REPUBLIC OF YEMEN

MINISTRY OF AGRICULTURE AND IRRIGATION

IRRIGATION IMPROVEMENT PROJECT

(IDA Credit No. 3412 – YEM)

Main Technical Assistance Package for IIP

WORKING PAPER 6

HYDROLOGICAL ANALYSIS

December 2002

ARCADIS EUROCONSULT

IN ASSOCIATION WITH

Halcrow

YEMEN CONSULT

YEMENI ENGINEERING GROUP

CONTENTS

LIST OF APPENDICES

1 INTRODUCTION

This is a note on work in progress. It defines the objectives of the hydrological studies, the work done so far, the options for completion of that work, and the implications of the findings so far on related aspects of the project.

1.1 OBJECTIVES

There are four main objectives:

- To describe the flood regime of the two Phase 1 wadis, in a way that will provide an input into the Spate Management Model so that its planning and operational functions can be developed. This includes an assessment of the water resources available in terms of both floods and base flows.

The most suitable way to achieve this is to develop a time series of flood events superimposed on a base flow time series so that alternative management scenarios can be tested through simulation. The assessment of resources available scales the time series and is based on detailed review of the observed data.

- To provide information on extreme flood discharges for engineering design.
- To provide information describing the context in which the Flood Warning process can be effective.
- This requires investigation of the characteristics of floods - their peak discharges, volumes and durations - that will define the categories of warning that are relevant to operational decisions and actions. It will also require some understanding of the processes of flood formation from rainfall in the catchment that will help define the deployment of instrumentation to provide the warning.
- To help define the most appropriate additional hydrometry that can be deployed in the Phase 2 wadis.

2 ANALYSES & RESULTS

The first objective listed in the introduction is the most demanding, and governs the scope of the hydrological investigations.

Based on previous experience of spate studies, it is possible to define the statistical distribution of rainfall in Yemen in terms of magnitude, frequency and timing (days, months and years). This knowledge can be used to generate long time series of rainfall in the relevant catchment areas that have similar characteristics to the rainfall observed over short periods at the rainfall stations in those areas. This knowledge of the rainfall at a daily time scale can be transposed into runoff using a catchment model that takes account of the characteristics of the basin of interest. Relevant characteristics include the land forms (permeable, impermeable) and land-use. The model can be used to generate a time series of runoff - separated into flood flow and baseflow - for the basin. Progressive refinement of both the rainfall simulation and the catchment model parameters ensures that the procedure is calibrated to produce a series with the same statistical characteristics as the observed floods and baseflow.

This form of analysis requires many peripheral analyses that bring to light characteristics of the hydrology that provide insight into the process of flood formation and its possible variation in time. There might be long-term variations or trends in rainfall. There might be developments in the wadi catchments that affect the magnitude and frequency of floods seen at the mountain foot. These peripheral analyses also provide the background information that enables solutions to the last two objectives set out above.

The analysis of extreme floods depends on the data available. Standard forms of extreme value analysis are used, supplemented by regional and external information.

2.1 AVAILABLE INFORMATION

Daily rainfall data have been obtained from the NWRA database for 245 stations throughout the country. These have been supplemented by additional records for recent years from TDA. Some data are available only in monthly summary form and these have also been obtained from the NWRA database. Few records are lengthy and complete. Only 82 of these stations have records exceeding 10 years and only 29 stations have 10 or more years of complete daily data. Records from two of these 29 stations were rejected after quality control tests (described in Appendix 1). TDA have provided detailed information on floods at Kolah on Wadi Zabid together with a copy of the rating curve used to convert water level to discharge. Records of peak discharge, flood volume and flood duration are available for 818 individual flood events in the 18-year period from 1982 to 2001 (excluding 1985 and 1999). Monthly records of baseflow are available for most of these years and monthly records of total flow cover the period 1970 to 1997. NWRA (Aden) has provided detailed records from the new water level recorder at Dukeim on Wadi Tuban. Unfortunately, this record covers only the most recent years, since the recorder was installed in 1997. The only other record appears to be the monthly summaries of flows in the 1970s from the consultant’s reports. The only rating curve currently available is that derived during the Soviet Yemeni Project.

2.2 RAINFALL

From an analysis of regional rainfall records (described in Appendix 1) several findings emerge:

1 The number of days of rain (raindays) is proportional to mean annual rainfall.

This means that the average rainfall on a wet day is the approximately the same at all places. Some places are wetter than others because it rains more often; not because it rains more intensely. A place in the mountains with 750mm of rainfall annually has more days of rain than a place on the plains with 150mm of rainfall. However, the average rainfall counting only the raindays is found to be approximately the same at both places.

2 The probability distribution of daily rainfall on raindays is found to be approximately the same for all places. (Some additional statistical tests are still needed to verify this finding).

This means that rainfall can be considered as drawn from the same probability distribution at any place in the region. A daily rainfall of say 50mm can occur anywhere. It will occur more often at a place with a high mean annual rainfall because there are more raindays and the therefore the distribution is sampled more often.

3 The variability of monthly rainfall at any place is inversely related to the mean monthly rainfall at that place.

This means that the distribution of raindays within a year at any place can be defined at least on a monthly time-scale. It has been found previously that a random distribution within the month preserves the tendency to clustering of raindays that is seen in reality.

Thus the statistical structure of the daily rainfall pattern can be defined from knowledge of the mean annual rainfall and its average monthly distribution at any place in the region. Therefore a synthetic daily rainfall record can be generated for points in a catchment area as the input to a catchment runoff model. These findings are sufficient to support a procedure that can simulate daily rainfall at any place in the region, subject to some further statistical tests.

2.3 FLOODS AND BASEFLOW

The kind of regionalisation that can be used in rainfall analysis can be developed for runoff. It is necessary to have records of runoff - preferably separated into floods and baseflow - that are sufficiently long to enable us to define their statistical structure reliably. Such records exist for Wadi Zabid where there are detailed records of individual floods from 1980 to date.

The analysis of the records for Wadi Zabid is described in Appendix 2. It appears that this is the first time that these records collected by the TDA have been analysed in detail.

The analysis reveals that:

- With the exception of a few years with extremely large floods, the number of floods each year is directly related to the annual flood volume. Furthermore the average number of floods in each month is related to the average monthly flood volume
- The probability distribution of flood volumes is well fitted by the log normal distribution.

These first two findings show that the statistical distribution of flood volumes is analogous to the statistical distribution of daily rainfall, which leads to a similar conclusion; namely that it should be possible to generate synthetic sequences of flood volumes from this information alone.

- The three attributes - volume, peak discharge and duration - effectively define a flood and are all needed to define the flood. There is not a simple correlation between flood volume and flood peak.

This is not unexpected: floods arising from rainfall near the mountain watershed will be attenuated during their travel to Kolah. The peak discharge will be reduced and the duration of the hydrograph lengthened. In contrast, floods arising from somewhere much closer to Kolah might have a higher peak discharge (and be of shorter duration) even when the flood volume is less. The relationship between peak, volume and duration therefore depends where in the catchment the flood-producing rainfall occurred.

- The number of floods above a given threshold volume declines rapidly from about 45 floods per year (no threshold volume) to less than five floods per year, each having a volume exceeding 2 million m^3 (mcm). The total annual volume of these floods declines from about 30mcm (no threshold) to around 10mcm for floods of 2mcm and more.
- The mean annual total runoff for 1980-94 (109mcm/year) is substantially less than the often-quoted 131 mcm/year that derives from the mean from the 1970-97 record.

There is some tentative evidence that water capture in the catchment area has increased so that the percentage of rainfall that forms runoff (baseflow plus flood flow) has declined from around 7% to around 5% of a provisional index rainfall. Of this 109mcm/year, about 70% is baseflow and around 30% is flood flow.

- Fragmentary data of baseflow at Weir 1 on Wadi Zabid suggests that losses to diversion and percolation between Kolah and the weir are between 10 and 15%. However, these data are unproved and for a short period. There is no information on losses during floods.

Comparable records of floods and baseflows are not available for Wadi Tuban. In fact the records of both runoff and rainfall for Wadi Tuban are very sparse.

2.4 EXTREME FLOODS

The analysis of annual maximum floods is described in Appendix 3. The 3-parameter GEV distribution has been fitted to the available data and used to predict floods of longer return period. The results are compared with published curves for other similar areas of the world and found to be in good agreement. The estimated flood of about 2800m3/s in 1984 - the only memorable flood of the past 30 years – probably has a return period of a little over 50 years. The predicted 100-year flood is about 3700m3/s. While this procedure works effectively for Wadi Zabid where there are reasonably good historical records, there is considerable uncertainty in the prediction of extreme floods for Wadi Tuban. There are few records on which to base such an analysis. This problem will be addressed later, and it is likely that we shall have to adopt a regional flood frequency curve - probably based on that for Wadi Zabid – scaled to account for differences in catchment area and rainfall.

