morphological processes on design water levels has been discussed in the preceding section. Another issue is the effect on design levels of ongoing non random sedimentation or erosion processes in certain areas, as observed e.g. in part of the Old Brahmaputra. Such processes do not show random behaviour, but instead create a tendency of increasing or decreasing water levels or discharges. The question has been raised whether such processes require the GM or regional models to be run with inclusion of a sediment module, to simulate the concerned morphological

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processes.

It is relevant to recall that the 'fixed bed' GM represents a certain condition of the physical system. Probability distributions of simulated annual maximum water levels, derived with a specific version of the GM under the assumption that historical boundary flows and rainfalls may occur in a similar sequence in the future, are only valid for the instant in time represented by that particular version of the model. Hence, when a continuous sedimentation in certain parts of the system is expected, one should for example estimate the total sedimentation for the next 25 years and change the model schematization accordingly. The model is then representative for the situation in 2015. Each and every historical flood may appear again in the year 2015 with its own probability of occurence and be exposed to the effects of that particular sedimentation. Results of simulations with the adjusted model, for all available historical hydrological conditions, can thus be used to estimate the 100 years annual maximum water level for 2015.

Inclusion of an ongoing sedimentation process in the simulations would be erroneous. The simulated annual maximum levels would then no longer belong to the same parent distribution, each annual maximum being affected by a different quantity of non-random sedimentation.

Obviously one may need model simulations with a hydrodynamic model, including a sediment transport module, to estimate the likely total sedimentation over a period of 25 years, using for example the quasi-steady state solution of MIKE 11.

7.9 Supply of Results to Others FAPs

The data provided to other FAP projects are water level and discharge time series at selected points in the model. The location of these points have been specified by the individual FAPs and are shown in Appendix 10.

Though the supplied hydrographs represent best estimates of the historical hydrographs and are statistically representative for the long term, it should be recalled that the "fixed bed" modelling approach in combination with error sources mentioned in section 7.5.1, result in deviations from the historic hydrographs.

When the historic hydrographs are used to derive design conditions at the locations of the supplied time series these deviations are taken into account by adding the safety margin proposed in section 7.7. When the historic hydrographs are used as boundary conditions for 25-year simulations with the regional models the hydrographs shall be used directly, as best estimate of historic hydrographs, to simulate hydrographs within the region. Design conditions within the region are derived from the latter hydrographs and suitable safety margins should be added following the methodology used in the FHS.

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7.10 Effects of Country-wide Flood Protection Schemes

The implementation of major flood protection schemes in the delta is likely to change discharge distribution in the main river system, and may hence affect the probability distribution of design variables at specific locations.

Probability distributions will change each time the system is modified. Protection levels of completed projects will alter when new projects are progressivelly implemented. As a consequence, a final future situation of the system, valid for the lifetime of the projects, should be considered for design, unless a phased implementation is adopted for the projects. As projects are still vague and roughly defined, the ultimate future flood protection scenario is, however, not yet known in details.

For the present stage of the FHS it has been decided to analyse the effects of an embankment along the left bank of the Jamuna as represented on the map of Figure 7.5. The shown alignment corresponds to the most likely alignment presently being considered by FAP 3. The embankment runs from the offtake of the Old Brahmaputra down to the Dhaleswari offtake. Thereafter, it follows the left banks of Dhaleswari and Kaliganga till the Kaliganga-Dhaleswari junction at Kalatia. The right embankment of Jamuna is already included in the existing situation. Simulations have been carried out for the period 1985-89 only.

Appendix 11 shows hydrographs for the "without" and "with" project at various locations in the sÿstem. Maximum water level profiles (envelopes of the peak water levels) have been plotted on Figures 7.6 a), b) and c) along three main axis, respectively:

- Jamuna - Dhaleswari - Lower Meghna;
- Jamuna - Padma - Lower Meghna;
- Ganges - Padma - Lower Meghna;

It can be seen that the main increase in water level is observed along the Dhaleswari and the Jamuna itself. This increase is mainly explained by the increase in the discharge due to the closure of the Jamuna left bank spillage channels. The increase reaches 1.3 m in the Dhaleswari located downstream of the embankment and 0.54 m at Serajganj. At Bahadurabad, the increase is only 0.07 m, although the rating curve at this location is directly under the influence of the embankment. In the Padma, the increase is around 0.20 m and at Chandpur in the lower Meghna it is only 0.05 m. It is stressed that the analyses do not consider possible effects on water levels due to morphological changes caused by the scheme and the results may thus be different from the the recent China-Bangladesh study and other studies where morphology has been included. To the extent that design life of the structure is much shorter than the time scale of long term morphological changes this simplification may be acceptable for deriving design water levels.

It can be observed on the hydrograph plots in Appendix 11 that even during the dry season the proposed embankment results in increased water levels in the Jamuna (in the order of 10-20 cm). This is explained by the cutting off of the four spillage channels to the Jamuna left bank flood plains. In the non-embanked situation in the dry season, the FAP 25-GM simulates flow of approximately 400 m3/s in these channels. These flows, which still need to be verified through field observations, are transferred to Jamuna in the embanked situation.

It is of interest to note that the main cause of changes in water levels throughout the system is the change in the distribution of discharges in its branches, thus supporting the overall methodology of the FHS, which is the only one capable of taking into account the changes in the statistical distribution of water levels in the system along with the changes in flow distribution. The changes in the Jamuna rating curves, see Figure 7.7, which is responsible for the water level increase at Bahadurabad, and the reduction of flood plains, which explains the increase at Chandpur, are also significant causes of water level changes.

A more comprehensive analysis of 7 alternative flood protection schemes will be carried out in stage 3 of the Flood Hydrology Study and reported in August 1992 as **Annex 2** to the present report. The simulation programme is described in Chapter 9. Morphology will still not be considered but comparison with other studies will be done.

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8. METHODOLOGIES FOR REGIONAL FAP STUDIES

8.1 Methodology for Estimating Design Water Levels at Regional Level

Chapter 2 provides the rationale for the adopted methodology for estimating design water levels for the main rivers in Bangladesh. The same reasoning applies for the regions and the regional FAPs and other FAPs should follow a similar approach. Due to the complexity of the Bangladeshi Delta and the interaction of the various flood causing factors, the definition of design events of a given return period in terms of standardized boundary conditions is simply impossible. Hence, long term simulations with the regional models for the same period as used in the FHS is strongly advocated, requiring:

- the development of dedicated versions of the regional models, allowing larger time steps to be used and enhancing the feasibility of this approach;

- the preparation of boundary conditions required to run such dedicated regional models for the period 1965-1989;

- running of the models for the full 25 years period, at least once for the present (baseline) conditions and once for the ultimately adopted regional flood alleviation scheme(s). Combination of various options to reach the final plan may be studied on the basis of simulations for only a few selected flood seasons;

- sensitivity analysis of ultimately adopted regional scheme considering changed boundary conditions in the major rivers due to proposed shemes outside the region;

- statistical analysis of the results, aimed at assigning return periods to historical peak, seasonal or sub-seasonal values of selected design variables.

In view of the large effort involved in running the regional models for a period of 25 years, such activity should only be undertaken once the development and calibration of these models have resulted in an acceptable degree of accurracy.

Run times of the models should not be prohibitive for adopting this methodologies, since with some simplifications of the regional models, it should be possible to run them with time steps of 2 hours, the same as used for the GM in the FHS. The creation of sufficient boundary conditions for the full simulation period may occasionally create a problem. Obviously, the situation is area-specific in this respect.

Whatever the precise situation is, a fair effort should be done by the regional study teams to implement this crucial component of the methodology of the FHS, possibly with some assistance from FAP 25 and SWMC in modifications of the models, as recommended in the report of the third CAT mission, Ref.18.

In the planning and conceptual design stage the main aim of using the regional model will be to assess the hydraulic efficiency of alternative flood protection schemes or components. For this purpose it will be quite sufficient to run the regional model only for some 3 historical flood seasons, for example 1987, 1988 and another year. The need to follow a practical approach in this is evident.

The role of FAP 25 vis à vis the regional studies is to provide:

- 25-year (1965-89) boundary conditions for the regional models for the present situation and for possible alternative future protection schemes, see section 7.9 and 7.10 and summarized in section 8.2;

- 5-year (1985-89) boundary conditions for a number of alternative future country-wide protection schemes, see section 7.10 and Annex 2 and summarized in section 8.2;

- guidelines for selection of probability distributions for various hydrological variables, see section 6.1 and 6.2 and summarized in section 8.3;

- guidelines for review and correction of regional data, which have not been processed under FAP 25, see section 8.4;

- recommendations on design water levels and discharges in the major rivers and Old Brahmaputra, see section 7.6;

- guidelines for determination of safety margins for design along regional rivers, see section 7.7 and summarized in section 8.5;

- guidelines for development of straightforward design events for situations where local flooding is only caused by local events, in particular rainfall, see section 8.6;

- guidelines for taking into account the effects of possible long term morphological developments on design water lecels, see section 7.8.

8.2 Boundary Conditions

Water levels and discharges at all computational points of the FAP 25 GM may be produced for the available period of 24 years. As the computational points have been chosen to match regional model boundary points, with the exception of some minor inputs, regional consultants can be provided with boundary conditions corresponding to the present and possible future situations.

It is recommended that the results from the existing situation (run 6 of the FAP 25-GM) are used by all the regional FAPs as the basic boundary conditions for the "future without" and "future with" project analysis on a regional level. By doing so, it will allow determination of the real benefits of a proposed scheme(A) within the region, the results not being distorted by changed hydrological conditions due to a proposed scheme(B) outside the region. Additional sensitivity analysis may be undertaken for the final, preferred development scheme with external water levels taken from the 5-year simulations done under stage 3 of the FHS for alternative country-wide protection schemes.

Only a limited number of rainfall stations has been considered in the GM and regional studies may need to use a denser network of rainfall stations. In that event data should be selected and reviewed in line with the methods used in the present study.

8.3 Frequency Analysis

A systematic analysis of suitable probability distribution functions for frequency analysis of hydrological variables in Bangladesh has been carried out. The following recommendations are valid for situations exhibiting the same statistical behaviour as the main river system:

- the log-normal distribution is appropriate for the analysis of annual, seasonal and sub-seasonal rainfall data; the FHS has not studied the most appropriate distribution for short term rainfall data (hourly or daily);

- the 3-parameter log-normal distribution is appropriate for the analysis of the following hydrological parameters:

    * annual maximum water levels

    * average annual, seasonal and sub-seasonal discharges (flood volumes)

- the 3-parameter GEV-2 or the 2-parameter Gumbel distribution are appropriate for the analysis of annual extreme discharges. The GEV-3 distribution may be considered, but it should be noted that this member of the GEV-family has an upper threshold, which may not be very realistic for the considered parameter.

It is stressed that the above recommendations should not be applied rigidly, without precaution. Probability analysis is too much a matter of judgment to justify application of such recommendations as if they would represent the only truth. Therefore, these recommendations are no more and no less than guidelines.

In some cases, in particular when local conditions induce a particular statistical behaviour other than observed in the main river system of Bangladesh, it may be necessary to repeat the full analysis for the selection of appropriate distributions for some key-stations in an area, along the same lines as described in Chapter 6.

It is further stressed that parameter estimation methods based on the first two or three moments should never be used under the prevailing conditions, given that generally only short records of observed or simulated events will be available. In such situations these events may induce a considerable bias in the derived design conditions. Instead, methods identical to, or of similar quality as those used in the FHS are recommended, viz.:

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- Maximum likelihood methods (in some cases a slight modification is necessary);

- probability weighted moment methods, or

- other methods of proven similar quality.

Minor differences between the results of various estimation methods are of no significance, in particular in view of the errors embedded in observations and model results and of the statistical uncertainty related to the generally short records of observations (confidence intervals).

For FHS (modified) maximum likelihood methods have been used, as embedded in the HYMOS system.

8.4 Data Review

Rainfall data need to be reviewed and screened in line with the analyses described in section 5.1 and should include also a graphical check, a check on outliers and temporal and spatial homogeneity tests.

Section 5.2 lists possible sources of error in water level observations. Some of these errors could be corrected for the stations along the main rivers through simple visual inspection and correlation techniques. Regional consultants must do the same for secondary stations.

The review of upstream boundary discharges for the GM could be restricted to the Jamuna and the Ganges. Rating curves were developed for each year to provide the best possible estimates of daily discharges. This effort appeared to improve the validation of the GM substantially. Regional consultants may need to do the same for upstream boundary stations on secondary rivers in their regional models.

For each year mean annual rating curve equations may have to be derived from the available rating measurements by fitting a two or three step power function or parabolic equation. Relevant water level observations have to be screened and validated and it is recommended to recompute daily discharge from daily water levels, using mean annual rating curves. Shift correction may or may not be applied depending on an assessment of reliability of discharge measurements. Shifts from one year to the next are taken into account by using annual rating curves.

8.5 Safety Margins for Design Water Levels

Section 7.7 provides a methodology for assessing safety margins for design levels, accounting for the effects of random morphological processes, modelling and observation errors, and statistical uncertainties. The regional studies may apply the methodology in a systematic way as follows:

a. determine standard deviations of shifts in rating curves at various locations, to quantify the effects of random morphological processes on design levels;

b. determine standard deviations of errors in computed maximum water levels due to modelling errors (in a broad sense) and observation errors for various locations, based on 25 years of simulation with the regional model, eventually after eliminations of long term trends in errors as caused by morphological changes etc.;

c. calculate the combined standard deviation for the errors mentioned under a. and b. above;

d. determine the standard deviation of annual maximum water levels, and the scale parameters B of the associated Gumbel distribution for various locations;

e. combine the results under c. and d. to arrive at the safety margin to be adopted for modelling errors and random morphological processes for various return periods (see Appendix 9);

f. estimate the additional safety margin to account for the difference between the expected and 'true' probabilities of the occurrence of design floods for various return periods;

g. determine the total safety margin dHmax for various return periods and locations to be added to design water levels as determined on the basis of the 'fixed bed' regional model;

8.6 Joint Probabilities

In Chapter 6 it is concluded that there is no need to consider the issue of joint probabilities of various flood causing factors at the regional and national scale of Bangladesh. Nevertheless, at a local level, where water level may only depend on local rainfall and flash floods generated in relatively small nearby catchments, a correlation between flood causing processes may exist. In such event, a joint probability analysis on the basis of simple correlations as described in Section 6.2 may be useful. Such analysis may result in the definition of straightforward design events, which may eliminate the need for lengthy, 1965-89, simulation runs for some areas.

8.7 The Effects of Long Term Morphological Developments on Design Water Levels

The methodology to cope with the effects of possible long term morphological developments in certain rivers has been discussed in section 7.8, to which is referred for briefness.

9. EXECUTION OF STAGE 3 OF THE FLOOD HYDROLOGY STUDY

As specified in the introduction, Chapter 1, the third stage of the FHS is running from February until end of July, 1992. The original scope of stage 3 was supposed to be limited to the analyses of alternative country-wide flood protection schemes. However, based on the findings in stage 2 of the FHS, including the identified need of recalibration of the GM, stage 3 has also include the final validation of the GM for the existing situation based on run 6 with the FAP 25-GM.

The tasks in stage 3 of the FHS may thus be summarized as follows:

Task 1: Updating/Recalibration of the GM

This task was undertaken by the SWMC. It was delayed for various reasons and finalized only in mid March, 1992. The updating/recalibration was done considering the findings and recommendations of FAP 1 and FAP 25.

Task 2: Run 6 with FAP 25-GM

Run 6 with the FAP 25-GM was carried out in late March, 1992. The output of this run is, as previously mentioned, the basis for all the analyses included in Chapter 7 of the present final Main Report.

Task 3: Analysis of Alternative Country-wide Protection Schemes with FAP 25-GM

In cooperation with the relevant FAPs, notably FAP 1-6, likely elements in a country-wide flood protection scheme for Bangladesh have been identified. On that basis a programme has been prepared and approved by FPCO, for analyses of hydrological effects of alternative combination of flood protection schemes using the FAP 25-GM. The run programme appears from Table 9.1.

The purpose of these analyses is to study inter-regional (upstream/downstream) consequences of major flood protection options including effects on hydrological design criteria. It is stressed that the analyses will only consider the hydrological effects (water levels and flow distributions) in the main river system as represented in the GM. Morphological consequences, however important they may be, are not considered.

The alternative combinations of flood protection schemes will be analysed for selected years only, while the most likely ultimate configuration will be simulated for the full 25-year period. Frequency analysis will be carried out on peak water levels and on peak annual, seasonal and subseasonal discharges at all selected stations.

Table 9.1: Simulation Programme for Stage 3 of the FHS

FAPs	OPTIONS	SCENARIOS								
		1	2	3	4	5	6	7	8	9
FAP1	Brahmaputra RE, present alignment	x	x	x	x	x	x	x	x	
	Brahmaputra RE, 2 km setback									
	Brahmaputra RE, 4 km setback									
FAP2	"Green River" in Lower Atrai		x	x	x	x	x	x	x	
	Ganges LE		x	x	x	x	x	x	x	
FAP3 & FAP3.1	Jamuna LE(N), West of Chatal		x	x	x	x	x	x	x	
	Jamuna LE(N), East of Chatal									
	Jamuna LE(S), Western alignment					x	x		x	
	Jamuna LE(S), Eastern alignment									
	Dhaleswari LE, to Kalatia		x	x	x	x	x	x	x	
	Dhaleswari LE, D/S Kalatia					x	x		x	
	Compartments							x		
	Padma LE					x				
	Dhaleswari RE					x				
	Old Brahmaputra, RE + LE					x	x		x	
FAP4	Ganges RE				x	x	x		x	
	Gorai Headworks				x	x	x		x	
	Padma RE					x				
FAP5	Lower Meghna LE	x	x	x	x	x	x	x	x	
FAP5B	Lower Meghna RE					x				
FAP6	Upper Meghna LE					x	x			
	Upper Meghna RE					x				
	Upper Meghna, Dredging									
	U/S confinement									
MISC.	Jamuna Bridge			x		x	x		x	
	Sea Level Rise					x				

Legend : R=Right, L=Left, E=Embankment

Notes : Scenario 1 : 1965-89, Scenario 2-8 : 1985-89

Scenario 9 : 1965-89 for one the scenarios 2-8 (to be decided later)

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Task 4: Supply of Results to Other FAPs

Boundary conditions for 25 years for the existing situation (run 6) have been supplied to regional and other FAPs as required. Results from the other runs will be supplied as and when they become available during the months of June and July, 1992.

Task 5: Advice to Regional FAPs on Application of Unified Methodologies

Throughout stage 3 of the FHS ad-hoc advice from FAP 25 will be provided to regional FAPs for implementation of the unified methodology proposed for regional studies, cf. Chapter 8.

Task 6: Reporting of Stage 3 of the FHS

The results from the analyses of alternative flood protection schemes will be reported in early August, 1992 as volume 3 (**Annex 2**) of the present Main report.

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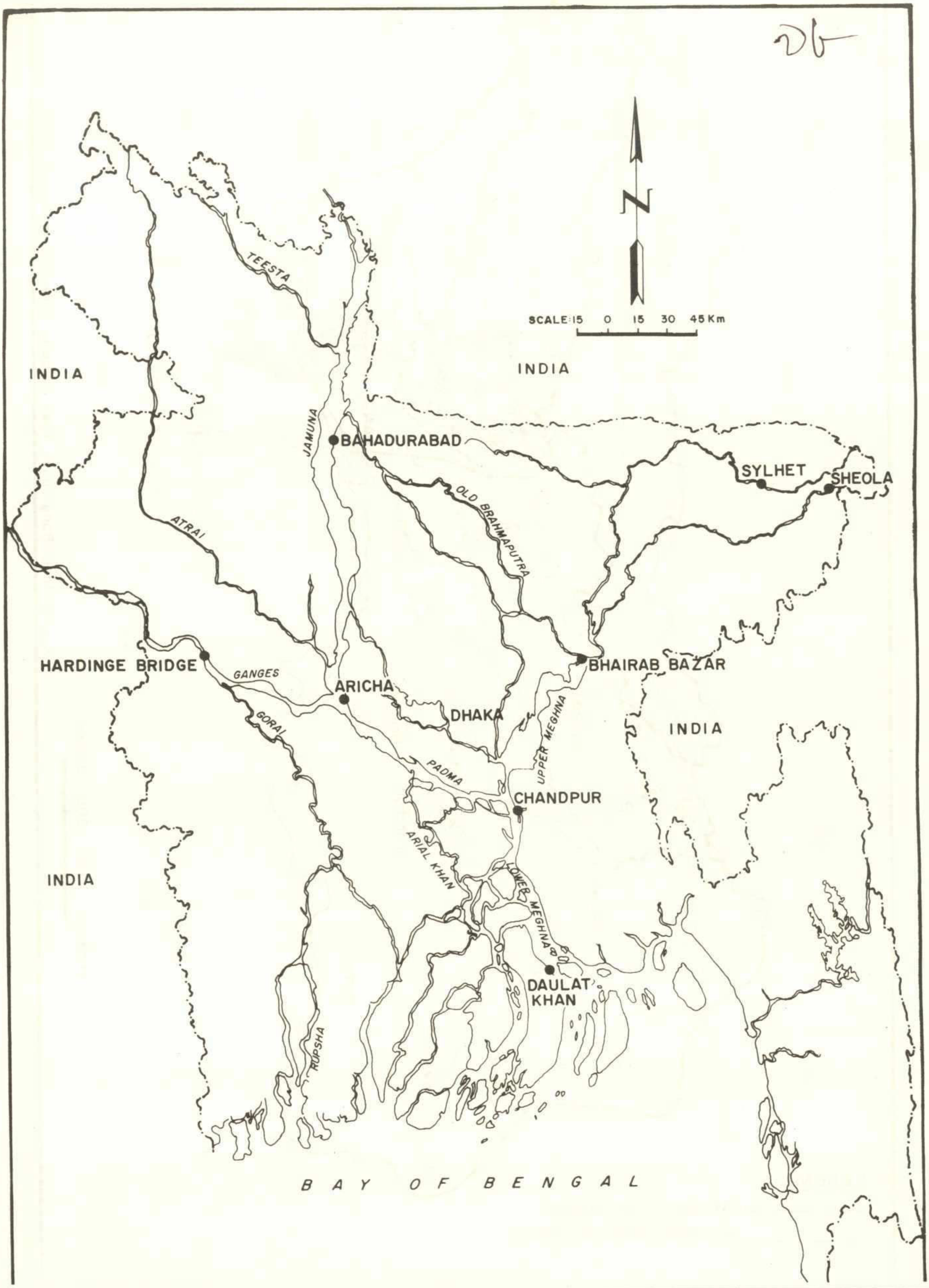
FIGURES



