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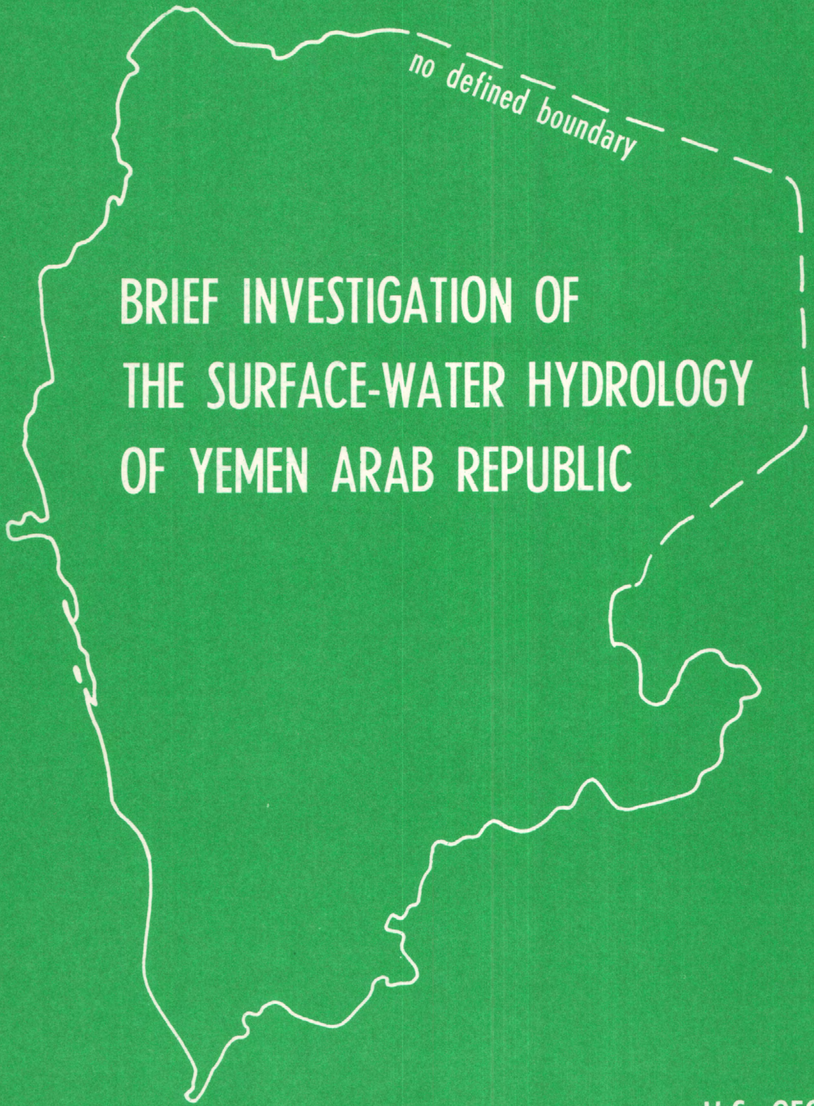

BRIEF INVESTIGATION OF THE SURFACE-WATER HYDROLOGY OF YEMEN ARAB REPUBLIC

U.S. GEOLOGICAL SURVEY

Open-File Report 77–150

Prepared in cooperation with the Yemen Arab Republic under the auspices of the United States Agency for International Development

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

A BRIEF INVESTIGATION OF THE SURFACE-WATER HYDROLOGY OF YEMEN ARAB REPUBLIC

By H. C. Riggs

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Reston, Virginia

1977

UNITED STATES DEPARTMENT OF THE INTERIOR

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CONVERSION FACTORS

Factors for converting the International System of Units (SI) to English units are given below to three or four significant figures. However, in actual use, the English equivalents should be determined only to the number of significant figures consistent with the values for the metric units.

Metric (SI)	Multiply by	English
millimeters (mm)	0.03937	inches (in)
meters (m)	3.28	feet (ft)
square meters (m^2)	10.76	square feet (ft^2)
kilometers (km)	.621	miles (mi)
square kilometers (km^2)	.3861	square miles (mi^2)
liters per second (L/s)	.03532	cubic feet per second (ft^3/s)
million cubic meters (Mm^3)	810.8	acre-feet (acre-ft)
kilograms (kg)	2.205	pounds (lb)
cubic meters per second (m^3/s)	35.3	cubic feet per second (ft^3/s)
meters per second (m/s)	3.28	feet per second (ft/s)
degrees Celsius (°C)	9/5(°C) + 32	degrees Farenheit (°F)

A BRIEF INVESTIGATION OF THE SURFACE-WATER HYDROLOGY OF YEMEN ARAB REPUBLIC

By H. C. Riggs

ABSTRACT

Yemen is a mountainous country bordered by a desert on the east and a coastal plain on the west. Rainfall is low and seasonal; consequently, most streams (wadis) are ephemeral. The natural flow regimens of many of the smaller wadis are modified by terracing for agriculture. The only streamflow data available in Yemen are short records on four large wadis. A brief field investigation and application of reconnaissance techniques are the bases for the largely qualitative description of the hydrology, and for the proposal to collect streamflow data needed for orderly development of the expanding economy.