3 ONGOING RESEARCH

3.1 GENERAL

Several issues are being investigated related to the very large floods of which there are three prominent examples in the Kolah record. Studies elsewhere in tropical and sub-tropical countries suggest that it is the coincidence of storms across the catchment area that gives rise to these events. These storms are being examined using records from all rainfall stations in and around the Wadi Zabid catchment. Also, the areal coherence of rainfall is being examined by looking at the records from clusters of rainfall stations. One such cluster near the town of Zabid should enable us to describe more precisely the nature of rainfall on the command area itself. Relating baseflow to rainfall is not simple. Normally, baseflow is seen as resulting from some medium to long-term storage within the catchment, either in shallow groundwater emanating as springs as it returns to the wadi, or as storage in the alluvium of the wadi channel system itself. However, it is likely that some low floods starting high in the catchment lose their identity as they are attenuated and become indistinguishable from baseflow.

It is uncertain at present whether it will be possible to attribute the variations in baseflow to variations in rainfall entirely. Certainly there is little correlation between annual baseflow and annual flood volumes. (This work continues).

3.2 COMPLETION OF THE ANALYSIS

The main question that must now be answered is how precisely we should proceed to the generation of wadi flow sequences for input to the SMM.

For Wadi Zabid it is clear that there is sufficient information to generate longer sequences from the statistical structure of the flood characteristics that has been identified from the historical records. There is no need to go through the longer process of generating rainfall sequences and transforming them into floods using a catchment model. This direct approach is preferable. However, a similar and direct approach is not applicable to Wadi Tuban where the historical records are very sparse.

Two options are identified:

- Generate rainfall sequences from our knowledge of the statistical structure of regional rainfall and convert the rainfall into runoff with a catchment model, or:
- Transfer the knowledge we have of the flood regime of Wadi Zabid to Wadi Tuban, scaling the results and adjusting the occurrence of the floods in a way suggested by the seasonality or other characteristics of the rainfall indicated by the short records available.

The second of these options is preferred, since it is simpler. Moreover, it avoids the difficulty of fitting a catchment model to the rainfall data when the detailed knowledge of the flows needed to calibrate the model are lacking. It is not easy in advance to guarantee the reliability of this preferred approach, and it is desirable to obtain confirmation of the generality and regional applicability of the findings for Wadi Zabid. This could be done by analysing the flood and baseflow data for another wadi. Wadi Bana is the obvious choice, but the lack of records in recent decades argues strongly against it. Wadi Mawr appears to have the longest record after Wadi Zabid although the availability of detailed information needs to be checked.

While this procedure would anticipate the work of Phase 2 to some extent, it is likely to be more effective and efficient to do this work now. It would provide an efficient method of developing flood series for the Wadi Tuban SMM, and provide a more straightforward procedure for the generation of inflows to the Phase 2 projects than one based on rainfall and catchment modelling.

The approach to be taken has to be defined by January 2003 on the present schedule of consultants.

3.3 ADDITIONAL DATA

More data can always be used to refine the analysis and to increase our general understanding of the hydrology of Yemen and of the target wadis in particular. However, in the limited time available, the following are seen to be important:

- Rating curves for Wadi Zabid and Wadi Tuban.

It is unrealistic to expect (or wait for) the current meter measurements during floods that are needed to define the rating curve over a reasonable range of flow. The curve for Wadi Zabid at Kolah should be verified by hydraulic analysis based on survey data; that for Wadi Tuban should be developed using the same procedure. A survey sufficient for the application of ISIS software should be made.

If possible the ISIS programme should be run with time-varying flow so that it can be established whether or not a rating curve for falling water level (flood recession) is different from that obtained using a steady-state flow simulation.

- Detailed hydrograph shapes for at least the 20 largest floods in the set of records for Wadi Zabid at Kolah. These should indicate the rise time (measured directly) and the slope of the recession curve (from values taken hourly from the chart record).
- (If the second option is chosen for flood analysis of Wadi Tuban) detailed records of floods for one other wadi basin, preferably one of the wadis in the list for Phase 2.

Wadi Mawr is the preferred wadi on the assumption that records of individual floods are available comparable to those for Wadi Zabid.

- Consultant’s reports and particularly the data collected during the early years of the projects on the two Phase 1 wadis. Specifically, the Italconsult reports for Wadi Tuban and the Tipton & Kalmbach reports for Wadi Zabid.
- Additional daily rainfall data from TDA and from NWRA (Aden). Records in the NWRA database for a further 20 (TDA operated) stations could be extended from 1994 to date.

These data would be useful in extending the regional analysis of rainfall and for more detailed application to the Phase 2 wadi catchments.

4 IMPLICATIONS FOR FLOOD WARNING AND HYDROMETRY

Floods rise very fast and the peak usually occurs within one hour of the onset of the flood. Thus, the easiest first step is to issue a warning on the basis of the flood peak. However, we have shown that the peak discharge is not a reliable indicator of the flood volume. Additional information is needed. Also, there is a significant proportion of double-peaked floods where the peak of a flood deriving from the lower catchment is followed by a second peak from rainfall occurring later or further away from the wadi station. Additional information might be the location of the storm giving rise to the flood, but many rainfall stations would be needed to monitor storm location reliably. It is probably better to continue monitoring discharge (water level) and to develop some method of predicting the volume of the flood from the rate of recession of the discharge. [This analysis should be achievable].

Most small floods probably result from an isolated storm covering a small proportion of the catchment area. It is therefore unlikely that one or a few rainfall stations would record the rainfall and contribute to a flood warning. However, we expect to be able to show that the larger floods result from the more widespread rainfall (This analysis is continuing). These larger or more widespread storms are easier to detect with few rainfall stations. Therefore, it is more likely that a rainfall component to the flood warning system can offer the prospect of an advanced warning of the floods that could be damaging and would need the most active gate operations.

It is noticeable that the attention paid to the routine collection of rainfall data is insufficient to maintain reliable records using traditional methods. The quality of records has been deteriorating, and quality control systems appear to be unable to detect spurious and erroneous data. In these circumstances it might be appropriate to link the funds available for flood warning with those for hydrometry in the Phase 2 wadis and install a network of telemetered stations both for water level and rainfall measurement. This network would operate continually, providing reliable data for future resources planning in addition to its role as part of the flood warning system. Such a combined scheme would add some immediate benefit to the less glamorous task of collecting data for future use.

How many stations should be installed? This is a difficult question to answer for the varied terrain of Yemen. The answer also depends on how much advance warning is needed and whether the flow of information can be maintained to the staff controlling the various structures in the command areas. If the warning is likely to be too short given only telemetered information from the existing wadi stations, a further station should be considered upstream of the present site. Beyond that the emphasis should be on monitoring rainfall. A minimum configuration of one rainfall station per major tributary should be followed in the first instance, requiring between two and four stations per wadi. Refinement of the number and placement of stations should follow an initial trial period.

LIST OF APPENDICES

A. ANALYSIS OF RAINFALL

(A general description of the climate and influences on rainfall can be found in WRAY 35 (1995))

A.1 AVAILABILITY OF DATA

Rainfall data have been collected at different times by different organisations often using measuring networks that were geared to short-term development projects. There are few rainfall records that might be considered as long term. Most of the daily rainfall data is now held in a database managed by NWRA and these data have been made available to us.

The database contains records from 245 stations across the country. Unfortunately, the database is not yet fully up to date. Records for stations operated by TDA have not been transferred since 1994, and there are still some other records, primarily from stations in the south, that are not yet in this central database.

We have obtained the manuscript records for 13 TDA stations for 1994 to 2001, coded them and integrated them with the earlier records for these stations. There are a further 21 stations relevant to the Phase 2 projects that still need to be updated.

A few records are available only as monthly summaries. There are also some records in the old HWC database that are not in the NWRA database. However, the work involved in identifying the differences and merging the two databases is beyond the scope of this project except where the records are of particular significance.

A.2 SELECTION OF DATA

Initially, length of record is the most important criterion for selection. Many stations have only short records or are newly established. They add little information on the long-term variability of rainfall.

From the 245 stations in the database, only 82 have a record spanning 10 years or more, and of these, only 29 have a complete record of 10 years or more.

Records from the 82 stations were subject to quality control tests. These tests included:

- Checks for monthly and annual totals outside the range expected, either on statistical grounds or by comparison with records from neighbouring stations.
- Checks for unexpected zero values on the same grounds.
- Checks for data repeated on successive days or on the same day in the following year.
- Checks for repeated months of daily data, either in consecutive months or for the same month in consecutive years.
- Some checks on repeated data between stations.

These tests revealed a number of cases of repeated data, some years where zero rainfall is entered when the data should be entered as ‘missing’, and a few cases of unexpected zero rainfall and extreme or unrealistically high values. One result was to highlight stations where the time-series is unrealistic in the sense that recent years have consistently much higher rainfall than earlier years. The most obvious case of this is Ibb where nowadays annual totals of 3500mm are claimed.

