

[Title page - to be made up to standard format]

# **Yemen Irrigation Improvement Project**

## **Hydrological analysis**

### **Final report**

**October 2003**

# CONTENTS

<b>1</b>	<b>INTRODUCTION</b>	
1.1	Objectives of the hydrological analysis	1
1.2	Form of the analysis	1
<b>2</b>	<b>REVIEW AND ANALYSIS OF RAINFALL</b>	
2.1	Climatic influences	3
2.1	Availability and selection of data	3
2.3	Rainfall analysis - daily rainfall	4
2.4	Rainfall analysis - monthly and annual rainfall	6
2.5	Conclusions	8
<b>3</b>	<b>ANALYSIS OF FLOW RECORDS FOR WADI ZABID</b>	
3.1	Available flow records	13
3.2	Review and analysis of the flood records	14
3.3	Assessment of the overall resource at Kolah	16
3.4	Losses between Kolah and Weir 1	17
3.5	Flood hydrographs	18
3.6	Conclusions	20
<b>4</b>	<b>FLOOD AND BASEFLOW SIMULATION FOR WADI ZABID</b>	
4.1	Introduction	31
4.2	The modelling approach	31
4.3	Simulation of flood events	32
4.4	Simulation of baseflow	35
4.5	Testing the model with Wadi Zabid data	37
4.6	Simulation of flood hydrographs	39
4.7	Hydrographs for Wadi Zabid	41
4.8	Inferred flood characteristics	41
4.9	Conclusions	42
<b>5</b>	<b>APPLICATION OF THE MODEL TO WADI TUBAN</b>	
5.1	Wadi Tuban flow data	52
5.2	Applying the flood simulation model	57
5.3	Inferred statistics from the simulations	59
5.4	Conclusions	60
<b>6</b>	<b>OTHER WADIS</b>	
6.1	Introduction	67
6.2	Review of monthly flood and baseflows	68
6.3	Distribution of flood volumes	69
<b>7</b>	<b>EXTREME FLOODS</b>	
7.1	Introduction	74
7.2	Flood frequency curves	74
7.3	Review of the results of the frequency analysis	76

---

<b>8</b>	<b>FLOOD WARNING AND HYDROMETRY</b>	
8.1	Factors affecting the flood warning system .....	79
8.2	Factors affecting the additional hydrometry .....	80
8.3	The argument for a combined system .....	81
<b>Appendix A</b>	<b>Quality checking and selection of rainfall data .....</b>	<b>66</b>
<b>Appendix B</b>	<b>FLOODSIM: the flood and baseflow simulation model .....</b>	<b>73</b>

## LIST OF TABLES

- 3.1 Summary of the flood component parameters for the floods analysed
  
- 4.1 Summary of the model testing on Wadi Zabid
- 4.2 Parameters used for hydrograph simulation for Wadi Zabid
- 4.3 Comparative annual statistics for Wadi Zabid
  
- 5.1 Comparative rating curves for Wadi Tuban at Dukame
- 5.2 Summary of the baseflow separation for 1980 (mcm)
- 5.3 Summary of annual flows for Wadi Tuban (mcm)
- 5.4 Parameters used for hydrograph simulation for Wadi Tuban
- 5.5 Summary of the model fitting for Wadi Tuban
  
- 7.1 Annual maximum floods reported for Wadi Zabid and Wadi Tuban
- 7.1 Predicted maximum floods from GEV analysis
- 7.3 Recommended design floods - Phase 1 wadis
  
- A.1 Rainfall stations selected for daily, monthly and annual analysis
- A.2 Mean monthly and annual rainfall for the selected stations

## LIST OF FIGURES

- 2.1 Annual raindays above selected thresholds
- 2.2 Monthly number of raindays related to aggregate rainfall
- 2.3 Mean monthly raindays related to mean monthly rainfall
- 2.4 Probability distribution of rainfall on raindays
- 2.5 Spatial variation of mean daily rainfall on raindays
- 2.6 Spatial variation of rainfall variability on raindays
- 2.7 Spatial variation of March to May rainfall
- 2.8 Spatial variation of July to October rainfall
  
- 3.1 Rating curve for Wadi Zabid at Kolah
- 3.2 Flood peak, volume and duration
- 3.3 Annual number of floods
- 3.4 Monthly number of floods
- 3.5 Probability distribution of flood volume
- 3.6 Floods above selected threshold volumes
- 3.7 The frequency of peak discharges
- 3.8 Flood duration related to volume
- 3.9 Time series of annual flow at Kolah
- 3.10 Variation in percentage runoff from Zabid catchment
- 3.11 Time series of annual flood flow and baseflow
- 3.12 Time series of March to June flood flow and baseflow
- 3.13 Time series of July to October flood flow and baseflow
- 3.14 Annual rainfall related to baseflow
- 3.15 Seasonal distribution of flood and baseflow at Kolah
- 3.16 Flood hydrograph at Kolah: 17 April 1988
- 3.17 Flood hydrograph at Kolah: 18 September 1993
- 3.18 Flood hydrograph at Kolah: 16 July 1994
- 3.19 Flood hydrograph at Kolah: 24 July 1994
  
- 4.1 The variability of the monthly number of floods
- 4.2 Observed and simulated monthly flood volume
- 4.3 Observed and simulated variability of monthly flood volume
- 4.4 Observed and simulated monthly flood number of floods
- 4.5 Observed and simulated variability of monthly number of floods
- 4.6 Observed and simulated monthly flood duration
- 4.7 Observed and simulated variability of monthly flood duration
- 4.8 Observed and simulated monthly baseflow
- 4.9 Observed and simulated variability of monthly baseflow
- 4.10 Observed and simulated flood volumes (from hydrographs)
- 4.11 Observed and simulated flood peak discharges
- 4.12 Observed and simulated flood durations (from hydrographs)
- 4.13 Percentage of flood volume below a limiting discharge
- 4.14 Years and time intervals that limiting discharge is exceeded
  
- 5.1 Comparative rating curves for Wadi Tuban at Dukame
- 5.2 Time series of annual total flows for Wadi Tuban
- 5.3 Probability distribution of flood volume for Wadi Tuban
- 5.4 Relationship between the CV and the mean of monthly volumes
- 5.5 Observed and simulated monthly volume for Wadi Tuban

- 
- 5.6 Observed and simulated variability of monthly volume for Wadi Tuban
  - 5.7 Simulated number of floods for Wadi Tuban
  - 5.8 Observed and simulated peak discharges for Wadi Tuban
  - 5.9 Percentage of flood volume below a limiting discharge
  - 5.10 Years and time intervals that limiting discharge is exceeded
  
