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Flood Action Plan

North West Regional Study (FAP-2)

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VOLUME 10

HYDROLOGY AND GROUNDWATER

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PART 1

HYDROLOGY

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HYDROLOGY

1 INTRODUCTION

1.1 Scope of Report

The major part of the hydrological data collection and analysis was carried out during 1991 and was reported in the Interim Report, Annex 3 (October 1991). This report updates that work and covers all the hydrological work undertaken during the study, but concentrates on that carried out during 1992, i.e. subsequent to the Interim Report. The major purpose of the hydrological component of the study was to provide information for other aspects of the study, and in particular the modelling and impact analysis. Rainfall/runoff was modelled using the NAM hydrological model, details of which are covered in Volume 6.

In addition to the hydrological data, analysis has also been required for the results of the hydraulic model runs. The programs developed for this purpose are outlined in this volume, together with example printouts and summary tables of the effects of the proposed development options; the interpretation of the model results is primarily addressed in Volumes 1, 2 and 6. The assessment of design discharge and regional discharge distribution is covered in Part 2 of this volume.

This chapter outlines the data requirements and approach to data collection and processing; Chapter 2 gives a summary of the climate and hydrology of the North West Region, with particular reference to flooding problems; Chapters 3 to 6 detail the work carried out on rainfall, water level, flow and climate data respectively; Chapter 7 covers hydrological aspects of the major drains and the Hurasagar regulator studied in the first part of the Study, Chapter 8 describes the procedures for analysing the results from the hydraulic model, and Chapter 9 comments on the limitations of the data and analysis, particularly for long-term impact assessment.

1.2 Data Requirements and Sources

The major data requirements of the study were rainfall, water levels and flows, all of which were required in daily format for the modelling studies. Climate data have also been needed for determination of evaporation and evapotranspiration, but in this case the much more manageable monthly format was sufficient (though monthly values of evapotranspiration were subsequently converted to daily estimates for the hydrological modelling).

The agencies mainly responsible for this data in Bangladesh are the Bangladesh Water Development Board, BWDB (all four parameters) and the Meteorological Department (climate data). In addition, the Meteorological Department has a small number of rain-gauges; these are at the main towns where gauges are also maintained by the Water Board, and it was decided that it was not necessary to collect such data. In general data has been collected direct from the Water Board (particularly its Surface Water Hydrology-II Directorate), but some data has been available in computerised or hard copy form from other FAP Study teams.

It became apparent at an early stage of the study that it would be necessary to collect data for almost all rain-gauge and river level stations in the region; attempts to limit data collection to selected long-term (and more reliable) stations proved hard to achieve because engineering computations for specific potential project locations often relied on data for short-term stations.

2 CLIMATE AND SOURCES OF FLOODING

2.1 Introduction

The North West Region of Bangladesh lies between latitudes 23°50' and 26°40' N, i.e. just outside the tropics. The region has a typical monsoon climate. Table 2.1 gives a summary of the main monthly climate parameters for example stations in the region, and Figure 2.1 displays the climatic norms for Bogra which is centrally located in the region. With the exception of rainfall, the main climatic parameters generally vary relatively little across the region.

Average annual rainfall ranges from less than 1400mm to just over 3000mm, with a regional average of about 1900mm. Well over 80% of the annual rainfall occurs during the five month monsoon season between May and September, and this rises to an average of 97% for the seven months from April to October.

In addition to the climate, the hydrology of the area is influenced by the topography and the drainage network, and in particular by the major rivers which bound it. The characteristic topographical feature of the region is its flatness. Elevations vary from less than 10 m above sea level in the south east corner to just under 100 m in the far north west; most of the region lies below 30m asl. In the southern part 1 m contours are typically up to 5 km apart, and even in the north west of the region average slopes rarely exceed 1 in 1000. As a consequence of the low gradients, the rivers and drainage channels within the region are generally heavily meandered and braided, and capacity for rapidly passing substantial flood peaks is very limited.

The region is bounded on its lower sides (south and east) by two of the world's great rivers, the Ganges and Brahmaputra; the latter is known as the Jamuna within Bangladesh. These rivers, which join to form the Padma at the south east corner of the region, drain a total area of nearly 1.5 million km^2, of which only about 7% lies within Bangladesh. The drainage basins are shown in Figure 2.2. The catchments cover some of the wettest areas in the world, together with the major part of the Himalayan mountains. Snowmelt from the Himalayas combines with runoff from the monsoon rains to produce very large flood peaks on the lower reaches of both rivers. Besides the potential for spillage from breaches of the embankments, high levels on the main rivers (particularly the Jamuna) make a significant contribution to flooding problems within the region because drainage from regional rivers is severely impeded.

2.2 Climate

There are two main seasons, separated by transition seasons. The monsoon season lasts from May/June until September and shows the typical monsoon characteristics of heavy rain and very high humidity. The dry season from November to February is sunny and relatively cool, with only occasional scattered showers. The transition from monsoon to dry seasons in October-November is relatively smooth, with declining temperature, humidity and storm frequency. The start of the transition period at the end of the dry season is also smooth, but the pre-monsoon period in April and May has somewhat unstable atmospheric conditions. This period is very hot and is characterized by thunderstorms and squalls, known as Nor'westers. This is also the peak season for cyclones in the Bay of Bengal which sometimes have catastrophic consequences in the coastal regions of Bangladesh. Cyclones themselves do not reach as far inland as the North West Region, but the area may be affected by associated storms.

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As a result of its sub-tropical location, temperature variations are more pronounced than in typical tropical regions; diurnal variation is a low 5°C during the monsoon but around 15°C in February. Maximum temperatures range from around 35°C in April/May to about 25°C in January, while minima peak at about 26°C in August and drop to 10-11°C in January. The monthly temperature pattern for Bogra, shown in Figure 2.1, is typical of the whole region; seasonal patterns and absolute values show relatively little variation with location. The occurrence of peak temperatures is closely connected with the passage of the monsoon; daily maxima occur just before the arrival of the monsoon, while the highest night-time minimum occurs at the peak of the monsoon season.

Humidity levels are consistently very high during the monsoon season, and only drop significantly for a relatively short period at the end of the dry season. Sunshine levels are of course low during the monsoon, but from November to May are consistently high. Wind speeds are at a maximum in the early part of the monsoon, but drop substantially by the beginning of the dry season.

Evapotranspiration reaches a maximum in April when temperature, sunshine and wind are all at or close to their maxima for the year, while humidity is a little below its peak. Evapotranspiration drops substantially thereafter as the humidity reaches very high levels and the other significant parameters all also become less favourable for evapotranspiration. Evapotranspiration is exceeded by average rainfall from May to October, while for the remaining months it is substantially higher than rainfall.

2.3 Rainfall

The North West Region has an average annual rainfall of a little over 1900mm; this is significantly below the estimated average for the whole of Bangladesh of 2320mm (MPO, Technical Report Nr. 10, 1985). Figure 2.3 shows isohyets of mean annual rainfall for the region. The driest area is in the south-west of the region where the annual rainfall of around 1400mm is the lowest in the country. The highest rainfall is in the far north of the region, where annual rainfall averages around 3000mm; however, this is much lower than in parts of the North East region of Bangladesh where the annual average reaches nearly 6000mm.

Annual rainfall shows considerable variability from one year to another as well as between different parts of the region in a single year. Over the period from 1962 to 1990 the regional average annual rainfall ranged from 1350mm in 1972/73 to 2600mm in 1987/88. The extreme annual rainfall totals at individual stations in this period were 554mm at Bagdogra in 1962/63 and 5633mm at Bhitargarh in 1974/75. There is some suggestion of a trend of increasing annual rainfall since 1962, but the available longer term records show that the variations in this period are of a similar magnitude to variations observed earlier in the century, so a continuation of the apparent recent trend cannot necessarily be expected (see Chapter 3).

The average monthly rainfall pattern is shown in Figure 2.4 (a); the absolute monthly rainfalls vary considerably, but this average pattern remains approximately the same across the region.

Storm rainfalls can be very heavy in all parts of the region. At almost all of the stations daily falls of 200mm have been recorded, with the absolute maximum being 485mm at Rajshahi (which is one of the driest places on the basis of long-term average rainfall) in 1965. 10-day totals of 700mm or more are not uncommon, with the most extreme recorded value being over 1100mm at Kaunia in 1987. Whilst heavy 1-day rainfalls can occur right across the region, the highest 10-day rainfalls are not surprisingly concentrated in the wetter northern part of the region. It may also be noted that at more than one third of the rainfall stations in the region the highest recorded 10-day rainfall occurred in 1987, which has already been noted as the wettest recorded year over the region as a whole.

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Because of the unavailability of rainfall data for the Ganges and Brahmaputra catchments outside Bangladesh it has not been possible to investigate the correlation between wet years in the region and over the upper catchments, but a qualitative assessment based on the recorded flows in the main rivers suggests that there is some correlation, and consequently that severe flood conditions within the region are quite likely to coincide with, and be exacerbated by, severe floods on the main rivers.

2.4 The River System

The region is bounded, and effectively defined, by the Jamuna (Brahmaputra) to the east and the Ganges to the south (Figure 2.5). These two rivers, into which the entire area drains, meet up at the south east corner of the region and play a dominant role in constraining its drainage. Before the construction of the confining embankments the Ganges and Jamuna rivers were major contributors to flooding in the region, and in more recent times they have also been so at times of breaches of the embankments. The major internal rivers are shown in Figure 2.5. Mean monthly flows at selected stations are given in Table 2.2, and for three of those stations are illustrated in Figure 2.4 (b); the maximum monthly mean discharges are also marked on Figure 2.5.

Three large tributaries of the Jamuna, the Teesta, Dharla and Dudhkumar, pass through the north east corner of the region, and the Mohananda, a tributary of the Ganges, passes through the south west corner. All other rivers in the region are connected to the Atrai-Karatoya-Bangali system which drains to the Jamuna through the Hurasagar at the south east corner of the region.

The Teesta, Dharla and Dudhkumar rivers originate in the Himalayas and Himalayan Piedmont Plains. Though they are large rivers they are relatively steep on entry from India into Bangladesh, and their floods can be flashy. On a number of occasions the Teesta has changed its course in the vicinity of its outwash fan, generally in an easterly direction, so that the watercourses internally draining most of the North West Region are in fact former Teesta channels.

The Mohananda river has a large catchment area in India to the west of the Barind Tract, but it is also fed by outflows from the north western corner of Bangladesh via the Tangon and Punarbhaba which pass through India before joining the Mohananda in the south west of the region.

The river Atrai rises in West Bengal to the north of Panchagarh. Its catchment area in India is fairly small, but it appears that it is subject to occasional spillage from the upper Teesta at times of exceptional flood flows. Together with the Tangon the Atrai drains the north west corner of the region. After passing southwards through Khansama, it bifurcates into the western Punarbhaba branch and the eastern Atrai branch, both of which pass through the Indian Barind enclave and return to Bangladesh further south. Subsequently the Atrai turns south eastward at Jotebazar and picks up various tributaries including the Little Jamuna, Nagor and Barnai before joining with the Bangali to become the Hurasagar which is the major outflow channel for the internal drainage of the region to the Jamuna.

The Karatoya rises as the Jamuneswari, which has only a very small contributing catchment in India. It also appears to be subject to occasional flood spillage from the Teesta. After flowing in a generally south or southeast direction the Jamuneswari becomes the Karatoya, and, having bifurcated at Chakrahimpur, its eastern main branch joins up south of Gaibandha with the Alai, part of the Ghagot system, a tributary flowing roughly parallel to the east. At times of low flow in the Jamuna, some of the Ghagot flow is discharged direct to the Jamuna via the Manos regulator. Further southwards, the Karatoya becomes the Bangali; channels bifurcate and rejoin at several places before joining the Atrai to form the Hurasagar.

The other branch of Karatoya, used to flow in a southerly direction past Bogra. But this part is completely disconnected from the main river and it now acts as a channel draining part of areas lying in the north and east of Bogra. it is rejoined by Bangali and flows out into Hurasagar river.

In the south of the region the Baral joins the Ganges to the lower Atrai. Natural flows are from the Ganges inland, but these are now regulated by a structure at Charghat. Within the region, the rivers in the north east corner have relatively steep gradients of 1 in 2000 or more, but in nearly all the remainder of the area river courses have very flat gradients of 1 in 5000 or less. The rivers are consequently heavily meandering and have limited capacity for passing flood discharges. The system is exacerbated in the lower areas by the tendency of some channels to overflow towards others during flood periods. An additional factor of fundamental importance to the flooding problems in the southern part of the region is the fact that flood levels in the Ganges and the Jamuna are often equal to or higher than internal river levels for long periods. This means that drainage from the region can freely outfall to the main rivers for only relatively short periods at the beginning and end of the flood season. The great bulk of the internal drainage therefore ponds in the lower Atrai/Hurasagar/Bangali against the backwater effects from the Jamuna. Even in a relatively dry year such as 1992 extensive areas are flooded for long periods. Past attempts to reclaim land in this area by constructing polders has in some cases seriously confined flood drainage courses, with a consequent increase in typical flood levels in other places.

2.5 The Flooding Regime

Flooding and drainage problems in the region may be separated into a number of categories depending on their cause and location. The Master Plan Organisation (MPO) distinguishes between "areas normally flooded by major river spills" and "areas normally flooded by minor rivers"; the former naturally lie along the main river embankments and the latter cover most of the rest of the region. This correctly identifies the general locations of flooding, but in the North West Region it is appropriate to distinguish more precisely between different causes of flooding in the region because different modes of analysis and provision are likely to be required.

The first type of flooding in the region is due to breaches in the embankments of the major rivers - primarily the Jamuna, but also the Teesta and to a lesser extent the Ganges, Dharla and Dudhkumar. Flood damage is only partially related to the severity of the flood event because accidental or intentional breaches can occur with "normal" as well as extreme floods.

