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Hydrological analysis

Interim report

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[revised following John Ratsey's comments]

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ACKNOWLEDGEMENT

Hydrology, in common with other environmental disciplines, depends on the historical acquisition of data. This is especially true in this study where we have attempted to build a statistical description of rainfall and flood events.

We are therefore very grateful to the organisations responsible for collection and processing of the relevant data in Yemen. Both the National Water Resources Authority and the Tihama Development Authority have given us free access to all their databases and files of rainfall and wadi flow data, and we are happy to acknowledge their generous contribution to this project.

1 INTRODUCTION

1.1 OBJECTIVES OF THE HYDROLOGICAL ANALYSIS

There are four main objectives:

- to describe the flood regime of the two Phase 1 wadis and the five Phase 2 wadis in a way that will provide an input into a 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.

1.2 FORM OF THE ANALYSIS

The first objective above is the most demanding and governs the scope of the hydrological investigations. We have adopted a regional and statistical approach to the description of floods rather than one based on rainfall-runoff modelling, which we believe to be inappropriate at short time scales when it is almost impossible to relate floods to the rainfall events that produced them. The rainfall network is sparse and floods often arise following rainfall in parts of the catchments that are not covered by rainfall stations.

We show that there are similarities between a statistical description of daily rainfall based on data from the national network and the description of the sequences of floods on those wadis where there are adequate records. There appears to be some regional coherence in these statistics, which can form the basis of simulations and predictions of flood and baseflow sequences for wadis where there is much less detailed information.

The format of this report follows the line of enquiry briefly described above.

In Chapters 2 and 3 we review the rainfall and the wadi flow data to try to identify the underlying characteristics of these variables. Rainfall is treated nationally; all stations in the national database are included in a process of selection and analysis. For flow data, that for Wadi Zabid is analysed in detail because this wadi has the best flow records as well as being one of the two wadis targeted in Phase I.

In Chapter 4 we discuss the options available for modelling and simulation of the flow regime in a way that will provide flood and baseflow sequences for the Spate Management Model (SMM), and we describe the development and testing of a simulation model.

In Chapter 6 we review the flow records and other information for the Phase I and Phase II wadis to assess the issues involved in transferring the model between wadis, how the parameter values might be set, and the results that follow from implementing the model in other wadis, notably Wadi Tuban.

In Chapter 7 we review the extreme floods on the two Phase I wadis and make recommendations for design floods for the structures.

Finally, in Chapter 8 we summarise our findings in the context of wadi flow and rainfall monitoring, its impact on the proposed Flood Warning System and the way in which records from the warning system might be interpreted in terms of scheme operation.

[This report is incomplete in some respects, primarily the sections dealing with the Phase 2 wadis. Work is continuing on data collection and analysis, and it is intended that this report will be finalised later this year]

2 REVIEW AND ANALYSIS OF RAINFALL

2.1 CLIMATIC INFLUENCES

The three main influences on rainfall in Yemen are the position and the moisture available in three climatic zones: the Red Sea convergence zone (RSCZ) the Intertropical convergence zone (ITCZ) that takes its moisture from the Indian Ocean, and the occasional influx of cyclonic events from the Mediterranean.

Considering the calendar year, the influence of Mediterranean air can be seen in rainfall and corresponding flood events in January. Normally in the season extending from October to March the air flow is easterly to north-easterly producing a southerly air flow across the Tihama.

In March to May, the RSCZ produces rainfall along the western slopes of the mountains. Orographic effects enure that the plains receive relatively low rainfall while the highest rainfalls probably occur over the western and southern slopes of the mountains with less rainfall on the areas facing the interior. Some exceptional rainfall and flood events can occur in this season, although their frequency is low - perhaps once or twice per decade.

From July to September, the ITCZ is active over Yemen and its north-south movement ensures that the southern part of the country receives higher rainfall than the more northerly regions. It is believed that the individual rain cells are larger during the ITCZ than during the rains deriving from the RSCZ.

Thus most parts of the mountainous region receive rainfall in two seasons where the first season is predominant in the northern area of the Tihama wadi catchments, and the second season more important in the southern basins.

More information on rainfall patterns linked to these climatic mechanisms is given in WRAY 35 (1995) and the Technical Secretariat of the High Water Council (TSHWC) Report Vol III (1992).

2.1 AVAILABILITY AND SELECTION OF DATA

Rainfall data have been collected at different times by different organisations often using measuring networks that were initially intended to support short-term development projects. There are few rainfall records that might be considered as long enough to derive a normal average. The World Meteorological Organisation (WMO) advocate 30 years as a satisfactory basis for a rainfall map. 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 included. We have obtained the manuscript records for 37 TDA stations for 1994 to 2001, coded them and integrated them with the earlier records for these stations.

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.

The NWRA database has been evaluated in two stages: the first to identify erroneous data, the second to identify records that can be considered as representative of long-term conditions. Details of the quality control checks applied, the major results of this checking, and the criteria used for selecting records for detailed analysis are described in Appendix A.

Essentially, two sets of records emerged from this process. A 37-station set of daily data, having at least ten years of complete record, that can be used for statistical analysis of daily rainfalls. The second comprised a 68-station set selected on less stringent criteria that can be used to define monthly and annual rainfall across the catchment areas.

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 will be entered into the database.

During our review of the quality of the data, it became apparent that much work is needed to bring the NWRA database to a reasonable standard. There are many cases of the same data repeated in different months, of confusion between ‘no record’ and zero rainfall, or of unreasonable values either in absolute terms or by comparison with other stations. These are normal problems associated with the compilation of rainfall data. However, there is a more serious problem developing and that is the tendency for the daily records to be nothing more than irregularly-monitored accumulations of rainfall. We have devised a simple test which shows that over the past decade many stations are not monitored daily; there are fewer raindays and the rainfalls recorded are much higher than in previous years. This could have serious implications for those using rainfall-runoff models who assume that the rainfall is recorded daily.

2.3 RAINFALL ANALYSIS - DAILY RAINFALL

Rainfall frequency

The ‘region’ set of 37 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 interest 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 2.1 shows that the average number of raindays per year above any threshold 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 rain-storms, not in the magnitude of the rainfalls they produce. A wet place is wetter because it rains more often, not because it rains more intensely.

Figure 2.2 shows that the relationship between number of raindays and total rainfall is relevant at the monthly time-scale. The graph includes all months in the record used for the 37-station region set. Figure 2.3 confirms that on average there is no change in the relationship through the year. Daily rainfalls are no less intense on average in the drier months than in the wetter months. Intensity here is defined on a daily time scale; we have no widespread information on rainfall intensity on hourly or other shorter time scales that might vary seasonally or from place to place.

Figure 2.4 shows the probability distribution of all the daily rainfalls of at least 5mm in the records used. The distribution is approximately log-normal as is that of individual flood volumes discussed in Chapter 3. The distribution shown here is an average distribution across stations. There are some variations between stations, which might be related to position of the station or might occur by chance given the short records and the fact that they cover different periods.

Spatial variations

Taking the mean of all daily rainfalls of at least 5mm for each station, Figure 2.5 shows that there is some tendency for the mean to fall from west to east. In this graph the points have been labelled to indicate ‘plains’ meaning stations on the Tihama, ‘hills’ meaning stations on the western escarpment and up to the watershed of the western wadis, and ‘east’ meaning the mountain slopes facing the interior. It is noticeable that the ‘plains’ stations tend to have the highest mean rainfall on raindays. Figure 2.6 looks at the relationship with position in terms of the variability of daily rainfalls. There is a tendency for the variability to decrease from west to east. No systematic variation was found in the mean or its variability in the north south direction.

It is generally believed that the rainfall occurs with higher intensity - and is therefore more likely to produce floods - on the first mountain range encountered by a moist air mass rising and cooling. To a limited extent the west to east variation shown by these data supports this interpretation.

The lines drawn on these graphs give an indication of the trend of the points; they are not intended to imply a specific linear relationship.

Finally, Figures 2.7 and 2.8 illustrate a marked tendency for seasonal rainfall as a proportion of annual rainfall to vary from west to east. The seasons chosen are March to May and July to September, which together make up about 85% of the annual rainfall on average. On the Tihama plain, rainfall tends to be concentrated in the second season. Further east, rainfall in the two seasons is comparable, and on the eastern facing slopes the first season predominates. Again, no systematic variation was seen in the north-south direction.

These findings suggest that the flood-producing rainstorms do not vary substantially across the region other than there are more of them in areas of high rainfall. Similarly, the mean storm rainfall appears to be stable particularly in a north-south direction, indicating that we should see similar floods in all the catchments of the western escarpment. Unfortunately, this analysis is least effective for the southern wadis where information is generally sparse. Some additional records for these wadis are reviewed and discussed in Chapter 5.

Later in this report we discuss the importance - and the difficulty in describing - some few exceptional floods that seem to occur primarily in the months March to May. This analysis of rainfall has not encountered any daily rainfalls that might be considered exceptional. However, this analysis is concerned with the characteristics of rainfall at a station. It is possible that exceptional floods, including those that give rise to the annual maximum peak discharge, are caused not by exceptional rainfalls at a point but by the coincidence of rainfall occurring over a wide area.

All attempts to identify a coherent pattern in the spatial correlation of rainfall have failed. The network of stations, particularly those with good data, is very sparse and the correlation is highly variable between pairs of stations. While this does not negate the idea of exceptional events being caused by widespread storms, the evidence must be found in a different way. This issue is carried forward in the next chapter where contemporary floods and rainfall are examined for Wadi Zabid.

2.4 RAINFALL ANALYSIS - MONTHLY AND ANNUAL RAINFALL

Annual rainfall

Several very similar isohyetal maps have been drawn in previous studies [WRAY35 and TSHWC 1992]. To get a general appreciation of the variation of annual rainfall across the region, we have used the map developed by the Technical Secretariat of the High Water Council. Some minor modifications have been made to accommodate the annual rainfalls derived from the 68-station set.

Map 1 shows the rainfall distribution and the location of the stations in the 37 and 68-station sets superimposed on an approximate outline of the catchment areas of the wadis of included in Phases 1 and 2 of this project.

Several general features are important:

- there is little reliable information on the rainfall distribution in the southern wadis and the isohyets are less reliable for these areas;

- differences between average rainfall in the Tihama wadis and also Wadi Tuban are likely to be small; all these catchments benefit from some areas of higher rainfall, say > 600mm. Only Wadi Bana and Wadi Hassan appear to be substantially drier than the rest.

We could infer that on grounds of rainfall alone, the all the wadis included in the project, with the exception of Wadis Bana and Hassan, might be expected to have a similar flood regime.

Monthly rainfall

Monthly rainfall data have not been used directly in developing our understanding of the flood-forming characteristics of rainfall across the region. However, they are useful in helping to define baseflow and indicative catchment averages have been derived when needed from relevant sub-sets of stations. For reference the monthly average rainfall for the stations in the 68 station set are listed in Table A2 in Appendix A.

2.5 CONCLUSIONS

The analysis of regional records of daily rainfall show that there is considerable order in the data. In general the number of rainfall events is related to aggregate 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 daily rainfall counting only the raindays is found to be approximately the same at both places.

Furthermore, the probability distribution of daily rainfall on raindays is similar for all places. This means that rainfall can be considered as drawn from a similar 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. The distributions are valid for all months; there is no tendency for high daily rainfalls to occur more or less often than would be suggested by the monthly aggregate rainfall in any month.

These rainfalls give rise to floods and it is not unreasonable to suppose that if the rainfall can be described by some fairly straightforward statistical ideas irrespective of place, then the occurrence of flood volumes in terms of their frequency and magnitude should be expected to follow some similar general pattern.

3 ANALYSIS OF FLOW RECORDS FOR WADI ZABID

3.1 AVAILABLE FLOW RECORDS

The Tihama Development Authority (TDA) have 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 used in any detailed analysis of the flood regime in any previous studies. Much of the analysis presented here is based on these individual flood records.

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. As shown in Figure 3.1, the rating table is well fitted by a conventional rating equation viz:

$$\mathbf{Q\ (m^3/s) = \quad 63.05 * (H\ (m) + 0.21)^{1.77}}$$

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.

During floods the water level (stage) is recorded by chart recorder, but only when the discharge is sufficient to ensure that the stage is above the bottom of the float well of the recorder. This threshold flow is of the order of 5 to $10m^3/s$. When the stage is below this threshold, nothing of relevance is recorded. However, even when there are no floods, there is baseflow that can in some months be above the recorder threshold causing some trace to occur on the chart.

Flows above the threshold are interpreted using the rating curve of the station. The measurement of baseflow is by intermittent current meter measurement independent of the chart recorder. These two independent measuring procedures overlap in months of high baseflow, which are also the months when floods most frequently occur. Thus the ‘separation’ of the two components of flow plays some part in determining the definition of a flood.

The staff of TDA, who carry out the observations and analysis for Wadi Zabid, determine the baseflow at the start of a flood (indicated by a rapid rise in stage). The base flow is then considered as a constant flow ‘beneath’ the flood. The flood volume is then computed as the total flow occurring above the baseflow, and the flood duration is taken as the elapsed time between the onset of the flood and the time when the stage returns to that corresponding to the assumed constant baseflow.

All hydrograph separation into flood flow and baseflow is bound to be arbitrary to some extent. The important point is to follow a consistent procedure and it appears that the procedure described has been followed throughout the period of record for Wadi Zabid that is used extensively in this report.

Two points follow from this description:

- since a flood event is not over until the stage returns to the baseflow level or the recorder threshold level, the event can include a number of flood components that arrive at the station in this period;

- it is possible for more than one flood event to occur in the same day, providing the stage returns to the starting level between the two or more events.

TDA has analysed the recorder charts by annotating the charts with hourly water level during times of floods. This information is then converted into a list of flood events for which the attributes of volume and duration are listed. For part of the record, the peak discharge is also listed. There is no digital version of the chart hydrograph and it is too time consuming to create one within the constraints of this project, although we have abstracted hydrograph shapes manually in order to review the detailed hydrographs of several large floods.

3.2 REVIEW AND ANALYSIS 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.

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 typescript errors and some arithmetic errors were found in the computed figures for flood volume, and these have been corrected. These corrections result in a decrease in the reported annual flood volume of about 6%.

Comparison of the three flood attributes - volume, peak and duration - showed no clear inter-relationship. Figure 3.2 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 number of floods appears to be related directly to aggregate flood volumes on a monthly and annual time scale. This is illustrated in Figures 3.3 and 3.4. Data for the years 1983, 1984 and 1994 are seen as outliers on the general relationship in Figure 3.3. The high volumes in these years are attributable to a few very large floods mainly in the months March, April or May. We shall call these exceptional floods and discuss them further, later in this report. The impact of these floods can also be seen in Figure 3.4 where the points for April and May plot significantly to the right of the general relationship indicated.

The probability distribution of flood volumes, shown in Figure 3.5, 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. In this case, the median is a better measure of the expected volume of the next flood, and the median of about 0.38 million m^3 (mcm) 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 3.6. Thus the number of floods that might be expected to pass down the wadi through the full system of diversion weirs is relatively small.

The frequency of floods with peak discharges in various ranges is shown in Figure 3.7. About 80% of floods have a peak discharge of less than $100m^3/s$.

Estimating the duration of a flood is difficult given the measuring procedures described above. Thus we should regard the duration data more as an indication of duration rather than a precise value. Nonetheless, Figure 3.8 shows that duration can be related approximately to flood volume. Unfortunately, peak discharge is not well related to volume or duration and, as was seen in Figure 3.2, the peak discharge cannot serve as an indicator of the volume or duration of a flood.

It is reported that some farmers perceive a reduction in flood duration over the years. However, it is difficult to substantiate this as the idea of flood duration is not precise. There is little evidence of a change in flood duration as estimated by TDA from the records at Kolah, and it is arguable that the farmers are seeing a reduction in the period of flood flows caused by the greater efficiency of diversion. This might follow from weir operations or from greater use of earth moving equipment to provide additional temporary diversions.

3.3 ASSESSMENT OF THE OVERALL RESOURCE AT KOLAH

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.

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. After 1997 the frequency of measurement declined sharply and there are insufficient observations of baseflow to compile a complete record for subsequent years.

However, using the data up to 1997 as well as the flood volumes compiled as monthly totals we can review the total resource available at Kolah as a time series. The early records (from 1970 to 1979) are available only as monthly total flows; there is no breakdown into baseflow and flood flow.

The time series of annual total flow at Kolah is shown in Figure 3.9. 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 since 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.

An index of catchment rainfall has been derived to assist this interpretation. Data are used from six rainfall 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 3.10. Unfortunately, there are too few data to define a rainfall index for the years 1989 and 1990. However, the impression gained is that 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.