  - 6.1 Monthly total runoff - the Tihama wadis
  - 6.2 Variability of total runoff - the Tihama wadis
  - 6.3 Monthly total runoff - Wadi Zabid and the southern wadis
  - 6.4 Variability of total runoff - Wadi Zabid and the southern wadis
  - 6.5 Seasonal growth of rainfall by sub-region
  - 6.6 Total annual runoff related to catchment area
  - 6.7 Wadi Rima - number of floods
  - 6.8 Wadi Rime - probability distribution of flood volumes
  
  - 7.1 Wadi Zabid - flood frequency curve
  - 7.2 Wadi Tuban - flood frequency curve
  
  - A1 Deterioration in quality of daily rainfall records
  - A2a } Effect of data source on rainfall frequency analysis
  - A2b }

## REFERENCES

- Komex International 'Water Resources Management Studies in the Tuban-Abyan Region'. Second Interim Draft Report, Vol 1, September 2001.
- Bertrand, Undefined reference to work on Abyan Delta, 1990
- MacDonald AK, 'Aspects of Spate Irrigation in PDR Yemen'. Spate Irrigation, Technical Background Papers: International 3
- Farquharson FAK, Green CS, Meigh JR, and Sutcliffe JV 'Comparison of Flood Frequency Curves for Different Regions of the World'. VP Singh (ed), Regional Flood Frequency Analysis, 223-256, 1987
- Farquharson FAK, Meigh JR, and Sutcliffe JV 'Regional Flood Frequency Analysis in Arid and Semi-arid Areas'. Journal of Hydrology 138 1992.
- Nouh MA 'On the Prediction of Flood Frequency in Saudi Arabia'. Proc ICE, London 85 1988.
- Natural Environment Research Council 'Flood Studies Report'. Institute of Hydrology, Wallingford, 1975
- Technical Secretariat of the High Water Council: Database and various technical papers written by UNDTCD consultants, 1990-1991
- Delft Hydraulics 'SIIP Mission Report (second draft)'. Prepared for the World Bank, December 2000.
- TNO Institute of Applied Geoscience 'The Water Resources of Yemen'. Report WRAY-35, March 1995.
- Northwest Hydraulic Consultants 'Erosion and Flood Control Measures Assessment for Wadi Tuban and Wadi Beihan in DPR Yemen'. For World Bank, Aug 1982.
- Italconsult 'Soil and Water Utilisation and Conservation in the Wadi Tuban Watershed Area', FAO/UNDP, Sep 1974
- Groundwater Development Consultants (International) 'Wadi Tuban Water Management Study Final Report', July 1981

## 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 provide a methodology that can be applied to the five Phase 2 wadis - in a way that will provide the input to the Spate Management Model (SMM) 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 allows scaling of the time series and is based on detailed review of the observed data.

- to provide information on extreme flood discharges for engineering design.

Estimates of peak discharge at various return periods can be found by applying statistical techniques such as extreme-value analysis to the observed data. It is not necessary to consider the full hydrograph as no storage is involved at the existing main diversion structures.

- 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.

The problem of insufficient hydrometric stations should be related to the needs of the hydrological analysis, and to the needs of the flood warning system. The two issues are closely related.

## 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.

Thus, the main effort has gone into the development and testing of a new stochastic description of the flood events and the development of a computer model that can be used to simulate flood events, baseflow and flood hydrographs from the characteristics of the short records.

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 SMM, and we describe the development and testing of a simulation model capable of generating sequences of flood events and transforming them into detailed hydrographs. The model is developed and tested using data for Wadi Zabid.

In Chapter 5 we interpret the information available for Wadi Tuban and apply the simulation model to this wadi to produce inflow data for the SMM.

In Chapter 6 we review selected information for other wadis, primarily those designated for Phase 2 of this project, that has some impact on parameter selection for subsequent applications of the simulation model.

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.

There two appendices: the first describes a short investigation into the quality and consistency of the daily rainfall data. A potentially important finding is that there is a tendency for aggregation of data within supposed daily records. The second describes the FloodSim simulation model in terms of its general use and application to other wadis.

## 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 ensure 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 from this source 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 are now held in a database managed by NWRA and these data have been made available to us.

For convenience in computer-based analysis we have used a numerical station identifier in preference to a station name that can be inconsistent between users when rendered in English. As NWRA have a nation-wide numerical ID in their database, we have used this to define rainfall stations throughout our analysis and in the hydrological database that forms part of the project MIS.

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; the daily data for these stations appear to have been lost. There are also some records in the old High Water Council (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 range of daily rainfalls in all parts of the country. Differences in the total rainfall observed across the country derive primarily 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. 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 2.2 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. 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 is some variation 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. But it is more likely that other factors affect the perception. Floods from the lower part of a wadi basin arrive at the mountain foot soon after the rainfall events and will be less attenuated (shorter with higher peaks) than floods that have travelled from areas nearer to the watershed.

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.

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.

A review of rainfall associated with the 50 largest flood events in the record for Wadi Zabid showed very few occasions when a flood could be associated directly with recorded rainfall at any of the 14 stations located in or near the basin. Unfortunately, the short periods of rainfall record available means that many of the floods occurred when none of the rainfall stations were operating. Conversely, we found that floods occurred on about 35% of the days when rainfall in the operational stations exceeded 15mm on average.

We can conceptualise these findings in terms of rainstorms and flood formation. If the meteorological conditions (moisture, convergence) are such as to produce rainfall, the rain storms tend to be of limited areal extent but can occur in different parts of the basin at the same or different times during the day. We can imagine small floods developing where the rain storms are sufficiently intense to produce runoff. As they move down the basin, these local floods will merge together and be attenuated sometimes resulting in a multi-peaked flood being recorded at the mountain foot. The particular spatial distribution of rain storms for each event will determine the characterisation of the flood hydrograph observed.

## **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 less, 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.

However, the rainfall network is very sparse, especially given that the rain storms are generally small relative to the area of the wadi basins. It is not possible to see a direct relationship between rainfall observed and a flood that results. We must look for consistency between the underlying statistical structure of rainfall and floods and not the direct correspondence of individual events.

### 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:

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

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  $\pm 25\%$ . 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  $\pm 25\%$  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<sup>3</sup>/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<sup>3</sup> (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<sup>3</sup>/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. 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 HWC database contains a fragmentary daily record of baseflow measured at Weir 1 as well as contemporary record of flows at Kolah. The record covers the period 21 May 1987 to the end of that year, and the daily flows are in fact interpolations between intermittent measurements. The reason for these measurements and the circumstances under which they were made is not known. However, they are the only data we have found relating to flows at the weir.

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

There are several issues that 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:

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

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)					Total
	A	B	C	D	E	
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 <sup>3</sup> /s)					Max	Hydrograph peak
	A	B	C	D	E		
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 is no discernable variation in this relationship 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 FOR WADI ZABID**

### **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 detailed flood records are very sparse and the emphasis is on generation of realistic flood sequences from more general information.