INTRODUCTION

This report is based on a one-month assignment to Yemen for the purpose of estimating the flow characteristics of ephemeral streams and for determining the feasibility of estimating ground-water recharge from hydrologic-meteorologic data. The investigation took place April 28 - May 26, 1976, and included field trips, literature searches, field measurements of channels, investigation of an outstanding flood, and surveys of high-water marks from some recent floods. G. C. Tibbitts, Jr., (U.S. Geological Survey, Sanaa) provided assistance without which my investigation would have been much less extensive.

Geography of Yemen

The Yemen Arab Republic (figure 1) lies near the southwest tip of the Arabian Peninsula. Most of the country is mountainous with several reaching over 3,000 meters in height; the highest is 3,620 meters. Within this mountainous region are the Sanaa Plain and many other areas of fairly flat land. West of the mountains along the Red Sea is a nearly flat coastal plain called the Tihama. East of the mountains is the Rab Al Khali, the Empty Quarter, a flat desert area which extends into Saudi Arabia. Figures 2 and 3 show typical topography.

Mean annual rainfall ranges from less than 100 mm along the Red Sea to as much as 1,000 mm near Ibb. East of the mountains, rainfall is low, but amounts are undefined. Most rainfall occurs in spring and summer. Storm totals are usually not large; although the rainfalls may be intense, the durations are usually short. Most storms are limited in areal extent as well.

Daily range in temperature in degrees Celsius in the Sanaa inter-mountain plain is from about zero to 20^{o} in winter and from 27^{o} to 30^{o} in summer. In the Tihama, summer maxima will be greater than 37^{o} but seldom exceed 40^{o}. Winter minima will rarely be below 20^{o}.

Streamflow is ephemeral in nearly all but the largest streams because of the spare rainfally concentrated in spring and late summer, the short duration of rainfall events, the high evapotranspiration rates, the impermeable rocks, and especially because of the extensive man-made terraces which provide water storage.

Village water supplies are from wells and cisterns. Most agriculture depends on rainfall.

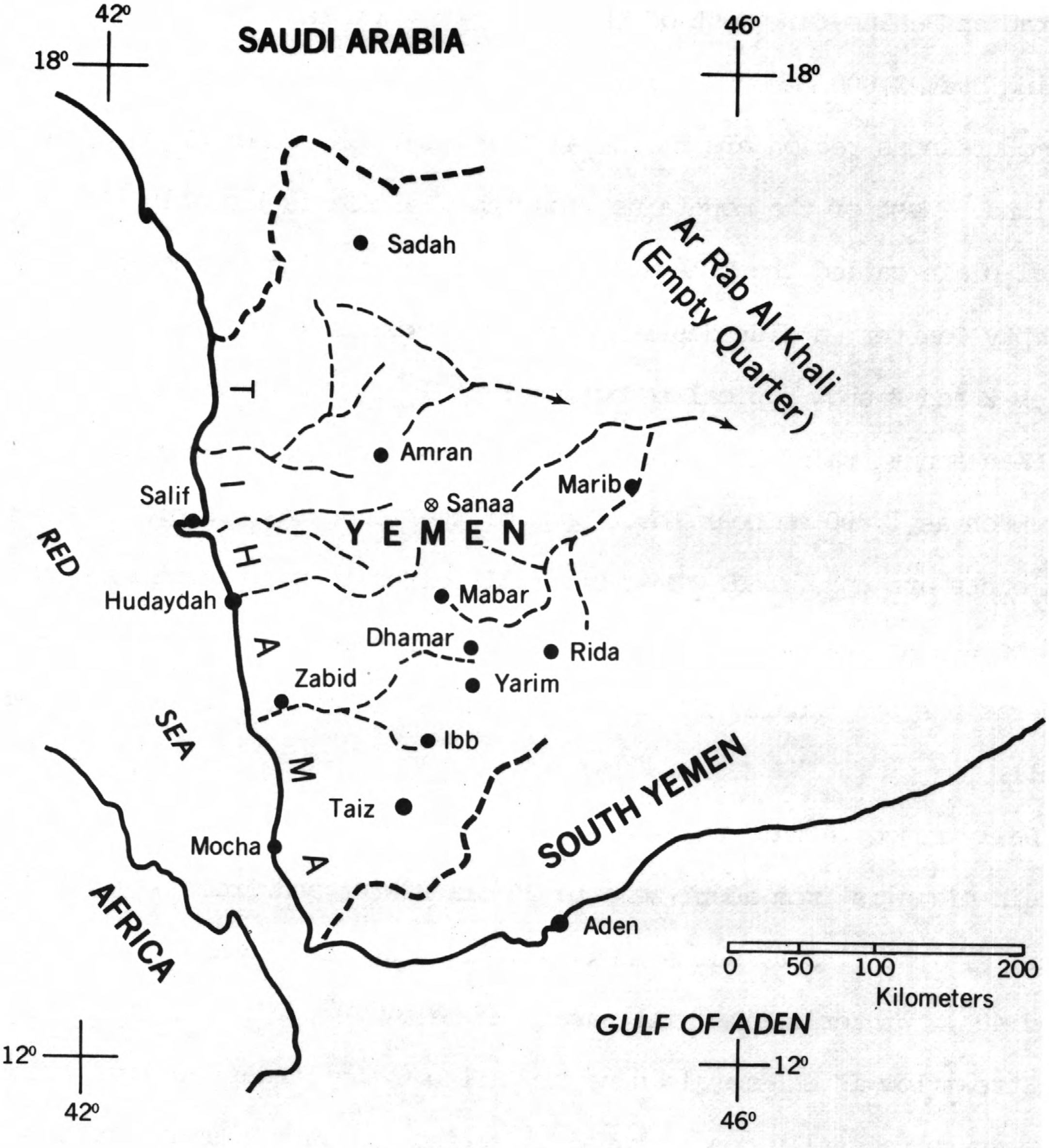

Figure 1.--Map of Yemen.