FAP25

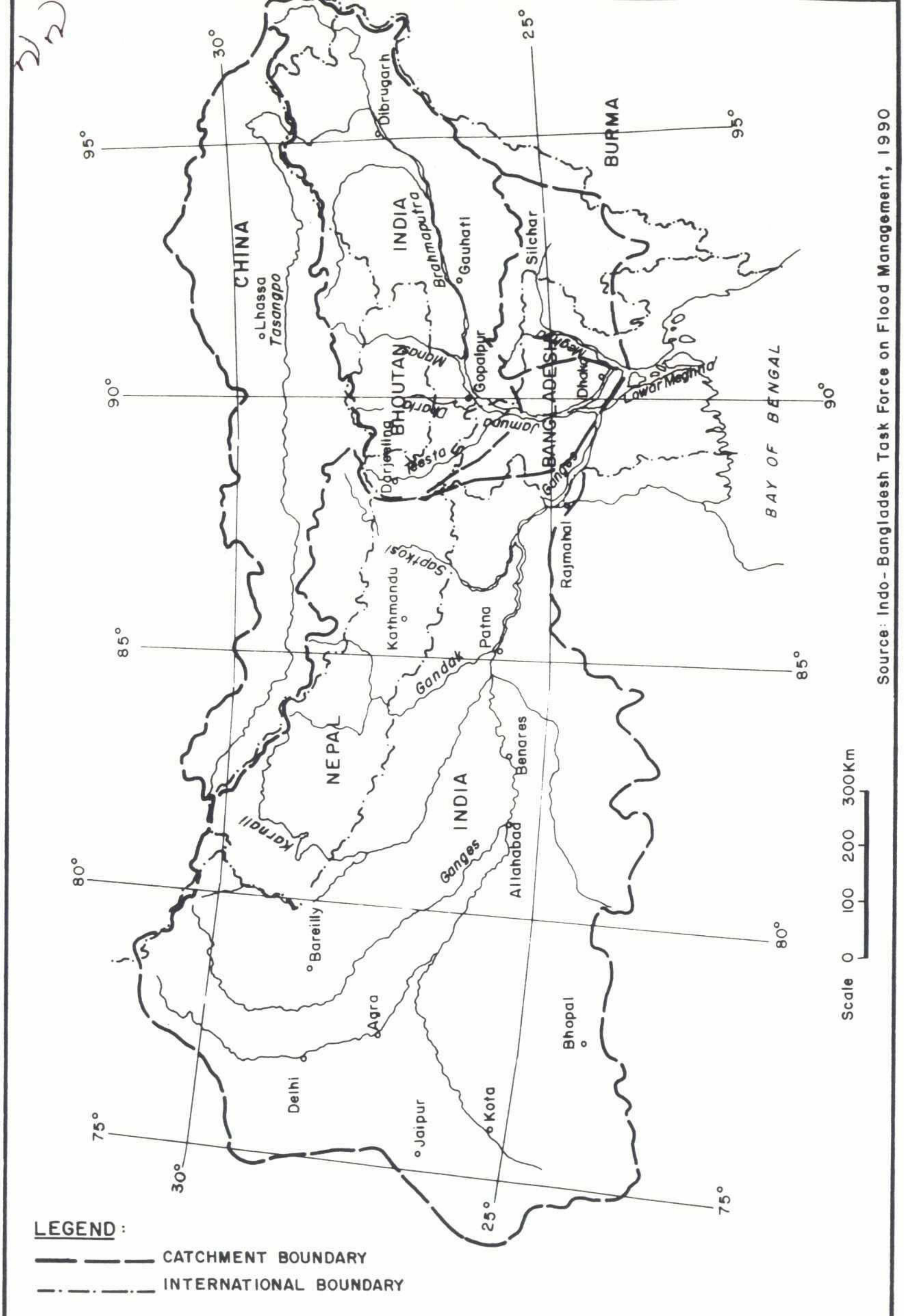
FLOOD MODELLING & MANAGEMENT

FLOOD HYDROLOGY STUDY

Bangladesh Base Map

JUNE 1992

FIGURE 3.1



FAP25 FLOOD MODELLING & MANAGEMENT	FLOOD HYDROLOGY STUDY	
	Total Catchment	
	JUNE 1992	FIGURE 3.2

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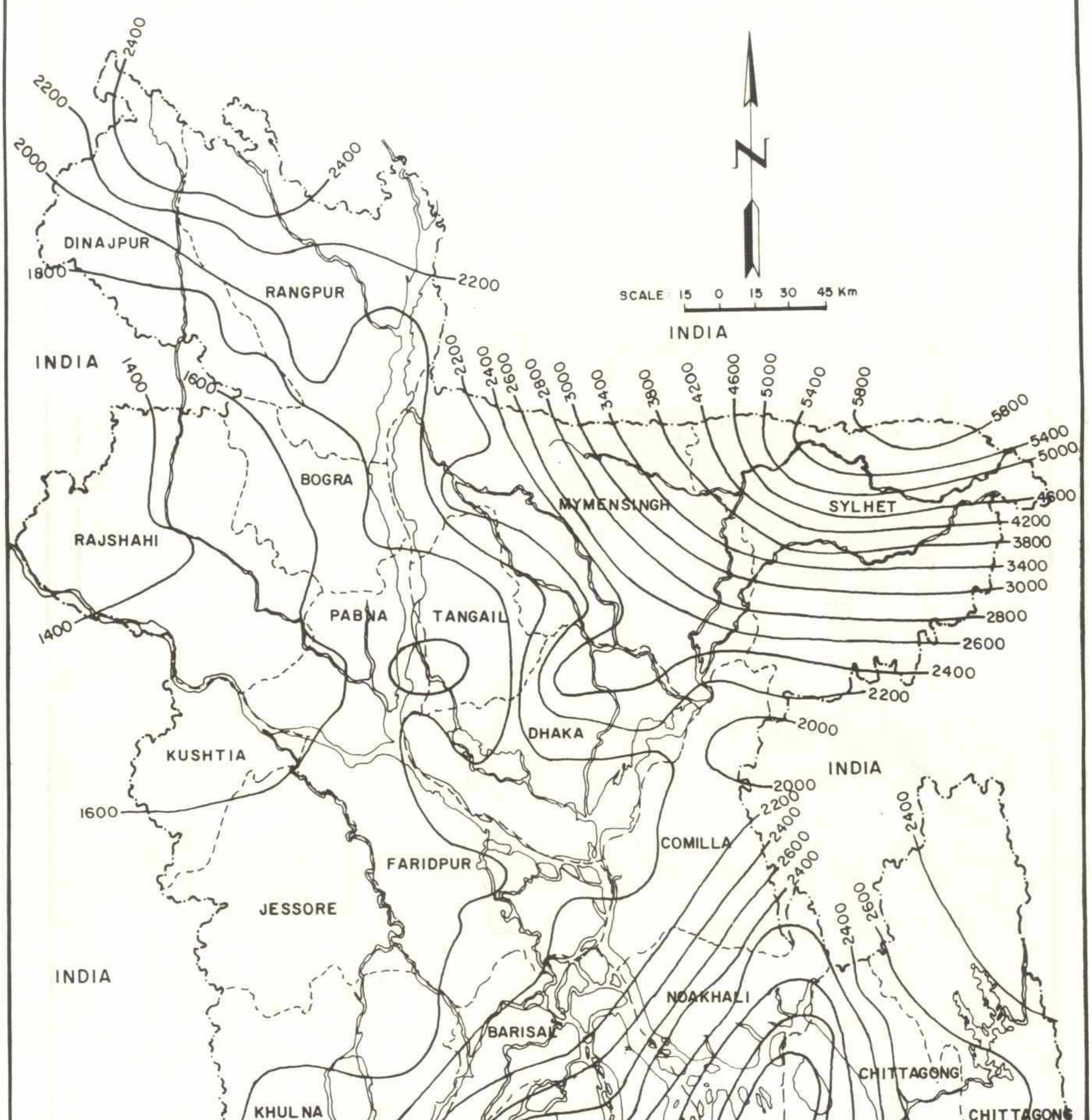
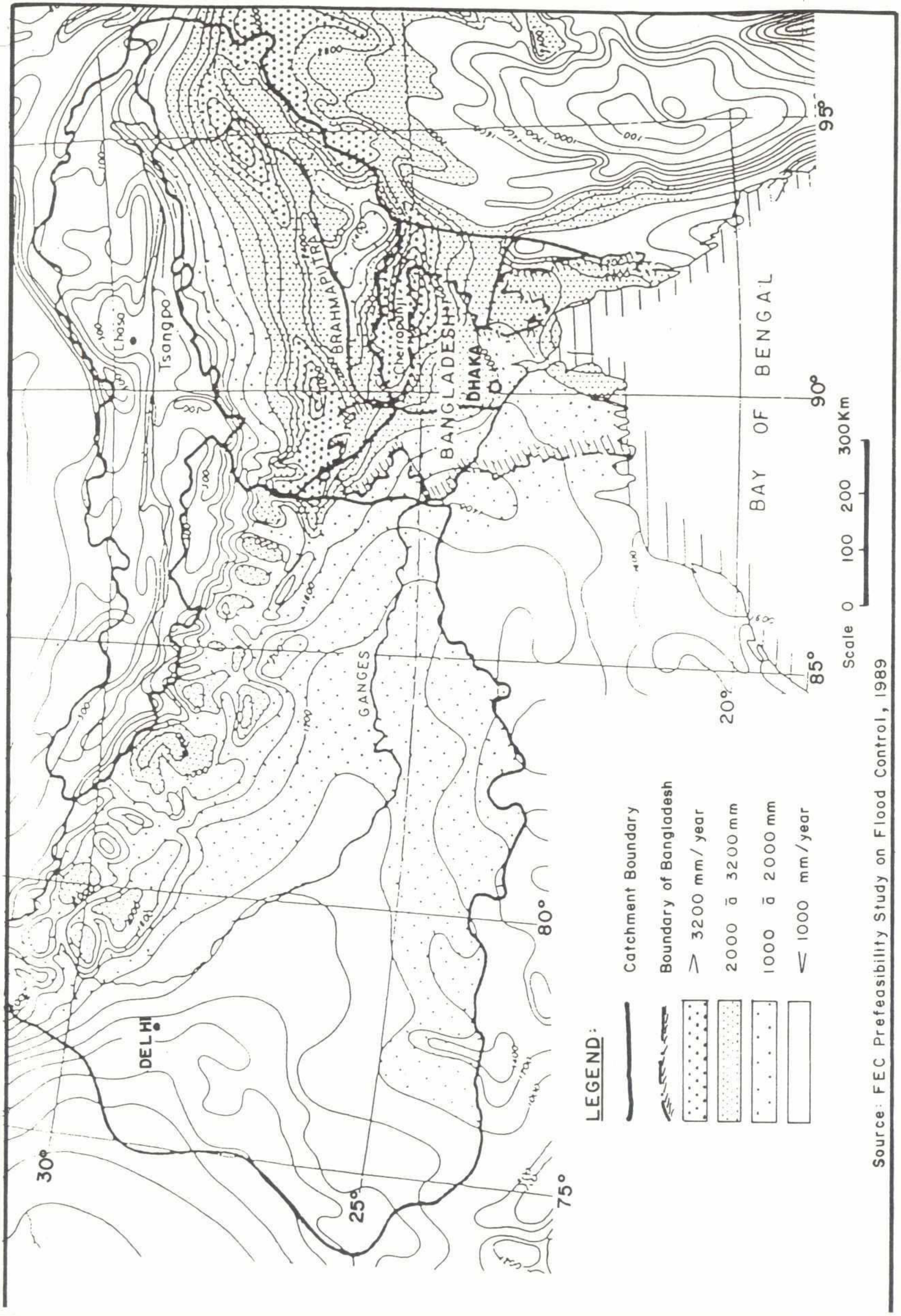


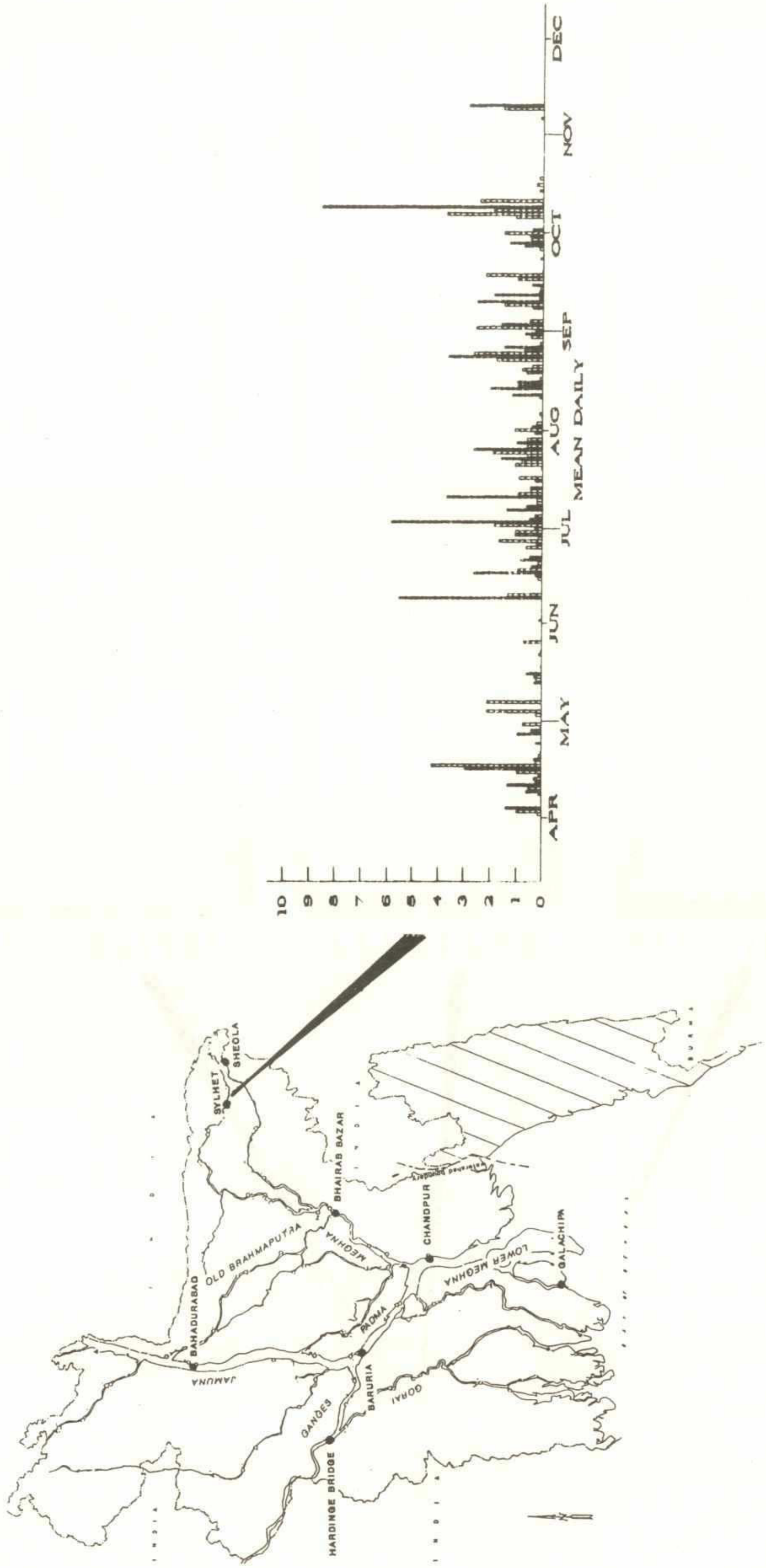
SOURCE: AGRO-CLIMATIC SURVEY OF BANGLADESH, 1976 (BY MANALO)

FAP25 FLOOD MODELLING & MANAGEMENT	FLOOD HYDROLOGY STUDY	
	Mean Annual Rainfall(mm) in Bangladesh	
	JUNE 1992	FIGURE 3.3



Source: FEC Prefeasibility Study on Flood Control, 1989

FAP25 FLOOD MODELLING & MANAGEMENT	FLOOD HYDROLOGY STUDY	
	Mean Annual Rainfall(mm) in the Catchment	
	JUNE 1992	FIGURE 3.4



FAP25 FLOOD MODELLING & MANAGEMENT	FLOOD HYDROLOGY STUDY	
	Daily Rainfall(mm) at Sylhet in 1986	
	JUNE 1992	FIGURE 3.5

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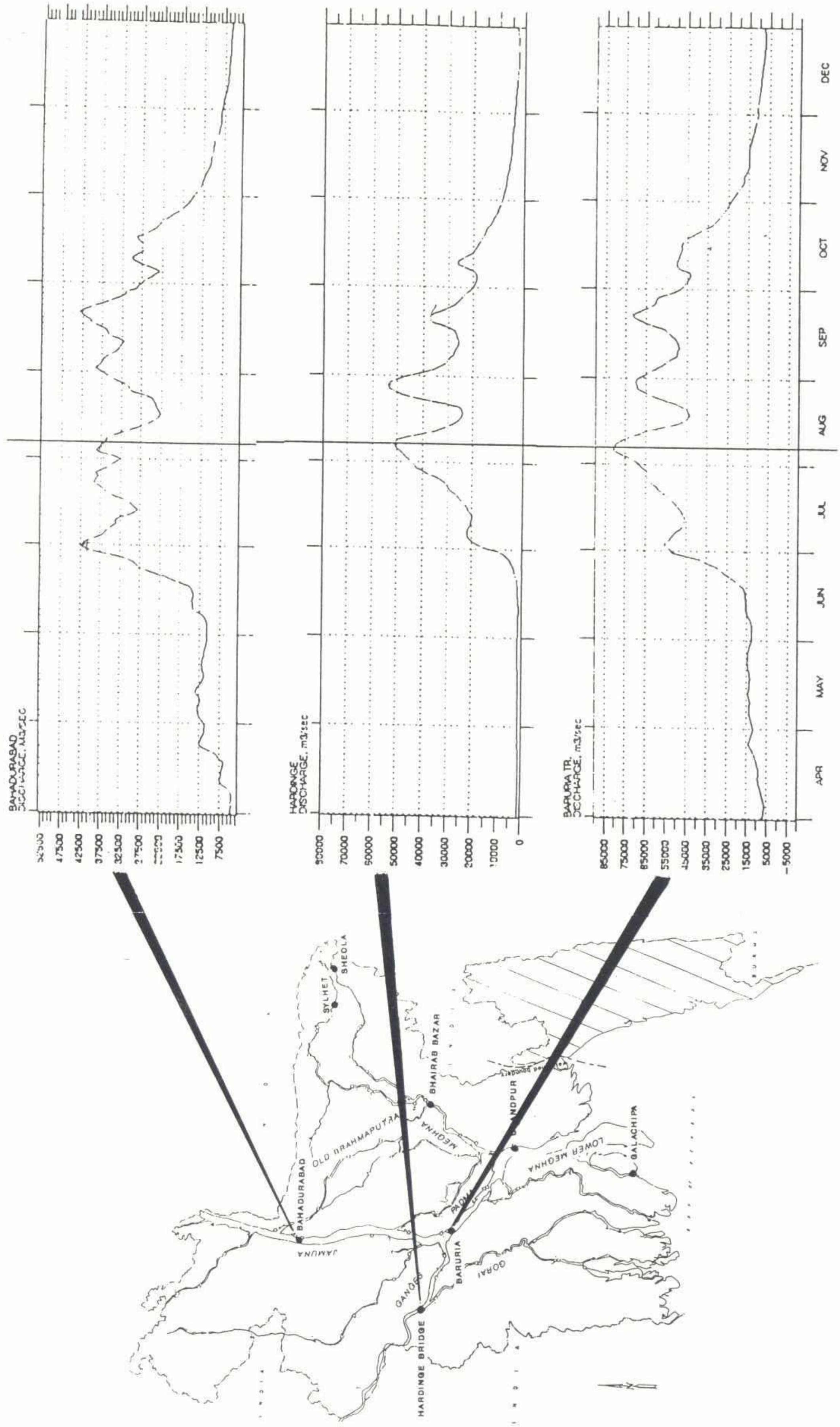

FAP25 FLOOD MODELLING & MANAGEMENT	**FLOOD HYDROLOGY STUDY**	
	1986 Discharge Hydrograph at Baruria, Hardinge Bridge and Bahadurabad	
	JUNE 1992	FIGURE 3.6

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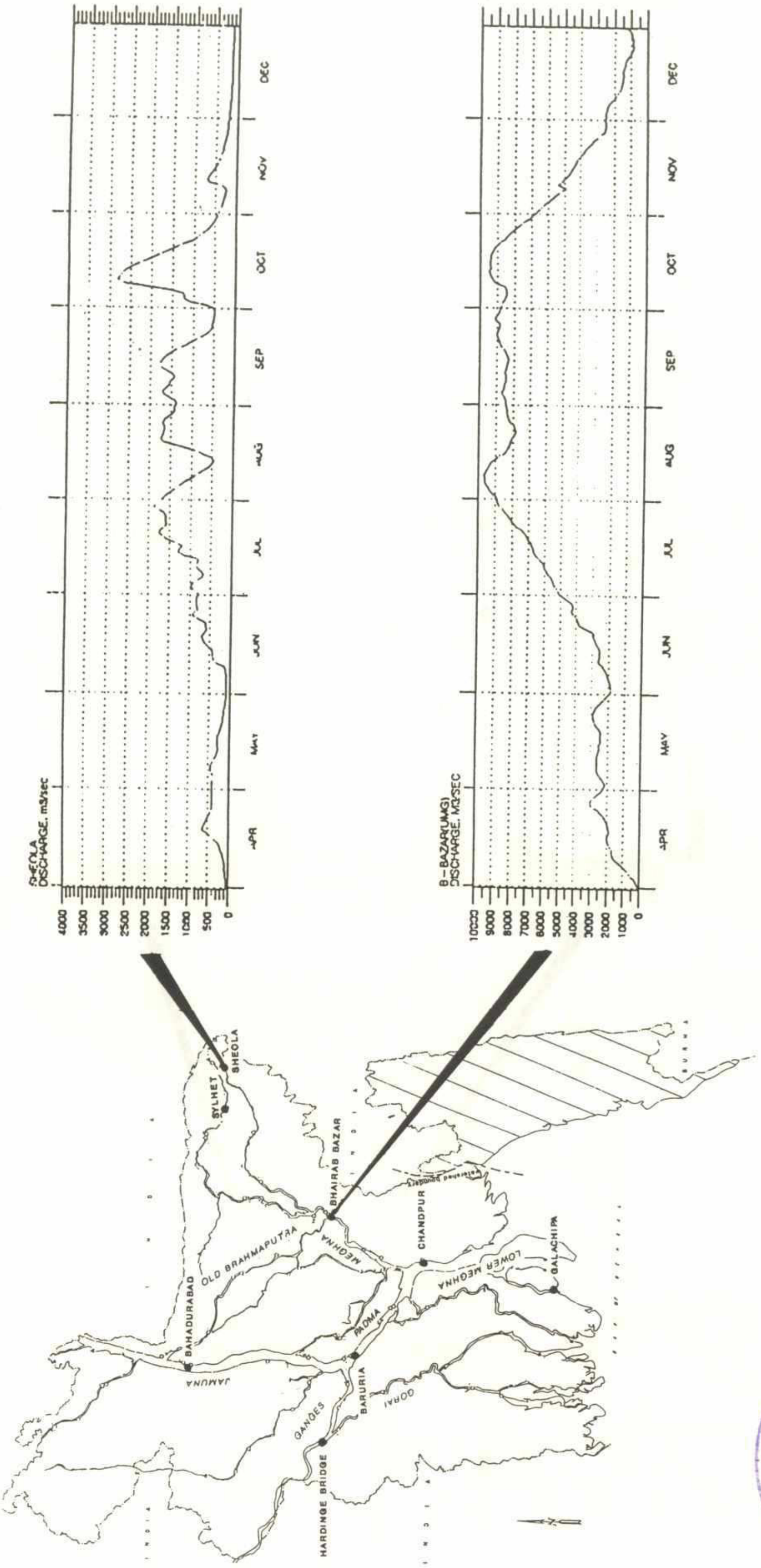
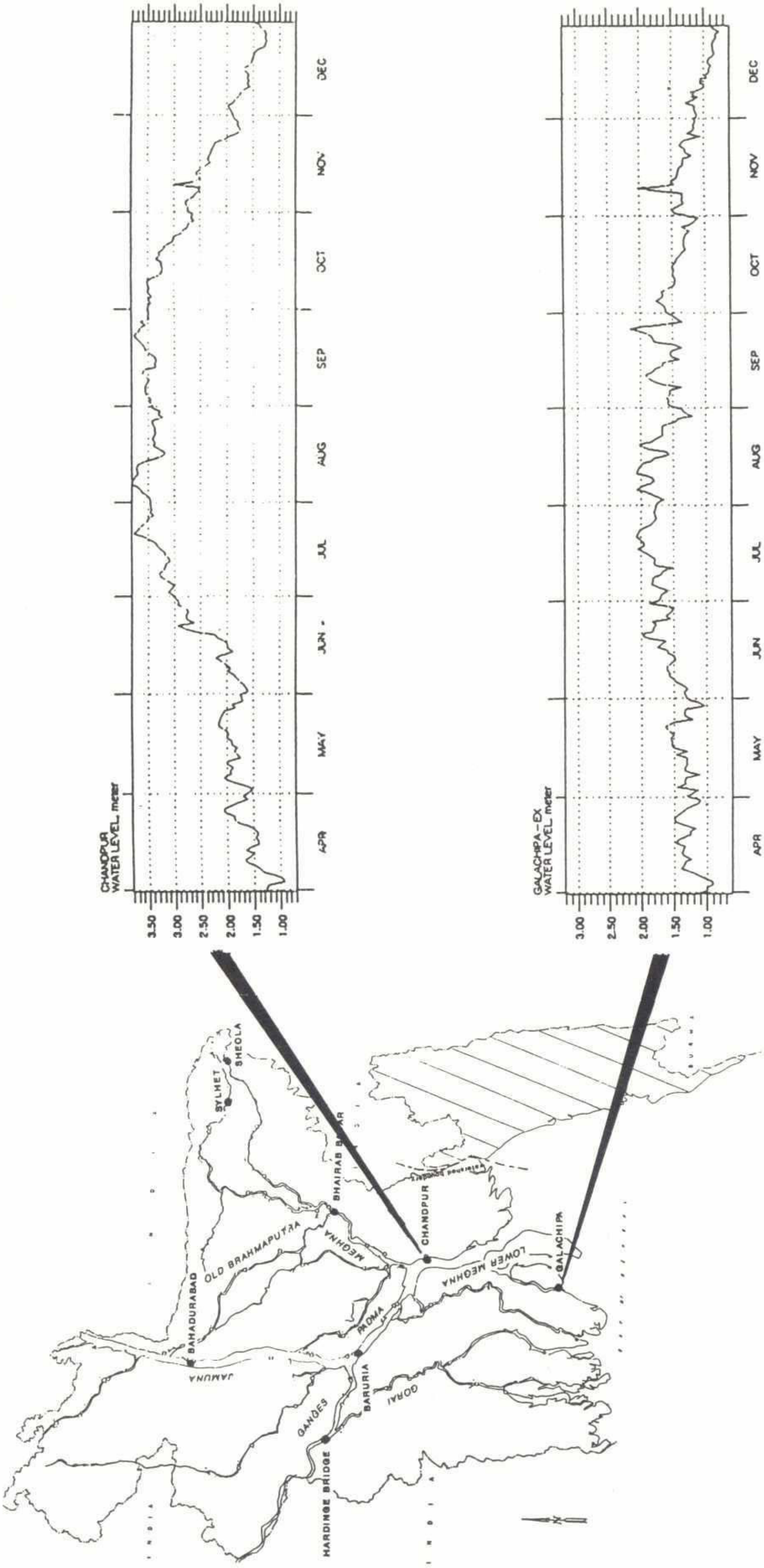
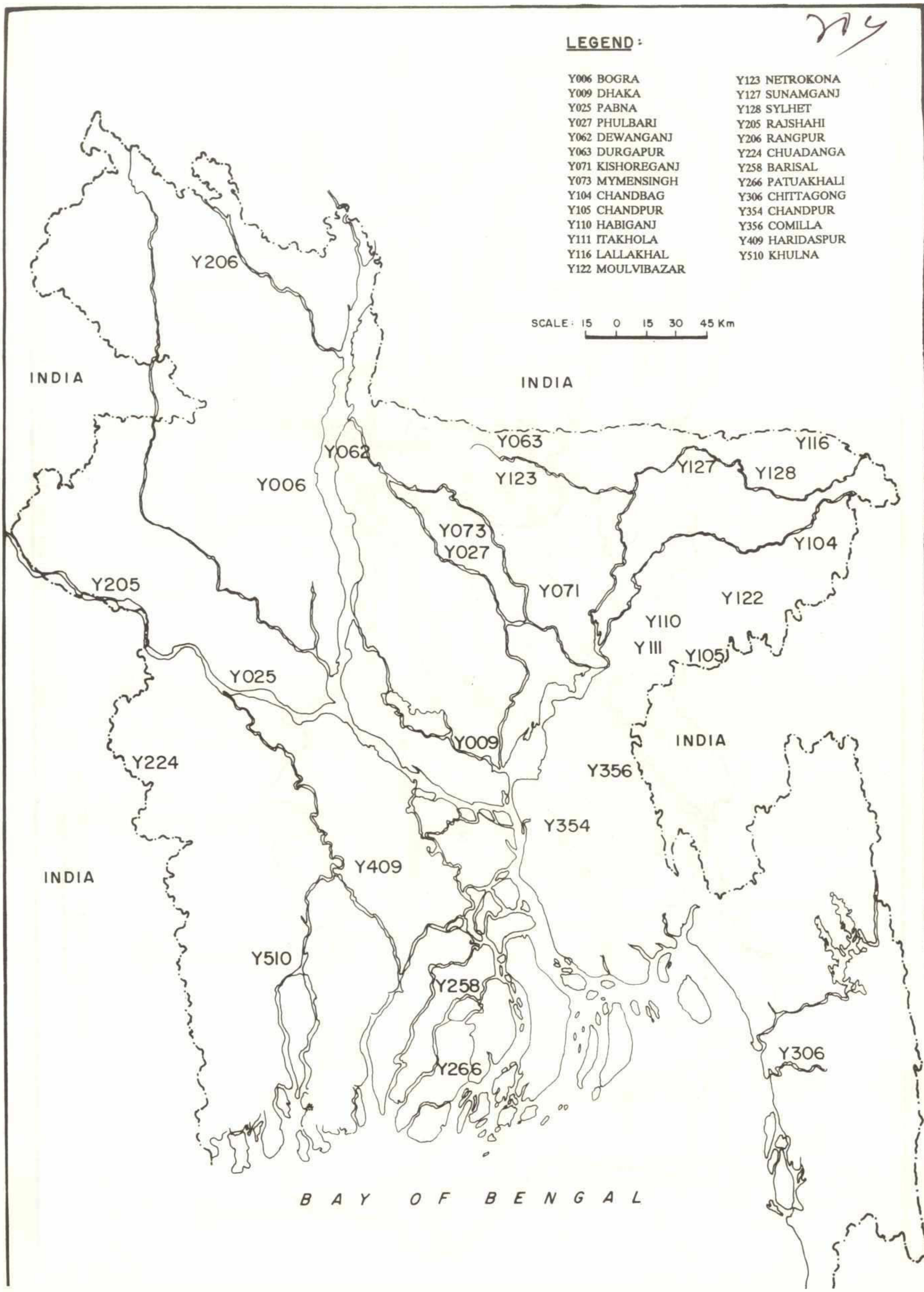


