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BHOLA II IRRIGATION PROJECT FEASIBILITY STUDY HYDROLOGY

Report to Coode Blizzard Ltd/ Asian Development Bank

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Executive Summary

The hydrological aspects of the project were divided into three areas: assessing irrigation water salinity; estimation of flood risk from drainage congestion and high tides; and calculation of crop water requirements.

A. ASSESSMENT OF IRRIGATION WATER SALINITY

A1. The preferred source of irrigation water for the Bhola Phase II project is the Mayar Don khal which, at present, is open to the Tetulia channel which has freshwater for most of the year but episodes of high salinity have been recorded.

A2. As the tide rises saline water is transported landward. When freshwater velocities are low, normally from February through April, the tidal currents are sufficiently strong to carry saline water with an electrical conductivity of 5000 microsiemens (3000 ppm) north of Bhola island.

A3. Previous work undertaken to assess the probability of given levels of salinity was based on annual maximum salinity levels plotted against the mean March discharge from the Ganges and Brahmaputra combined. However, in 1990 the mean March flow was 7079 m^3s^{-1}, but the salinity level reached 2060 mS at Mayar Don, when only 1100 mS would be predicted. Recalculation using the 1990 data suggested that salinity would exceed 1000 mS in 4 years out of 5 at Mayar Don.

A4. In April 1991 EC levels in the Mayar Don area reached 5640 mS. Unfortunately, discharge data were not readily available to indicate whether this could be attributable to an unusually low freshwater discharge earlier that year.

A5. The two main factors influencing salinity levels are freshwater discharge and tide levels, but no simple relationship between these variables was found. However, the number of days salinity levels remain above critical values, given the peak, was found to be consistent between events. Thus the entire shape of the salinograph could be constructed by reference to the peak salinity level alone.

A6. Analysis of flows from the River Ganges were based on the period 1975-1989 (ie after construction of the Farraka Barrage). The level of compensation flow from the Barrage had not been agreed between the Bangladesh and Indian governments, but flows might be reduced in future.

A7. Deposition of sediment in the Meghna delta has led to a constantly changing pattern of sand bars and islands, which affects the distribution of freshwater flows and tidal movements and hence salinity levels. Implementation of land reclamation projects, linking islands and sand bars to Bhola island would change salinity levels in the Tetulia channel further.

A8. Since simple empirical relationships have failed to provide adequate models for predicting salinity levels, a physically based modelling approach may be necessary, such as that being constructed by the Master Plan Organisation in collaboration with the Danish Hydraulics Institute.

A9. It was recommended that further measurements of salinity levels at various location within the Tetulia channel should be made, with a sampling frequency of at least twice daily (at high and low tide) by conductivity meter.

B. ASSESSMENT OF FLOODING

B1. There are four main sources of flooding: (i) storm and tidal surges; (ii) high tides; (iii) excess rainfall; and (iv) overflow from the mainland rivers. Potential flooding from sources (i), (ii) and (iii) were considered as Bhola island is not affected by flooding of the mainland rivers.

B2. The island of Bhola is almost totally surrounded by an earthen embankment of around 6 - 7 m in height, with the exception of a number of khal openings including the Mayar Don khal. Whilst providing a barrier against flooding from the outside, during periods of heavy rainfall the embankment causes drainage congestion and flooding.

B3. The 1990 Statistical Yearbook of Bangladesh lists 60 cyclones which have occurred since 1797. Thus one has occurred, on average, once every 3 to 3.5 years. Twelve of the 60 appear to have affected the Bhola area, thus a surge tide of perhaps 3-10 metres will affect Bhola about once every 15 years.

B4. Normal high water levels were analysed using 16 years of data from Dasmonia. Higher levels are experienced during the summer months when the tides are elevated by high river discharges. There is only a small range in tide height with the 50 year return period maximum being only 0.5 metres greater than the average and only the areas immediately around the khal openings would be subject to flooding.

B5. Sluice gates have been provided to allow excess water on the landward side to drain through the embankment. The Bangladesh Water Development Board (BWDB) has produce standard procedures to size the structures, which require design rainfalls of 1 to 10 days duration with a return period of 10 years.

B6. Extreme value distributions were fitted separately to annual maximum daily rainfalls from the four rainfall stations on Bhola. The resulting standardised frequency curves did not vary by more than which might be expected due to sampling variability. Hence they were combined to form a regional rainfall frequency relationship applicable to all sites within on Bhola.

C. CROP WATER REQUIREMENTS

C1. Monthly average values of ETo were evaluated using data from the meteorological station at Bhola and were found to range from 2.73mm day^{-1} in December to 5.19 in April.

C2. FAO recommended kc values were used to assess the water requirement for each crop likely to be grown in the project area. The total farm water requirement was evaluated for each crop in l s^{-1}, separately for each half month. As an example the maximum total requirement to grow boro/aus rice was 11166 l s^{-1} (in the second two weeks of April and first two weeks of May) or approximately one l s^{-1} for each hectare.

C3. Analysis of the monthly rainfall data was undertaken to define an 'average' and a 'dry' year. It was concluded that, for return periods up to 5 years, estimates from individual rain gauge sites could be used. But for return periods of 10 years or greater, regional analysis of rainfall data was required.

Contents

C. ASSESSMENT OF CROP WATER REQUIREMENTS

A. Assessment of irrigation water salinity

A1. BACKGROUND

The FAO report on Water Quality for Agriculture (1976) indicated that water with an electrical conductivity (EC) of 750 micro-siemens (mS) - equivalent to a salinity level of 450 ppm - provides an upper limit for the salinity of irrigation water for rice paddies. The Leedshill-Deleuw report (1968) suggests that supplementary irrigation water with an EC up to 2000 mS (1200 ppm) will only slightly reduce crop yields and that rice can tolerate short duration applications of water up to 6000 mS.

The preferred source of irrigation water for the Bhola Phase II project is the Mayar Don khal which, at present, is open to the Tetulia channel which has freshwater for most of the year but episodes of high salinity have been recorded. This report provides for an assessment of the potential salinity of water sources for irrigation.

A2. INTRODUCTION

All the rivers in Bangladesh, apart from those in the south east around Chittagong, flow into a single large estuary (Figure A2.1). The influence of the tidal cycles reaches up the estuary far into interior of the country. As the tide rises saline water is transported landward. The limit of saline intrusion depends upon the relative magnitudes of the tide and of freshwater flowing seaward. When freshwater velocities are low, normally from February through April, the tidal currents are sufficiently strong to carry saline water along the Shahabazpur channel north of Bhola island. Figure A2.2 shows for Ilishaghat. However, at the end of March 1979 the EC of the water at Ilishaghat was recorded as 5000 mS (3000 ppm). Along the east coast of the island the salinity frequently reaches 18,000 mS. Salinity levels in Tetulia channel have generally been found to be much lower and rarely exceed 3000 mS.

A3. SALINITY SURVEYS

The Master Plan Organisation's (MPO) Land Reclamation Project (LRP) was involved in salinity data collection in the Bay of Bengal including the Shahabazpur and Tetulia channels. However, water samples were taken at a series of locations during monthly cruises, thus only one value of salinity is available for each site during any month and may be coincident with a period of low salinity. Consequently, these data do not provide sufficient information to justify detailed analysis. Data obtained, for example, during the survey of 21-28 March 1986 give an indication of the salinity profile in the Tetulia channel. Salinity values of 600 ppm (1000 mS) were recorded in the region of Mayar Don khal increasing to 800 ppm near Kachapia (at the entrance of the Lalmohan khal) and decreasing to 500 ppm towards Ilishaghat. These gradients are the reverse of those expected for a single time and presumably reflect the time lag between sampling.

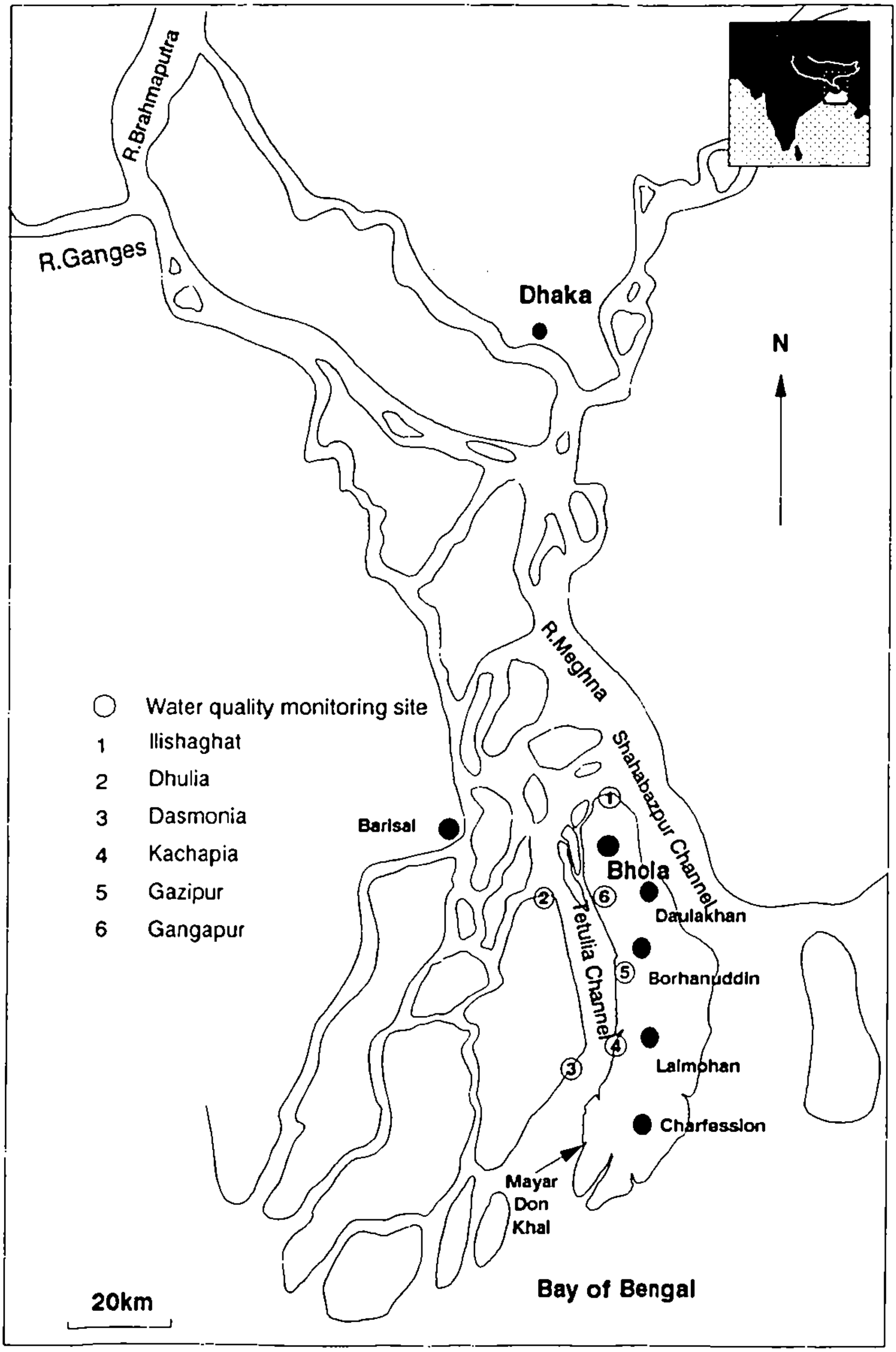


Figure A2.1 Location map

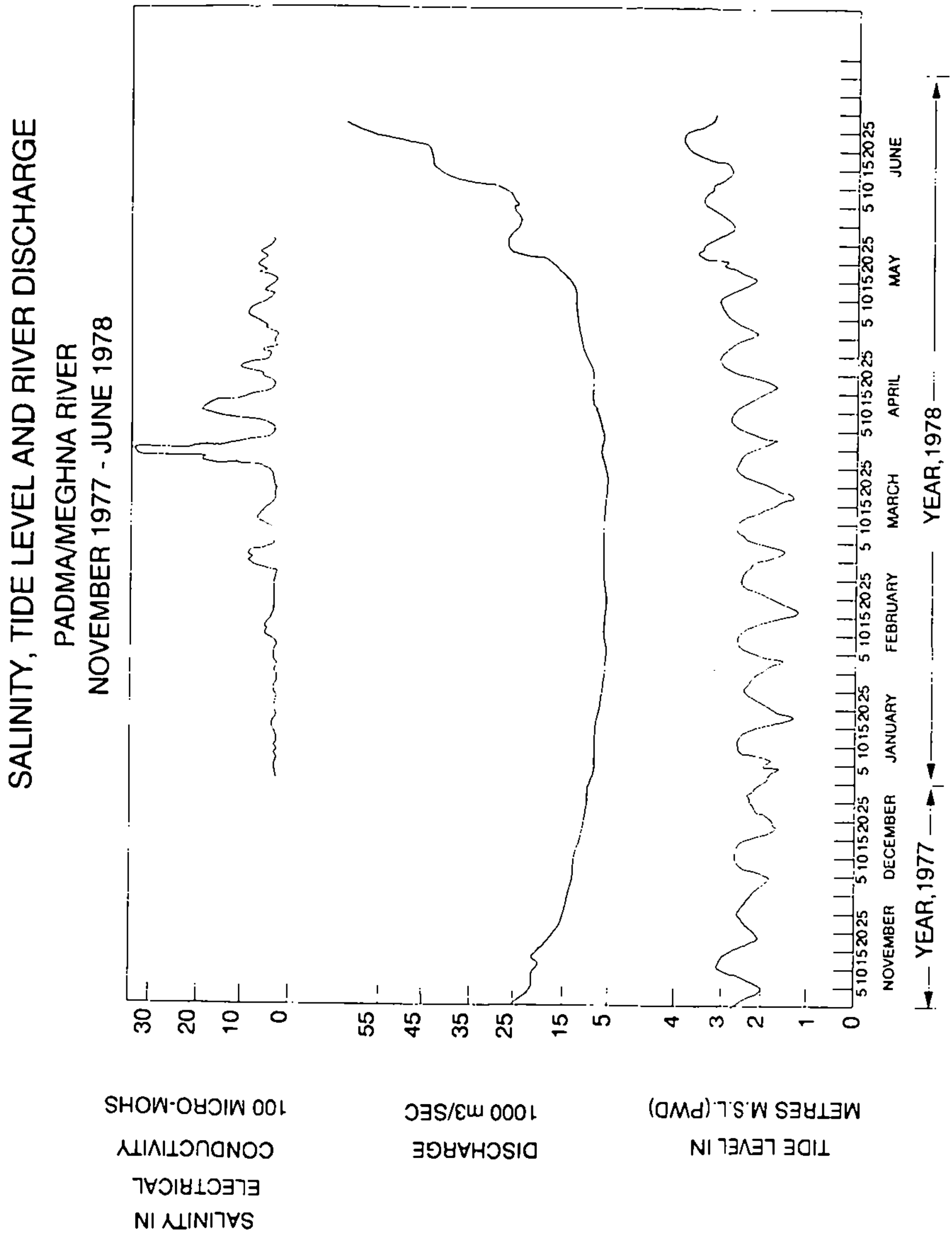


Figure A2.2 Salinity, tide level and river discharge for the Meghna estuary

A4. TIME SERIES DATA

Twice daily EC measurements, at high and low water levels, have been taken at a number of locations along the Tetulia channel. Since salinity remains high for several days this frequency of sampling is considered adequate for most assessment purposes. Table A4.1 details the data available for this study.