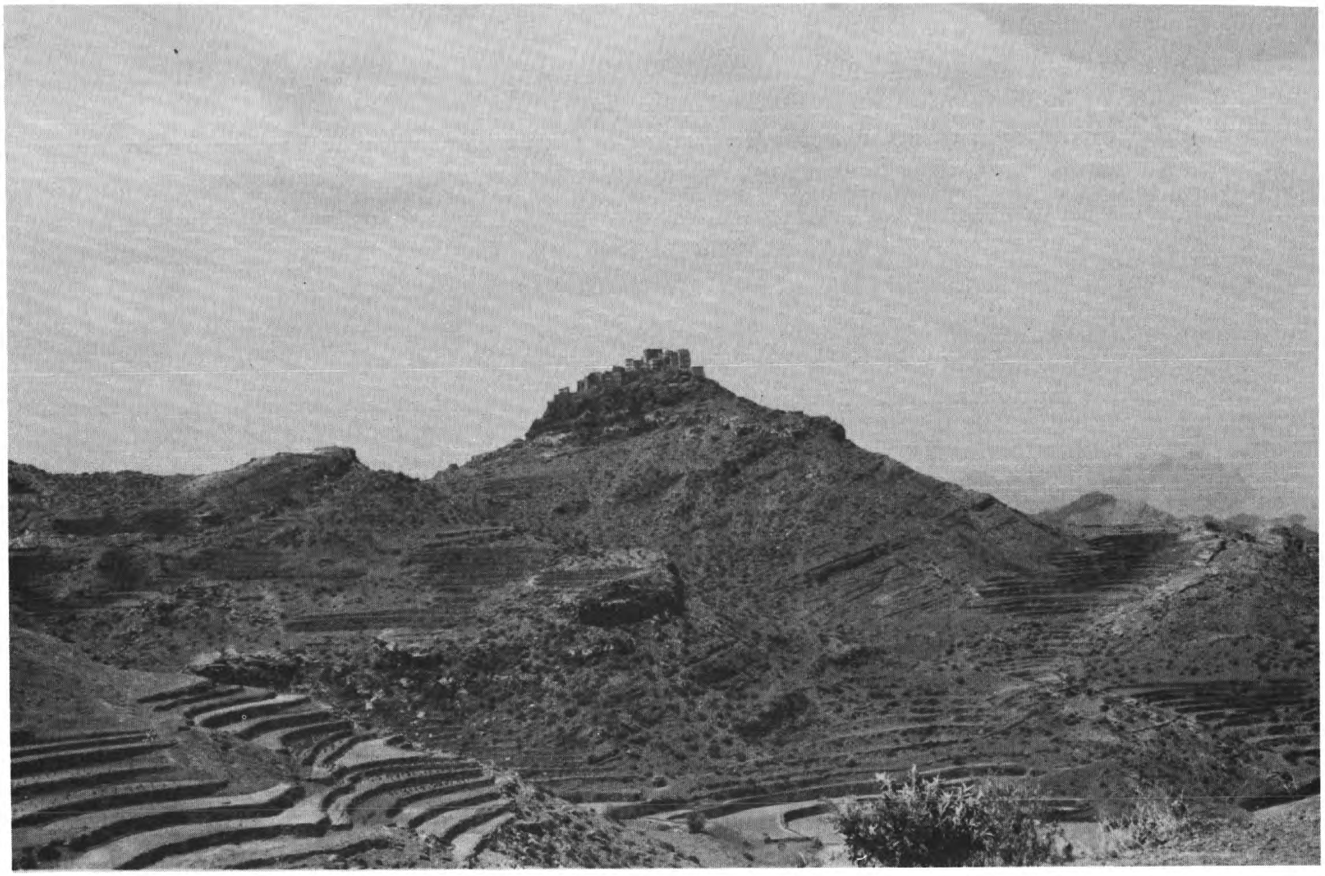

Figure 2.--Typical mountain topography.