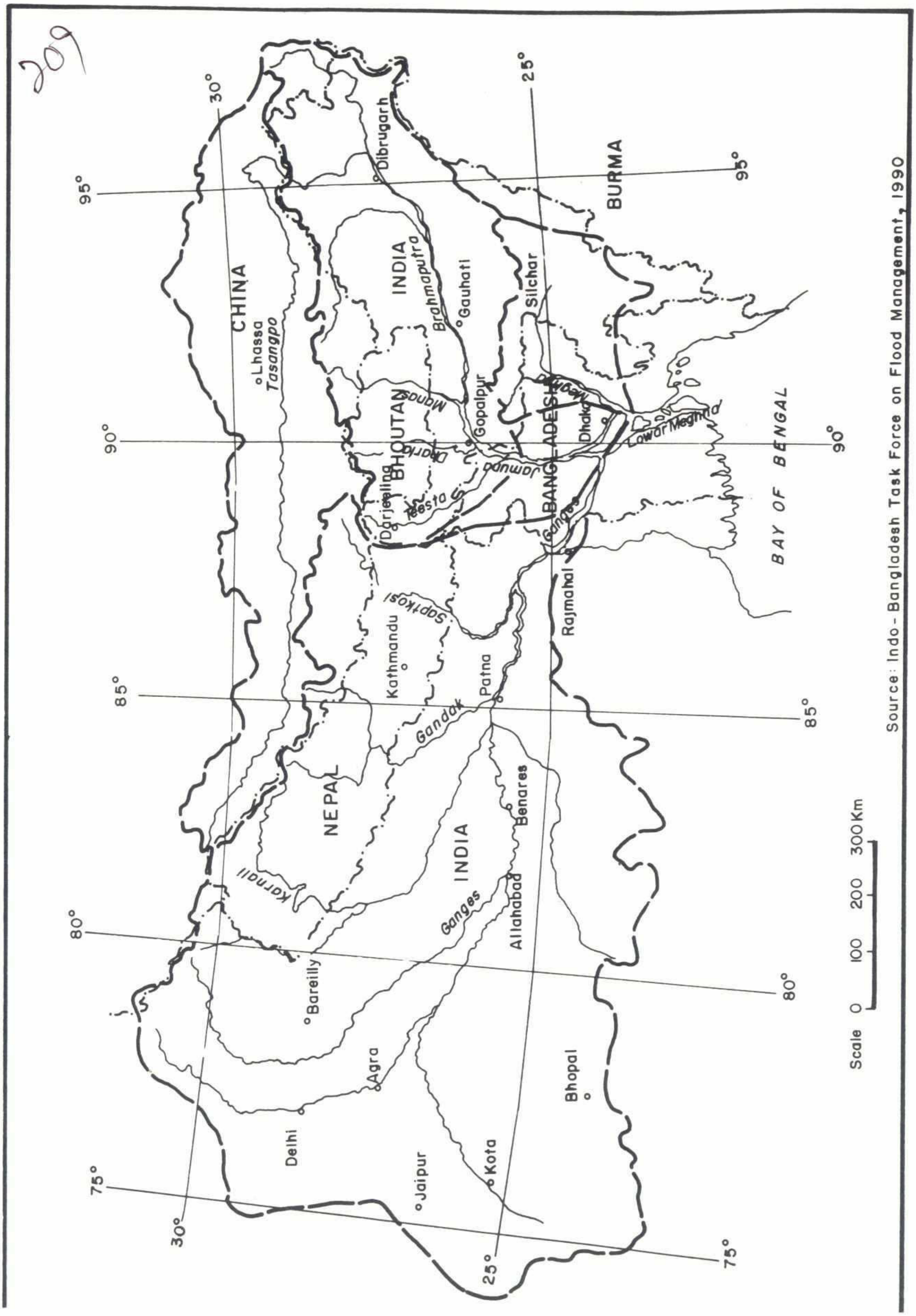
FAP 25 FLOOD MODELLING & MANAGEMENT	FLOOD HYDROLOGY STUDY 1986 Discharge Hydrograph at Sheola and Bhairab Bazar in the Meghna Catchment
	JUNE 1992 / FIGURE 3.7



FAP 25 FLOOD MODELLING & MANAGEMENT	FLOOD HYDROLOGY STUDY	
	1986 Water Level Hydrograph at Chandpur and Galachipa in the Lower Meghna	
	JUNE 1992	FIGURE 3.8



FAP 25 FLOOD MODELLING & MANAGEMENT	FLOOD HYDROLOGY STUDY
	Rainfall Stations in Bangladesh in the FHS
	JUNE 1992 — FIGURE 5.1



Source: Indo-Bangladesh Task Force on Flood Management, 1990

FAP25 FLOOD MODELLING & MANAGEMENT	**FLOOD HYDROLOGY STUDY**
	Rainfall Stations in India and Nepal used in the FHS
JUNE 1992	FIGURE 5.2

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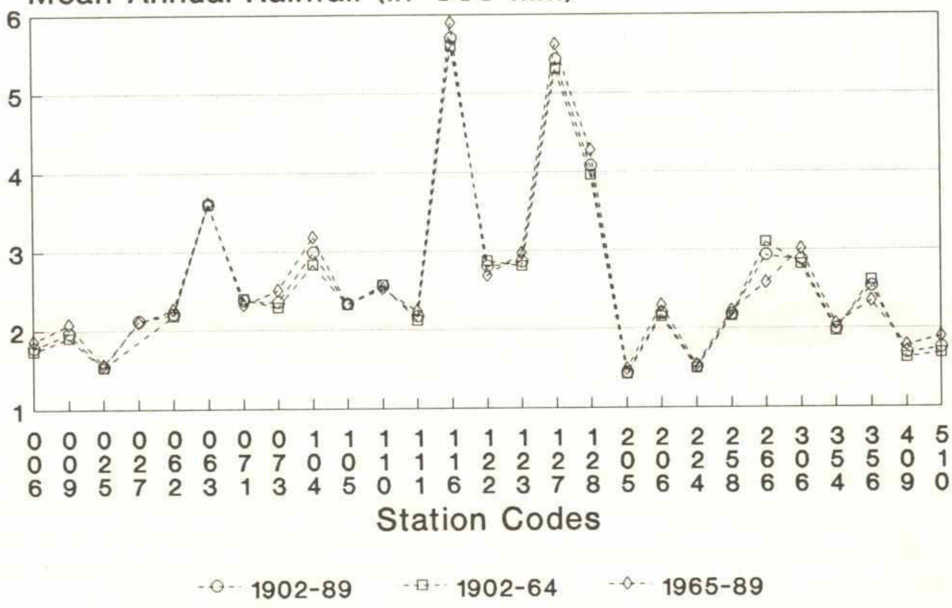
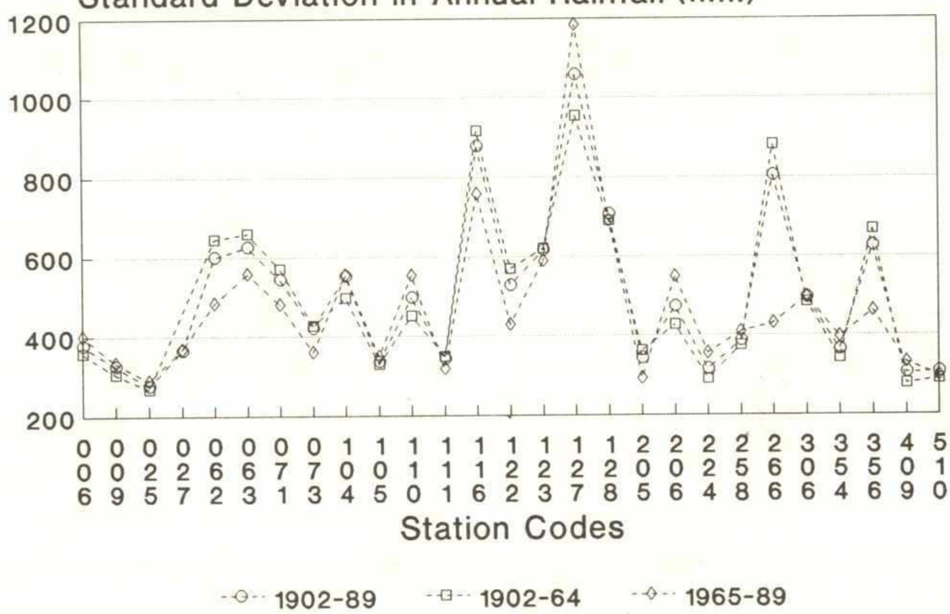
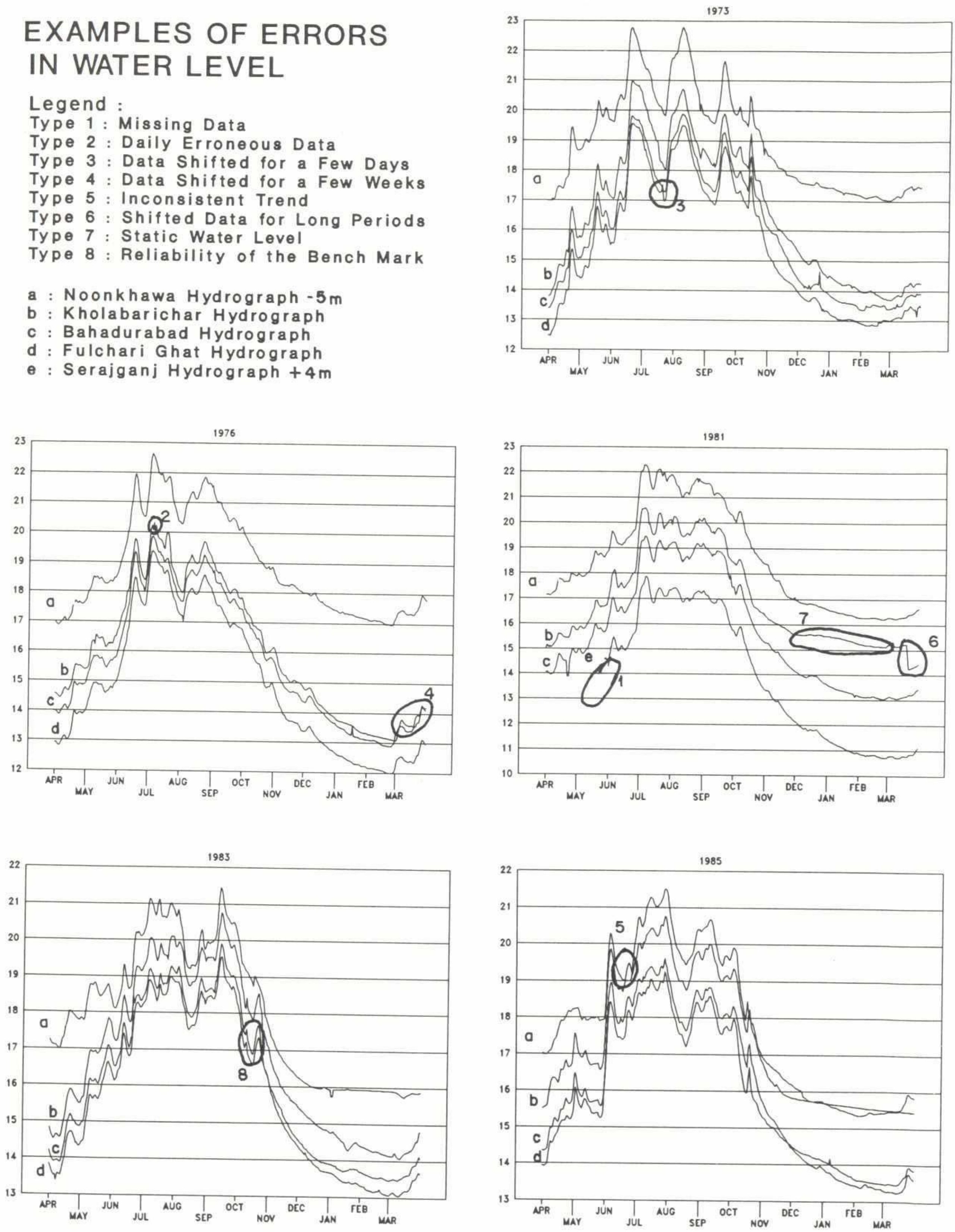
a)
Mean Annual Rainfall (in '000 mm)



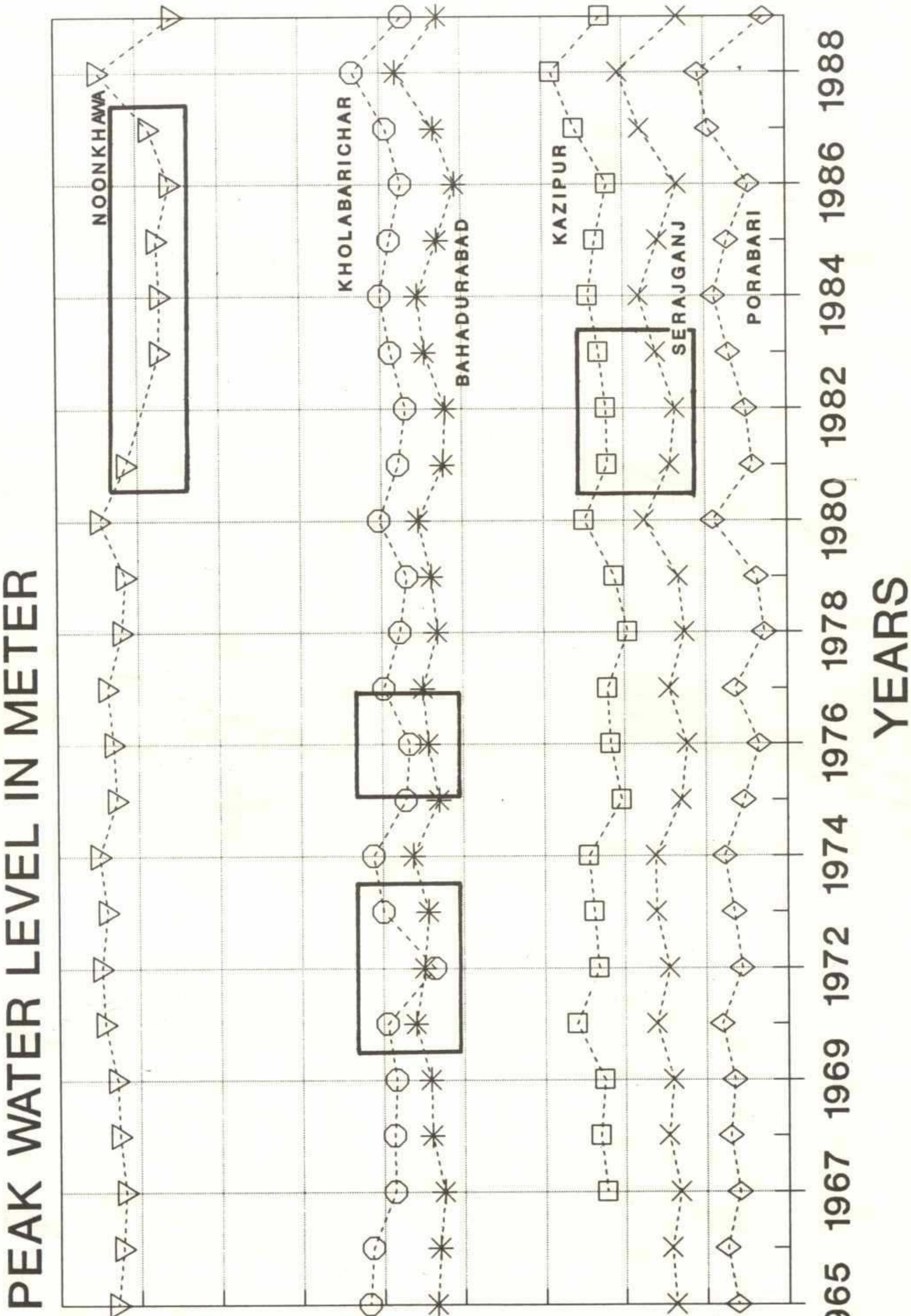
b)
Standard Deviation in Annual Rainfall (mm)



FAP25 FLOOD MODELLING & MANAGEMENT	FLOOD HYDROLOGY STUDY	
	Rainfall Data Review : Mean and Standard Deviations in Annual Rainfall in Bangladesh	
	JUNE 1992	FIGURE 5.3 a) & b)



FAP25 FLOOD MODELLING & MANAGEMENT	FLOOD HYDROLOGY STUDY Water Level Data Review : Examples of Errors	
	JUNE 1992	FIGURE 5.4



FAP25

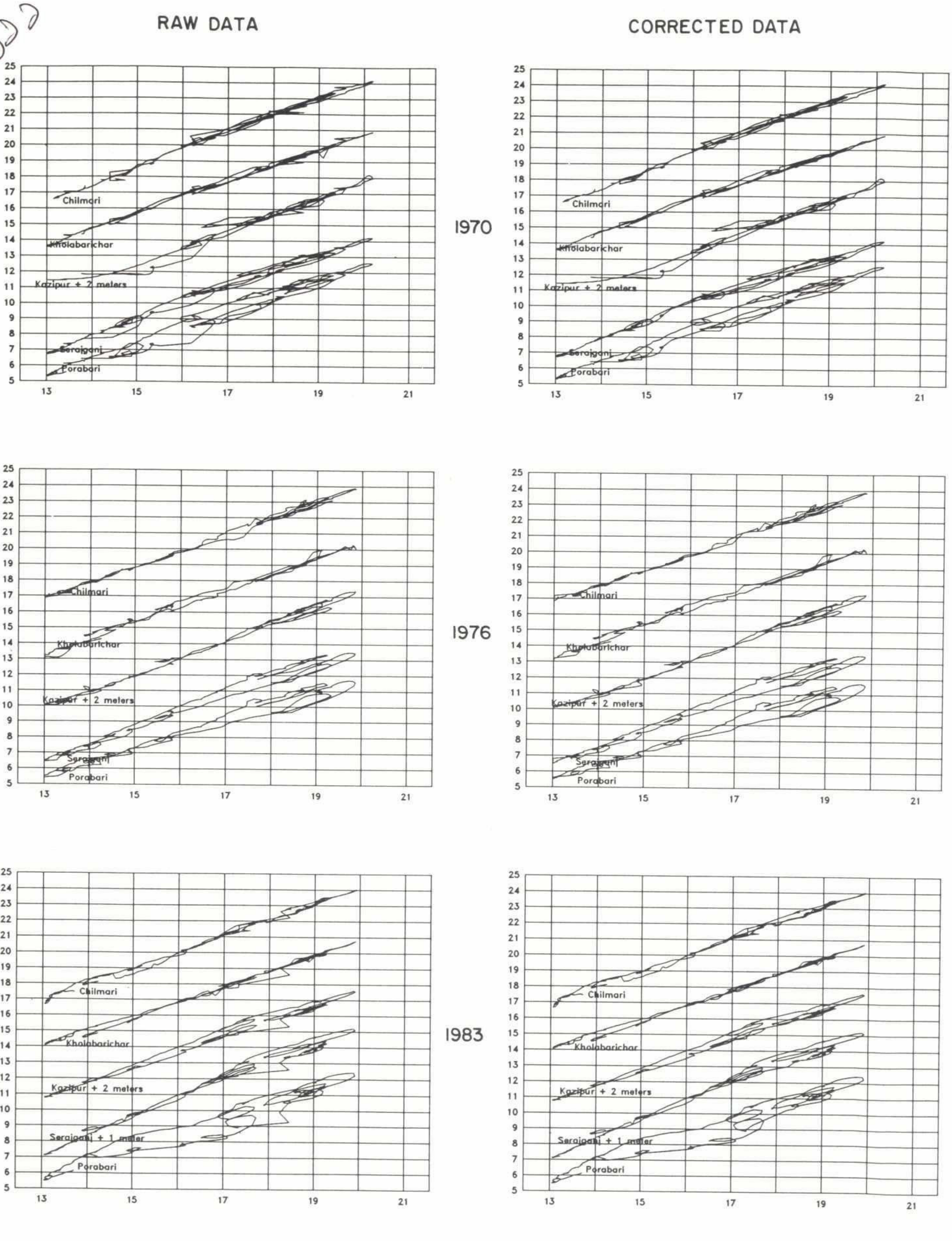
FLOOD MODELLING & MANAGEMENT

FLOOD HYDROLOGY STUDY

Water Level Data Review : Peaks in Jamuna

JUNE 1992

FIGURE 5.5



FAP25

FLOOD MODELLING & MANAGEMENT

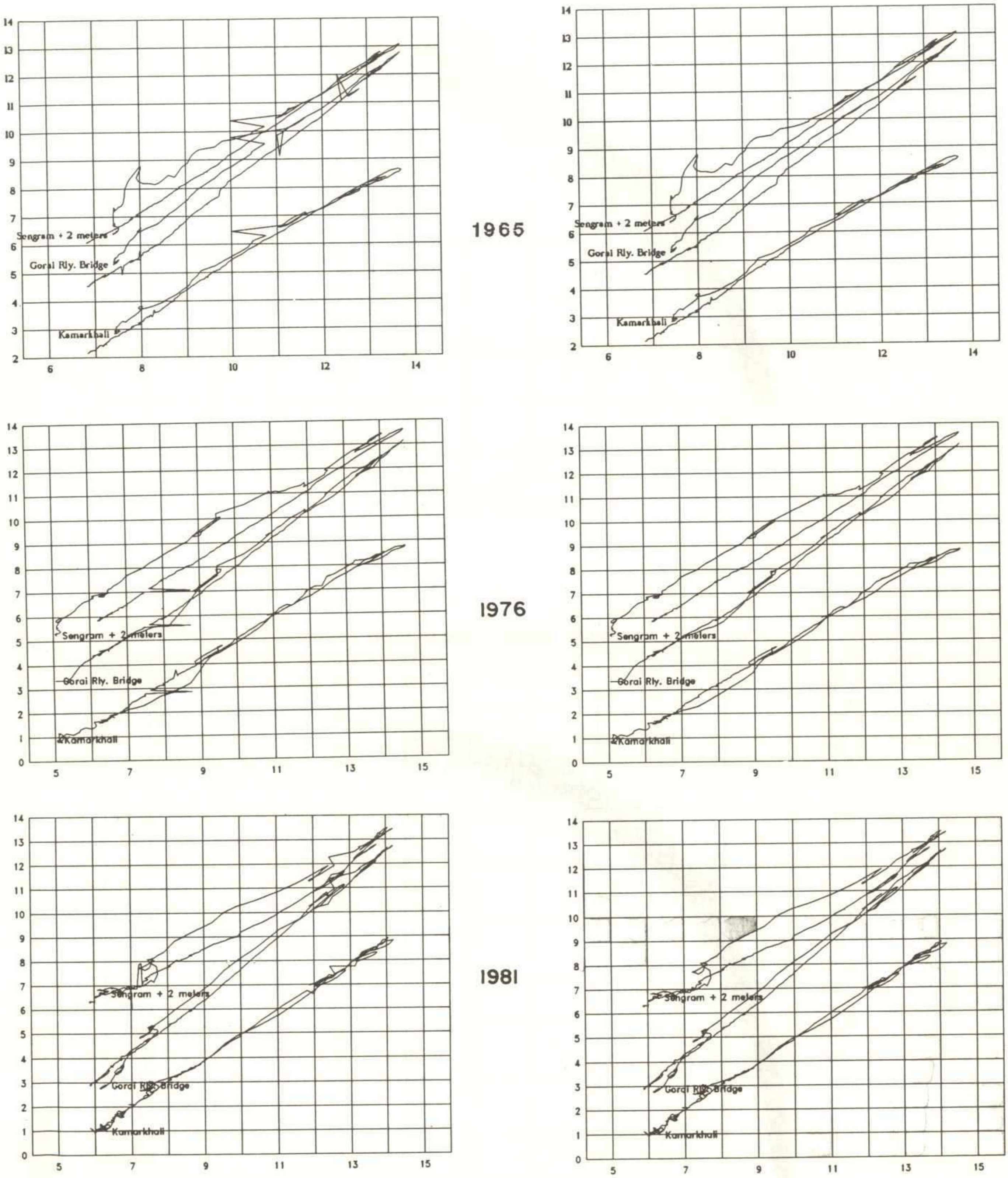
FLOOD HYDROLOGY STUDY

Water Level Correlation Between Stations on the Jamuna Against Bahadurabad Observations