The SMM requires flood hydrographs and baseflows at 15-minute time intervals. We have seen in the previous chapter that it should be possible to generate sequences of flood events characterised by volume and perhaps by duration from the statistical description of the recorded events. However, even when detailed hydrographs have been recorded, it is not possible to identify a generalised shape that could be regarded as a typical flood. It is therefore 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.

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 based on longer records from other wadis.

### 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, and it appears to be 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<sup>3</sup>/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<sup>3</sup>/s but subsequently revised to 2640m<sup>3</sup>/s) and 24 May 1977 (2150m<sup>3</sup>/s). A similarly memorable flood is noted for Wadi Rima (19 April 1976) with a peak flow of about 1000m<sup>3</sup>/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 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. A 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 Year1 as 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 22<sup>nd</sup> 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.

<b>Year 1</b>													
month	J	F	M	A	M	J	J	August	S	O	N	D	Year
number of floods	0	0	3	5	5	1	7	<b>6 floods</b>	10	3	0	0	40
days of month					<b>2</b>	<b>5</b>	<b>6</b>	<b>9</b>	<b>22</b>	<b>30</b>			
flood volume					<b>V22</b>	<b>V23</b>	<b>V24</b>	<b>V25</b>	<b>V26</b>	<b>V27</b>			
<b>Year 2</b>													
month	J	F	M	A	M	J	J	August	S	O	N	D	Year
number of floods	1	0	2	3	5	0	3	<b>4 floods</b>	8	4	1	0	31
days of month						<b>10</b>	<b>12</b>	<b>23</b>	<b>25</b>				
flood volume						<b>V55</b>	<b>V56</b>	<b>V57</b>	<b>V58</b>				

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 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, although the parameters of the relationship can be changed where there is evidence available.

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

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

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. In their analysis a flood is considered to end when the discharge falls to about 4m<sup>3</sup>/s.

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<sup>3</sup> (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 some extent to annual rainfall as 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 observed 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 500-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. The simulated duration is longer than the observed because of differences in the cut-off discharge defining the end of the flood as described above. However, 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, is held in the database Floods.mdb with the identifier ZD207. All the corresponding text output files have this identifier as a prefix to the file name]*

**Table 4.1 Summary of the model testing on Wadi Zabid**

<i>Version 1 simulation</i>		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
<b>Flood volumes (mcm)</b>														
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	0.8	3.6	6.0	2.9	4.6	8.0	4.6	1.0	0.2	0.0	32.0
	cv	6.6	0.0	3.5	1.4	1.3	1.0	0.7	0.5	0.9	1.6	4.7	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
<b>Number of floods</b>														
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	0.1	0.0	0.9	4.5	6.5	4.4	7.2	12.4	6.9	1.7	0.4	0.1	45.0
	cv			1.5	0.8	0.7	0.9	0.5	0.4	0.7	1.5	4.1		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
<b>Duration of flood events (hours)</b>														
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	0.0	5.8	10.8	12.5	9.0	8.4	8.5	8.6	6.1	1.8	0.9	
	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	
<b>Baseflow (mcm)</b>														
Observed	mean	2.0	1.97	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	1.9	1.9	2.5	5.3	9.6	10.1	8.7	13.4	12.9	6.0	3.0	2.1	77.5
	cv	0.5	0.6	0.6	0.6	0.5	0.5	0.5	0.4	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

## 4.6 SIMULATION OF FLOOD HYDROGRAPHS

### General considerations

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 that probably represent separate flood components arising from different parts of the catchment.

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 simpler approach must be found to meet the needs of the SMM. We have therefore developed a procedure that simulates flood components that are aggregated to produce a single hydrograph for each flood event.

For each flood we need to know or be able to generate:

- the number of components making up the flood event;
- 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 time of onset and the rise time of hydrographs and the way in which duration might be computed that are dealt with in the detailed sections that follow.

Although in principle there is no limit to the generality of the proposed model, we have imposed certain constraints in view of the limited knowledge available. The main constraint is that there shall be no more than two components in each flood event. Trials with up to three components made parameter fitting much more difficult.

## **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 described in the Chapter 3, and to reproduce reasonably well the range and distribution of flood peaks and flood durations while retaining the volume of the flood event.

Generally, the parameters for each flood component define a range (maximum and minimum values) over which the set chosen to characterise the flood component is chosen randomly. A rectangular distribution is used to select specific values within a range.

### ***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 are considered equally likely to have one or two components. The threshold value is a parameter.

When there are two components, the flood volume is distributed randomly between them 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***

The onset of the flood - the time when the water level begins to rise at the recording station - is not usually recorded, although the information is available in the mass of charts for some stations. It is well known that floods tend to occur at certain periods of the day and we have divided the day into eight 3-hour periods for which the percentage of floods arising in each period can be specified. Selection of these parameters has no other effect on the shape of the hydrographs produced.

The rise time of the first component is allowed to vary within a narrow range. Usually, floods in Yemen rise very rapidly and it is unusual for the peak to arrive much more than one hour after onset of the flood. The parameters are the maximum and minimum limits to this rise time. The component volume is added to the linear reservoir for the component uniformly over the number of 15-minute time steps defined by the rise time. Thus the choice of rise time has some impact on the peak of the component hydrograph.

The remaining parameter governing timing is the delay or gap between successive components in a multi-component flood.

### ***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. These values are allowed to fall within ranges set by the parameters in the model.

## **Baseflow**

The mean maximum monthly baseflow (taking the average of the highest monthly baseflow in each year) is around  $6.5\text{m}^3/\text{s}$  for Wadi Zabid, which is small compared with the range of flood peaks. We have therefore considered baseflow as a constant value that can be added to the flood hydrograph to produce the total flow hydrograph. The values used for baseflow are those given

by the baseflow simulation for the relevant month.

## 4.7 HYDROGRAPHS FOR WADI ZABID

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.

The parameter values shown on the following table 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 flood discharge falls below  $1\text{m}^3/\text{s}$ . Because this criterion differs from that used by TDA to define flood duration from the chart data, we expect that the simulated durations will be longer than those recorded.

**Table 4.2 Parameters used for hydrograph simulation for Wadi Zabid**

Parameter	Unit	Maximum	Fixed	Minimum
Max number of components			2	
Threshold volume for multi-component flood	tcm		250	
Rise time	hours	0.5		1.0
Time constant 1	hours	1.0		8.0
Time constant 2	hours	10.0		14.0
Time lag between components	hours	0.25		3.0

Figures 4.10 to 4.12 show the results of this fitting the model to data for Wadi Zabid. The close result in Figure 4.10 is entirely expected. It confirms that the flood volumes are correctly handled by the hydrograph routing process. Figures 4.11 and 4.12 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.