The second type of flooding is due to outfall constraints, primarily from the Hurasagar to the Jamuna. This comprises flooding in the lower Atrai and Karatoya-Bangali systems, and is predominantly caused by high stages in the Jamuna causing backing up of levels in the river system. The severity of flooding is also related to rainfall conditions within the region (and to a small extent cross-border flows on the minor rivers from India) because the total flow volume from the internal rivers must be stored until the levels in the Jamuna permit natural drainage via the Hurasagar. The severity of the flooding is therefore directly linked to the severity (i.e. return period) of the conditions both in the main rivers and in the region itself.

It is appropriate to make a distinction between a backwater effect and backflow; the latter refers to reverse flow, while the former is the backing up of water levels caused by high downstream water levels inhibiting drainage. It is not possible to precisely define the importance of high river flows from upstream and of backing up from high downstream levels because the two are closely interlinked, but the problems in the Atrai system are substantially due to backwater effects caused by high Jamuna levels, the effects of which may extend to Atrai Railway Bridge or beyond (i.e. well in

excess of 100 km) in a high Jamuna flood. Actual reverse flow in Hurasagar river may occur in pre-monsoon season in some years and would only affect a short distance near to the outfall. The problems of drainage from the Hurasagar are considered in more detail in Chapter 7.

Similar problems occur on the Mohananda and associated river systems when localised storm runoff coincides with high stages in the Ganges which constrain outflow.

The third type of flooding is that caused by storm runoff in the upper catchments of the region. These problems are often very localised in nature and may best be alleviated by specific localised measures.

The third type of flooding is caused by storm runoff in the upper catchment of the region.The problems are at times localised in nature and may best be alleviated by specific localised measures ie. improved drainage; such work must take the effect downstream into account. There are years eg. 1987 and 1991 when high intensity rainfall cause quite widespread flooding.The land slope in the northern part of the region is sharper than that in the lower region and naturally rainfall runoff drains out rather quickly. But in case of extremely high intensity rainfall the local drainage rivers can not cope with the generated huge runoff and as a result water spills over the land. The development of roads and other infrastructures in the area in recent past prevent the spontaneous overland flow, which might have taken place in the years prior to such development, exacerbating the flooding condition. Hence, infrastructural development in this area should take such unusual event into consideration.

Although flooding problems have been separated into different categories there is obviously considerable overlap between them. Flooding in the lower Karatoya-Bangali basin, for example, may be predominantly caused by the lack of drainage to the Hurasagar, but it is also likely to be exacerbated by spills from the Jamuna further upstream.

The severity of flood problems can be critically influenced by the timing of the flood peaks on the two main rivers. In 1988, which was by far the most severe year on record for flooding in Bangladesh as a whole, the peaks of the Ganges and Jamuna were both very high and were almost coincident (see Figure 2.6). Recession from flood levels was further restricted by the peaking a few days later of the Meghna, which combines with the other rivers before they outfall to the sea. Figure 2.7 gives an indication of the flooded areas in Bangladesh in that year; note that this shows the areas still flooded two weeks or more after the peak of the flood. The extent of backing up of flood waters on the Atrai and Karatoya-Bangali systems is clearly shown. Parts of the centre and north of the region which escaped relatively unscathed in 1988 suffered greater flooding problems from more localised causes in 1991.

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3 RAINFALL DATA

3.1 Introduction

There are 94 Water Board stations with usable data records in the North West Region; their locations are indicated in Figure 3.1 and they are listed in Figure 3.2 which also shows the availability of data over the period from 1962. For the purposes of the study a 28-year standard period (1962/3 to 1989/90) was adopted; data was later added for 1990/1 and for 1991/2 (up to October 1991) when it was decided that model studies would look at the 1990 and 1991 flood seasons in addition to the 25-year model runs covering 1965-89. The starting date of 1962 was selected because a number of gauges were installed at that time, and many of the longer-term stations had substantial gaps in the records in the immediately preceding years. Some 77 of the 94 stations had data for all or part of 1962/63; the data availability rose rapidly to very nearly 100% by 1965. Figure 3.3 shows the average data availability for each year, with 1991/2 being calculated for the period April to October only. A number of stations closed around 1980, and others did not open until after 1962; the calculations for Figure 3.3 have been based on the number of stations which were meant to be operating in each year rather than the overall total of 94 stations. The average data availability for the whole period is in the region of 95%.

3.2 Data Quality Control and Infilling

For the purposes of the modelling work, and for general hydrological analysis, it was necessary to check the quality of the data (making corrections where appropriate) and to infill gaps in the data. These gaps refer both to periods where the original record was not available and to years when a station was not open. The data quality control and infilling was carried out initially for the standard period (1962-90), and was written up in Working Paper Nr. 6 ("Quality Control and Infilling of Rainfall Data", FAP-2, February 1992). The major aspects of the checking and infilling procedures were as follows:

- random cross checks between data collected on disk from MPO and others and monthly printouts of Water Board data;
- checking of records of zero rainfall in wet season months; where substantial rainfall was recorded at other nearby stations it was assumed that missing data had been incorrectly entered as zero rainfall;
- identification of periods of implausibly high rainfall, by abstracting maximum rainfalls for various durations and cross-checking against neighbouring stations;
- cross correlation analysis to identify stations whose records required particular checking; each station was analysed with a group of nine nearby stations;
- double mass analysis comparing each station of interest to a group of neighbouring stations whose records were believed to be reliable;
- as result of the above checking procedures, a number of periods of data were adjusted or set to missing;

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- missing data was infilled from one or more nearby stations using the normal ratio method (the precise method of calculation is detailed in the Working Paper); most gaps were filled from the closest stations (primary infilling), most of the remainder from slightly more distant stations (secondary infilling) and a few from other stations (tertiary infilling); no data was infilled from stations whose records had already been infilled;

- infilled series for all stations were produced which were complete for all years except 1971/72 when the original records were extremely sparse, particularly in the north west of the region.

Following the presentation of the Working Paper, some additional data was collected, particularly for 1990-91. Infilling of the 1990-91 data was carried out using the same principles, but with some changes to the stations used for infilling (see list in Appendix A). Values have been estimated for all periods of missing data in the 19-month period up to October 1991. Basic quality control was carried out for the additional data; this resulted in some additional periods of data modification (both for 1990-1 and for some earlier periods not previously identified) which are included in Appendix A. It is emphasised that data quality should be further reviewed when the remaining 1990-1 data has been collected.

As indicated in the Working Paper, because of the time pressures on the project, the data quality checking was much less thorough than would have been desired; if or when more time is available the data should be the subject of more rigorous checks. The methodology and programs developed for data infilling could then be used to rapidly revise the infilled data files as required. As an indication of the potential for further improvement in data quality, Figure 3.4 shows double mass plots for two stations whose records have been accepted to date; in each case the cumulative rainfall at the station under review is plotted against the average of about half the stations in the region. At station 16 (Joari) there appear to have been some changes in the relative catch of the gauge around 1972, 1978 and 1990, while the record for station 200 (Patgram) looks very inconsistent.

3.3 Data Analysis

Mean monthly and annual rainfall for each station (using the infilled series for the standard 28-year period) are presented in Table 3.1 and Figure 2.4 (a). The mean annual rainfall for the 94 stations is 1915mm, and this is a good representation of average regional rainfall. 1- to 10-day rainfalls have been estimated for each station for return periods of 2 to 50 years. Table 3.2 shows the printout of 10-day rainfalls; most of these values are close to those presented in the Interim Report, but in a few instances there are major differences resulting from the deletion of erroneous data. The largest change is in the estimated 50-year 10-day rainfall at station 3 (Atrai) which has dropped from 980mm to 570mm. Table 3.3 gives 1- to 10-day rainfalls for three example stations.

The highest observed 1-day rainfall is 485mm at Rajshahi on July 1st 1965, while the station with the lowest extreme rainfall is Dhunot (189mm). The highest 2-day rainfall is also at a station in the relatively dry southern part of the region (677mm at Chatmohar in June 1964), but for the longer periods the most extreme rainfalls have, as expected, been in the northern part of the region. The 5-day maximum is 870mm at Pirgachha in 1976 and the 10-day is 1118mm at Kaunia in 1987. Figure 3.5 shows that at about one third of the stations the highest 10-day rainfall occurred in 1987, but that no particular year stands out with regard to highest 1-day rainfall. The year 1987/88 was the wettest year during the period at 35 of the 94 stations, and had average regional rainfall more than 300mm higher than in any other year. 1972/73 was the driest year at 31 of the stations, and had an average regional rainfall only just over half that of 1987/88.

During the study it has become clear that the severity of flooding in any particular year may vary substantially across the region; although 1987 and 1988 are recognised as severe flood years, in some parts of the North West Region 1991 was worse than both of them. This largely reflects the variability in rainfall over the region. The degree of correlation between rainfall at two stations is clearly related to the distance between the stations; Figure 3.6 shows this relationship between rainfall at station 1 (Atghoria) and at each of the other stations. This station was selected because it was one of only four with complete records, and the data quality appears to be good; in addition its location close to the south-eastern extremity of the region means that almost the full range of inter-station distances is covered. The correlations were derived from monthly data for wet season months from 1962 to 1989, using the modified data series. A similar graph using the original uncorrected data was broadly similar, but had several additional outliers with poor correlation for the distance involved. Use of the infilled data series made virtually no difference to the average correlation, or to the relationship between correlation and distance.

Inter-station correlation decreases steadily with distance - from the range 0.7-0.9 up to 60 km down to 0.45-0.55 at in excess of 200 km. This lends some support to the data infilling procedure. Almost all primary infilling was done using check stations well within a radius of 40 km, and all secondary infilling stations were within 60 km. The most distant station used for tertiary infilling was a little over 60 km; this is considered acceptable for the limited period of dry season infilling undertaken to complete records for the year 1970/71, but more extensive tertiary infilling to complete 1971/72 records (which would have required more distant infilling stations) would not be justified.

Examination of the annual rainfall totals for the period 1962/3 to 1989/90 suggests that there could be a rising trend in rainfall in the North West region. Figure 3.7 shows the variation in the 5-year moving average annual rainfall of all 94 stations with respect to the long-term mean. This pattern is clearest in the middle and northern parts of the region, while some stations in the south east show no sign of trend at all. It must be noted that 28 years is a relatively short period for the identification of rainfall trends; longer term records are available for a few stations, with the most complete records being at Rajshahi, Bogra and Rangpur. These three stations are well spread across the region, and an average of the three records gives a reasonable representation of regional rainfall. Figure 3.8 shows the 5-year moving average for data from 1902 to date; the variations in the period since 1962 (which are greater for the three stations than for the average of 94) are shown to be only slightly larger than those observed earlier in the century, and it is concluded that there is no clear evidence of trend in the data.

4 WATER LEVEL DATA

4.1 Introduction

The major needs for water level data were for use in the surface water hydraulic modelling and for determining embankment levels and other engineering design considerations. Determination of design flood levels is complicated by the effects of polder and embankment developments which have caused significant rising trends in peak water levels in many parts of the region. Frequency and trend analysis was addressed in some detail in Annex 3 of the Interim report, and is discussed further in section 4.3 below.

There are over 100 river water level observation stations with potentially usable data records in or bordering the North West Region, though some of these are new and therefore have very short records. The locations of the stations are shown in Figure 4.1. The station names and periods of data available during the Study are shown in Figure 4.2.

4.2 Data Correction and Infilling

All water level records were checked by plotting hydrographs to identify major errors. Individual days with substantial errors (usually whole metres out) were corrected, and a number of unrealistic sudden shifts in the data were identified and corrected; these may well have occurred when a staff gauge was moved and an error made in determining the relative level of the new gauge. Apart from occasional missing values which were infilled by interpolation between adjacent days, the records at stations required for the hydraulic modelling were generally complete.

Mean monthly river levels for a selection of river gauging stations throughout the region are shown in Table 4.1.

4.3 Trends in Water Levels

Study of the recorded annual maximum water levels indicated that there were apparent trends in peak levels at a number of stations. Figure 4.3, reproduced from the Interim Report, shows the annual maxima, 5-year running mean and apparent trend for four locations. These trends are the result of human intervention by means of polder and embankment construction, and in some cases of breaches of existing river embankments. Frequency analyses were carried out for the Interim Report in order to give some guidance on the return periods of recent major floods and the approximate magnitude of design flood levels such as 5-year and 20-year floods. However, for accurate design flood levels it is necessary to remove the trend before undertaking frequency analyses. This has effectively been done during the second stage of the Study by carrying out analysis of the results from the hydraulic models (in which the configuration of embankments remains constant), and determining design levels from that analysis.

Figure 4.4 shows the annual maximum levels from the models for the nodes corresponding to the four stations shown in Figure 4.3, together with the 5-year running mean; the 5-year running mean of observed data from Figure 4.3 is shown for comparison. It may be seen that the model results show no significant trend.

Frequency analysis of the model results is covered in Chapter 8.

5 RIVER FLOW DATA

5.1 Available Data

River flow data are a major input to the hydraulic models. Daily mean flows for more than 40 stations were collected; some were in computer form but much had to be entered by hand. The initial data checking was similar to that for water level data; in addition a major effort was made to resolve errors relating to stage-discharge ratings (see subsequent section).

There are 57 river gauging stations in the region for which flows have at some time been recorded; more than 30 of these are still active. The station locations are marked on Figure 4.1, with different symbols from stations at which only water level is measured. The station names and periods of data record are shown in Figure 5.1. Monthly mean flows for selected gauging stations are shown in Table 2.2.

5.2 Stage-Discharge Ratings

The accuracy of flow data depends fundamentally on the accuracy both of the water level data and of the rating equation(s) used to convert the level data to discharges. Extensive checking and analysis of the flow data was undertaken before the Interim Report (as for water level data), but at that stage little attention was paid to the ratings.