Table A4.1 Data available for the Tetulia channel during February - April

Location	Sampling frequency	Period of record
Ilishaghat	HWL LWL daily	1976-1987, 1990
Dhulia	HWL LWL daily	1976-1981, 1983-1985, 1990
	HWL LWL fortnightly	1986-1989
Dasmonia	HWL LWL daily	1976-1981, 1985
	HWL LWL fortnightly	1982, 1986-1989
	HWL LWL daily	1990
Gangapur	HWL LWL daily	1981, 1990
Gazipur	HWL LWL daily	1981-1982, 1990 (April)
Kachapia	HWL LWL daily	1981, 1990
Mayar Don	HWL LWL daily	1990, 1991 (April)

A5. HYDRAULICS RESEARCH 1981 REPORT

As part of the preparation for the Bhola Phase I irrigation project, Hydraulics Research Limited (HRL) undertook a study of salinity in the Tetulia channel. The conclusion of this study was that when upstream freshwater flows are low, high spring tides carry saline water into the Meghna channel north of Bhola. On the ebb tide there is a strong flow from the Meghna into the Tetulia channel carrying with it a slug of saline water. As a result, maximum salinity levels (3400 mS during April 1976) recorded at Ilishaghat for any single event (which may last about 7-10 days) occur at low water a day or so after the spring tide. The slugs of saline water are then transported seaward along the Tetulia channel becoming dispersed and diluted. Observations of salinity at Dhulia, some 25 km downstream of Ilishaghat, show lower peak levels (2800 mS during April 1976), reaching a maximum some 3-4 days later (see Table A5.1).

At Dasmonia, 60 km further south than Dhulia, high salinity levels tend to occur about 10 days after peak values at Ilishaghat. However, patterns of salinity are not as well defined in this region of the Tetulia channel as at Ilishaghat. Salinity levels at Dasmonia are normally lower than at Dhulia (2400 mS during April 1976) but are occasionally higher (eg in March 1976 and 1977). These later data are not consistent with slugs of saline water being diluted as they travel southward. It is likely therefore that saline intrusions from the southern end of the Tetulia channel also reach

Dasmonia. There is little evidence of a double peak in salinity which suggests that saline water from the north and south arrive simultaneously. Although limited data were available, salinity levels recorded at Kachapia (across the Tetulia channel from Dasmonia) are similar, suggesting no cross channel salinity gradient.

Table A5.1 Peak salinity measurements in the Tetulia channel in 1981

Location	Date	EC (mS)	Distance from Ilishaghat (km)	lag time from Ilishaghat (days)
Ilishaghat	8 March	2000	0	0
	5 April	1100		0
Dhulia	12 March	1450	25	4
	9 April	550		4
Gangapur	11 March	1400	35	3
	8 April	710		3
Gazipur	16 March	950	45	8
	3 April	750		-2 ?
Kachapia	18 March	1250	70	10
	15 April	650		10
Dasmonia	18 March	1200	85	10
	16 April	300		11

A one-dimensional mathematical model of tidal flows and salinity in the Meghna delta was developed by HRL assuming a steady freshwater flow of 6000 m^3s^{-1}. The model predicted realistic patterns of discharge and the maximum limit of the saline intrusion in the area; but was not designed to predict salinity levels at precise locations. To assess the probability of given levels of salinity, freshwater discharges, from the Ganges and Brahmaputra combined, for March (typically the month with the lowest discharge) were correlated with the number of days the EC was greater than critical levels (1000 and 1500 mS) at Dhulia and Dasmonia. Flow duration curves were constructed to assign a probability of there being less than a given discharge and thus more than a given number of days above each critical level of salinity (Figure A5.1). For example, the salinity level at Dasmonia would only be expected to exceed 1500 mS for more than 8 days, once every 4-6 years. The analysis assumed two equal episodes of high salinity during the period February to April each year. This feature of the salinity behaviour is very important since a number of high salinity events of short duration could be tolerated by cessation of irrigation pumping for a few days, whereas long periods of salinity may necessitate providing a control structure at the khal outlet to prevent saline intrusions.

A6. FURTHER WORK FOR BHOLA PHASE I

The project preparation report for Bhola Phase I also included an assessment of the possible effects of reductions in upstream freshwater discharge, due to increased abstraction, on salinity levels. Annual maximum salinity levels in the Tetulia channel were plotted against the mean March discharge for each corresponding year. The points depicted a consistent relationship, with maximum salinity increasing as discharge decreased (Figure A6.1). Flow duration curves, for three scenarios, were constructed to assign a probability of there being less than a given discharge and thus more than a given maximum level of salinity. The scenarios were: (i) the current freshwater flows; (ii) as (i) but with Ganges flows reduced by 50%; and (iii) as (i) but with no flow from the Ganges. It is noteworthy that the maximum recorded salinity level in the Tetulia channel in 1990 was 2060 mS at Mayar Don on 30 March, but the mean March flow was 7079 m^3s^{-1} (250,000 cusecs). These data do not conform with the model in the Phase I report, which suggests that the maximum salinity would reach only 1100 mS given that discharge.

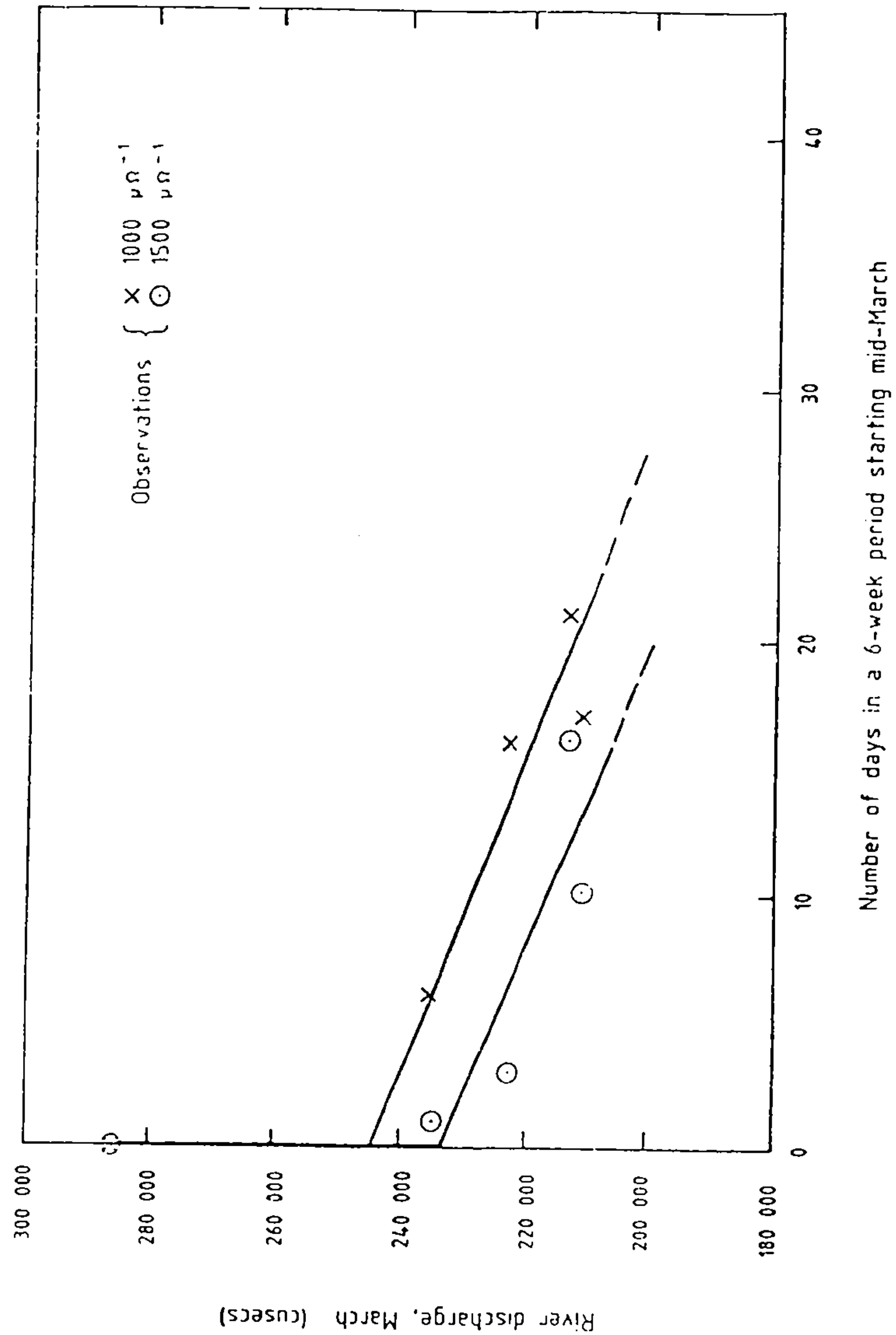


Figure A5.1 ***Durations when EC exceeds critical values at Dasmonia as function of river discharge***

A7 RECENT STUDIES

It seems clear that the two main factors influencing salinity levels are freshwater discharge and tide levels. However, there appears to be no simple relationship between these variables. Figure A7.1 shows maximum EC levels recorded during salinity events at Dasmonia. It is expected that in the lower right of the graph (where freshwater flows are high and high water levels are low) salinity would be low. In contrast, the upper left of the graph (where freshwater flows are low and high water levels are high) should exhibit high salinity measurements. This pattern is not well defined, though further data would be required for verification.

Figure A7.2 shows annual maximum peak salinity as a function of mean March flows for each year. There is a clear tendency for low freshwater flows to result in high maximum levels of salinity during that year. Figure A7.3 show the return period for a given mean March flows which can be used, in conjunction with Figure A7.2, to determine the probability of given maximum levels of salinity.

The mean flow during March had been used in other reports as an indication of the magnitude of flows during each dry season. To assess whether this was the best index, mean 10-day flows for February, March and April were assembled.

The peak salinity value for each year was plotted against the mean flow for the 10 days preceding the date of the salinity peak. These statistics were poorly correlated. In successive graphs peak salinity was plotted against mean 10-day flows from earlier periods in the year. This was to model different time-lags between flows being measured at the gauging stations and influencing peak salinity. In no case was the correlation with peak salinity better than when mean March flows were used.

Figure A7.4 shows detailed data for the low flow period February to April, 19777. It suggests a relationship between the height of the spring tide and maximum levels of salinity. To exclude the influence of freshwater discharge, peak salinity values associated with similar March flows were collated. However, no generalised relationship could be found between these salinity levels and the height of the preceding Spring tide.

One consistent characteristic of salinity events is the shape of the salinograph. Figure A7.5 shows the number of days EC levels remain above critical values, given the peak salinity. This suggest that the entire shape of the salinograph may be constructed by reference to the peak salinity level alone. The data were recorded at Dasmonia, but salinographs at other stations also exhibited similar standard shapes.

A8 HYDRAULICS RESEARCH 1991 REPORT

As part of the preparatory work for the Bhola Phase II project HRL updated its risk assessment of saline intrusions into Mayar Don khal. This merely involved reevaluating the freshwater flow duration curve and considering salinity data collected during 1990, notably at Mayar Don khal. Using the methodology developed in the 1981 report, the main conclusion was that EC values at Mayar Don will exceed 1000 mS in 4 years out of 5.