JUNE 1992

FIGURE 5.6

RAW DATA | CORRECTED DATA



FAP25 FLOOD MODELLING & MANAGEMENT	FLOOD HYDROLOGY STUDY	
	Water Level Correlation Between Stations on the Ganges Against Hardinge Bridge Observations	
	JUNE 1992	FIGURE 5.7

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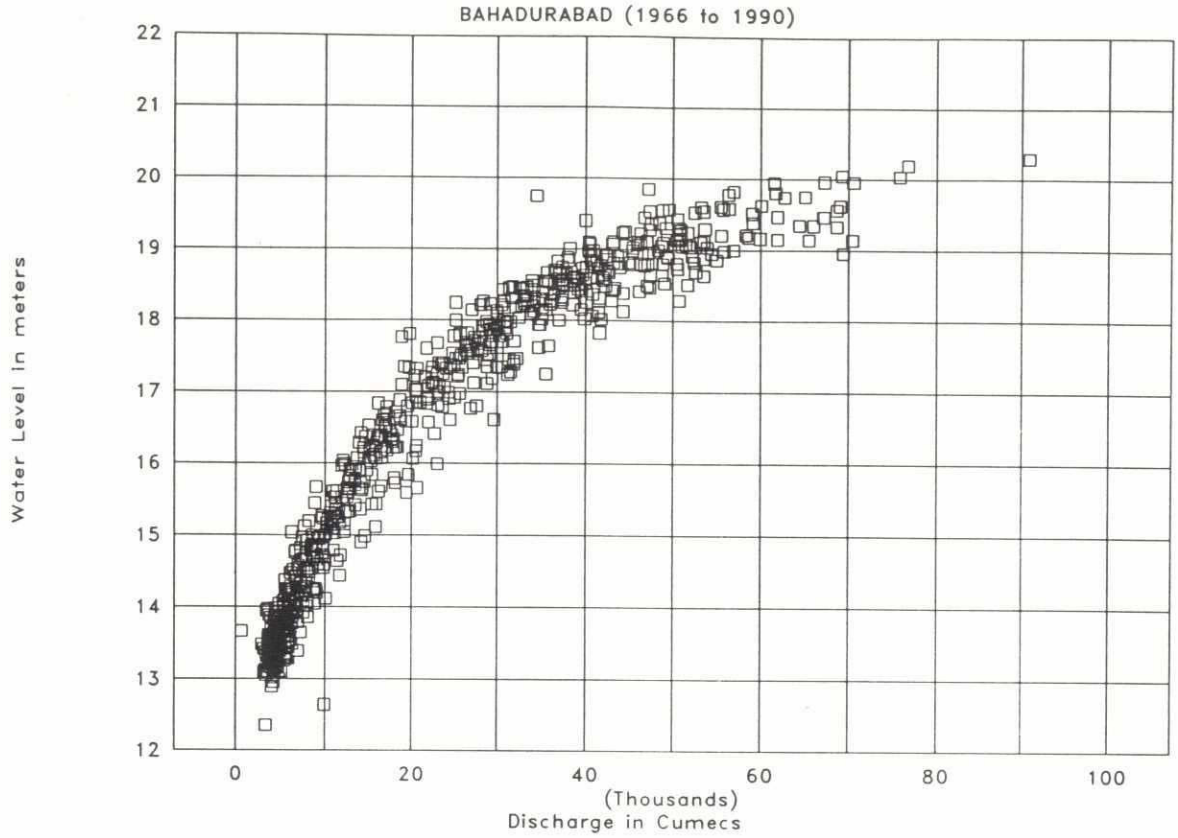
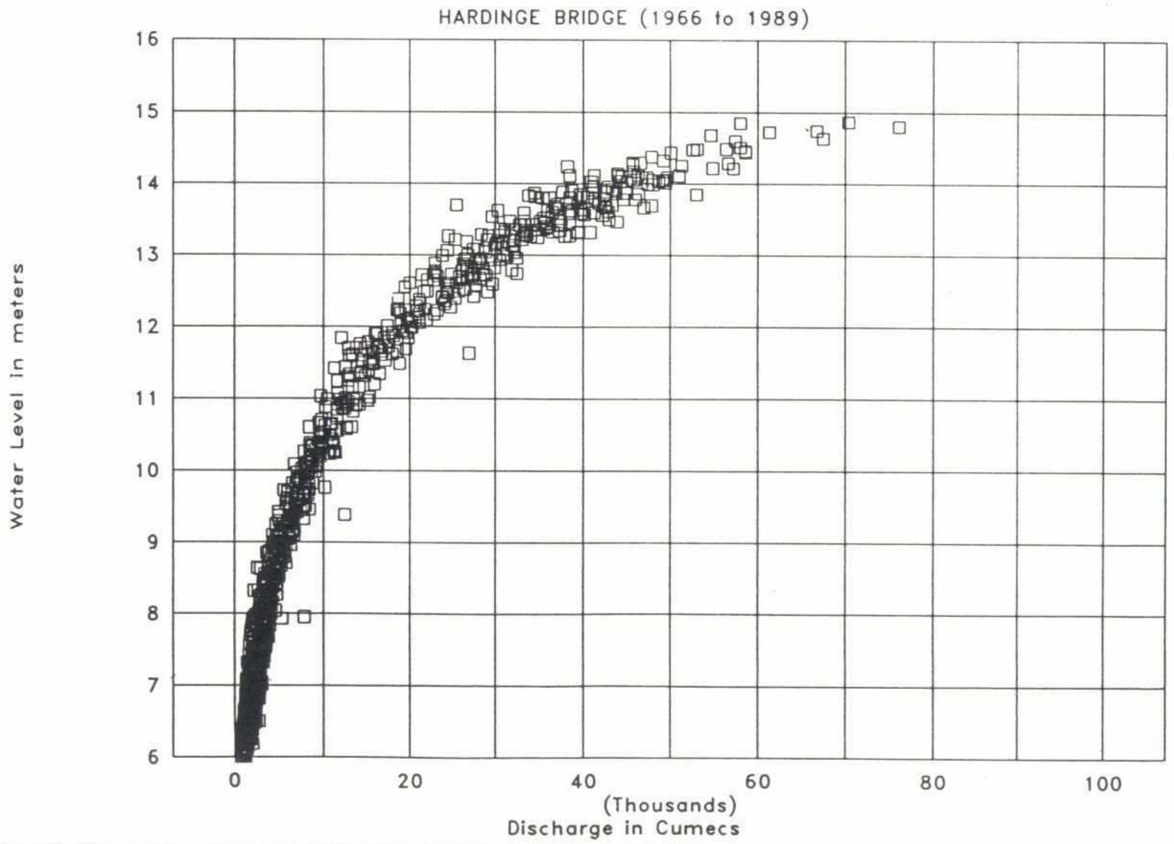




FAP25

FLOOD MODELLING & MANAGEMENT

FLOOD HYDROLOGY STUDY

Plot of 25 Years Gauged Data at Bahadurabad and Hardinge Bridge

JUNE 1992

FIGURE 5.8

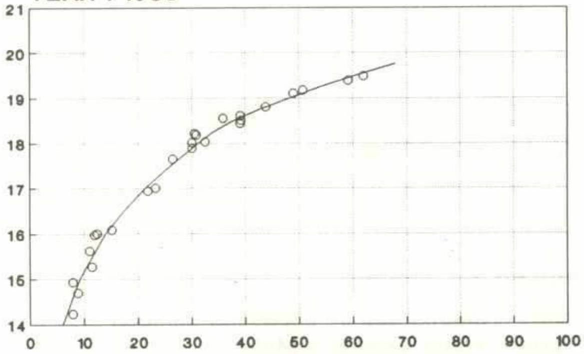
RATING CURVES
(POWER FUNCTION)

STATION : BAHADURABAD
RIVER : JAMUNA

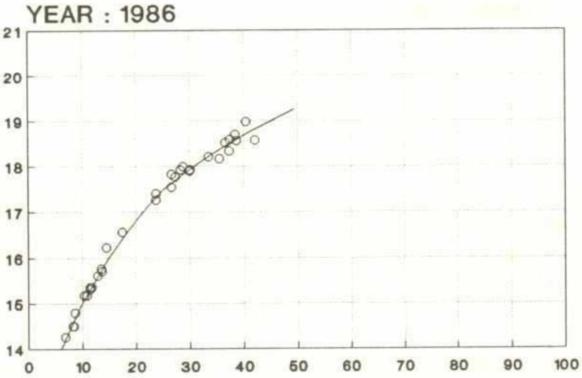
Legend :

X-axis = Discharges in Thousand cumecs
Y-axis = Water Levels in Meter
o = Gauged data

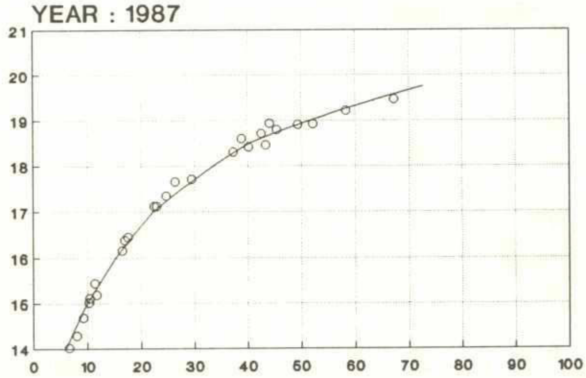
YEAR : 1985



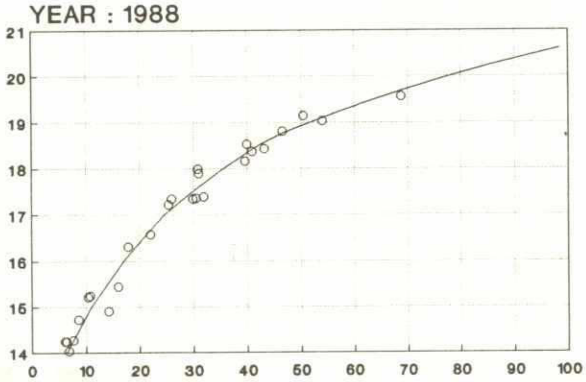
YEAR : 1986



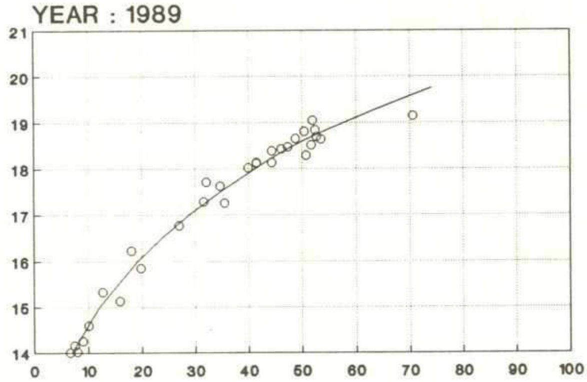
YEAR : 1987



YEAR : 1988



YEAR : 1989



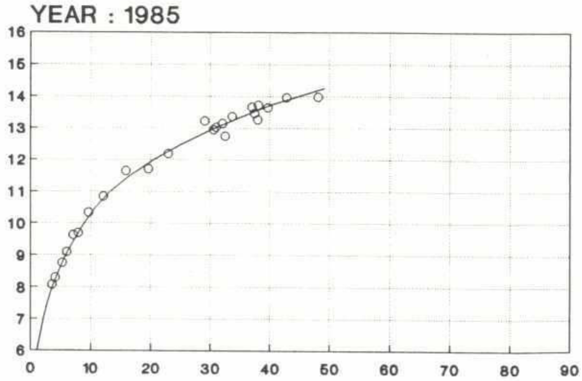
FAP25 FLOOD MODELLING & MANAGEMENT	FLOOD HYDROLOGY STUDY
	Annual Mean Rating Curves at Bahadurabad for 1985-89
JUNE 1992	FIGURE 5.9 a)

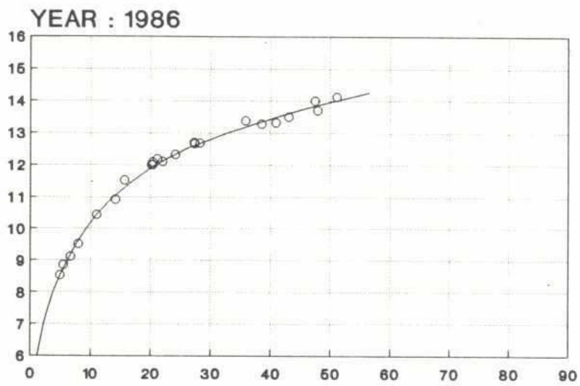
RATING CURVES
(POWER FUNCTION)

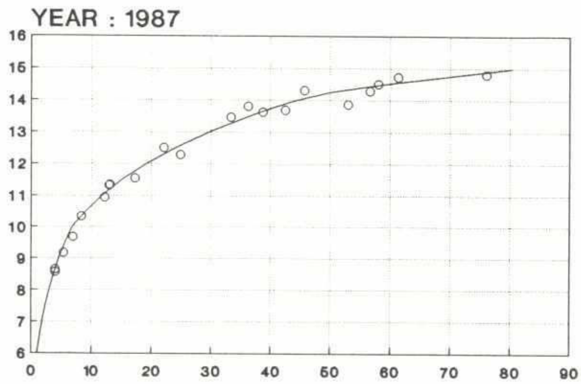
STATION : HARDINGE BRIDGE
RIVER : GANGES

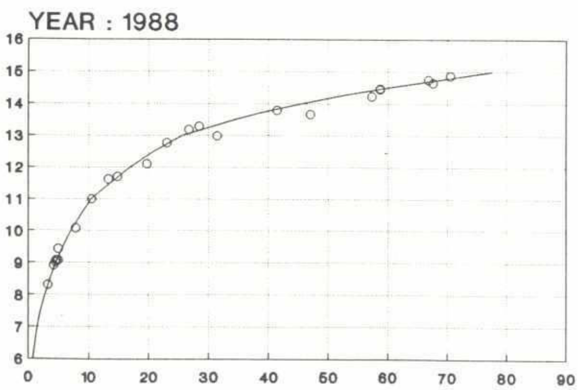
Legend :

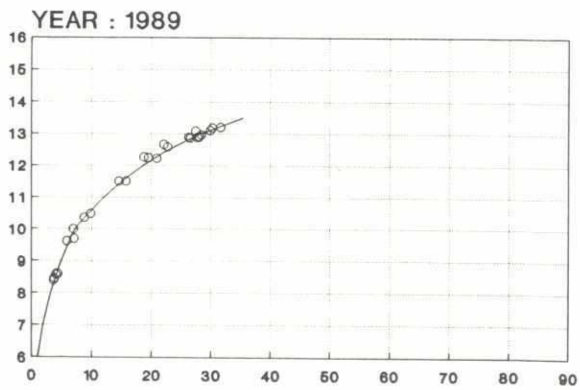
X-axis = Discharges in Thousand cumecs
Y-axis = Water Levels in Meter
o = Gauged data











FAP 25 FLOOD MODELLING & MANAGEMENT	FLOOD HYDROLOGY STUDY
	Annual Mean Rating Curves at Hardinge Bridge for 1985-89
JUNE 1992	FIGURE 5.9 b)

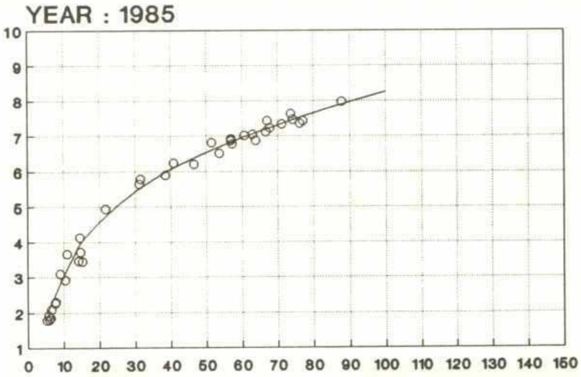
RATING CURVES
(POWER FUNCTION)

STATION : BARURIA
RIVER : PADMA

Legend :

X-axis = Discharges in Thousand cumecs
Y-axis = Water Levels in Meter
o = Gauged data

YEAR : 1985



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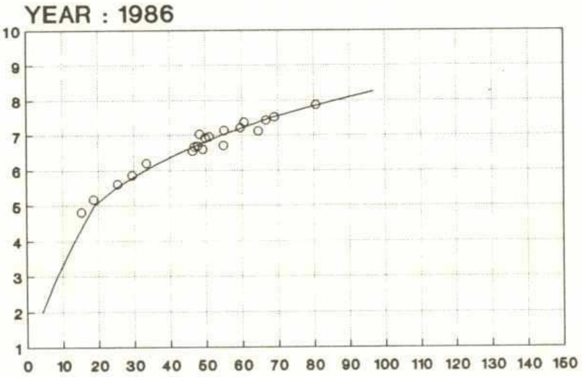

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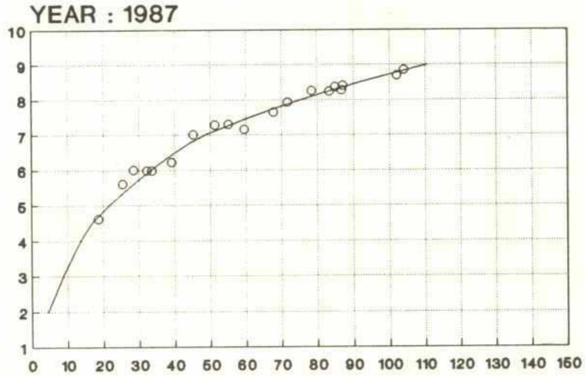

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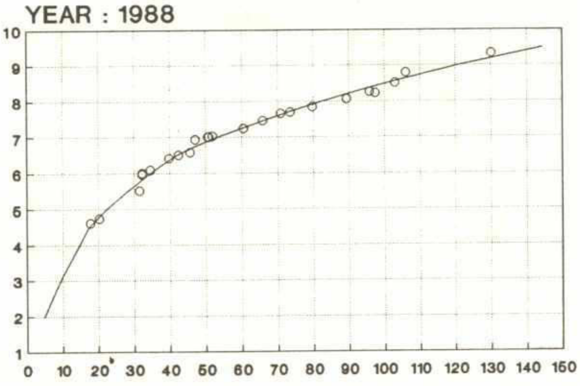
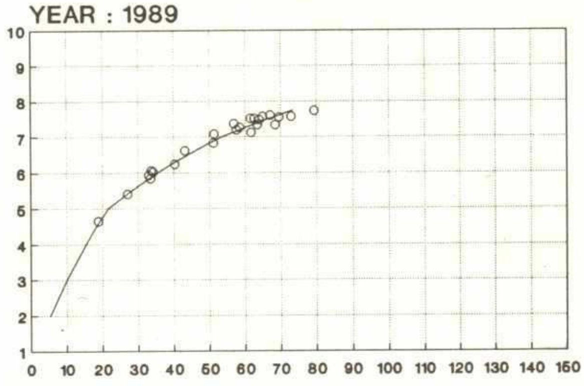


YEAR : 1989



FAP25 FLOOD MODELLING & MANAGEMENT	FLOOD HYDROLOGY STUDY	
	Annual Mean Rating Curves at Baruria for 1985-89	
	JUNE 1992	FIGURE 5.9 c)

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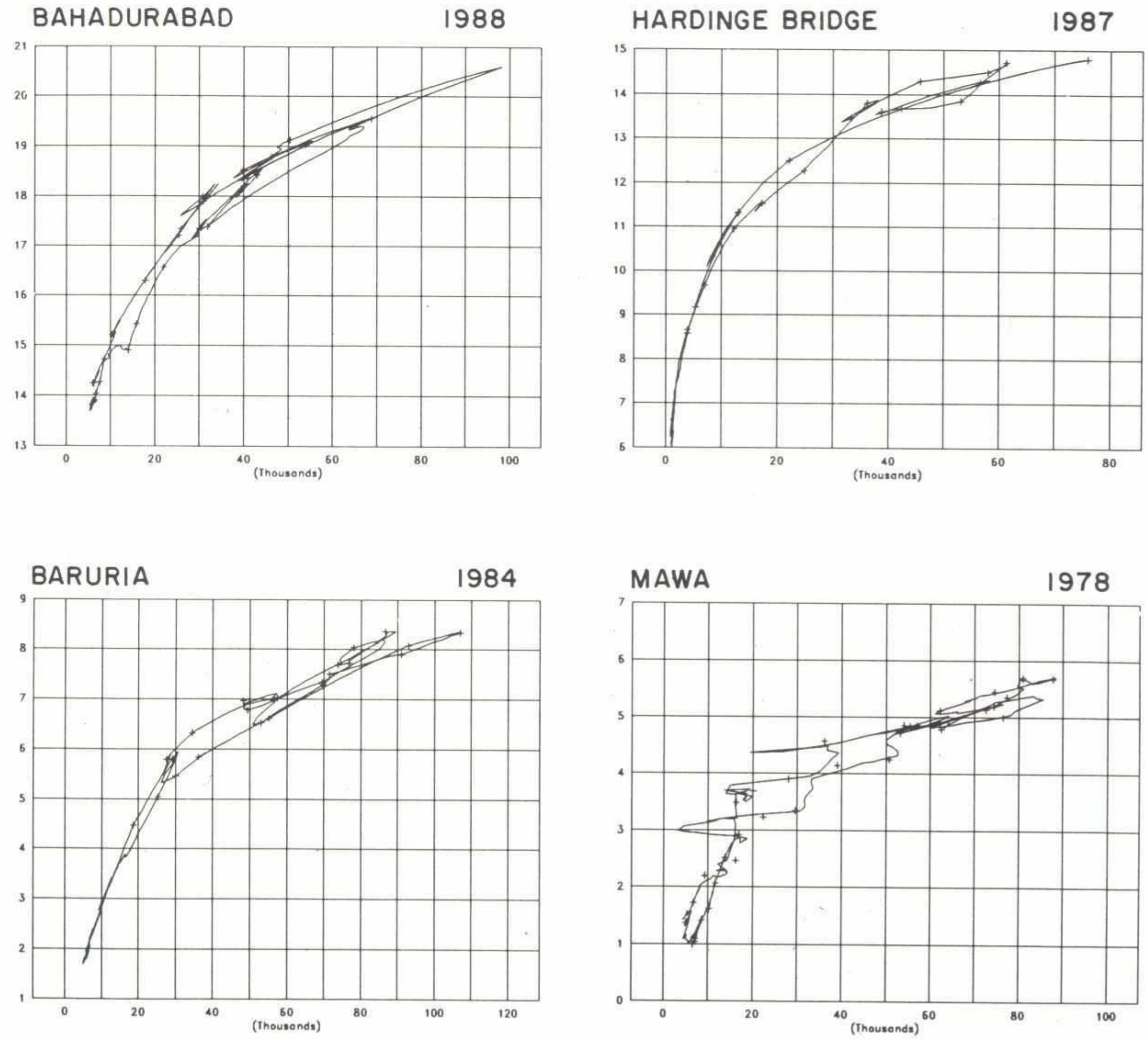
EFFECT OF SHIFT CORRECTION ON COMPUTED DAILY DISCHARGES

SOURCE : BWDB

LEGEND :

X - axis = Discharges in Cumecs (Thousands)
Y-axis = Water Level in Meter (PWD)
x = Measured Discharges



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FLOOD MODELLING & MANAGEMENT

FLOOD HYDROLOGY STUDY

Effect of Shift Correction on Estimated Mean Daily Discharge

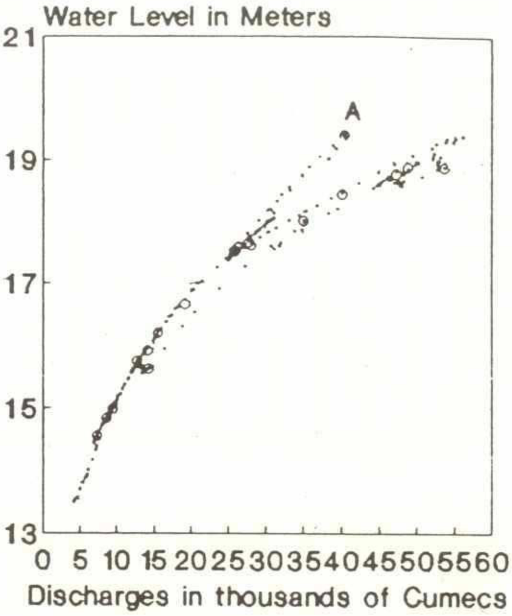
JUNE 1992

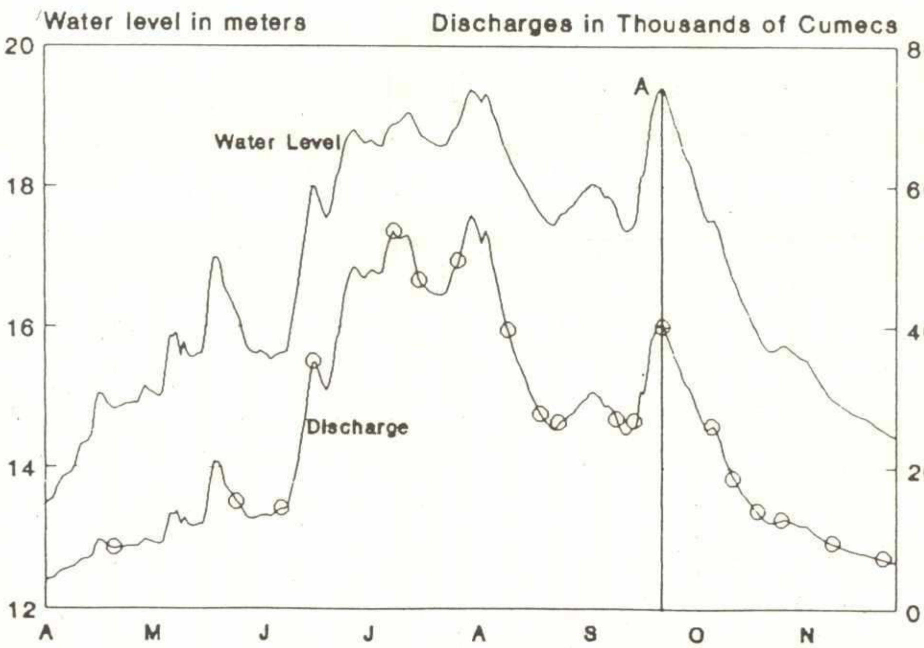
FIGURE 5.10 a)

