Rainfall and runoff in Yemen

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Abstract This paper makes use of a water balance study of a mountainous area with a wide range of average annual rainfall in an arid and semiarid region to illustrate the development of both a statistical model of daily rainfall and a rainfall-runoff model. The models are appropriate for these conditions and may be relevant to similar areas. Comparisons of mean rainfall and runoff at the arid end of the scale suggest that runoff coefficients do not conform to common assumptions.

Précipitation et écoulement au Yémen

Résumé Cet article utilise une étude du bilan hydrologique d'une zone montagneuse où la variabilité des précipitations moyennes annuelles est importante dans une région aride à semi-aride pour illustrer l'élaboration d'un modèle statistique des pluies journalières et d'un modèle pluie-débit. Ces modèles sont spécialement conçus en fonction des conditions de la région et devraient être appropriés pour des régions similaires. La comparaison des précipitations et des écoulements moyens quant ils tendent vers zéro conduit à penser que les coefficients d'écoulement ne sont pas conformes aux hypothèses classiques.

INTRODUCTION

A study of the surface water resources of the northern part of Yemen and a review of the hydrological data available for the southern part of the country, which formed part of a UNDP/DTCD project (Technical Secretariat, 1992), have provided information on rainfall and runoff over a wide range of average rainfall in an arid and semiarid climate. Information on the water balance in such a range of rainfall, from less than 50 mm to over 800 mm, is not commonly available but is relevant to research into global climate modelling and climate change. The evidence from this study presents an interesting example of runoff in an arid mountainous climate, with some unique features such as terracing to retain water for agriculture. The paper describes the combined use of two models developed to synthesise both storm rainfall and runoff in such an area. It has also revealed an unusual pattern of relationship between mean rainfall and runoff. It is generally accepted that runoff coefficients decrease as

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rainfall decreases; empirical formulae are often used for modelling rainfall and runoff which suggest that the runoff coefficient decreases to zero as rainfall approaches zero. However, evidence from these studies suggests that the runoff coefficient in this area does not decrease in this way but rather reaches a minimum value.

THE ENVIRONMENT OF YEMEN

An important feature affecting the hydrology in Yemen is the mountainous nature of the country, which rises from sea level to over 3700 m a.s.l. within about 100 km of the Red Sea coast. The topography affects the climate in terms of both temperature and rainfall, while land use and runoff are in turn related to climate and morphology.

The topography (Fig. 1(a)) is dominated by the mountain ranges running parallel to the Red Sea coast through Sana'a towards Aden, with three ridges interspersed by upland plains. The geology consists of basement complex, sandstones and volcanics. These mountains merge with ranges running parallel to the coast of the Gulf of Aden, which reach altitudes of about 2000 m a.s.l. The drainage in the northwest of the country divides along the north-south watershed between steep rivers which run west from the mountains towards the Tihama plain, with a width of about 50 km along the Red Sea coast, and those which drain towards the desert interior to the east. In the southern part of the country, the coastal plain is largely limited to the western parts of the region near Aden, into which the wadis Tuban and Bana drain from areas of Precambrian metamorphics. Further east the coastal plain is more limited in extent and the rivers drain south to the sea from the mountains and the plateau behind the coastal hills. To the north of these coastal rivers, in the centre of the country, the Wadi Hadramaut drains a large area of limestone plateau underlain by sandstones, fissured conglomerates and sediments. The various tributaries of the Wadi Hadramaut are used for irrigation and little runoff flows down the lower valley towards the Indian Ocean (MacDonald, 1985). To the north of the Hadramaut valley a number of ephemeral streams drain towards the desert of the Rub al Khali or 'Empty Quarter'.

Erosion from the steep basins has resulted in talus fans with coarse gravel and silt along the foothills and gently sloping areas of fine silt along the alluvial plains below the outfalls of the wadis in the coastal and interior plains. The natural vegetation of acacia scrub in the foothills has been degraded by the search for firewood, but the mountain areas, especially near the Red Sea, have a semi-humid climate with more soil formation and denser vegetation.

Climate

The rainfall depends on two main mechanisms, the Red Sea Convergence Zone (RSCZ) and the monsoonal Intertropical Convergence Zone (ITCZ). The