This record and one other were rejected completely; others were corrected as far as possible, usually by omitting particularly questionable data by months or years.

The result is a ‘regional’ or countrywide set of 29 stations having at least 10 years data of reasonably acceptable quality. A further set is defined covering the Wadi Zabid catchment comprising 25 stations of which 16 stations cover the mountainous area and 9 stations are in the plains. This ‘Zabid’ set includes some stations with less than 10 years of complete data.

As yet there are no stations in the database for Wadi Tuban that meet the criterion of at least 10 years of complete data. There is a long (monthly) record for Khormaksar but this is of limited relevance to the catchment area. Additional records are being sought and entered into the database.

A.3 RAINFALL ANALYSIS

(The rainfall analysis has only recently started - much of the time has been spent assembling and checking the data - and relatively few results can be reported at this time. Details of the selection of stations, the quality control checks, and derived statistics are held in RainAnalysis1.wb3)

The ‘Region’ set of 29 stations has been used to define the general characteristics of daily rainfall. The frequency of floods is related to the frequency of rainfall and this is the initial concern of the analysis.

Some care is needed when determining rainfall frequency. It is noticeable that observers at some stations record diligently all rainfalls, whereas at other stations rainfalls below about 5mm are neglected or aggregated with the next significant fall. This shows up as an unrealistic variation in the number of days of rainfall between zero and 5mm. Therefore, we define a wet day (rainday) as one having at least 5mm of rainfall.

Figure 1.1 shows that the average number of raindays per year is directly related to mean annual rainfall irrespective of station position or altitude. This implies that the average rainfall per rain-day is approximately constant throughout the country. This average is about 17 mm based on the number of days when rainfall is at least 5 mm; the true average will be lower if the days with rainfall below 5 mm are taken into account.

One possible interpretation of this result is that the rainfall-producing storm cells are, on average, equally effective in producing the same magnitude of daily rainfalls in all parts of the country. Differences in the total rainfall observed across the country derive from differences in the frequency of occurrence of rainstorms, not in the magnitude of the rainfalls they produce. A wet place is wetter because it rains more often, not because it rains more intensively.

Figure 1.2 shows the probability distribution of these daily rainfalls. The distribution is approximately log-normal as is that of individual flood volumes discussed in Appendix 2. The distribution shown here is an average distribution across stations. Further statistical tests will establish whether or not the distributions for each station can be regarded as belonging to the average distribution. If they can, it is possible to describe the basic statistics of daily rainfall across the country in a relatively simple way (This work is continuing).

As an indicator of rainfall variability and possible trends in the Wadi Zabid catchment, for comparison with the flood information, an index rainfall is derived from the ‘Zabid’ set of stations. Records have been standardised and then averaged spatially to minimise the impact of variations in the period of record between stations. This series is intended only to provide information about variations in rainfall over time; it is not intended as a definitive measure of total rainfall. Use of this series is described in Chapter 2.

A.4 CONTINUING ANALYSIS

Work is continuing on the following issues:

- Determining whether the larger floods (Wadi Zabid) are the result of particularly widespread rainfall.
- Assessing the spatial coherence of daily rainfall from clusters of stations to characterise rainfall on the command areas and in the mountains.
- Assessing the potential for simulation of daily rainfall in case it necessary to derive flood series from rainfall.
- Analysing the longer records for evidence of long-term variations or trends.

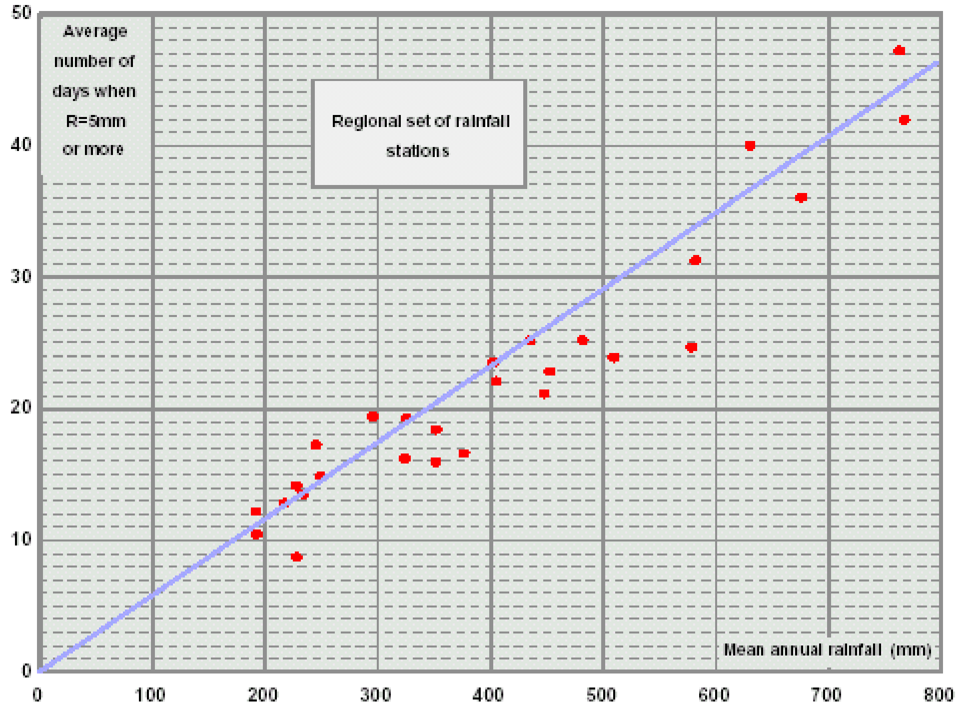


Figure A.1 Average number of raindays as a function of mean annual rainfall

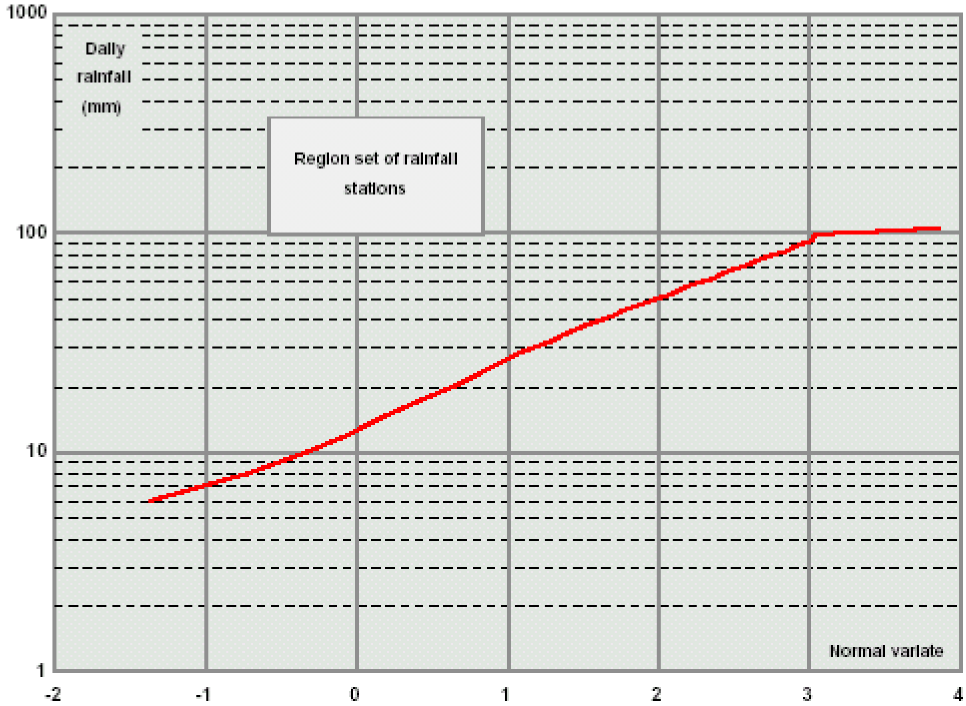


Figure A.2 the average probability distribution of daily rainfall on raindays

B. ANALYSIS OF FLOW RECORDS FOR WADI ZABID

B.1 BACKGROUND

The Tihama Development Authority (TDA) has maintained the wadi gauging station at Kolah since its construction in 1970. Water level is recorded by chart during floods; baseflows are estimated from periodic current meter measurements. Various reports quote the monthly total flows from 1970 and there are monthly summaries of baseflow and flood flow for the years since 1980. In addition, TDA have abstracted records of individual floods from the charts. These records are available only in hard copy and they do not appear to have been analysed in detail until now. Much of the analysis presented here is based on these individual flood records.

B.2 THE KOLAH RATING TABLE

The rating curve for Kolah remains unchanged; there has been only one curve since 1970. Its origin is not yet established. It has the appearance of being derived by indirect methods and no records of current meter measurements have been seen. (We need to refer to the Tipton & Kalmbach report for information) As shown in Figure 2.1, the rating table is well fitted by a conventional rating equation viz:

$$Q = 63.05 * (H + 0.21)^{1.77}$$

Where Q is in m^3/s and H in m.