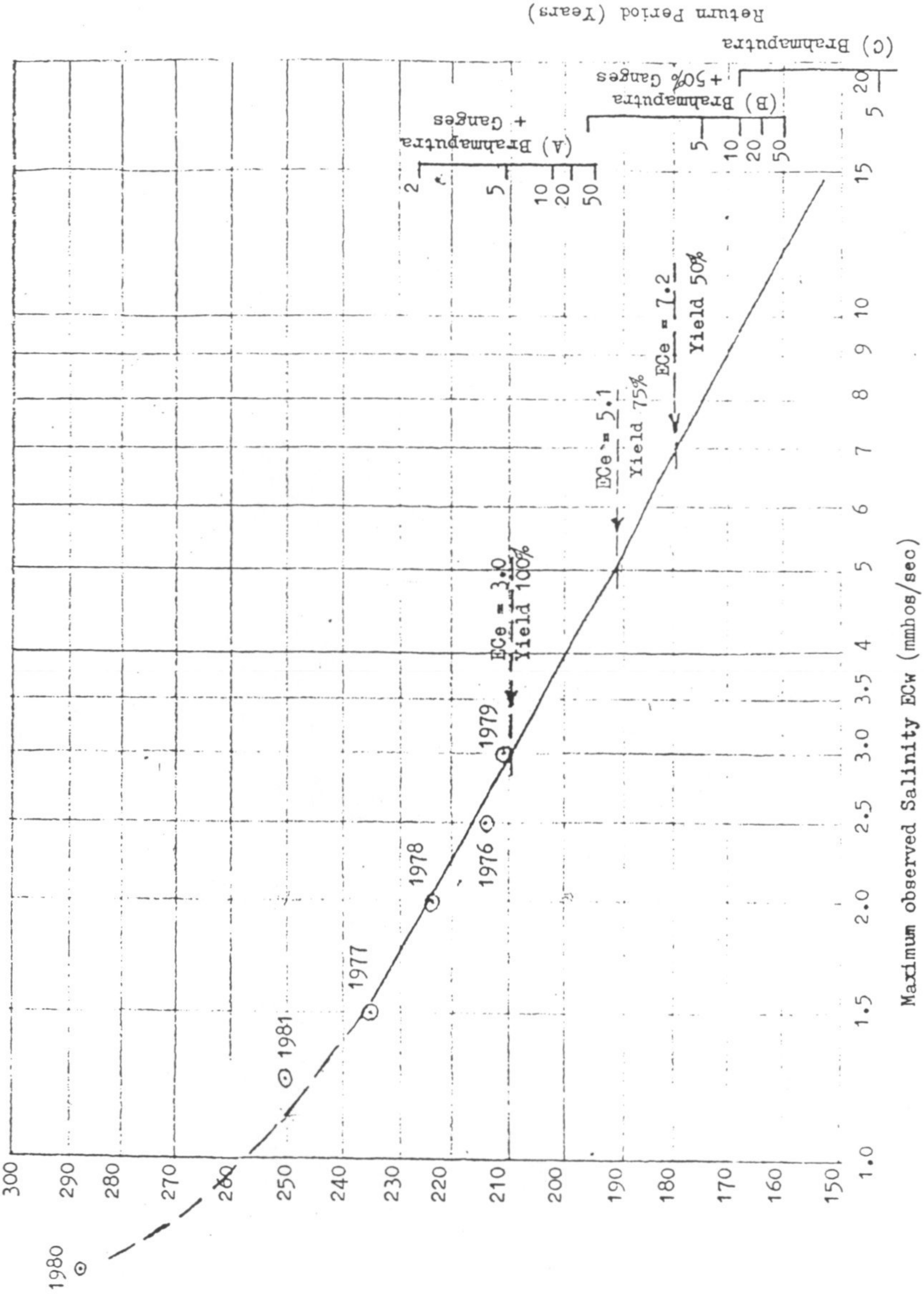


Figure A6.1 Return periods of maximum salinity levels in the Tetulia channel

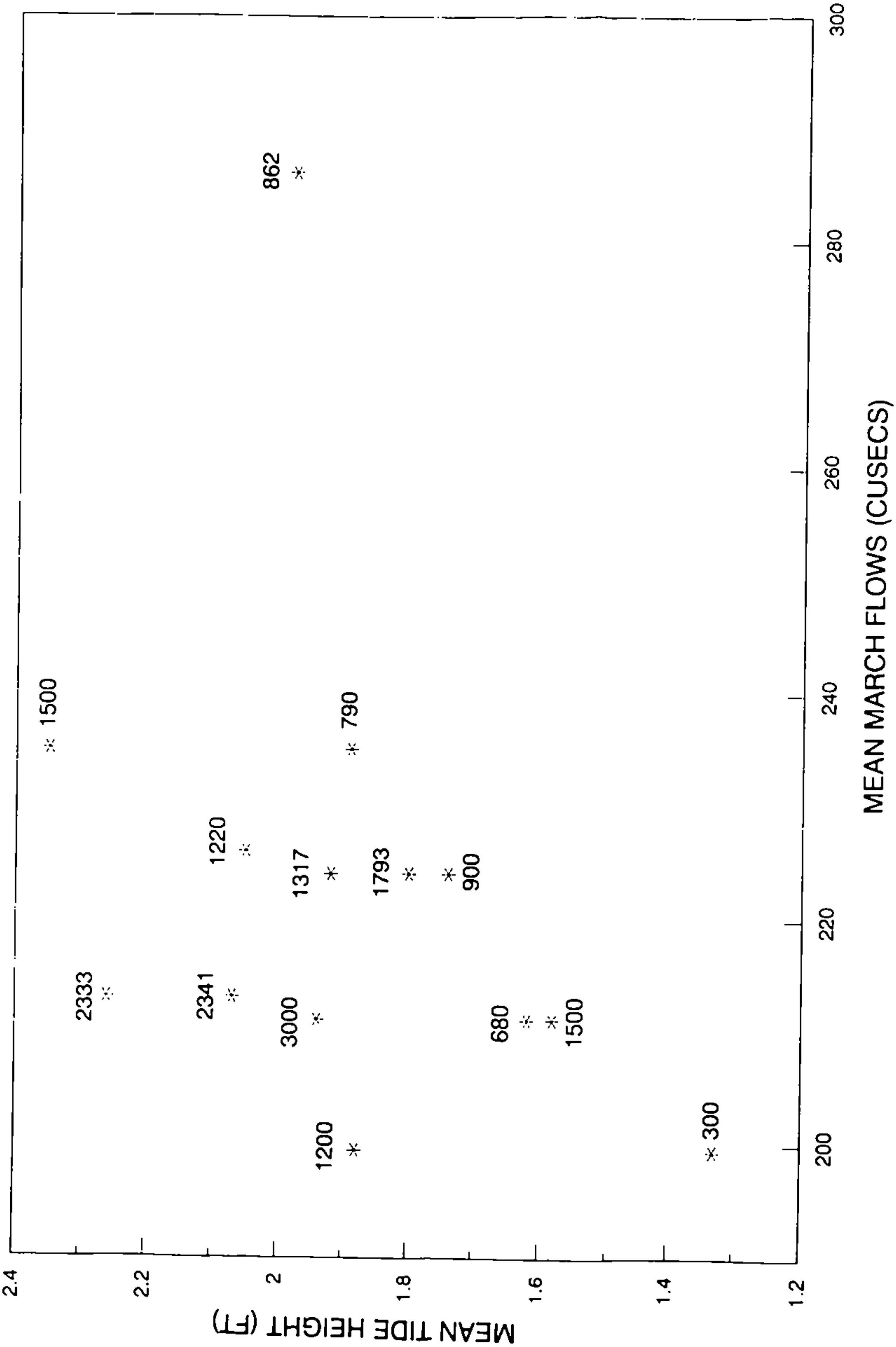


Figure A7.1 ***Maximum salinity as a function of river flow and tide height at Dasmonia***

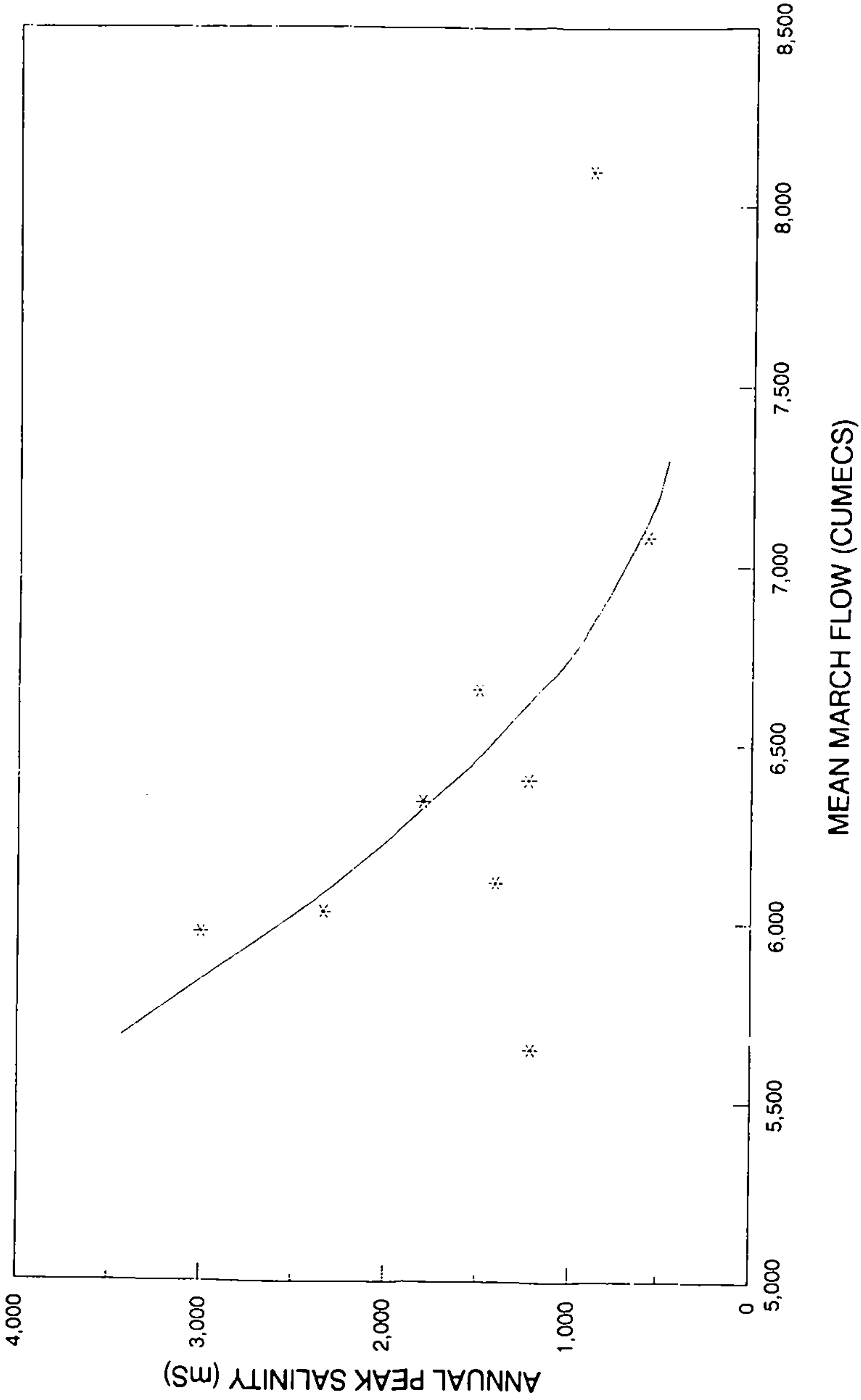


Figure A7.2 Annual maximum salinity as a function of river flow at Dasmonia

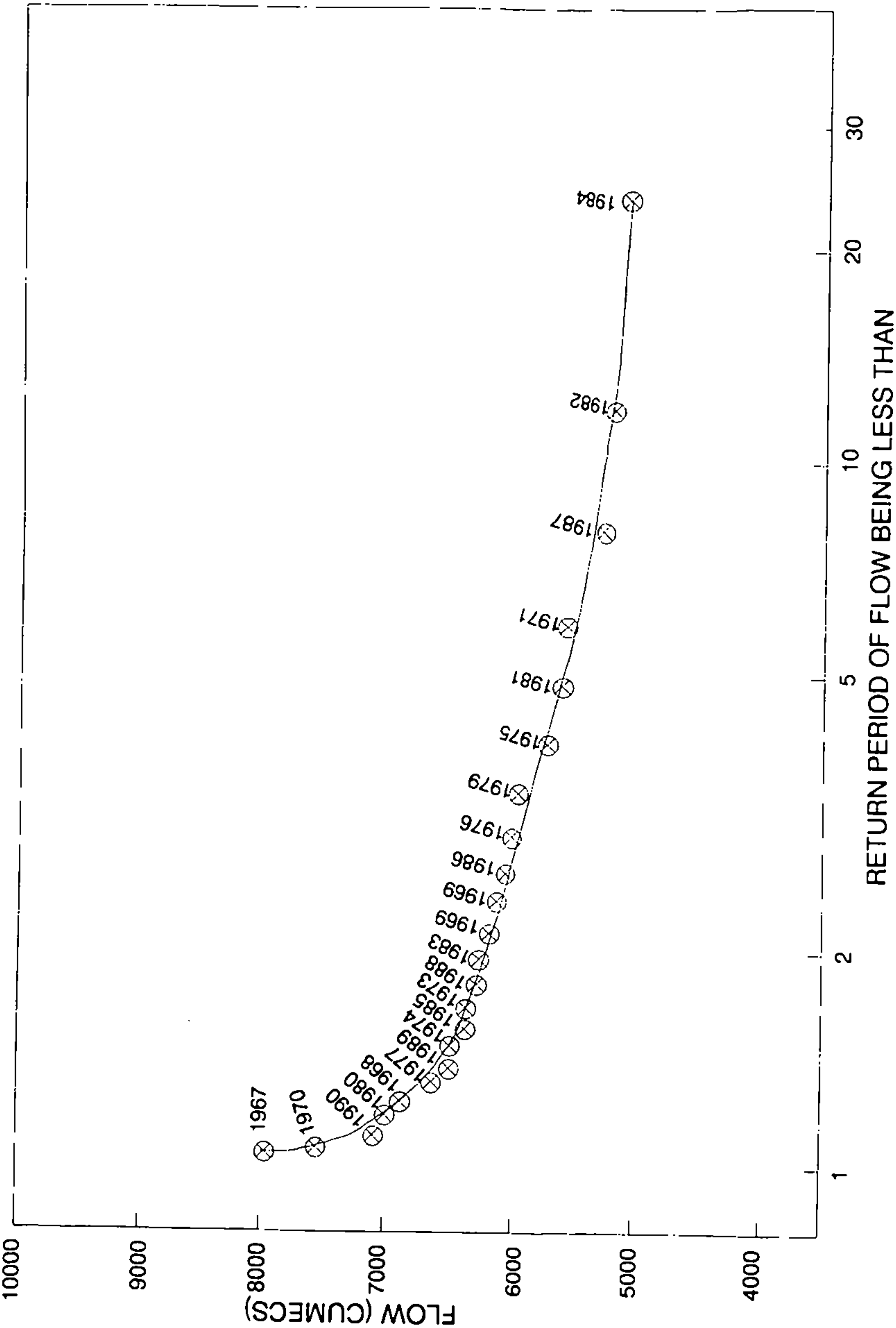


Figure A7.3 ***Low flow frequency curve for the March mean flow of the River Meghna***

A9 SALINITY MEASUREMENTS MADE IN THE MAYAR DON KHAL

Data collected up until 1990 indicated that the salinity levels around Kachapia (at the mouth of the Lalmohan khal) would be similar to those at Dasmonia and it was hoped that these would also provide a good analogy for levels in the Mayar Don khal area. Table A9.1 demonstrates that this is not the case. The freshwater discharge during March was the third highest recorded and peak salinity levels were low at most sites in the middle and northern Tetulia channel (this corroborated further the similarity in salinity levels between Dasmonia and Kachapia). However, much higher levels were recorded at Mayar Don khal. In April 1991 EC levels in the Mayar Don area reached 5640 mS. Unfortunately, discharge data were not readily available to indicate whether this could be attributable to an unusually low freshwater discharge earlier that year.

Table A9.1 Peak salinity measurements inthe Tetulia channel in 1990

Location	Date	Peak salinity (mS)	Location	Date	Peak salinity (mS)
Mayar Don	28 February	1929	Dasmonia	27 February	324
	13 March	2020		14 March	569
	30 March	2060		29 March	361
	24 April	1305		25 April	304
Kachapia	28 March	315		1 April	709
	23 April	441		19 April	210

A9 MPO 1987 REPORT

The Master Plan Organisation's Surface Water Availability report (1987) addressed the problem of salinity, agreeing with the generally held view that there was no simple relationship between salinity levels during individual events and freshwater discharge. It pointed out that EC levels also depend on river geometry and tide levels. This is exemplified by data from Ilishaghat for April 1978 and March 1981 when on both occasions EC levels reach 2000 mS, but mean monthly discharges were quite different, ie 7010 and 3820 m^3s^{-1} respectively. However, the report utilises correlations between annual maximum salinity and mean discharge to evaluate the amount of freshwater required to ensure that EC levels do not exceed 2000 mS for more than 15 days in any month. For March this was estimated at 1375 m^3s^{-1} at Ilishaghat and 555 m^3s^{-1} at Dhulia.

A10 MPO'S SALINITY MODEL OF THE DELTA

The Master Plan Organisation's Surface Water Modelling Centre, in collaboration with the Danish Hydraulics Institute had produced a hydraulic model of the Bay of Bengal and the lower Meghna delta to investigate the movement of saline water.

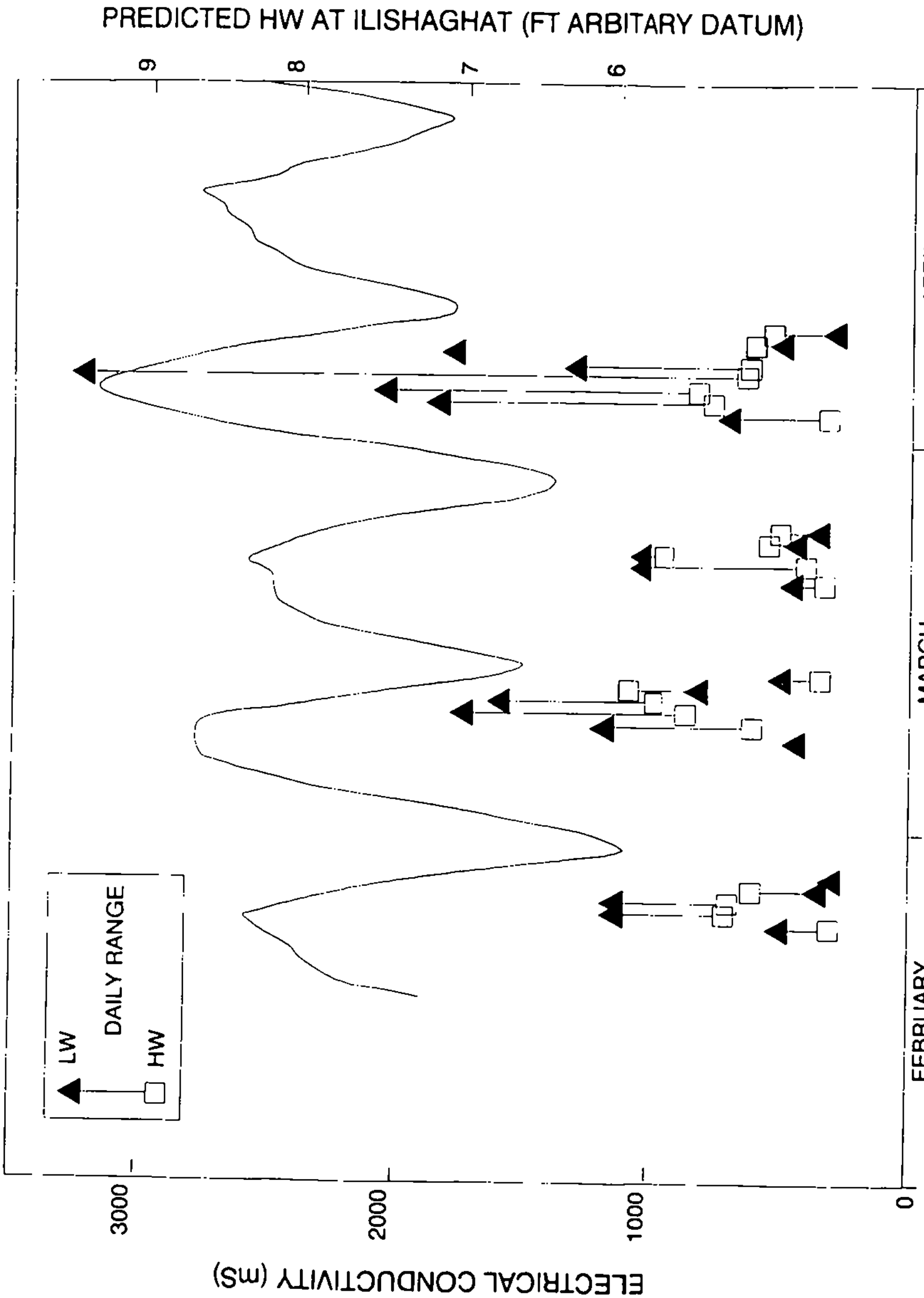


Figure A7.4 Observed salinity variations at Ilishaghat, 1977

Output from the model shows a longitudinal profile of salt concentrations along a chosen path. The profile changes at each specified time interval (eg 1 hour) thus depicting the movement of saline water with the incoming and outgoing tide. At present, each model run has a fixed freshwater discharge input from the Meghna channel. The model parameters had been chosen with reference to the ship-borne salinity surveys and, as yet, have not been calibrated against time series data for any specific location. Consequently, the results of the model are provisional. However, the model displayed decreasing salinity levels from Mayar Don khal and Dasmonia northwards to Kachapia and Dhulia and from there increasing towards Ilishaghat. The model implied that high salinity levels in the south of the Tetulia resulted predominantly from intrusion from the south and that saline water from the north imparted a negligible contribution due to dilution on its journey southward.
Since no simple empirical relationships have failed to provide adequate models for predicting salinity levels, a physically based modelling approach may be necessary. This model could be calibrated against time series data for the recording stations in the Tetulia channel.