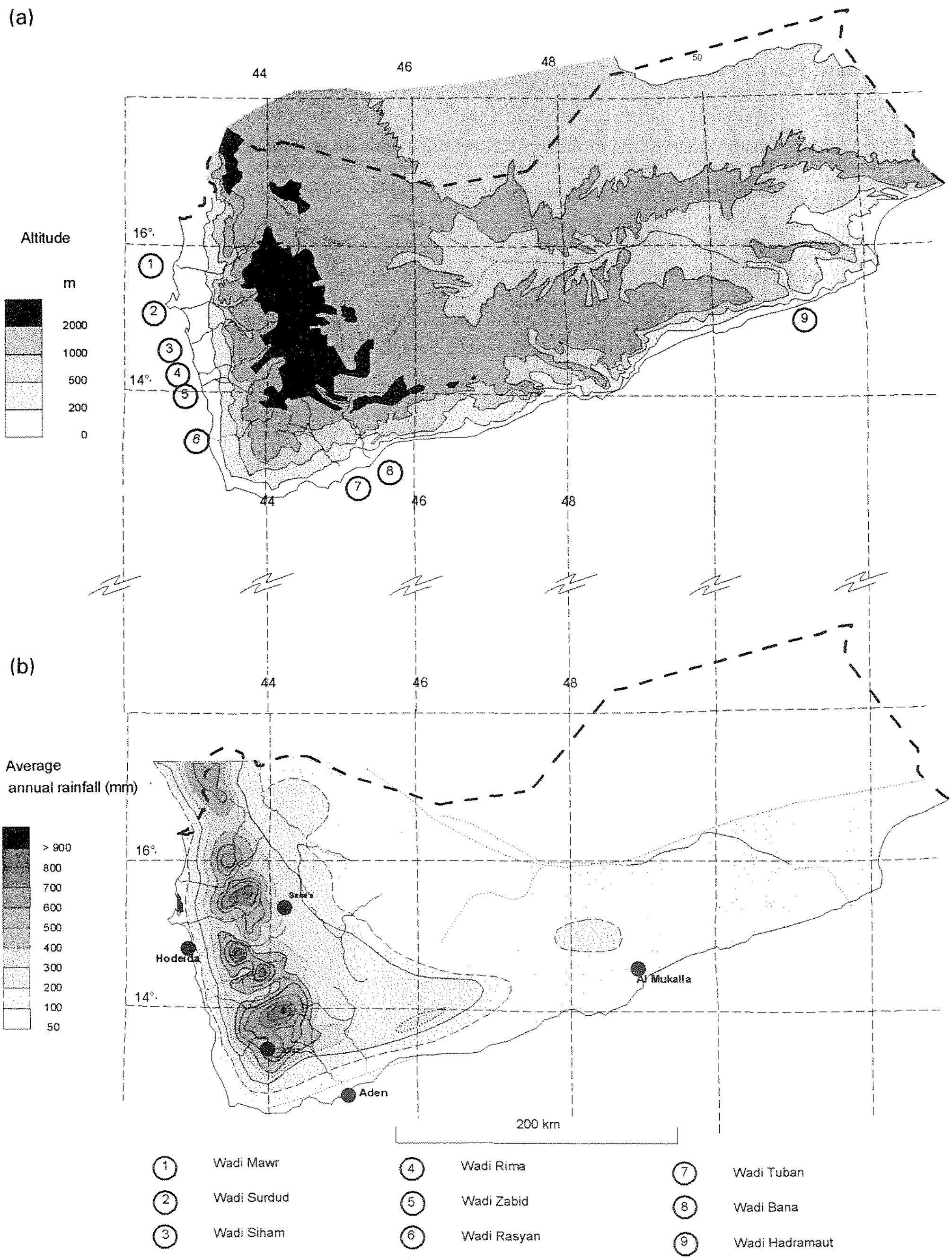

Fig. 1 (a) Topography of Yemen; and (b) mean annual rainfall of Yemen.

RSCZ, whose influence is most noticeable in the west of the country, is active from March to May and to some extent in the autumn, while the ITCZ reaches Yemen in July-September, moving north and then south again so that its influence lasts longer in the south. Both the RSCZ and the ITCZ produce precipitation in convective storms of high intensity and limited duration and extent, but the ITCZ storms have a larger areal extent than those of the RSCZ. The relative importance of the RSCZ and the ITCZ in different parts of the country is reflected in the seasonal rainfall distribution, which is summarized in a later section. The annual rainfall distribution is included in Fig. 1(b), and shows a combination of the rainfall mechanisms and the orographic influence of the mountain ranges.

Land use

The land use of the upland areas of Yemen, particularly in the north, is based on the unique practice of bunding and terracing which permits reliance on rain-fed agriculture, in an area where rainfall is relatively sparse, by impeding the immediate runoff and erosion which the topography would otherwise allow, and ensuring the recharge of soil moisture and local groundwater. This terracing is extremely ancient and highly labour-intensive, with entire hillsides covered with stone bunds and earth banks interspersed with terrace areas which may be as narrow as one metre in steep areas. It is noteworthy that runoff is delayed during intense storms, with the terraces flooded as though with surface irrigation, and this allows the cultivation of such crops as cereals and vegetables on areas of steep slopes and sporadic storms. The runoff regime must be affected by the existence and the intensity of this terracing, which is observed to be greatest on steeper and wetter hillsides and becomes less intense as the slopes and average rainfall decrease inland or towards the southeast. Insofar as the terracing provides soil moisture which is used for agriculture, its effect must be to reduce total runoff and especially storm runoff. Any assessment of the water resources or investigation of the hydrology of the area must take account of this practice, and of differences in its intensity over the area or with time; the cost of maintenance is making it more economical to pump groundwater for irrigation, so that the use of terracing is becoming less intense with time.