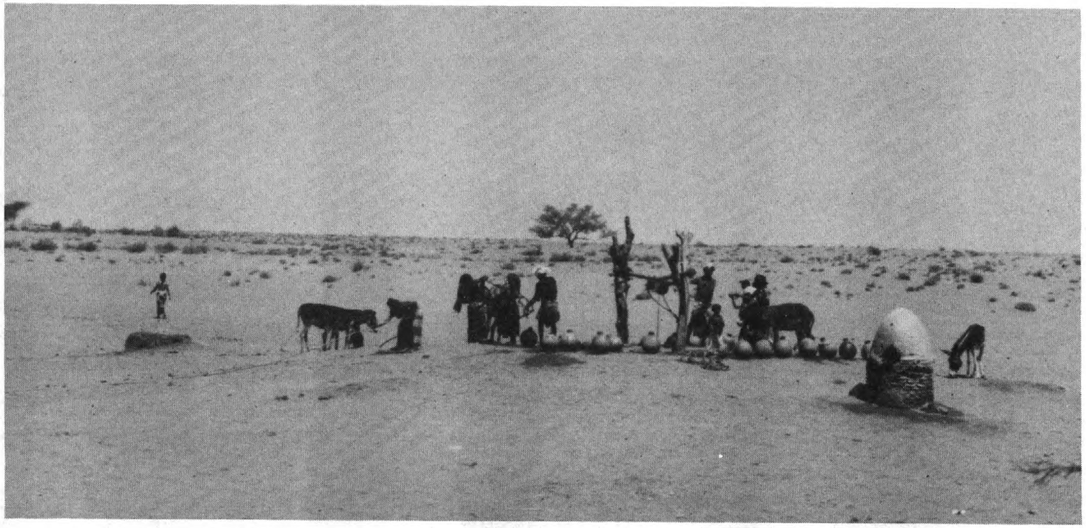

Figure 3.--A well in the Tihama.

Rainfall Characteristics

Yemen is arid. Annual mean precipitation as high as 1,000 mm occurs over a small area near Ibb, but generally ranges from about 400 mm in much of the mountain area to as little as 100 mm east and west of the mountains. Annual precipitation is highly variable from year to year as shown by figure 4 for Sanaa (from ITALCONSULT, 1973, and other sources). Distribution of rainfall within the year is shown by the monthly means for Sanaa and Taiz in figure 5; data from Toffolon (1956). Sanaa has appreciable rainfall only in the spring and midsummer; June is usually dry. In contrast, Taiz has a rainy season of 7 consecutive months.

Notable daily rainfalls at Sanaa from 1963-70 are the basis for frequency estimates by ITALCONSULT (1973). The concluded that daily rainfalls greater than 30 mm occurred with an average frequency of twice a year; greater than 35 mm, once a year; greater than 40 mm, once in 2 years; and greater than 60 mm, once in 10 years.

The limited areal extent of most storms is indicated by monthly rainfall records collected in Amran Valley during most of 1975. Four rain gages, operated by the U.S. Geological Survey, lie nearly on a straight line in which the extremes, Thillah and Raydah are about 35 km apart. Precipitation totals are listed in table 1.

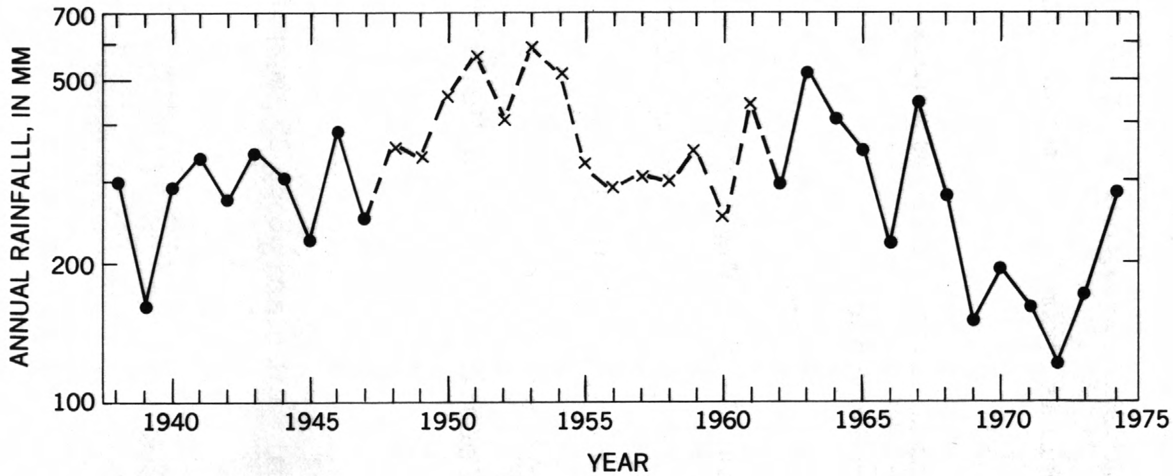

Figure 4.--Annual rainfall at Sanaa (graph for 1938-72 is from ITALCONSULT, 1973).