Figure 3.11 shows the breakdown into flood flow and baseflow where these data are available, and Figures 3.12 and 3.13 show comparable time series for the two main wet seasons: March to June and July to October. Both flood flows and baseflow are seen to be depressed in the late 1980s and early 1990s. Thereafter, baseflow rose significantly perhaps in response to higher rainfall, although with the exception of 1994, flood flows did not increase. Figure 3.14 shows that annual total baseflow is responsive to rainfall. The average monthly distribution of flood and baseflows is shown in Figure 3.15, based on data for 1980-94. In total the flood flows amount to about 30% of the total.

Much of our perception of the trend in the total resource at Kolah depends on the accuracy of the high values observed in the 1970s. The high value for 1977 is caused by very high flows in November and December, that in 1975 by an exceptional flow in August. While some of the monthly values look unrealistic in these early years, it would be unreasonable to reject these data without more detailed evidence. The 1980s were perceived by Yemenis to be drier than average, implying that the 1970s were wetter, although the rainfall data do not appear to support this perception.

It is clear that there is no simple answer to the question of the long-term resource available at Kolah. It is possible that the 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 is also possible that there are variations in annual rainfall that are not ‘seen’ by the small sub-set of stations used in constructing the index rainfall, or that there are errors in the early flow records.

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 impact of upstream agricultural development on the surface water resource available to the spate projects on the plains, a question of wider significance.

We recommend that data for the period 1980-97 should be used to represent the present runoff conditions for planning purposes. 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, although we have shown that part of the reduction (about 6%) arises from corrections in the calculation of flood volumes.

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.

Only in the long-term, and with conjunctive-use, can a high efficiency of water utilisation be achieved. During high floods, the surplus that cannot be fully controlled for immediate irrigation can recharge the groundwater storage. This water becomes available for future use by pumping.

3.4 LOSSES BETWEEN KOLAH AND WEIR 1

The TSHWC 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 makes 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.

3.5 FLOOD HYDROGRAPHS

Rainfall occurs as more or less distinct events with duration of a few hours or less. These events, which cover an area that is small relative to the size of the catchment might occur sequentially on one part of the catchment, or on a number of separate parts of the catchment at the same or different times. If these events are sufficiently intense to cause runoff, a flood will be seen at the mountain foot. It follows that this flood can be made up of a number of distinct flood components resulting from the rainfall events described.

Review of the charts from the water level recorder at Kolah shows that many of the flood hydrographs are complicated and difficult to describe in simple terms. They appear to contain several components that we assume derive from rainfall events on different parts of the catchment within the duration of the flood. The initial rise time of the flood cannot be identified precisely; the chart scale is such that times of less than one hour cannot be distinguished clearly given that the trace is usually blurred.

Some disaggregation of the total flood hydrograph into its components can be made if an idealised form of flood is postulated. Here we have used the idea of a linear reservoir in which outflow is directly related to storage. If the runoff occurs in a short time (of the order of the time interval of the analysis) then the runoff can be regarded as an instantaneous input into the linear reservoir. Outflow will occur until the reservoir is empty and it will follow the form:

$$\mathbf{q_t = q_{t-1} * \exp(-\delta t/k)}$$

where q is discharge and k is the time constant governing the decline of flow

If k is 1, the discharge will reduce by a factor of **e** (2.718) in each time interval.

Figures 3.16 to 3.19 show how this simple disaggregation procedure can be applied to the complex observed hydrographs for four different flood events. A time interval of 1 hour is adopted in each case and the initial rise time is fixed at one hour . The graphs have been plotted with discharge on a logarithmic scale so that the idealised hydrographs from the linear reservoir appear as triangular shapes. In each case the observed hydrograph (in red) can be matched very closely by postulating a few components, usually three or less, although five components are needed to match the flood of 17 April 1988. The individual components are shown in blue and the sum of these components in black.

The components making up a single flood event can be quite different in the rate of decline of discharge. They each have a different time constant, k. The short, steeply declining, components have a time constant of the order of 1 to 2 hours. The longer, gradually declining, components have time constants as long as 22 hours. A summary of the components found in the four floods analysed in this way are listed in Table 3.1 below.

Table 3.1 Summary of the flood component parameters for the floods analysed

Component volume (mcm)

	A	B	C	D	E	Total
24-Jul-1994	3.0 (53%)	1.6 (29%)	1.0 (18%)			5.6
17-Apr-1988	2.0 (52%)	0.3 (9%)	0.5 (12%)	0.9 (24%)	0.1 (2%)	3.8
18-Sep-1993	1.4 (67%)	0.7 (33%)				2.1
16-Jul-1994	0.5 (19%)	0.6 (21%)	1.4 (54%)	0.2 (7%)		2.7

Component peak discharge (m^3/s)

	A	B	C	D	E	Max	Hydrograph peak
24-Jul-1994	393	299	32			393	393
17-Apr-1988	187	9	104	250	10	250	265
18-Sep-1993	282	19	0	0		282	282
16-Jul-1994	116	11	119	6		119	131

Component time constant (hours)

	A	B	C	D	E
24-Jul-1994	2.1	1.5	10.0		
17-Apr-1988	2.9	16.0	1.2	1.0	2.5
18-Sep-1993	1.4	15.0			
16-Jul-1994	1.2	22.0	3.3	13.0	

A possible explanation of this range could be related to the distance of the rainfall event from the wadi measuring station. Floods arising from rainfall in the more distant parts of the catchment are attenuated (the peak is reduced and the time base lengthened) before arriving at the station. Floods derived from local rainfall are not attenuated and appear as short, high-peaked components in the flood hydrograph.

There are other possible explanations. The short, high-peaked events could result from more intense rainfall over a small area, while the longer flood components might result from less intense rainfall over a wider area.

It could be argued that the components with long time constants should be regarded as part of the baseflow. Usually, baseflow arising from deep storage and manifested through springs or seepage into the wadi bed has a time constant measured in days if not months. In these wadis the source of the baseflow is not well understood and it is possible that it derives from shallow storage (in the wadi bed and associated alluvial units) where shorter time constants might be relevant. Insufficient data are available to evaluate whether or not a flood arising in the distant headwaters of the catchment would be attenuated sufficiently to appear as one of the longer components when it reaches the mountain foot.

Some work by Bertrand (1980) on Wadi Bana and Wadi Hassan suggests a compound standard hydrograph where the time constant is changed (increased) when the discharge declines to one-third of the peak, and again when the discharge declines to one-tenth of the peak. This compound recession is conceptualised as rapid and slower ‘drying out’ periods, referring to the drainage of water temporarily stored in the alluvium of the wadi bed.

We are unable to distinguish clearly the merits of the disaggregation approach or the ideas put forward by Bertrand. There are hydrographs that could be used to support either interpretation. Difficulties arise primarily because the total hydrograph is not continuous; flood flows and baseflows are measured independently in different ways and the baseflow measurements are not sufficiently frequent to allow short term variations to be identified.

3.6 CONCLUSIONS

The description of floods put forward in this chapter has strong similarities to the description of rainfall in the previous chapter. In both cases individual events can be seen to be well described by a skewed distribution such as the log-normal. The numbers of events are related to aggregate totals and show consistent relationships applicable at annual and, more importantly, at monthly time scales. There are no discernable variations during the year. Some months have more floods than others, but the total volume in these months is also higher.

This simple description can be used in some form of simulation model to generate sequences of floods provided we have some information on the number of floods (or the average volume) occurring in each month. It remains to be seen to what extent this information is transferrable from one wadi to another and the extent to which the probability distribution of flood volumes can be regarded as a regional characteristic. Indications from the rainfall analysis are that the similarities in the statistical description of rainfall suggests that similarities exist between floods over many of the wadis in this project.

Other attributes of floods such as the peak discharge and the duration of the flood - all of some importance in the management of a spate scheme - are less well related to each other or to flood volume. This is not surprising; if we follow the description of rain storms as covering relatively small areas of the catchment, it follows that floods appearing at the mountain foot will have travelled from different parts of the catchment. Their hydrographs will have been transformed (attenuated) by different amounts, and it is likely that several floods will merge into complex hydrographs by the time they reach the gauging station. One possible interpretation of some of the hydrographs for Wadi Zabid shows how the more complex floods could be considered as the sum of a number of identifiable component floods.

The issue of the reliability of the resource, both flood and baseflow, begs many questions. There are indications of variations that cannot be ascribed to rainfall alone, although the sparse distribution of rainfall stations makes the areal rainfall estimate suspect. Three explanations are possible: either the rainfall was more variable in time than indicated by the data available, or there are variations in the amount of water harvesting (terraces, small dams) and use in the catchment area, or there are errors in the data that invalidate the time series. This issue cannot be easily resolved although some view has to be taken as to the resource in planning terms.

4 FLOOD AND BASEFLOW SIMULATION

4.1 INTRODUCTION

A simulation procedure is needed to generate or extend observed sequences of flow records for use with the Spate Management Model. In the case of Wadi Zabid where there are reasonably good records, the emphasis is on extending the length of record; in others, notably Wadi Tuban, the records are extremely sparse and the emphasis is on generation of realistic flood sequences from very little and very general information.

The SMM requires flood hydrographs and baseflows to be specified on a short time scale. [The precise time-scale is not yet known, but it is likely to be less than one hour]. We have seen in the previous chapter that even when hydrographs have been recorded, it is not possible to identify a generalised shape that could be regarded as a typical flood. It is sensible to separate the simulation process into two parts - prediction of the volume and duration of flood events, and using these flood attributes to derive a continuous hydrograph for the SMM.

Thus the model described in this chapter is concerned with the simulation of flood events, their volume and duration, and with the simulation of a contemporary baseflow sequence that has some (small) correlation with the flood flows. Because short-term fluctuations of the baseflow are not known, monthly values are simulated.

Further details of the model operation and its linkage with the MIS and the SMM is given in Appendix B.

4.2 THE MODELLING APPROACH

Floods are caused by rainfall that occurs as storms covering only a fraction of the wadi catchment. But the rainfall measurement network is sparse, and the records are not of high quality especially in the past decade. As a result, it is not possible to relate more than a few of the observed floods to contemporary observed rainfall events. Even in these few cases it is far from clear whether the rainfall observed is a good measure of the magnitude of the rainfall causing the floods.

In the past, rainfall-runoff models such as the SCS Curve Number model [TSHWC 1992] have been used to generate flood events from daily rainfall records in the catchment area of the Tihama wadis. More recently, [Komex, 2001], a similar model has been used on the Tuban catchment to generate flood series for studies of groundwater recharge.

These models take account of the permeability of the catchment by defining zones where runoff is produced and where it is absorbed. Curve numbers can also be adjusted for antecedent rainfall conditions. But, ultimately, it is the short-term (daily) rainfall data that drives the model and produces the runoff. If the network of rainfall stations is sparse, it follows that the rainfall causing some floods will be missed and that there will be considerable difficulty calibrating the model.

Komex reported that simulated flows matched the observed record poorly, although the total runoff compared reasonably well with the observed total. When the number of floods and the statistics of flood volume are important, as they must be in a spate management context, it appears unlikely that conventional rainfall-runoff modelling will yield a reliable solution without a very substantial increase in the density of the rainfall station network, an unrealistic expectation. A different approach is needed, one that is not dependent on the direct ‘flood by flood’ linkage of rainfall and runoff.

The approach adopted in this study is based on the recognition that rainfall-runoff modelling does not offer a simple solution to the problem of predicting the flood regime of wadis where flood records are scarce or non-existent. It is easier, more direct and probably more reliable to define a generalised statistical description of floods similar to the statistical description of rainfall. This approach can also benefit from being regional. Just as the description of rainfall can be based on records from the whole network, a description of floods can be strengthened by looking at the records from several wadis, particularly those with good flood records covering a period of decades. In this way the short or intermittent records can be used to scale the flood description defined from the longer records.

4.3 SIMULATION OF FLOOD EVENTS

General considerations

From our analysis of the detailed records from Wadi Zabid, it is possible to characterise the flood regime from two findings:

- both annual and monthly flood volumes are closely related to the number of floods;
- the volume of observed flood events can be described by a skewed distribution such as the log-normal distribution.

Because the monthly flood volumes are directly proportional to the monthly number of floods, it appears that the floods at any time of year can be considered as samples from a parent distribution. We discuss below a possible exception to this general description for occasional large floods in the March, April or May. In the general case - what might be termed the normal floods - it follows that the monthly occurrence of floods can be described either by the expected number of floods or by the expected volume; they are inter-related.

The distinct seasonal pattern of flood events can usually be described from historical records, even from quite sparse records. There is little correlation between the flood volumes observed in successive months. Thus, it is unnecessary to provide serial correlation components in any model of flood occurrence.

The exceptional floods are experienced on all wadis. They are the floods of memory both in terms of large volume and peak discharge, and they usually occur in the period March to May. In the analysis of the data for Wadi Zabid described in the previous chapter, they affect the flood volumes for 1983, 1984 and 1994 and appear as outliers on the graphs where the ‘normal’ years show reasonably consistent relationships between volume and number of floods. The high flood volumes of 1983 and 1984 resulted from single exceptional floods on 27 April and 25 May respectively. The high volume in 1994 derived from a succession of medium-sized floods in August and September, none of which could be regarded as exceptional.

The flood of May 1984 was partially recorded in the data set of individual floods provided by

TDA. The peak water level was well known - about 8m - and the discharge of about 2800m^3/s over-topped the emergency spillway at Weir 1. The volume of this flood is less reliably estimated at about 36 mcm, of the same order as the annual average flood volume.

In Wadi Tuban, similar exceptional floods are reported as occurring on 29-30 March 1982 (peak discharge variously estimated between 4000 and 6000m^3/s but subsequently revised to 2640m^3/s) and 24 May 1977 (2150m^3/s). A similarly memorable flood is noted for Wadi Rima (19 April 1976) with a peak flow of about 1000m^3/s.

Little is known about the genesis of these floods. In most cases their volume is not known, and there are too few recorded to be able to describe them in terms of a statistical distribution or even frequency of occurrence. While they have little impact on the number of floods experienced, their volume is important and their impact is probably highly significant in terms of the distribution of spate water across the project and possibly in recharging groundwater. They are therefore modelled as an additional isolated and infrequent events.

We have chosen to define the seasonal distribution of floods in terms of the mean and variability of the monthly number of floods, and the model works by assigning volumes to these floods drawn from a probability distribution of flood volumes. This should result in greater model stability given occasional exceptional floods. An single exceptional flood increases the monthly count only by one even though it might increase the monthly volume by several times the mean.

The simplest case

Considering first a situation where much is known: Assume, for example, that the mean and variability of the number of flood events is known by calendar months as it is for Wadi Zabid. It follows that a model can be constructed generating numbers of events that can be assigned attributes such as volume from the known probability distribution of volumes. The procedure is described below with reference to the diagram on the following page:

> In Year1 the number of floods in each month can be found by sampling (drawing a random sample from) a distribution defined by the known mean and standard deviation. Here, as in other parts of the model, the distribution is skewed (large values occur less frequently than small values). Whichever distribution is chosen, the result is a number of flood events for each month of Year1as shown in the diagram.
>
> The diagram highlights August and shows how, for example, the 6 floods for August can be assigned to days in the month at random or in some other more structured way, and a volume can be assigned to each flood (V22, V23 and so on in the diagram) from the known statistical distribution of flood volumes. This ‘parent’ distribution is sampled sequentially for each flood event - V22 is the 22nd event of the simulation in this illustration.
>
> The procedure is continued into Year2. In this case August has only 4 floods and these are assigned to days in the month and associated with flood volumes drawn from the same ‘parent’ distribution of flood volumes. This procedure can be continued for each month of the desired period of simulation.

Year 1

month	J	F	M	A	M	J	J	**August**	S	O	N	D	Year
number of floods	0	0	3	5	5	1	7	**6 floods**	10	3	0	0	40
days of month					**2**	**5**	**6**	**9**	**22**	**30**			
flood volume					**V22**	**V23**	**V24**	**V25**	**V26**	**V27**			

Year 2

month	J	F	M	A	M	J	J	**August**	S	O	N	D	Year
number of floods	1	0	2	3	5	0	3	**4 floods**	8	4	1	0	31
days of month						**10**	**12**	**23**	**25**				
flood volume						**V55**	**V56**	**V57**	**V58**				

If summary statistics are prepared from the simulated data, it is possible to verify that the outcome is what is expected. The mean number of flood events and the aggregate flood volume for each month should be close to the values indicated by the observed data from which the parameter values were estimated. Increasing the length of the simulation period makes it more likely that the sample statistics (the mean annual flood volume for example) will converge on the expected or ‘population’ values implied by the parameter set. The simulation has not determined these values; they were specified in advance. The simulation model is designed to produce a more detailed time sequence of flood events from the resource estimates given.

Other tests can be performed to check that the program is behaving correctly and to check that the model can reproduce any other characteristic of the flood record reasonably well. These checks are presented and discussed below.