The lower reaches of the wadis and the coastal plains are used for irrigated agriculture to the extent that water resources allow, with crops like cotton, sorghum, millet and sesame, and rely on the runoff from wadis draining areas of higher rainfall. This irrigation is based in the upper basins on the diversion of normal flows and on the lower plains through the use of spate flows to recharge the soil moisture directly or to recharge the underlying aquifer with groundwater which is later pumped for irrigation. Spate irrigation was traditionally based on temporary embankments, but permanent structures have been built on the major deltas to divert water into distribution canals.

HYDROLOGICAL DATA

The records available for the study of the water balance in Yemen are in general relatively short. The measurement of wadi flows has been the responsibility of individual basin authorities or of consultants operating for limited periods, and a number of the rainfall stations are also under local control.

Some 200 rainfall stations have operated at some time in the northern part of the country (Technical Secretariat, 1992) but only about 40 stations have as many as 10 complete years of record available. The available records for the much larger area of southern Yemen are even more sparse, and records for only some 40 stations have been assembled by Binnie (1987), with very short term stations established in the Hadramaut also listed. Although the geographical coverage of stations in northern Yemen is reasonable, the stations in the south are concentrated in the area around Aden and the coverage in much of the area is very sparse.

The number of meteorological stations from which climate records are available to estimate evaporation and potential transpiration by the Penman method is adequate for most purposes. Estimates have been made for 18 stations in the north and for three stations in the south, although climate records are available for some additional stations.

The records for wadi flows are more sparse and sporadic, with some information on some 50 stations in the north and only four stations with reasonable periods of records in the south; these are supplemented by seven tributaries of the Wadi Hadramaut with flow measurements available between 1977 and 1981.

Rainfall

The distribution of rainfall in both space and time is the main factor controlling the distribution of water resources. Because of the sparse and short term nature of the rainfall records it was necessary not only to derive an isohyetal map from incomplete data but also to generalize the time distribution of storm rainfall. From the stations available on the data base assembled for the UNDP/DTCD project, 57 stations in northern Yemen with at least six complete years of recent records were selected for analysis. The monthly and annual averages for these stations were estimated and were used to derive the annual isohyetal map summarized in Fig. 1. In order to derive this map in areas where rainfall records were absent relationships between average rainfall and elevation, distance from the coast and latitude were used to fill gaps.

In southern Yemen a small number of long term gauges were used to give rainfall indices for individual years, and averages for short term stations were derived by comparison with these long term stations. However, large areas were devoid of gauges and the isohyets for the southern area in Fig. 1 were guided (Binnie, 1987) by considering the likely effect of topography on rainfall and also the evidence from vegetation distribution.

The relationship between mean annual rainfall and topography is clearly evident. Rainfall rises from less than 50 mm along the Red Sea coast to a maximum of 700-800 mm to the west of the main watershed west of Sana'a, and falls steadily to below 50 mm along the Gulf of Aden and also inland.

The seasonal rainfall distribution is illustrated by monthly averages for typical stations, given in Table 1 and in Fig. 2. All the averages are to some extent bimodal but the relative importance of the main rainfall-producing mechanisms is illustrated by this distribution. The RSCZ in the early season is more important in the west nearer the Red Sea coast, and also in the north of the country where the effect of the ITCZ loses its impact. The effect of topography on the rainfall distribution is illustrated by these stations as well as the isohyetal map.

To enable the rainfall pattern to be understood and thus modelled statistically, the rainfall records from the northern area were examined for evidence of spatial correlation, but the results were disappointing, suggesting that spatial coherence was not a feature of the rainfall. In order to derive a