DISCHARGES ANALYSIS
STATION : BAHADURABAD

YEAR : 1982

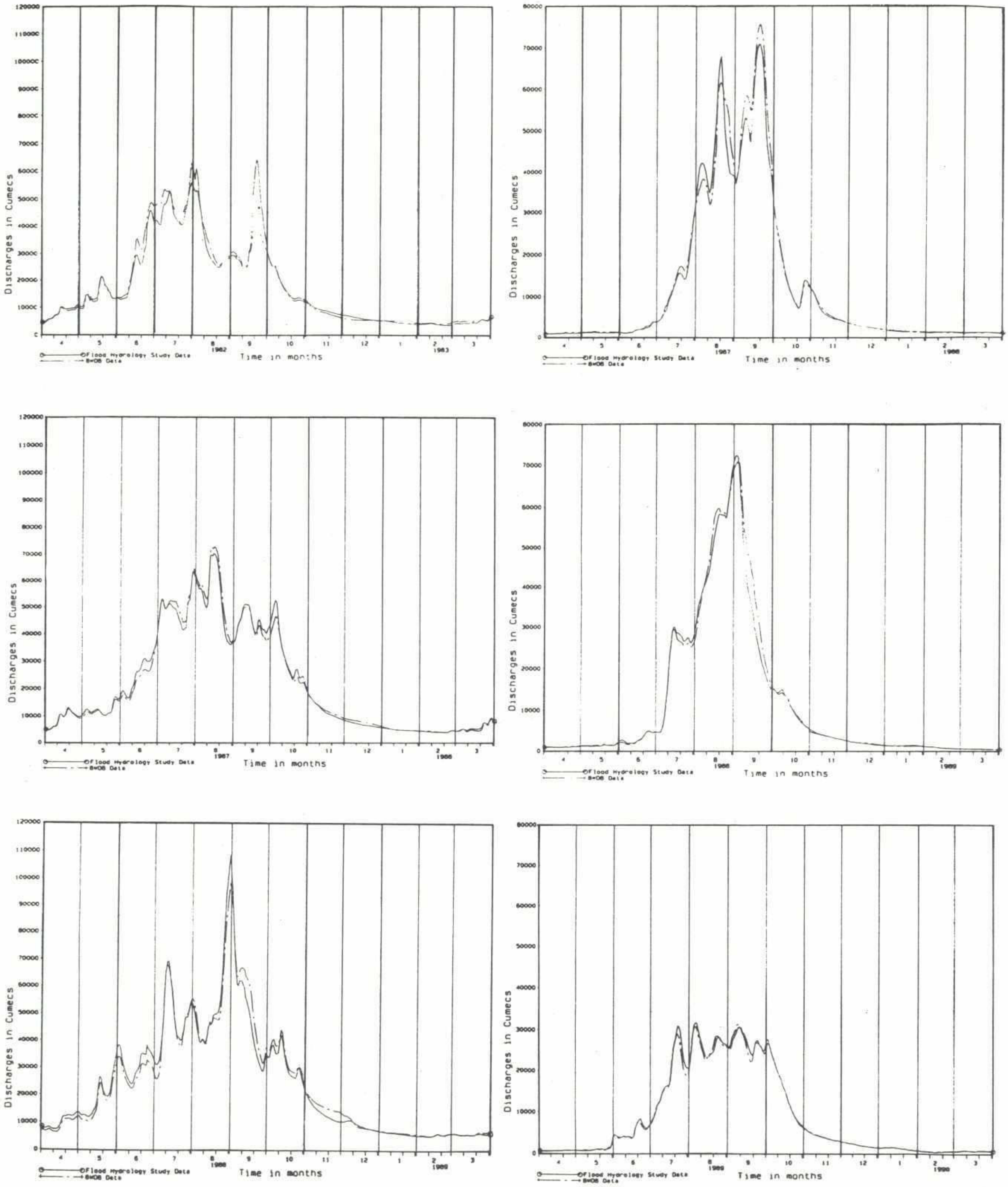
Legend
- o : gauged discharge
- —: mean daily water level
- —: mean daily discharge





FAP25 FLOOD MODELLING & MANAGEMENT	FLOOD HYDROLOGY STUDY Effect of Shift Correction on Bahadurabad 1982 Discharge Data JUNE 1992 — FIGURE 5.10 b)

Bahadurabad **Hardinge Bridge**



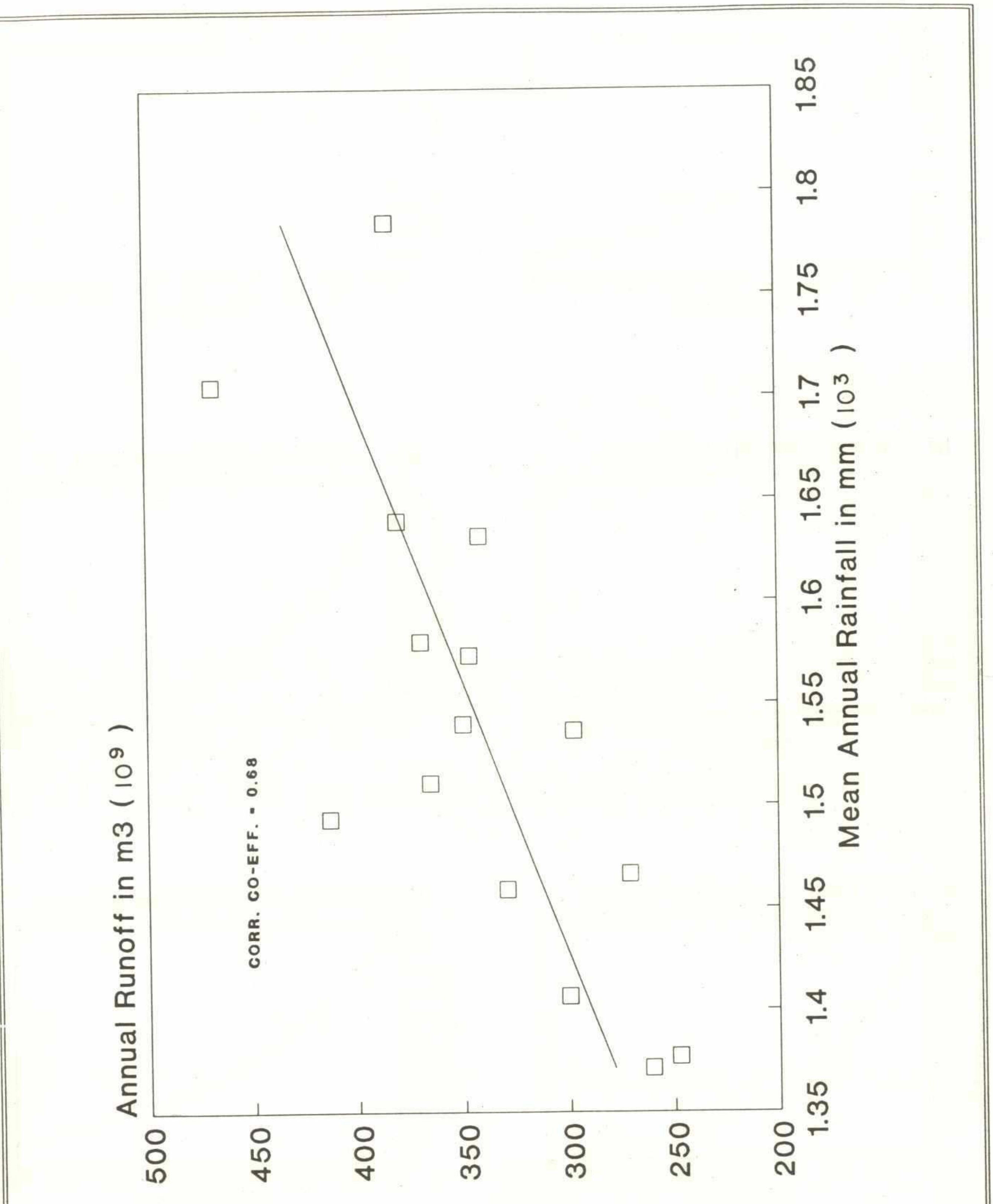
FAP25

FLOOD MODELLING & MANAGEMENT

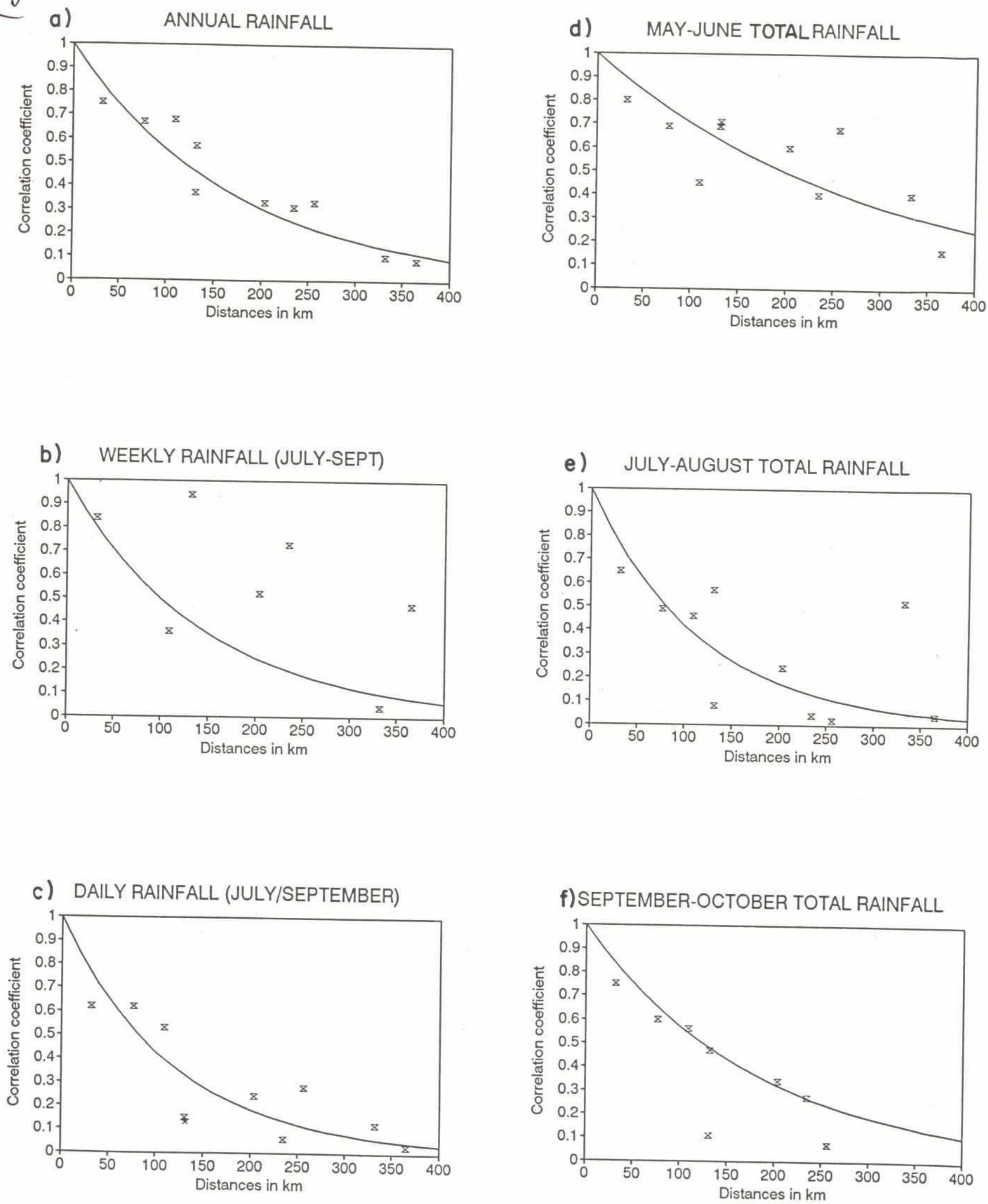
FLOOD HYDROLOGY STUDY

Comparison of BWDB and FAP25 Corrected Discharge Hydrographs at Bahadurabad and Hardinge Bridge for Selected Years

JUNE 1992 **FIGURE 5.11**

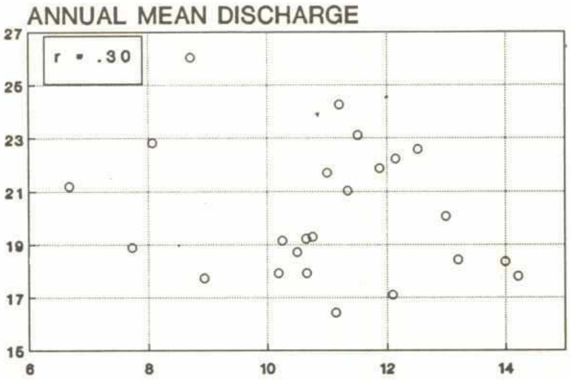


FAP25 FLOOD MODELLING & MANAGEMENT	FLOOD HYDROLOGY STUDY	
	Correlation Between Rainfall on the Ganges Catchment and the Runoff at Hardinge Bridge (1934-50)	
	JUNE 1992	FIGURE 6.1



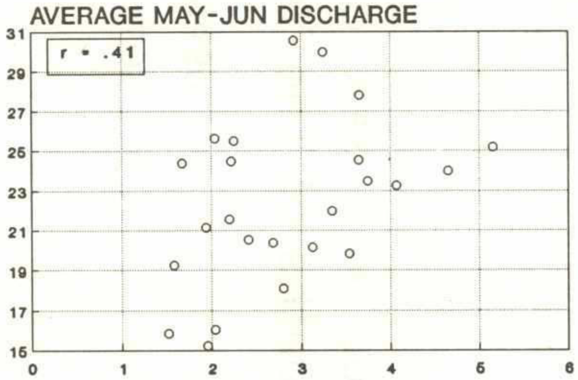
FAP25 FLOOD MODELLING & MANAGEMENT	FLOOD HYDROLOGY STUDY Rainfall Spatial Correlation for Selected Stations (R009 Dhaka, R110 Habiganj, R116 Lallakhal, R128 Sylhet and R510 Khulna)
JUNE 1992	FIGURE 6.2

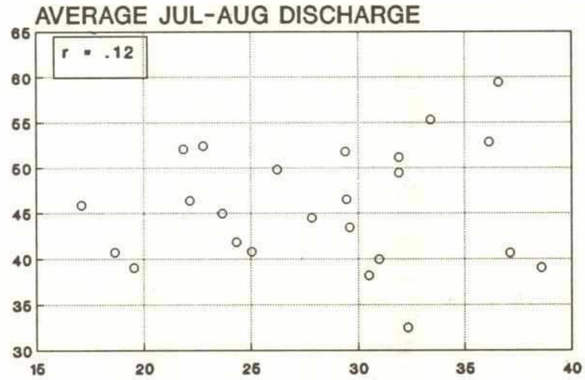
HARDINGE BRIDGE VS BAHADURABAD (DISCHARGE OF DIFFERENT CATEGORY)

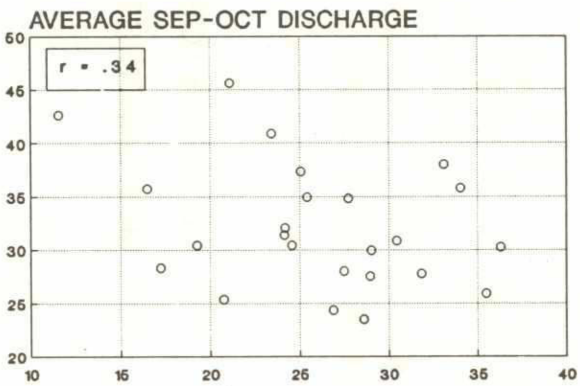


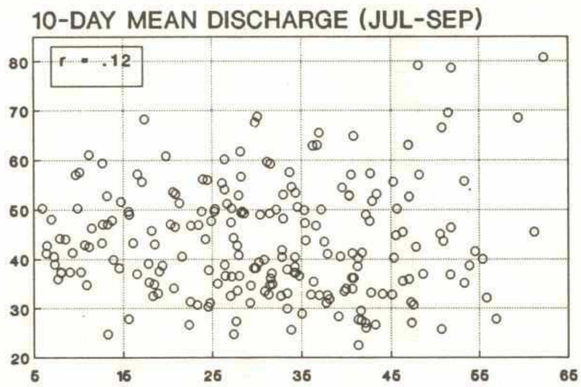
Legend :

X-axis = Hardinge Bridge Discharge in Thousand Cumecs
Y-axis = Bahadurabad Discharge in Thousand Cumecs
r = Coefficient of Correlation

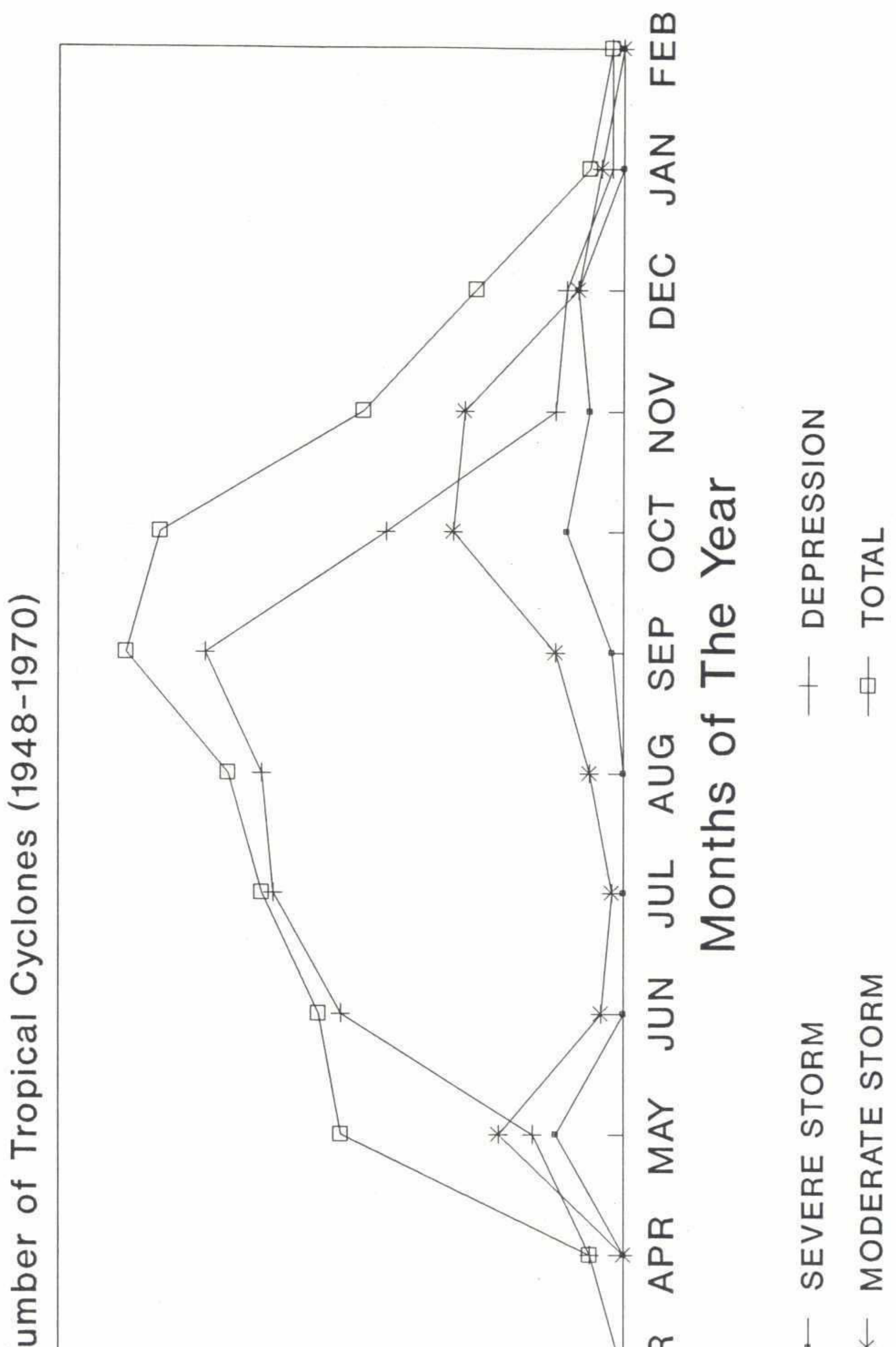




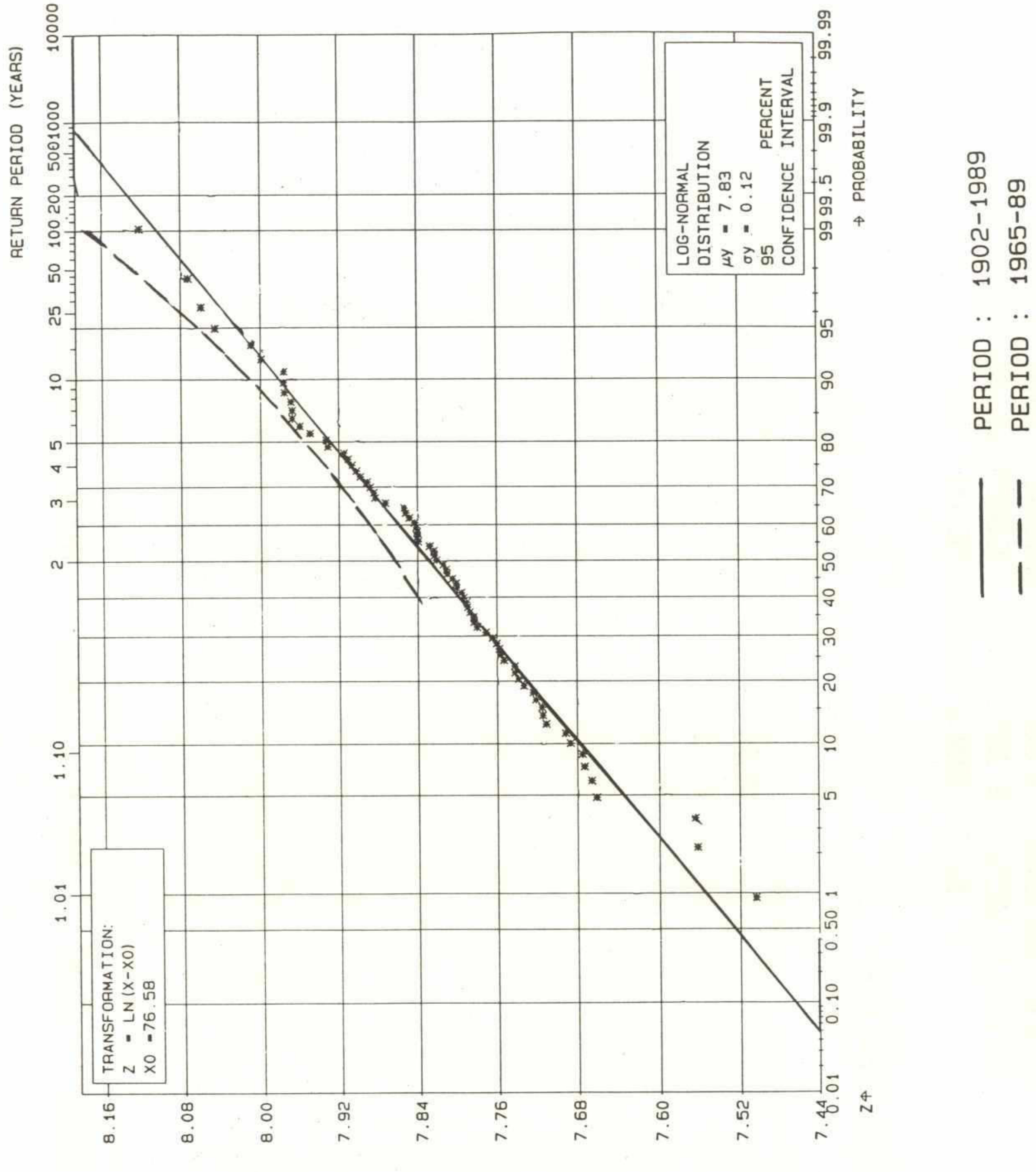




FAP 25 FLOOD MODELLING & MANAGEMENT	FLOOD HYDROLOGY STUDY	
	Correlation Between Discharges at Bahadurabad and Hardinge Bridge	
	JUNE 1992	FIGURE 6.3