Also, a curve derived by Manning's equation (for a rectangular channel 45m wide, 'n' value of 0.05, and slope of 0.01) suggests that the curve is of realistic shape.

The channel cross-section is controlled by hard rock cliffs on both sides. The only variable is the height of the bed. That comprises coarse to fine sediments with some larger material. It is likely that the whole bed is mobile during floods. It is not known whether there are long-term shifts in the average elevation of the bed. However, the presence of some exposed rock in the wadi bed further downstream would suggest that large fluctuations are unlikely.

A cable way has existed at the site although it has not been used for some considerable time. It is being rehabilitated by the Land and Water Conservation Project (LWCP) but is not yet operational. Given that it will be some time before useful information is collected and having regard to the difficulties of measuring high flows of very short duration, it is recommended that the wadi be surveyed to a standard that will enable a rating curve to be derived by the ISIS hydraulic model. This should provide an adequate check on the existing rating curve pending an accumulation of direct discharge measurements. If possible the ISIS programme should be run with time-varying flow so that it can be established whether or not a rating curve for falling water level (flood recession) is different from that obtained using a steady-state flow simulation.

Flood flows cannot easily be measured accurately. The flow is not constant for long enough for velocity measurements to be made in many cross-sections. We must rely on extrapolated curves or hydraulic analysis based on surveys and considerations of channel conditions. Thus it is unlikely that the accuracy of peak floods is better than ±25%. That is not to say an individual measurement is inaccurate to this extent, it means that we do not know whether or not it is accurate and the ±25% is a measure of our uncertainty or our confidence in the measurement.

In the following analysis, in the absence of other information, it is assumed that the rating curve is applicable for all years.

B.3 DERIVATION AND CHECKING OF THE FLOOD RECORDS

The record comprises flood events from 1982 to 2001, excluding 1985 when the recorder was not operating after being drowned by the 1984 flood, and 1999 for which the record was not found in the file. In total, there are 818 floods recorded in this 18-year period, an average of 45 floods per year, although many of these are insignificant in terms of effective spate irrigation. TDA have used a convention for separation of flood and baseflow in which the baseflow recession at the start of the flood is extended through the flood period. Flood flow is then estimated as discharge above this base line.

The data comprising the date of occurrence, peak water level and flow, mean flow and duration have been entered into an Access database [Zabid.mdb] for analysis and reference by others requiring this information. The precise time of occurrence is known but is not entered into the database. During this analysis some of the computed figures for flood volume have been corrected. Some typescript errors and some arithmetic errors were found and corrected. These corrections result in a decrease in annual flood volume of about 6%.

B.4 ANALYSIS OF THE FLOOD RECORDS

Comparison of the three flood attributes - volume, peak and duration - showed no clear inter-relationship. Figure 2.2 compares flood volume and peak discharge, the points being colour-coded into ranges of flood duration. The absence of a clear relationship between peak and volume is not unexpected. Floods arising from rainfall near the mountain watershed will be attenuated during their travel to Kolah. The peak discharge will be reduced and the duration of the hydrograph lengthened. In contrast, floods arising from somewhere much closer to Kolah might have a higher peak discharge (and be of shorter duration) even when the flood volume is less. The relationship between peak, volume and duration therefore depends on where in the catchment the flood-producing rainfall occurred.

The probability distribution of flood volumes, shown in Figure 2.3, is found to be well fitted by the log normal distribution. This is a skewed distribution in which there are a few large floods and very many more smaller floods. In these circumstances the mean is not an appropriate or useful measure of the expected value of the next event. Many lower than average events are balanced by relatively fewer high values. For example, the three largest individual floods in the 18-year record have a combined volume of more than 1.5 times the mean annual flood volume.

In this case the median is a better measure of the expected volume of a flood. The median of about 0.38mcm is substantially less than the mean value of 0.7mcm.

A consequence of this statistical description of the flood volumes is that the number of floods above a given threshold volume declines rapidly from about 45 floods per year (no threshold volume) to less than five floods per year each having a volume exceeding 2mcm. The total annual volume of these floods declines from about 30mcm (no threshold) to around 10mcm for floods of 2mcm and more. This is illustrated in Figure 2.4. Thus the number of floods that might be expected to pass down the wadi through the full system of diversion weirs is relatively small.

With the exception of a few years with extremely large floods, the number of floods each year is directly related to the annual flood volume, shown in Figure 2.5. (Analysis is continuing to relate large flood volumes to characteristics of the rainfall). Furthermore the average number of floods in each month is related to the average monthly flood volume, shown in Figure 2.6.

B.5 IMPLICATIONS OF THE ANALYSIS OF FLOODS

The extent of the flood information available and the simple statistical structure of flood volumes is such as to offer the opportunity of generating the flow sequences for the SMM directly from these flood data. It is not necessary to work from rainfall or to use a catchment model to convert the rainfall to runoff. Indeed the same techniques can be used for flood synthesis as were envisaged for rainfall synthesis. The advantage is that the cumbersome procedure of catchment modelling is avoided.

Whether this direct approach can be taken in other wadis depends on the availability of detailed flood data. We know such data are lacking for Wadi Tuban. However, serious consideration should be given to the possibility that the results for Wadi Zabid can be generalised for application elsewhere. The problem is analogous to that of regional descriptions of extreme floods where dimensionless frequency curves are derived from available data and used to extrapolate or transfer information to ungauged sites. The problem might be simply a matter of scaling, with some attention also given to the variation in the occurrence of floods between months.

B.6 ASSESSMENT OF THE OVERALL SURFACE WATER RESOURCE AVAILABLE AT KOLAH

Baseflows are measured intermittently (usually more than once each month) by current metering. A pseudo daily record is obtained by linear interpolation, and the results are presented by TDA as a monthly time series. The intermittent observations are not sufficiently frequent to analyse the recession curves effectively in terms of storage.

We have reviewed the flood flows as described above together with the baseflows in the context of the overall resource available. [At present details of this compilation and analysis can be found in the spreadsheet Zabid.wb3. Summary tables will be prepared for the final report on the hydrology]

The time series of annual total flow at Kolah is shown in Figure 2.7. The range of annual total flows is very wide - from less than 50mcm in 1991 to well over 200mcm in 1975 and 1977. There is also a steep decline in flow from the late 1970s to the early 1990s when there has been some recovery. Estimating the mean annual total flow likely to be available in the future depends on the interpretation of these data.

A provisional index of catchment rainfall has been derived using data from 16 stations in and around the catchment area but excluding stations on the Tihama Plain. This index rainfall series together with the annual percentage runoff (total annual flow expressed as a depth over the catchment and divided by the annual rainfall) is shown in Figure 2.8. The annual percentage runoff declines from about 7% in the 1970s to about 5% in the 1980s. There was some increase in 1994 but the value has reverted to around 5% thereafter. This suggests that annual total flows declined not as a result of lower rainfall, but as a result of less runoff for the same rainfall. This change over time could result from increased water capture and use in the catchment area above Kolah. Indeed, the odd result for 1994 could have followed from the political events of that year having some impact on the agriculture activity in the area.

It would be prudent to make some allowance for this change in runoff even though it cannot be fully explained at the present time. A detailed study of the water use in the mountain catchments should establish the likely future impact of upstream agricultural development on the surface water resource available to the spate projects on the plains, a question of wider significance.

Provisionally, we have taken the period 1980-94 as representing the present runoff conditions taking account of the conditions described. [At present, this period is used because we have no detailed baseflow data for 1995-99]. The average annual runoff is about 109mcm/year, substantially less than the often-quoted 131mcm/year that derives from the mean from the 1970-97 record. The differences between the average monthly runoff computed for these two periods are shown in Figure 2.9. It is noticeable that the higher runoff from the longer record is concentrated almost entirely in the months August to December. [We need to assess whether this results from a different seasonal pattern of rainfall or whether it coincides with likely additional agricultural water use in the hills]

The average monthly distribution of flood and baseflows is shown in Figure 2.10, based on data for 1980-94. In total the flood flows amount to about 30% of the total.

The variations in the possible interpretation of average flows, together with the inter-annual variability shown by these data, indicate clearly that irrigation from spate flows alone cannot be reliable for more than a very limited area. The conjunctive use of surface and groundwater is inevitable especially if perennial crops are grown. We have shown that the skewed distribution of the individual flood volumes makes the use of mean monthly and annual volumes inappropriate for planning, yet much of the literature quotes the 1970-1994 or 1970-97 mean monthly statistics as representing the resource available.

While the most effective way of analysing the true potential for irrigation is through simulation using the SMM, the flows available to the SMM still have to be scaled according to the expected long-term volume. The flows generated for use in the SMM will encapsulate all the variability seen in the data on which they are based but it is necessary to establish the scale of the resource first.