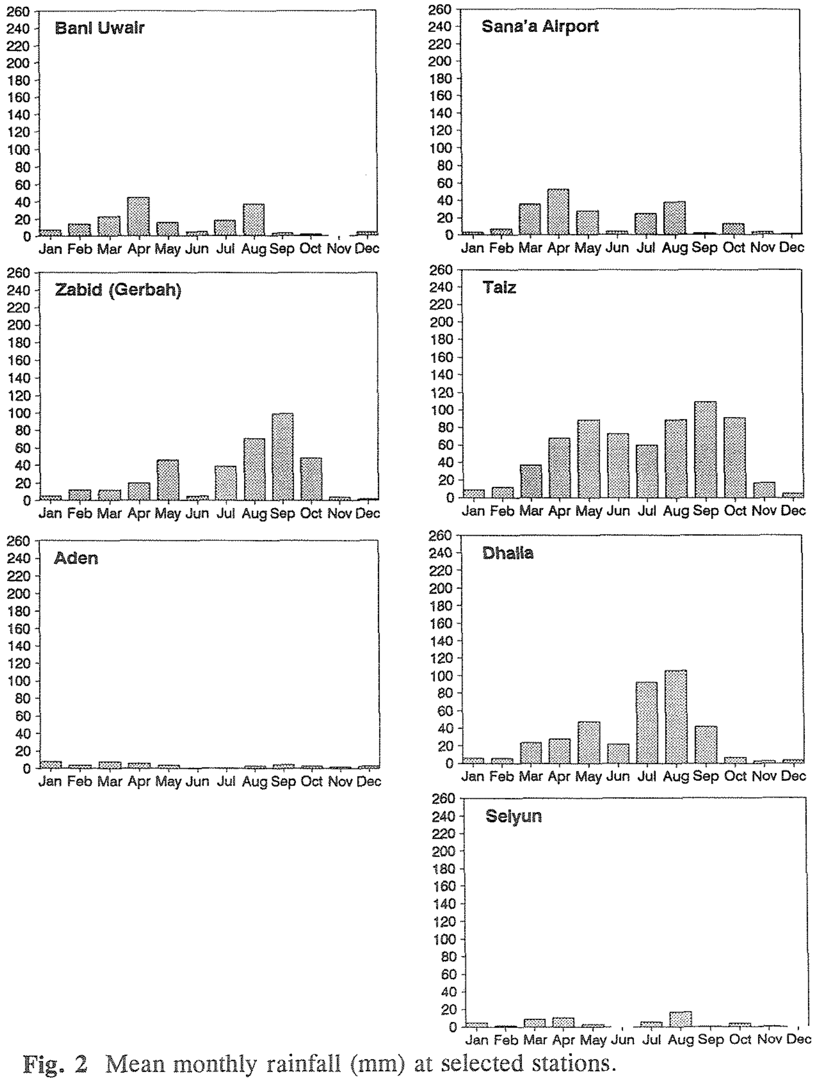

Fig. 2 Mean monthly rainfall (mm) at selected stations.

Table 1 Monthly mean rainfall (mm) at selected stations

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Bani Uwair (43°41'E, 16°46'N, 2100m)	7	14	23	45	16	5	18	37	3	2	0	4	174
Sana'a Airport (44°13'E, 15°28'N, 2190m)	3	7	36	53	28	4	25	38	2	13	3	1	213
Zabid (Gerbah) (43°26'E,14°09'N, 240m)	5	12	12	20	46	5	39	71	99	48	4	2	363
Taiz (44°01'E,13°35'N, 1400m)	9	12	37	68	89	73	60	89	110	91	17	5	660
Dhalla (44°44'E,13°42'N, 1500m)	6	6	24	28	48	22	93	106	42	7	3	4	387
Aden (45°02'E,12°47'N, 27m)	8	4	8	6	4	1	1	3	5	3	2	3	48
Seiyun (48°49'E,15°57'N, 635m)	5	2	9	11	3	0	6	17	1	4	1	0	59

general model of daily rainfall which could be used to generate falls which were consistent with experience, some ten stations with daily records over the northern area were selected for analysis. The first result was that when the number of rain-days with rainfall over 5 mm (a quantity chosen to avoid inconsistencies of recording low falls) was compared with mean annual rainfall, there was a direct relationship between the two irrespective of station position or altitude. This implies that the average fall per rain-day is approximately constant throughout the country; the average value of storms over 5 mm was found to be about 17 mm. This finding suggests that storm cells are able to produce the same magnitude of rainfall across the country and that the isohyetal map mainly reflects differences in the number of storms. No difference between seasons was detected. High daily rainfall totals were found in all ten stations irrespective of the mean annual rainfall. This, together with the finding on the number of rain-days, suggests the hypothesis that daily falls observed at any one station are effectively samples from a statistical population of falls which is constant irrespective of position or altitude.

A statistical model was developed to generate daily rainfall values to accord with this hypothesis. The details of this model will be described elsewhere (Plinston, work in progress), but the model may be summarized briefly as follows. It is assumed that the number of rain-days in a month is linearly related to the mean monthly rainfall and the expected rainfall in each rain-day is constant irrespective of the month. Thus the appropriate number of storms in any month is chosen to reflect the monthly rainfall pattern and their magnitudes are drawn from an underlying log-normal distribution. The use of this model enabled rainfall series based on the observed pattern to be provided for conversion to runoff series.

The rainfall in the southern part of the country has not yet been subjected to the same analysis since complete daily falls were not readily available.

However, preliminary comparison of maximum rainfall records over a wide range of average annual rainfall suggests that the same model is appropriate. Records of annual maximum daily falls are available for 11 stations (Binnie, 1987) and it was noted that the mean annual maximum daily rainfall tended to increase with mean annual rainfall, doubling as the station annual averages ranged from 48 to 380 mm. However, this is not inconsistent with the individual storms being drawn from an identical distribution, with the number of events proportional to the mean annual rainfall. The individual annual maximum rainfall series were analyzed statistically to derive storm magnitudes corresponding to a range of annual frequencies. The hypothesis requires that the number of storms is proportional to the mean annual rainfall. The series were made comparable by dividing a nominal annual return period by the mean annual rainfall to give an index return period proportional to the number of individual storms. When this is done there is no tendency for the storm magnitude to increase with average rainfall.