A11 FUTURE CHANGES IN FRESHWATER FLOW REGIME

The Master Plan Organisation's Surface Water Modelling Centre had produced a water balance for the Meghna, Ganges and Brahmaputra rivers showing major abstractions from, and discharges to, the system. Two sets of results were available (Figure A11.1). First, the current situation ie. at March 1990 and second, a forecast for the year 2010. Each set contained mean monthly streamflow figures for an average year and a once in five year drought. Flows from the River Ganges are based on the period 1975-1989 (ie after construction of the Farraka Barrage) and no attempt has been made to forecast any reduction in flows up to 2010. At the time of writing the compensation flow from the Barrage was under discussion between the Bangladesh and Indian governments and had not been resolved.

The present mean March discharge for the Meghna channel was given as 6356 m^3s^{-1} (including a 354 m^3s^{-1} contribution from the Meghna river itself). The mean March flow during the once in five year drought is estimate at 5636 m^3s^{-1} (with only 82 from the Meghna river). Projections for 2010 are that the mean March flow will have reduced to 5726 m^3s^{-1} and for the five year drought to 5267. Contributions from the Meghna river are assumed to be unchanged.

Calculations for the Bhola area are based on a fixed 60% of the flow from the Meghna channel reaching the Shahabazpur channel, whilst the remaining 40% is apportioned between the Barisal channel (37.5%) and the Tetulia channel (62.5%). Projections for 2010 show a abstraction of 41 m^3s^{-1} during March and April to satisfy the irrigation requirements of Bhola. For March 2010 the mean flow in the Tetulia channel is estimated at 1430 m^3s^{-1} compared with 1589 m^3s^{-1} for 1990 (Table A11.1). Figures of 1257 and 1409 are given respectively for the five year drought. Also shown is the discharge required to maintain critical EC levels. For the Tetulia channel, 550 m^3s^{-1} is required for levels not to exceed 2000 mS for more than 15 days during March. These results were derived from the analysis described in section A9.

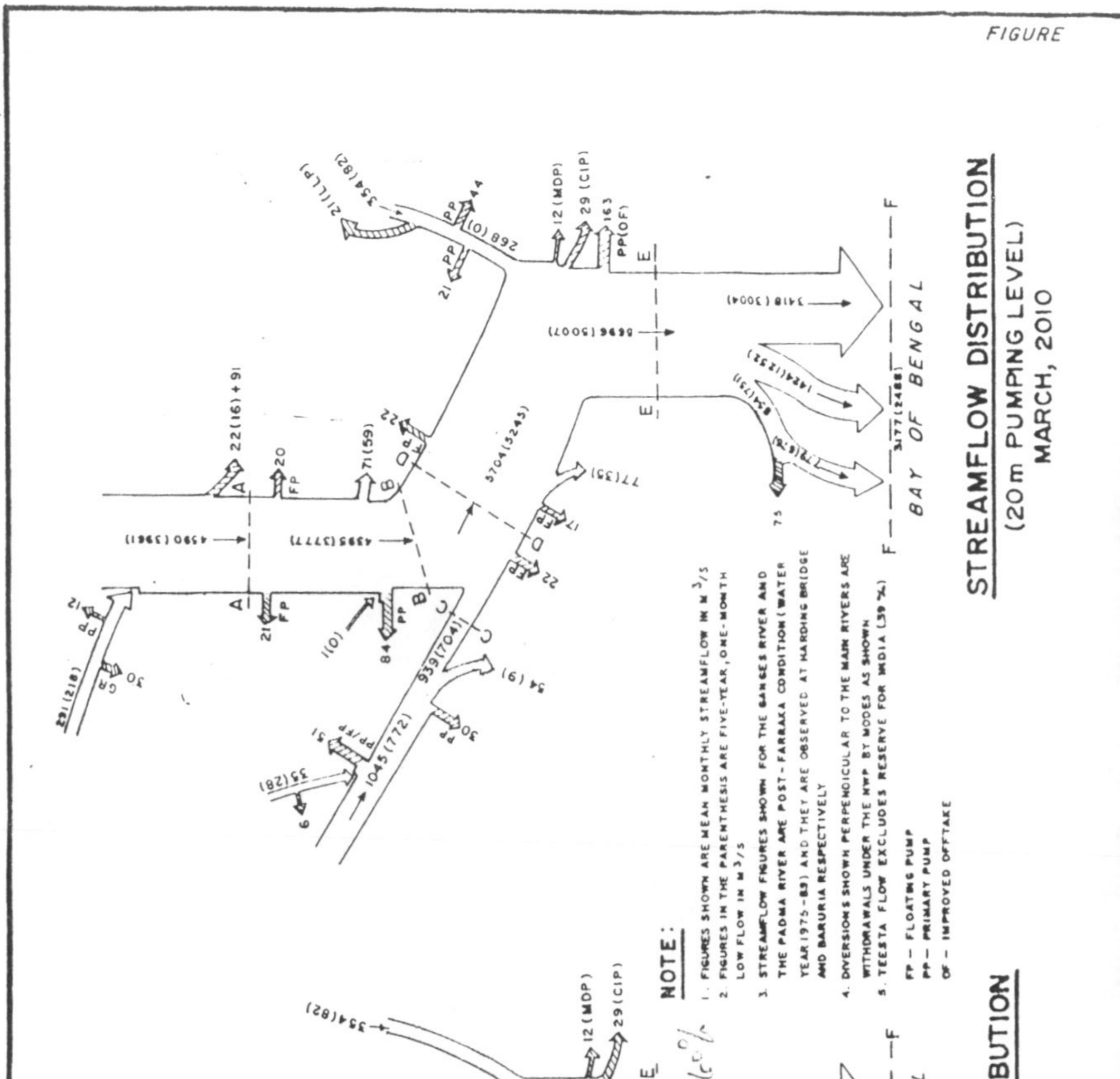


Figure A11.1 *Water balance of the Meghna, Ganges and Brahmaputra rivers showing current situation and a forecast for 2010.*

Table A11.1 Current (1990) amd projected (2010) March flows for the rivers and channels around the Meghna channel.

	Brahmaputra 1	Ganges 2	Meghna 3	Tetulia
1990				
Mean flow	4730	1045	6356	1589
5 year drought	4081	772	5636	1409
2010				
Mean flow	4417	1080	5718	1430
5 year drought	3799	800	5029	1257

Notes 1 Brahmaputra upstream of confluence with Ganges
2 Ganges at Harding Bridge
3 Meghna channel below Meghna river confluence

A12 CHANNEL PATTERN CHANGES

The rivers feeding the Meghna delta carry a high sediment loads which had increased in recent times due to soil erosion in the headwater catchments. Deposition of the sediment has led to a constantly changing pattern of sand bars and islands. As a consequence, discharges and velocities in the dividing channels are also changing. Recent maps show considerable changes in the seaward and landward ends of the Tetulia channel. Sedimentation to the north of Bhola may influence the percentage of the Meghna's flow entering the Tetulia and Shahabazpur channels. Sedimentation may also influence the pathways of slugs of saline water during their passage along the Tetulia channel. This would mean that the relationship between freshwater flows, as measured upstream of the tidal limit, and tide levels is not constant for any location. This is another area where a physical model of the delta may provide important results.

An indication of the high sediments yields has been the practice of building barrages between islands to trap sediment and thereby reclaim land. As part of the Master Plan Organisation's Land Reclamation Project, a number of barrages have been considered linking the islands and sand bars off the south west coast to Bhola island. One scheme considered in some detail was to link the island of Kukrimukri to Bhola with the intention of allowing sediment to build up behind the barrage to a depth at which the land could be reclaimed for agricultural use. However, estimates of sediment transport in the Tetulia channel suggest that accretion would be too slow to make this scheme viable. Before other major schemes are considered in detail, a small pilot scheme may be undertaken, linking two small islands in the Tetulia channel in order to quantify likely rates of sedimentation. If any of these major schemes are implemented, changes in salinity levels in the Tetulia channel are very likely.

A13 SUMMARY

Salinity levels in the Mayar Don khal opening, taken in April 1991, were higher than any other measurements taken in the southern Tetulia channel and levels recorded in

1990 were far higher than at Dasmonia which, it had been hoped, could be considered as comparable location. At present the rarity of hydrological conditions in 1991 is unknown.

There appears to be no satisfactory empirical relationship between freshwater flows, tidal levels and salinity levels in Tetulia channel around the entrance to the Mayar Don khal. Furthermore, although there is a consistent time lag between peak levels of salinity at Ilishaghat and further down the Tetulia channel, there is no obvious relationship between the values of salinity reached at these locations which might allow real-time forecasting. Further data might illuminate some relationship which could be of practical use.

March flows may not be the best indicator of maximum salinity, but mean flows of shorter durations for different periods failed to show an improvement in correlation. An independent estimate of the lag time between measurement of the discharge upstream and its effects downstream might be useful.

Sedimentation and bar formation may play an important role in distributing saline water within the delta. Since this is constantly changing, it might continually redefine the relationship between upstream freshwater discharges, high water levels and salinity at any particular location.

No official forecast of reduction in flows from Farraka barrage is available. However, the flow duration curve derived for the Meghna channel could easily be amended to accommodate changes in flow regime.

A14 RECOMMENDATIONS

Ideally Mayar Don khal should be closed to prevent highly saline water from intruding into the irrigation water sources. However, other, overriding considerations such as navigation and construction costs may preclude this. If the khal is left open, further measurements of salinity levels at Ilishaghat, Kachapia, Dasmonia and, most importantly, Mayar Don khal should be made. Sampling frequency should be at least twice daily (at high and low tide) by conductivity meter. A dedicated observer should be located at each site during the period February to April. Further data may allow a real-time salinity forecasting model to be developed based on the peak level at Ilishaghat (giving a 10 day warning) and Mayar Don. To compliment these data, estimates of the mean 10-day discharge in the Tetulia channel should be derived.

MPO's hydraulic model of the delta should be calibrated using the existing, and future, time series data and provision should be made for the effects of changes in channel pattern.

B. Assessment of flooding

B1. BACKGROUND

Flooding is a major problem in Bangladesh with between 20 and 60% of the land area inundated each year. This results in loss of life, destruction of crops and properties. There are four main sources of flooding:

(i) storm and tidal surges;
(ii) high tides;
(iii) excess rainfall; and
(iv) overflow from the mainland rivers: Ganges, Brahmaputra.

This report provides for an assessment of the potential flooding resulting from sources (i) to (iii) on Bhola island. Bhola is not affected by flooding of the mainland rivers.

B2 FLOOD EMBANKMENT

The island of Bhola is almost totally surrounded by an earthen embankment of around 6 - 7 m in height. The exceptions to this, at the time of writing, were a number of khal openings including the Mayar Don khal and Lalmahon khals, on the western side of the island. Whilst providing a barrier against flooding from the outside, during periods of heavy rainfall the embankment might hinder evacuation of excess water from the interior of the island thereby exacerbating flooding. The cyclone protection Flood Action Plan suggests that it is not necessary to close all opening in the embankment, thus it is very unlikely that this will be undertaken.

B3 STORM AND TIDAL SURGES

Flooding affected many parts Bangladesh on 29-30 April 1991 following a severe cyclone. However, the dynamics of this particular cyclone were such that high water level in the Mayar Don khal was actually around one metre lower than would normally be expected. In contrast the islands in the east of the Bay of Bengal and the mainland around Chittagong experienced a tidal surge with high water levels up to 6 metres above normal.

During the cyclone of November 1970, Bhola did suffer serious flooding, up to 3 metres deep. If the embankment around the island is not completed, future cyclones could produce further flooding. For this reason it is worth considering the frequency of occurrence of cyclone surges.

The 1990 Statistical Yearbook of Bangladesh lists 60 cyclones which have occurred since 1797. Thus one has occurred, on average, once every 3 to 3.5 years. It is noteworthy that 24 of these storms occurred between April and June, and all but two (September 1991 and August 1974) of the remaining 36 were in the October to December period. The Yearbook provided wind speed data and surge tide height for some cyclones as well as information on loss of life. The lack of consistent records for each cyclone renders it impossible to quantify their relative magnitude and to evaluate the probability of occurrence of certain parameters, such as wind speed or surge tide height.

It is clear from the information available on the historical cyclones that coastal districts around Chittagong and islands in the eastern Meghna estuary are most at risk. Table B3.1 lists 12 that appear to have affected the Bhola area; which amounts to only one in every five to have occurred in Bangladesh. Thus it can be inferred that a surge tide of perhaps 3-10 metres will affect Bhola about once every 15 years.

Table B3.1 Cyclones and tidal surges between 1797 and 1991 to have affected Bhola

Date		Wind spped (km/hr)	Surge height (metres)	Death toll in Bangladesh
May	1822			40,000
October	1831			
October	1876		4-14	
September	1919			
May	1941			
November	1950			
May	1958			
May	1965	161	3-4	19,270
November	1970	222	3-10	300,000
May	1975	96-112		41
May	1977	124		
November	1986	110	4-5	5,708

B4 HIGH WATER LEVELS IN THE DELTA AREA

Since the only gaps in the embankment are found on the side of island facing the Tetulia channel, the risk of flooding from high water levels can be assessed by analysing the water levels at Dasmonia for which 16 years of record are available.

Figure B4.1 shows the maximum and minimum water levels recorded in each month at Dasmonia. It can be seen that higher levels are experienced during the summer months when the tides are elevated by high river discharges.

In order to assess the probability of water exceeding a critical level the maximum level reached in each year was extracted from the data. These values can be expected to follow an extreme value distribution. The extreme value distribution type I distribution was fitted to these data using the method of probability weighted moments. The results are given in Table B4.1 and shown graphically in Figure B4.2. It can be seen that there is only a small range in tide height with the 50 year return period maximum being only 0.5 metres greater than the average.