*[A record of the parameter values used in these simulations, is held in the database Floods.mdb with the identifier ZD207. The relevant text output files have this identifier as a prefix to the file name]*

## 4.8 INFERRED FLOOD CHARACTERISTICS

The chart records available for some of the wadis on the Tihama have not been digitised. Consequently, the information is not in a form that allows computation of flow duration or flow frequency curves that could be of some value in the design or rehabilitation of spate irrigation systems.

While it might be considered as stretching the credibility of the simulation procedure a little, it is clearly possible to use the simulated flow sequences to derive some indicative measures that

characterise the flood regime of a wadi.

Figure 4.13 shows the total flood volume that occurs at discharges below the threshold shown on the x-axis. In a simple scenario where a diversion with a given capacity is provided at the recording station, this graph relates the proportion of the total flood volume that could be captured with this diversion capacity. The curve is of the expected shape and the benefit of providing marginal additional capacity yields a progressively smaller return once most of the flood flow has been captured.

Figure 4.14 shows the percentage of years in which the flood discharge might be expected to exceed the diversion capacity, and the average duration of this exceedence, both as functions of diversion capacity.

These results have been derived from a 500 year simulation in order to reduce the sampling variance associated with short sequences. Nevertheless, it must be emphasised that the results are based solely on the hydrograph simulations and should therefore be treated with some caution until there are data available to validate them directly.

## 4.9 CONCLUSIONS

Given a basic statistical knowledge, the simulation model (FloodSim) is not difficult to understand. We have demonstrated that it can meet the objectives set for it, namely that it should produce short sequences (one or a few years) of flood hydrographs with baseflow data to support the work on spate management, specifically through the SMM..

Since the model can generate long sequences (up to 1000 years) of floods and baseflow for a wadi, we have shown that it is possible to use FloodSim to derive other statistics of some relevance to irrigation planning. These might include the mean and variability of annual total flows or statements about the volume that can be diverted with a given diversion capacity.

However, before believing that the model can answer all these questions reliably it is important to recognise some basic limitations to the model and to consider why these might inhibit the reliability of some of the statistics that can be derived from the output.

In Table 4.3 the comparison of annual statistics is summarised for Wadi Zabid. While the means of all the measures are well matched by the simulation model, the variability of all these measures is underestimated on an annual basis, even though the monthly variability is well reproduced (Table 4.1).

**Table 4.3 Comparative annual statistics for Wadi Zabid**

Measure	Observed data			Simulated data		
	mean	sd	cv	mean	sd	cv
Annual flood volume	32	20	0.62	32	13	0.41
Annual baseflow	80	32	0.41	78	23	0.30
Annual total volume	112	39	0.35	110	30	0.27
Annual number of floods	45	17	0.37	45	11	0.25

Note: the observed statistics relate to the period 1982-97

There are three possible explanations for this:

- the model is based on direct relationships - such as between monthly number of floods and the monthly flood volume - that are in practice subject to some variability (unexplained variance or noise) that is not explicitly added in the model;
- the exceptional events cannot be well defined as discussed earlier in this chapter;
- the possibility that there is some auto-correlation between months - a wetter than average month is more likely to be followed by another month that is wetter than average - is not allowed for.

The model could be made more complicated and the first and third of the points made above could be added. The problem is one of specifying the amount of noise or auto-correlation structure that should be included. We have seen that it is difficult enough to specify the parameters of the model when applied to Wadi Zabid where the data availability is reasonably good. It would be impossible to estimate the additional parameters needed where the data are poor or sparse such as for Wadi Tuban that is described in the next chapter.

But, there is an over-riding reason why the model is not developed further at this time: it is needed for a very specific purpose, which is the definition of typical sequences of floods over a time span of one year or a few years. It is adequate for this purpose, which is largely unaffected by factors of the long term annual statistics. It is likely that years will be selected from the simulated sequence to represent say wet, average and dry conditions, perhaps supplemented by particular years that show the impact of exceptional floods. Providing these years are selected and used with some reference to the observed data available, it should not be necessary to attempt to refine the modelling procedure further at this stage.

Further testing of the hydrograph procedure is inhibited by the lack of digitised short time interval wadi records. Despite the lack of these data, 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.

## 5 APPLICATION OF THE MODEL TO WADI TUBAN

### 5.1 WADI TUBAN FLOW DATA

Records of some kind exist from 1955 with some gaps, notably from 1962-1967 and from 1987-1999. Until 1972 the records refer to flow at Ras al Wadi where the channel is very wide and there are two diversion structures. It is almost impossible to imagine that reliable flow data could be obtained from that station. From 1973 the station is at Dukame. Subsequently, Italconsult rated the section at Dukame and derived flow records for 1973-1974. In 1980, GDC substantially reworked the Italconsult data and added their interpretation of the recorded water levels up to 1981. From 1981 to 1987 the records derive from information held by the Irrigation Department in Aden. It is clear from these records that the attention paid to monitoring declined and monitoring ceased at the end of 1987.

Since April 1999, water level records have been collected by NWRA (Aden) using a new data-logger recorder installed in the original stilling well. These records continue to the present with some gaps when the data were not collected.

#### Rating curves

The rating curve for the Dukame station - converting recorded water level to discharge - is key to the accuracy of the discharges and hence the volumes derived from the records. Unfortunately, the rating at Dukame has been revised many times given the history of the station outlined above.

It is clear that the rating has to be extrapolated from concurrent water level and discharge measurements at the site. These measurements are few, and as far as we can determine, none was made at a discharge much in excess of  $350\text{m}^3/\text{s}$ . In fact, GDC consider it too dangerous to attempt to such measurements. Their 1981 report states:

“Although a cableway was erected at the gauging station in 1979, this has been used only once. The flow of the wadi in flood is really too violent and debris laden for the satisfactory use of a current meter. Measurement with floats or slope/area methods would be more appropriate to these conditions. Crest-stage gauges were erected for slope/area measurement in 1980.”

We can infer that the many curves derived related primarily to the variations of bed level and configuration affecting low and medium flows, and that extrapolation to higher flows was not substantiated by measurements at these higher flows, or it appears by other techniques such as slope/area information.

We can find no information about rating curve development after GDC completed their studies in 1981. Only recently, during the Komex study, has there been some attempt to review and recalibrate the station at Dukame. Komex have used Manning's equation to derive a rating curve that is based on the geometry of the section, the slope of the wadi channel and an estimate of the roughness of the section.

The rating curves developed at different times probably reflected real changes in the water level/discharge relationship within the constraints of the range of measurement in each case. For low flows it is expected that changes in the configuration of the wadi bed would cause the relationship to change, particularly after high floods had substantially rearranged the sediments

forming the wadi bed. Our concern is with extrapolation of these curves beyond the range of direct measurement and to periods when there were few if any measurements.