Exceptional floods

As little is known about these events whose occurrence appears to be confined to the months March to May, they can be described and included in the simulation only in very general terms. We have described them simply in terms of an expected mean volume and standard deviation and allowed for a different probability of occurrence in each of the three months. These probabilities are kept low to ensure that on average one of these exceptional floods appears in the record about once every five to fifteen years on average.

This component of the model must be regarded as speculative. The description of these exceptional events, and therefore the description of them in a statistical model, can be improved only by more robust monitoring over a long period. This is little help in the short term. They are included because of their likely importance in spate management, both in terms of routing the floods safely through the system, and in terms of their likely importance in water spreading and recharge of the groundwater storage. Their infrequent occurrence means that the SMM will need to be run for fairly long sequences in planning mode if a representative number of these events is to be modelled.

When there is less information

The minimum information required to run the model is the average monthly distribution of flood and baseflow volumes, although not even this information is available for Wadi Tuban. The model also needs a measure of the monthly variability of either the number of floods or the flood volume.

However, the latter requirement could be met by a generalised relationship derived from the Wadi Zabid records.

Intuitively, the variability of the number of floods is expected to be higher in months having fewer floods. Figure 4.1 shows that this is true for Wadi Zabid. The CV of monthly number of floods can be well described by an inverse logarithmic relationship with the monthly number of floods (or the flood volume). This is a very similar relationship to that found for rainfall, and we might suppose that it holds for all wadis.

Thus, we have defined two versions of the model:

- Version 1 where the mean and CV of the monthly number of floods can be defined from the data;
- and Version 2 where the variability of the monthly number of floods is defined by the relationship

  $\mathbf{CV(n) = 1.519 * n^{-0.408}}$ (from Figure 4.1)

  where n is the mean number of floods in month m, and the parameter values refer to Wadi Zabid

Duration and peak of flood events

The duration of flood events is a difficult concept. The receding flood flow merges with the current baseflow and separation into flood and baseflow is an arbitrary procedure. Even for Wadi Zabid, the charts have not been digitised and the flood volumes and durations used in our present analysis are based on the interpretation of each flood by TDA. They in turn are hampered by the fact that the chart record does not cover the full range of flow at the lower end, and when baseflow is not sufficient to cause a trace on the chart, there is effectively a ‘gap’ between the flood and baseflow records.

Figure 3.8 in the previous chapter showed that there is some correlation between flood volume and duration for individual floods. The scatter is probably due to the fact that many hydrographs are compound shapes made up of a number of flood components arriving from different parts of the catchment at different times during the event.

Nevertheless, an estimate of duration can be derived from this equation, which for Wadi Zabid takes the form:

$$\mathbf{Duration = 13.1 * Volume^{0.58}}$$

where duration is measured in hours and volumes in million m^3 (mcm).

4.4 SIMULATION OF BASEFLOW

There is much conjecture and little hard evidence for the baseflow regime of the wadis. It is clear that baseflow is highly seasonal and generally uncorrelated from year to year. This lack of persistence argues against a large hard-rock/spring source and in favour of fairly extensive shallow, probably alluvial, storage that is replenished and drained on a regular seasonal or shorter-term cycle. Replenishment of the storage could derive from small floods that are totally absorbed before they reach the catchment outlet and by any other runoff that is less concentrated than would merit the description of a flood. Some proportion of the larger floods is also likely to contribute.

Annual baseflow is related to annual rainfalls shown in Figure 3.14. There is also some substantial increase in baseflow following periods of floods that cannot be defined from the rainfall records alone.

Given these considerations we have derived a baseflow simulation procedure with three components:

- a proportion of monthly catchment rainfall;

  An index of catchment rainfall can be derived from available records. This can give a mean and variability of catchment rainfall for each month. Again, the distribution for each month is seen to be skewed and this can be approximated by assuming a log-normal distribution when deriving samples during the simulation. It is not necessary to put excessive effort into scaling the index rainfall precisely as any error can be compensated for by adjusting the percentage forming baseflow.

- a volume related to the simulated flood volume for each month;

  It is not intended that this volume should be subtracted from the flood volume. The floods are already scaled to reproduce the volumes seen at the wadi gauging station at the catchment outlet. Rather the flood volume is used to scale a contribution that derives from intermittent flood events that are not necessarily or directly related to the total rainfall.

- a small persistent component that is allowed to vary from year to year.

  This component is added because it is otherwise impossible to simulate the observed baseflows during the dry season. Whether there is a real longer-term component of baseflow is not known. It is possible that this component is a substitute for full baseflow routing that is impractical when working at a monthly time-scale.

We have introduced a time lag, measured in days, that allows the monthly simulated baseflow to be pushed forward in time. This is a substitute for full baseflow routing that would be used if the time scale was shorter, and it simulates the delay inherent in outflow from a storage that is gradually draining. Replenishment of the storage in August, for example, will result in baseflow at the catchment outlet days or possibly a month or two later on average.

There is no information available on the short-term fluctuations in baseflow; measurements are made at irregular intervals of several days or even weeks. No attempt has been made to invent a variation that cannot be substantiated.

The baseflow model with these components is probably over-parameterised; it is more complicated than can be justified by the data available for fitting and testing it. The three components described above are added because it would otherwise be impossible to reproduce the monthly baseflow distribution seen. One reason might be that floods are a better measure of rainfall than the rainfall network itself, which in Wadi Zabid is sparse and unrepresentative of the rainfall in the middle part of the catchment.

4.5 TESTING THE MODEL WITH WADI ZABID DATA

Model fitting and testing cannot be exact procedures. There are significant differences between the data sets depending on which data are included. For a comparison of floods, the simulated data are compared with the statistics derived only from the records of individual floods and with the statistics derived from all the data available.

Figures 4.2 to 4.9 compare the observed and simulated values for flood and baseflow volumes, the number of floods and the duration of floods. The observed data refer to the 18-year data set for Wadi Zabid in the period 1982 to 2001. The simulated data are taken from a single 1000-year sequence generated by Version 1 of the simulation model. This length of sequence is used to reduce the impact of samples departing from the expected mean values entirely by chance.

Figure 4.2 shows that the monthly flood volumes are reproduced reasonably well. In this case the line ‘Obs2' refers to whole length of record starting in the 1970s, whereas ‘Obs1' refers only to the period for which data on individual floods are available. Figure 4.3 shows that despite the facility for adding occasional exceptional floods in the months March to May, it is not possible to fully account for the variability of flood volumes in these months.

In purely numerical terms a better match could be achieved by increasing the mean value assigned to the exceptional floods from the 25,000tcm assumed. We are reluctant to do this without some direct evidence that such large flood volumes do occur. There are no recorded hydrographs for the largest floods on Wadi Zabid. The volumes have been estimated.

Figures 4.4 and 4.5 are included for completeness. The model is based on a sampling procedure using parameters based on the number of floods. It is therefore inevitable that the model should provide a good fit to the data.

The predicted average monthly flood duration and its variability are shown in Figures 4.6 and 4.7. While the average flood duration is reasonably well predicted, the model is unable to reproduce fully the variability in the months March to May. This again is due to the problem of exceptional floods. The fit would be better if exceptional floods of higher volume were allowed.

Figures 4.8 and 4.9 show that baseflow is reasonably well defined by the simulation model. There is some tendency to underestimate the variability of baseflow, particularly in September and October. No specific reason for this has been found, but we believe that the differences might arise from unusually high observations in 1997 that are not corroborated by high flood flows or particularly high rainfall in that period. It might be significant that the completeness of the data (the frequency of recording baseflow) declined significantly from this time.

Table 4.1 summarises the results that are illustrated above. The observed values for flood and baseflow volumes refer to the 1980 to 1997 ‘planning’ period recommended in Chapter 3. The simulated values are from a 1000-year simulation. The first set is from Version 1 of the model. A second set is shown in the lower part of the table, simulated using Version 2 of the model.

[A record of the parameter values used in these simulations, together with the output data, is held in the database Floods.mdb with identifiers ZD800 and ZD801 respectively]

4.6 DEFINING THE FLOOD HYDROGRAPHS

This chapter has been concerned primarily with defining a model that can describe the time series of flood events and the underlying baseflow in a way that will allow short records to be extended and some estimate made of the likely sequence of events in catchments where there is little information. Floods have been described in terms of the volume of individual flood events; baseflow has been defined as a monthly average flow. However, the SMM has to consider how these flows might be managed so as to maximise the utility of the water resource, and to do that requires some additional information about the shape of the hydrographs, particularly during floods.

Some analysis was introduced in Chapter 3 where hydrographs were interpreted for several of the larger floods in the historical record for Wadi Zabid. It quickly became clear that there is no simple way in which hydrographs can be defined. They are not always single events; many exhibit double or treble peaks, as separate flood components, probably arising from different parts of the catchment, coalesce at the mountain foot.

At present there are no computerised records of the hydrographs available that would allow detailed analysis leading to an algorithm that could be used to develop further the output of the simulation model. And, it is too time consuming to create this record within this project. Some other, simpler approach must be found to meet the needs of the SMM.

[This work is continuing in an experimental way. Current ideas and a possible solution is presented in Appendix C. It is probably useful to wait for some feedback from the SMM trials before reviewing whether further improvements are desirable or necessary]

Table 4.1 Summary of the model testing on Wadi Zabid

Version 1 simulation		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Flood volumes (mcm)														
Observed	mean	0.2	0.0	1.8	4.3	7.0	2.6	4.8	7.0	3.9	0.8	0.1	0.1	32.2
	cv	4.2	4.2	3.3	2.0	1.8	1.4	0.9	0.7	1.3	1.8	4.2	3.4	0.6
Version1 simulation	mean	0.0	0.0	0.7	3.8	5.9	2.7	5.0	8.0	4.7	1.2	0.2	0.0	32.5
	cv	8.6	9.1	3.4	1.4	1.3	1.1	0.8	0.6	0.9	1.6	4.2	6.3	0.4
Version2 simulation	mean	0.0	0.0	0.9	3.7	5.7	2.9	5.0	8.0	4.6	1.3	0.2	0.1	32.3
	cv	6.8	0.0	3.3	1.3	1.2	1.0	0.8	0.6	0.8	1.5	3.1	8.3	0.4
Number of floods														
Observed	mean	0.1	0.1	0.9	4.6	6.3	4.4	7.3	12.2	7.1	1.8	0.4	0.2	45.4
	cv	4.2	4.2	1.5	0.8	0.7	0.9	0.6	0.4	0.7	1.4	3.2	2.3	0.4
Version1 simulation	mean	0.0	0.0	0.9	4.7	6.4	4.3	7.6	12.1	7.1	1.8	0.3	0.1	45.4
	cv			1.5	0.8	0.7	0.9	0.6	0.4	0.7	1.3	3.2		0.2
Version2 simulation	mean	0.1	0.0	0.9	4.5	6.4	4.5	7.4	12.3	7.1	1.9	0.3	0.1	45.4
	cv			1.5	0.8	0.7	0.8	0.6	0.5	0.7	1.2	2.5	8.5	0.3
Duration of flood events (hours)														
Observed	mean	1.1	0.3	2.5	7.9	7.6	8.3	7.5	8.3	7.7	3.7	1.0	1.4	
	cv	4.2	4.2	1.5	0.7	0.6	0.7	0.5	0.3	0.5	1.1	2.9	2.6	
Version1 simulation	mean	0.4	0.2	6.0	10.7	12.4	8.2	8.6	8.6	8.5	6.5	1.7	0.5	
	cv	9.00	9.07	3.98	1.44	1.36	0.75	0.64	0.41	0.62	1.45	3.39	5.62	
Version2 simulation	mean	0.5	0.0	5.6	9.6	9.9	9.0	9.2	9.1	9.0	7.8	1.9	0.6	
	cv	5.4	0.0	1.5	0.5	0.4	0.4	0.3	0.2	0.3	0.7	2.3	4.0	
Baseflow (mcm)														
Observed	mean	2.0	1.7	2.6	5.0	9.6	7.9	9.7	14.2	13.4	7.6	3.7	2.2	79.6
	cv	0.6	0.6	1.2	0.6	0.8	0.6	0.4	0.5	0.6	1.0	1.1	0.8	0.4
Version1 simulation	mean	1.8	1.8	2.4	5.4	10.3	10.7	8.7	13.9	13.0	6.1	3.0	2.0	79.0
	cv	0.4	0.6	0.6	0.6	0.5	0.5	0.5	0.5	0.4	0.5	0.7	0.6	0.3
Version2 simulation	mean	1.9	1.8	2.4	5.3	9.8	10.4	8.9	14.0	13.0	6.2	3.2	2.0	78.8
	cv	0.5	0.6	0.6	0.6	0.5	0.5	0.5	0.5	0.4	0.5	0.7	0.6	0.3

5 APPLICATION OF THE MODEL TO OTHER WADIS

[This chapter in incomplete. Work is continuing on collection of data for the Phase 2 wadis. It will be completed during the final input of the international Hydrological Analyst scheduled for later this year]

5.1 INTRODUCTION

The aim in this chapter is to apply the knowledge of the statistical characteristics of floods gained from the study of Wadi Zabid to other wadis where the database is less detailed and in some cases where there is little information beyond an approximate knowledge of the monthly pattern of aggregate flood volume.

It is worth considering the variations that might be expected between wadis, what reasons there are that the flood distribution might be the same or why it might be different, and what impact differences in catchment area or mean rainfall might be expected to have.

We showed in Chapter 2 that there are strong similarities between the statistical description of rainfall between stations. The number of raindays above any threshold of daily rainfall is well related to the aggregate rainfall on a monthly or annual time scale. In addition, the frequency distribution of rainfall on raindays is broadly similar between stations. Thus, at a point in the catchment, the flood-producing characteristic of rainfall should be similar. More floods should derive from wetter parts of the catchment, fewer from the drier areas, and the scaling of floods between catchments should be a matter of frequency and not necessarily the magnitude of individual flood events.

What is not known is the spatial scale of rain storms. Whether there is a ‘normal’ size, whether this varies with amount of rainfall, and whether or not there is a tendency for separate storm cells to affect different parts of the catchment on the same day. In other words it is difficult to make the step forward to interpret the information available for point rainfall to the areal rainfall that produces the flood.

We believe that storm cells are usually smaller, and in many cases much smaller, than the size of the catchment. We have suggested that the exceptional floods that cause much difficulty in the simulation derive from particularly widespread rainfall where much if not all the catchment is contributing to the floods.

If for example the storm covers 100km^2 and its rainfall can be characterised by the record at a hypothetical station somewhere in the area of the storm. Then a similar area with a similar aggregate rainfall in another catchment might be expected to experience the same magnitude of flood in terms of flood volume. If the magnitude of rainfall events is the same between the two areas in different catchments, it follows that the magnitude of floods should be the same discounting differences of catchment morphology.

If one catchment is bigger than another, we might expect to see more storms on the larger catchment. Thus there should be more floods, but the distribution of flood volumes in the individual floods could still be the same. Similarly, if one catchment has a higher average rainfall than the other, the number of storms should be higher and again the number of floods should be higher.

Given these considerations we might expect that the number of floods will vary between catchments although the frequency distribution of the volume of individual floods might not vary much. If this is the case then annual or monthly aggregate flood volume will give a measure of the number of floods and the simulation model can be used to develop a realistic time-series of floods. Thus the model can be used where only a monthly average flood volume is known. Obviously, in cases where there is some more detailed record of flood history, the assumption of regional similarity can be checked and verified.

Differences might arise if the catchment areas have a different shape and geomorphology. Many consultants have used the ideas of flood-producing and flood-absorbing zones in the wadi catchments. Where modelling has been done using the SCS model, these ideas have been used to derive ranges of Curve Number which control runoff formation in these models.

Turning to baseflow, it has been much more difficult to define a suitable simulation procedure because the short-term variations in baseflow are not well defined by the data. Baseflow is measured intermittently and it is not possible to verify alternative ideas about its variation and its relationship with flood flows.

This presents difficulties in attempting to transfer information from one catchment to another. It might be true that baseflow is much more dependent on natural storage within catchments, the extent of alluvial deposits in the wadi channels and the occurrence of other permeable formations that store water on a seasonal time-scale. If this is the over-riding control on baseflow then there is little to be gained from a regional analysis, each catchment must be dealt with individually and reliable simulation of baseflow must rely local observations to scale the balance between flood and baseflows.

While the data available will be used to support (or refute) the ideas discussed above, it is clear that considerable additional research could be done on many of these questions. Unfortunately, it is not possible to follow up several interesting lines of enquiry in the limited time available in this project, where the emphasis is on design and implementation.

5.2 REVIEW OF MONTHLY FLOOD AND BASEFLOWS

A summary of the monthly total wadi flow is given in WRAY 35. More up to date information as well as the breakdown into flood and baseflow volumes has been sought from TDA who are responsible for the observations on the Tihama wadis, and from NWRA who cover the southern wadis. Where possible we have also sought detailed information on the individual flood volumes.