To translate these results into potential flood levels on Bhola island the datum at Dasmonia needs to be related to a bench mark on Bhola. Furthermore the volume

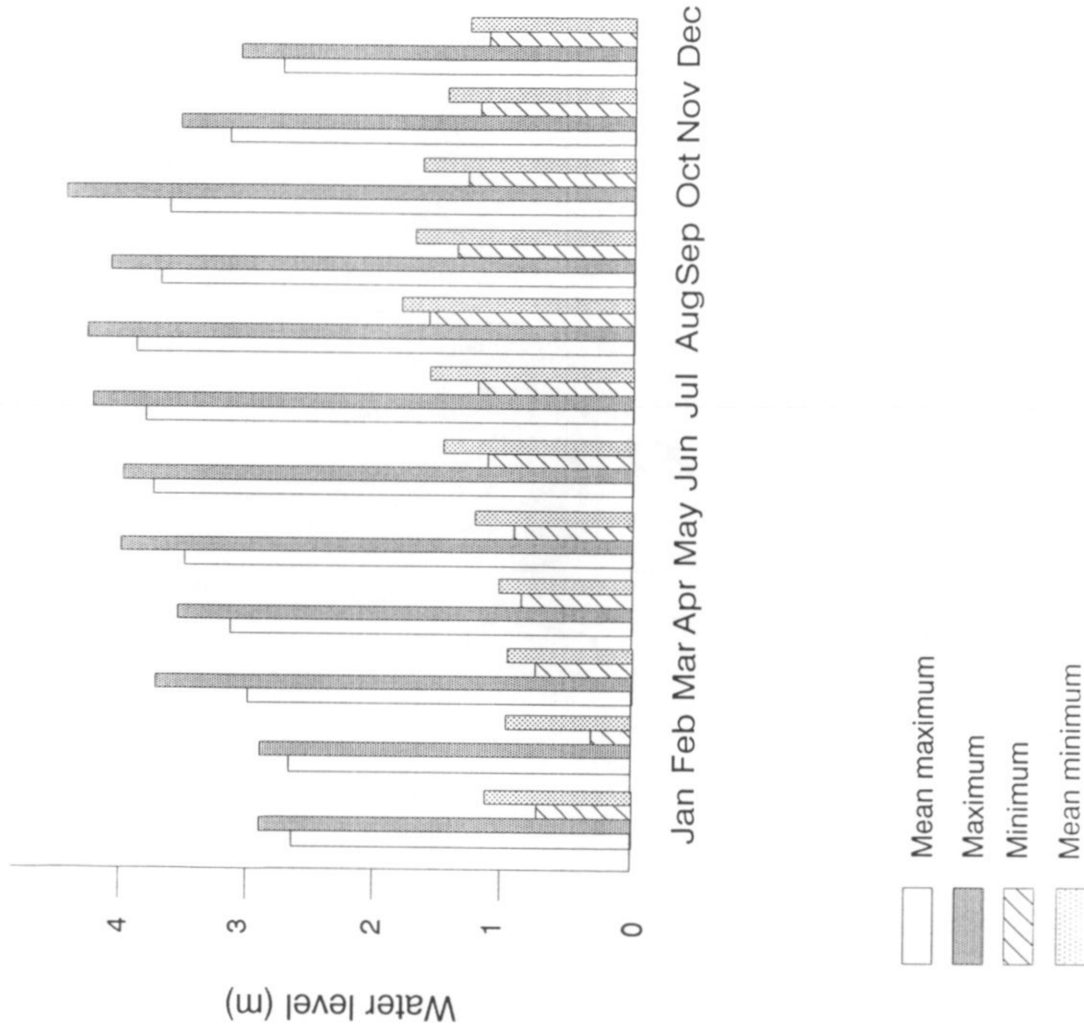


Figure B4.1   Maximum and minimum water levels at Dasmonia of water affecting the island through the embankment during a tidal cycle, for a given tide height, must be evaluated to determine the resulting flood depths and their extent. However, experience of high tide levels suggests that only the areas immediately around the khal openings would be subject to flooding.

Table B4.1 Extreme value analysis of water level data at Dasmonia

Period of record used from 1970 to 1985
Number of years... 16
mean...... 2.99 m max. flood... 3.47m in 1985
CV......... .06 skewness..... 1.007

Return period (years)	Peak water level (metres)	Standard error	
2	2.96	0.04	Parameters of fitted distribution
5	3.14	0.06	
10	3.26	0.08	
25	3.41	0.12	
50	3.52	0.14	u=2.903
			a=0.159

B5 EXCESS RAINFALL

The entire island of Bhola is only about 2-4 metres above mean sea level. Consequently, the drainage channel gradients are very low and excess rainfall often results in drainage congestion, particularly at the mouths of khal mouths during high tides.

In general, where the embankment crosses khals, drainage regulators had been installed. Sluice gates were provided to allow excess water on the landward side to drain out; tidal flaps close automatically when exterior water levels rise. These flaps protect the island from saline intrusions and tidal flooding.

It is essential to design the regulators with sufficient capacity to allow excess water to be evacuated at low tide. However, to minimise the cost of construction, they need to be as small as practicable. Most crops, especially rice, can withstand short periods of inundation, thus it not necessary to evacuate all excess water from within the island during a single tidal cycle.

The Bangladesh Water Development Board (BWDB) has produce standard procedures to evaluate the required size of structures. An essential input to the method is a design rainfall profile, whose derivation requires estimates of rainfalls of 1, 2, 3, 5 and 10 days duration with a return period of 10 years.

Daily rainfalls from the four rainfall stations (Bhola, Borhanuddin, Charfession and Daulakhan) were considered for derivation of the design rainfall storm parameters (Annex 1). Charfession is in the centre of the main project area, but data for only 11 years were available for analysis. For this reason data from all four stations were employed. The mean annual rainfall at Bhola was estimated as 2433 mm and that for

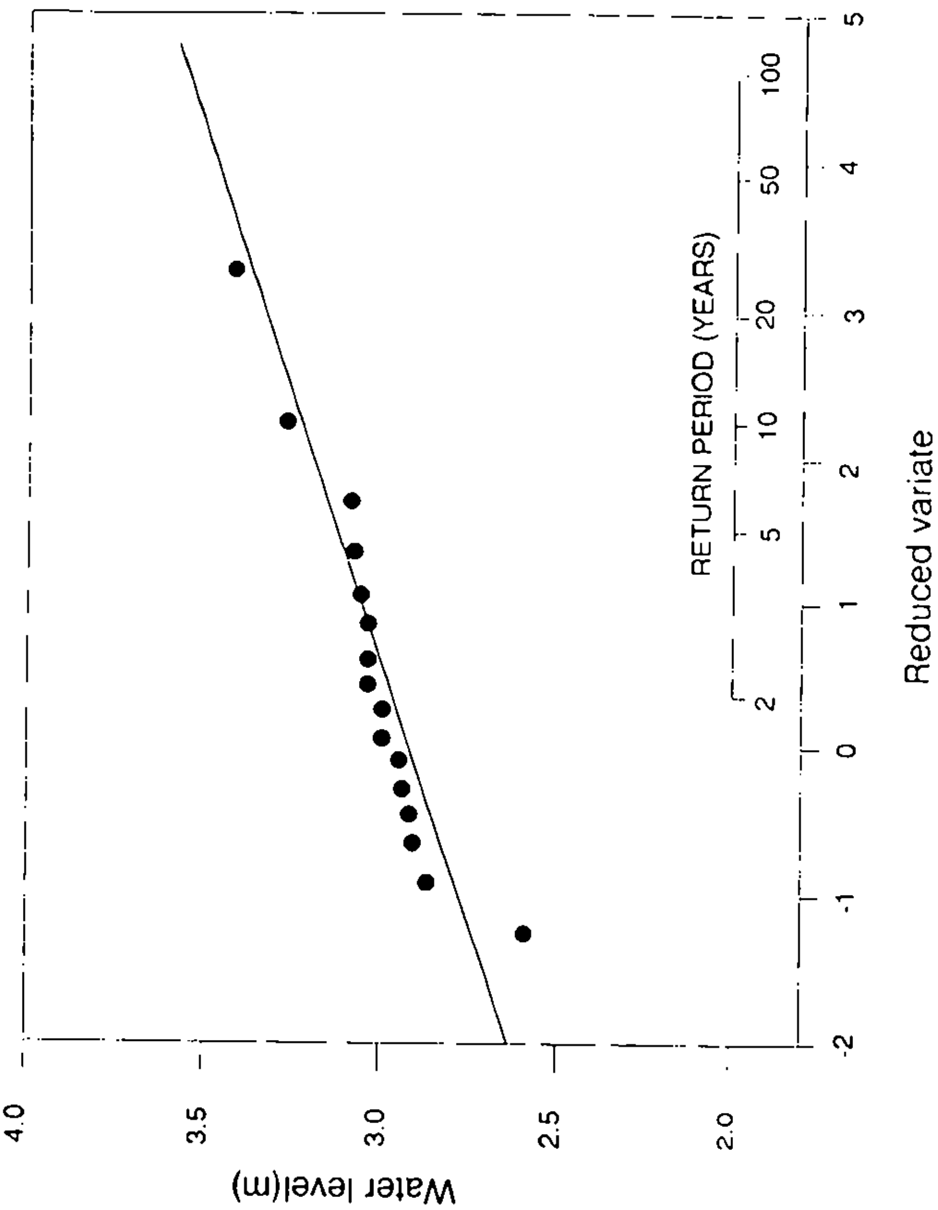


Figure B4.2 Water level frequency analysis for Dasmonia

Charfession was 3175 mm. The equivalent statistics for Borhanuddin and Daulakhan were 2702 and 2770 mm, respectively. These results are consistent with mean annual isohyets given in the Bangladesh National Water Plan (1986) which suggest that there is a rainfall gradient down the island with an average of about 2400 mm falling each year around Bhola increasing to 2800 mm at Charfession.

The maximum 1, 2, 3, 5 and 10-day rainfalls for each year were extracted from the record at each of the four sites. Table B5.1 indicates the mean annual maximum rainfalls, which are highest at Charfession.

Table B5.1 ***Mean annual maximum rainfalls of 1, 2, 3, 5 and 10 days duration at Bhola, Daulakhan, Borhanuddin and Charfession (mm).***

Duration (days)	Bhola	Daulakhan	Borhanuddin	Charfession
1	160.2	143.6	168.2	176.8
2	213.8	232.9	227.8	297.5
3	252.3	284.8	280.8	360.0
5	296.1	341.1	333.7	423.7
10	420.1	475.5	474.4	572.7
data	1962-89	1961-89	1962-89	1968-78

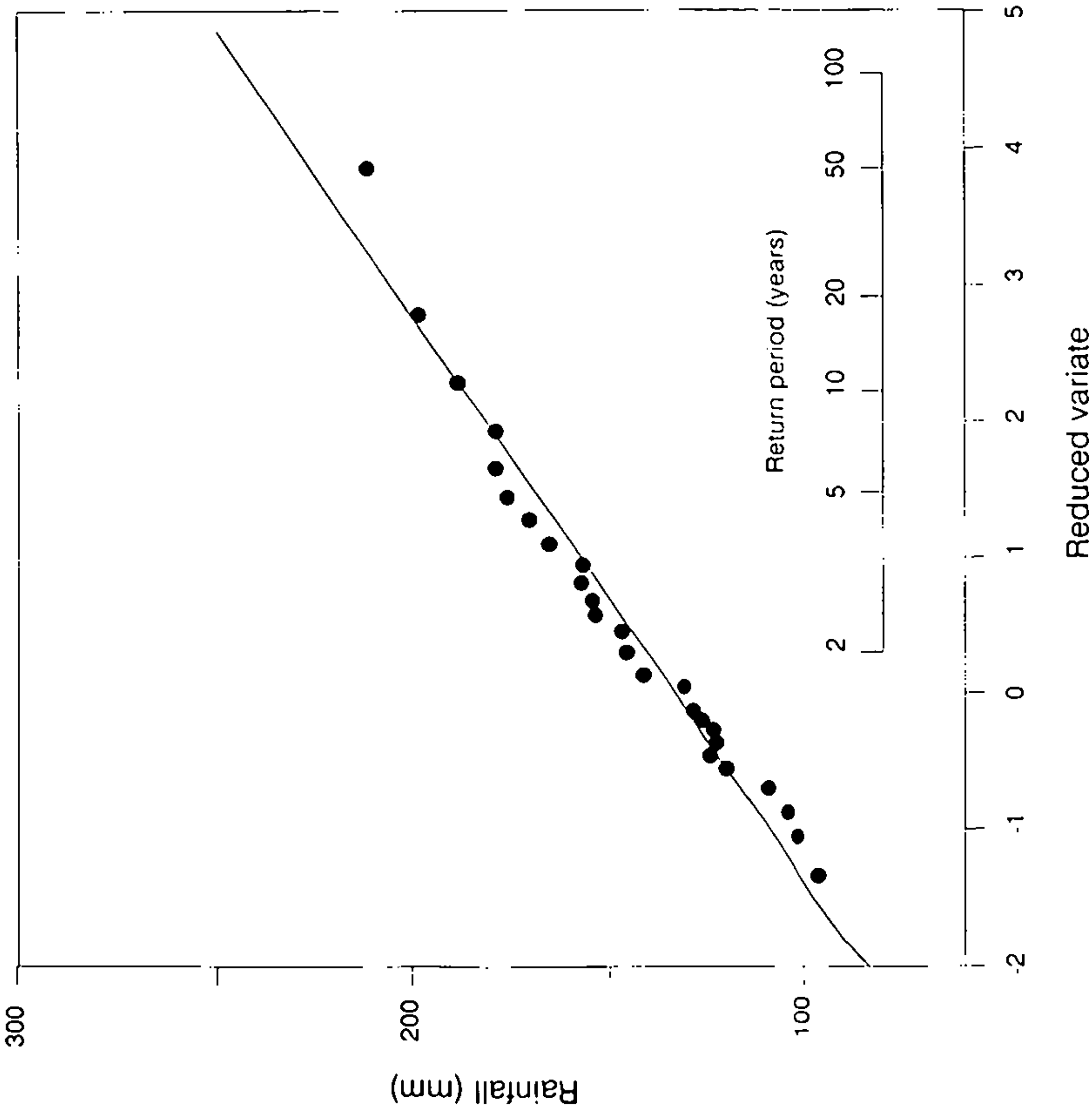
An extreme value type I (EV1) distribution was fitted separately to each data set using the method of moments. As an example, the results of the analysis for 10-day rainfalls at Borhanuddin are presented in Table B5.2. In each case the EV1 distribution displayed a close fit to the data plotted using the Gringorten plotting position (Figure B5.1), with the exception of 1 and 2 day rainfalls at Daulakhan (Figure B5.2). These data sets each included one rainfall value (for 1976) far larger than the rest. As a regional rainfall frequency approach was to be adopted these outliers were not excluded from the analysis.