[The precise period for assessment and therefore the estimate of the likely future resource is still under review pending other analyses and possible improvement in the rainfall estimate. The figures given here are illustrative of the issues that should be considered and are not the final answer].

B.7 LOSSES BETWEEN KOLAH AND WEIR 1

The Technical Secretariat of the High Water Council (HWC) database contains a fragmentary daily record of baseflow measured at Weir 1 as well as contemporary record of flows at Kolah. The record covers the period 21 May 1987 to the end of that year, and the daily flows are in fact interpolations between intermittent measurements. The reason for these measurements and the circumstances under which they were made is not known. However, they are the only data we have found relating to flows at the weir.

These data suggest that losses amount to between 10 and 15% of the flow at Kolah in the 20km reach between the two locations.

There are several issues that make interpretation of these figures somewhat speculative. Some baseflow (and to a lesser extent some proportion of the low floods) is probably diverted by farmers along the wadi as well as infiltrating to some extent into the wadi bed. A further issue is the relationship between wadi flow seen on the surface and flow in the gravels and sediments comprising the wadi bed. They are both part of the same total baseflow. This flow could appear on the surface in some places and be entirely contained in the wadi bed sediments in other places. The configuration of the near-surface geology is all important in determining whether baseflow is forced to the surface or not. While there is some evidence of rock bars in the gorge at the Kolah station, it is not known whether or not the conditions exist for subsurface baseflow further downstream where the wadi enters the alluvium of the Tihama. There is no information on losses during floods.