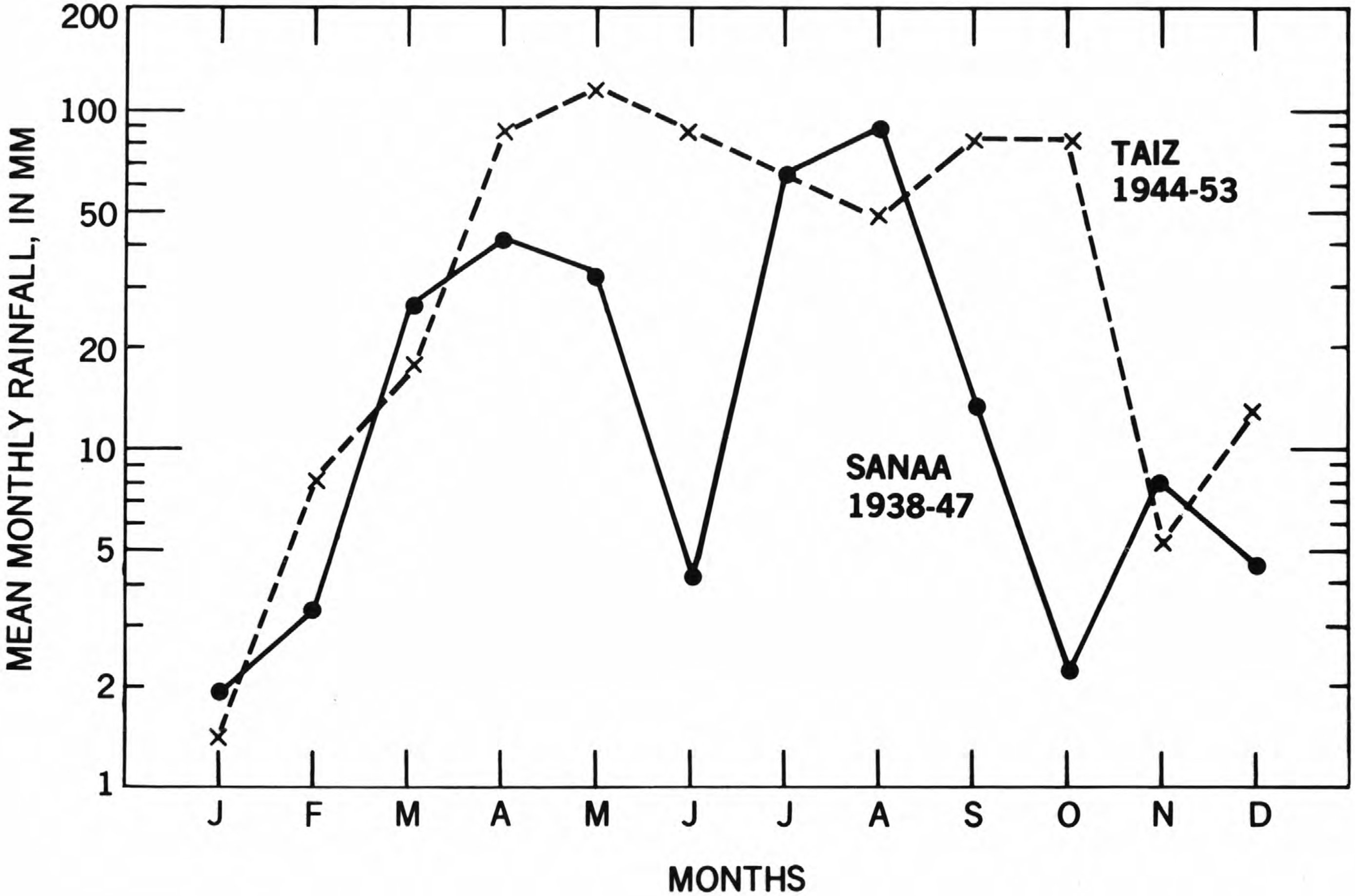

Figure 5.--Mean monthly rainfall at Sanaa and Taiz.

TABLE 1.--Monthly rainfall in Amran Valley, March to December 1975, in millimeters

Station	Month									
	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Thillah	43.3	38.3	0	57.5	115.	0	0	0	0	0
Al Jannat	0	44.3	0	0	70.8	92.6	0	0	0	0
Mengida	55.0	65.3	0	0	72.5	81.3	0	0	0	0
Raydah	7.8	120.6	0	20.8	40.2	109.8	0	0	0	0

Streamflow Characteristics

Continuous records of streamflow in Yemen are available only on Wadi Zabid (1969 to present, fragmentary), Wadi Mawr (1973 to present), Wadi Laah (1975 to present) and Wadi Rima (1975 to present). Figure 6 shows the channel and the 1969 gage on Wadi Zabid. Mean discharges and flood-peak frequency characteristics of a few Yemen wadis have been estimated from records on Wadi Jizan in Saudi Arabia and on records of several wadis in the Peoples Democratic Republic of Yemen (South Yemen). The data available are grossly inadequate even for the large streams. Some published estimates of mean discharge are shown in table 2. These are no known records on small perennial streams, although the discharge of Wadi Dahr (Yemen A.R.) was measured as 60 L/s, date unknown (ITALCONSULT, 1973).