Table B5.2 ***Analysis of 10-day maximum rainfalls at Borhanuddin***

Period of record used from 1970 to 1989
Number of years... 20
mean...... 474.4 mm max. flood... 770.0 mm in 1983
CV......... .30 skewness..... 1.142

Return period (years)	Peak water level (metres)	Standard error	
2	449.5	31.2	Parameters of fitted distribution
5	583.8	52.6	
10	672.8	71.0	
25	785.2	95.7	
50	868.2	114.5	u=406.01
			a=118.55

Figure B5.1 Rainfall frequency analysis for Bhola



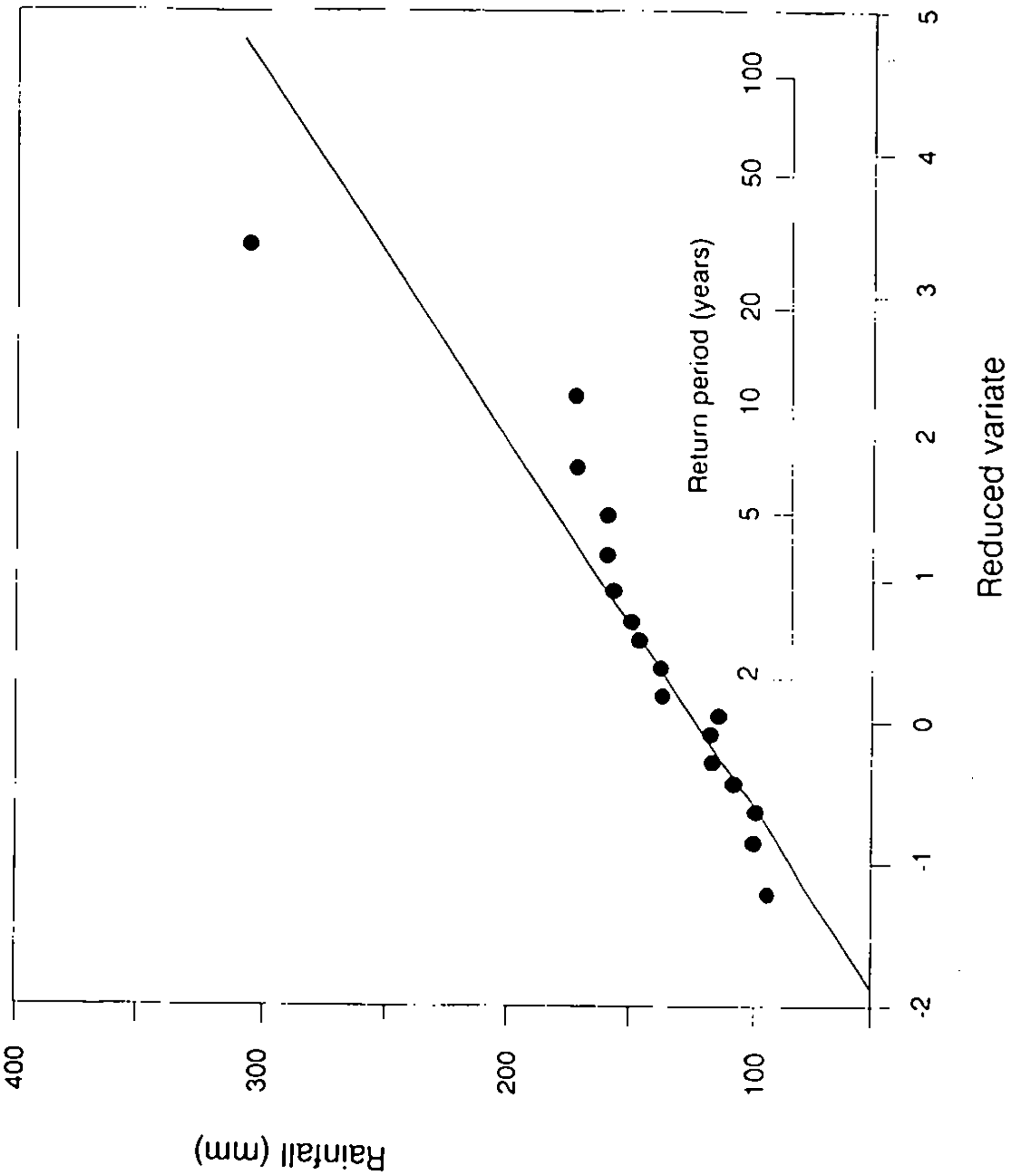


Figure B5.2 Rainfall frequency analysis for Daulakhan

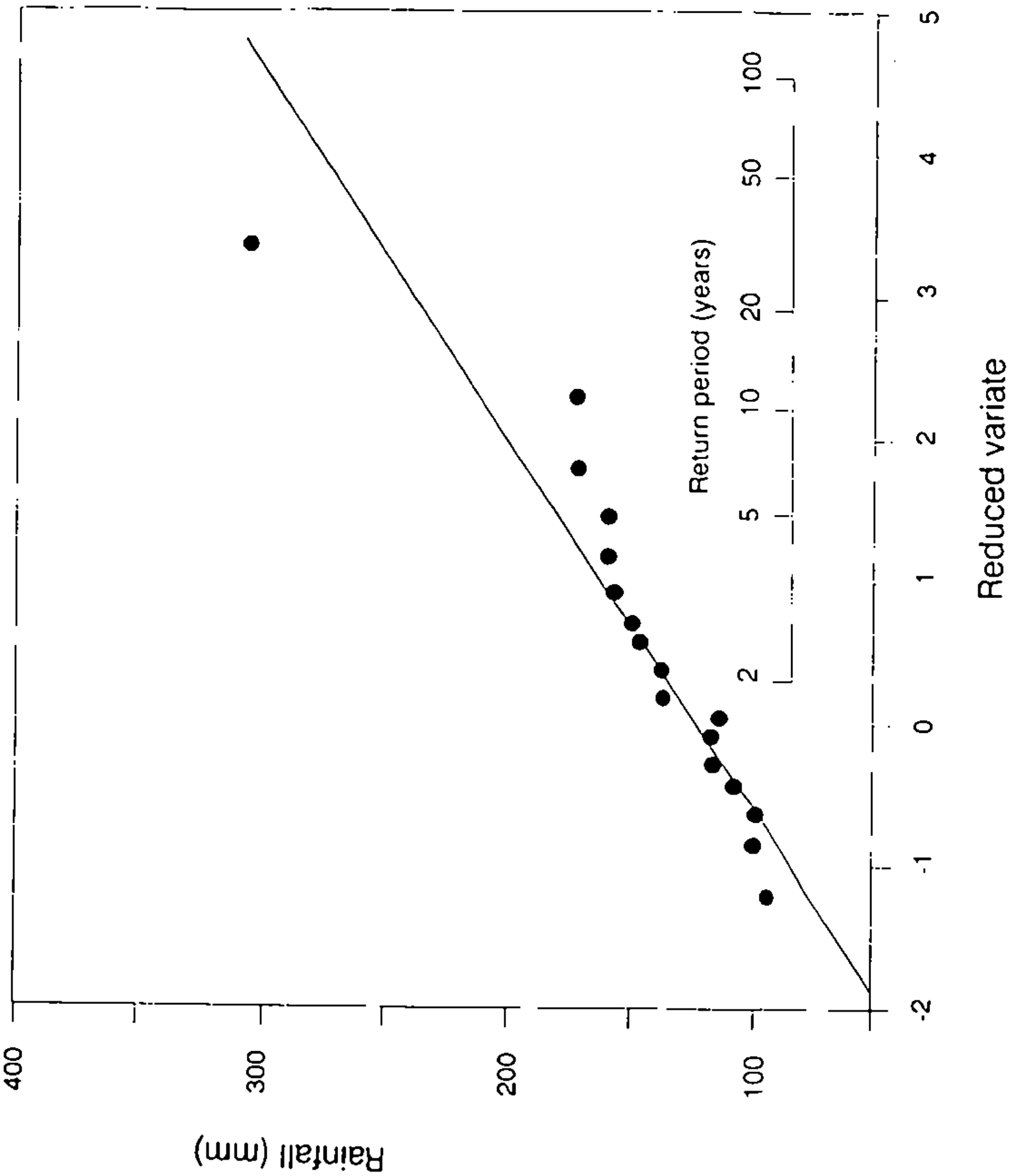


Figure B5.2 Rainfall frequency analysis for Daulakhan

For each duration, the four frequency curves were plotted together on the same graph. To standardise the curves, each quantile was divided by the mean value, ie the 2, 5, 10 and 25 year return period rainfalls were expressed as multiples of their means. An example is given in Figure B5.3. In each case the four curves were coincident at the mean annual rainfall level (by definition) and diverged towards higher return periods. However, the divergence was not more than might be expected due to sampling variability. Hence the four curves can be assumed to be random samples from a single population and an average of the four curves can be assumed to be the best estimate at each site. This is termed a standardised regional rainfall frequency curve, since it is applicable to all sites within a region (in this case Bhola island). The rainfall frequency curve applicable to any site is constructed by multiplying the mean rainfall at the site by the scaling factors defined by the regional standardised curve.

Table B5.3 2, 5, 10 and 25 year return period scaling factors to be applied to the mean annual rainfall for a given duration.

	Return period (years)			
	2	5	10	25
Duration (days)				
1	0.95	1.21	1.37	1.61
2	0.95	1.23	1.43	1.67
3	0.95	1.24	1.44	1.69
5	0.95	1.24	1.43	1.67
10	0.95	1.21	1.38	1.60
average	0.95	1.23	1.41	1.65

The five regional curves were then drawn on a single graph (Figure B5.4). It was anticipated that they would display some systematic behaviour, such as the 1-day curve being the steepest and the 10-day curve the shallowest. However, no obvious pattern was evident and the curves were remarkably similar. As a result, it was considered that all five regional curves could be amalgamated to produce one standardised frequency curve. The result of this analysis showed that the 10 year return period rainfall for durations 1 to 10 days, at any site in Bhola island is 1.41 times as large as the mean annual maximum rainfall of that duration. Table B5.4 shows the 10 year return period annual maximum rainfalls of 1, 2, 3, 5 and 10 days duration at the four stations on Bhola island after rescaling by the mean annual rainfall at each site.

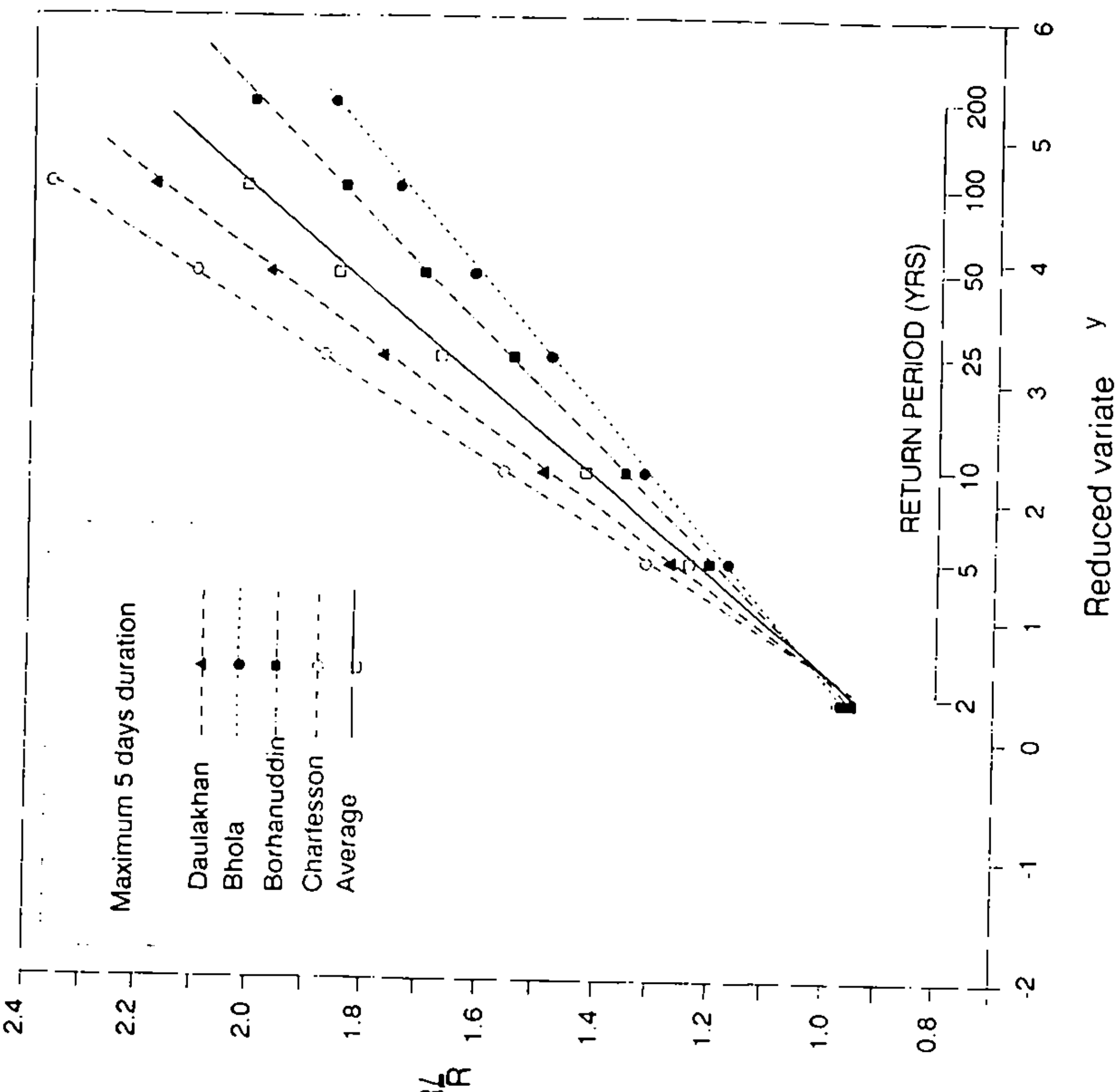


Figure B5.3 Standardised rainfall frequency curves of 5-days duration for four sites on Bhola island together with the regional average

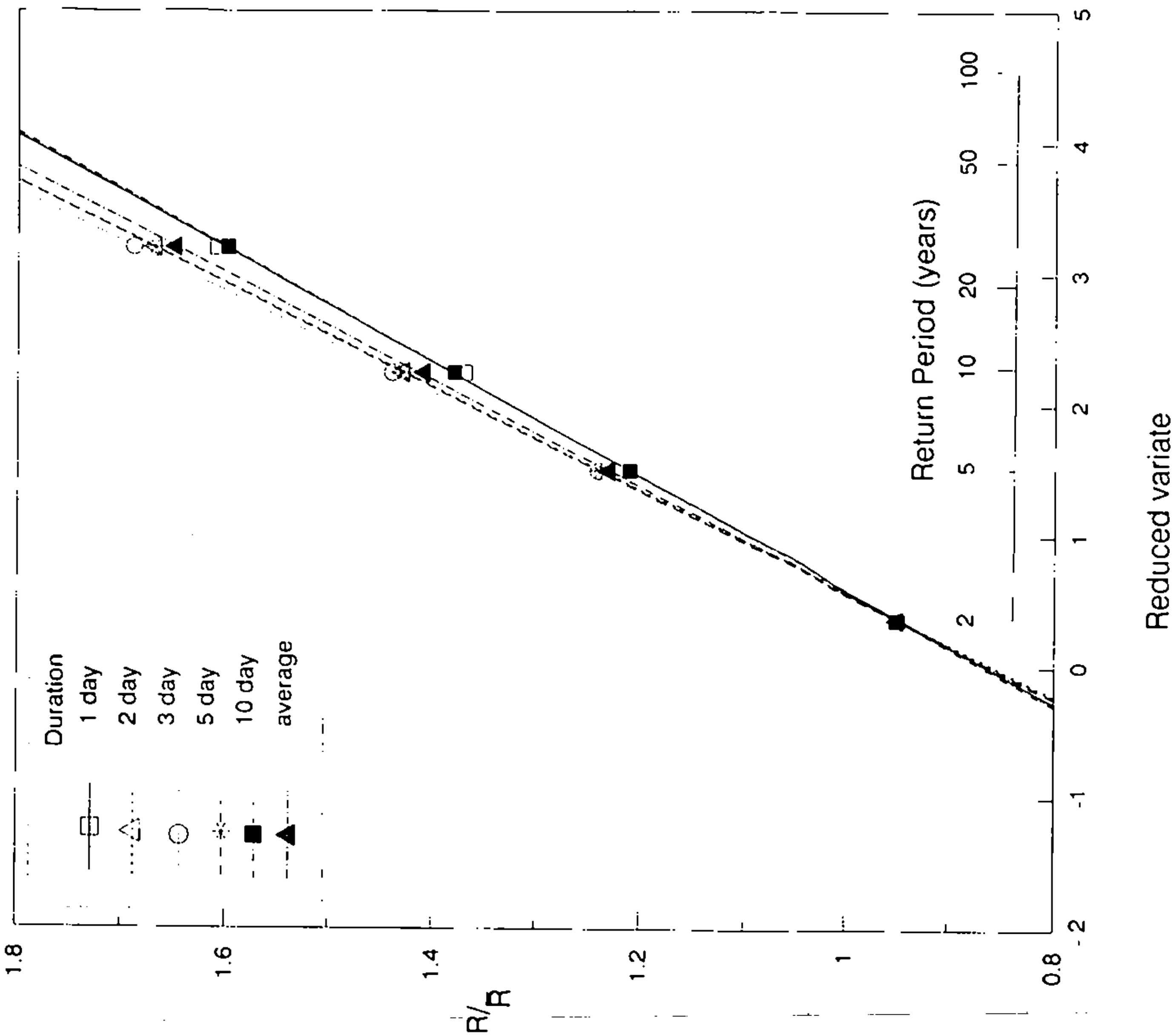


Figure B5.4 Standardised regional rainfall frequency curves for Bhola island of 1, 2, 3, 5 and 10 days duration together with the average curve

Table B5.4 ***10 year return period annual maximum rainfalls of 1, 2, 3, 5 and 10 days duration at Bhola, Daulakhan, Borhanuddin and Charfession (mm).***

Duration (days)	Bhola	Daulakhan	Borhanuddin	Charfession
1	225.9	202.5	237.2	249.3
2	337.7	328.4	321.2	419.5
3	355.7	401.6	395.9	507.6
5	417.5	481.0	470.5	597.4
10	592.3	670.5	668.9	807.5

B6 SUMMARY AND CONCLUSIONS

The earthen embankment around Bhola, which is 6 - 7 m in height, provided a barrier against external flooding from high water levels, but might aggravate internal flooding from excess rainfall.