[This process of data collection, review and verification is continuing. When complete, these records will be summarised in an Appendix and used to complete the analysis in this chapter]

Using these records we are able to illustrate the seasonal distribution of flood and baseflows for the wadis included in Phase 1 and 2 of this project.

Figures 5.1 and 5.2 show the monthly variation of total flow and its variability for the Tihama wadis. Figures 5.3 and 5.4 show a comparison between runoff from Wadi Zabid and from two of the southern wadis, Tuban and Bana. In these graphs the runoff is shown in depth terms (mm over the catchment area) in order to remove the effects of different catchment areas from the comparison.

The three Tihama wadis, Zabid, Siham and Mawr show similar seasonal patterns of runoff and comparable annual total runoff in depth terms. Data for Wadi Rasyan is included (although this wadi is not in the project) to show the impact of large runoff absorbing zones in the catchment and highly developed terraced agriculture. The variability of monthly runoff is also consistent between the three project wadis. The variability of flow in Wadi Rasyan tends to be a little higher than for the other wadis. This might be expected when much of the base of the hydrograph goes into storage or consumptive use and only the high floods reach the mountain front.

The comparison with the southern wadis is reassuring given that we need to transfer the model to these basins. The general scale of runoff is the same as for the Tihama wadis, although there is a tendency for more runoff to occur in the second season (primarily August and September). Again the level of variability is consistent with that observed for Wadi Zabid.

The distinct differences in the seasonality of runoff in the southern wadis conflicts with the general picture of rainfall variation described in Chapter 2 where there appeared to be a tendency for rainfall in the first season (March to May) as a proportion of the annual total to increase from west to east. However, this finding is based on analysis of data from the stations having 10 or more years of complete record. None of these stations are in the catchment areas of the southern wadis.

Unfortunately, the data available for the south are very short, mainly for the last few years since 1997. And even though these are modern recording stations, the records are not continuous. Nevertheless, they are the only records available and, as Figure 5.5 shows, they do indicate a markedly different monthly rainfall pattern for the southern wadis. The graph shows the cumulative monthly rainfall expressed as a percentage of the annual total for each of the sub-regions identified. The previous finding that rainfall in the March to May period increases (as a proportion of the total) from west to east is also seen here. Stations on the Tihama plain see less than 30% of the annual total by the end of May, whereas stations in the east catch over 60% of the total in the same period. However, the southern basins appear to experience the same pattern as those in the Tihama plain where more rainfall occurs in the second season (July to October). Although these results for the southern basins are taken from stations with very short and broken records, the pattern is consistent between stations and can be taken to support the monthly pattern of runoff seen in Figure 5.3.

Figure 5.6 shows the annual runoff in volume terms plotted against catchment area. The growth of volume is clearly not linear with catchment area, otherwise we might expect about 50mcm per year from zero catchment area. A relationship where total runoff volume increases with the square root of area is indicated, which suggests that runoff is limited by the other factors that might include geomorphological characteristics and the spatial distributions of rainfall, as well as the possibility that the data are erroneous.

5.3 DISTRIBUTION OF FLOOD VOLUMES

Some data on individual flood volumes are available for Wadi Rima. Although not as numerous as the data for Wadi Zabid, they can be used to compare the flood statistics with those found in Chapter 3.

Figure 5.7 shows that the number of floods each year is linearly related to the annual flood volume. From inspection of the records it is clear that the data for the years after 1986 are partial records; they do not include all the floods experienced in those years. The probability distribution of for individual floods plotted in Figure 5.8 is seen to be very similar to that for Wadi Zabid. This lends support to the idea that the distribution might be used regionally to describe the flood regime in wadis where there are insufficient records to define the distribution directly.

5.4 APPLICATION OF THE MODEL TO OTHER WADIS

Wadi Tuban

[This section is provisional and might be adjusted following interbasin comparison of the all the wadis when the data collection is completed. Also, we await access to the final Komex report. Their model results might throw some light on the balance between flood and baseflow]

The information available for Wadi Tuban amounts to a series of monthly total flows for the period 1973 to 1980, which give a mean annual total flow of 110mcm. There is no breakdown into flood and baseflow. NWRA have given us copies of files of 15-minute water levels recorded at Dukame from the new automatic data logger. These cover the periods:

```
01 Jan 2000 to 31 Dec 2000 - 13 floods
05 Jul 2001 to 05 Sep 2001 -  7 floods
11 Mar 2002 to 21 Apr 2002 -  2 floods
```

None of these data have been processed by NWRA, mainly because the rating curve for the station has not been re-established, although a new cableway is under construction. Baseflow measurements are not made on a regular basis.

To provide some indication of the flood volume indicated by these records, we have used the rating curve derived by Komex (2001) to make an approximate assessment of flood volumes for the complete record for 2000. This analysis needs to be refined when a new rating is established. There are difficulties of interpretation, similar to those arising on other wadis, because the recorder zero is some distance above the wadi bed, and for some (short periods) baseflow is sufficient to trigger a water level rise on the recorder.

This review of the 2000 record indicates a total volume of 33mcm during the period of floods, and an average flood duration of 12.5 hours from the 13 flood events recorded. As there are no baseflow records, it is not possible to emulate the kind of baseflow separation carried out by TDA for the Tihama wadis. Therefore this 33mcm includes baseflow during 150 hours when flood flow is indicated. The baseflow component could amount to almost 50% of this flow given that the water level logger is active only above a flow equivalent to 0.1mcm/hour. The rainfall records are fragmentary and it is difficult to assess the rainfall for that year. However, there are indications that 2000 was an average to wet year in the catchment area.

Several previous reports have quoted 50 to 60 floods per year for Wadi Tuban, though we have found no reference to the division of total flow into flood and baseflow components.

Komex refer to a GDC (1981) report that indicates 50 floods per year measured at Dukame and they also refer to an exceptional flood in 1989 (no date given) that washed away several historical flow gauging stations. A later report by Northwest Hydraulic Consultants (1982) refers to an exceptional flood on 29-30 March 1982 with an estimated peak discharge of 2800m^3/s. Coincidentally, this is the estimated magnitude of the highest known flood on Wadi Zabid, whose catchment area is comparable to that of Wadi Tuban.

Deriving parameters for the simulation model is largely guesswork on the basis of this fragmentary and largely contradictory information, and any simulation must be regarded as a provisional basis for planning until improvements in monitoring and interpretation of records are made.

The modern data, at least that for the year 2000, do not substantiate the flow volumes indicated by the historical data and the number of floods recorded is a fraction of that suggested for the historical period. Records for Tuban and Bana do not cover the same period, and those for Zabid and Tuban overlap only in the 1970s, and we have reservations about the record for Wadi Zabid in this period. Thus, it is not possible to test the historical data directly with any other data set.

If the modern data are to be believed, the total flood volume is of the order of 15 to 20mcm per year, occurring in 10 to 15 flood events mainly in the months August to October. In order to reconcile these data with the historical data, the baseflow must be of the order of 80 to 85 mcm per year, or 75 to 80% of the total flow. We believe that this is too high given the typical values of 50 to 70% from the Tihama wadis. It is more likely that the modern record underestimates the number of floods as some small floods might not be seen by the recorder, and while they might not add substantially to the aggregate flood volume, they would significantly increase the number of floods.

Given these uncertainties, our basic simulation for planning has been made on the assumption that there are 35 floods per year on average and that the total resource amounts to about 90mcm per year. The monthly distribution of the number of floods has been adjusted to fit the seasonal pattern of total flow, and a monthly rainfall distribution has been derived from eight stations in the catchment using data from 1997 to 2001. Baseflow generation parameters have also been adjusted to give the total volume and seasonal distribution that is indicated by the historical record of total flow.

The simulated total runoff volume is compared with the historical observed data in Figure 5.9. The line ‘pred35' refers to the assumptions described above. Flood flows and baseflows cannot be compared as there is no information on the components of total flow in the observed records.

A further simulation was made with the number of floods increased to 40 per year on average. The result is shown as line ‘pred40' on Figure 5.9. As expected, the simulated result moves closer to the observed record, particularly for the peak flow months of August and September. This additional simulation is intended primarily as a sensitivity trial, indicating the importance of the basic assumptions about the number of floods. It is not intended that it should form the basis of planning work until there is more direct evidence on the number of floods that are experienced in present catchment conditions.

Table 5.1 summarises the results for these two cases.

[A record of the parameter values used in these simulations, together with the output data, is held in the database Floods.mdb with identifiers ZD810 and ZD811 respectively]

Table 5.1 Summary of the model application on Wadi Tuban

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Base case - 35 floods per year on average														
Flood volumes (mcm)														
	mean	0.0	0.0	0.1	1.3	2.7	2.7	3.9	6.0	5.6	1.0	0.2	0.1	23.4
	cv	0.0	0.0	22.4	2.5	1.6	1.0	0.9	0.7	0.7	1.6	3.7	4.4	0.4
Number of floods														
	mean	0.0	0.0	0.0	1.6	3.5	4.0	5.6	8.9	8.4	1.5	0.3	0.1	33.9
	cv	0.0	0.0	0.0	1.1	0.8	0.8	0.8	0.5	0.6	1.2	2.8	3.2	0.3
Duration of flood events (hours)														
	mean	0.0	0.0	0.2	7.6	9.3	9.2	9.5	9.0	9.3	6.8	1.7	1.0	9.3
	cv	0.0	0.0	22.4	0.9	0.6	0.4	0.4	0.2	0.2	0.9	2.4	3.3	0.1
Baseflow (mcm)														
	mean	1.9	1.8	1.8	2.9	5.4	5.9	5.4	8.9	13.6	8.6	3.7	2.2	62.1
	cv	0.5	0.6	0.6	0.7	0.7	0.6	0.5	0.4	0.4	0.4	0.6	0.7	0.3
Total runoff (mcm)														
Simulated		1.9	1.8	1.9	4.2	8.1	8.5	9.3	14.9	19.2	9.6	3.9	2.3	85.5
Observed		0.9	0.5	0.3	4.6	8.8	8.9	12.4	27.7	31.0	9.5	3.2	1.7	109.5

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Sensitivity case - 40 floods per year on average														
Flood volumes (mcm)														
	mean	0.0	0.0	0.4	1.4	2.8	2.6	5.4	7.1	5.9	1.0	0.1	0.1	26.7
	cv	0.0	0.0	8.1	2.3	1.5	1.0	0.8	0.7	0.7	1.8	5.7	4.6	0.4
Number of floods														
	mean	0.0	0.0	0.0	1.7	3.6	3.8	8.0	11.2	9.0	1.6	0.2	0.1	39.3
	cv	0.0	0.0	0.0	1.3	0.9	0.8	0.7	0.5	0.6	1.5	5.2	4.1	0.3
Duration of flood events (hours)														
	mean	0.0	0.0	1.4	7.3	9.3	9.1	9.2	8.9	9.2	6.4	1.2	1.0	9.2
	cv	0.0	0.0	7.9	0.9	0.6	0.4	0.3	0.2	0.3	0.8	2.9	3.6	0.1
Baseflow (mcm)														
	mean	0.6	0.5	0.7	3.2	6.4	6.4	7.9	16.1	18.3	9.2	2.4	0.9	72.5
	cv	0.8	0.6	2.0	1.2	0.8	0.7	0.5	0.4	0.4	0.5	1.0	1.5	0.4
Total runoff (mcm)														
	mean	0.6	0.5	1.1	4.5	9.2	8.9	13.3	23.2	24.2	10.2	2.5	1.0	99.2

6 EXTREME FLOODS

[At present this chapter covers only the flood regimes of Wadi Zabid and Wadi Tuban. Further data collection is continuing for other wadis. When this procedure is complete it could be possible to review the findings presented here in a broader regional context.]

6.1 INTRODUCTION

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 they 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. Here we have made use of the regional flood frequency analysis carried out by Farquharson et al (1992) based on 378 station-years of data from 30 stations in 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 2050m^3/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 on Wadi Zabid has been washed out only once, in 1984, as a result of the highest flood on record.

6.2 FLOOD FREQUENCY CURVES

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, rain storms 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 exceptional floods that tend to occur infrequently in the months March to May are perceived to arise during several days of widespread rainfall.

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 2800m^3/s to 2620m^3/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 2620m^3/s is consistent with our extrapolation of the present TDA rating table.

The second highest flood (2370m^3/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, and it should be accorded less weight in any review of the flood frequency curve.

The observed annual maxima are shown in Table 6.1 and the fitted distribution is shown in Figure 6.1. The GEV curve shown is derived from the parameters for Saudi Arabia and Yemen published by Farquharson et al. While some adjustment might be made to this curve, objective schemes for curve fitting are not useful when there is one or more floods of substantially higher magnitude in the series. Estimates of the 95% confidence limits are shown on this and the similar graph for Wadi Tuban. It is not surprising that these confidence limits envelop a wide range of values; the records are short and they contain outliers.

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 6.1. 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 3700m^3/s.

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. We have not been able to assess the accuracy of these data. They refer to the years in the 1960s and 1970s and no maximum water levels or rating curve appear to have survived from this period.

While the values used are based on the FAO summary, reference has been made to contemporary reports such as Northwest Hydraulic Consultants (1982). We understand that the 1977 flood was observed at Dukame, but that the 1982 flood was estimated approximately from water level marks on the Al Arais weir some distance downstream.

Nonetheless, we have applied the same techniques as those described above for Wadi Zabid. The data are listed in Table 6.1, the frequency curve based on the same parameters is shown in Figure 6.2, and the predicted floods for a range of return periods are shown in Table 6.2.

6.3 REVIEW OF THE RESULTS OF THE FREQUENCY ANALYSIS

The results of the frequency analysis illustrated above are not entirely credible. It is very unlikely that floods on Wadi Tuban are over 30% higher than on Wadi Zabid. Intuitively, they should be comparable; the catchment areas are very similar and the rainfall regime is different only in the seasonality of rainfall. Both catchments appear to experience exceptional floods in the same March to May period. In 'normal' years the annual maxima can occur in any month between March and October.

The reason for the difference is clear: the mean annual flood is different. And it is different primarily because the length of record is different at the two stations. There are two exceptional events - outliers to the general trend - in each record that bias the mean substantially. If they are in a record of 17 years, the mean is different from that seen when the two outliers are in a record of 11 years. This cannot be acceptable as a basis for a real difference in the estimate of 50 or 100 year floods.

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:

$$\textbf{Mean annual flood} = 0.346 * (\text{Area})^{0.705} * (\text{Elevation})^{0.5}$$

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 Dukame 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 Dukame 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.

We have discussed earlier the impact of exceptional floods in the simulation of flood volumes. In that case some arbitrary allowance for these floods was made because there are insufficient data to define their characteristics. So it is with flood peaks. There is an argument for treating such events as deriving from a separate population, different from the one from which 'normal' floods might be considered to be drawn. This would lead to a compound flood frequency curve if its form could be identified from the data.

An alternative approach would be to look at the rainfall data for some indication of frequency. But we have shown that many of the floods form the Wadi Zabid catchment cannot be associated directly with rainfall recorded at any of the stations. The network is just too sparse and, in recent years at least, the data are not reliably recorded on a daily basis.

Pooling the data does not resolve the problem either. It would be easy to argue that floods on the two catchments are independent events, a situation where data are normally pooled to produce a regional frequency curve. In this case the procedure would yield results that split the difference between the two frequency analyses carried out.

Our recommendation in these circumstances is to regard the frequency analysis for Wadi Zabid as more reliable than that for Wadi Tuban - there are more data and we have been able to review these data to a much larger extent. Design parameters for Wadi Tuban should also be based on the figures for Wadi Zabid with some allowance (about 6%) for the small difference in catchment area. Our recommended design figures are summarised in Table 6.3.

The true flood regime of these wadis can only be resolved by more and better monitoring. Diligent operation of the recorders is essential as is the validation of the rating curve for Kolah and the re-establishment of a rating for Dukame. These and other matters relating to rainfall monitoring are discussed in the next chapter.