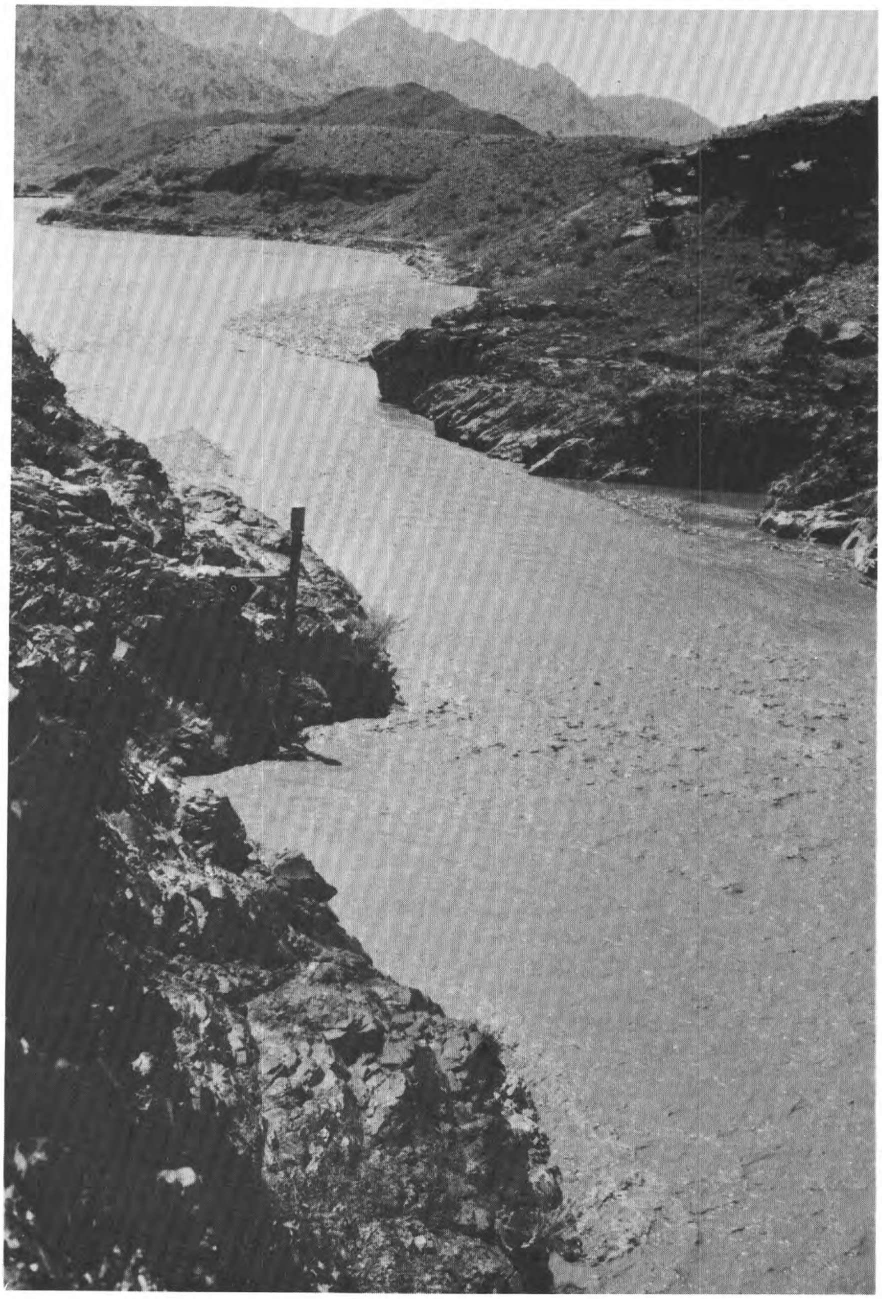

Figure 6.--Wadi Zabid and the gage used in 1969-70.

TABLE 2.--Mean annual discharges of some wadis in the Arabian Peninsula

Wadi	Drainage area, square kilometers (km^2)	Annual precipitation, millimeters (mm)	Mean annual discharge, millions of cubic meters (Mm^3)	Reference
Tiban, S. Yemen	5,060	460	200	Camacho, 1967
Bana, S. Yemen	6,420	290	167	do
Jizan, Saudi Arabia	1,100	480	90	do
Zabid, Yemen A.R.	4,630	400	145	Tipton & Kalmbach Inc., 1975
Mawr, Yemen A.R.	7,500	400	200	Unpublished

The mean annual discharges of large wadis appear to be related to drainage area and rainfall as shown in figure 7 based on data from table 2. But this relation is only approximate because the mean discharges are not well defined; that for Wadi Zabid is based on about 4 years of record, and that for Wadi Mawr on an incomplete year. Furthermore, the mean rainfalls are only approximations; and finally, the drainage areas, at least of the Yemen wadis, can be defined only approximately because of the nature of the topography.

Daily and annual variability of discharge is high. Characteristic flood hydrographs on Wadi Zabid at Kolah as taken from TESCO (1971) are shown in figure 8. Annual variability of Wadi Zabid is indicated by the 1970 runoff of 112 Mm^3 (million cubic meters) and the runoff from July to December 1969 of 174 Mm^3. Maximum floods experienced on the large wadis of the southern Arabian Peninsula appear low relative to those in United States