To illustrate the impact of changes in the rating, we have used an equation of the form:

$$Q \text{ (m}^3\text{/s)} = A * (H \text{ (m)} - C)^B$$

where **A**, **B** and **C** are parameters of the equation usually determined by fitting the curve to observed data.

The different published curves are summarised for a range of water levels in Table 5.1. Figure 5.1 also illustrates these curves. These curves have been extrapolated to 6m to illustrate the possible range of error associated with estimating the peak of exceptional floods - an issue that is further discussed in Chapter 7.

**Table 5.1 Comparative rating curves for Wadi Tuban at Dukame**

	Italconsult		GDC				ID	Komex		max	min	range/ mean	
	1973	1974	1975	1976	1979	1980a	1980b						
A	114	71.75	35.23	59.12	36.12	44.12	31.44	68.41	48.4	81			
B	1.6	1.96	2.58	2.15	2.69	2.15	2.69	1.87	2.1	1.6			
C	0.75	0.52	0.26	0.49	0.34	0.25	0.2	0.49	0.3	0.3			
WL (m)													
0.6		1	2	1		5	3	1	4	12	12	1	3.31
0.8	1	6	7	5		12	8	8	11	27	27	1	2.74
1	12	17	16	14	12	24	17	19	23	46	46	12	1.69
1.2	32	34	30	28	24	40	31	36	39	68	68	24	1.23
1.4	57	56	49	48	42	60	51	57	59	94	94	42	0.91
1.6	88	83	75	74	67	84	78	83	84	123	123	67	0.67
1.8	123	116	107	106	100	113	111	113	113	155	155	100	0.47
2	163	155	147	143	141	147	153	148	147	189	189	141	0.31
3	417	426	475	428	502	388	502	382	390	397	502	382	0.28
4	751	827	1059	879	1184	756	1141	716	755	657	1184	657	0.60
5	1154	1356	1952	1507	2268	1258	2138	1144	1248	963	2268	963	0.87
6	1619	2013	3198	2319	3827	1896	3557	1664	1871	1312	3827	1312	1.08

Sources: Italconsult (1974), GDC (1981), Irrigation Department, Komex (unpublished information)

The right-most column shows the range of estimates as a factor of the mean, as a measure of how consistent the rating curves are when applied to the expected range of water level. As expected the highest variation is at the extremes of the water level range. Low flows are most susceptible to minor changes in the wadi bed configuration; high flows are most susceptible to extrapolation of a rating beyond the range of discharge covered by the direct measurements.

## Resource estimates

There are few records of individual floods available. Much of the detailed record has been lost during unification of the country and discharges for much of the recorded period is in the form of monthly and annual summaries of total flow. Some detailed records survive in the GDC report that contains daily flows for 1980. The other main feature of the data is the lack of any separation of flood and baseflow volumes. This separation is important in terms of spate management. The current record exists only as unprocessed 15-minute water levels. There is an added complication: the sensor is mounted well above the wadi bed to reduce the impact of sediment in the stilling well; it therefore 'sees' only the larger floods.

These fragmentary data are examined here in the context of defining parameter values for the flood simulation model. In the process of doing this it is necessary to come to a view on the resource currently available both as flood flow and baseflow, and to assess as far as possible from the historical data whether or not there is any indication that this resource is changing.

## Interpretation of the NWRA data

These data have been made available to us by NWRA. They are 15-minute water levels recorded above an arbitrary sensor datum. The data cover the following periods:

14 Apr 1999 - 01 Dec 1999  
 01 Jan 2000 - 31 Dec 2000  
 05 July 2001 - 05 Sep 2001  
 11 Mar 2002 - 31 Dec 2002  
 17 Mar 2003 - 15 Sep 2003

We have chosen to apply our interpretation of the Komex rating. Allowing for the position of the sensor relative to the survey datum for the section, this means applying the following equation to convert recorded water level to discharge.

$$Q \text{ (m}^3\text{/s)} = 81.0 * (H \text{ (m)} + 0.4)^{1.6}$$

Some peculiarities of the water level record should be noted:

- after the peak of a flood has passed, the recorded water level falls normally until a reading of about 0.2m on the sensor, and then falls very slowly back to zero. This is unreasonable given that the sensor is well above the wadi bed. The fall in water level should be continuous at more or less the same rate.
- there are periods of several days when the sensor reading rises very slowly up to a value of around 0.2m before falling abruptly back to zero. This is unexplained at the present time.
- the sensor sometimes records negative instead of positive values. This also is unexplained.

Given these peculiarities, we have adopted the following rules for interpretation of the record:

- the record is searched for floods - baseflow cannot be recorded with the sensor in its present position;
- the start of a flood is assumed if the water level on the sensor exceeds 0.22m;
- a flood is confirmed only if the peak water level on the sensor rises above 0.3m;
- a flood is provisionally ended when the water level on the sensor falls to 0.22m.

What is seen by this analysis is the top part of those floods that have a peak discharge exceeding about  $46\text{m}^3/\text{s}$  and floods are truncated at a discharge of about  $38\text{m}^3/\text{s}$ . Floods below these criteria are not recorded at all. The truncation of the rise of the flood makes little difference to the volume of the flood; rise times are very fast. However, truncation of the flood recession is very important as the longer floods can have substantial volume in the recession that is not seen by the sensor.

We have therefore used the upper part of the recession (up to the last ten 15-minute values available) to estimate a recession constant, and used this to extend the flood until the discharge falls to  $1\text{m}^3/\text{s}$ . The total flood volume and the duration of the flood are then computed.

While little more can be done with these data at the present time, the general position is unsatisfactory. There are several questions about the performance of this new instrumentation, and it is not sufficient to collect data without processing it to the point where these limitations come to light and can be reviewed and corrected. Consideration should be given to relocating the sensor at the wadi bed and comparisons with the new instrumentation proposed for the flood warning system should be made as soon as that is installed and operational.

Interpreting this record in resource terms requires further assumptions to be made. The questions are: how many floods were not recorded and what proportion of the annual flow volume did these missed floods represent? We have used the detailed flood data for 1980 (from GDC (1981)) to try to resolve this issue. 1980 was not an exceptional year and it is likely that the distribution of flood volumes recorded then could reasonably represent the flood distribution in recent years.

These data suggest that about 75% of floods have a peak discharge below the  $46\text{m}^3/\text{s}$  threshold used in our interpretation of the recent water level record. Further, these floods represent about 50% of the annual flood volume.

Applied to the 1999 - 2002 data, these factors would give annual flood volumes of 58 and 53mcm respectively.

## Baseflow

GDC (1981) present a table of daily total flows for 1980. These are the only data we have found that allow some estimate to be made of the balance between flood flow and baseflow in the total record. Baseflow separation was carried out by eye with the result shown in Table 5.2.