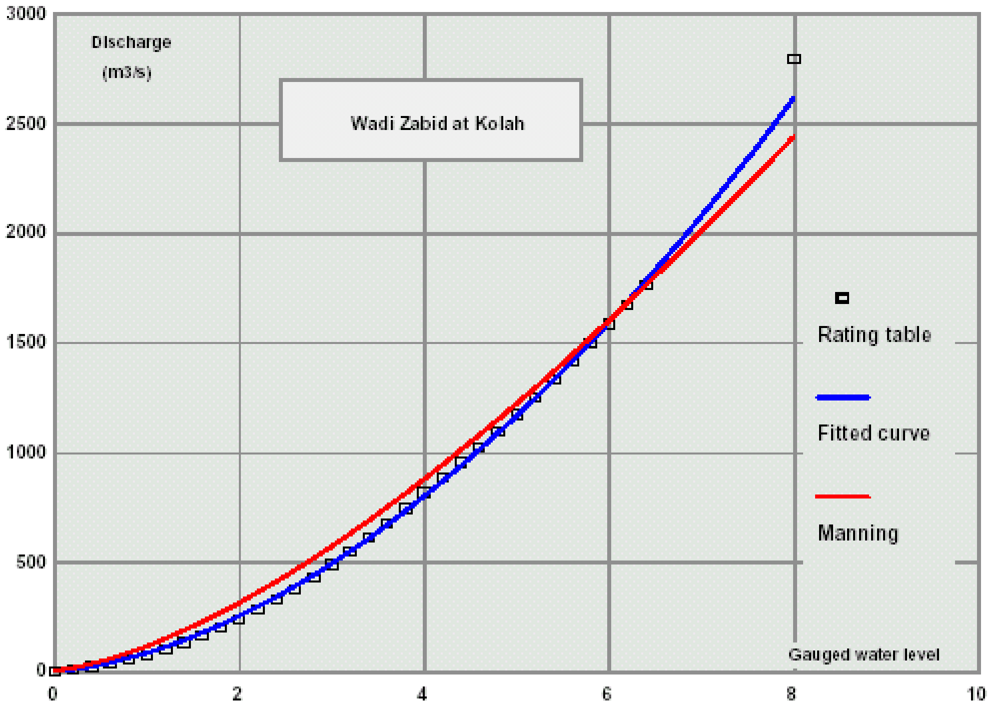


Figure B.1 Rating curve for Wadi Zabid at Kolah

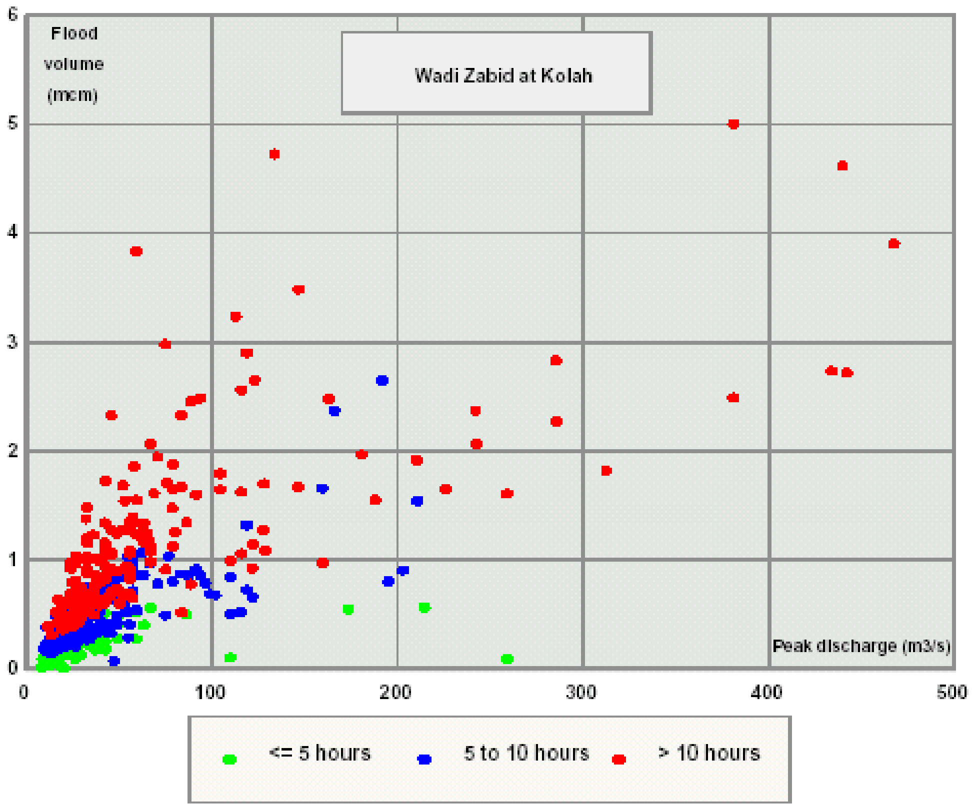


Figure B.2 the inter-relationship of flood volume, peak discharge and duration

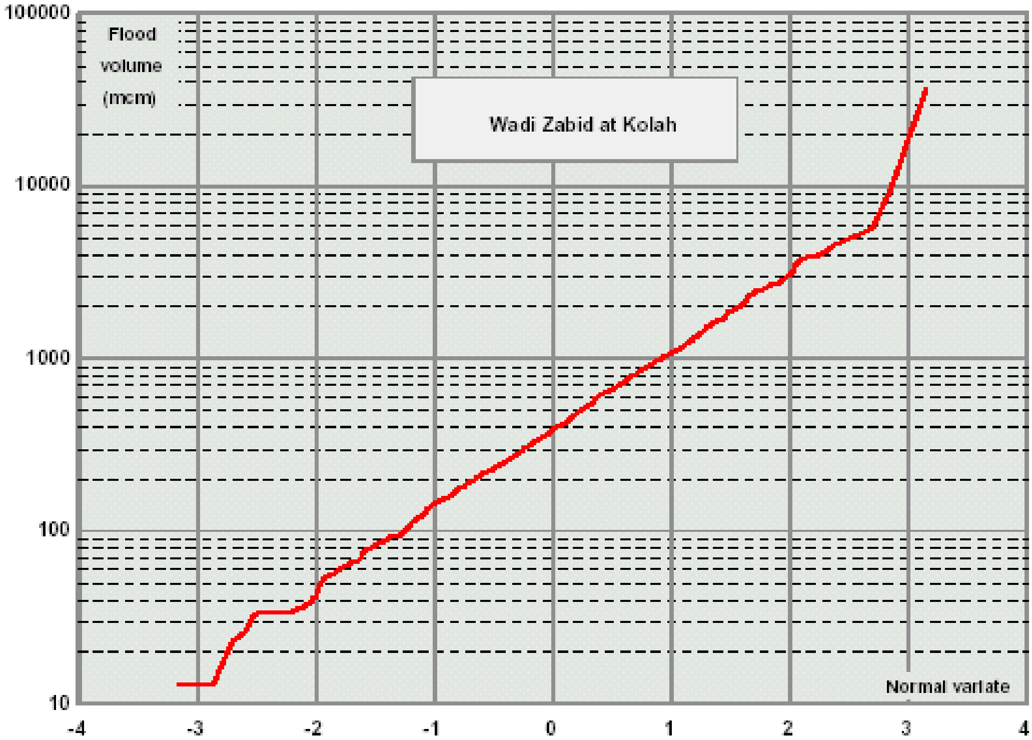


Figure B.3: Probability distribution of flood volumes

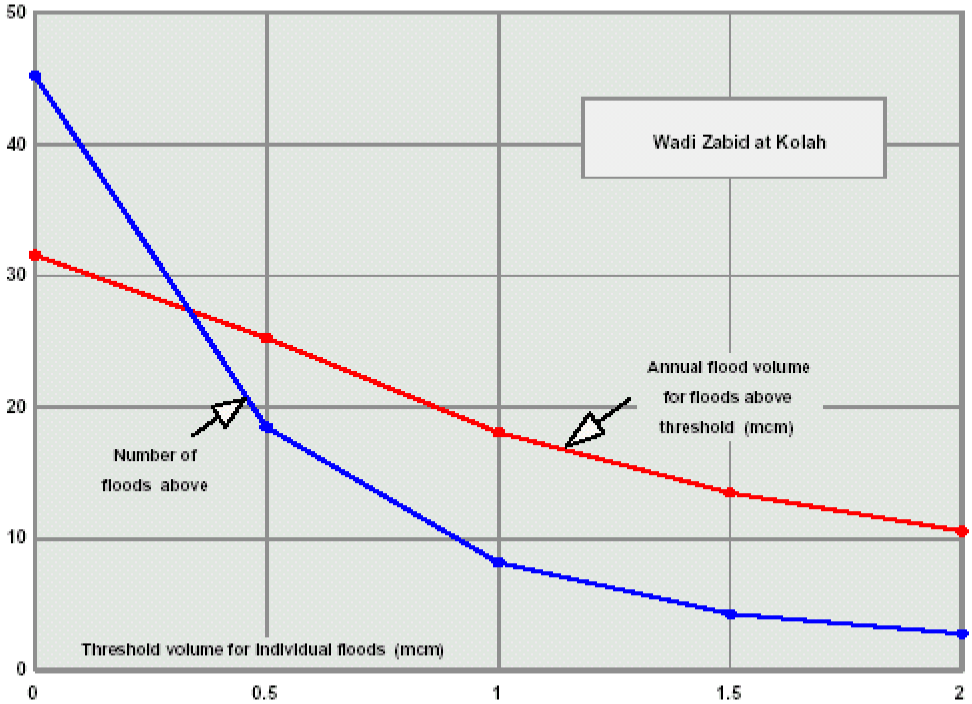


Figure B.4: Annual volume and number of floods above a threshold volume

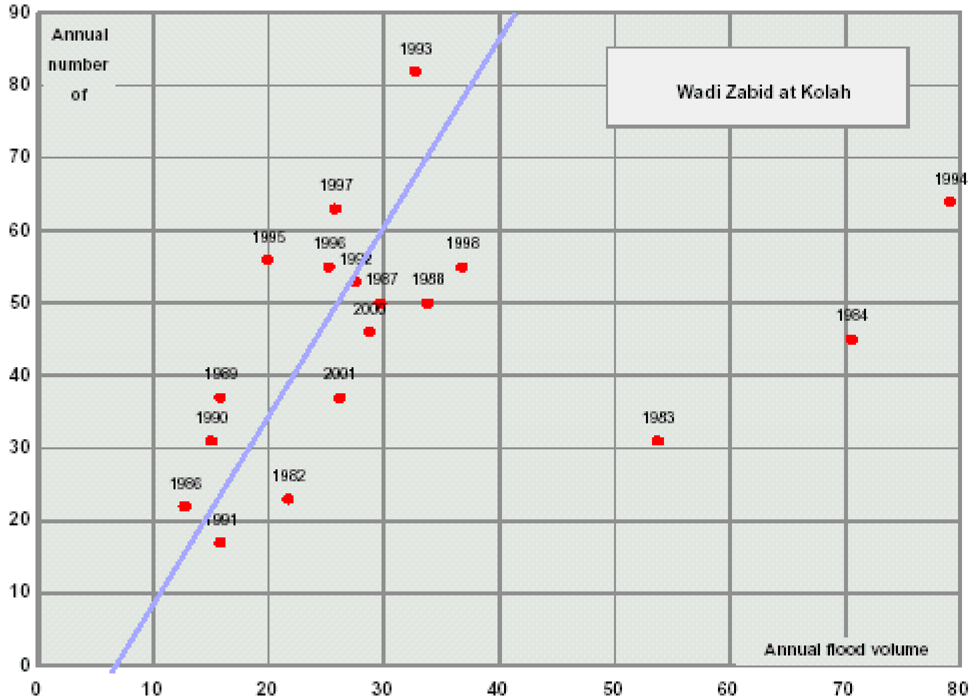
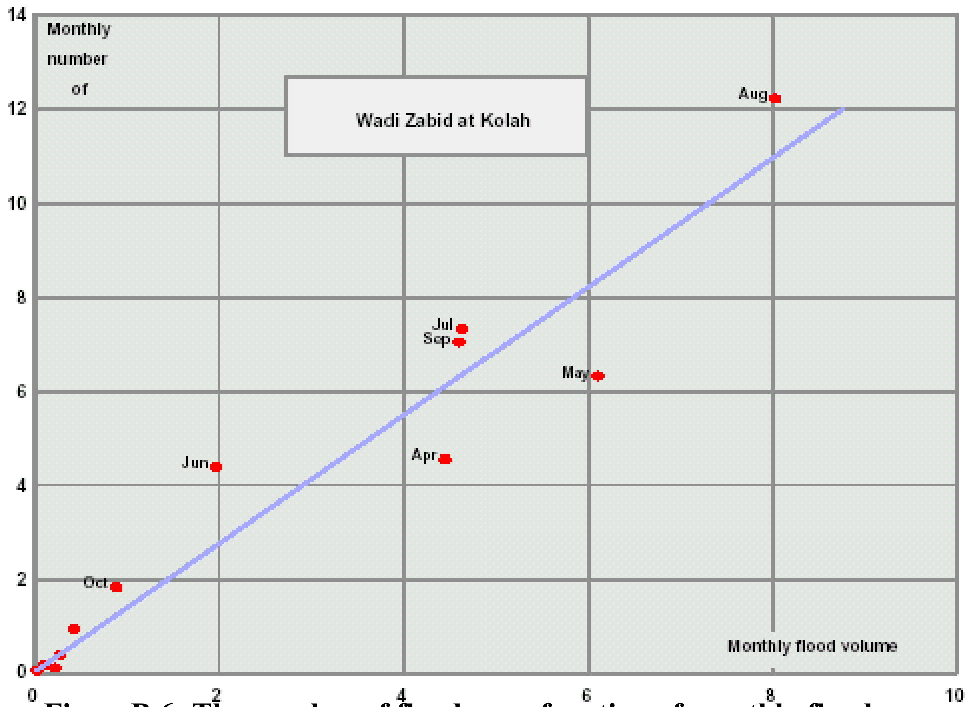