Evaporation

Estimates of potential evapotranspiration have been made at 10 sites in the northern part of Yemen (Technical Secretariat, 1992) and at three sites in southern Yemen using slightly different coefficients (Binnie, 1987). Monthly estimates at selected stations are shown in Table 2 and in Fig. 3. The effect of elevation through the influence on temperature is offset by its influence on humidity. However, because potential transpiration greatly exceeds average rainfall, the effect of evaporation on the water balance is limited to the degree by which soil moisture storage is drawn down between runoff-producing storms. Thus evaporation is to an extent a secondary factor on the distribution of runoff.

Runoff

The intermittent nature of the wadi flows and the instability of many sites in the alluvial beds of the wadis make it difficult to measure runoff without

Table 2 Mean monthly potential evaporation (Penman) (mm)

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Sana'a Airport	140	137	165	151	209	212	183	192	186	190	149	136	2050
Zabid (Gerbah)	125	124	152	197	204	176	152	167	163	174	154	125	1913
Taiz	141	126	163	175	178	162	145	137	154	162	141	140	1824
Al Kod	121	127	155	167	186	177	176	182	167	154	133	120	1865
Seiyun	92	108	149	165	186	180	191	188	163	141	116	89	1768

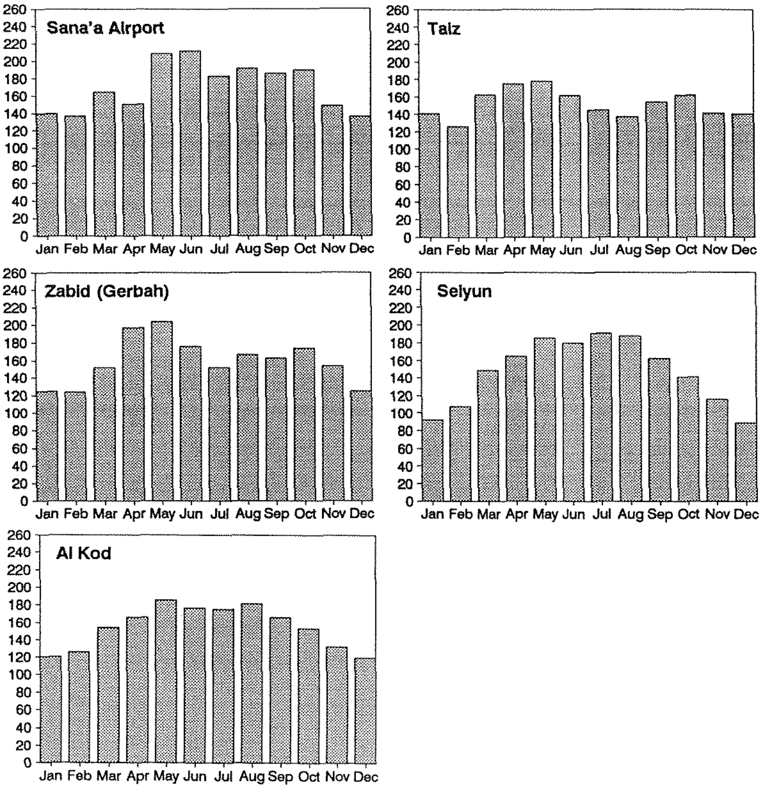

Fig. 3 Mean monthly potential evapotranspiration (mm) at selected stations.

continuous calibration of gauging sites. The difficulties of access have meant that reliable long term records of runoff are available only for the main wadis entering the Tihama plain in northwest Yemen and the two main wadis flowing on to the southern plain near Aden. There are only three sites with more than 10 years of record in northwest Yemen and two sites with over 20 years of data from southern Yemen. At other sites the flow series are too short to be useful for planning purposes and the only method by which reasonable lengths of record can be obtained is by extending the measured flows using measured and generated rainfall data. This technique should provide flow records which are typical of the long term regime.

Rainfall records in general cover a longer period than flow records and because point rainfall is easier to measure than wadi flow the reliability of rainfall records should be greater. Because the structure of rainfall incidence has been shown to be relatively simple, with the number of storms varying seasonally but their magnitude drawn from a common population, it is possible to generate synthetic rainfall data with the same characteristics as those of the measured records. There remains the need to develop a complementary rainfall-runoff model which can convert rainfall data to runoff series and which reproduces the characteristics of measured flows.