The standard procedure in Bangladesh is for discharges to be measured every two weeks at each measurement location, and for a rating equation to be determined for each water year (April to March). Occasionally there may be a change in the rating during the year, or one rating may apply for two consecutive years. Good records are available of discharge measurements, and usually also of the rating equations; however, changes in rating which result solely from a shift in the zero flow intercept have not always been fully documented, so it is not necessarily easy to reproduce BWDB flow data from the water level data and the available information on the rating.

BWDB rating equations were reviewed by (wherever possible) plotting the recorded discharge measurements together with the rating. In most cases it was found that there was reasonable agreement, though at certain stations the relationship between stage and discharge is much less clearly defined than at others. Recalculation of ratings generally produced very little change from those determined by BWDB.

Particular problems concerning ratings were identified at Bogra and Talora. Site visits indicated that both sites have significant problems with regard to discharge measurement. At Bogra the river goes out of bank (on the left bank) at a relatively low level. In addition, no BWDB rating was available for 1988/89 (or later), and the data for both 1988/89 and 1989/90 appears dubious - all measurements during those two years are very low, and it is understood that the local BWDB employee responsible for discharge measurements was off work due to illness during those years. The quality of the water level data at that time is also uncertain, so the accuracy of flow data must be considered to be very doubtful. At Talora the measurement location was recently moved some 100-200 m upstream from a position affected by a lateral inflow channel to one very close to a sharp bend in the river; both locations are problematical, and the change of site introduces additional uncertainty. All flow data for Talora must be considered doubtful.

6 CLIMATE DATA

6.1 Introduction

Climate data are of interest in the study in the context of evaporation and evapotranspiration - as inputs to the surface water hydrological modelling routine (NAM), and for drainage and crop water requirement calculations. Because the rates of evaporation and evapotranspiration only change relatively slowly during the year it is considered that monthly estimates are sufficient; the manual for NAM states that very little benefit is to be expected from using daily rather than monthly data for evapotranspiration.

6.2 Evapotranspiration

The standard international procedure for estimating evapotranspiration for crop water requirements is the Modified Penman formula used in the FAO Irrigation and Drainage Paper Nr. 24, and this has already been widely applied in Bangladesh. Table 6.1 gives the estimates of potential evapotranspiration for five stations in the North West Region, as presented in the Interim Report. For one station (Rajshahi) these were derived from climate data collected from the Meteorological Department; for the other four stations the values are those published by the Bangladesh Agricultural Research Council (BARC). These are considered satisfactory, though it should be noted that readily available sources of climate data in Bangladesh do not always mention a number of significant details, such as the height at which wind speeds are measured, the ratio of day to night wind speed, and the manner in which mean daily temperatures and humidities have been calculated. This means that assumptions have had to be made in the calculation of evapotranspiration estimates, and consequently the accuracy of the results is less certain than is desirable. However, for the purposes of this study they should be satisfactory. There is a slight increase in evapotranspiration from the north to the south of the region, but overall there is relatively little variation; this reflects the fact that important parameters such as temperature and sunshine are broadly similar across the region. It may be noted that the values presented in Table 6.1 are somewhat higher (particularly during the wet season) than those presented at a much earlier date by Manalo in the "Agro-Climatic Survey of Bangladesh" (and calculated by a quite different method to that of Penman).

In order to obtain a daily sequence of potential evapotranspiration values, the average of the monthly values (in mm/day) for each pair of consecutive months was assumed to apply at the end and beginning of the respective months; the mid-month value was calculated such that the required monthly average was achieved, and the values for the remaining days were interpolated. In a few instances this led to an unrealistic trough or peak in the daily values; such values were smoothed by fixing the daily value for (eg) the 10th or 20th of the month rather than the mid-point. Figure 6.1 shows the resulting daily evapotranspiration values for Dinajpur, together with the monthly mean values which show a stepped form; values for June and March were adjusted in the manner described.

The Surface Water Modelling Centre (SWMC) have adopted a different procedure with regard to evapotranspiration data for use in the NAM model. SWMC studied evaporation data from the ten stations in the region (see subsequent section), and selected three stations (Bogra, Rangpur and Rajshahi) as being the most reliable. This data (after quality control procedures referred to below) was used for mean areal evapotranspiration and entered directly to the NAM model. The SWMC report (Report on Pilot NAM:NWRM, April 1991) states that the pan coefficient of 0.7 used by BWDB to "calculate evapotranspiration" was not used "in order to obtain more realistic evapotranspiration from paddy field with water standing on the surface." This is an incorrect interpretation of the pan coefficient which BWDB correctly use to calculate open water evaporation

from pan evaporation. Potential evapotranspiration cannot readily be calculated from evaporation data, but it is generally some 10-20% lower than open water evaporation - and therefore some 40% lower than pan evaporation. However, it is understood that SWMC chose a factor of 1.0 because it provided a better water balance result when using NAM than a theoretical lower value.

Figure 6.2 shows the average monthly values of evapotranspiration used by SWMC (average of 1986/87 to 1989/90) and this study; it may be seen that there is very little difference between them, so the possibly questionable approach previously adopted by SWMC would not in practice introduce substantial errors.

6.3 Evaporation

Evaporation estimates may also be calculated by the Penman formula, but some measured data is available. Evaporation data has been collected from ten stations in the North West Region; this has been determined from Class A Evaporation Pans. Figure 6.3 lists the stations and indicates the periods of daily data collected from BWDB. It may be noted that the period of data availability is limited, and there are significant gaps in the records. Furthermore, evaporation pans are subject to errors arising from intervention by cattle, birds and children, and the data must always be treated with due caution.

The accurate measurement of evaporation is much more difficult than rainfall or water level, particularly in a wet climate. On a dry day the evaporation is determined by measuring the amount of water required to refill the evaporation pan to the reference level. In Bangladesh the usual practice is to do this with a measuring cup which represents 0.02 inches over the surface area of the pan; the application of a standard pan coefficient of 0.7 (to allow for evaporation from a pan being higher than from a large expanse of open water) means that daily open water evaporation is recorded in multiples of 0.36 mm, rounded to the nearest 0.1 mm. Recorded evaporation on dry days therefore consists of daily values from the series 0.4, 0.7, 1.1, 1.4, 1.8, 2.1, 2.5, 2.8, 3.2, 3.6, etc. As a result, the value for any one day is not accurate to the one decimal place to which it is presented, but the accumulated value over a number of days would be more reliable.

When rainfall has been recorded, the measured rainfall must be added to the measured (net) evaporation; this introduces additional uncertainty to the evaporation estimate because the amount of rain measured in the rain-gauge (even if it is almost adjacent to the evaporation pan) is not necessarily the same as that which was received by the pan. When rainfall exceeds evaporation, water has to be removed from the pan to achieve the reference level (again in multiples of 0.02 inches); in such a situation the pan evaporation is calculated by subtracting the amount removed from the measured rainfall. On days of heavy rainfall this estimate is subject to very large potential error because it is the small difference between two large numbers; on many occasions the calculated value is negative, or unreasonably high, and even when it is within a typical range for daily evaporation its reliability is very limited.

These difficulties with evaporation measurements mean that data quality must be carefully reviewed. BWDB records replace all calculated negative values by zero, and values higher than the maximum for the month on a dry day by an estimated value; these modifications are flagged on the printouts. This is a significant improvement on the raw data, but still tends to result in under-estimation of actual evaporation because evaporation will not actually be zero - even on a day of continuous rainfall. In addition, calculated values of marginally above zero are almost certainly underestimates. BWDB data has been further modified for this study by replacing flagged zeroes (i.e. originally calculated negatives) by the mean value for the remaining days of the month; monthly means for the

available data are presented in Table 6.2. While this adjustment is significant for some station-months of data, on average it only increased values by 1-2 %. These values still appear to be very low. There is also very substantial variation in the evaporation data, with the highest annual total (Bogra, 1274 mm) being almost twice the lowest (Ruhea, 638 mm); this degree of variation is not compatible with the relatively minor changes in climate across the region. In addition, the values for individual stations show unexpectedly large variability from one year to another.

As noted in the previous section, the problem of evaporation data has also been addressed by staff at SWMC. They have used the same basic data (though not for identical periods), but have applied different modifications and corrections. From the ten stations, SWMC identified three (Rangpur, Bogra and Rajshahi) as having better quality data. Their reports state that values outside the range 2-7 mm have been rejected; for the years 1986/7 to 1989/90 at the three stations their values are generally within that range (absolute range 0-8.0), but from 1990 a number of higher values are present (presumably because the data had not been checked at the time it was made available to this study). SWMC have also used a pan coefficient of 1.0 (see previous section on evapotranspiration). The monthly means of data from SWMC for the three selected stations are given in Table 6.3; these are based on the data for 1986/7 to 1989/90 only because the subsequent data does not appear to have been subjected to SWMC's standard data quality control. Furthermore, the data presented by SWMC for Rangpur appears doubtful for two periods: in 1987/88 the daily figures for the last 134 days were all 2.9 mm, and the figures for 1989/90 were virtually identical to those for 1988/89. SWMC's values are of course substantially higher than those calculated from BWDB data using the pan coefficient of 0.7, and they also show excessive variation between stations.

The most extensive readily available previous study of evaporation in Bangladesh is the "Agro-Climatic Survey of Bangladesh" (B. Manalo, Bangladesh Rice Research Institute, date circa 1976) which has already been referred to. Evaporation data presented there for stations in the North West Region is presented in Table 6.4. No information was presented concerning the periods of data records from which the means were derived. All values are very low, possibly because of the presence of zero or negative daily evaporation values during the wet season, as explained above. However, the values for the different stations are much more consistent than the BWDB data, with the highest only about 15% higher than the lowest - a realistic range.

It is not easy to draw conclusions about evaporation from the somewhat conflicting information which has been available. After much consideration it was decided that the available evaporation data was not sufficiently reliable and it was decided that for the purposes of drainage design monthly evaporation estimates would be taken to be 10% higher than the evapotranspiration estimates obtained by the Penman procedure. Resulting values for the five stations are contained in Table 6.5.

7 MAJOR DRAINS AND REGULATORS

7.1 Introduction

In the first part of the Study, investigations were undertaken concerning the possibility of reducing flooding problems in the southern part of the region by constructing new Diversion Drains to carry water from northern and central parts of the region direct to the main rivers, thereby reducing pressure on the lower Atrai. It was concluded that such schemes were very unlikely to be economic, even though the indications were that they might be technically feasible and effective. A further proposal for the construction of a Hurasagar Tail Regulator to stop river Jamuna flow from backing up the Hurasagar/Atrai/Bangali system was also found to be extremely expensive. Furthermore, a study of the hydrological conditions showed that such a regulator would not have the full desired effect because flooding problems in the area are mostly caused by the high Jamuna levels inhibiting drainage rather than reverse flow of Jamuna water into the Hurasagar.

The subsequent sections of this chapter have been reproduced from the Interim Report.

7.2 Major Drain Options

In the course of investigating the Major Drain Options, a comparison was made between main river levels and internal river levels at stations close to potential outlet locations.

Examples of these comparisons are indicated in Figures 7.1 to 7.4. For the four years 1986-89, Figure 7.1 shows the annual water level hydrographs for the Jamuna at Mathurapara (Station 15j) and for the Bangali at Sariakandi (Station 11a), while Figure 7.2 shows the same for the Ganges at Rampurboalia (Station 88) and the Sib at Nowhata (Station 261). Figures 7.3 and 7.4 show the level differences. They show that the Jamuna typically remains above the internal Bangali at Sariakandi for the 6 month period mid-April to mid-October, reaching a maximum difference annually of at least 2 metres and often nearly 3 metres. The Ganges at Rampurboalia is typically above the Sib at Nowhata for the 4 month period mid-June to mid-October, though often much more of the year, generally reaching a 4 metre difference and occasionally nearly 6 metres. Both of these results, which are of course dependent on the accuracy of the station datum levels, are discouraging for the notion of interceptors or diversions at these locations, and similar results were found at other potential outlet locations.

Further level comparisons were made between main river levels and levels for gauging stations further inland with a view to assessing potential hydraulic driving heads, assuming interceptor/diversion embankments could be taken back inland to avoid backflow.

Two examples are presented here of the potential hydraulic heads, the first being for the Interceptor Option No.4, and the second being for the Diversion Option No.1. The IC4 Option would take part of the flow from the Upper Atrai near Bhushirbandar, transfer it into an enlarged Jamuneswari channel, and then pass the accumulated flow into an enlarged Karatoya channel near Siraj. The latter would follow the Karatoya/Bangali main channel to an outlet into the Jamuna probably near Sariakandi. Figure 7.5 shows the hydraulic head along part of the proposed alignment for IC4 which would have been available to push the IC4 flows though to the Jamuna in the course of the heavy internal floods of 1987. It shows that upstream of Sariakandi at Mohimaganj (Station 155), less than 1 metre of driving head was available for much of the wet season, and that Jamuna levels were higher for part of June and July. Further upstream at Chakrahimpur (Station 63), a minimum of 0.6 metres driving head was available at the height of the flood, and 1.8 to 2.8 metres was available for most

of the wet season. By Badarganj (Station 62) further upstream on the Karatoya, the terrain has steepened considerably, and a minimum of 12 metres was available. At Bhushirbandar (Station 142.1) on the Upper Atrai, a minimum of 20 metres was available.