Figure B.5: Number of floods as a function of annual flood volume



FigureB.6: The number of floods as a function of monthly flood volume

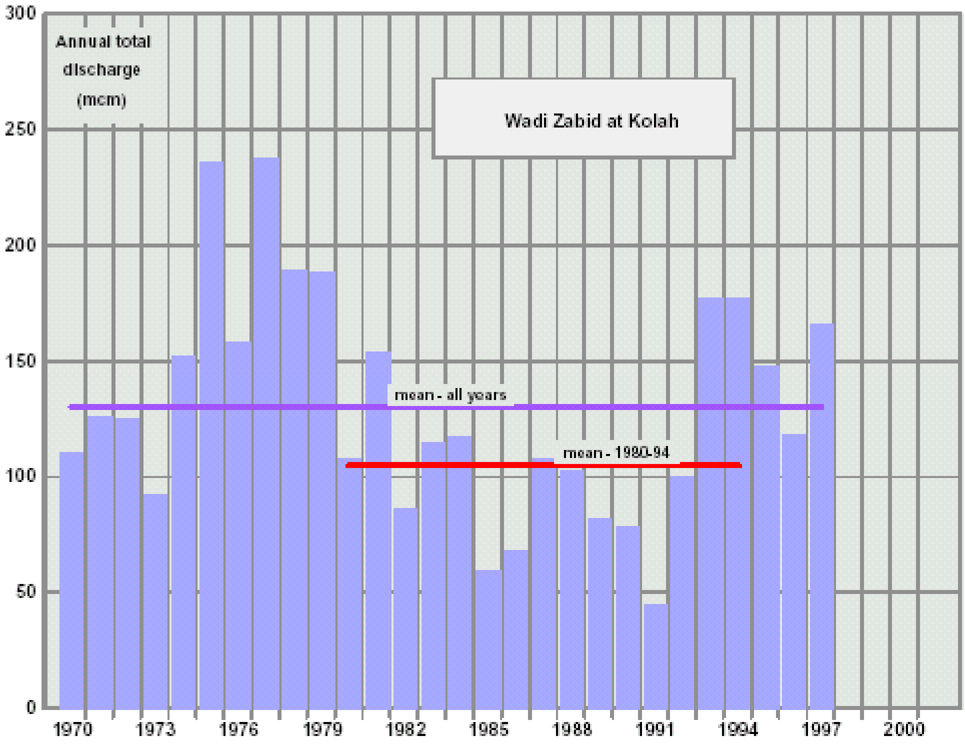


Figure B.7: Annual time series of total flow at Kolah

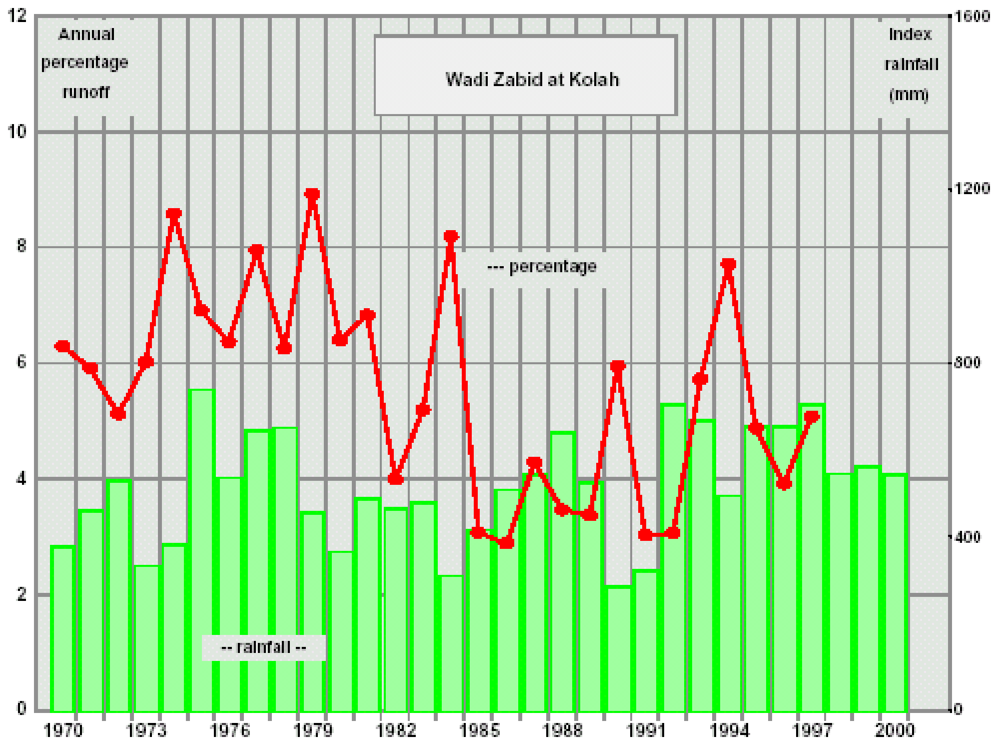


Figure B.8: Apparent variation in runoff percentage in Wadi Zabid

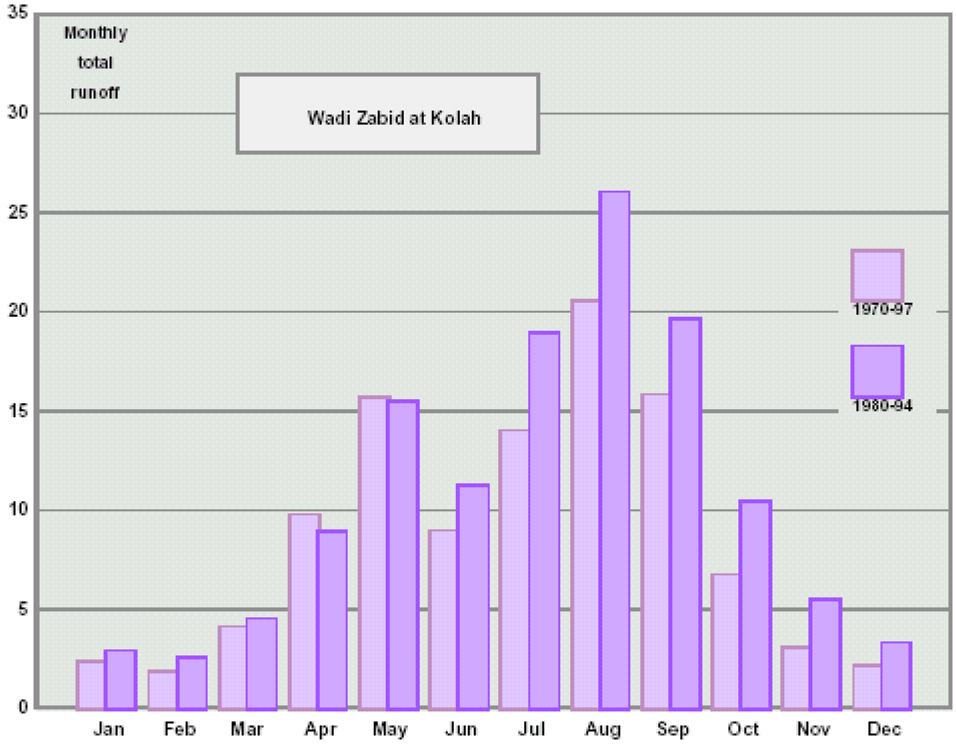


Figure B.9: Monthly differences between runoff from different periods of record

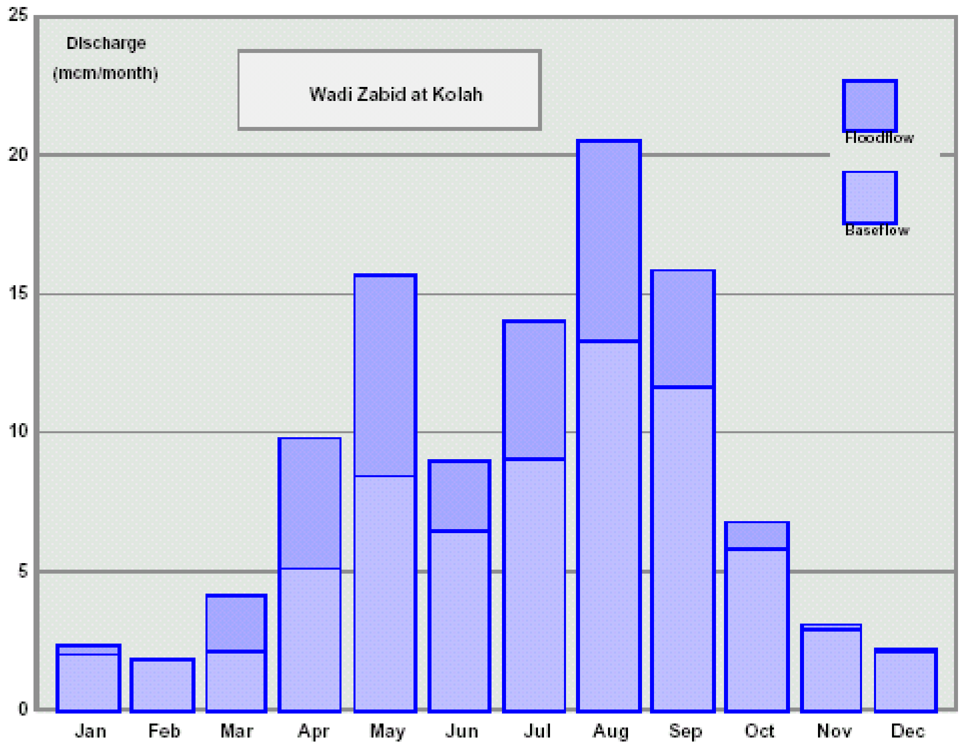


Figure B.10: The average monthly distribution of flood flows and baseflows

C. EXTREME FLOODS

C.1 BACKGROUND

Estimates of floods of different frequency (or return period) are needed for the design of structures. Inevitably, these estimates have to be based on a small sample of events and the estimates are subject to a large measure of uncertainty; estimating the 100-year flood from as little as 17 years of record is bound to be difficult. In these circumstances it is normal to try to bring other information to bear on the problem of extrapolation. This information might be in the form of regional flood frequency curves or other techniques of bringing together information from a wider range of catchment areas. Two such kinds of information are cited here. One from WRAY 35 (1995) relates maximum observed floods to catchment area using Creager's technique; the other is a regional flood frequency curve derived by Farquharson et al (1970) based on data from Yemen and SW Saudi Arabia.

Delft Hydraulics (2000) examined briefly the problem of peak flood estimation from the time series of annual maxima for Wadi Zabid. Using data from the TDA records, they concluded that the two highest floods are outliers to a (two-parameter) Gumbel distribution and that the 100-year flood is about 2050m3/s. It was noted that the two highest floods both occurred in the early 1980s and that annual maximum flood peaks have been substantially lower in all subsequent years. However, it is also noted that the fuse plug of Weir 1 has been washed out only once, in 1984, as a result of the highest flood on record.