Qualitative details of previous cyclones to have affected Bangladesh since 1797 were extracted from the 1990 Statistical Yearbook of Bangladesh, but little quantitative information is available. However, it seems likely that a surge tide of perhaps 3-10 metres will affect Bhola about once every 15 years. Since the 1970 cyclone resulted in severe flooding on Bhola, it seems that the earthen embankment does not provide defence against tidal surges.

Analysis of annual maximum water levels in the Tetulia channel (at Dasmonia) demonstrated that there is only a small range in maximum tide height, with the 50 year return period maximum being only 0.5 metres greater than the average. It seems most likely that the embankment will restrict flooding to the areas immediately around the khal openings.

The shallow gradients on the khals and restrictions on drainage imposed by the embankment mean that some local flooding is inevitable following heavy rainfall in the wet season. However, correct design of the drainage structures, where the khals pass through the embankment, should ensure that flooding would only occur about once every two or three years and would only last for a few days at most. Design rainfalls of 1, 2, 3, 5 and 10 days were derived for Bhola island as input to the drainage design.

C. Assessment of crop water requirements

C1 BACKGROUND

All crops require moisture during growth and maturity. When rainfall is insufficient to meet these needs directly, efficient agriculture depends on indirect supply by diversion from open water sources through gravity or by pumping from open water courses or groundwater: this is termed irrigation. Design of an irrigation system requires the evaluation of the crops' water requirements and the effective rainfall, ie that fraction of the rainfall which is used by the crops after losses due to surface runoff and percolation have been subtracted. The difference between these factors needs to be met by irrigation. This report provides for an assessment of the irrigation requirements for the project area.

C2 INTRODUCTION

Bangladesh has a marked uneven distribution of rainfall with high rainfall depths recorded in July and August and almost none occurring in the months of November to March. This is well exemplified by data for Charfession on Bhola island where the modal and median rainfall in both December and January is zero, whereas the mean for July exceeds 756 mm. Without irrigation only deep rooted crops such as wheat, chillies and ground nuts (termed rabi crops), which can depend on the residual soil moisture, may be grown in the winter months. The early rice crop planted in late March-early April (aus) is planted in man-made holes in the dry soil (dibbles) and only germinates when the first rains arrive.

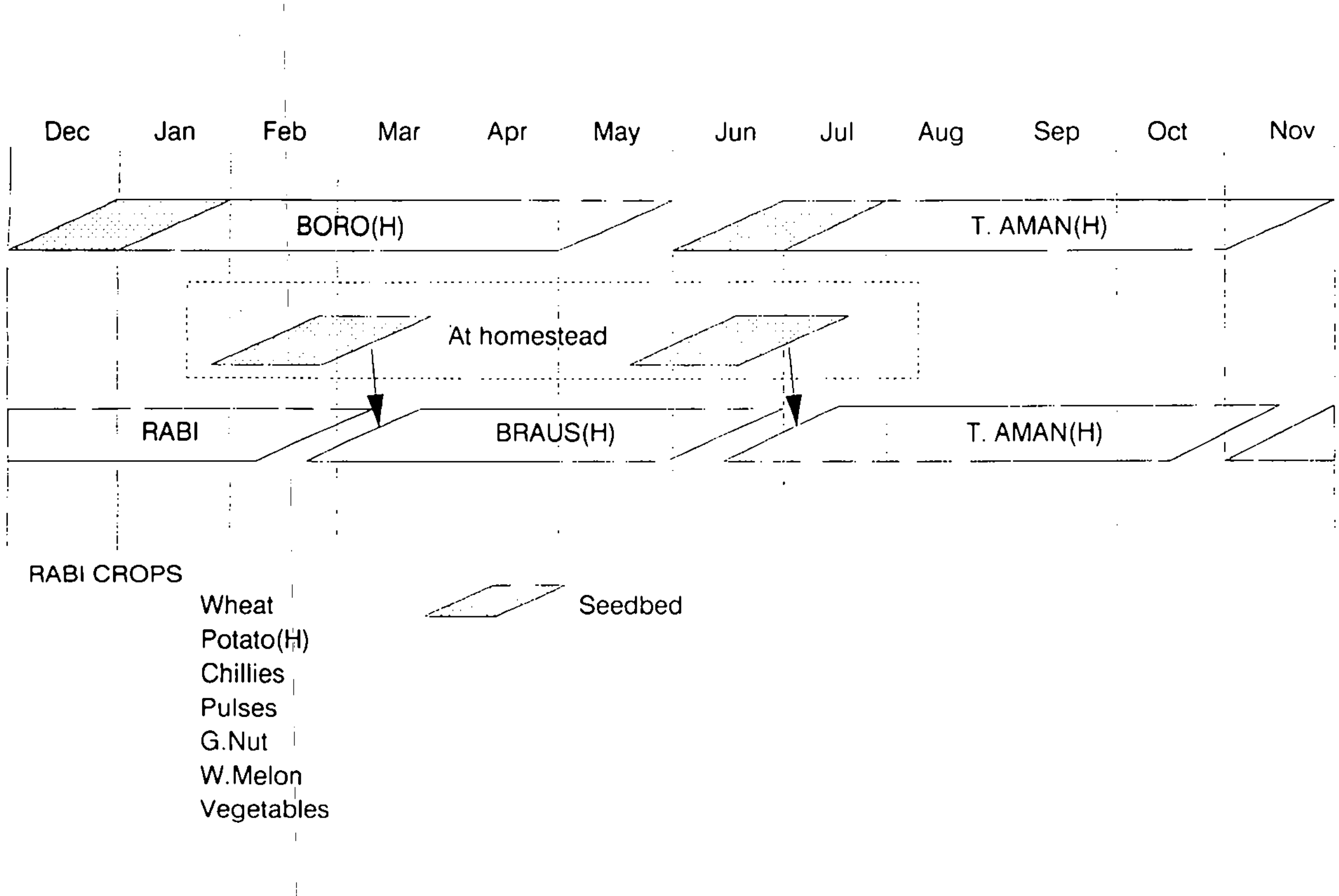
Irrigation allows optimal growth of rabi crops, immediate germination of the aus crop and the potential to grow a much earlier rice crop (boro), which is planted in February. The other rice crop (aman) is planted in July and August when rainfall meets all the crop's water requirements in the early and growth stages.

In the proposed irrigation programme for Bhola Phase II, the farmer would be encouraged to choice from two main cropping patterns (Figure C2.1). First, three crops: rabi (November to February); boro/aus (March to June); and aman (July to November). The alternative was to grow, two rice crops only: boro (December to May) and aman (June to November). The production of high value rabi crops, such as water melon, can provide the farmer with a good return but the prices fluctuate from year to year inducing a risk element. Growing two rice crops is a safer investment but does optimise the economic land potential.

C3 CALCULATION OF THE REFERENCE EVAPOTRANSPIRATION RATE

Rice cultivation requires a flooded field, paddy, both during for land preparation and for growth. Water is lost to the atmosphere both by direct evaporation from the soil and water surface (which continues throughout the night and day) and by transpiration through the plant's leaves (which is effectively confined to daylight hours when the

Future cropping pattern (Project condition)



plant is photosynthesising). These two processes are considered together as evapotranspiration.

A modification of Penman's basic equation was developed by the United Nations' Food and Agricultural Organisation (FAO, Irrigation and Drainage Paper 24) and is widely used to calculate evapotranspiration. The inputs are standard meteorological records of temperature, humidity, sunshine and windspeed. The altitude and latitude of the station are used in the calculation of other factors, such as solar radiation. The output is the evapotranspiration rate of a standard crop (grass) in mm day^{-1} termed ETo.

This modified Penman equation was applied to the meteorological data from Bhola (see Annex 1) to evaluate ETo for each calendar month. The results achieved using the FAO's computer programme CROPWAT, are given in Table C3.1, together with ETo calculated by FAO for Phase I using meteorological data from Barisal. Barisal is slightly further north (22.7o) and situated on the mainland of Bangladesh, where estimated evapotranspiration rates are higher than at Bhola. This reflects higher meteorological parameters, ie. higher wind speeds, more sunshine hours and higher temperatures. Data from Bhola have been adopted for this study as they are considered to reflect more accurately the meteorological conditions on Bhola island.

Table C3.1 Evapotranspiration ETo according to modified Penman for Bhola

Altitude = 5.5 m   Latitude = 22 degrees 29 minutes north

	Temp (DegC)	Humidity (%)	Wind speed (km day^{-1})	Sunshine (hr day^{-1})	Radiation (mm day^{-1})	ETo Bhola (mm day^{-1})	ETo Barisal (mm day^{-1})
Jan	18.4	79	124	6.3	2.8	2.78	3.3
Feb	21.3	75	151	6.7	3.5	3.77	4.7
Mar	25.7	75	151	7.3	4.6	4.87	5.7
Apr	28.0	81	178	6.7	5.1	5.19	6.7
May	28.6	83	163	6.0	5.1	5.03	6.3
Jun	28.1	88	148	3.3	4.2	3.92	4.4
Jul	27.9	89	161	2.9	4.0	3.75	4.2
Aug	27.9	88	156	3.3	4.0	3.82	4.1
Sep	28.0	88	140	4.2	4.1	3.79	4.2
Oct	27.1	85	130	6.4	4.1	3.93	4.1
Nov	23.7	81	130	6.6	3.3	3.32	3.5
Dec	19.4	80	130	6.4	2.7	2.73	3.3
Data used	1966-89	1975-89	1971-89	1981-89			

The calculation of crop and farm water requirements was undertaken on a half-month time step. Half-monthly average values of ETo were evaluated by visual interpolation between the monthly mean estimates of ETo plotted on a graph.

C4 CALCULATION OF THE EVAPOTRANSPIRATION RATE FOR INDIVIDUAL CROPS

Each crop has a different evapotranspiration rate depending on the species and the stage reach in the growth cycle. Rates for common crops are given in FAO 24 expressed as a multiple of ETo, termed the crop Coefficient (kc). For this study, kc values for rice crops (boro, aus and aman) adopted by FAO for the Bhola Phase I were used (Table C4.1).

Table C4.1 *Coefficients (kc) for rice and rabi crops grown on Bhola island in mm per half monthly period*

Boro	November		December		January		February		March	
	0.000	0.090	0.94	1.01	1.05	1.05	1.05	0.88	0.66	0.00
	April		May		June					
Aus	1.10	1.09	1.06	1.05	1.04	0.98				
	July		August		September		October		November	
Aman	1.10	1.10	1.09	1.07	1.05	1.05	1.05	1.01	0.96	0.00
	November		December		January		February		March	
Rabi	0.00	0.90	0.94	1.01	1.05	1.05	1.05	0.88	0.66	0.00

For Phase I, all rabi crops were considered together and assigned the same set of coefficients. For the Phase II study the rabi crops were considered separately, using kc values given in CROPWAT guidelines (see Table C4.2). For crops not listed in this manual (chillies and vegetables), the rabi crop coefficients given in the Phase I report were utilised.

Table C4.2 *Coefficients (kc) for some rabi crops grown on Bhola island in various stages of crop growth*

	Initial	Crop development	Mid season	Late season	At harvest
Groundnut	0.4	0.7	0.95	0.75	0.55
Potato	0.4	0.7	1.05	0.85	0.8
Pulse	0.3	0.7	1.0	0.7	0.4
Water melon	0.4	0.7	0.95	0.8	0.65
Wheat	0.3	0.7	1.05	0.65	0.2

Using these coefficients, ETcrop, the evapotranspiration rate for each crop, was calculated for each half-month period.

C5 CROP WATER REQUIREMENTS

In addition to evapotranspiration, a number of other factors need to be considered when calculating the crop water requirement. First, some water standing in the rice fields will be lost due to percolation into the soil. This was assumed to be equal to 3 mm per day. Second, before planting the crop, the soil needs to be prepared. The field is flooded, during which time the soil is ploughed and then harrowed. Allowance for evaporation and percolation must be made during the period of land preparation.

Calculation of the crop water requirement was undertaken on a spreadsheet (Table C5.1). The basic table had 24 columns, one for each half-month, plus labels, with each crop occupying a number of rows. The first row contains the proportion of the land allocated to that crop which is under cultivation for any half-month: clearly, not all farmers will begin planting and harvest at the same time. The second row indicates the coefficient, kc, and the third, ETcrop, ie the evaporation rate for that crop in mm half-month^{-1}. Other rows are: the land area dedicated to nurseries, which is assumed to have a kc value of 1 for rice and 0.9 for chillies; evaporation from land under preparation (50 mm half-month^{-1}); and the percolation rate (3 mm day^{-1}).

The total water requirement was given as the sum of four products:

(i) the area under each crop multiplied by its ETcrop value;
(ii) the area under nurseries multiplied by its ETcrop value
(iii) the area under preparation multiplied by the evaporation rate (during the land preparation phase the area was assumed to be all land allocated to the crop but not under cultiavtion or nursery)
(iv) the total area under preparation, nursery and cultivation multiplied by the percolation rate

Using this methodology, the total farm water requirement was evaluated for each crop in l s^{-1}, separately for each half month.

As an example the maximum total requirement to grow boro/aus is 11166 l s^{-1} (in the second two weeks of April and first two weeks of May) or approximately one l s^{-1} for each hectare.

C6 IRRIGATION REQUIREMENTS

The irrigation requirement is that part of the farm water requirement not met by rainfall. To evaluate this quantity, effective rainfall must be calculated first ie that fraction of the rainfall which is available to the crops. Clearly the rice fields will not be able to store all rain which falls on them, some will leak through and over the paddy dykes and eventually to drainage ditches. Effective rainfall is thus equal to total rainfall after losses due to surface runoff have been deducted.

The calculations require rainfall for an average year and a dry year, such as the 5 year return period rainfall, expressed as half-monthly totals.