[the conclusions reached here will be further reviewed when data collection for the Phase 2 wadis is completed]

Table 6.1 Annual maximum floods reported for Wadi Zabid and Wadi Tuban

Annual maximum flood discharge (m^3/s)					
Wadi Zabid				Wadi Tuban	
1981	2370	1996	116	1968	200
1982	760	1997	122	1969	500
1983	460	1998	442	1970	150
1984	2620	1999	nr	1971	350
1985	nr	2000	285	1972	450
1986	nr	2001	203	1973	350
1987	nr			1974	nr
1988	392			1975	962
1989	166			1976	206
1990	128			1977	2150
1991	440			1978	nr
1992	259			1979	233
1993	119			1980	nr
1994	468			1981	nr
1995	110			1982	2640

Source: TDA, WRAY35, FAO, present analysis

Table 6.2 Predicted maximum floods from GEV analysis

Maximum flood discharge (m3/s) for different return period T		
T	Wadi Zabid	Wadi Tuban
mean	556	745
5	769	1030
10	1182	1582
20	1717	2298
50	2691	3600
100	3704	4957

Table 6.3 Recommended design floods - Phase 1 wadis

Maximum flood discharge (m3/s) for different return period T		
T	Wadi Zabid	Wadi Tuban
20	1700	1800
50	2700	2850
100	3700	3900

7 FLOOD WARNING AND HYDROMETRY

7.1 FACTORS AFFECTING THE FLOOD WARNING SYSTEM

Our detailed analysis of the flood regime of Wadi Zabid can be considered as a general description applicable to all the wadis from the point of view of the flood warning and additional monitoring that is needed. We discuss here only the hydrological issues that affect the flood warning system. Specification of the equipment and institutional issues are raised elsewhere.

It is useful to summarise the relevant findings from our analysis:

- Floods rise very fast and the peak usually occurs within one hour of the onset of the flood;
- Floods also recede rapidly;
- Many floods are compound floods; they have multiple peaks;
- A sparse rainfall monitoring network might miss major flood-producing storms completely;
- The initial peak is not a reliable indicator of the flood volume or its duration;
- Floods with high peak discharges might arise from the lower part of the catchment.

These factors complicate the design and operation of an effective flood warning system. Normally, additional warning time can be gained by positioning equipment further towards the headwaters and by monitoring rainfall rather than, or as well as, the floods themselves. However, in these wadis, floods with high peak discharges can arise from rainfall in the lower part of the catchment, and they might be missed by positioning equipment in this way.

It is not possible to devise the best possible scheme using present knowledge; some experimentation is necessary and this is implied in the proposals for this aspect of the project. Our present recommendation is to install an additional water level recorder 15-20km upstream of the existing station to double the warning time from the existing wadi gauging stations. Suitable sites are being reviewed.

In addition, we propose telemetered rainfall stations in the lower half of the catchment. In Wadi Zabid, this is an area where there are no rainfall stations at the present time. The options for extension of the system would then be to upgrade some existing stations in the upper catchment to connect with the telemetry system. Additional information could be gathered from observers warning of high rainfalls in their vicinity by telephone. In Wadi Tuban, a similar strategy is recommended. There are some stations in suitable locations in the lower part of the catchment that could be upgraded initially to connect with the telemetry system. Existing equipment at these sites could be deployed elsewhere in the catchment.

If our supposition is correct that the higher floods, including the exceptional floods that are discussed in Chapter 4, are caused by more widespread rainfall, it follows that rainfall observation should be more effective in contributing to the flood warning process than would be expected for the less extreme events. It should be noted that satellite images showing cloud formations on a regional scale are available several times per day from the web sites of meteorological organisations such as the UK Meteorological Office. Access to these images should also be considered as part of the flood warning system, especially for warning of extreme events.

Operation of the system should take account of all the issues highlighted above. The easiest first step is to issue a warning on the basis of the flood peak. This is clearly important in terms of safety during severe floods irrespective of considerations of the utility of the flood for irrigation. Warning times will be short and rapid dissemination of the warning is vital.

In terms of flood management and the diversion of water for irrigation, it is also clear that a single determination based on flood peak is not sufficient. Monitoring and evaluation of the flood must be a continuous process for the duration of the flood. While it is anticipated that there will be some pre-arranged gate settings in advance of any flood, the operators might have to change their response as the flood progresses, particularly in the case of the high volume floods. Only by continuous monitoring of the flood and the use of an algorithm to interpret the rate of recession can the operators be expected to respond effectively. This is particularly true in the case of multiple-peaked floods. There are many examples in the records of floods deriving from the lower catchment followed by a second peak from rainfall occurring later or further away from the wadi station.

7.2 FACTORS AFFECTING THE ADDITIONAL HYDROMETRY

Data are collected, but increasingly there are signs that the system is not being maintained, that the data are not verified, digitised or used routinely. While this observation applies most keenly to the rainfall data, there are also indications that flood and baseflow measurements are being neglected. This said, there are also some positive developments particularly in the southern wadis where new equipment has been installed, although the data return is not as high as it should be because of operational difficulties and operational budgets. These operational considerations are at least as important as the provision of equipment. The system must be seen as a whole if the objective is to build up a body of data for future planning.

The climate and terrain of Yemen makes hydrometry doubly difficult. Storms are short, often isolated events and a dense rainfall measuring network is needed if rainfall is to be monitored accurately at a daily or shorter time scale. Similarly, floods are short and violent. Water levels can rise and recede within a few hours making direct measurement and calibration of measuring sections very difficult. Equipment has to be robust and protected from flood damage and from the impact of large amounts of sediment moved by the floods.

Some difficulties of interpretation of flood hydrographs has followed from the historical separation of the monitoring process into flood measurement by water level recorder and measurement of baseflow by intermittent current metering. Raising the datum of the water level recorders has been necessary in order to avoid sediment accumulation in the stilling wells. New types of equipment such as the ultra-sonic devices should mean that water level measurement can be continuous over the full range of flood and baseflow levels.

7.3 THE ARGUMENT FOR A COMBINED SYSTEM

As the project was originally framed, the equipment for flood warning was seen as separate from the need for additional hydrometry, although it was probably intended that they could be complementary in operation. We are increasingly persuaded that they should be seen as part of the same environmental monitoring system.

By system we mean the whole process from field observation or electronic record, through to digitising or direct transfer of the data to a computer, and continuing through some computer program or spreadsheet or database to produce some useful outcome. The idea of flood warning requires this whole process to operate in real time if the warning is to be effective. Other objectives can tolerate a more leisurely time scale, but nonetheless they require that the process be completed through all stages.

During the data collection and analysis for this project we have had excellent cooperation from the different organisations in Yemen responsible for data collection and processing. Yet we have to point out some of the shortcomings of the data and issues that we see arising.

We have shown in Appendix A that in recent years there has been some marked deterioration in the quality of daily rainfall observations. Increasingly, raingauges are not being read every day and the characteristics of daily rainfall can no longer be established reliably from these recent data. Modelling or frequency analysis becomes difficult and the results unreliable. This is not a problem confined to Yemen. The general deterioration in the quality of rainfall observations that are carried out manually is evident in many countries.

One answer is to move increasingly to automatic stations that monitor rainfall electronically and, apart from security considerations, need be visited less frequently. NWRA are moving to this type of station, but have not yet solved the problem of regular data collection. Data can be lost (or over-written) when the memory cards are not replaced on time. These devices also provide useful information about short-term rainfall intensities.

It is one more step to make these stations into part of a telemetered network in which the station is interrogated remotely and the data transferred to a computer automatically. This would ensure that at least the first two stages of the system are accomplished. The data would be available for analysis and the final step is to ensure that the programs for quality control, verification and analysis are available and functioning. Only then can spurious and erroneous data be identified and rejected.

In these circumstances it would 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 derive immediate benefit from its role in flood warning process while supporting and revitalising the long term monitoring of the wadis and their catchments.

The obvious question is always asked: 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.

This chapter has looked at the issues of flood warning and additional hydrometry entirely within the context of the hydrological issues involved. There are other factors that must be considered.

Institutional and operational management arrangements are as crucial to the success of the systems as the deployment of the equipment and the organisation of the computing and other systems designed to process, store and disseminate the information.

Appendix A

QUALITY CHECKING AND SELECTION OF RAINFALL DATA

A1 QUALITY CONTROL

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, 94 were selected as having more than 5 complete years of data.

Records from these 94 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.

A monthly summary of data from the 94 stations was produced to help in the interpretation of the quality checks described.

These tests revealed a number of cases of repeated data, some months and in some cases 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 in recent years 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.

It must be stated that the modifications made to the data at this stage are an attempt to clean the data set for use in this project. They are not a substitute for the essential task of reviewing and evaluating the national database of rainfall in Yemen. That this task is essential is beyond doubt given the results of this preliminary review of the daily data.

During this review of the daily rainfall data, one further and highly significant feature became obvious. At some stations it is clear that rainfall is recorded less frequently and in greater amounts than in earlier years at the same station. The most likely explanation is that rainfall (or the lack of it) is not recorded every day and that falls are allowed to accumulate until the gauge is read at irregular intervals of several days or even weeks.

This finding is of some importance to the analysis of storm rainfall. It directly affects any analysis of the probability distribution of daily falls, and it means that rainfall ascribed to a particular day could have fallen in any of the days since the gauge was last read. This affects the linkage of rainfall events to observed floods. It also affects attempts to carry out rainfall runoff modelling on a daily time scale, where runoff generation is directly affected by the sequence of rainfall. A few high rainfalls at intervals of several days will give a quite different result to a true daily sequence of correctly measured values.

A test was devised to check for years when accumulations of rainfall are suspected. A reasonably effective test is to compute the ratio of days with less than 15mm (excluding all zero or missing records) to days with more than 15mm recorded. An example of the time series of this ratio is shown in Figure A1 for station 717 Wash'ha. The series of values around 0.5 are typical of the early years when diligent reading of the gauge is assumed. In the later years, the ratio becomes unacceptably high, and reference to the record itself confirms the absence of the lower rainfalls that should be expected.

This test identified 137 station-years from 31 stations affected by this process of rainfall accumulation between gauge readings, mainly years in the 1990s indicating a general deterioration in the quality of rainfall measurement in recent years. A threshold of 0.75 for the ratio was used as a criterion for rejection. All years of record with a ratio exceeding this value were removed from the active data set.

A2 A REVIEW OF THE DIFFERENCES BETWEEN MANUAL AND AUTOMATIC STATIONS

The finding that quality of daily records has been deteriorating in recent years has some bearing on the choices for future monitoring and the flood warning system.

As the historical records derive from a number of sources, usually past projects, there are records from recording as well as manual stations throughout the last three decades. Significant differences might be seen when the stations are segregated according to their type. In recent years NWRA have installed and are continuing to install recording stations based on solid-state technology.

Four sets are used in this comparison:

- a 37-station set using all years of data - all manually read stations
- a 37-station set after censoring years with suspicious accumulations
- a 17-station set of automatic modern stations (with more than 1 complete year of data)
- a 25-station set of automatic historical stations with more than 3 complete years of data.

For each set a frequency table was compiled giving the number of days when rainfall was recorded in intervals of 5mm. The results are accumulated as a frequency of exceedence and plotted in Figure A2a.

The results from the two sets of recording stations are reasonably comparable. Some differences might be expected as the records from the recording stations are short and cover different periods. The result for the 37-station set plots significantly to the right indicating a higher proportion of larger rainfalls in the data from these manual stations, even though this set includes many station-years of good quality data. The results for the censored set lie between the extremes indicating that the censoring has been partially successful.

Closer examination suggests that the main issue is the recording of rainfalls of less than 5mm. This has been noticed before [TSHWC 1992]. Re-working of the data to omit rainfalls (raindays) of less than 5mm results in Figure A2b where it can be seen that the censored set now gives results that are comparable with the recording stations. It is clear that all frequency analysis should not include rainfall from years when accumulations of rainfall are suspected.

Regarding future rainfall monitoring, higher quality data are likely to result from recording rainfall stations (tipping bucket gauges with solid-state recording devices). There is a down-side to this. It is noticeable that none of the historical recording stations have produced as much as ten years of complete data. Also the data return measured in terms of complete data as a percentage of the nominal period of operation of the station is only about 75% for the recording stations compared with about 95% for the manual stations.

A3 SELECTION OF DATA

Two main types of analysis are envisaged:

- one is concerned with the statistical characteristics of daily rainfall - the probability distribution of daily falls and the relationships between number of days of rain and the monthly and annual totals;
- the second for analysis of the regional variation in rainfall across the country on a monthly or annual time-scale.

The first requires data of a higher standard than the second. The monthly and annual totals are less affected by the accumulation of rainfall in the gauge whereas the statistical characteristics of the daily data are rendered meaningless if the records are not a true record of daily rainfall.

Different criteria were adopted to define data sets for these purposes. For the statistical analysis, a minimum of 10 years of complete data are desirable, exclusive of years rejected as having suspiciously large accumulations of rainfall. 37 stations met this criterion out of the 94 stations included in the quality checking procedure described above.

For the regional analysis, the records for years of suspicious accumulations were included and the 94-station set used for quality checking was reduced to 68 stations - partly by rejecting stations that are in areas not relevant to the catchment areas of the main wadis, and partly as a result of unacceptable data revealed by the quality checks.

Table A1 summarises these 68 stations, indicates which are included in the 37-stations set, and indicates their position and mean monthly rainfall.

Table A.1 Rainfall stations selected for daily, monthly and annual analysis

NWRA station ID		First year	Last year	Years of record		Position (km)	
				nominal	complete	E	N
58	Kudayhah	1981	1992	7	6	330.4	1493.0
60	Habashi	1982	2000	15	11	368.3	1496.5
65	Hajdah	1980	2000	13	11	370.2	1502.0
68 **	Taizyard	1974	1990	13	11	394.4	1502.3
81 **	Al-Udein	1977	1997	14	14	401.0	1542.4
82	Ibb-1	1981	1991	11	5	413.6	1544.2
87 **	Addalil	1980	2000	17	16	411.8	1560.8
89 **	Aljirbah	1969	1992	18	15	330.9	1564.9
94 **	Rihab	1969	2000	28	27	411.9	1571.9
96 **	Alqahmah	1978	2000	18	15	331.0	1577.8
99	Madaf	1982	1991	10	5	480.7	1580.9
101 **	Almahatt	1978	2000	18	16	316.6	1581.6
104 **	Basat	1978	2000	19	18	323.8	1585.2
109	Ashshaqb	1975	1985	10	6	444.0	1588.0
110	Mishrafa	1978	2000	15	10	345.4	1588.8
111 **	Addimnah	1978	2000	19	17	331.1	1588.9
113	Alkhadra	1981	1992	12	6	471.0	1590.3
115 **	Khabar	1976	1993	18	12	481.4	1590.4
118 **	Rada'	1976	1992	17	12	482.4	1594.0
120 **	Sanaban	1976	1988	13	13	463.6	1594.5
124	Habaka	1981	2000	14	11	361.7	1597.9
125 **	Samah	1975	1988	13	11	444.2	1601.1
127	Azzuwab	1980	1994	14	7	480.6	1603.1
134 **	Dhamar-1	1975	1988	14	10	435.5	1607.7
136 **	As-Sanam	1978	2000	19	16	421.0	1608.7
139 **	Maram	1975	1989	15	14	457.8	1612.8
141	Addarb	1976	1984	8	7	430.1	1613.5
146 **	Masna'ah	1975	2000	22	15	415.6	1619.8
148 **	Ashshirq	1981	2000	15	12	388.7	1618.0
149	Dafrd	1978	1990	13	9	428.0	1626.3
151 **	Al-Hamal	1979	2000	18	14	387.0	1631.0
158	Rizwa	1975	1987	13	8	409.8	1634.7
159 **	Aldabira	1981	2000	15	14	369.1	1634.7
161	Gumischa	1972	1977	6	5	293.4	1637.7
165	Maghreba	1981	1992	7	7	335.0	1644.2
169 **	Dhaf	1975	1988	13	11	422.3	1646.8
173	Alfowara	1981	1991	7	7	408.6	1658.5
174 **	Al-Amir	1979	2000	18	17	360.2	1662.4
183 **	Al-Haima	1979	1999	18	16	381.8	1667.9
185	Asal-A	1986	2001	10	6	455.5	1669.6
192	Qadam-A	1984	2000	15	5	352.0	1671.9
217	Khamis-A	1978	1992	11	7	340.2	1679.3
222	Khamlu-A	1984	2000	14	8	330.3	1692.3
238	Addahi-A	1984	1992	9	7	290.8	1682.3
243	Assalf-A	1978	2000	19	7	385.8	1683.4
255	Yusuf-A	1984	1997	12	7	373.4	1685.4
280	Mind	1972	1979	7	5	399.7	1690.3
288	Zuhaif-A	1984	1992	9	8	329.4	1692.3
298	Ghamr-A	1984	2000	16	7	344.6	1695.4
371	Mayan-A	1984	2000	17	5	381.5	1709.1
384	Sana'a	1974	1979	6	5	416.7	1711.2
389	Mahwit	1974	2000	18	11	344.4	1710.5
436	Darwan	1972	1979	7	6	401.0	1719.8
469 **	At-Tur	1974	2000	22	18	326.7	1723.6
485 **	Hajjah	1974	2000	20	13	350.0	1734.4
505 **	Khamir	1972	2000	20	13	389.4	1769.2
679 **	Milh	1974	2000	20	17	266.0	1733.3
717 **	Wash'ha	1975	2000	18	13	327.2	1797.3
721	Zuhrah	1972	1992	15	7	287.4	1736.8
722 **	Shibam-T	1975	2000	19	16	383.8	1715.8
724 **	Shamiri	1979	2000	16	12	322.6	1657.2
725 **	Wallan	1980	1999	16	15	421.2	1671.4
726 **	Waqir	1979	2000	17	15	315.3	1646.2
727 **	Zinqah	1979	2000	17	14	331.6	1662.6
728	Sukhnah	1979	2000	17	13	331.4	1638.7
729 **	Wadi-Har	1975	2000	20	17	417.4	1605.0
730 **	Yarim	1969	2000	25	24	433.5	1581.0
731 **	Zabid	1969	2000	27	22	321.9	1568.6
720 **	Saqayn	1975	1992	12		343.8	1865.4