**Table 5.2 Summary of the baseflow separation for 1980 (mcm)**

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Total volume	1.4	0.6	0.3	4.3	6.9	10.2	11.7	23.9	17.6	4.8	2.3	1.7	86
Baseflow volume	1.4	0.6	0.3	0.2	0.2	1.4	1.6	4.5	6.4	4.1	2.3	1.7	25
Flood volume	0.0	0.0	0.0	3.9	6.7	8.8	10.1	19.4	11.2	0.8	0.0	0.0	61

Source: GDC and own analysis

We have no information about the annual variation of the baseflow or of the factors affecting its seasonal variation, measurements are not being made despite there being equipment available..

## Annual total flow

The 1980 baseflow separation has yielded a figure of 25mcm for baseflow for a year that might be taken to be typical of 'normal' years, that is ones without large or exceptional floods. We have also taken the general factors derived above to infer that the NWRA record for recent years can be interpreted to give annual volumes that are the sum of twice the flood volume 'seen' by the recorder and a baseflow of 25mcm. The value for 2003 is obtained directly from the water level record following relocation of the sensor to wadi bed level in July 2003.

For the earlier years we have taken the data as published except that where there is inconsistency between the Irrigation Department record and that published by GDC, we have used the latter.

Table 5.3 shows the annual total volume of flow quoted in the various reports and supplemented by our interpretation of the current records. Figure 5.2 shows these data as a time series graph.

**Table 5.3 Summary of annual flows for Wadi Tuban (mcm)**

Ras al Wadi		Dukame	
1955	103	1973	63
1956	138	1974	81
1957	120	1975	116
1958	74	1976	46
1959	183	1977	222
1960	206	1978	170
1961	150	1979	92
		1980	86
1968	128	1981	141
1969	90	1982	249
1970	126	1983	46
1971	145	1984	50
1972	140	1985	52
		1986	371
		1987	90
		1999	83
		2000	77
		2001	57 (inc)
		2002	51
		2003	39
mean	134		112
sd	37		86
cv	0.27		0.77
median	133		83

Note: (inc) indicates an incomplete year that is not included in the analysis

Sources: All sources cited in the text

GDC (1981) rated the quality of the records from 1973 to 1980 as 'poor', and that for 1978 as suspect due to blockage of the stilling well. This assessment is probably due to difficulties in rating the station and the extrapolation of the rating to the higher floods. As considerable detailed work went in to the processing of these records, we must assume, without evidence to the contrary, that the other records are less reliable. The records from 1955 to 1972 for Ras al Wadi were rated 'very poor' by GDC and are now generally ignored. The assumptions that have had to be made to derive estimates for recent years mean that the figures for 1999 and 2003 are only indicative of the

likely total volume.

The unsubstantiated high flow for 1986 affects the mean considerably, and also increases the variability of annual flows. On Wadi Zabid the coefficient of variation of annual total flow was just under 0.4. Given these uncertainties, we consider that the resource is more reliably characterised by the median rather than the mean annual total flow, given by the data for Dukame, ignoring that for Ras al Wadi. This means a long term average resource at Dukame of 83mcm of which around 25mcm is baseflow.

### **Flood characteristics**

The simulation model requires two parameters that define the statistical distribution of the volume of individual flood events. There is little information other than the list of events monitored by GDC for 1980. Figure 5.3 shows the distribution for this year. It is a skewed distribution, like that found for Wadi Zabid. The mean flood event volume of 0.925mcm is larger than that for Wadi Zabid (0.656mcm); the standard deviation at 0.75mcm is smaller (0.848mcm for Wadi Zabid). These data are derived from 55 flood events recorded in that year, a figure consistent with the perceived average of 50-60 floods per year quoted by GDC.

Given the regional homogeneity of rainfall events as described in Chapter 3 and the comparable catchment areas, we might have expected the flood event statistics to be more consistent between the two basins. It is not known whether the differences arise primarily because the Tuban figures are derived from only one year of data. The recent records cannot be used in this analysis because nothing is known of around 75% of the flood events that have a peak water level below the zero of the gauge.

### **Trends**

We are aware that water use in the catchment areas is not static, developments have taken place over the past decades and are continuing as small or medium sized dams are built and new modern terraces constructed. It follows that the resource available for diversion in the scheme area is probably declining. It is likely that the impact of upstream development will affect baseflows (more readily diverted) and the small floods (within the range of storage of the small dams) rather than having a noticeable impact on the large and exceptional floods.

Unfortunately, the wadi flow data are not continuous nor are they sufficiently detailed or reliable to discern these trends. However, we believe that the likelihood of upstream development continuing is another reason for using the median rather than the mean annual flow as a basis for our simulation studies and the SMM.

## **5.2 APPLYING THE FLOOD SIMULATION MODEL**

It is clear from the previous section that the data available for parameter definition for Wadi Tuban are much less comprehensive than is the case for Wadi Zabid. Deriving parameters for the simulation model is largely guesswork on the basis of this fragmentary and information, and any simulation must be regarded as a provisional basis for planning until improvements in monitoring and interpretation of records are made.

Furthermore the modern data do not appear to substantiate the flow volumes indicated by the historical data. This might be by chance; it might be due to the difficulties of interpretation of the

partial data; it might be due to increased water use upstream. Our use of a median total flow of 83mcm per year rather than the often-quoted 109mcm is a response to reduced flows in recent years and the uncertainty inherent in the records.

### **Selection of flood event parameters**

Further regional study is required to establish whether the distribution of flood event volumes is consistent across the region and how it is affected by basin size. The choice here is between using the parameters defined by the distribution of flood events for 1980, or importing the values used for Wadi Zabid. We chose to use the former as they are taken from a period when the monitoring of flows at Dukame was probably better than at any time before or since.

The monthly distribution of flood volumes has been derived from the 1973-1980 period scaled to our estimate of annual flood flow of 58mcm, that is 83mcm total flow less 25mcm of baseflow.

We have chosen to use Version 2 of the FloodSim and to derive a relationship between the CV and the mean of monthly volumes. In practice we have used the total flow data to derive a suitable relationship, as flood flows are known only for 1980, on the grounds that most of the variability is likely to be in the flood flow and less in the baseflow. This relationship is illustrated in Figure 5.4.

There is little information to assess the frequency and months of occurrence of exceptional floods. We have assumed that they occur primarily in the March to May season, and the fragmentary information available appears to confirm that. Their scale and frequency appears to be lower than for Wadi Zabid, although this is largely conjecture. We have assumed a typical exceptional flood amounting to 10mcm with a frequency of 1% of years in each of the three months.