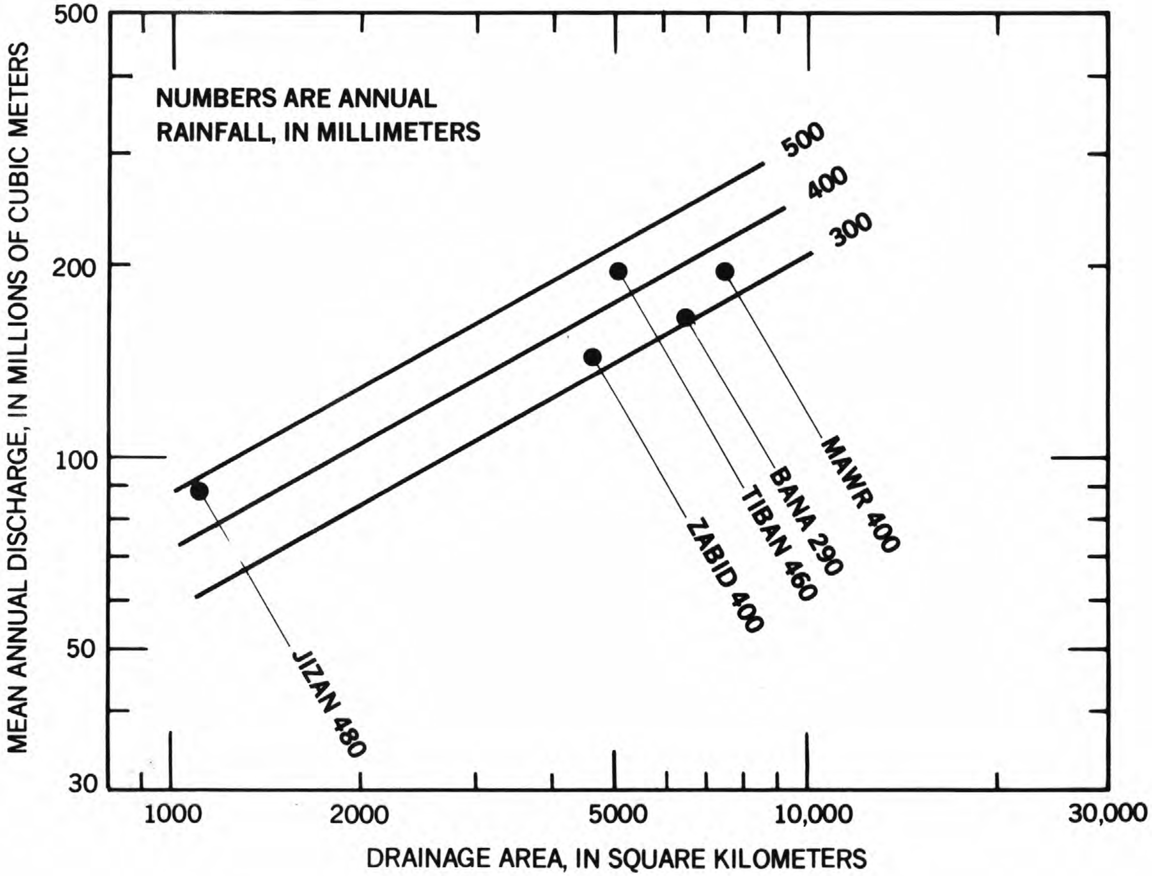

Figure 7.--Tentative relation of mean annual discharge to drainage area and annual precipitation for large wadis.

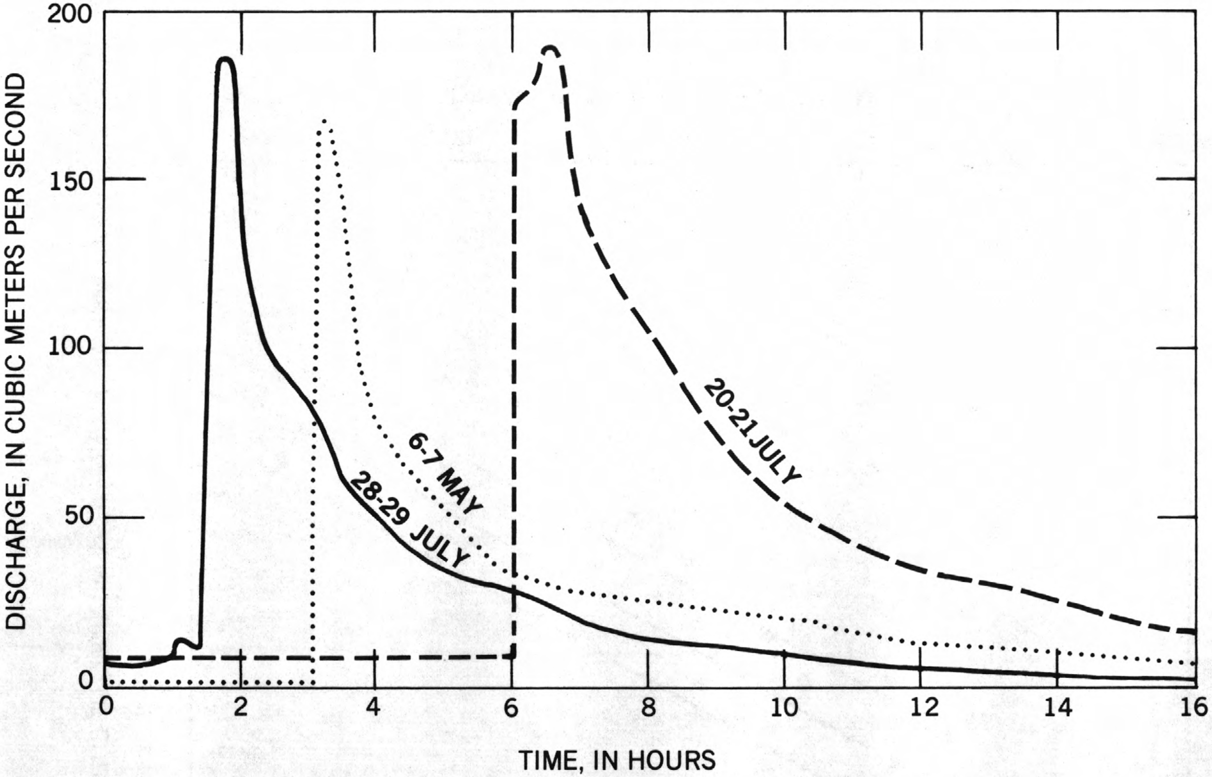

Figure 8.--Flood hydrographs of Wadi Zabid in 1970 (from TESCO, 1971).

as shown by figure 9, in which maximum floods reported by TESCO (1971) are plotted with the enveloping curve of maximum United States floods (from Matthai, 1969). However, this is not conclusive because of the limited data.