Notes: ** indicates the station is included in the 37-stations set
station 720 is included in the 37-station set but not in the 68-station set

Table A.2 Mean monthly and annual rainfall for the selected stations

(mm)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year	Sum
58	13	10	9	28	33	5	4	11	28	16	14	4	181	175
60	7	9	20	75	111	83	58	76	118	45	26	6	646	634
65	2	9	23	46	43	40	33	33	50	20	4	1	295	304
68	7	15	38	79	99	71	62	84	106	83	10	5	676	659
81	6	19	51	113	124	104	133	109	90	67	25	9	850	850
82	9	11	46	79	116	125	163	157	104	21	17	2	854	850
87	6	7	55	92	97	76	105	126	63	32	21	6	691	686
89	4	11	12	21	46	6	38	66	110	52	5	1	377	372
94	5	9	34	75	98	46	91	118	55	32	14	3	582	580
96	8	7	19	11	50	14	40	60	80	33	9	2	324	333
99	4	9	23	34	21	4	8	29	3	0	2	2	129	139
101	10	5	14	8	28	11	20	44	44	24	11	4	229	223
104	7	7	14	8	44	23	32	56	90	50	14	4	352	349
109	1	3	24	23	24	11	30	46	16	14	1	3	169	196
110	21	14	37	33	70	18	53	50	46	31	17	9	447	399
111	8	1	14	22	65	22	46	58	77	64	20	12	422	409
113	4	14	46	42	22	2	22	38	9	2	4	2	211	207
115	13	11	39	42	22	3	23	46	6	6	3	2	234	216
118	13	14	53	32	24	4	22	35	7	6	4	2	218	216
120	3	12	40	32	23	3	22	33	7	14	3	0	192	192
124	5	7	20	36	41	28	67	90	16	14	3	0	342	327
125	3	6	34	48	32	1	40	68	18	11	3	2	246	266
127	5	15	26	35	26	10	12	21	3	3	3	1	206	160
134	2	16	45	66	53	5	61	117	14	11	7	3	403	400
136	10	21	62	77	32	25	46	74	27	14	6	8	405	402
139	4	11	43	44	30	3	28	60	4	7	6	2	228	242
141	6	9	80	44	46	23	58	76	18	6	25	10	390	401
146	8	12	52	63	44	24	53	78	35	22	18	16	430	425
148	13	38	31	94	89	52	56	125	47	42	17	14	582	618
149	7	14	50	52	29	6	43	65	6	4	3	7	299	286
151	5	5	45	80	83	45	62	117	39	31	7	5	529	524
158	2	5	64	87	50	10	24	44	10	8	14	5	265	323
159	11	6	23	42	34	19	21	39	16	19	2	6	239	238
161	2	3	11	13	1	0	3	11	12	16	6	0	76	78
165	20	50	112	107	78	16	53	100	48	25	54	15	676	678
169	2	7	59	84	40	2	29	63	7	7	5	5	296	310
173	24	19	83	52	37	25	21	33	7	2	5	3	312	311
174	9	8	49	94	94	22	76	84	27	25	25	8	509	521
183	4	8	38	65	49	25	53	74	18	15	4	3	356	356
185	2	6	28	60	2	1	22	19	10	12	0	3	158	165
192	1	4	6	42	60	15	52	57	20	13	7	3	288	280
217	1	7	5	48	54	29	57	83	48	6	2	6	352	346
222	1	5	7	30	48	24	36	87	42	19	6	5	326	310
238	0	5	2	12	12	1	7	39	32	16	1	4	130	131
243	4	10	48	109	38	14	105	120	15	14	14	18	442	509
255	2	4	16	77	71	61	99	114	36	13	10	5	495	508
280	4	1	20	41	57	6	56	66	41	9	2	2	291	305
288	10	13	18	70	81	35	54	106	47	18	14	13	481	479
298	2	5	26	74	60	33	33	74	31	25	17	6	378	386
371	3	9	25	58	29	13	35	51	3	4	3	10	254	243
384	6	3	24	43	38	3	47	44	8	19	7	1	239	243
389	12	19	33	106	96	42	80	140	68	49	23	8	631	676
436	4	1	10	31	41	4	44	60	4	10	2	2	227	213
469	3	4	17	48	86	55	64	107	78	52	17	2	467	533
485	0	10	46	90	68	31	62	88	30	12	8	12	501	457
505	1	1	37	60	31	24	36	42	2	7	1	2	209	244
679	8	3	2	4	9	1	4	13	2	8	11	6	72	71
717	14	9	31	74	77	24	46	62	24	39	16	17	422	433
721	6	4	3	13	27	2	20	27	27	43	5	17	176	194
722	5	8	41	77	54	28	78	129	11	14	8	1	461	454
724	5	3	8	29	74	29	43	86	124	53	26	7	492	487
725	2	8	46	58	34	11	17	54	7	17	9	5	273	268
726	3	9	7	21	37	28	39	71	74	65	16	2	389	372
727	1	2	21	32	50	46	72	106	74	22	14	1	455	441
728	9	8	17	43	80	46	58	101	90	54	30	6	571	542
729	5	16	46	66	68	34	90	80	35	19	19	1	475	479
730	8	21	57	82	87	47	95	159	43	16	10	5	630	630
731	11	4	7	9	19	3	20	34	49	35	6	0	193	197

Note: The column marked 'Sum' shows the sum of the monthly averages for each station. When there is much missing data, this is usually a better estimator of the mean annual rainfall than the mean of the totals for complete years.

Figure A1 Deterioration in quality of daily rainfall records

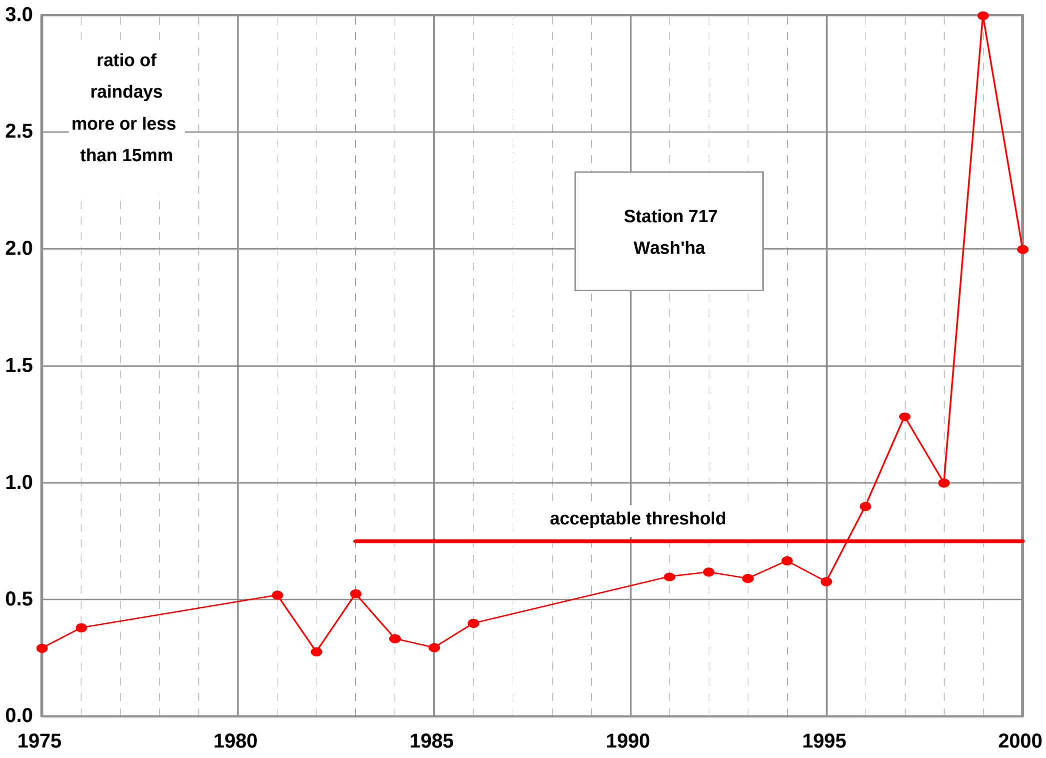


Figure A2a Effect of data source on rainfall frequency analysis

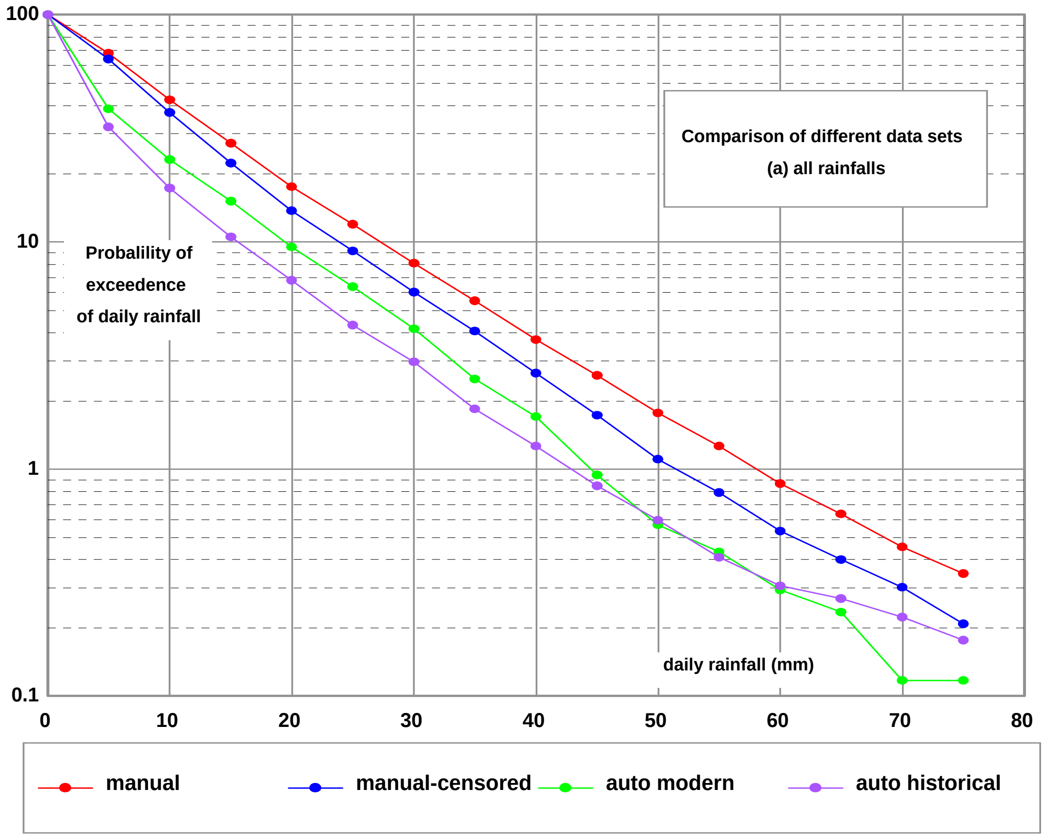
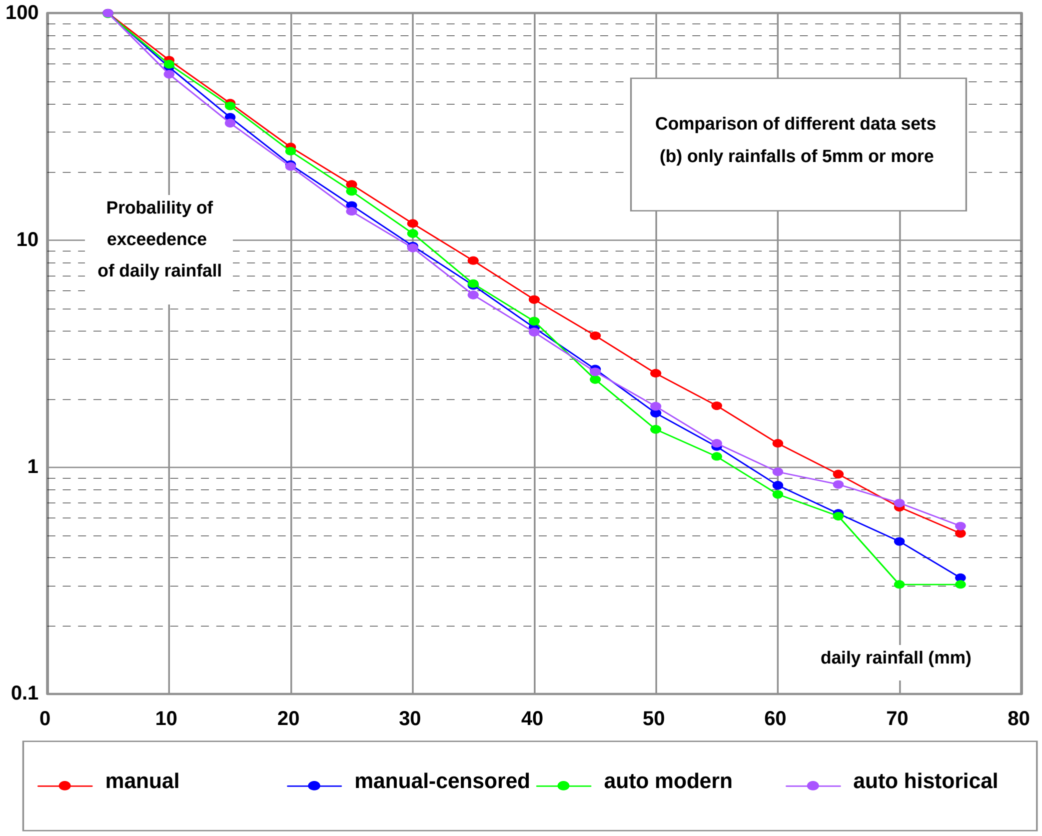


Figure A2b Effect of data source on rainfall frequency analysis



Appendix B

FLOODSIM
THE FLOOD AND BASEFLOW SIMULATION MODEL

B1 BACKGROUND

The program is intended to produce extended time sequences of floods (defined by volume and duration) and of baseflows from information about the water resources of the wadi basin. These data are required as input to the Spate Management Model (SMM).

The program comprises three parts: A Visual Basic applications program that provides a user-interface, a Fortran program that carries out the number-crunching, and an Access database that stores parameter values and output data from previous and current runs of the model. Only the VB screens are available at run time. The Fortran program is available as a dynamic linked library file (dll) and the Access database can be interrogated independently in the normal way.

This appendix covers model operation using the VB screens and the setting of options and parameter values.

B2 INSTALLING THE PROGRAM

The installation program is on the CD “FloodSim”.

Run ***Setup.exe*** and when asked for the install location enter **D:\FloodSim**

After installation, set up the following directory structure:

```
D:
|......... FloodSim
           |.......... Fortran
           |.......... Working
                      |.......... Data
```

Move the following files into Fortran: **FloodSim.dll**
Move the following files into Data: **DatavbM1.dat**, **DatavbM1template.dat** and **Log.dat**
Move the following files into Working: Floods.mdb, and all the remaining .dat.files

At present the program expects the Access database **‘Floods.mdb’** to be in the directory ‘Working’. This can be replaced by a direct link to the MIS database when the system is fully operational. The internal program links are specified in code and cannot be changed externally.

After installation, the program is started by running **FloodSim.exe**.

The VB screens will fill the display if the monitor display settings are for 1024*768 pixels.