The results are presented in Figures 5.5 to 5.7. Figures 5.5 and 5.6 compare observed and simulated monthly distribution of the mean and standard deviation of flood volumes. Figure 5.7 shows the mean monthly number of floods simulated as well as the variability of that statistic. There is no observed information on the number of floods other than the perception that 50-60 floods per year pass Dukame. The simulation gives an annual mean of 60 floods per year with current parameter values.

### **Baseflow parameters**

We have no evidence whatsoever for the variability of baseflow either annually or in terms of its seasonal distribution. There is scant evidence for its total; the 25mcm is taken from the only year of data for which a baseflow separation could be performed. However, we are aware that little if any of this baseflow reaches Al Arais as a surface flow that would contribute to the total volume diverted. It appears to be diverted by farmers for irrigation of crops upstream of Al Arais, and to infiltrate into the alluvium of the wadi channel below the confined section around Dukame.

Baseflow is therefore not important in terms of an input to the SMM and it is unnecessary to attempt to model the variability of baseflow if it will play no part in the spate management process. However, we have included baseflow for completeness but assumed that it is invariant at 25mcm per year with the same seasonal distribution as seen in the 1980 analysis.

This is achieved by using an implied rainfall value and setting a constant percentage contribution to baseflow so as to produce the intended baseflow. These parameters have no direct significance other than to achieve the result intended.

## Hydrograph parameters

Some indications of the values for the hydrograph parameters are gained from the analysis of the partial flood record of recent years. Unfortunately, the full range of floods has not been monitored due to the position of the water level sensor. It appears that fewer floods have multiple peaks than is the case for Wadi Zabid, even though the monitoring has been confined to the larger floods where multiple peaks might be expected. This is a perception; it remains to be confirmed when better records become available following installation of the flood warning system. It is possible that there are fewer floods deriving from the lower part of the catchment and relatively more from the wetter areas that are a greater distance from the mountain front. Flood components that arise from higher in the catchment might coalesce sufficiently for them to appear as a single peak.

Inevitably, the parameter selection is a process of trial and error. We have used only the supposed distribution of flood peaks to test the hydrograph part of the simulation.

**Table 5.4 Parameters used for hydrograph simulation for Wadi Tuban**

Parameter	Unit	Maximum	Fixed	Minimum
Max number of components			2	
Threshold volume for multi-component flood	tcm		250	
Rise time	hours	1		2.0
Time constant 1	hours	1.0		8.0
Time constant 2	hours	8.0		14.0
Time lag between components	hours	2.0		10.0

Figure 5.8 shows the comparison of the number of observed and simulated flood peaks falling into predefined ranges. This comparison suggests that the simulation reproduces the distribution for 1980 reasonably well. There is less agreement with the data for recent years. But this is not unexpected; the assumptions that had to be made to estimate the frequency of flood peaks from the partial data would have a considerable impact on this comparison.

*[A record of the preferred parameter values used in these simulations, together with the output data, is held in the database Floods.mdb with identifier TB530]*

## 5.3 INFERRED STATISTICS FROM THE SIMULATIONS

As in Section 4.6 above for Wadi Zabid, we have used the hydrograph data to derive the flow duration information that can be used to infer the likely efficiency of diversion structure assuming diversion takes place at Dukame. Some further interpretation of these figures is needed to transfer the information to the weirs downstream.

Figure 5.9 shows the total flood volume that occurs at discharges below the threshold shown on the x-axis. In a simple scenario, where a diversion with a given capacity is provided at the recording station, this graph relates the proportion of the total flood volume that could be captured with this diversion capacity. The curve is of the expected shape and the benefit of providing marginal additional capacity yields a progressively smaller return once most of the flood flow has been captured.

Figure 5.10 shows the percentage of years in which the flood discharge might be expected to exceed the diversion capacity, and the average duration of this exceedence, both as functions of

diversion capacity.

These results have been derived from a 100 year simulation and it must be emphasised that the results are based solely on the hydrograph simulations and should therefore be treated with some caution until there are data available to validate them directly.

## 5.4 CONCLUSIONS

Monitoring of Wadi Tuban has not been as consistent or for as long a period as Wadi Zabid. It follows that the data are not as easily used for parameter estimation. The large gap between 1987 and the resumption of monitoring in 1999 is particularly unfortunate because it is not clear whether the historical data are representative of present conditions given the greater opportunity for diversion of water and for irrigation development in the upstream parts of this basin.

The difficulties encountered in selecting parameter values suggests that the data available are the minimum needed for application of the flood simulation model. This is not an issue peculiar to this model; any kind of model would be difficult to fit to the sparse and fragmentary data. As far as possible we have used the local data to determine appropriate parameter values. It is possible that regional values might be preferable in some cases. However, we believe that further work needs to be done in verifying and analysing data from other wadis before regional parameters can be established with any confidence.

Our interpretation of the data suggests 61mcm/year of flood flow. This appears excessive; it is almost double the mean annual flood volume on Wadi Zabid whose catchment area is only 6% smaller and whose rainfall regime is comparable. The geomorphology is different: there are larger areas that can be defined as 'rainfall-absorbing' in the Wadi Tuban basin. This would argue for less flood runoff in Wadi Tuban, not substantially more than in Wadi Zabid. Also, there appears to be greater opportunity for water capture in Wadi Tuban and the increasing development of groundwater might suggest that more rainfall went to infiltration and less to surface runoff.

In addition, there is indirect evidence of a smaller flood volume. The maximum extent of the spate irrigation area does not support the idea of a high flood volume and the number of floods perceived to reach Al Arais appears to be significantly fewer than are thought to pass Dukame. It is possible that the losses between Dukame and Al Arais are high. All the baseflow and many of the smaller floods could infiltrate before reaching Al Arais or be so attenuated as to offer little irrigation benefit.

It is clear that the scale of the resource remains uncertain. Baseflow is not measured and our interpretation of the scale of flood flows derived from the recent records has involved several assumptions that cannot be verified directly. The reason for the disparity between flows on Wadi Tuban and Wadi Zabid is not at all clear. The weakest information is that supporting the separation of baseflow and flood flow on Wadi Tuban. Arguably the baseflow should be higher and the flood volume smaller. But without some direct measurement this cannot be substantiated.

Several steps should be taken to resolve this important issue:

- baseflow monitoring should be carried out regularly by NWRA who have the equipment needed;
- the current water level data should be reviewed thoroughly; the recorder datum should be checked and an authoritative rating curve established;

- the reasons for some of the unusual features of the record should be sought and remedial steps taken;
- there should be a survey of areas irrigated in recent years to assess by inference the volume diverted and to provide some evidence for high flood volumes in the wadi.

Until these steps are taken the level of uncertainty in the flood events and hydrographs simulated by the model will remain high and the simulated data should be regarded as no stronger than indicative.