A rainfall-runoff model had previously been used to extend flows for the Wadi Jawf basin, but a general model was needed which could be transferred from one basin to another, or even to an ungauged site, with its parameters estimated from basin characteristics. The model output should be based on monthly time scales, but should distinguish between baseflow and flood runoff which are measured separately and used for different water resource purposes; daily flow generation is also needed for irrigation planning, though the reliability of generated flows will depend on the availability of daily records for calibration. The model should take account of the effect of the terracing which is an important factor in controlling runoff in this area, though empirical evidence on which this component could be tested may have to await direct experiments.

The details of the development and structure of the hydrological model used for this project are described elsewhere (Farquharson, in press), but the model may be summarized as a distributed one which takes account of the wide variations of rainfall input and land type over each basin. The northern part of the country was classified into surface runoff characteristic zones, five of them runoff-producing types, and three runoff-absorbing zones as far as surface runoff was concerned. The concept of runoff-absorbing zones may seem strange, but significant areas within Yemen have very deep layers of alluvium and have virtually no outflow. Examples of these types of zone are the Tihama coastal plain, the eastern desert and the intermontane plateaux within the Central and Northern Highlands. These runoff-absorbing zones may contribute baseflow runoff, but generate negligible surface runoff. The runoff producing zones are generally in the steeper, rocky parts of catchments with thin soils, but also include some flat parts of the central highlands and eastern plains having impermeable soils.

The core of the model involves the conversion of daily rainfall data within each separate rainfall zone to runoff, with the response of each runoff zone being modelled separately in each case. The model is illustrated in Fig. 4. The model uses the Soil Conservation Service (1964) curve number (CN) method to convert the rainfall within each runoff zone to runoff. The CN is adjusted dynamically during the year according to antecedent precipitation indices for each runoff zone. These curves estimate an appropriate initial abstraction and continuing infiltration for a given rainfall depth, with the estimated runoff as the residual. The computed runoff from each zone is summed and a proportion of this runoff is routed through a storage representing interflow and terrace storage. The remainder, together with the excess from the interflow store, is routed through a baseflow store which divides runoff into flood runoff and baseflow.

This model was calibrated subjectively for the six wadis flowing towards the Tihama, using about five years of rainfall and flow data in each case. The calibration was based on comparisons of observed and predicted monthly flood flows, baseflow and total flows, with some attention to the magnitude and frequency of daily flood flows. Because the main factor affecting the conver-