B3 RUNNING THE PROGRAM

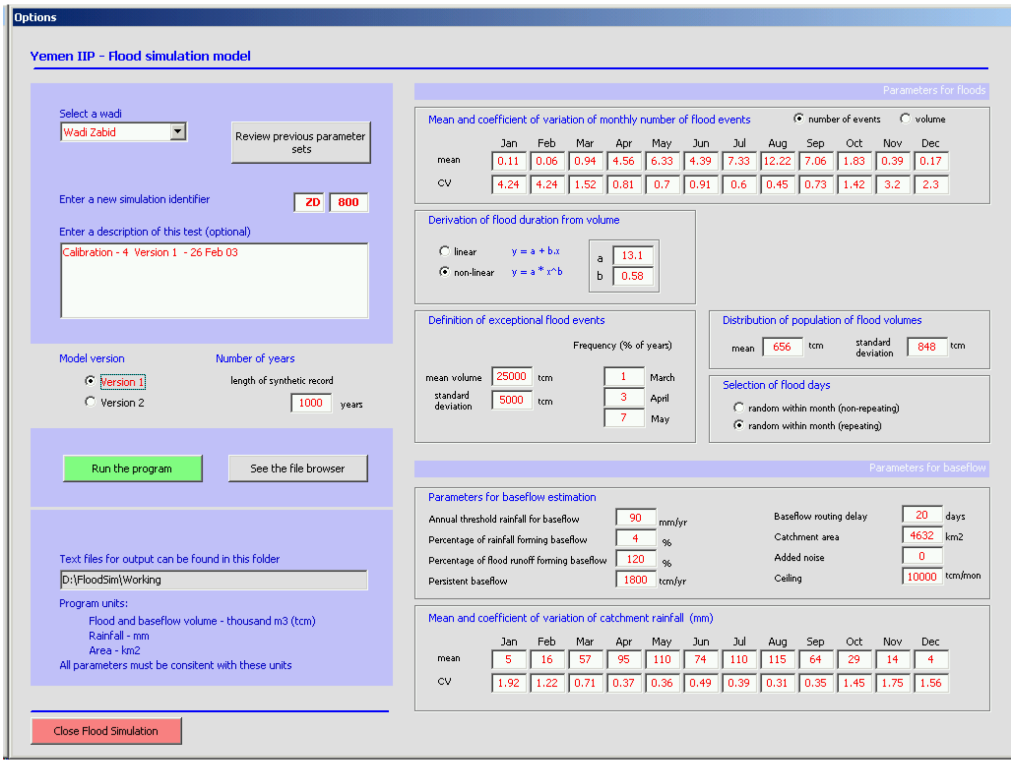
Double-click on **FloodSim.exe** in the directory D:\FloodSim.

Click on **'Start'** on the opening screen to open the *Options* screen.

Using the screens

The *Options* screen for model Version 1 is shown below.

All program controls are clustered in the blue boxes on the left; all parameter values are set in the grey frames to the right. The values shown on loading the program will be for the last simulation. All parameter values are set on this screen.



Yemen IIP - Flood simulation model

Select a wadi: Wadi Zabid

Enter a new simulation identifier: ZD 800

Enter a description of this test (optional): Calibration - 4 Version 1 - 26 Feb 03

Model version: ● Version 1 ○ Version 2

Number of years: length of synthetic record 1000 years

Text files for output can be found in this folder: D:\FloodSim\Working

Program units:
Flood and baseflow volume - thousand m3 (tcm)
Rainfall - mm
Area - km2
All parameters must be consitent with these units

Mean and coefficient of variation of monthly number of flood events ● number of events ○ volume

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
mean	0.11	0.06	0.94	4.56	6.33	4.39	7.33	12.22	7.06	1.83	0.39	0.17
CV	4.24	4.24	1.52	0.81	0.7	0.91	0.6	0.45	0.73	1.42	3.2	2.3

Derivation of flood duration from volume
○ linear y = a + b.x
● non-linear y = a * x^b
a 13.1
b 0.58

Definition of exceptional flood events
mean volume 25000 tcm
standard deviation 5000 tcm
Frequency (% of years): 1 March, 3 April, 7 May

Distribution of population of flood volumes
mean 656 tcm
standard deviation 848 tcm

Selection of flood days
○ random within month (non-repeating)
● random within month (repeating)

Parameters for baseflow estimation
Annual threshold rainfall for baseflow 90 mm/yr
Percentage of rainfall forming baseflow 4 %
Percentage of flood runoff forming baseflow 120 %
Persistent baseflow 1800 tcm/yr
Baseflow routing delay 20 days
Catchment area 4632 km2
Added noise 0
Ceiling 10000 tcm/mon

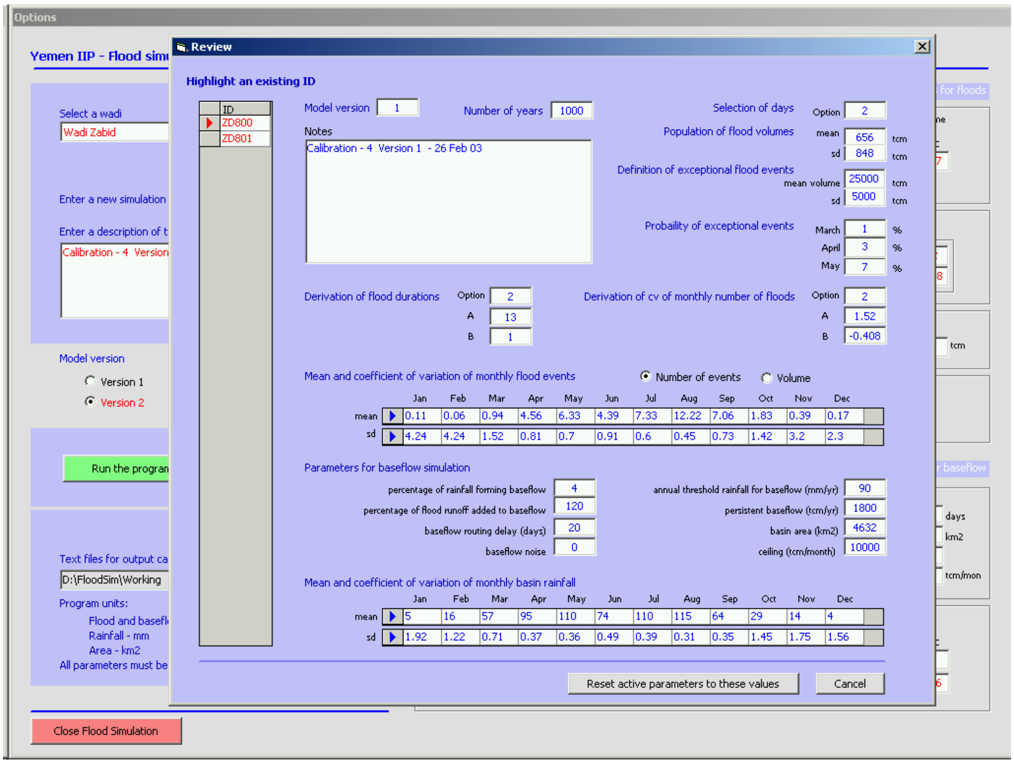
Mean and coefficient of variation of catchment rainfall (mm)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
mean	5	16	57	95	110	74	110	115	64	29	14	4
CV	1.92	1.22	0.71	0.37	0.36	0.49	0.39	0.31	0.35	1.45	1.75	1.56

Click the 'Review previous parameter sets' control button to open the *Review* screen which will appear on top of the *Options* screen.

The *Review* screen shows the parameter values used for the simulations listed (in red) in the box on the left. Clicking on one of the previously used simulation identifiers on the left displays the parameter set on the *Review* screen. These are shown for information; they cannot be edited.

However, the current parameter set on the *Options* screen can be replaced by the set currently displayed on the *Review* screen by clicking 'Reset active values to these values'. This is a useful procedure if the it is intended to carry out a new simulation following minor changes to a previously-used parameter set. Alternatively, click Cancel to return to close the *Review* screen.



ID
ZD800
ZD801

Model version: 1
Number of years: 1000
Notes: Calibration - 4 Version 1 - 26 Feb 03

Selection of days: Option 2
Population of flood volumes: mean 656 tcm; sd 848 tcm
Definition of exceptional flood events: mean volume 25000 tcm; sd 5000 tcm
Probaility of exceptional events: March 1 %; April 3 %; May 7 %

Derivation of flood durations: Option 2; A 13; B 1
Derivation of cv of monthly number of floods: Option 2; A 1.52; B -0.408

Mean and coefficient of variation of monthly flood events ● Number of events ○ Volume

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
mean	0.11	0.06	0.94	4.56	6.33	4.39	7.33	12.22	7.06	1.83	0.39	0.17
sd	4.24	4.24	1.52	0.81	0.7	0.91	0.6	0.45	0.73	1.42	3.2	2.3

Parameters for baseflow simulation

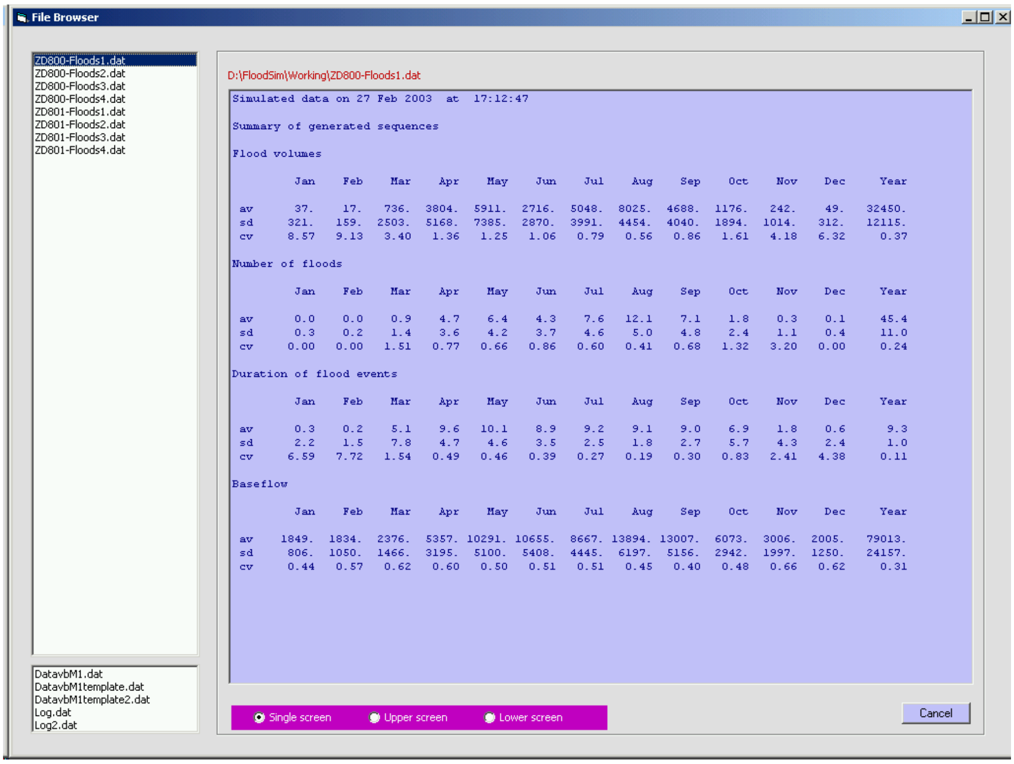
percentage of rainfall forming baseflow: 4
percentage of flood runoff added to baseflow: 120
baseflow routing delay (days): 20
baseflow noise: 0
annual threshold rainfall for baseflow (mm/yr): 90
persistent baseflow (tcm/yr): 1800
basin area (km2): 4632
ceiling (tcm/month): 10000

Mean and coefficient of variation of monthly basin rainfall

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
mean	5	16	57	95	110	74	110	115	64	29	14	4
sd	1.92	1.22	0.71	0.37	0.36	0.49	0.39	0.31	0.35	1.45	1.75	1.56

Current or previous results can be reviewed using the *File Browser* screen. Click the button ‘See browser’ to give access to this screen.

Click on any file name shown in the lists on the left to view the contents. These files are the text file versions of the output held in the ‘Working’ sub-directory. Click ‘Cancel’ to return to the *Options* screen.



ZD800-Floods1.dat
ZD800-Floods2.dat
ZD800-Floods3.dat
ZD800-Floods4.dat
ZD801-Floods1.dat
ZD801-Floods2.dat
ZD801-Floods3.dat
ZD801-Floods4.dat

DatavbM1.dat
DatavbM1template.dat
DatavbM1template2.dat
Log.dat
Log2.dat

D:\FloodSim\Working\ZD800-Floods1.dat

```
Simulated data on 27 Feb 2003  at  17:12:47

Summary of generated sequences

Flood volumes

         Jan    Feb    Mar    Apr    May    Jun    Jul    Aug    Sep    Oct    Nov    Dec      Year

 av      37.    17.   736.  3804.  5911.  2716.  5048.  8025.  4688.  1176.   242.    49.    32450.
 sd     321.   159.  2503.  5168.  7385.  2870.  3991.  4454.  4040.  1894.  1014.   312.    12115.
 cv     8.57   9.13   3.40   1.36   1.25   1.06   0.79   0.56   0.86   1.61   4.18   6.32      0.37

Number of floods

         Jan    Feb    Mar    Apr    May    Jun    Jul    Aug    Sep    Oct    Nov    Dec      Year

 av      0.0    0.0    0.9    4.7    6.4    4.3    7.6   12.1    7.1    1.8    0.3    0.1      45.4
 sd      0.3    0.2    1.4    3.6    4.2    3.7    4.6    5.0    4.8    2.4    1.1    0.4      11.0
 cv     0.00   0.00   1.51   0.77   0.66   0.86   0.60   0.41   0.68   1.32   3.20   0.00      0.24

Duration of flood events

         Jan    Feb    Mar    Apr    May    Jun    Jul    Aug    Sep    Oct    Nov    Dec      Year

 av      0.3    0.2    5.1    9.6   10.1    8.9    9.2    9.1    9.0    6.9    1.8    0.6       9.3
 sd      2.2    1.5    7.8    4.7    4.6    3.5    2.5    1.8    2.7    5.7    4.3    2.4       1.0
 cv     6.59   7.72   1.54   0.49   0.46   0.39   0.27   0.19   0.30   0.83   2.41   4.38      0.11

Baseflow

         Jan    Feb    Mar    Apr    May    Jun    Jul    Aug    Sep    Oct    Nov    Dec      Year

 av    1849.  1834.  2376.  5357. 10291. 10655.  8667. 13894. 13007.  6073.  3006.  2005.    79013.
 sd     806.  1050.  1466.  3195.  5100.  5408.  4445.  6197.  5156.  2942.  1997.  1250.    24157.
 cv     0.44   0.57   0.62   0.60   0.50   0.51   0.51   0.45   0.40   0.48   0.66   0.62      0.31
```

Starting a fresh simulation

Choose a wadi name from the drop-down box and enter the remaining part of the ID manually.

Enter a brief description (optional) in the Notes box as a reminder of the purpose and conditions of the simulation.

Enter the length of simulation required and the Version of the model required. Setting the version reveals a different combination of frames (containers that separate the parameters into groups).

Ensure that all revealed frames and text boxes are completed - see below on Setting the parameters

Click the green 'Run the program' control button to initiate the simulation. The button will change colour to red.. When it returns to green, the simulation will have completed and the results will have been transferred to the database Floods.mdb.

The text version of the results files can be reviewed using the *File browser* screen as described below.

Note that parameter sets from a previous simulation can be used as a basis for the current set. In this case a new simulation ID will be required.

Program units

The program uses a consistent set of units throughout, and these units are assumed in the scaling of any of the relationships:

rainfall in millimetres (mm)
flood and baseflow volume in thousand m^3 (tcm)
basin area in square kilometres (km^2)

This list is shown for reference on the *Options* screen.

All parameter values must be consistent with these units.

Setting the parameters

Model version

Version 1 is used when the coefficient of variation of the number of floods (or flood volumes) for each month is known or can be estimated from the data.

Version 2 is used when these coefficients are derived from a relationship with the mean values for the months (see below).

Flood parameters

Mean and coefficient of variation of monthly number of floods

The mean and coefficient of variation of the number of floods each month are derived from the data (if available) or estimated from regional ideas perhaps based on values for neighbouring wadis. Optionally, the data can be entered in terms of flood volume since a direct relationship is assumed between monthly flood volume and the number of floods.

If Version 2 of the model is used the coefficient of variation is estimated from the mean by a linear or logarithmic relationship. Enter the parameters to describe this relationship in the box labelled ‘Derivation of cv of monthly number of floods’.

If the linear option is chosen, the relationship is taken to be of the form:

$$\mathbf{CV = A + B * Mean}$$

If the logarithmic option is chosen, the relationship is taken to be of the form:

$$\mathbf{CV = A * Mean^{B}}$$

Flood duration

It is assumed that there is a relationship between flood duration and flood volume. This is defined in the same way as that for the CV of the monthly number of floods described above.

Exceptional floods

The provision for defining exceptional floods allows the mean and standard deviation of exceptional flood volumes to be set, and the probability of occurrence of exceptional floods in the months March, April and May. These probabilities, expressed as percentages, define the average annual probability of occurrence. Thus 5% entered for May would indicate an exceptional flood in that month once every 20 years on average.

Distribution of the population of flood volumes

This distribution is assumed to be log-normal in the simulation model, but it is described using the arithmetic mean and standard deviation of flood volumes.