FAP25 FLOOD MODELLING & MANAGEMENT	FLOOD HYDROLOGY STUDY	
	Cyclonic Activity	
	JUNE 1992	FIGURE 6.4



FAP25

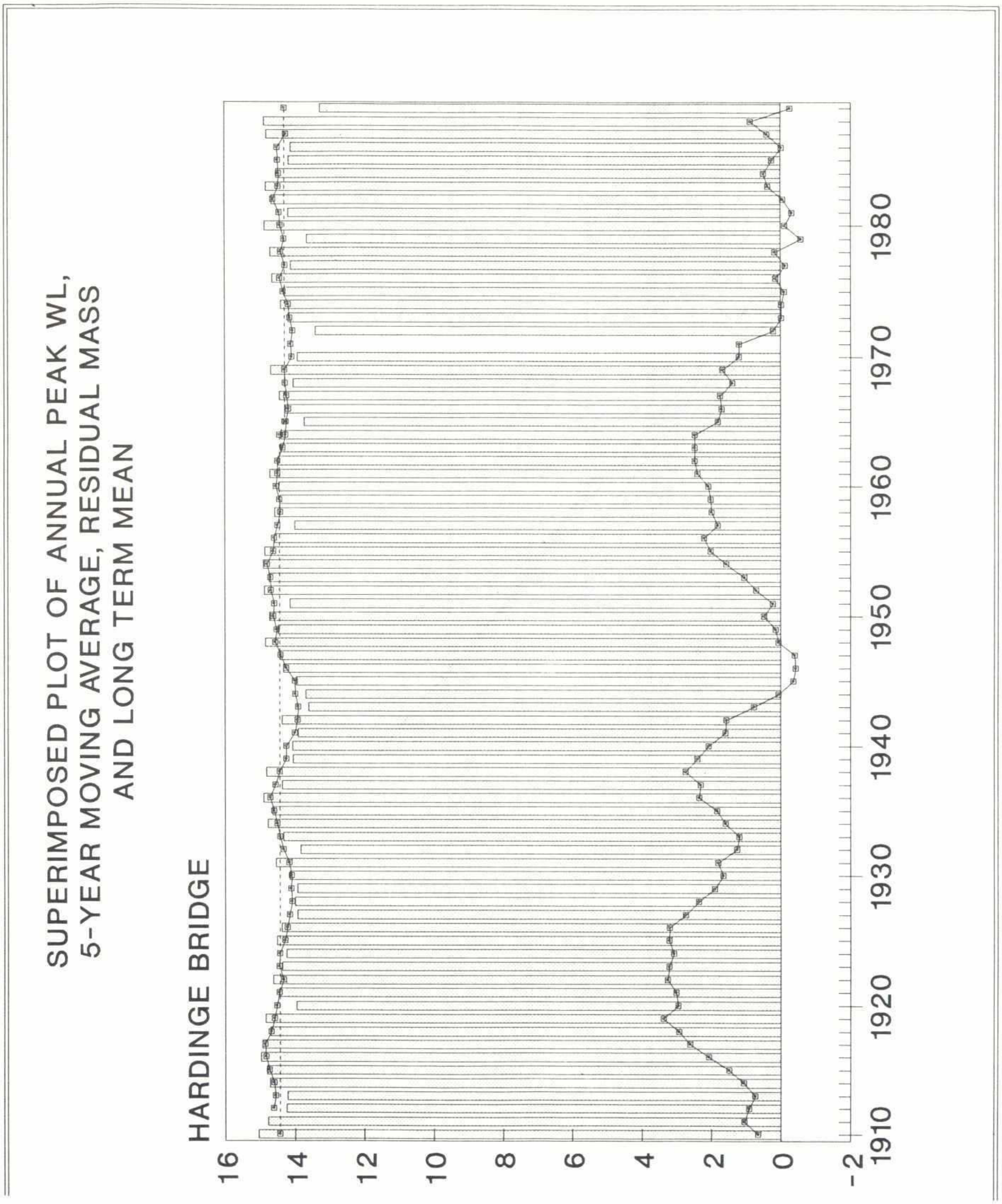
FLOOD MODELLING & MANAGEMENT

FLOOD HYDROLOGY STUDY

Frequency Analysis of Mean Annual Rainfall in Bangladesh for Two Periods

JUNE 1992

FIGURE 6.5



FAP25

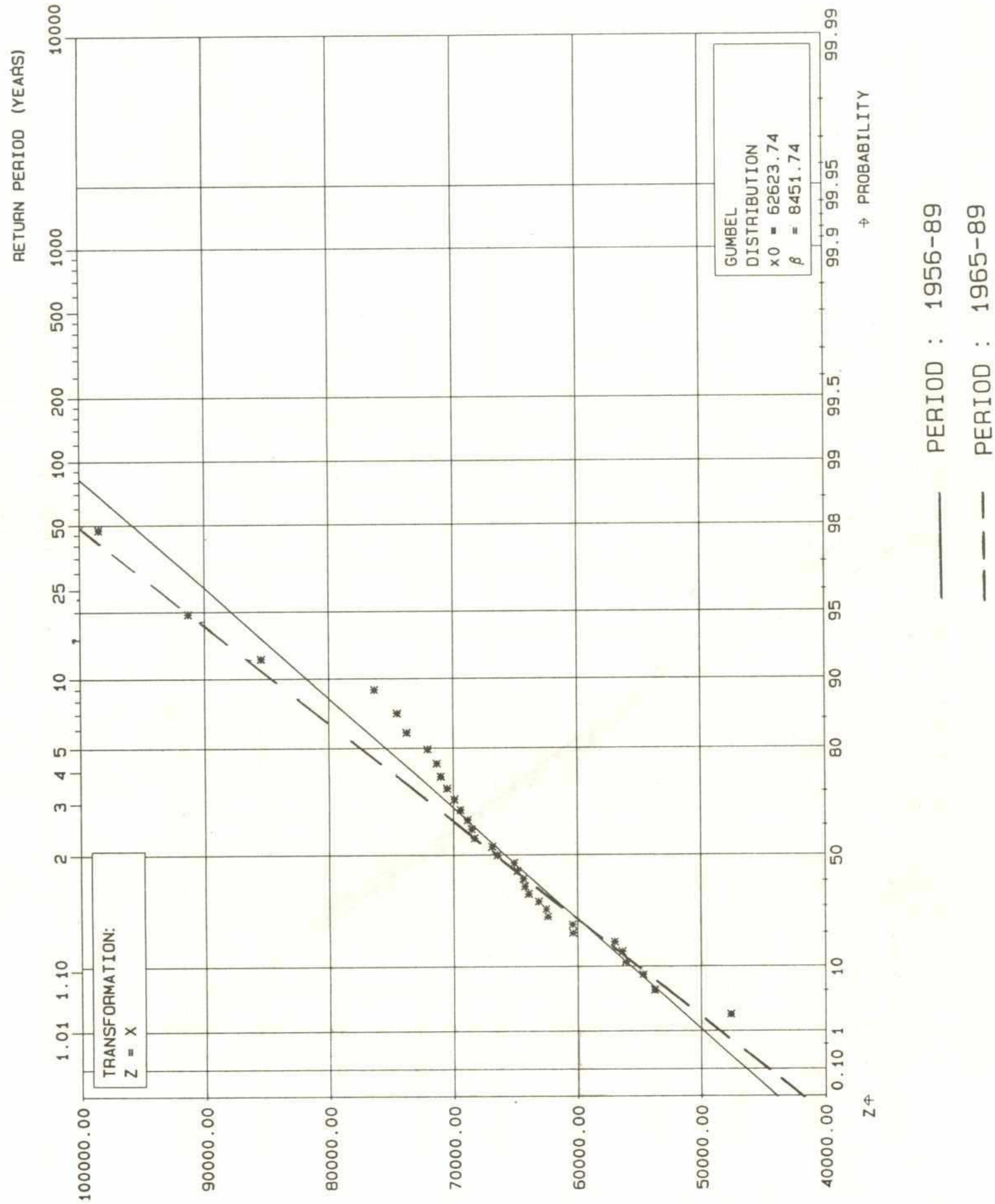
FLOOD MODELLING & MANAGEMENT

FLOOD HYDROLOGY STUDY

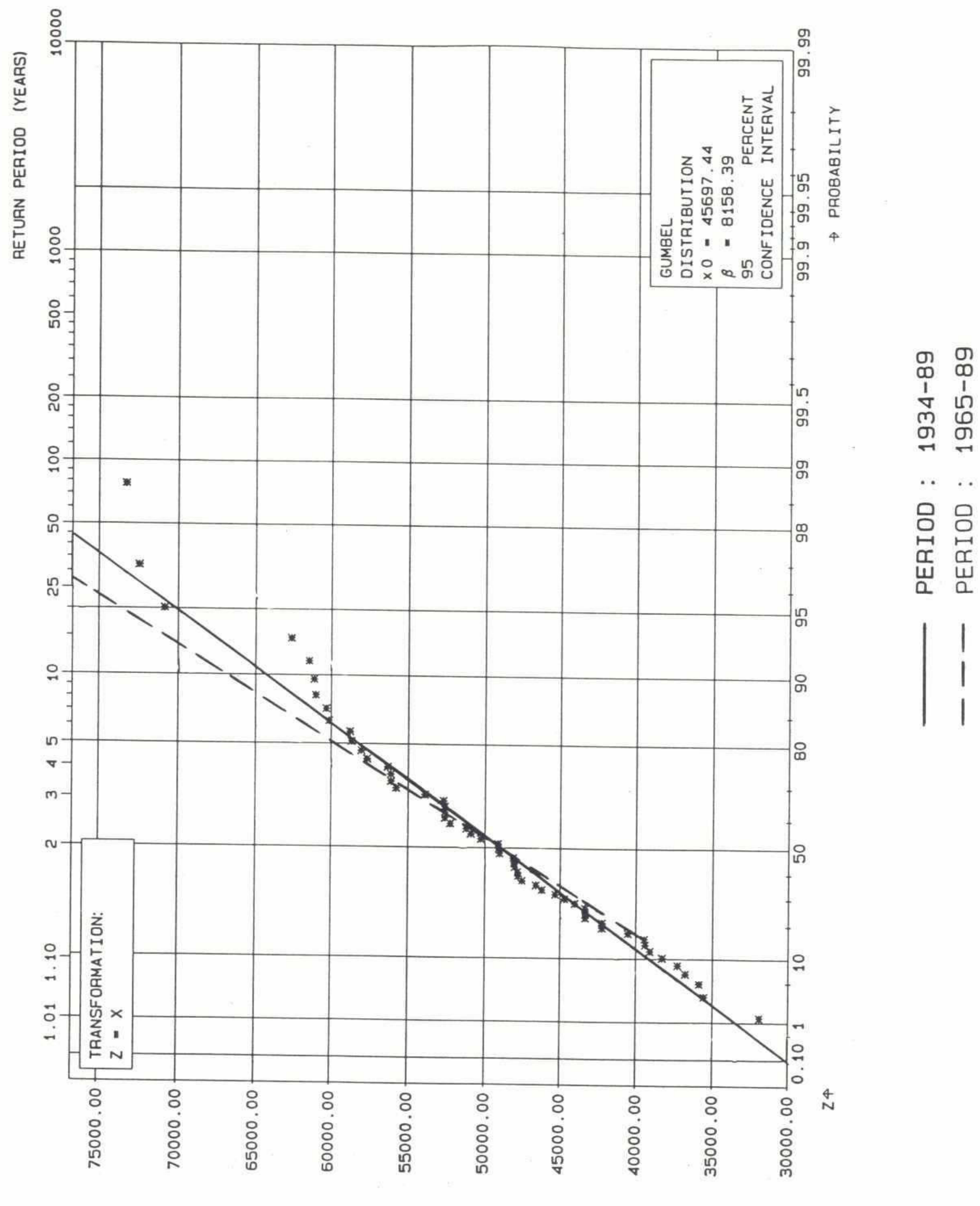
Water Level Data Review : Hardinge Bridge (1910-89)

JUNE 1992

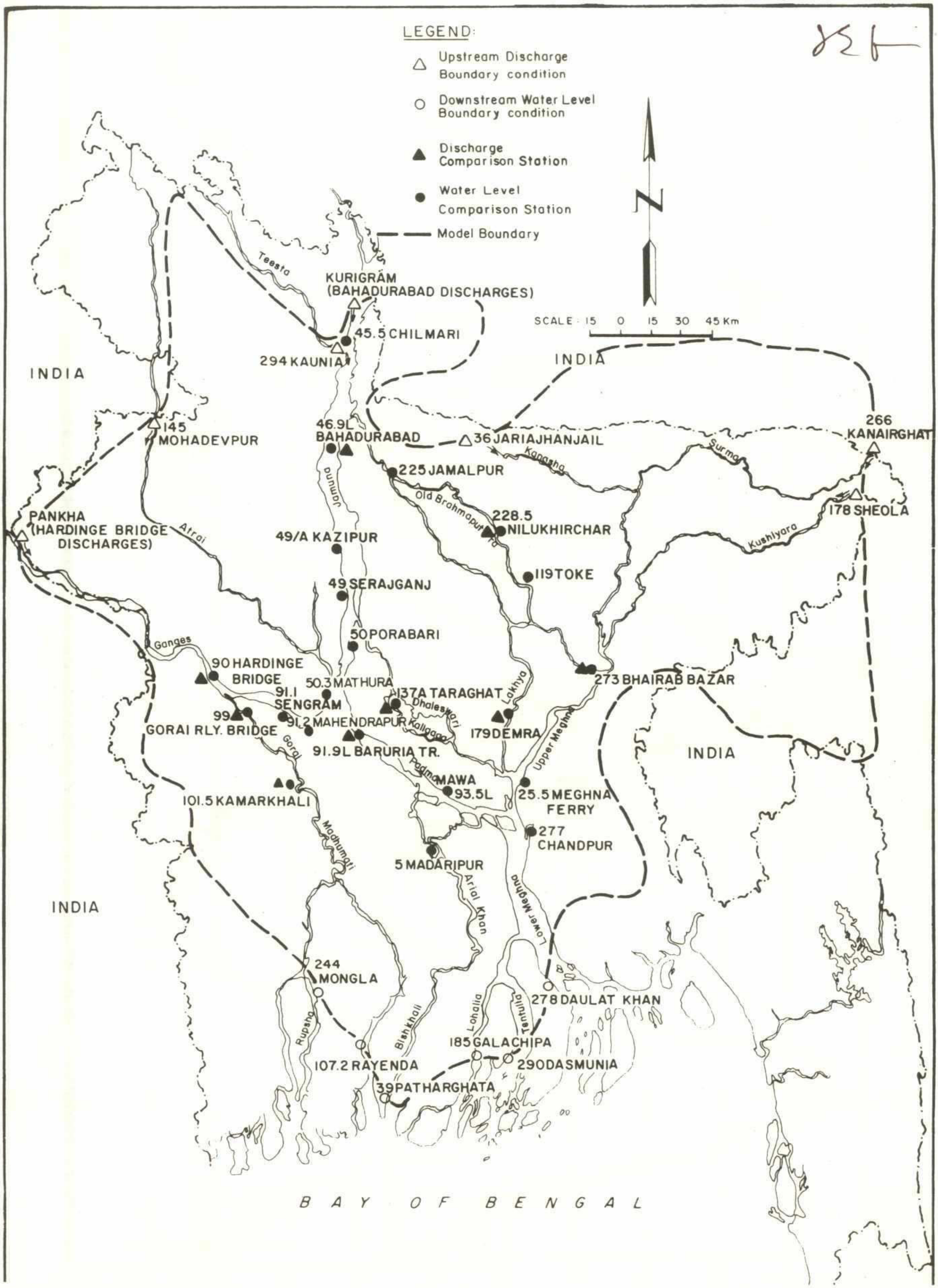
FIGURE 6.6



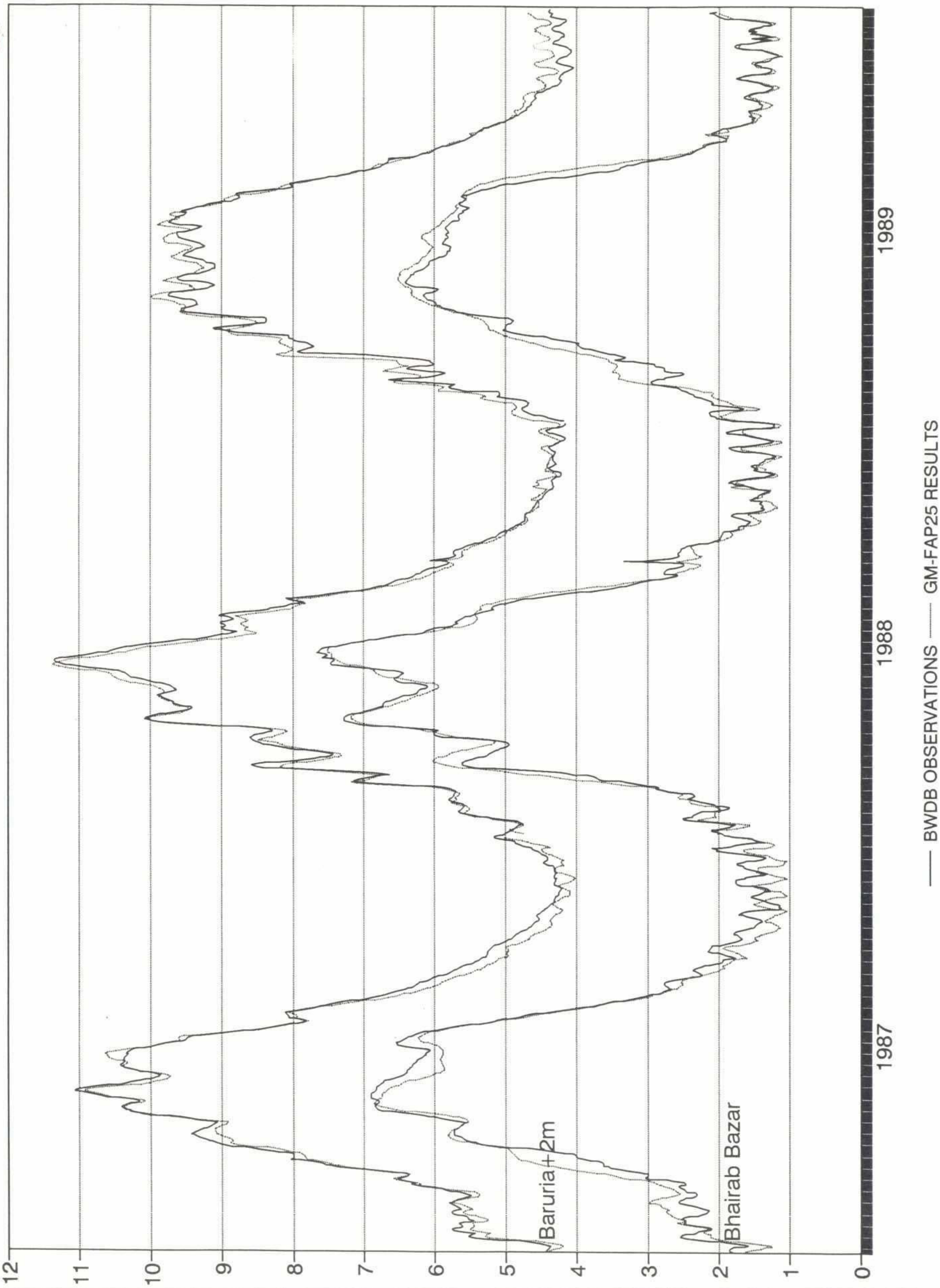
FAP25 FLOOD MODELLING & MANAGEMENT	FLOOD HYDROLOGY STUDY	
	Frequency Analysis of Peak Discharges at Bahadurabad for Two Periods	
	JUNE 1992	FIGURE 6.7 a)



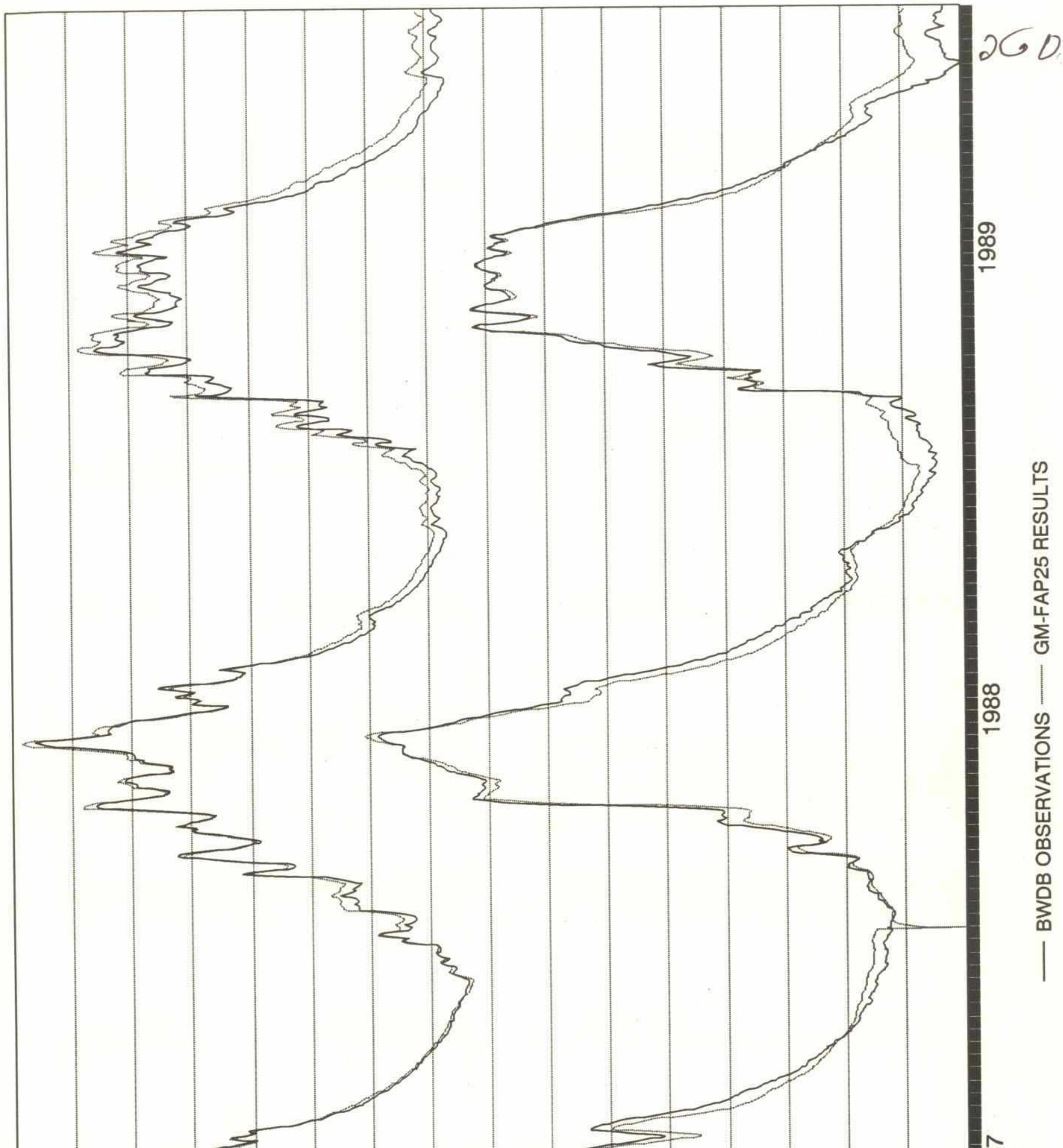
FAP25 FLOOD MODELLING & MANAGEMENT	**FLOOD HYDROLOGY STUDY** Frequency Analysis of Peak Discharges at Hardinge Bridge for Two Periods
JUNE 1992	FIGURE 6.7 b)



FAP25 FLOOD MODELLING & MANAGEMENT	FLOOD HYDROLOGY STUDY	
	FAP25-GM Model Schematization	
	JUNE 1992	FIGURE 7.1



FAP25 FLOOD MODELLING & MANAGEMENT	FLOOD HYDROLOGY STUDY Comparison Between Observed and Simulated Water Level Hydrographs at Baruria and Bhairab Bazar	
	JUNE 1992	FIGURE 7.2 a)