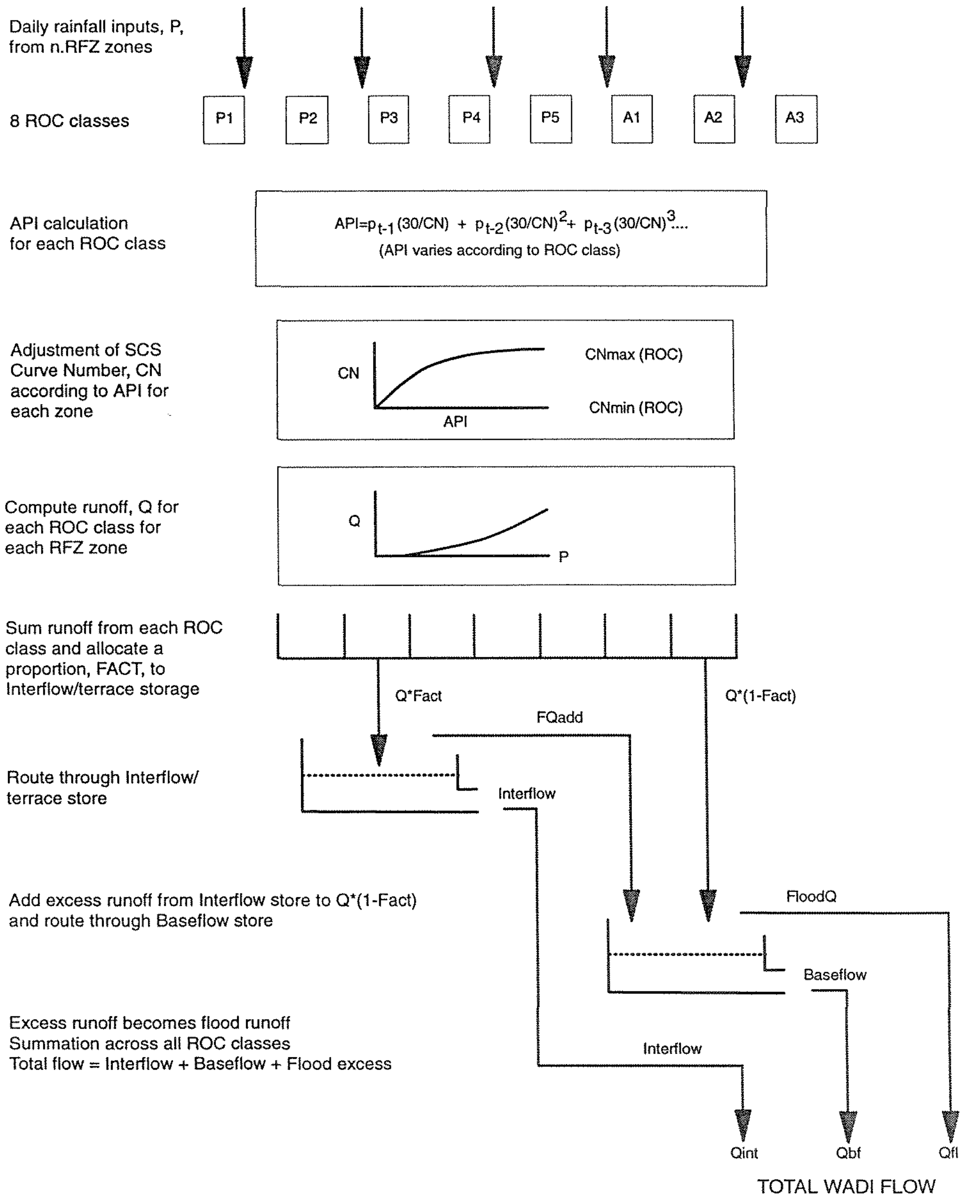

Fig. 4 Schematic description of distributed daily rainfall-runoff model based on the SCS method.

sion of rainfall to runoff is the curve number, which could be estimated from the runoff characteristic zones, the model was also used to generate runoff series from rainfall series for other wadis of the northern area. The average seasonal distributions of wadi flows at selected sites are given in Table 3 and illustrated in Fig. 5; the flows quoted are those from 20-year generation studies for the two northern sites and available measured flows at the southern sites. (Although annual runoff values are available for 20 years between 1955 and

Table 3 Mean monthly wadi runoff ($m^3 \times 10^6$)

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Wadi Mawr ($7910 km^2$)	4.06	6.50	5.86	18.7	30.0	7.20	8.65	19.0	10.3	8.43	5.25	4.71	129
Wadi Zabid ($4630 km^2$)	1.67	1.71	3.75	6.51	18.0	7.41	9.83	15.7	11.0	5.80	2.88	1.86	86.1
Wadi Tuban ($5340 km^2$)	0.89	0.52	0.25	4.58	8.83	8.87	12.4	27.7	31.0	9.53	3.24	1.69	110
Wadi Bana ($7400 km^2$)	2.28	3.70	5.73	17.0	15.3	5.17	24.2	43.5	24.8	5.06	4.67	2.89	154

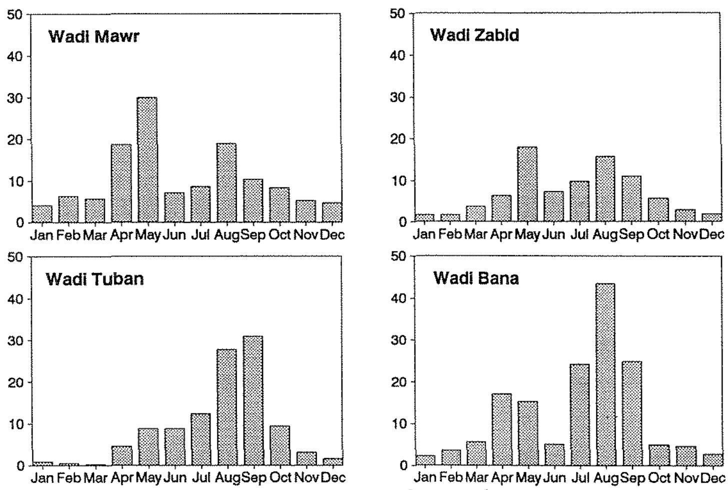

Fig. 5 Mean monthly wadi runoff ($m^3 \times 10^6$).

1980 for the Wadi Tuban, reliable monthly flows are available only for the drier period of 1973-1980 (Groundwater Development Consultants, 1981)). These flows further illustrate the relative importance of the two rainfall-producing mechanisms in the different parts of the country, with the importance of the early season RSZC in the northern basins contrasting with the dominance of the later ITCZ in the southern sites.

Because the project was initially confined to the northern area, the study of runoff potential of the rest of the country is at present limited to the sparse and sporadic flow records for wadis in the southern and eastern parts of the country. The existing flow records may be used to assess the mean runoff as a function of rainfall over these areas and to compare the relationship with that deduced for the northern area where hydrological modelling has been carried out.