When there are data of individual flood volumes as in the case of Wadi Zabid and some other Tihama wadis, the values can be estimated directly. In other cases, regional values can be used.

Selection of flood days

This parameter controls the way in which the flood events are distributed in days for the current month of the simulation. At present the events are distributed at random, the only choice being whether or not two or more events can occur by chance on the same day.

Two options are available and the choice depends on the form of the flood data implied by the statistics of the distribution.

If the data refer to individual floods some of which might occur on the same day, then the ‘repeating’ option should be chosen. The simulation model will, by chance, assign some floods to the same day. Otherwise, if the data are for daily total flood volumes, the ‘non-repeating’ option should be chosen and all flood volumes will always be assigned to separate days.

Baseflow parameters

Baseflow is derived from three sources:

- a percentage of the basin rainfall specified

  Three parameters are used; one is the percentage of the rainfall specified, the second is a monthly threshold above which the percentage is applied, and the third is the basin area. These parameters are interdependent to some extent. For example; reducing the percentage has a similar effect to that of reducing the effective basin area;

- an amount proportional to the annual (generated) flood volume

  This amount is scaled by the parameter controlling the percentage of flood runoff added to the baseflow. The flood flow is used only to scale this component of the baseflow; the model does not reduce the flood volumes by this amount.

- a persistent element

  The average of this component is specified in tcm/year. It is varied randomly from year to year.

The ‘Baseflow routing delay’ measured in days, delays the baseflow and allows the timing of the seasonal peaks and troughs to be controlled. It has a maximum value of 60 days.

‘Ceiling’ modifies the contribution of flood flows to the baseflow by defining an upper limit to monthly flood volume that ‘contributes’ to the overall volume of baseflow.

The ‘Noise’ is intended to control the variability of baseflow from year to year. At present this parameter is not active.

B4 INPUT AND OUTPUT

All input is specified on-screen there are no other input files.

Output is stored on in the ‘Floods.mdb’ database file in the form of the following tables.

‘Parameters’ keeps a record of all parameter values used in each run of the model. The parameter set and all output is linked through an simulation identifier unique to each simulation. The identifier <id> is a 5-character code; the first two characters identify the wadi, the last three are any alpha-numeric characters.

This identifier is used to index parameter sets in the ‘Parameters’ table in the database, and as a table name for output. There are two output tables: ‘<id>FL’ for floods output and ‘<id>BF for baseflow.

In addition a series of text files are used:

- the parameter values for the previous model run are stored in a text file ‘DatavbM1.dat’ in the Data sub-directory. These parameter values are used to populate the *Options* screen when the VB program is started.
- progress of a model run is recorded in a text file ‘Log.dat’ for reference should anything cause the program to crash.
- the output is stored in a series of text files in the Working sub-directory. All these files are identified by the simulation identifier.

  <id>Floods1 contains a summary of the simulation;
  <id>Floods2 lists the simulated flood events (date, flood volume, duration);
  <id>Floods3 contains summary of daily flood volumes in calendar format;
  <id>Floods4 gives the monthly simulated baseflow for each year.

  These text files are used to provide a rapid review of the output from within VB, but they can be deleted without losing the basic output, which is stored in the ‘Floods.mdb’ database.

All output refers to calendar years starting in January. This is reasonably consistent with ideas of hydrological years starting at the time of minimum expected rainfall and wadi flow.

B5 THE EFFECTS OF RANDOM PROCESSES IN THE SIMULATION

This program will produce a different output - a different sequence of different flood volumes and a different baseflow sequence - every time it is run, even with identical parameter settings. Each simulation is a sample of the floods and baseflow sequences that conform to the underlying statistical description of the regime that is specified by the parameters.

Increasing the length of the simulation period, makes it more likely that the sample statistics (the mean annual flood volume for example) will converge on the expected or ‘population’ values implied by the parameter set. Thus it is possible to simulate repeatedly a flood sequence of 20 years duration for a given parameter set. If the mean annual flood volume is computed for each simulation, the values will be found to conform to some statistical distribution with a mean value close to the expected mean, and a standard deviation that is a measure of the uncertainty associated with estimating the mean annual flood volume for a 20-year period.

Of course the value of such sampling statistics depend on how well the original distributions and relationships underlying the simulation describe the reality. But, in principle, they could offer an approach to the estimation of ‘design’ values for the resources available to the project.

B6 PROGRAM CRASH

This is a program under continual development and it is written for a specific purpose for limited use within the Yemen IIP. It is therefore uneconomic to spend a large amount of time testing the program under all possible conditions and providing comprehensive error trapping and help systems. Consequently, the program is likely to crash from time to time, usually when faced with parameter values that cause mathematical errors to arise (logs of negative numbers for example), or when some parameters are not set (interpreted as zero).

With experience, some of the more likely ‘errors’ can be identified and error traps set. Otherwise, it is a matter of trial and error to avoid parameter values that cause the program to fail.

When the program crashes, the VB application will usually close or a dialogue box will appear asking whether the program should be closed or whether it should be debugged. In the latter case, the close options should be used, the VB program restarted, and the parameter values re-examined for possible errors or unrealistic values.

Because the parameter values are written to a text file before the Fortran dll is called, the program will show the last set of parameter values when FloodSim.exe is re-started, although these values will not yet have been saved to Floods.mdb. Files are not written out to the Floods.mdb database until the number-crunching has been completed satisfactorily and the Fortran program has executed normally.

Check the values carefully, ensuring that values have been set in all visible frames on the screen before clicking ‘Run the program’ again.

Appendix C

DEFINING HYDROGRAPHS

C1 GENERAL CONSIDERATIONS

We discussed the limited information on the shape of flood and baseflow hydrographs in Chapter 3, where we illustrated some of the variations that occur for a few of the hydrographs of major floods selected from the chart record. In the case of Wadi Zabid, these constraints are largely due to the sheer amount of work needed to digitise the chart records. This work is beyond the scope of this project. There are similar records for other Tihama wadis, and we can use only the information that has been processed from these detailed records. On other wadis there are different constraints. For Wadi Tuban, there are no hydrographs associated with the historical records of the 1970s. Records are becoming available from the new water level recorders, although these records are uncalibrated at the present time and they are yet too few to give a complete picture of the range of flood hydrographs that can occur.

It is therefore inevitable that any attempt to describe the hydrographs - and specifically to interpret our sequence of flood and baseflow volumes - on a short time-step is bound to be an uncertain procedure.

We have used a procedure that is capable of producing the complex hydrographs illustrated in Chapter 2 based on the ideas presented there whereby a flood can be interpreted as being made up of a number of separate and identifiable components that can each be represented by a volume of water passing through a linear reservoir. The sum of the volumes of the components is equal to the total volume of the flood, which is known. We also know something about the range and statistics of the flood peaks and the flood durations from the observed data.

We need to identify the following characteristics of the components that make up a single compound flood:

- the number of components in each flood;
- the distribution of the total volume between the components;
- the timing of the components relative to each other;
- the time constants associated with each component.

If we can devise a set of rules that determine these factors, and some rules that ensure that the model introduces variability into the process of hydrograph generation, it will be possible to transform the sequence of flood volumes into flood hydrographs and to add in the contemporary sequence of baseflows to produce a continuous hydrograph for use with the SMM.

There are other considerations, such as the rise time of hydrographs and the way in which duration might be computed that are dealt with in the detailed sections that follow.

C2 DEFINITION OF THE HYDROGRAPH MODEL

Component hydrographs

Although there is no limit to the generality of the proposed model, we have imposed certain constraints in view of the limited knowledge available. These are:

- there are no more than two components in each flood event;

- the component volume is distributed over the first four, 15-minute time steps of the component hydrograph;

  This ensures that rise time of each component is one hour, which is the rise time seen in the floods examined in detail (Figures 3.16 to 3.19). It is likely that the rise time varies, and that it could be significantly less than one hour in some cases. However, the charts cannot be interpreted with sufficient precision to identify these variations.

- other characteristics of the hydrographs (time constants, timing) are randomly chosen from within a defined range.

Selection of parameters

The selection of parameter values for the characteristics of the components is based on the data available for Wadi Zabid. Values have been chosen intuitively to conform to our understanding of flood formation that is described in the main report, and to reproduce reasonably well the range and distribution of flood peaks and flood durations.

Number of components

We have used a volume threshold whereby floods having a total volume below the threshold are single-component floods; those with a total volume above the threshold have two components. The threshold value is 250mcm.

Distribution of volume

The flood volume is distributed randomly between components with the limitation that each component shall have a minimum of 30% of the flood volume. Randomisation is based on a uniform probability distribution.

Timing of components

Without further detailed analysis, we have no detailed knowledge of the timing of floods. However, this is important only in the sense of the time difference between the different flood components. The clock time of the start of the flood should not be important to the SMM in planning mode; and in operational mode, the system must respond to events as they happen. Thus we have taken the clock time of the first component as zero and the specified a range of values for the relative timing of the second component within which the actual time for each flood is selected at random. This range is 0 to 9 time steps, or 1 to 2 hours.

Time constants

In general it is expected that the first flood component will arise from rainfall in the lower part of the catchment and that subsequent components will arise from areas further from the mountain front. This should result in shorter time constants associated with the first component than with the second. Accordingly, we have used time constants of 1 to 3 hours and 4 to 10 hours for the first and second components respectively. For each flood, values have been chosen randomly for each component from within the ranges specified.

C3 RESULTS FOR WADI ZABID

The parameter values identified above have been found by trial and error in order to reproduce the known frequency distributions of flood peaks and flood durations. Durations have been estimated by assuming that the flood is ended when the discharge falls below 4m^3/s, a criterion that accords with the procedures used by TDA to define flood duration from the chart data.

Figures C.1 to C.3 show the results of this fitting exercise. The close result in Figure C.1 is entirely expected. It confirms that the flood volumes are correctly handled by the hydrograph routing process. Figures C2 and C3 indicate that the objective of describing the frequency distributions of flood peaks and durations are met reasonably well. Note that these graphs use arbitrary ranges on the x-axis, and the precise shape of the graph is not meaningful.

During the trial and error process of model fitting it was found that the result is more sensitive to the parameter ranges for the first flood component, and less sensitive to those of the second component. In fact, it was found that a third component could not be reasonably defined on present information. Direct information on the time intervals between components and on the range of time constants is needed before the model can be developed further, or be shown to produce results that are entirely realistic.

C4 ADDING BASEFLOW

The mean maximum monthly baseflow (taking the average of the highest monthly baseflow in each year) is around 6.5m^3/s or 17mcm/month. This is small compared with the range flood peaks as illustrated in Figure C2.

C5 CONCLUSIONS

Despite the lack of sufficient data in a numerical format to define the model parameters fully, the model itself appears to be capable of describing compound hydrographs reasonably well. It has much inherent flexibility in terms of the number of hydrograph components, their time constants and the timing of the components. We recommend that model development and fitting be continued when more data become available from the new instrumentation so that planning scenarios based on the model output can be revised and kept up to date.

While there are many characteristics of the hydrographs that should ideally form part of the model fitting and testing process, we believe that the tests carried out - fitting the histograms of flood peaks and durations - are sufficient to incorporate the model

The parameters selected are based primarily on the data available for Wadi Zabid, and until further information becomes available for Wadi Tuban, we recommend using the same parameters there.

[It is hoped that information on hydrographs shapes might be available for some of the Phase 2 wadis that will help us to assess the regional validity of the model and the parameter values used so far]

Figure C1 Distribution of observed and simulated hydrograph volumes

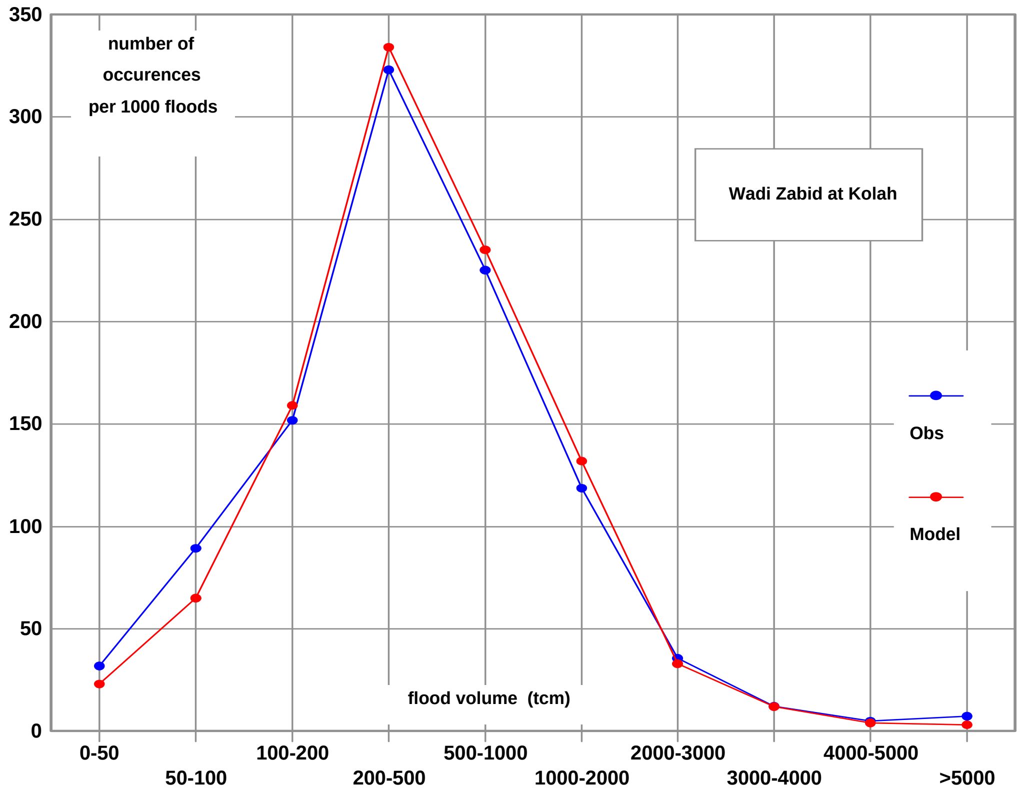


Figure C2 Distribution of observed and simulated hydrograph peaks

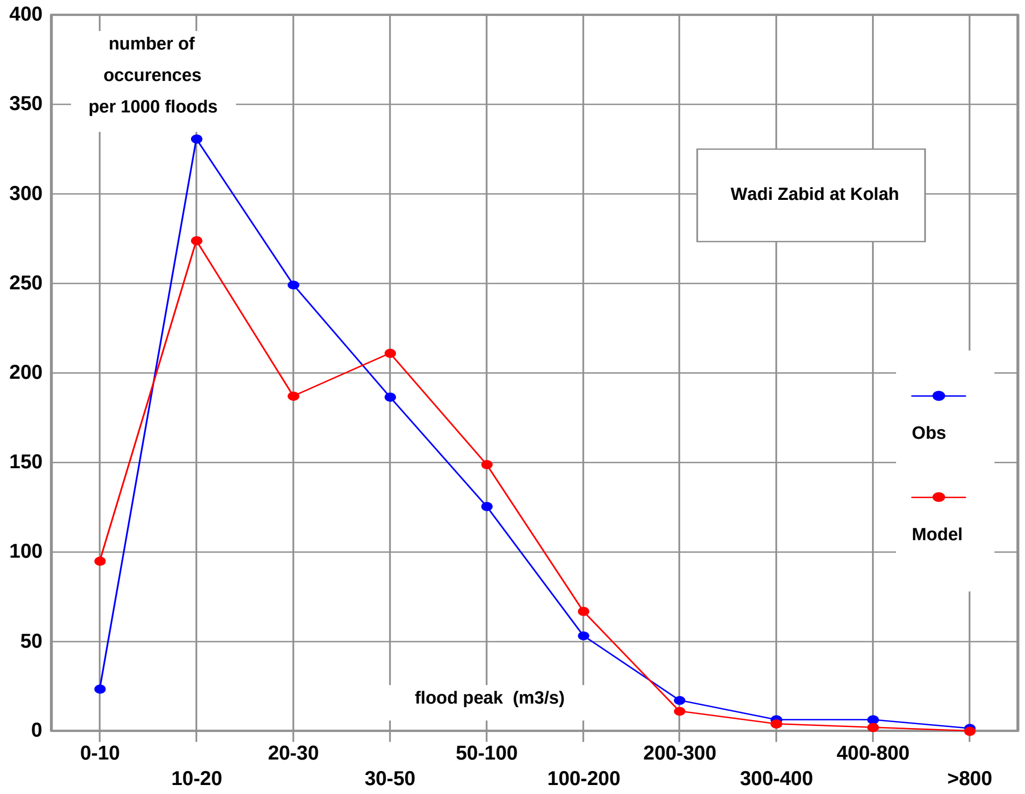


Figure C3 Distribution of observed and simulated hydrograph durations