**Table 5.5 Summary of the model application to Wadi Tuban**

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
<b>Flood volumes (mcm)</b>													
mean	0.0	0.0	0.1	3.7	5.3	5.1	6.7	15.3	14.9	3.8	0.7	0.0	55.8
cv	0.0	0.0	10.0	1.15	0.9	1.0	0.9	0.6	0.5	1.3	3.6	0.0	0.3
<b>Number of floods</b>													
mean	0.0	0.0	0.0	3.7	5.6	5.6	7.5	16.5	16.5	4.2	0.8	0.0	60.3
cv	0.0	0.0	0.0	1.0	0.9	1.0	0.9	0.5	0.5	1.3	3.8	0.0	0.3
<b>Baseflow (mcm)</b>													
mean	1.4	0.6	0.3	0.2	0.2	1.4	1.6	4.5	6.4	4.1	2.3	1.7	24.8
<b>Total runoff (mcm)</b>													
mean	1.4	0.6	0.4	3.9	5.5	6.5	8.3	19.8	21.3	7.9	3.0	1.7	80.6

## 6 OTHER WADIS

### 6.1 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  $100\text{km}^2$  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.

## 6.2 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.

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 6.1 and 6.2 show the monthly variation of total flow and its variability for the Tihama wadis. Figures 6.3 and 6.4 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 6.5 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 record over 60% of the annual 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 6.3.

Figure 6.6 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.

### 6.3 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 6.7 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.

## 7 EXTREME FLOODS

### 7.1 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 recorded 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<sup>3</sup>/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.

### 7.2 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. Although, even in temperate regions, exceptional floods can be linked to intense convective storms. 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 for Wadi Zabid is to reduce the estimate of the peak

discharge in 1984 from  $2800\text{m}^3/\text{s}$  to  $2620\text{m}^3/\text{s}$ . 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  $2620\text{m}^3/\text{s}$  is consistent with our extrapolation of the present TDA rating table.

The second highest flood ( $2370\text{m}^3/\text{s}$  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 7.1 and the fitted distribution is shown in Figure 7.1. 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 7.1. These indicate that there is a 1 in 20 chance that the 100 year flood could lie outside the range of  $2260$  to  $5140\text{m}^3/\text{s}$ , and that the 50 year flood could lie outside the range  $1250$  to  $3700\text{m}^3/\text{s}$ .

## Wadi Tuban

Annual maximum values for 11 years in the period 1968 to 1982 are quoted in the FAO Project Preparation Report. These derive from the period when Italconsult and GDC were engaged in studies of the wadi. Subsequently, we have a monthly summary of flow characteristics including peak discharges produced by the Irrigation Department in Aden. The annual maximum discharges from these sources are listed in Table 7.1. The data from the Irrigation Department has been listed separately to highlight the difference in interpretation of the highest flood on record, that of March 1982.

The different rating curves used at Dukame over the period since the 1970s have been reviewed and discussed in Chapter 5. They are illustrated in Figure 5.1. No direct measurements have been made of discharge above a few hundred cubic metres per second. This is not surprising: it is extremely hazardous, and the chances of being at the station at the right time are remote, especially when there is no flood warning system.

Consequently, the rating for high floods is based on an extrapolation of curves or equations that are fitted to low and medium discharges. We have attempted to interpret the ratings used by fitting a general 3-parameter equation to the data available in the historical reports. The results, illustrated in Figure 5.1, indicate that estimates of the discharge at a water level of 6.6m range from  $1866\text{m}^3/\text{s}$  to  $2716\text{m}^3/\text{s}$ . The recent Komex data, when extrapolated, give a value of  $1540\text{m}^3/\text{s}$ , well below even this wide range. While this illustrates the difficulty of estimating extreme flood discharges; it does little to add to our knowledge of which estimate is the more accurate.

There is a further complication. Reference has been made to contemporary reports such as Northwest Hydraulic Consultants (1982) who reviewed the flood estimates made up to that time. They note 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.

In the present analysis we have taken all the data available and chosen to use the higher figure for 1982. Applying the same techniques as for Wadi Zabid, the frequency curve based on the same parameters is shown in Figure 7.2, and the predicted floods for a range of return periods are shown in Table 7.2.

### 7.3 REVIEW OF THE RESULTS OF THE FREQUENCY ANALYSIS

Coincidentally, the additional data found for Wadi Tuban means that the length of record is the same for the two wadis, and the difficulties of interpretation discussed in our interim version of this report (March 2003) are largely avoided.

We have used the regional curve proposed by Farquharson et al. There is no benefit to be gained from attempting to fit site-specific curves to these data. The outliers on both graphs mean that objective curve-fitting is meaningless.

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:

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

where Area is in km<sup>2</sup> 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 Nouh 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.

The relative magnitudes of the floods of 20, 50 and 100-year return periods predicted by our analysis and shown in Table 7.3 are supported by Nouh's analysis.

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. 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.

However, these exceptional events are infrequent. They would not be exceptional if they were not. This means that much longer records are needed if we are to define a statistical distribution that

would describe their magnitude and frequency of occurrence.

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 from 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. A more reliable curve might result when the population of records is substantially increased. This is the basis of the Farquharson et al curve where records from Yemen and SW Arabia were pooled to give a 378 station-year set. We cannot improve on that regional analysis with these short record sets.

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.

**Table 7.1 Annual maximum floods reported for Wadi Zabid and Wadi Tuban**

Annual maximum flood discharge ( m <sup>3</sup> /s)					
Wadi Zabid			Wadi Tuban		
			FAO/Ital/GDC		Irrig Dept
1981	2370		1968	200	
1982	760		1969	500	
1983	460		1970	150	
1984	2620		1971	350	
1985	nr		1972	450	
1986	nr		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	220
1994	468		1981	nr	419
1995	110		1982	2640	1896
1996	116		1983		388
1997	122		1984		147
1998	442		1985		252
1999	nr		1986		nr
2000	285		1987		303
2001	203				

Source: TDA, WRAY35, FAO, Italconsult, GDC, Irrigation Dept

**Table 7.2 Predicted maximum floods from GEV analysis**

Maximum flood discharge (m <sup>3</sup> /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 7.3 Recommended design floods - Phase 1 wadis**

Maximum flood discharge (m <sup>3</sup> /s) for different return period T		
T	Wadi Zabid	Wadi Tuban
20	1700	1800
50	2700	2800
100	3700	3880

## 8 FLOOD WARNING AND HYDROMETRY

### 8.1 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 tend to 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 have been selected on both Wadi Zabid and Wadi Tuban as described in a separate report.

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 further 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 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. Some examples that have been analysed show that the volume in the second component flood might well exceed that of the first component even when the peak is lower.

## 8.2 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. Also, these data are not being routinely processed so that there is no check of the validity of the data that might require instrument maintenance or other action to ensure the quality of the records. 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 some locations 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.

### 8.3 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 overwritten) 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.