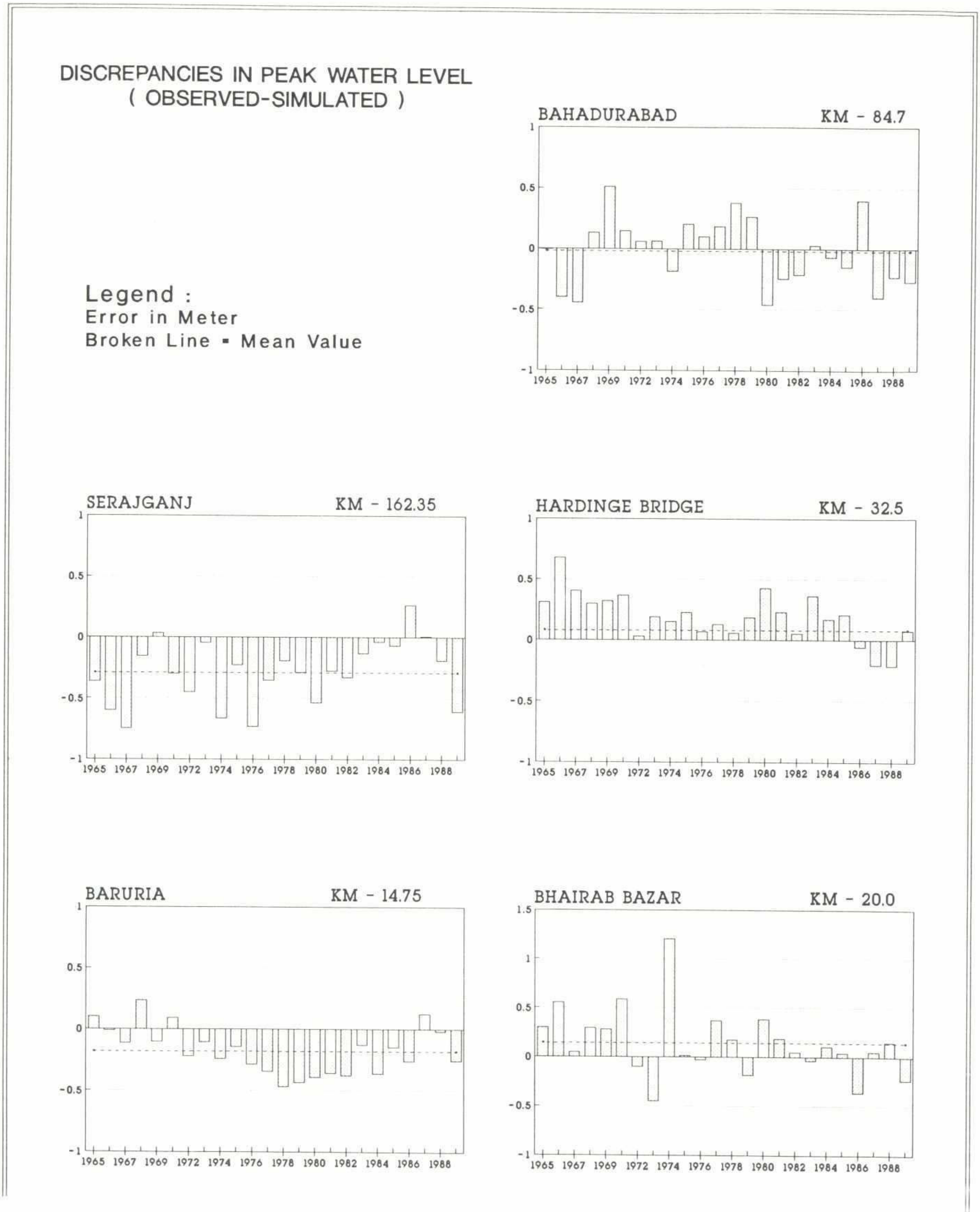
FAP25

FLOOD MODELLING & MANAGEMENT

FLOOD HYDROLOGY STUDY

Comparison Between Observed and Simulated Water Level Hydrographs at Bahadurabad and Hardinge Bridge

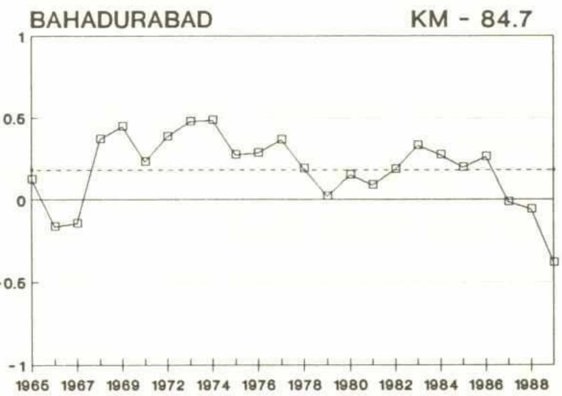
JUNE 1992	FIGURE 7.2 b)

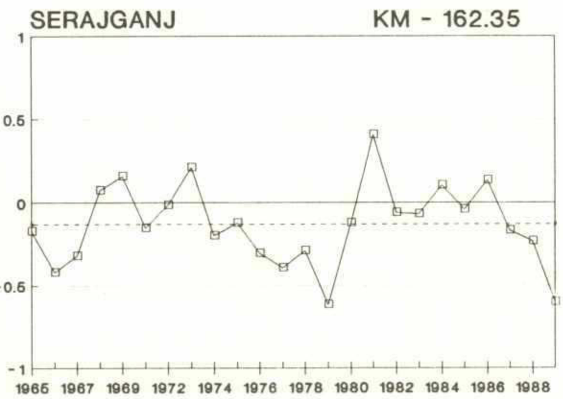


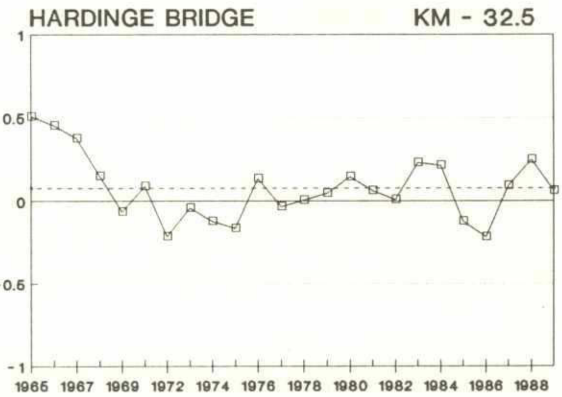
FAP 25 FLOOD MODELLING & MANAGEMENT	FLOOD HYDROLOGY STUDY Discrepancies Between Observed and Simulated Peak Water Levels
JUNE 1992	FIGURE 7.3 a)

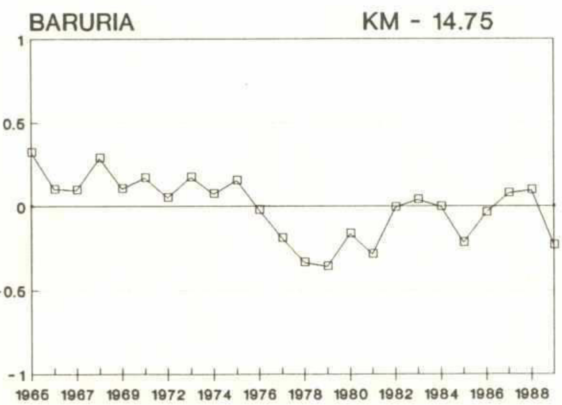
DISCREPANCIES IN MEAN SEASONAL WATER LEVEL (OBSERVED-SIMULATED)

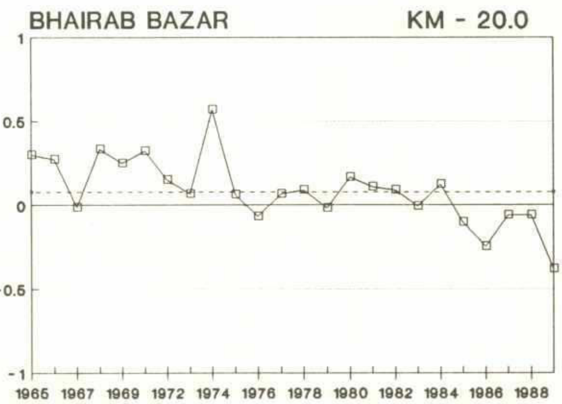
Legend :
Error in Meter
Broken Line = Mean Value



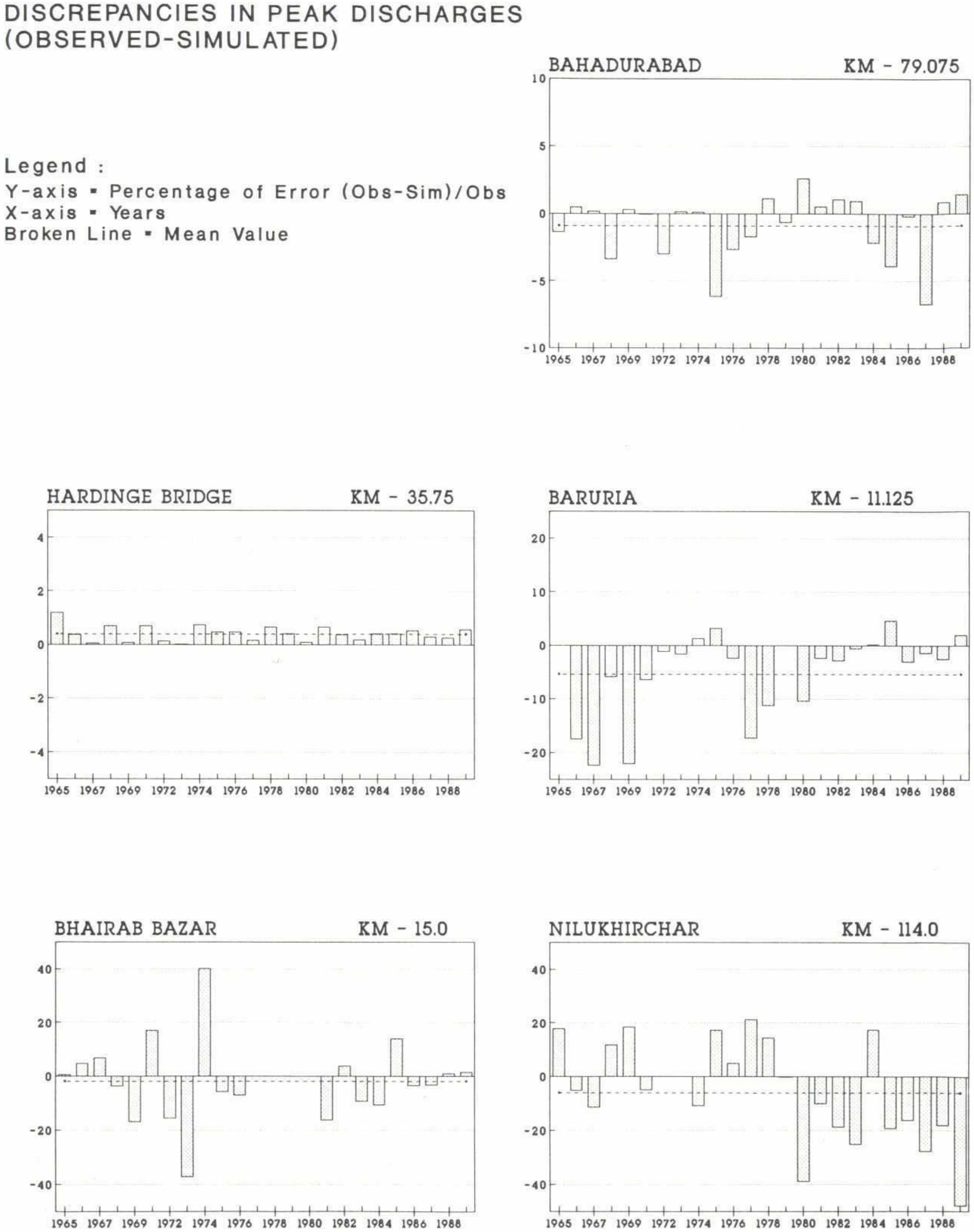








FAP25 FLOOD MODELLING & MANAGEMENT	FLOOD HYDROLOGY STUDY
	Discrepancies Between Observed and Simulated Mean Seasonal Water Levels
JUNE 1992	FIGURE 7.3 b)



FAP25

FLOOD MODELLING & MANAGEMENT

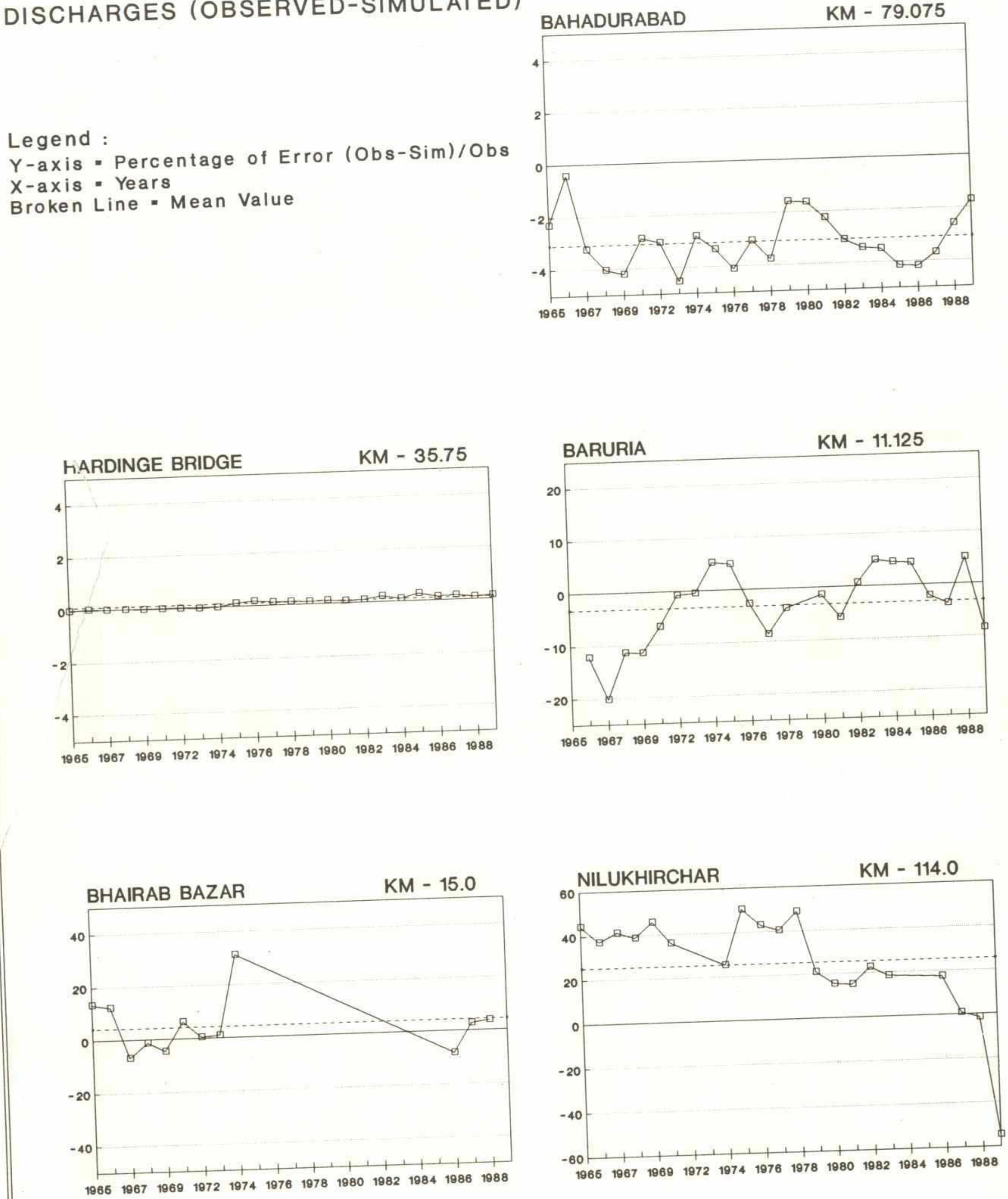
FLOOD HYDROLOGY STUDY

Discrepancies Between Observed and Simulated Peak Discharges

JUNE 1992

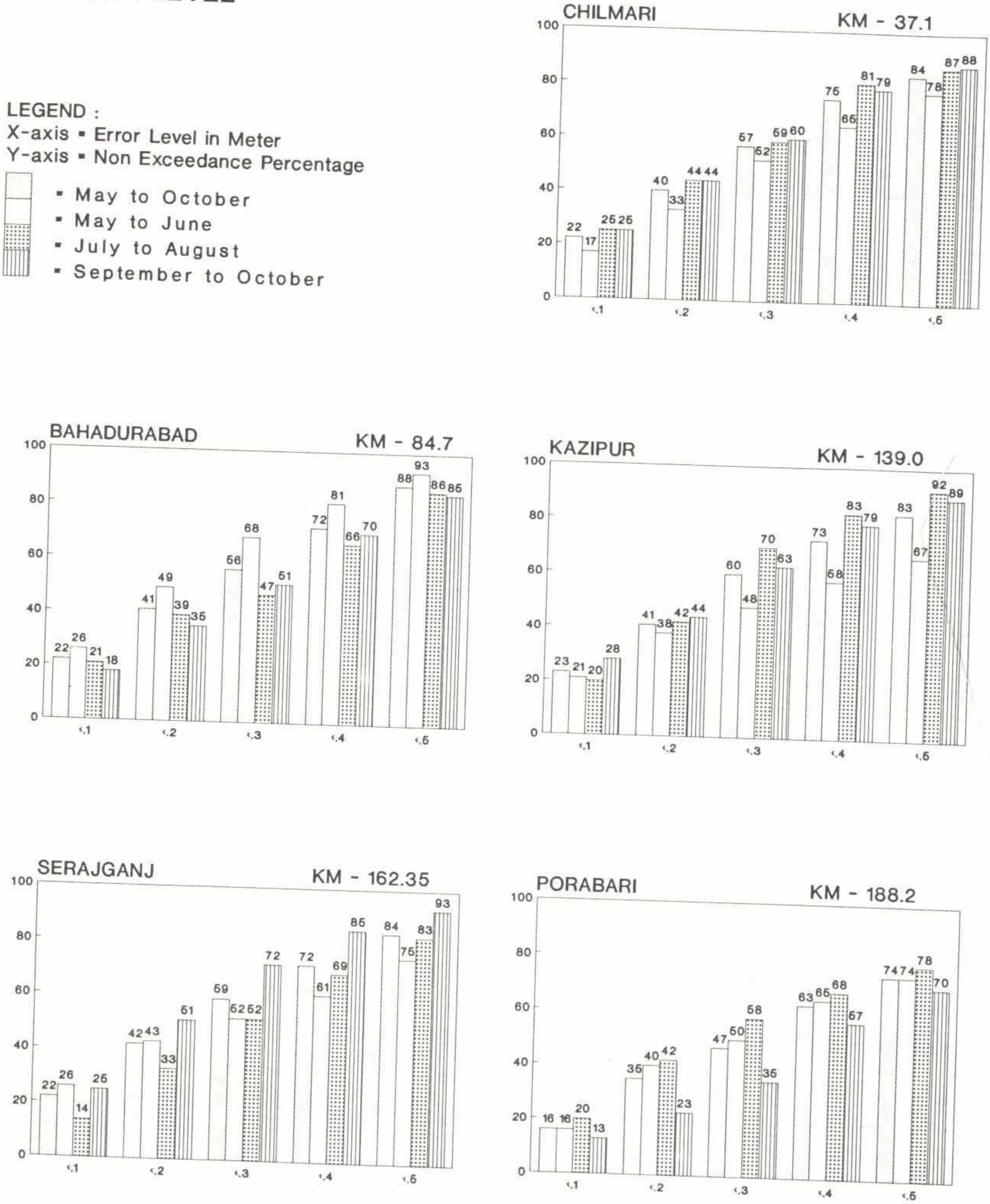
FIGURE 7.3 c)

DISCREPANCIES IN MEAN SEASONAL DISCHARGES (OBSERVED-SIMULATED)



FAP25 FLOOD MODELLING & MANAGEMENT	FLOOD HYDROLOGY STUDY	
	Discrepancies Between Observed and Simulated Mean Seasonal Discharges	
	JUNE 1992	FIGURE 7.3 d)

DISTRIBUTION OF ERRORS IN WATER LEVEL



FAP25

FLOOD MODELLING & MANAGEMENT

FLOOD HYDROLOGY STUDY

Distribution of Errors in Water Level

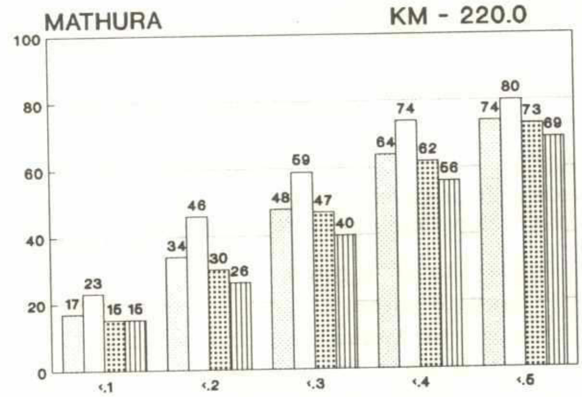
JUNE 1992

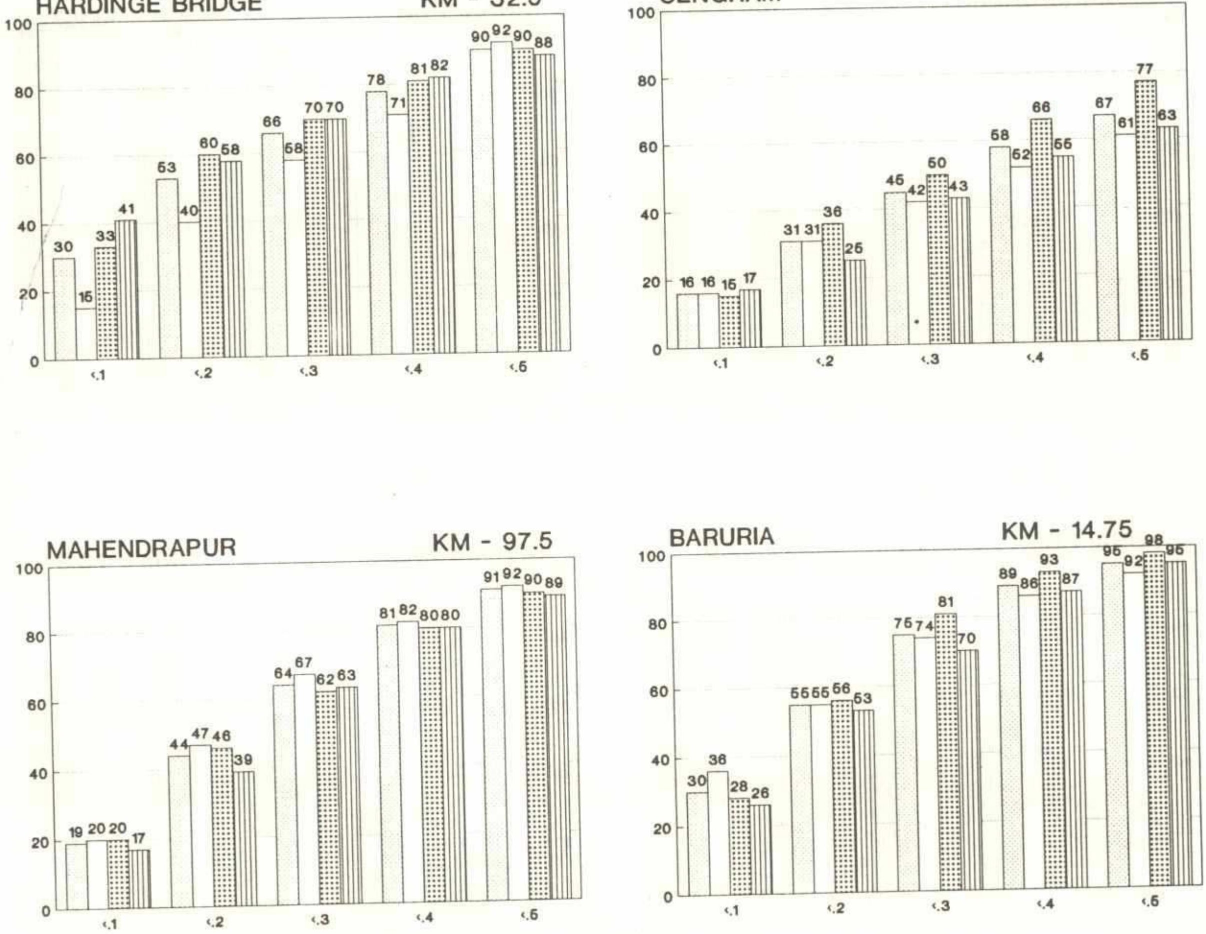
FIGURE 7.4 a)

DISTRIBUTION OF ERRORS IN WATER LEVEL

LEGEND :
X-axis = Error Level in Meter
Y-axis = Non Exceedance Percentage

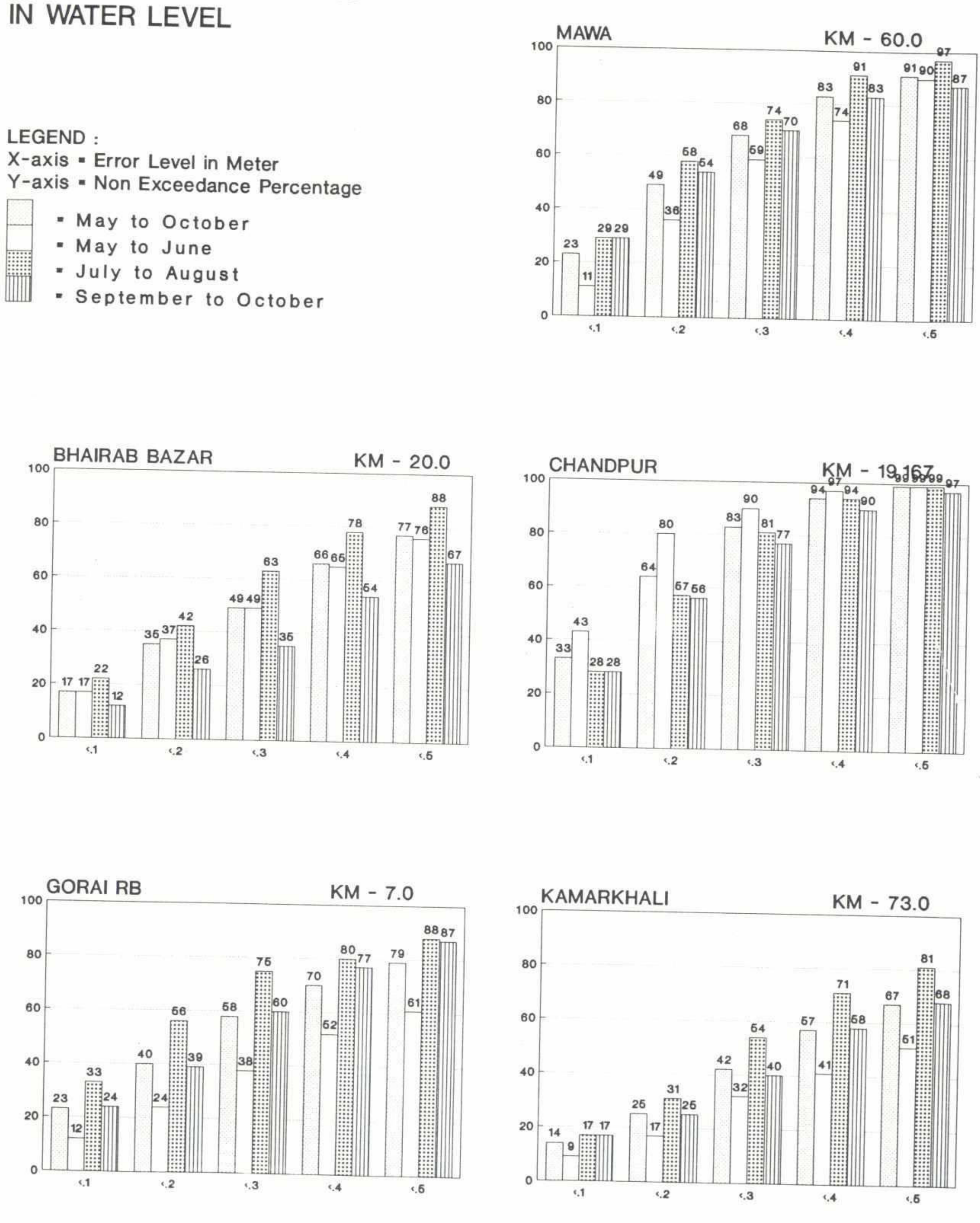
- May to October
- May to June
- July to August
- September to October