Although only two wadis, near Aden, have been measured for a reasonable period of time, there are several other sites where estimates of mean runoff may be made from shorter periods of record. The results of these assessments are summarised in Table 4, though the effect of sampling error

Table 4 Mean basin rainfall and runoff

Wadi	Gauging station	Area (km²)	Rainfall (mm)	Years of data	Runoff ($m^3 \times 10^6$)	Runoff (mm)
Mawr	Float Recorder	7910	405	(20)	129	16.3
Surdud	Faj al Hussein	2300	495	(20)	81.8	35.6
Siham	Mahal Saleem	4900	410	(20)	72.6	14.8
Rima	Al Mishrafah	2250	465	(20)	50.4	22.4
Zabid	Kohlan	4630	515	(20)	86.1	18.6
Rasyan	Gorge	1990	595	(20)	16.4	8.2
Mawza		1480	480	est	20	13.5
Jawf	Al Hazm	14000	178	est	150	10.7
Adhanah	Marib	12600	163	est	100	7.9
Najran	Border	4400	151	est	70	15.9
Tuban	Dukeim	5340	460	20	125	23.4
Bana	Bateis	7400	310	27	154	20.8
Rabwa	Al Miyuh	455	320	9	3.09	6.8
Ahwar	Fuad	6410	210	10	84	13.1
Amd / Duan	Qaudah	6553	100	4	20.3	3.1
Al Ain	Ajlaniyah	1500	80	4	9.68	6.5
Saar	Otfa	2540	45	4	3.0	1.2
Bin Ali	Mawshih	743	65	4	4.15	5.6
Juaymah	Juaymah	743	35	4	0.225	0.3
Idim	Ghuraf	5485	70	4	41.3	7.5
Thibi	Tarim	718	40	4	1.9	2.6

Note: (20) indicates estimate based on 20 years of simulated flows.

may obscure much of the long term differences. The comparison of estimated average rainfall and runoff for the whole country is illustrated in Fig. 6, where it appears that the runoff coefficients for the northwest basins are quite variable and may reflect the varied topography and effects of terracing or diversions, while the coefficients for the relatively dry southern and eastern basins do not fall below about 5%. This result is surprising at first sight, but is consistent with the models for rainfall and runoff developed for the wetter parts of the country. If the magnitude of storms is independent of average rainfall, which is related only to the number of storms in each month or year, then the runoff generated by each storm depends only on the basin characteristics which are constant and the antecedent rainfall conditions affecting the basin soil moisture. The distribution of antecedent moisture conditions will depend on the incidence of previous rainfall and thus on the frequency of storms for the wetter basins, but this effect will decrease with average rainfall. If this rainfall is sufficiently low, the antecedent conditions may rarely affect the percentage runoff, and the runoff coefficient will depend on geology and other fixed basin characteristics.

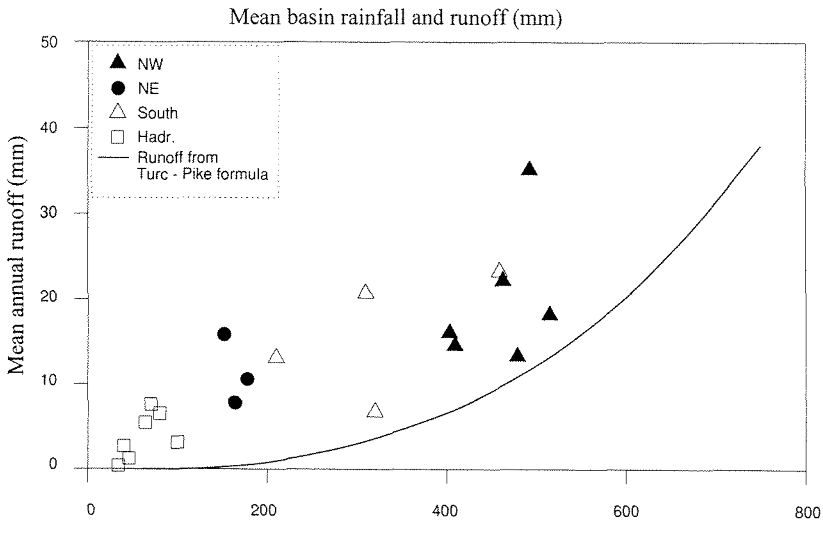

Fig. 6 Mean annual basin rainfall and runoff (mm) showing Turc-Pike runoff estimate.

This result is surprising to those who are used to expect runoff coefficients to decrease with mean rainfall, and that in the limit as rainfall approaches zero the runoff coefficient also approaches zero. For example, in a discussion of the role of the hydrological cycle in climate, Dooge (1989) discusses several empirical relationships which have been proposed, and notes that "all these relationships reflect the asymptotic behaviour expected on physical grounds for the limiting cases of extreme aridity ($AE = P$) and extreme humidity ($AE = PE$) and are similar in general shape". Dooge notes the Turc-Pike equation (Pike, 1964) to be much easier to handle than the other equations. This is:

$$E_a = RE_o/(R^2 + E_o^2)^{1/2}$$

where E_a is actual evaporation, R annual rainfall, E_o open water evaporation. In order to illustrate this point, the results of this equation, with E_o set at 2250 mm, are included in Fig. 6. The results of this comparison will require further investigation by extension of the rainfall analysis to these drier areas and confirmation of the rainfall-runoff process by continued measurements of wadi flows and by hydrological modelling, but it is consistent with the existing data and the analysis which has been carried out during the project.

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