C.2 PRESENT ANALYSIS FOR WADI ZABID

This analysis uses a similar approach to that described by Delft Hydraulics. The differences are that some annual peak discharges have been adjusted for errors of interpretation of the rating curve, and for a revised extrapolation to the maximum observed water level of 8m,additional data for 2000 and 2001 have been added; and a 3-parameter General Extreme Value (GEV) distribution is used rather than the Gumbel distribution, The GEV is more suitable in arid and semi-arid conditions.

Perhaps the most significant change to the data is to reduce the estimate of the peak discharge in 1984 from 2800m3/s to 2620m3/s. It is accepted that this does not necessarily increase the accuracy of the estimated discharge. The maximum water level on this occasion is itself an estimate given that the water level rose above the level of the recorder, which was put out of action then and for some time afterwards. However, a peak water level of 8m is accepted and the equivalent flood peak of 2620m3/s is consistent with our extrapolation of the present TDA rating table.

The second highest flood (2370m3/s in 1982) is understood to be based on an estimate from an upstream location. It is impossible to say for certain whether this peak was attenuated as it travelled to the Kolah station, or whether it was augmented by additional flood runoff from the intervening catchment area. Therefore its precise value should be regarded as less certain than the other floods in the annual maximum series. However, it is retained as a marker for some intermediate high flood, while less weight is given to it in fitting the flood frequency curve.

The observed annual maxima are shown in Table 3.1 and the fitted distribution is shown in Figure 3.1. The GEV curve is fitted by eye; objective fitting is not helpful when there are one or more floods of substantially higher magnitude in the series. Comparison with the estimates of the other workers cited above can be found in Table 3.2.

In arid and seasonally arid areas flood magnitudes increase rapidly at the higher return periods. The slope of the curve and its upward curvature is than greater than would be found in temperate latitudes subject to frontal rainfall where it is common for the whole catchment area to experience storm rainfall in the same period. In Yemen, as in many tropical and sub-tropical countries, rainstorms occur as isolated cells covering an area substantially smaller than the catchment area of the major wadis. Thus there are two factors that influence the 'growth' of storm rainfall at longer return periods. The magnitude of rainfall in the cells increases and the proportion of the catchment area subject to the storm rainfall also increases. This results in rare storms such as that of 1982. There are other mechanisms at work. For example, the unusual flood of January 1993 was probably caused by a particularly strong influx of moist air from the Mediterranean.

The results of the present analysis are in close agreement with those from Farquharson et al., who considered records from 30 stations covering a combined 378 station-years of data. They accord less well with those of Delft who considered a simpler 2-parameter frequency distribution that is arguably less appropriate in the environment of Yemen.

The implied return period of the 1984 flood is a little over 50 years. Since it is the highest flood of memory, this estimate of return period is reasonable. Some measure of the uncertainty of the present estimates is indicated by the 95% confidence limits on Figure 3.1. These indicate that there is a 1 in 20 chance that the 100-year flood could lie outside the range of 2260 to 5140m^3/s, and that the 50-year flood could lie outside the range 1250 to 3700m3/s.

C.3 ANALYSIS FOR WADI TUBAN

Flood records are not available for Wadi Tuban to the same extent as for Wadi Zabid. Annual maximum values for 11 years in the period 1968 to 1982 are quoted in the FAO Project Preparation Report. These have been analysed using the GEV approach and the results are found to be inconsistent with those for Wadi Zabid. The main difference arises when estimating the mean annual flood. This is a consequence of both records containing two very large floods but within a different length of record. It is inevitable that the mean annual flood appears to be different. Since the mean is used to scale a dimensionless frequency curve, its value is crucial to the estimates of flood magnitude at higher return periods. (This issue is still under review).

Nouh (1988) in his study of floods in Saudi Arabia found that the mean annual flood is related to catchment area and the mean elevation of the basin. The latter parameter is intended to incorporate variation in slope, geology and stream density. His recommended prediction equation is:

$$\textit{Mean Annual Flood} = 0.346 * (\textit{area})^{0.705} * (\textit{elevation})^{0.5}$$

Where Area is in km^2 and Elevation in m.

The lack of a rainfall term in this equation is a matter for concern and it is assumed that variations in rainfall between catchments are subsumed in the elevation term. The catchment area of Wadi Tuban to Dukeim is about 9.2% larger than that of Wadi Zabid to Kolah.

If the mean elevation can be assumed to be about the same, the Noah equation would give a mean annual flood at Dukeim about 6% higher than Kolah. This difference is relatively trivial compared with the large range of uncertainty in the flood estimates generally. Applying the regional flood frequency curve (Farquharson et al) that was supported by the data for Wadi Zabid, the predicted floods should also be scaled by the same factor.

(This interim conclusion is open to further analysis and amendment following further review of the detailed information available for Wadi Tuban. Ultimately, a consistent approach should be taken for the two wadis).

Table C.1: Annual maximum floods at Kolah (m3/s)

		Previous estimate	Revised estimate			Previous estimate	Revised estimate
1981	09-Apr	2370	2370				
1982	26-Sep	760	760	1992	16-Sep	259	259
1983	23-May	460	460	1993	24-Jul	119	119
1984	25-May	2800	2620	1994	21-Apr	434	468
1985				1995	28-Apr	110	110
1986				1996	12-May	79	116
1987				1997	28-Apr	90	122
1988	21-Apr	355	392	1998	17-Aug	442	442
1989	15-Jul	253	166	1999			
1990	24-Jul	204	128	2000	09-Nov		285
1991	29-Aug	332	440	2001	05-May		203

Source: TDA, WRAY35, present analysis

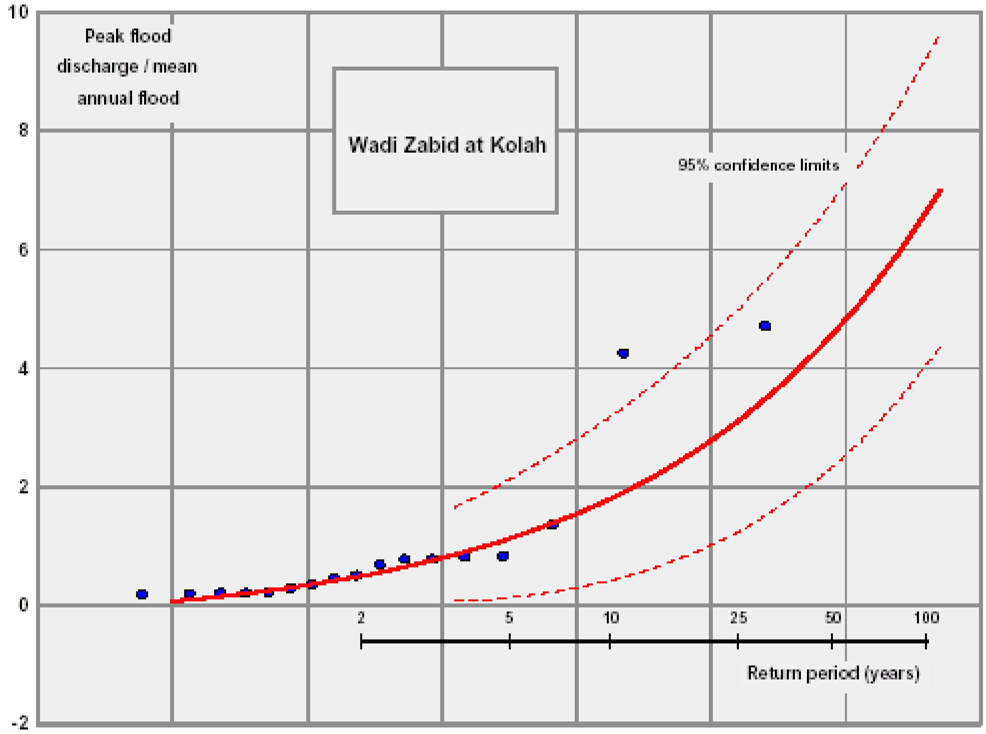


Figure C.1: Annual maximum flood frequency curve for Kolah

Table C.2: A comparison of flood estimates for Kolah

	Return period (years)				
	5	10	20	50	100
This study	632	1006	1525	2546	3691
Farquharson et al				2691	3703
Delft (2000)	880	1160	1440	1800	2050

D. REFERENCES

Farquharson FAK, Green CS, Meigh JR, and Sutcliffe JV 'Comparison of Flood Frequency Curves for Different Regions of the World'. Journal of Hydrology 138 1992.

Nouh MA 'On the Prediction of Flood Frequency in Saudi Arabia'. Proc ICE, London 85 1988.

Natural Environment Research Council 'Flood Studies Report'. Institute of Hydrology, Wallingford, 1975

Technical Secretariat of the High Water Council: Database and various technical papers written by UNDTCD consultants, 1990-1991

Delft Hydraulics 'SIIP Mission Report (second draft)'. Prepared for the World Bank, December 2000.