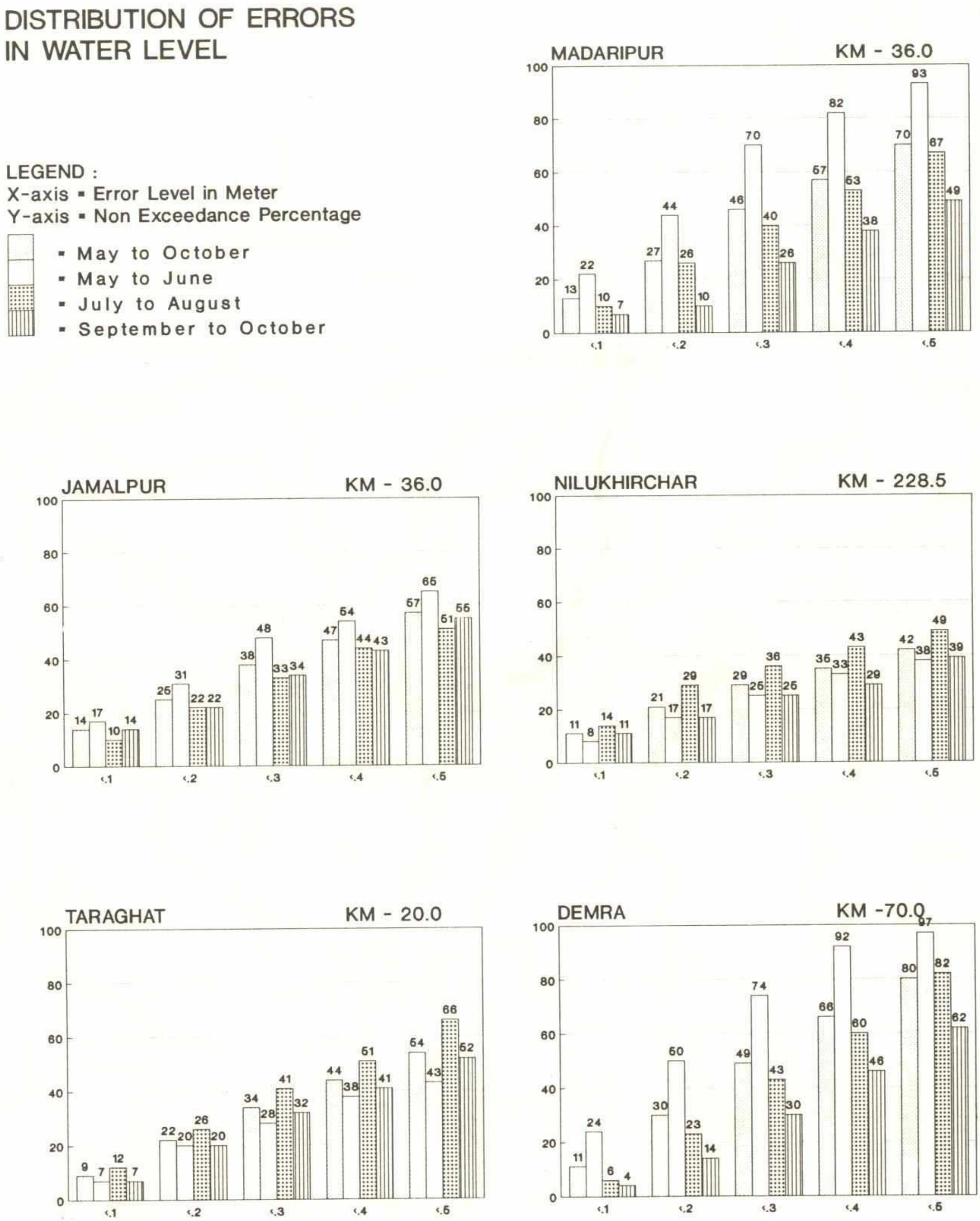


FAP25 FLOOD MODELLING & MANAGEMENT	FLOOD HYDROLOGY STUDY Distribution of Errors in Water Level
JUNE 1992	FIGURE 7.4 b)

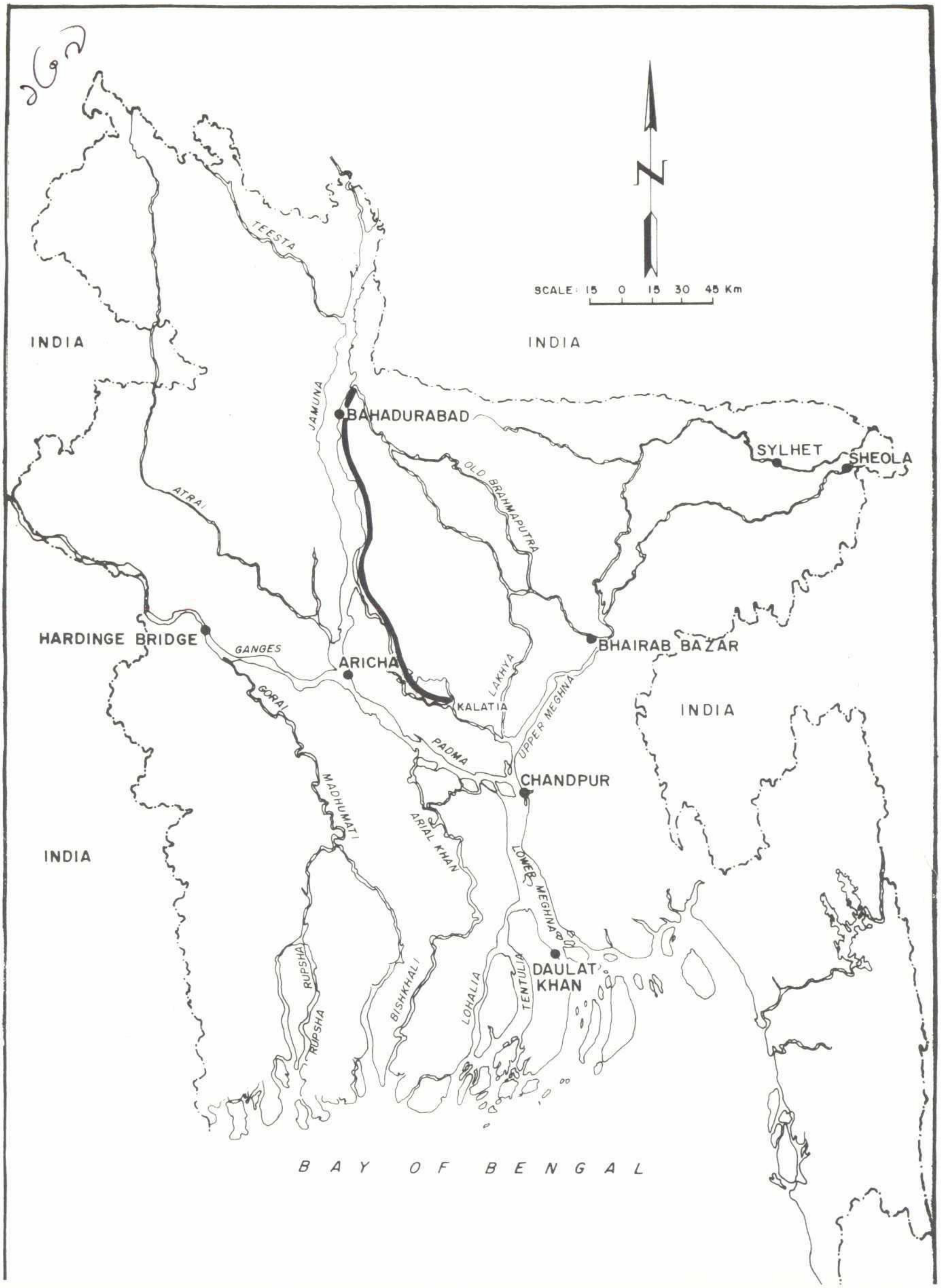
DISTRIBUTION OF ERRORS IN WATER LEVEL



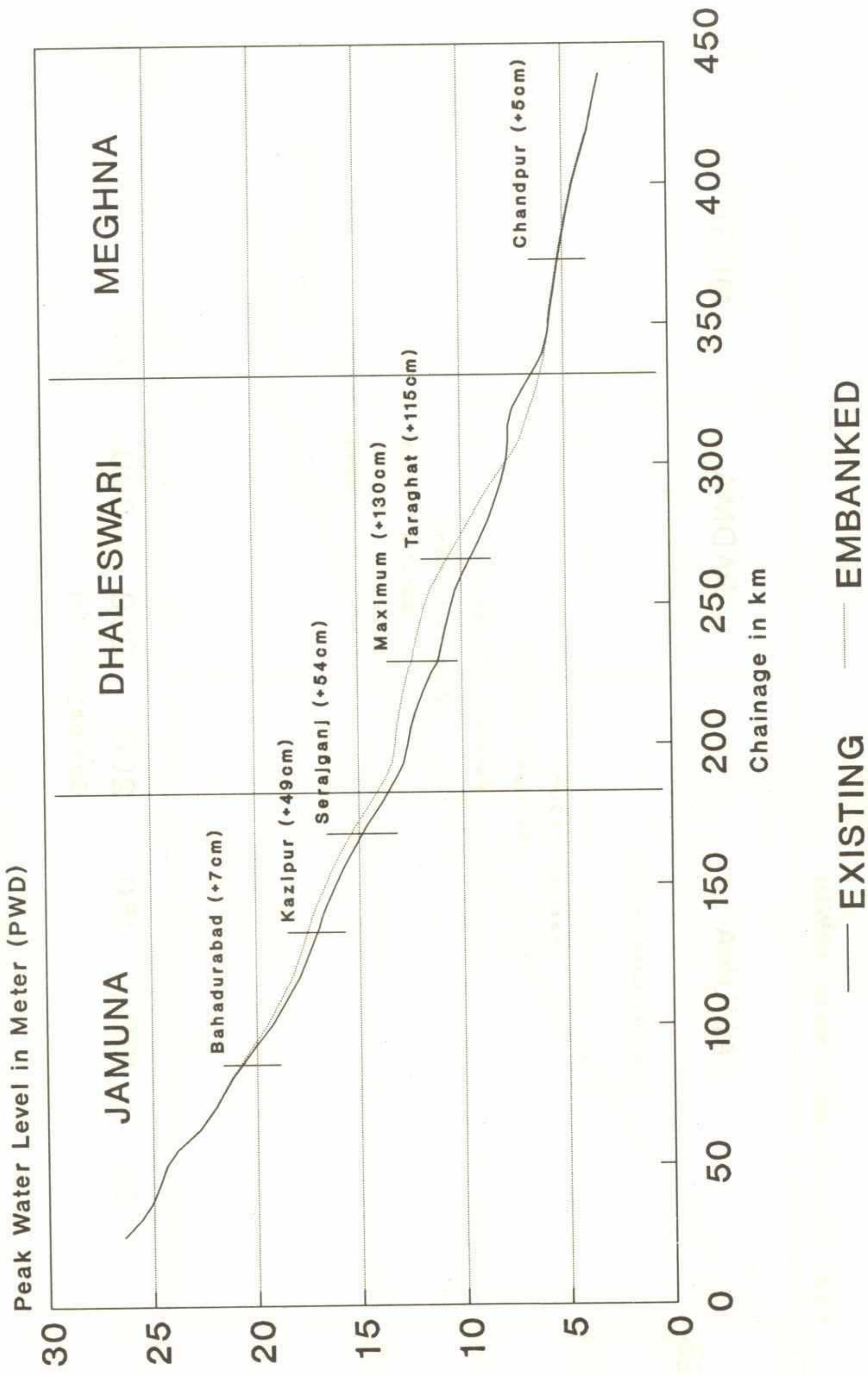
FAP25 FLOOD MODELLING & MANAGEMENT	FLOOD HYDROLOGY STUDY
	Distribution of Errors in Water Level
JUNE 1992	FIGURE 7.4 c)



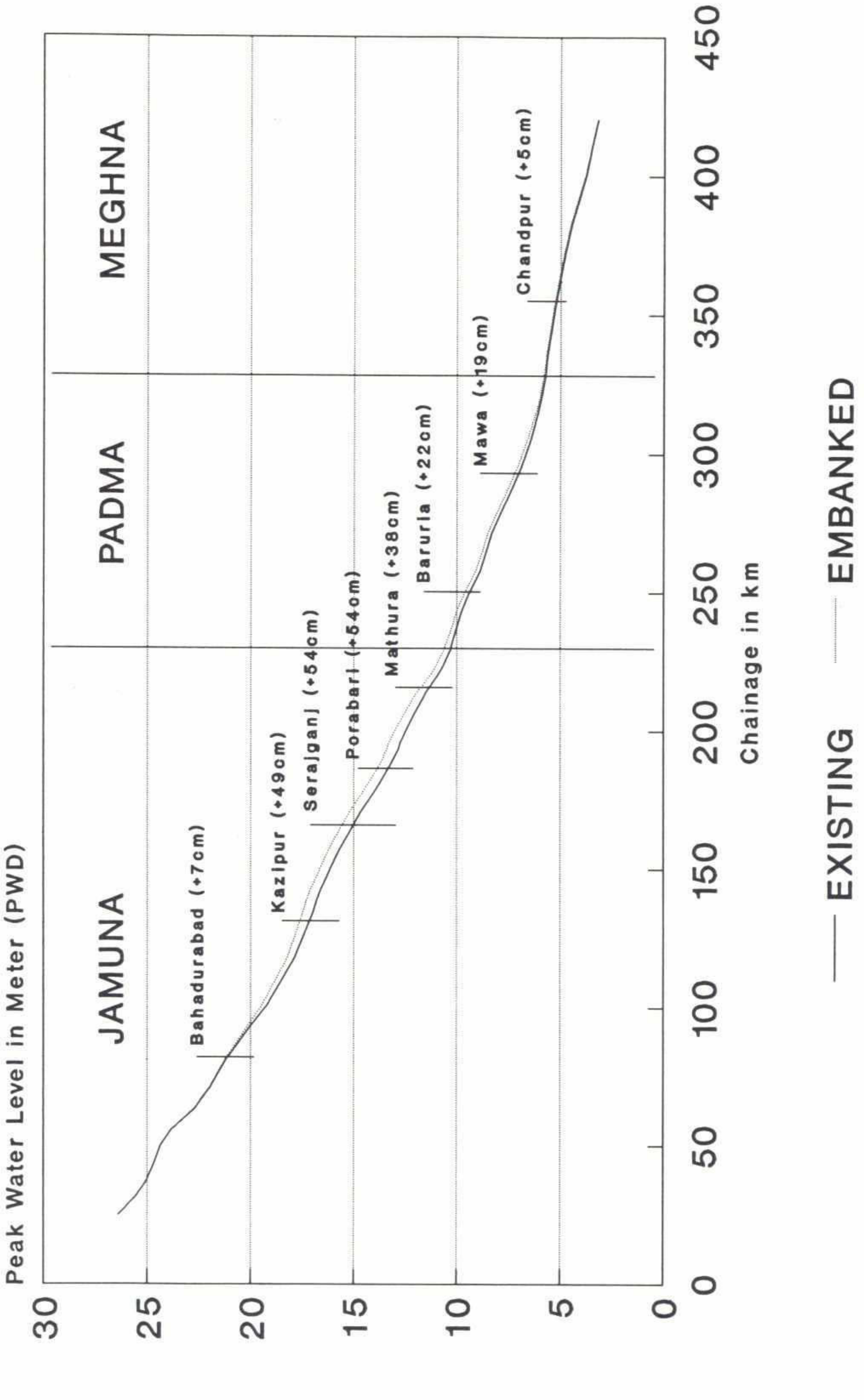
FAP25 FLOOD MODELLING & MANAGEMENT	FLOOD HYDROLOGY STUDY
	Distribution of Errors in Water Level
JUNE 1992	FIGURE 7.4 d)



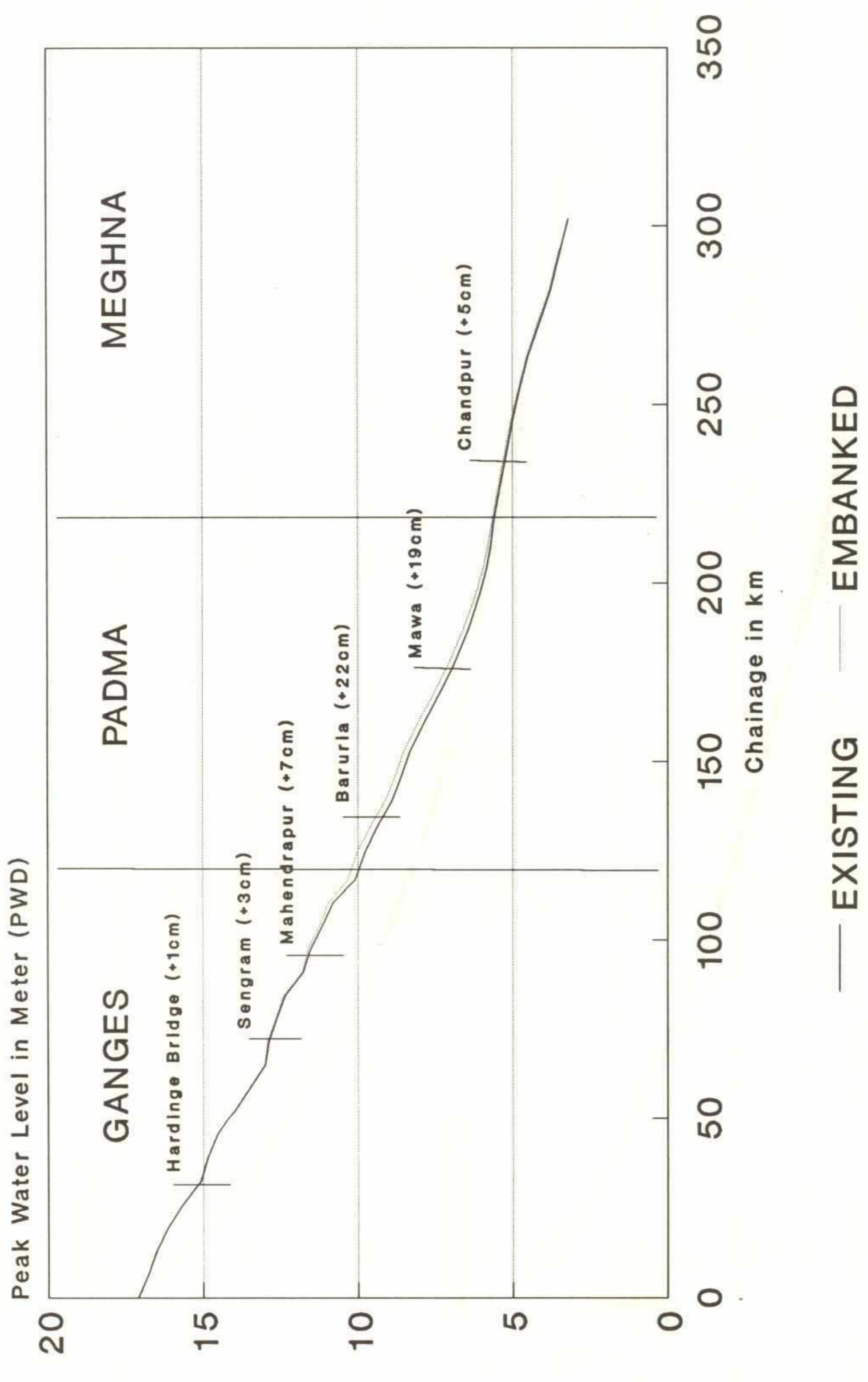
FAP25 FLOOD MODELLING & MANAGEMENT	FLOOD HYDROLOGY STUDY	
	Location of Embankment used to run FAP25-GM	
	JUNE 1992	FIGURF 7.5



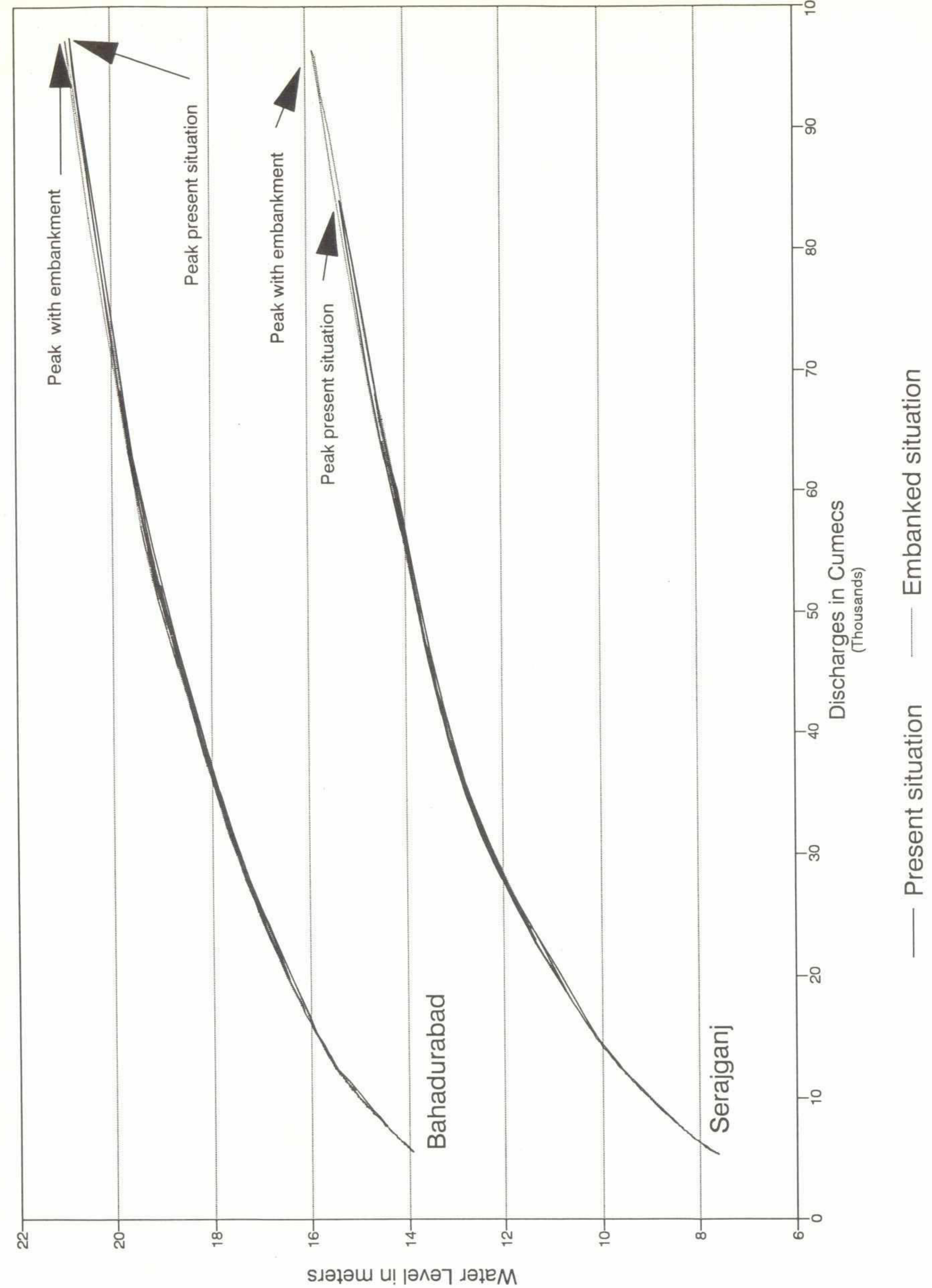
FAP25 FLOOD MODELLING & MANAGEMENT	FLOOD HYDROLOGY STUDY Comparison of Peak Water Level Profile : Jamuna-Dhaleswari-Meghna System in 1988
JUNE 1992	FIGURE 7.6 a)



FAP25 FLOOD MODELLING & MANAGEMENT	FLOOD HYDROLOGY STUDY
	Comparison of Peak Water Level Profile : Jamuna-Padma-Lower Meghna System in 1988
	JUNE 1992 — FIGURE 7.6 b)



FAP 25 FLOOD MODELLING & MANAGEMENT	FLOOD HYDROLOGY STUDY Comparison of Peak Water Level Profile : Ganges-Padma-Lower Meghna System in 1988
JUNE 1992	FIGURE 7.6 c)



FAP 25 FLOOD MODELLING & MANAGEMENT	FLOOD HYDROLOGY STUDY	
	Effect of Embankment on the Rating Curves at Bahadurabad and Serajganj	
	JUNE 1992	FIGURE 7.7