Figure 7.6 shows the hydraulic head which would have been available during the 1987 floods along the Diversion Option D1. D1 would divert part of the Little Jamuna flows into the Atrai above Mohadevpur, and then part of the increased Atrai flows into the Sib, which would outfall into the Ganges near Rampurboalia. It shows that, on the assumption that the gauging station datum levels are reasonably accurate, levels in the Sib at Nowhata were lower than the Ganges at Rampurboalia for most of the year. Far upstream on the Atrai at Mohadevpur (Station 145), the levels were lower than the Ganges for September and part of October, and even at Chakhariharpur (Station 144) near the international border the water level was lower than the Ganges for a short period in September. Driving heads would have varied rapidly depending on the relatively flashy internal flood runoff rates, resulting in up to 6 metres at Mohadevpur and up to nearly 10 metres at Chakhariharpur. At Jaipurhat on the Little Jamuna (Station 132.5), the water levels exceeded those of Rampurboalia by at least 1 metre throughout 1987, and 3 to 7 metres was available for most of the flood season.

Though useful driving heads can be achieved, they entail, as explained in the Main Report, long, high and expensive embankments, and further local drainage problems.

7.3 Hurasagar Tail Regulator

The Hurasagar is the outlet for the major part of the North West Region's internal drainage, consisting of the Atrai and Karatoya/Bangali river systems. The low lying area through which the Hurasagar passes before its confluence with the Jamuna is seriously affected throughout most of each flood season by the backwater influences of the Jamuna. The possibility has often been considered that a regulator across the Lower Hurasagar might alleviate these backwater effects and reduce the habitual flooding in the Chalan Beel and Lower Atrai area. Our investigations suggest that, as many have suspected, such a regulator would be very costly, and its beneficial effects on local flood levels would be minimal.

A preliminary cost estimate for a Hurasagar regulator has been prepared and is shown in Table 7.1. This shows the cost to be in the order of Tk 3 billion ($80 million): such a high cost is to be expected in view of the capacity of the Hurasagar and the complexity of the structure.

The total catchment area within the North West Region which drains towards the Hurasagar is about 21,640 km^2, or 71% of the net North West Region excluding the major rivers' active flood plain. A small area of West Bengal also drains into this system through the Karatoya from north of Bangladesh. Occasional breaches in the Brahmaputra Right Embankment and the Teesta Right Embankment are also a source of spillage into the Karatoya and therefore Hurasagar system. Only a very small part of this total drainage is able to bypass the Hurasagar, mainly for a short period through the Manos regulator when Jamuna levels permit. The average annual rainfall on this large drainage area is of the order of 2000 mm, mostly in the flood season, and it is sufficient to ensure that large flood volumes pass down to the Hurasagar annually. It appears that it is this large volume of flood water which accumulates in the lower Atrai, rather than actual backflow from the Jamuna which is reported to have been observed only rarely. The major effects of the Jamuna therefore appear to be to obstruct outflow rather than to cause inflow, which would mean that a regulator would inevitably not significantly improve local drainage condition.

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For the four years 1986-89, the outflow volumes through the Hurasagar as integrated through the various sub-catchments in the Regional Model, are presented in Table 7.2. They range from 12,600 Mm^3 to 19,100 Mm^3, for the less than average year 1986 and the quite rare flood year of 1988 respectively. These volumes represent runoff rates of 580 mm to 880 mm from the 21,640 km^2 main catchment area, and in 1988 would have included some Jamuna spillage through breaches.

The water levels in the Hurasagar are effectively those of the Jamuna. They vary typically throughout the year from a minimum of just over 3m pwd to a maximum of 10m pwd or more, a range of at least 7 metres. The order of flood levels reached in the Hurasagar in recent years is indicated in Figure 7.7. Though an apparently upward trend is indicated, for so few years of data and with the two recent high years (1987 and 1988) causing a bias, this trend cannot be considered significant. Figure 7.8 shows a frequency plot of the annual maximum flood peak levels, which shows that the range between a mean annual flood and a 100 year flood is about 3.5 metres. The highest recorded flood level was in 1988, which, at 12.32m amsl, was a 22 year return period event on the basis of the short data period available for the station.

Elevation/storage relationships derived from 1 m contours over the Lower Atrai/ Hurasagar area are presented in Figure 7.9. The latter relate to the two cases: with and without the Pabna FCD area. The storage below 8 m amsl, which is essentially within bank, is small, and has been only approximately estimated. Above this level, for the more appropriate case excluding Pabna, the total storage to the Baghabari (Station 151) mean annual flood level of 10.2 m amsl is 1,500 Mm^3. Above this level much greater storage becomes available, with an additional 4,000 Mm^3 up to 12 m amsl, and a further 9,000 Mm^3 up to 14 m amsl. However, there is already severe flooding at the level of 12 m amsl, and so it would be undesirable to use storage beyond this point.

The levels recorded throughout the flood seasons of 1986 and 1987 are presented in Figure 7.10. Also shown in this figure are the levels which would have been reached if all flows in the Hurasagar had been stopped by a regulator, providing an indication of the cumulative flood volume and the available storage. Superimposed on the latter sets of levels are the levels which would have resulted from the idealised operation of a regulator such that it would be closed when observed rates of level rise exceed those related to the General Model inflows (which imply occasional reverse flows). Under such operation rules, outflow would be permitted to the maximum whenever possible, and reverse flows excluded. This case represents the upper limit of effectiveness for such a regulator, and could not be fully achieved in practice. It can be seen that the effects of such regulation are very small, providing slight relief for only a few days annually, and virtually no change to peak levels.

Hence it can be seen that only a small proportion of annual floods can be accommodated in the available storage if a regulator were to be constructed. On closure, the ponded flows would quickly rise to unacceptable levels. The operation of a regulator to alleviate the effects of rapidly rising flood levels has been shown to have very little effect. The only further option is the possibility of combining a regulator with pumping, but the great expense of a regulator in addition to the very high capital and running costs needed for massive drainage pumps makes this possibility extremely unlikely to be economic. Moreover, the regulator will interfere with the free movement of fish from the Brahmaputra into Chalan Beel area through Atrai river system. The navigation will also be affected badly. It is concluded that a Hurasagar regulator would not be feasible, and does not merit further detailed study.

8 ANALYSIS OF HYDRAULIC MODEL RESULTS

8.1 Introduction

The MIKE-11 hydraulic models, both the regional sub-model and the Gaibandha area model, output daily water levels at each node specified in the model and daily mean discharges in each reach. With over 200 nodes in the regional sub-model and about 60 in the Gaibandha model, and model runs covering a total of 25 years, an enormous quantity of data was available for analysis. To facilitate this analysis, programs were developed to abstract and analyse particular bits of data (eg annual maximum series, level exceedance/duration, time series of 10-day mean levels) for specified single nodes or groups of nodes.

In this volume the programs are described and examples of the output are shown. Most of the interpretation of the results is given in the volumes on Regional Planning, the Gaibandha Improvement Project and Hydraulic Studies (volumes 1, 2 and 6 respectively).

8.2 Analysis Programs and Example Outputs

8.2.1 Introduction

Output from the hydraulic model was available in 5-year blocks, it not being practicable to run the model for the full 25 years at once. Model locations were specified in groups of up to 5 nodes (for water levels) or reaches (for discharges). An example of the first part of an output file is shown in Table 8.1. Although the model was run for all years, and the results cover 25 years, analysis was limited to 24 years because many output values for 1971/72 were obtained from incomplete data.

8.2.2 Assessment of Return Periods

Groups of five 5-year output files were analysed to determine annual maximum exceedance levels for a range of durations, and to estimate water levels for a range of return periods. Table 8.2 shows the results for one example node for the "Present condition" model run. The second page of the output ranks the years for each duration to assist with the identification of the severity of a particular year. Two calculation methods were used for estimating return period levels; for return periods within the length of the data set estimates based on interpolating between calculated plotting positions are generally most appropriate, whereas for longer return periods the Gumbel Extreme Value distribution is appropriate. On a number of sample results it was found that the upper part of the annual series was reasonably well fitted by the Gumbel distribution, but that there was generally a poor fit when Gumbel was applied to the full data set. Figure 8.1 shows an example for a node on the river Atrai. It was therefore decided that Gumbel estimates would be determined by fitting the distribution to the top half of the data points; this produces more realistic estimates of design levels for medium and high return periods. A similar procedure was used for analysing the recorded annual maximum water levels in the Interim Report.

For selecting appropriate cropping patterns, and other agricultural considerations, the date at which certain flood levels could be expected is of critical importance. Return periods were therefore also assessed for time series of 10-day mean levels or flows. An example printout is shown in Table 8.3.

8.2.3 Selection of Design Years

For the purposes of assessing potential development options, the hydraulic model results were analysed to select years whose severity approximated to that of the required design return periods of 2, 5, 10 and 20 years (subsequent assessment concentrated on the 5- and 20-year return periods). It was apparent from early in the Study, both from data analysis and from information obtained directly from the field, that the severity of conditions in any particular year may vary substantially across the region. It is therefore not possible to select a single year to represent a specified return period across the whole region. The approach adopted, therefore, was to look at each planning unit independently, and to choose design years on the basis of model results in each unit. The severity of conditions obviously varies within each unit, but the areas are relatively small and the variation is generally not too substantial. Planning unit 7 was sub-divided because there were some significant variations in conditions over the area, and because its status as the Gaibandha Improvement Project required more detailed study.

Within each planning unit (sub-unit for Gaibandha), the ranking of years for the various durations (second page of Table 8.2) were averaged over a representative selection of nodes; example results for planning unit ?? are shown in Table 8.4. It may be seen that the ranking of years, and hence the return periods, may vary for different exceedance durations. In selecting design years, most weight was given to the results for the 10-day duration, because this was considered most generally significant for agricultural considerations, but rankings for other durations were also taken into account if the 10-day value seemed to be anomalous. For practical reasons related to the time required for model runs, it was found to be desirable to limit the selected years to not more than two 5-year blocks. It was found that the 1970-74 and 1985-89 blocks covered the most appropriate years for the return periods of 5, 10 and 20 years; for some units the year which was mathematically closest to a 2-year event was in one of the remaining blocks, but in such cases there was an alternative year in one of the two blocks which was sufficiently close to the required return period, particularly in view of the fact that the 2-year return period was expected to be of much less significance than 5 and 20 years.

The selected design years are summarized in Table 8.5; the actual estimated return periods for these years are given in Table 8.6. Two extreme values deserve additional comment. The highest value of 39 years for 1988 in unit 15 arises because it was the worst year at all nodes in the planning unit, and 39 years is the return period allocated by the formula to the worst year in a data set of 24 years; in several places 1988 was the worst year by no more than a few millimetres, so a very small change (well within the margin of error of the model) could bring the estimated return period down to close to 20 years. (Similar comments apply to Gaibandha sub-unit 7 (d).) In unit 8 the occurrence of severe levels varied substantially across the area, and consequently no one year represents conditions as severe as 1-in-20 across the unit as a whole.

8.2.4 Assessment of Proposed Development Options

The over-riding consideration for assessing the suitability of development options (prior to economic assessment) is that there should be no significant adverse effects elsewhere (i.e. downstream). It was therefore necessary to determine the effects of each proposed option on water levels in the selected design years. Following selection of preferred option(s), comparison results were then required for the full 25 year run for economic analysis and final appraisal.

Analysis programs were produced for comparison of proposed options (one of which would normally be the Present Condition "do nothing" option) for both the level exceedance-duration and 10-day time series analyses. Example printouts are given in Tables 8.7 and 8.8 to show the effect on flood durations and levels between future without project condition and proposed with project condition. Table 8.9 shows an example printout for the change in level exceedance-duration results between two runs over the full 25 years.

8.3 Frequency Analyses of 25-Year Runs

The previous section described the principles involved in the estimation from the model results of water levels for specified return periods, and showed example printouts. This section presents some summary outputs for the Present Condition and for the proposed With-project Condition.

Table 8.10 gives the maximum observed water level at a number of gauging stations, together with the maximum levels from the 25-year model run for the nodes corresponding to the gauging station locations. Estimated levels for the model nodes are also presented for return periods from 2 to 50 years to show the effect on flood durations and levels between future without project condition and proposed with project condition.

The comparison is not strictly like-with-like because the Present Condition has the model configured in line with 1991 embankments which were not in identical conditions in previous years. The model considers BRE sealed which, actually, is not the present condition.

Comparison of observed and modelled maximum levels at flow station is subject to the rating curves, the accuracy of which is doubtful at flood levels. (Flow stations are Mohadevpur, Naogaon, Jafarganj and Kaunia).

It may be seen that the model maxima are, generally, lower than the observed historical values in Atrai and Bangali river basins. In the middle and lower Atrai and Bangali basins this is due to the effects of the model assumption that Teesta and Brahmaputra right embankments will be sealed. In Sib and middle Atrai the model assumes that the embankments of Atrai river system are breached at certain locations while the historic data may contain the peak levels attained before the breaches occurred. Slight increase in the water level of Teesta and Ghagot rivers in the model output partly reflects error in calibration for peak levels or poor ratings for the model up-stream boundary station at Jafarganj which did not have any flow record from 1981 to 1987.

Table 8.11 shows the equivalent information for the with-project condition. It may be seen that significant increase in water level, over present condition, will take place in lower Bangali and Atrai due to completion of ongoing developments, partial protection, sealing of some of the breaches, proposed future development in the area and change in downstream boundary condition for future without and with projects conditions. (The model considers a higher down stream water level estimated from observed water levels of nearby station while the present condition considers that simulated by FAP 25). The ongoing Barnai Project will contribute to the increase in water level in Sib river due to confinement effect. The impact on middle Bangali will be negligible as is shown at Simulbari. Water Level of Ghagot river at Jafarganj will be significantly reduced due to sealing of TRE in the upstream while that at Gaibandha will increase insignificantly due to non-existence of Manas regulator. This would rather allow free flow into the Brahmaputra helping quick drainage which was being impeded by Manas Regulator. The proposed projects will not have appreciable effect on Teesta water level. Table 8.12 summarizes the peak levels for the 5-and 20-year return periods for a representative selection of locations within the area covered by the Gaibandha model.