Table C5.1 Crop water requirements

	June		July		August		September		October		November		December		January		February		March		April		May	
ETo (mm/day)	3.92		3.75		3.82		3.79		3.93		3.32		2.73		2.78		3.77		4.87		5.19		5.03	
ETo (mm/month)	117.6		116.3		118.4		113.7		121.8		99.6		84.6		86.2		105.6		151.0		155.7		155.9	
Days	15.0	15.0	15.5	15.5	15.5	15.5	15.0	15.0	15.5	15.5	15.0	15.0	15.5	15.5	15.0	15.0	14.0	14.0	15.5	15.5	15.0	15.0	15.5	15.5
Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
ETo (1/2 month)	63.6	58.6	57.9	58.4	59.9	58.5	56.0	57.7	64.9	56.9	58.8	40.8	45.4	39.2	38.3	47.9	38.4	67.2	61.0	90.0	76.6	79.1	88.8	67.1
BORAUS 11268	0.75	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.50	0.94	1.00	1.00	1.00	1.00
kc	0.98	0.98																1.10	1.10	1.09	1.09	1.06	1.05	1.04
ETcrop	62.33	57.43																				83.85	93.24	69.78
Nurseries	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nurseries ET																								
Land prep																								
Percolation																								
AMAN 47658	0.00	0.13	0.50	0.88	1.00	1.00	1.00	1.00	1.00	0.88	0.50	0.13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
kc		1.10	1.10	1.10	1.09	1.09	1.07	1.07	1.05	1.05	1.01	0.96	0.96											
ETcrop		64.46	63.69	64.24	65.29	63.77	59.92	61.74	68.15	59.75	59.39	19.17	43.58											
Nurseries 2274	0.25	0.50	0.75	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nurseries ET	50.00	50.00	50.00	50.00																				
Land prep																								
Percolation																								
BORO 36390	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.25	0.75	1.00	1.00	1.00	1.00	1.00	1.00	0.75	0.25
kc															1.10	1.10	1.09	1.07	1.07	1.05	1.05	1.03	0.98	0.98
ETcrop															42.13	52.69	41.86	71.90	65.27	94.50	80.43	81.47	87.02	65.76
Nurseries 2274	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.25	0.75	0.75	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nurseries ET													50.00	50.00	50.00	50.00								
Land prep																								
Percolation																								
CHILLIES 953	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.25	0.75	1.00	1.00	1.00	1.00	1.00	0.75	0.25	0.00	0.00	0.00	0.00
kc												0.90	0.94	1.01	1.05	1.05	1.05	0.88	0.66	0.66				
ETcrop												36.72	42.68	39.59	40.22	50.3	40.32	59.14	40.26	59.40				
Nurseries 94	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.50	0.88	0.50	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nurseries ET																								
Land prep																								
Percolation																								
WHEAT 3869	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.94	0.50	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.25	0.75	1.00	1.00	1.00	1.00
kc								0.95	0.88	0.66									0.90	0.94	1.01	1.05	1.05	1.05
ETcrop								63.84	53.68	59.40									36.72	42.68	39.59	40.22	50.30	40.32
POTATO 1939	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.94	0.50	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.25	0.75	1.00	1.00	1.00	1.00
kc								0.95	0.88	0.66									0.90	0.94	1.01	1.05	1.05	1.05
ETcrop								63.84	53.68	59.40									36.72	42.68	39.59	40.22	50.30	40.32
VEG 1248	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.94	0.50	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.25	0.75	1.00	1.00	1.00	1.00
kc								0.95	0.88	0.66									0.90	0.94	1.01	1.05	1.05	1.05
ETcrop								63.84	53.68	59.40									36.72	42.68	39.59	40.22	50.30	40.32
GRD NUT 476	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.94	0.50	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.25	0.75	1.00	1.00	1.00	1.00
kc								0.95	0.88	0.66									0.90	0.94	1.01	1.05	1.05	1.05
ETcrop								63.84	53.68	59.40									36.72	42.68	39.59	40.22	50.30	40.32
WAT MELON 867	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.75	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.25	0.75	1.00	1.00	1.00	1.00
kc								0.95	0.88	0.66									0.90	0.94	1.01	1.05	1.05	1.05
ETcrop								63.84	53.68	59.40									36.72	42.68	39.59	40.22	50.30	40.32
PULSE 1915	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.75	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.25	0.75	1.00	1.00	1.00	0.75
kc								0.95	0.88	0.66									0.90	0.94	1.01	1.05	1.05	1.05
ETcrop								63.84	53.68	59.40									36.72	42.68	39.59	40.22	50.30	40.32
ET total (mm)	112.3	121.9	113.7	114.2	65.1	63.0	59.9	514.1	422.6	510.3	[illegible]	165.1	180.3	135.5	61.7	68.1	59.7	59.4	296.2	392.3	327.1	373.6	454.8	324.1

C7 RAINFALL DATA ANALYSIS

Rainfall for an 'average' year can be defined in many ways. At one extreme, daily rainfalls (or shorter durations if data are available) can be analysed independently, such that the mean rainfall for January 1st, 2nd, 3rd and so on can be derived. Together these rainfalls make a synthetic series which may be labled 'an average year'. However, it may be totally unrealistic since there is likely to be significant correlations between successive observed daily rainfalls. Markov models of daily rainfall, for example, make explicit use of the serial correlation specifying the probability of a given depth of rainfall falling in a day, as a function of the rainfall falling on the previous day. At the other extreme, the mean annual rainfall total could be derived, then that calendar year for which the total rainfall was closest to the mean could be termed an average year. In this way the correlation between daily rainfalls will be preserved and the series will be realistic. However, the chosen year may have an unusually wet July and a very dry August, thus components of the series may be more extreme than the label 'average year' would imply. Perhaps the optimal solution to this problem is to choose the shortest duration for which there is no significant correlation between successive rainfall totals. Clearly, detailed analysis would be required to evaluate the serial correlation present in the data at different durations. However, it appears that there is little correlation between successive montly rainfall totals observed on Bhola island.

A preliminary analysis was undertaken to define an 'average' (mean) and a 'dry' (5 year return period) year using the available monthly rainfall data from the four rain gauge sites on Bhola island: Bhola, Daulatkhan, Borhanuddin and Charfession. Individual totals for each month were sorted into ascending order and plotted on a graph against probability using the formula

$$n+1/m$$

where n is the number of years of record and m is the mth ranked year. The results are presented in Table C7.1. Some differences are apparent between the stations, even between Borhanuddin and Daulatkhan which are only 10 km apart. Charfession lies within the centre of the main project area, but has only 11 years of rainfall records (just over half as many as Daulatkhan). However, 11 years probably provides reliable estimates of return periods up to 5 years, therefore the results from individual rain gauge sites could be used directly. But if return periods of 10 years or greater were required, regional analysis of the rainfall data should be undertaken (see section B5). Table C6.1 shows that the mean rainfall for January at Charfession is 2.0 mm. The closest observed January rainfall total was 3.8 mm in 1970. The February mean rainfall is 17.4 mm, the closest is 1976 for which 20.8 mm were recorded in February. By repeating this procedure, a 12 month series of data can be derived for which each month has the average rainfall. Table C7.2 indicates the year from which to draw the appropiate month of data. This series can be labled an 'average' year. The same procedure can be applied to the estimates of the 5-year rainfall for each month, resulting in a typical 'dry' year. Clearly, if the 5 year return period rainfall is zero then there is no need to indicate a particular year to adopte, since rainfalls of all durations during the month will be zero. For many of months, there exisits an observed monthly total close to the mean or 5-year value.

Table C7.1 **Total monthly rainfall expected in an average (mean) year and a dry (5 year return period) year at four sites on Bhola island.**

	Borhanuddin		Bhola		Charfession		Daulatkhan	
	mean (mm)	5-year (mm)	mean (mm)	5-year (mm)	mean (mm)	5-year (mm)	mean (mm)	5-year (mm)
January	7.0	0.0	4.4	0.0	2.0	0.0	4.7	0.0
February	17.2	0.0	23.2	0.0	17.4	0.0	14.2	0.0
March	45.4	0.0	39.7	0.0	46.2	0.0	23.1	0.0
April	120.6	31.3	136.3	59.8	112.3	2.7	95.3	17.5
May	231.3	105.0	255.1	95.8	227.8	110.0	260.0	120.0
June	556.5	420.0	489.4	312.0	602.7	414.4	485.1	305.0
July	613.8	374.7	474.3	298.0	756.4	426.5	599.9	353.3
August	528.6	330.0	461.0	310.0	611.9	420.0	551.4	350.0
September	353.7	205.0	320.9	210.1	447.2	180.0	346.5	230.0
October	211.9	95.0	190.3	67.0	181.0	60.0	209.9	50.0
November	49.2	0.0	44.5	0.0	94.7	0.0	48.0	0.0
December	11.8	0.0	11.6	0.0	10.7	0.0	12.0	0.0
Data used	1962-1989		1962-1989		1968-1978		1961-1989	

For example, the mean September rainfall at Daulatkhan is 346.5 mm, and September 1983 had a total of 348.1 mm. In constrast, for some there is no close parallel. The 5-year rainfall estimate for April at Charfession is 12.7 mm, but the closest to this total are April 1970, when the rainfall was 25.4 mm, and 1973, when no rainfall was recorded. To further refine the procedure the observed daily rainfalls could be scaled by a common factor which would result in a total rainfall for the month equal to the mean or 5-year statistic required.

Table C7.2 **Years which contain 'average' and 'dry' months at four sites on Bhola island, except those dry months where rainfall is zero.**

	Borhanuddin		Bhola		Charfession		Daulatkhan	
	Mean	5-year	Mean	5-year	Mean	5-year	Mean	5-year
January	1964	0.0	1985	0.0	1970	0.0	1964	0.0
February	1982	0.0	1989	0.0	1976	0.0	1976	0.0
Mar	1985	0.0	1985	0.0	1978	0.0	1976	0.0
April	1976	1988	1963	1985	1968	1970	1985	1980
May	1984	1972	1963	1967	1974	1972	1961	1987
June	1970	1974	1966	1986	1969	1974	1974	1985
July	1981	1983	1982	1982	1971	1977	1968	1985
August	1979	1973	1967	1962	1969	1978	1983	1981
September	1987	1985	1979	1982	1969	1968	1983	1981
October	1976	1978	1965	1985	1973	1977	1966	1985
November	1983	0.0	1982	0.0	1977	0.0	1983	0.0
December	1981	0.0	1981	0.0	1977	0.0	1981	0.0

C8 SUMMARY AND CONCLUSIONS

Monthly average values of ETo were evaluated using data from the meteorological station at Bhola and were found to range from 2.73 mm day^{-1} in December to 5.19 in April. The equivalent figures for Barisal, used in the Phase I were 3.3 and 6.7. The lower values at Bhola were the result of lower wind speeds, fewer sunshine hours and lower temperatures. Data from Bhola have been adopted for this study as they are considered to reflect more accurately the meteorological conditions on Bhola island.

FAO recommended kc values were used to assess the water requirement for each crop likely to be grown in the project area. The total farm water requirement was evaluated for each crop in l s^{-1}, separately for each half month. As an example the maximum total requirement to grow boro/aus is 11166 l s^{-1} (in the second two weeks of April and first two weeks of May) or approximately one l s^{-1} for each hectare. For Phase I the equivalent figure was 1.54 l s^{-1}. The reflects the lower ETo values calculated from the Bhola meteorological data. Analysis of the monthly rainfall data was undertaken to define an 'average' and a 'dry' year. Investigations of the correlation structure of the data rainfall data could be undertaken to evaluate whether an average and a dry year could be constructed from durations of rainfall shorter than one month. It was recommended that, for return periods up to 5 years, estimates from individual rain gauge sites could be used.

But if return periods of 10 years or greater were required, regional analysis should be undertaken.

Annex 1 Rainfall stations

Data were available for four rain gauge sites on Bhola island: Bhola, Daulatkhan, Borhanuddin and Charfession. This Annex provides details of the rain gauge sites and monthly rainfall data.

CHARFESSION (not inspected)

Data for this station were only available up to December 1978, when recording was discontinued. At the time of visiting Charfession the former location of the gauge could not be identified.

BORHANUDDIN (inspected 5 May 1991)

The rain gauge was moved in 1989 due to trees growing up around it. This site was covered by vegetation and shaded by trees when inspected. However, there was no evidence of systematic decline in the rainfall measurements; thus it was assumed that the gauge was moved before the site deteriorated significantly. The gauge was temporarily located in a good position, on a building site in the compound of the government rest house near to its proposed permanent location. It was fixed in a concrete block, but was quite not vertical when inspected. The gauge itself was in reasonable condition. Building work was due to be completed soon after, when the gauge was to be sited permanently.

DAULATKHAN (inspected 5 May 1991)

The gauge was well sited in a vegetable garden between two houses, but in its own small fenced compound. The gauge was set vertically in a concrete pedestal. The tube and filter were absent from the base of the funnel and some force was needed to remove the collecting vessel from the outer casing.

BHOLA (inspected 6 May 1991)

The gauge was well sited next to the Police station in Bhola town. The fence around its small compound had been temporarily removed to allow construction of a track. A small tree was growing some 10 m from the gauge. Although a present this did not impart a rain shadow, it may become a problem in the future.

Annex 2 Meteorological station

This Annex provides details of the meteorological observations available for Bhola island.

METEOROLOGICAL STATION: visited 6 May 1991

Meteorological records (wind speed, sunshine, humidity, temperature and evaporation) were available for Bhola town. The temperature, humidity recording instruments was sited in a compound adjacent to the meteorological office. The wet and dry bulb thermometers, housed in a Stevenson screen, were read every three hours throughout the day and night providing humidity and temperature data. There was also a pair of maximum and minimum thermometers, which were read daily, and a thermograph taking weekly charts. The compound also contained a number of rain gauges, both storage and autographic, though data from these were not used. The altitude of the site was given as 5.5 metres (18 feet).

The anemometer and sunshine recorder were sited on the roof of the office about 8 metres from the ground. This was just below the tops of the trees in the surrounding area, so the site is not over-exposed. The anemometer had been damaged during the cyclone on 29-30 April when the wind reached a maximum speed of 160 km hr^{-1}.

No records were held at the office, but the data were transmitted to Dhaka every three hours by radio.

The evaporation tank was operated by BWDB and was sited next to the rain gauge in Bhola town. The fence along one side of the compound had been removed recently to allow construction of a track, this may have allowed cattle and dogs to drink occasionally from the tank, leading to overestimation of evaporation. However this occurred after the period for which data have been used for this study.

WIND SPEED DATA

Data for individual months show little variation, after 1970, when the highest monthly value was 3 m s^{-1}. The only exception to this is a value of 12 m s^{-1} for November 1976. Up to 1970 mean wind speeds up to 9 m s^{-1} were recorded. These data were compared with wind speeds measured at Barisal. Here a figure of 2.0 m s^{-1} was recorded for November 1976, consequently the value of 12 m s^{-1} for Bhola was discounted for that month. Other data at Barisal display a strong similarity with the post-1970 data for Bhola, with the majority of monthly values around 2 m s^{-1}. Even in November 1970, when a severe cyclone hit Bangladesh and individual gusts reached 38 m s^{-1}, the mean wind speed recorded at Bhola and Barisal were only 1.5 m s^{-1} and 2.5 m s^{-1} respectively. Since these high speeds only lasted for a few hours the mean for the month may not be unreasonable. As a result of these investigations, data for 1971 to 1989 at Bhola were adopted for calculation of the monthly means.

Table AN2.1

	Wind speed ($m\ s^{-1}$)	Total sunshine (hr)	Total evaporation (mm)	Humidity (%)	Temperature (degrees C)
January	1.4	196.6	69.4	79.0	18.4
February	1.8	188.8	76.0	75.0	21.3
March	1.8	225.2	111.5	75.0	25.7
April	2.1	200.7	112.9	81.0	28.0
May	1.9	186.0	110.1	83.0	28.6
June	1.7	97.8	106.1	88.0	28.1
July	1.9	86.0	79.1	89.0	27.9
August	1.8	102.1	72.1	88.0	27.9
September	1.6	125.4	76.8	88.0	28.0
October	1.5	199.6	107.1	85.0	27.1
November	1.5	198.6	88.1	81.0	23.7
December	1.5	197.0	84.9	80.0	19.4
Data used	1971-89	1981-89	1985-89	1975-89	1966-89

SUNSHINE DATA

Hours of sunshine for individual months ranged from 29.1 in July 1987 (< 1 hr day^{-1} on average) to 247.7 for March 1986 (around 8 hr day^{-1}). In general the data showed a decrease in sunshine hours during the wet season, June - September, when the cloud thickens, and longer hours during the relatively cloudless dry season. All data from 1981 to 1989 were adopted for calculation of the monthly means.

HUMIDITY DATA

The humidity data for individual months exhibit a consistent pattern from year to year with a peak of around 89% in July when rainfall is high, falling to 75% in February and March during the dry season. A minimum monthly mean value of 69% was recorded on several occasions and a maximum of 93% was measured in July 1975. All data from 1975 to 1989 were adopted for calculation of the monthly means.

TEMPERATURE DATA

The temperature data showed a consistent pattern from year to year rising to around 28 °C for most of the summer months (April - September) and falling to about 18 °C in January. A minimum monthly mean figure of 16.7°C was recorded for January 1989 and a maximum value of 29.6 °C was measured during March 1987. All data from 1966 to 1989 were adopted for calculation of the monthly means.

EVAPORATION DATA

The evaporation data exhibited an intuitively reasonable pattern, high before (March - June and October) and lower during the wet season (July - September) and in the cooler winter months (November - February). There is little apparent variation from year to year. A minimum monthly evaporation of 48.6 mm was recorded for December 1985 (on average 1.6 mm day^{-1}) and a maximum figure of 119.7 (3.9 mm day^{-1} on average) was measured in March 1987. All data from 1975 to 1989 were adopted for calculation of the monthly means.