9 LIMITATIONS OF THE HYDROLOGICAL ANALYSIS

9.1 Introduction

The hydrological data collected for this study has been used for very extensive hydrological and hydraulic modelling studies, and the results of that modelling have been used as the basis for the establishment of a proposed development plan for the North West Region which will have a substantial impact on the lives of the people of the region (and perhaps to some extent the rest of Bangladesh) over the medium and long term. It is therefore appropriate to review the data used, together with the approximations and assumptions inherent in the analysis; this may assist in defining the limitations within which the results of the modelling should be considered.

Virtually all the hydrological data used in the study was restricted to the period from 1962 to date, and the modelling covered only the period from 1965. This period is similar in length to the strategic planning horizon of the Flood Action Plan, but is much shorter than the timescale under which potential environmental impacts are to be considered. In Chapter 3 it was shown that the very limited amount of long-term hydrological data indicated that conditions in the region since 1962 are not out of line with those prevailing during the rest of the 20th century. It may therefore be considered to be not unreasonable to base planning decisions on the 25-year model analysis, because there is no evidence to suggest that the type of hydrological conditions to be expected in the next 25 years will be significantly different from those experienced in the last 25 years. In the longer term, however, there are many factors which could come into play. The scope of this report does not cover the effects of such long-term factors on the region, but this chapter outlines some of the factors which might be borne in mind in a long-term impact assessment.

9.2 Climate Change

Most of the potential long-term changes come under the broad heading of Climate Change. This is a subject which has grown in prominence in recent years, but there is in most cases insufficient data or other evidence from which reliable forecasts of future conditions may be made. The areas under which climate change might be considered include:

- rise in sea level : a substantial rise in sea level could cause backwater effects which might inhibit drainage from the Ganges and Jamuna rivers, and hence the region;
- changes in rainfall : an increase in rainfall in the region would have obvious implications on flood inundation levels; conversely, a reduction in rainfall might affect the types of crops being grown, and the economic appraisal of flood protection and other development schemes;
- temperature change : changes in amounts, rates and timing of snowmelt runoff from the Himalayas could significantly affect flood peaks in Bangladesh;

- coincidence of events : the significance of the coincidence of flood peaks on the Ganges and Jamuna was referred to in Chapter 2; various aspects of climate change could influence the likelihood of such coincidence in the future, together with timing of local runoff in the region, and in the long-term this could significantly affect the return period of particular levels of flood inundation;

There is fairly widespread agreement that there is a strong likelihood of a rise in sea levels in the medium term, though there is much less of a consensus on the magnitude of such a rise. A rise in sea level in the range of typical climate change scenarios is unlikely to have any significant direct effect on the North West Region, but other areas of Bangladesh are liable to suffer very severe consequences, and this may be expected to have indirect effects throughout the country.

There is even less consensus about probable future changes in rainfall, both in terms of absolute quantities and in the spatial and temporal distribution of such changes. Similar comments apply to temperature changes which could significantly affect snowmelt, and its contribution to flooding in the region.

In conclusion it may be said that the hydraulic modelling studies (and by inference the overall approach of the study) should provide reasonable guidance for potential development over the strategic planning horizon; speculation about changes in the longer term may be very interesting, but the factors affecting the region are so numerous, and their future changes (if any) so uncertain, that any attempt to quantify the likely effects on the region would be at best extremely tenuous. The most realistic approach to assessing potential long-term effects would probably be a sensitivity study.

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Table 2.1

Recorded Climatic Norms for Selected Locations

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
	Mean Daily Maximum Temperatures (deg C)												
Bogra	24.9	28.1	33.2	35.7	34.2	32.2	31.3	31.1	31.6	30.8	28.7	26.0	30.7
Dinajpur	24.8	27.6	32.1	35.2	33.8	32.0	31.6	31.4	31.8	30.9	28.4	25.7	30.4
Ishurdi	24.5	28.4	33.1	36.1	35.4	32.8	31.7	31.6	31.9	30.4	28.3	25.4	30.8
Rangpur	24.6	27.3	31.1	34.4	32.6	31.4	32.0	31.5	32.3	30.9	26.7	25.7	30.0
	Mean Daily Minimum Temperatures (deg C)												
Bogra	11.5	13.4	18.1	22.6	24.2	25.7	26.2	26.0	25.8	22.9	17.2	12.8	20.5
Dinajpur	10.5	12.6	17.3	21.5	23.9	25.4	26.6	26.1	25.6	22.3	16.3	11.8	20.0
Ishurdi	9.8	11.8	16.9	22.6	24.7	25.3	25.7	25.9	25.7	22.9	16.6	11.8	20.0
Rangpur	9.8	11.6	15.1	20.7	22.9	25.5	25.3	26.2	25.7	24.8	16.4	11.8	19.7
	Mean Daily Maximum Relative Humidity (%)												
Bogra	89	85	79	83	88	94	95	96	95	94	93	91	90
Dinajpur	89	84	75	76	85	92	93	93	93	93	91	91	88
Ishurdi	94	90	82	85	92	93	96	96	96	96	94	94	92
Rangpur	94	90	87	87	92	94	94	95	94	95	94	93	92
	Mean Daily Minimum Relative Humidity (%)												
Bogra	63	57	38	46	66	82	83	83	82	80	74	70	69
Dinajpur	60	48	37	44	62	78	81	80	80	74	68	66	65
Ishurdi	64	50	40	44	61	81	86	84	83	79	75	70	68
Rangpur	72	63	56	56	71	79	81	79	81	81	79	78	73
	Mean Rainfall (mm)												
Bogra	9	10	23	84	242	340	435	293	263	148	12	10	1867
Dinajpur	9	7	28	74	194	327	507	338	298	119	9	4	1913
Ishurdi	7	15	29	81	152	294	296	269	228	132	15	8	1526
Rangpur	4	10	33	90	288	451	522	322	353	134	14	5	2226
	Mean Wind Speed (km/day)												
Bogra	55	63	95	130	135	135	118	107	75	55	40	58	89
Dinajpur	14	26	46	69	51	63	58	52	49	23	23	12	40
Ishurdi	58	49	92	156	181	150	121	121	109	72	43	61	101
Rangpur	37	49	76	107	109	115	95	83	75	55	46	40	74
	Mean Sunshine (hours/day)												
Bogra	8.7	9.2	8.6	9.1	8.4	5.1	5.0	4.9	6.0	6.4	9.1	8.8	7.4

Table 2.2

Mean Monthly River Flows
(cumecs)

No	Station	River	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Year	Data Period
10	Simulbari	Bangali	9	39	150	356	371	363	279	67	41	29	19	14	145	1974–88
17.1	Baral R B	Baral	8	24	45	98	174	184	164	89	35	14	6	4	70	1964–87
62–1	Baratia	Deonai	2	6	38	127	89	85	50	9	5	4	3	2	35	1964–87
66	Ullapara	Karatoa	17	45	175	493	706	633	408	132	67	50	39	21	232	1964–89
76	Taluksimulbari	Dharla	81	177	455	926	646	686	463	189	125	99	80	66	333	1968–80
77	Kurigram	Dharla	92	194	741	1440	1340	1170	585	223	155	121	90	81	519	1973–88
81	Pateswari	Dudhkumar	115	246	656	1380	1390	1100	651	243	166	131	105	91	523	1968–89
83.1	Naldanga R B	Barnai	3	7	34	76	98	100	97	65	27	9	5	4	44	1965–88
96a	Jafarganj	Ghahgot	0	2	11	33	26	23	16	2	1	1	1	0	10	1964–80
133	Naogaon	L Jamuna	1	10	74	179	182	180	122	24	9	4	2	1	66	1973–89
140	Panchagarh	Karatoa	5	7	30	137	134	102	41	15	10	8	7	5	42	1964–89
145	Mohadevpur	Atrai	9	27	122	431	359	353	165	39	25	20	16	13	132	1973–89
147	Atrai R B	Atrai	9	25	102	312	401	381	297	126	51	29	17	11	147	1964–89
211.	Ch. Nawabganj	Mohananda	31	49	289	1027	1687	1793	1365	436	134	80	55	43	582	1981–88
238	Rohanpur	Punarbhaba	6	11	41	186	385	416	266	55	23	17	13	7	119	1966–89
261	Nowhata	Sib	0	2	12	43	65	60	58	34	12	2	1	1	24	1973–89
285	Thakurgaon	Tangon	2	3	14	57	52	43	18	5	4	3	3	2	17	1964–88
294	Kaunia	Teesta	261	561	1360	2430	2240	1920	938	380	237	175	150	166	902	1972–89
90	Hardinge Bridge	Ganges	1280	1590	3500	20500	40800	37400	15600	5060	2830	1660	1370	1100	11100	1975–82
46.9L	Bahadurabad	Jamuna	7520	14700	30700	46300	42700	36000	22600	10300	6590	4790	4130	4730	19300	1965–82

Notes: Ganges/Jamuna data from National Water Plan, MPO, 1986 (post–Farakka Barrage for Ganges)

Remaining data collected from Directorate of Surface Water Hydrology II, BWDB, or MPO.
(for most stations some raw data was collected from both BWDB and MPO, and analysis carried out by FAP–2)

Values over 1000 cumecs rounded to 3 significant figures.

There are missing years or part–years in the data records at some stations.

Table 3.1 – Mean Monthly and Annual Rainfall

		APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	YEAR
1	Atghoria	98	170	335	350	300	243	138	17	11	8	21	38	1730
3	Atrai	53	161	287	370	281	279	111	12	3	4	12.	18	1590
4	Bera	75	191	269	303	251	212	126	17	7	8	14	28	1501
6	Bogra	84	242	340	435	293	263	148	12	10	9	10	23	1867
7	Chatmohar	83	174	366	336	305	236	114	16	4	6	18	28	1686
11	Dhunot	98	240	365	407	311	263	135	15	10	12	10	28	1893
12	Banwarinagar	99	210	321	336	292	235	128	17	8	5	20	35	1705
14	Gurudaspur	66	154	319	344	317	295	143	24	6	6	11	30	1715
15	Ishurdi	81	152	294	296	269	228	132	15	8	7	15	29	1526
16	Joari	64	156	293	334	258	244	132	16	8	6	13	26	1550
22	Nandigram	70	180	303	381	299	252	138	10	6	7	9	22	1676
23	Natore	57	162	297	344	291	245	130	18	7	8	14	28	1601
24	Naokhila	82	217	293	382	259	243	118	15	7	6	9	21	1652
25	Pabna	78	187	277	297	267	225	125	19	11	6	22	30	1544
29	Raiganj	80	213	308	332	325	283	147	18	8	6	14	27	1762
33	Sherpur	81	228	303	413	304	250	160	16	8	5	12	26	1805
34	Serajganj	94	239	344	352	278	251	139	20	10	8	14	31	1779
35	Shajadpur	96	188	291	327	300	258	146	19	12	7	20	32	1697
36	Singra	73	176	291	338	312	263	123	14	4	6	12	29	1642
38	Sujanagar	91	197	290	331	283	232	123	20	6	6	15	30	1623
39	Taras	69	179	294	339	296	265	155	22	9	7	13	22	1669
40	Ullapara	93	190	320	333	307	282	133	17	7	7	18	30	1735
151	Adamdighi	63	164	266	322	282	274	125	10	3	7	6	16	1539
152	Badalgachi	61	166	280	390	309	306	138	11	4	8	8	16	1695
153	Badarganj	82	236	369	491	298	336	113	13	4	5	8	26	1981
154	Bagdogra	81	277	361	442	301	298	104	7	4	4	8	31	1917
155	Baliadangi	72	190	361	555	379	340	135	4	3	6	3	15	2061
156	Bhawaniganj	88	310	396	424	264	268	139	12	3	4	7	21	1935
157	Bhitargarh	90	247	623	954	662	511	131	4	8	3	11	18	3263
158	Bholahat	31	114	264	370	289	317	100	10	10	11	6	13	1534
159	Bhurungamari	146	327	621	631	580	448	143	15	3	4	11	35	2963
160	Birganj	96	255	347	520	375	320	126	9	3	5	4	27	2088
161	Boda	87	233	509	679	498	424	128	8	4	5	9	24	2607
162	Bullibundh	80	232	456	637	501	356	121	8	1	9	6	19	2426
163	Chilmari	90	319	470	504	287	283	150	10	6	5	11	22	2158
164	Ghoraghat	73	267	348	534	286	336	171	20	3	6	6	24	2073
165	Chotodhap	59	211	443	646	468	327	121	2	0	4	3	15	2300
166	Debiganj	84	286	465	636	489	411	137	8	6	5	8	21	2556
167	Dimla	104	277	535	636	470	427	154	9	3	5	11	25	2654
168	Dinajpur	74	194	327	507	338	298	119	9	4	9	7	28	1913
169	Dubchachia	70	217	275	362	253	262	146	9	5	6	8	20	1634
170	Durgapur	54	161	312	336	277	261	124	16	4	6	9	22	1580
171	Gobindaganj	77	222	311	448	268	240	123	7	7	5	6	21	1734
172	Godagari	60	128	223	280	240	241	107	14	5	10	12	23	1342
173	Gomostapur	39	155	203	367	305	273	112	10	5	4	7	16	1495
174	Hatibandha	96	289	533	696	543	390	146	6	5	5	11	34	2753
175	Hilli	70	224	323	472	327	309	128	14	6	8	10	24	1914
176	Mohasthan	77	288	323	325	200	211	116	3	5	5	14	18	1586

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Table 3.1 – Mean Monthly and Annual Rainfall

		APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	YEAR
177	Kaliganj	102	261	440	573	447	386	142	11	6	5	11	30	2414
178	Kaunia	106	330	504	597	346	367	136	12	3	17	8	23	2446
179	Khansama	89	242	394	569	399	355	142	8	7	4	8	23	2240
180	Kantanagar	71	220	340	522	315	321	109	8	5	6	6	28	1950
181	Khetlal	75	208	341	411	283	272	165	9	8	4	6	17	1798
182	Kurigram	107	334	515	518	296	347	128	15	5	5	11	33	2314
183	Lalmonirhat	121	342	499	604	419	348	137	14	5	4	8	33	2533
184	Lalpur	70	170	274	339	281	212	109	18	6	8	14	35	1536
185	Manda	51	123	225	316	268	243	101	7	7	8	8	21	1376
186	Mithapukur	107	281	423	574	337	397	108	13	6	5	11	30	2293
187	Mahadevpur	61	172	263	393	277	282	105	14	5	7	11	18	1606
188	Mahipur	102	300	461	545	352	353	122	8	6	5	13	24	2292
189	Mohanpur	73	194	297	498	320	264	103	8	1	7	9	26	1800
190	Nachol	56	164	203	302	278	243	116	10	8	6	10	14	1411
191	Naogaon	55	160	256	369	286	253	128	11	6	8	10	20	1561
192	Nazirpur	57	143	261	402	282	292	111	8	6	8	7	21	1597
193	Nekmard	59	183	368	569	401	380	99	9	3	6	7	23	2107
194	Nithpur	53	128	220	365	272	270	98	7	7	10	8	15	1454
195	C. Nawabganj	31	112	212	260	231	199	93	9	3	7	6	16	1178
196	Nawabganj	62	234	342	498	283	307	110	10	3	3	5	17	1874
197	Panchagarh	61	194	447	886	584	402	97	4	4	2	12	13	2704
198	Panchbibi	54	178	314	426	260	238	125	11	1	6	7	15	1634
199	Parbatipur	74	179	321	451	274	244	96	9	0	5	1	22	1675
200	Patgram	93	258	480	588	405	380	118	9	1	3	5	19	2359
201	Phulbari	76	197	369	474	318	285	101	14	4	7	8	24	1877
202	Pirgachha	102	286	401	511	275	304	123	17	9	4	8	23	2061
203	Pirganj	82	259	334	446	306	296	128	20	4	7	6	23	1911
204	Puthia	61	155	284	347	302	270	115	11	6	9	9	24	1592
205	Rajshahi	74	133	256	336	252	253	105	16	7	10	11	22	1474
206	Rangpur	90	288	451	522	322	353	134	14	5	4	10	33	2226
207	Ranishankail	109	221	367	607	383	370	127	12	0	3	2	15	2216
208	Rohanpur	42	116	211	375	278	236	101	7	5	8	10	18	1406
209	Ruhea	92	248	472	702	459	429	148	10	7	7	10	32	2614
210	Saidpur	82	216	351	552	339	308	123	11	6	5	6	27	2026
211	Sapahar	56	120	213	420	242	237	113	5	7	6	8	16	1443
212	Sardah	57	134	266	285	245	227	125	14	7	7	9	23	1398
213	Setabganj	53	163	298	524	398	329	137	6	6	5	4	23	1946
215	Shibganj (R)	43	126	211	336	303	235	107	6	3	8	9	17	1403
216	Shibganj (B)	77	242	333	442	300	299	167	9	9	5	12	25	1920
218	Sundarganj	81	315	428	466	286	295	110	6	4	3	7	21	2021
219	Tanore	55	140	254	351	277	247	101	8	6	9	5	20	1473
220	Tetulia	70	216	475	865	607	454	126	6	6	7	9	15	2855
221	Thakurgaon	69	220	380	586	448	438	111	8	5	6	11	22	2304
222	Ulipur	97	323	459	551	309	313	124	10	6	6	11	31	2240
226	Dalia	119	329	580	737	554	425	174	6	3	11	20	23	2979
520	Joypurhat	71	183	263	495	314	285	167	13	7	7	6	23	1833
	Overall Mean	77	212	349	461	333	301	126	12	5	6	10	24	1915

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Table 3.2

10-Day Rainfalls for Various Frequencies (mm)

Station number	Return Period (years) 2	5	10	20	50	Max. in period 1962–89
1	316	425	498	567	657	673 in 1986
3	280	373	435	494	570	511 in 1986
4	275	372	437	499	578	569 in 1989
6	346	453	524	591	679	716 in 1973
7	367	506	598	686	801	797 in 1964
11	320	383	425	465	517	486 in 1973
12	318	421	490	556	641	676 in 1986
14	309	411	478	543	626	611 in 1965
15	291	413	494	572	672	808 in 1987
16	279	361	414	466	532	516 in 1977
22	327	431	499	565	650	596 in 1986
23	278	359	412	463	530	639 in 1965
24	304	372	417	460	516	496 in 1987
25	273	384	457	528	619	636 in 1986
29	308	407	473	536	617	615 in 1986
33	333	406	454	501	561	549 in 1987
34	332	415	471	524	592	661 in 1986
35	302	433	519	603	710	795 in 1986
36	301	375	424	471	532	602 in 1965
38	267	372	442	508	595	724 in 1986
39	318	427	499	568	658	750 in 1986
40	307	418	492	563	655	740 in 1986
151	283	352	398	442	500	479 in 1987
152	300	405	474	541	628	622 in 1973
153	358	475	552	627	723	866 in 1987
154	329	405	456	504	567	524 in 1986
155	405	536	623	706	814	919 in 1968
156	367	472	541	607	693	725 in 1987
157	607	712	781	847	933	879 in 1987
158	300	425	508	588	691	655 in 1971
159	500	640	732	821	936	985 in 1988
160	380	467	524	578	649	603 in 1969
161	495	615	696	772	872	957 in 1987
162	466	543	594	643	706	697 in 1988
163	416	555	646	735	849	775 in 1987
164	395	544	642	736	858	879 in 1987
165	458	550	611	670	746	711 in 1968
166	478	604	687	767	870	901 in 1965
167	482	610	695	776	881	945 in 1987
168	346	465	544	620	718	689 in 1979
169	296	418	498	575	675	669 in 1973
170	304	387	441	494	562	519 in 1965
171	333	434	501	565	648	626 in 1973
172	258	330	378	423	483	480 in 1988
173	274	347	396	442	502	504 in 1971
174	503	652	750	845	967	971 in 1987
175	329	433	502	568	653	740 in 1987

Table 3.2

10-Day Rainfalls for Various Frequencies (mm)

Station number	Return Period (years) 2	5	10	20	50	Max. in period 1962-89
176	282	373	434	492	568	657 in 1988
177	421	552	638	721	828	874 in 1987
178	448	598	697	792	916	1118 in 1987
179	395	472	523	571	635	679 in 1988
180	363	468	537	604	690	680 in 1988
181	327	443	520	594	689	669 in 1968
182	409	527	605	680	777	711 in 1973
183	450	554	623	689	775	791 in 1987
184	277	369	429	487	563	585 in 1977
185	285	379	441	500	577	547 in 1971
186	441	602	708	810	943	1029 in 1987
187	302	392	451	508	582	552 in 1973
188	443	576	665	750	859	866 in 1967
189	335	442	513	581	669	657 in 1987
190	271	336	379	420	473	422 in 1971
191	284	357	406	452	513	498 in 1973
192	291	392	459	523	606	613 in 1987
193	413	515	583	647	731	703 in 1976
194	276	346	392	437	494	458 in 1987
195	226	294	339	383	439	421 in 1971
196	354	503	602	696	818	992 in 1987
197	533	676	771	862	980	886 in 1988
198	306	400	462	521	598	586 in 1987
199	320	438	515	590	687	825 in 1987
200	450	578	662	743	848	800 in 1968
201	349	499	598	693	817	1028 in 1987
202	401	530	616	698	804	908 in 1976
203	323	480	584	684	813	997 in 1987
204	301	386	442	496	566	537 in 1965
205	273	385	459	529	621	742 in 1965
206	385	515	601	684	791	933 in 1987
207	412	492	545	596	661	586 in 1966
208	266	351	407	461	531	567 in 1971
209	510	642	730	814	922	908 in 1975
210	386	514	599	681	787	819 in 1987
211	283	357	405	452	512	467 in 1973
212	285	375	434	492	566	514 in 1965
213	358	448	508	565	639	636 in 1969
215	281	343	384	423	474	481 in 1965
216	373	508	597	682	793	839 in 1988
218	373	487	562	634	727	778 in 1987
219	294	375	429	480	547	553 in 1965
220	542	651	723	792	882	829 in 1985
221	433	542	615	684	774	751 in 1987
222	418	532	608	680	774	711 in 1973
226	535	652	729	803	899	927 in 1987
520	351	440	498	555	628	644 in 1987

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Table 3.3

1- to 10-Day Rainfalls for Selected Stations

MAXIMUM RAINFALLS FOR STATION R006 (mm)

Period	Return Period (Years)					In Period
(days)	2	5	10	20	50	1962-89
1	133	179	209	238	276	268 in 1971
2	193	251	290	328	376	333 in 1983
3	236	319	374	426	494	503 in 1973
4	259	340	394	446	513	516 in 1973
5	269	348	400	451	516	518 in 1973
6	286	360	409	456	517	520 in 1973
7	302	384	439	491	559	568 in 1988
8	316	401	458	512	583	593 in 1988
9	329	427	493	555	636	656 in 1973
10	346	453	524	591	679	716 in 1973

MAXIMUM RAINFALLS FOR STATION R015 (mm)

Period	Return Period (Years)					In Period
(days)	2	5	10	20	50	1962-89
1	126	176	210	242	283	268 in 1964
2	172	249	300	349	413	465 in 1964
3	200	281	335	387	453	465 in 1964
4	218	304	362	417	488	465 in 1964
5	234	326	387	445	521	482 in 1964
6	247	346	411	474	555	558 in 1987
7	257	367	440	511	601	685 in 1987
8	267	382	459	533	628	736 in 1987
9	275	395	474	550	649	783 in 1987
10	291	413	494	572	672	808 in 1987

MAXIMUM RAINFALLS FOR STATION R206 (mm)

Period	Return Period (Years)					In Period
(days)	2	5	10	20	50	1962-89
1	163	207	236	263	299	258 in 1979
2	218	284	328	371	425	412 in 1987
3	251	332	387	438	506	508 in 1987
4	284	384	451	514	597	652 in 1987
5	308	416	488	557	646	735 in 1987
6	324	437	511	582	674	754 in 1987
7	338	450	524	596	688	763 in 1987
8	356	469	544	616	708	789 in 1987
9	372	494	574	652	752	872 in 1987
10	385	515	601	684	791	933 in 1987

Table 4.1

Mean Monthly River Levels (m)

No	Station	River	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Year	Data Period
10	Simulbari	Bangali	12.37	12.87	13.95	15.23	15.41	15.44	14.80	13.45	13.03	12.85	12.65	12.45	13.71	1964–89
17.1	Baral R B	Baral	4.49	5.69	7.51	9.42	10.16	10.32	9.35	7.40	5.66	4.88	4.60	4.42	6.99	1964–89
65	Bogra	Karatoya	12.30	12.60	13.08	13.92	14.17	13.91	13.62	12.67	12.57	12.60	12.51	12.32	13.02	1960–89
66	Ullapara	Karatoya	5.14	6.14	7.94	9.84	10.45	10.22	8.79	6.66	6.03	5.87	5.62	5.18	7.32	1964–89
76	Taluksimulbari	Dharla	27.39	27.80	28.69	29.58	29.27	29.19	28.37	27.77	27.56	27.45	27.38	27.33	28.15	1965–89
81	Pateswari	Dudhkumar	26.32	26.80	27.77	28.65	28.56	28.35	27.60	26.89	26.56	25.35	25.24	25.17	26.94	1962–89
83.1	Naldanga R B	Barnai	8.17	8.64	10.07	12.02	12.95	13.01	12.80	11.71	9.93	9.00	8.69	8.48	10.46	1965–89
97	Gaibandha	Ghagot	17.68	18.05	19.42	20.72	20.65	20.38	19.41	18.20	18.17	17.56	17.39	17.08	18.73	1960–89
133	Naogaon	L Jamuna	9.58	10.32	11.66	13.48	13.85	13.74	13.27	11.84	11.02	10.62	10.41	9.98	11.65	1965–89
140	Panchagarh	Karatoya	67.54	67.59	67.90	68.75	68.59	68.53	68.10	67.81	67.71	67.65	67.61	66.34	67.84	1964–89
145	Mohadevpur	Atrai	13.61	13.95	14.99	16.68	14.46	16.22	15.41	14.24	13.95	13.84	13.73	13.62	14.56	1961–89
147	Atrai R B	Atrai	8.78	9.27	10.36	11.91	12.65	12.65	12.34	11.20	10.08	9.51	9.22	8.96	10.58	1960–89
155	Mohimaganj	Katakhali	14.39	14.78	15.88	17.30	17.42	17.25	16.70	15.27	14.88	14.71	14.55	14.41	15.63	1964–89
238	Rohanpur	Punarbhaba	13.87	14.10	14.97	18.20	20.68	20.75	18.61	15.37	14.49	14.33	14.19	13.94	16.12	1964–89
261	Nowhata	Sib	9.11	9.42	10.48	12.38	13.37	13.47	13.29	12.10	10.40	9.65	9.50	9.28	11.04	1964–89
287	Kodalkatigaon	Tangon	30.98	31.04	31.42	32.33	32.35	32.35	31.83	29.83	29.78	28.36	28.13	28.17	30.55	1961–89
294	Kaunia	Teesta	27.97	28.40	28.99	29.35	29.25	29.18	28.61	28.01	27.76	3.41	2.29	2.29	22.13	1963–89

Notes: Data collected from Directorate of Surface Water Hydrology II, BWDB, or MPO.
(for most stations some raw data was collected from both BWDB and MPO, and analysis carried out by FAP–2)

There are missing years or part–years in the data records at some stations.

07–Sep–92

C:\NWRS\TAB41.WK1

Table 6.1

Monthly Potential Evapotranspiration (mm)

Station	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	YEAR
Bogra	189	181	134	133	127	123	95	95	82	87	108	163	1517
Dinajpur	154	171	130	131	125	122	106	88	73	86	97	146	1429
Ishurdi	198	195	136	130	127	148	109	95	78	83	102	158	1559
Rangpur	170	168	133	134	129	123	110	89	73	72	94	135	1430
Rajshahi	196	184	135	120	144	126	112	107	87	88	106	163	1568
Average	181	180	134	130	130	128	106	95	79	83	101	153	1501

Source of Original Data: BARC Soils and Irrigation Publication Nr. 11, Dec 1982

Table 6.2

Monthly Mean Evaporation (mm)

Station	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	YEAR
Bogra	142	130	116	98	110	112	116	97	84	67	75	125	1274
Dinajpur	117	120	97	76	86	66	81	67	61	59	69	95	994
Mahipur	83	74	62	63	74	62	74	63	58	62	67	81	824
C. Nawabganj	108	86	98	46	65	79	65	52	39	34	48	81	801
Pabna	117	112	90	65	72	61	63	58	49	45	50	81	865
Rajshahi	131	132	109	87	89	75	77	74	53	44	54	80	1005
Rangpur	126	100	84	69	79	63	72	57	42	41	60	115	908
Ruhea	121	62	50	39	41	47	41	38	34	31	58	76	638
Serajganj	131	128	116	100	108	100	98	78	65	60	82	120	1186
Thakurgaon	156	157	126	70	89	67	77	50	39	35	46	80	992
Average	123	110	95	71	81	73	76	63	53	48	61	93	949

Source: BWDB, with modifications for zero values

Table 6.3

Monthly Evapotranspiration used by SWMC (mm)

Station	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	YEAR
Bogra	201	188	163	145	162	151	169	139	117	87	114	188	1821
Rajshahi	179	173	143	114	124	119	129	110	82	68	90	137	1469
Rangpur	185	141	118	93	111	77	103	80	65	67	76	124	1241
Average	188	167	141	118	132	116	134	109	88	74	93	149	1510

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Table 6.4

Monthly Mean Evaporation (mm)

Station	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	YEAR
Bogra	165	152	108	110	98	105	100	90	75	70	85	132	1290
Dinajpur	176	159	117	109	100	97	85	73	62	68	84	144	1274
Ruhea	166	146	91	98	100	91	89	83	76	75	102	150	1266
Pabna	187	175	120	110	94	99	98	88	68	69	85	151	1343
Sirajganj	176	164	123	122	99	100	97	77	64	67	93	156	1337
C. Nawabganj	183	171	116	98	91	101	102	77	65	60	83	146	1290
Rajshahi	190	177	121	128	92	111	99	82	73	70	84	147	1373
Kaliganj	167	140	114	106	91	91	91	73	62	68	92	160	1254
Rangpur	162	135	99	97	99	88	89	72	59	61	79	144	1184
Average	175	158	112	108	96	98	94	79	67	67	87	148	1290

Source: Agro-Climatic Survey of Bangladesh (Manalo)

Table 6.5

Adopted Monthly Evaporation (mm)

Station	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	YEAR
Bogra	208	199	147	146	140	135	105	105	90	96	119	179	1669
Dinajpur	169	188	143	144	138	134	117	97	80	95	107	161	1572
Ishurdi	218	215	150	143	140	163	120	105	86	91	112	174	1715
Rangpur	187	185	146	147	142	135	121	98	80	79	103	149	1573
Rajshahi	216	202	149	132	158	139	123	118	96	97	117	179	1725
Average	200	198	147	143	143	141	117	104	86	92	112	168	1651

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Table 7.1

Hurasagar Tail Regulator: Preliminary Cost Estimate

Hurasagar Weir					
(1)	Design W.L	HWL	12		
(2)	Riverbed EL.	GL	-3		
(3)	River width	Wr	430		
(4)	Nos. of gates	N	22		
(5)	Span length of gate piers	W1	20		
(6)	Distance of approach roads on both banks (m)	L0	220		
(7)	Average embankment height of approach road	h0	7		
(8)	Total width between shoulders of approach roads	W0	650		
(9)	Water depth between HWL and GL	H	15		
(10)	Total length of weir	L	443		
(11)	Average thickness of weir bottom slab concrete	Wb	3		
(12)	Total length of weir bottom slab concrete	L1	103		
(13)	Total length of riverbed protection works	L2	44		
(14)	Total weir height	Ht	20		
(15)	Area of typical section of wing wall	Aw	60		
(16)	Width of wing wall base concrete	Ww	13		
(17)	Area of typical section of embankment for approach roac	Aem	176		
			Q'ty	Unit Price	Amount
				(TK)	(Tk mil.)
(1)	Preparatory works (10 % of Total of 2 to 11)	L.S.			178
(2)	Excavation	cu.m	555,072	40	22
(3)	Embankment/Fill	cu.m	372,045	70	26
(4)	Concrete for weir	cu.m	191,602	4600	881
(5)	Steel sheet pile	sq.m	3,250	4300	14
(6)	R.C.pile	m	156,113	1400	219
(7)	Rip rap	cu.m	53,400	3600	192
(8)	Bank slope protection	sq.m	13,860	1330	18
(9)	HBB for approach road	sq.m	924	140	0
(10)	Steel gate	ton	493	500000	247
(11)	Other equipment (generating equipment, building, etc.)	L.S.			162
	(10 % of total of Items 2 to 10)				
I.	Direct construction cost				1,959
II.	Land acquisition for borrow area (2m depth)	sq.m	186,023	30	6
III.	Physical contingency (25% of Total of Itm I and II)				491
IV.	Engineering service (15 % of Total of Item I to III)				368
	Total				2,824

Table 7.2

Hurasagar Flood Season Outflows, 1986–89

Year	Mm3	mm
1986	12600	582
1987	17900	827
1988	19100	883
1989	12700	587
Average	15600	720

Runoff calculated on basis of drainage area of 21640 km2.

C:\NWRS\TAB72.WK1 06-Sep-92

Table 8.1

Example of Part of MIKE-11 Output File

DATA FILE : REGSUB-P.RDF BOUNDARY FILE: R65-69-P.BSF
RESULT FILE : R65-69-P.RRF CALCULATED : 19-MAY-1992, 20:00

HOURS:MIN					ATRAI 3.170	ATRAI 23.450	ATRAI 43.750	ATRAI 67.157	ATRAI 89.030
1965	4	1	12	0	13.056	11.772	10.538	8.800	7.683
1965	4	2	12	0	13.227	11.914	10.564	8.805	7.692
1965	4	3	12	0	13.227	11.927	10.602	8.872	7.703
1965	4	4	12	0	13.227	11.929	10.613	8.916	7.732
1965	4	5	12	0	13.227	11.930	10.617	8.931	7.759
1965	4	6	12	0	13.260	11.949	10.621	8.935	7.774
1965	4	7	12	0	13.104	11.879	10.617	8.939	7.782
1965	4	8	12	0	13.242	11.887	10.588	8.920	7.782
1965	4	9	12	0	13.250	11.948	10.612	8.908	7.770
1965	4	10	12	0	13.250	11.952	10.625	8.921	7.760
1965	4	11	12	0	13.239	11.946	10.628	8.929	7.760
1965	4	12	12	0	13.228	11.936	10.625	8.932	7.762
1965	4	13	12	0	13.227	11.931	10.621	8.935	7.772
1965	4	14	12	0	13.227	11.931	10.621	8.934	7.778
1965	4	15	12	0	13.238	11.937	10.621	8.935	7.776
1965	4	16	12	0	13.271	11.960	10.626	8.955	7.776
1965	4	17	12	0	13.317	11.999	10.642	8.991	7.788
1965	4	18	12	0	13.389	12.059	10.669	9.045	7.811
1965	4	19	12	0	13.393	12.087	10.697	9.144	7.850
1965	4	20	12	0	13.381	12.083	10.703	9.250	7.911
1965	4	21	12	0	13.420	12.103	10.706	9.331	7.979
1965	4	22	12	0	13.458	12.139	10.721	9.399	8.043
1965	4	23	12	0	13.473	12.161	10.738	9.446	8.103
1965	4	24	12	0	13.474	12.168	10.748	9.458	8.151
1965	4	25	12	0	13.499	12.184	10.757	9.533	8.196
1965	4	26	12	0	13.501	12.193	10.768	9.581	8.246
1965	4	27	12	0	13.487	12.187	10.771	9.610	8.290
1965	4	28	12	0	13.450	12.161	10.768	9.644	8.327
1965	4	29	12	0	13.448	12.147	10.763	9.699	8.364
1965	4	30	12	0	13.408	12.122	10.759	9.738	8.402
1965	5	1	12	0	13.422	12.116	10.751	9.759	8.436
1965	5	2	12	0	13.435	12.127	10.754	9.778	8.464
1965	5	3	12	0	13.435	12.132	10.761	9.800	8.488
1965	5	4	12	0	13.435	12.132	10.765	9.818	8.509
1965	5	5	12	0	13.424	12.126	10.768	9.836	8.528
1965	5	6	12	0	13.458	12.142	10.747	9.767	8.542
.									
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.									
1970	3	21	12	0	13.355	12.047	10.681	8.991	7.875
1970	3	22	12	0	13.371	12.064	10.689	8.995	7.872
1970	3	23	12	0	13.372	12.071	10.697	9.004	7.872
1970	3	24	12	0	13.396	12.086	10.702	9.013	7.876
1970	3	25	12	0	13.339	12.061	10.705	9.021	7.881
1970	3	26	12	0	13.335	12.039	10.689	9.016	7.886
1970	3	27	12	0	13.394	12.072	10.689	9.005	7.887
1970	3	28	12	0	13.386	12.087	10.704	9.011	7.884
1970	3	29	12	0	13.380	12.081	10.707	9.021	7.885
1970	3	30	12	0	13.360	12.068	10.704	9.024	7.889

MIKE 11 SYSTEM Page: 1

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Table 8.2 (page 1)

Example Output: Level Exceedance-Duration Analysis

! DATA FILE : REGSUB-P.RDF BOUNDARY FILE: R65-69-P.BSF !
! RESULT FILE : R65-69-P.RRF CALCULATED : 19-MAY-1992, 20:00!
MIKE-11 file : R65-P-AL.TXT (all files also R70...., R75.... etc)
This analysis file: P-ATR003.17

MAXIMUM LEVELS FOR GIVEN DURATIONS

ATRAI (ATR) Chainage 3.170

	DURATION IN DAYS									
Year	1	3	5	10	15	20	30	45	60	90
1965	18.72	18.67	18.60	18.43	17.98	17.51	17.46	15.81	15.68	14.95
1966	19.00	18.97	18.91	18.54	17.44	16.92	16.12	15.66	15.50	14.86
1967	18.81	18.66	18.54	18.50	17.21	16.19	15.29	15.19	15.03	14.49
1968	19.06	19.02	18.98	18.31	17.65	16.44	15.87	15.84	15.70	14.87
1969	19.06	19.02	18.98	18.31	17.64	16.42	15.83	15.82	15.66	14.89
1970	19.05	19.04	18.98	18.87	18.73	18.73	17.71	16.11	15.35	15.15
1971										
1972	18.98	18.85	18.46	17.00	16.30	16.30	15.09	14.88	14.83	14.34
1973	19.11	19.04	18.68	17.90	17.90	16.36	15.46	14.65	14.28	14.28
1974	18.89	18.86	18.67	18.59	18.55	17.93	15.94	15.87	14.61	14.61
1975	18.03	17.63	17.55	17.32	16.69	16.30	15.39	15.39	14.58	14.41
1976	18.76	18.68	18.48	17.46	17.30	17.30	15.26	14.84	14.84	14.80
1977	18.35	18.18	17.83	16.30	16.24	16.04	15.00	14.54	14.54	14.27
1978	18.63	18.49	18.44	16.77	16.77	16.54	15.31	14.86	14.65	13.98
1979	18.89	18.82	18.68	18.20	16.31	15.85	15.74	14.58	14.58	14.08
1980	18.43	18.34	18.19	17.72	17.05	16.83	16.58	16.53	15.62	15.31
1981	18.24	18.13	17.88	16.94	16.87	16.22	16.15	15.28	15.28	15.02
1982	17.89	17.81	17.57	16.81	16.19	16.19	16.10	14.94	14.79	14.49
1983	18.37	18.24	18.06	17.97	17.32	16.70	15.88	15.43	15.24	14.72
1984	18.70	18.61	18.36	17.35	16.69	16.69	15.81	15.29	15.29	14.78
1985	18.76	18.74	18.71	18.12	17.24	17.24	15.82	15.19	14.61	14.50
1986	18.49	18.17	17.67	16.48	16.45	16.24	15.57	15.25	15.25	14.61
1987	18.87	18.86	18.85	18.72	18.17	16.88	16.88	15.93	15.93	15.75
1988	18.88	18.85	18.77	18.34	17.54	17.54	15.83	15.41	15.10	15.00
1989	18.71	18.62	18.36	17.35	16.90	16.90	16.75	15.92	15.75	15.29
Max.	19.11	19.04	18.98	18.87	18.73	18.73	17.71	16.53	15.93	15.75
Mean	18.69	18.60	18.43	17.76	17.21	16.76	15.95	15.38	15.11	14.73
Min.	17.89	17.63	17.55	16.30	16.19	15.85	15.00	14.54	14.28	13.98

For return periods calculated by Blom formula
(years)

2	18.76	18.67	18.51	17.94	17.23	16.61	15.83	15.34	15.17	14.75
5	19.00	18.95	18.83	18.49	17.84	17.29	16.48	15.86	15.65	15.02
10	19.06	19.02	18.98	18.62	18.24	17.61	17.00	15.97	15.71	15.29
20	19.08	19.04	18.98	18.78	18.62	18.26	17.57	16.29	15.82	15.50

For return periods estimated by Gumbel Extreme Value Analysis
(on upper half of points only)

5	18.96	18.90	18.79	18.43	17.82	17.31	16.49	15.83	15.54	15.08
10	19.03	18.98	18.89	18.59	18.14	17.70	16.90	16.04	15.69	15.26
20	19.09	19.05	18.98	18.74	18.43	18.05	17.28	16.23	15.83	15.42
50	19.17	19.14	19.10	18.93	18.79	18.49	17.75	16.47	16.00	15.63
100	19.24	19.21	19.19	19.07	19.06	18.82	18.11	16.65	16.13	15.79

Table 8.2 (page 2)

Example Output: Level Exceedance-Duration Analysis

! DATA FILE : REGSUB-P.RDF BOUNDARY FILE: R65-69-P.BSF !
! RESULT FILE : R65-69-P.RRF CALCULATED : 19-MAY-1992, 20:00!
MIKE-11 files : R65-P-AL.TXT (all files also R70...., R75.... etc)
This analysis file: P-ATR003.17

RANKING OF YEARS FOR GIVEN DURATIONS

ATRAI (ATR) Chainage 3.170

	DURATION IN DAYS									
Rank	1	3	5	10	15	20	30	45	60	90
1	1973	1973	1970	1970	1970	1970	1970	1980	1987	1987
2	1968	1970	1968	1987	1974	1974	1965	1970	1989	1980
3	1969	1969	1969	1974	1987	1988	1987	1987	1968	1989
4	1970	1968	1966	1966	1965	1965	1989	1989	1965	1970
5	1966	1966	1987	1967	1973	1976	1980	1974	1969	1981
6	1972	1974	1988	1965	1968	1985	1981	1968	1980	1988
7	1979	1987	1985	1988	1969	1966	1966	1969	1966	1965
8	1974	1972	1973	1968	1988	1989	1982	1965	1970	1969
9	1988	1988	1979	1969	1966	1987	1974	1966	1984	1968
10	1987	1979	1974	1979	1983	1980	1983	1983	1981	1966
11	1967	1985	1965	1985	1976	1983	1968	1988	1986	1976
12	1976	1976	1967	1983	1985	1984	1969	1975	1983	1984
13	1985	1965	1976	1973	1967	1978	1988	1984	1988	1983
14	1965	1967	1972	1980	1980	1968	1985	1981	1967	1986
15	1989	1989	1978	1976	1989	1969	1984	1986	1976	1974
16	1984	1984	1984	1984	1981	1973	1979	1967	1972	1985
17	1978	1978	1989	1989	1978	1972	1986	1985	1982	1982
18	1986	1980	1980	1975	1975	1975	1973	1982	1978	1967
19	1980	1983	1983	1972	1984	1986	1975	1972	1985	1975
20	1983	1977	1981	1981	1986	1981	1978	1978	1974	1972
21	1977	1986	1977	1982	1979	1967	1967	1976	1975	1973
22	1981	1981	1986	1978	1972	1982	1976	1973	1979	1977
23	1975	1982	1982	1986	1977	1977	1972	1979	1977	1979
24	1982	1975	1975	1977	1982	1979	1977	1977	1973	1978

Note: 20-year event lies between rank 1 and 2
10-year event lies between rank 2 and 3
5-year event lies between rank 5 and 6
2-year event lies between rank 12 and 13

(based on Blom formula)

Table 8.3

Example Output: 10-Day Time Series

```
 ! DATA FILE      : REGSUB-P.RDF          BOUNDARY FILE: R65-69-P.BSF    !
 ! RESULT FILE    : R65-69-P.RRF          CALCULATED : 19-MAY-1992, 20:00!
MIKE-11 file      : R65-P-AL.TXT   (all files also R70...., R75.... etc)
This analysis file: PLATR003.17S
```

ANALYSIS OF 10-DAY MEAN WATER LEVELS
(Model output for 24 years - run P)

ATRAI (ATR) Chainage 3.170

		Min.	Mean	Max.	Return Period (years) 2	5	10	20	50	100
Apr	1	11.84	13.11	13.52	13.16	13.25	13.37	13.46	13.50	13.56
	2	11.84	13.09	13.40	13.13	13.25	13.33	13.40	13.43	13.48
	3	11.84	13.15	13.47	13.18	13.39	13.44	13.47	13.55	13.61
May	1	11.84	13.25	13.64	13.28	13.48	13.58	13.61	13.68	13.74
	2	12.47	13.46	14.88	13.37	13.79	14.01	14.51	14.67	14.91
	3	13.00	13.66	14.74	13.55	14.03	14.22	14.74	14.80	15.01
Jun	1	12.93	14.01	16.04	13.75	14.46	15.06	15.83	15.96	16.35
	2	13.12	14.63	17.15	14.47	15.38	16.05	17.04	17.22	17.71
	3	13.47	15.36	16.92	15.36	16.35	16.80	16.85	17.20	17.48
Jul	1	13.76	16.11	17.90	16.25	16.92	17.38	17.80	17.96	18.22
	2	14.34	16.64	18.51	16.75	17.51	18.06	18.33	18.67	18.99
	3	15.00	17.20	18.77	17.13	18.39	18.71	18.77	19.33	19.68
Aug	1	15.21	16.77	18.84	16.54	18.03	18.38	18.77	19.32	19.78
	2	14.70	16.28	18.66	15.98	17.81	18.58	18.62	19.43	19.98
	3	14.43	16.43	18.18	16.53	17.42	17.87	18.07	18.36	18.64
Sep	1	14.20	16.22	18.26	16.25	17.27	17.47	18.05	18.28	18.60
	2	14.97	16.42	17.66	16.61	17.29	17.44	17.66	17.84	18.00
	3	14.48	16.36	17.93	16.09	17.69	17.76	17.87	18.47	18.78
Oct	1	14.71	16.00	17.78	15.74	17.00	17.71	17.77	18.25	18.65
	2	14.17	15.25	17.56	14.85	15.99	16.82	17.56	17.85	18.34
	3	13.77	14.56	16.44	14.41	15.01	15.30	16.03	16.16	16.45
Nov	1	13.61	14.03	14.55	13.96	14.28	14.43	14.49	14.59	14.68
	2	13.46	13.80	14.12	13.78	13.99	14.09	14.12	14.19	14.26
	3	13.31	13.66	13.92	13.66	13.83	13.89	13.91	13.97	14.02
Dec	1	13.25	13.58	13.76	13.60	13.71	13.73	13.76	13.80	13.82
	2	13.22	13.51	13.71	13.54	13.64	13.66	13.70	13.73	13.75
	3	13.22	13.47	13.69	13.47	13.60	13.63	13.65	13.71	13.74
Jan	1	13.23	13.43	13.67	13.45	13.54	13.61	13.64	13.69	13.73
	2	13.19	13.42	13.66	13.42	13.50	13.58	13.63	13.66	13.71
	3	13.19	13.39	13.62	13.40	13.48	13.50	13.56	13.59	13.62
Feb	1	13.11	13.35	13.57	13.35	13.44	13.47	13.52	13.55	13.58
	2	13.04	13.32	13.55	13.33	13.41	13.43	13.48	13.52	13.55
	3	13.10	13.30	13.53	13.29	13.38	13.41	13.52	13.53	13.57
Mar	1	13.11	13.28	13.61	13.28	13.35	13.43	13.51	13.55	13.60
	2	13.04	13.23	13.34	13.24	13.33	13.34	13.34	13.37	13.39
	3	13.00	13.20	13.52	13.20	13.31	13.37	13.44	13.50	13.55

Note: Estimates for return periods of more than 20 years should be viewed with particular caution because they result from extrapolation beyond the period of model simulation.

Return periods up to 20 years from Blom formula; 50 and 100 years by Gumbel Extreme Value Analysis on upper half of points.

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Table 8.4 (page 1)

Example Output: Ranking of Years Over One Planning Unit

PLANNING UNIT NUMBER 12 - ATRAI L.B.

AVERAGE RANKINGS OF YEARS BY FLOOD EXCEEDANCE LEVELS

	DURATION IN DAYS									
Year	1	3	5	10	15	20	30	45	60	90
1965	6.7	6.6	6.6	6.2	6.7	5.3	3.3	3.3	3.5	15.1
1966	15.9	16.1	15.9	15.2	15.9	14.5	14.7	16.9	18.3	18.1
1967	16.5	17.0	17.0	17.4	18.7	20.8	21.6	21.0	21.9	20.4
1968	7.6	7.5	7.3	7.9	7.7	8.5	6.1	5.4	7.5	13.1
1969	7.3	7.0	6.7	7.9	8.7	10.2	11.7	9.9	6.3	4.7
1970	10.2	9.7	9.3	8.3	7.3	5.5	5.3	5.7	6.7	6.1
1971										
1972	20.0	20.7	21.5	21.1	22.1	21.7	22.3	21.4	20.9	23.1
1973	4.3	4.3	5.1	5.3	5.0	8.3	9.0	15.6	14.1	15.1
1974	3.5	3.4	3.6	2.3	2.0	2.3	3.5	2.9	4.8	2.7
1975	21.9	21.9	21.5	20.5	20.4	20.3	21.1	20.5	20.5	16.3
1976	11.7	11.6	12.3	12.6	12.8	11.7	14.7	16.2	11.2	11.7
1977	16.6	16.4	16.2	16.7	16.0	15.7	15.4	9.9	10.1	9.0
1978	18.1	18.7	18.5	18.9	16.5	16.1	19.5	17.3	14.3	20.1
1979	17.5	18.1	18.1	18.6	19.9	20.5	15.7	12.7	10.5	9.7
1980	14.9	14.9	15.3	16.8	16.5	14.8	10.3	6.6	6.8	6.4
1981	17.1	17.1	16.9	16.7	15.2	15.4	11.6	14.1	11.1	9.3
1982	22.3	22.4	22.6	22.5	22.6	22.7	20.7	22.1	22.3	22.0
1983	11.2	11.1	10.7	10.1	11.6	13.3	14.1	10.4	17.1	18.7
1984	11.0	10.9	10.6	11.0	10.5	8.3	9.2	13.8	14.7	11.1
1985	11.8	11.5	11.1	12.3	14.7	13.6	14.7	14.9	14.7	9.1
1986	8.0	8.3	8.6	8.6	8.7	10.7	11.3	12.9	14.7	18.2
1987	3.7	3.0	2.6	1.9	2.3	2.4	1.3	1.2	1.2	2.2
1988	6.4	6.3	5.8	5.4	4.2	3.3	7.6	7.9	11.2	6.3
1989	15.7	15.6	16.2	15.8	14.3	14.3	15.3	17.3	15.7	11.5

Note: 20-year event has a rank of about 1.6
10-year event has a rank of about 2.8
5-year event has a rank of about 5.2
2-year event has a rank of about 12.5

Data read from the following files (total = 15 nodes):

P-ATR003.17	P-ATR023.45	P-ATR043.75	P-ATR067.16	P-ATR089.03
P-ATR110.42	P-LJA012.20	P-LJA031.25	P-NPO000.00	P-NPO018.12
P-NAG000.00	P-NAG016.78	P-NAG031.68	P-NAG048.65	P-CEL010.00

Table 8.4 (page 2)

Example Output: Ranking of Years Over One Planning Unit

PLANNING UNIT NUMBER 12 - ATRAI L.B.

AVERAGE RETURN PERIODS OF YEARS BY FLOOD EXCEEDANCE LEVELS

	DURATION IN DAYS									
Year	1	3	5	10	15	20	30	45	60	90
1965	4	4	4	4	4	5	8	8	8	2
1966	2	2	2	2	2	2	2	1	1	1
1967	2	1	1	1	1	1	1	1	1	1
1968	3	3	4	3	3	3	4	5	3	2
1969	4	4	4	3	3	2	2	3	4	6
1970	2	3	3	3	4	5	5	5	4	4
1971										
1972	1	1	1	1	1	1	1	1	1	1
1973	6	6	5	5	5	3	3	2	2	2
1974	8	8	8	13	15	13	8	10	5	11
1975	1	1	1	1	1	1	1	1	1	2
1976	2	2	2	2	2	2	2	2	2	2
1977	1	2	2	1	2	2	2	3	2	3
1978	1	1	1	1	2	2	1	1	2	1
1979	1	1	1	1	1	1	2	2	2	3
1980	2	2	2	1	2	2	2	4	4	4
1981	1	1	1	1	2	2	2	2	2	3
1982	1	1	1	1	1	1	1	1	1	1
1983	2	2	2	3	2	2	2	2	1	1
1984	2	2	2	2	2	3	3	2	2	2
1985	2	2	2	2	2	2	2	2	2	3
1986	3	3	3	3	3	2	2	2	2	1
1987	7	9	11	16	13	12	27	29	29	13
1988	4	4	4	5	6	8	3	3	2	4
1989	2	2	2	2	2	2	2	1	2	2

Data read from the following files (total = 15 nodes):

P-ATR003.17	P-ATR023.45	P-ATR043.75	P-ATR067.16	P-ATR089.03
P-ATR110.42	P-LJA012.20	P-LJA031.25	P-NPO000.00	P-NPO018.12
P-NAG000.00	P-NAG016.78	P-NAG031.68	P-NAG048.65	P-CEL010.00

Table 8.5

Selected Design Years

Planning Unit	1-in 20	1-in-10	1-in-5	1-in-2
7 (a)	1988	1987	1985	1989
7 (b)	1987	1988	1984	1983
7 (c)	1987	1988	1985	1980
7 (d)	1987	1988	1985	1980
8	1988	1973	1970	1985
12	1987	1974	1973	1985
13	1987	1988	1970	1985
14	1988	1987	1970	1985
15	1988	1974	1970	1973

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