Flows of most of the smaller streams are greatly modified by terracing in the basin, and often in the bottom of the stream valley itself. See figures 10 and 11. The storage behind terraces retains all the runoff from storms of average magnitude with the result that there is no stream channel in the valley bottom. On larger drainages a small channel may be maintained, with the overflow going to the terraced areas. Because of the effect of off-stream storage on flow the topographic drainage area is not related to the flow. In addition, the drainage area is usually indeterminate. Floods in a completely terraced valley produce flow successively from one terraced area to the next with some erosion. Some bunds (terraces) have rock spillways to transfer water from one area to the next. Extreme floods may depost rock and debris on the upper terraced area and may breach the bunds and cause considerable erosion downstream, even making a channel downstream. However, the damage to terraces will usually be repaired within a year. The effect of terracing on runoff is shown by the following hypothetical example. Assume a basin draining 2 km^2 in which the lower part of the valley, 0.2 km^2, is completely terraced. A 50 mm rainfall might produce 15 mm of runoff from the unterraced 1.8 km^2. This would run onto the terraced area and would result in a depth of 15 (1.8/0.2) = 135 mm. Adding this to the 50 mm that fell directly on the terraced area would give a depth of 185 mm of water on the terraced area. Much of that water could be retained; little would flow out of the basin. Thus, it can be seen that farmers make

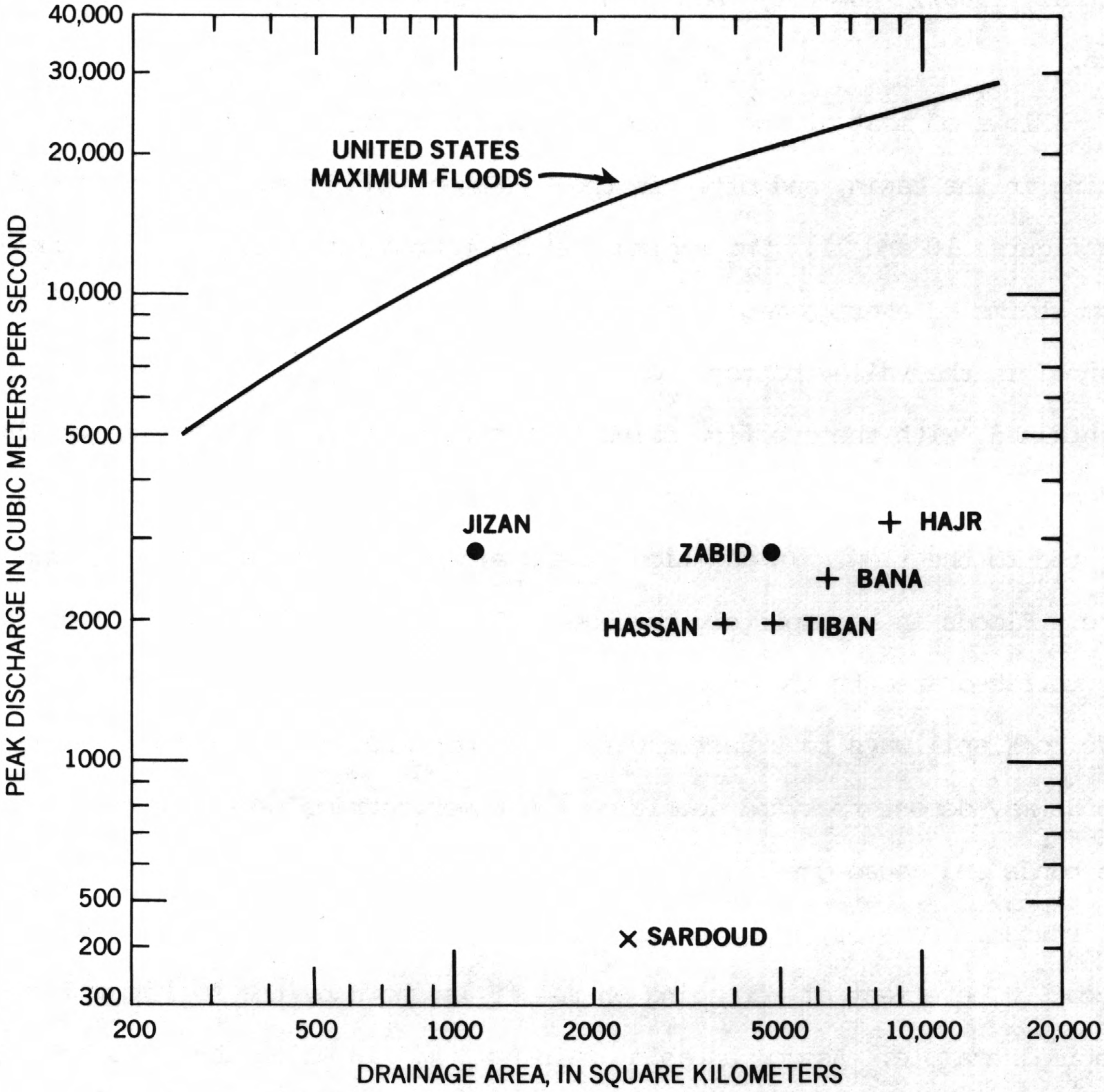

Figure 9.--Maximum known floods in the southern Arabian Peninsula compared with maximum floods in the United States.

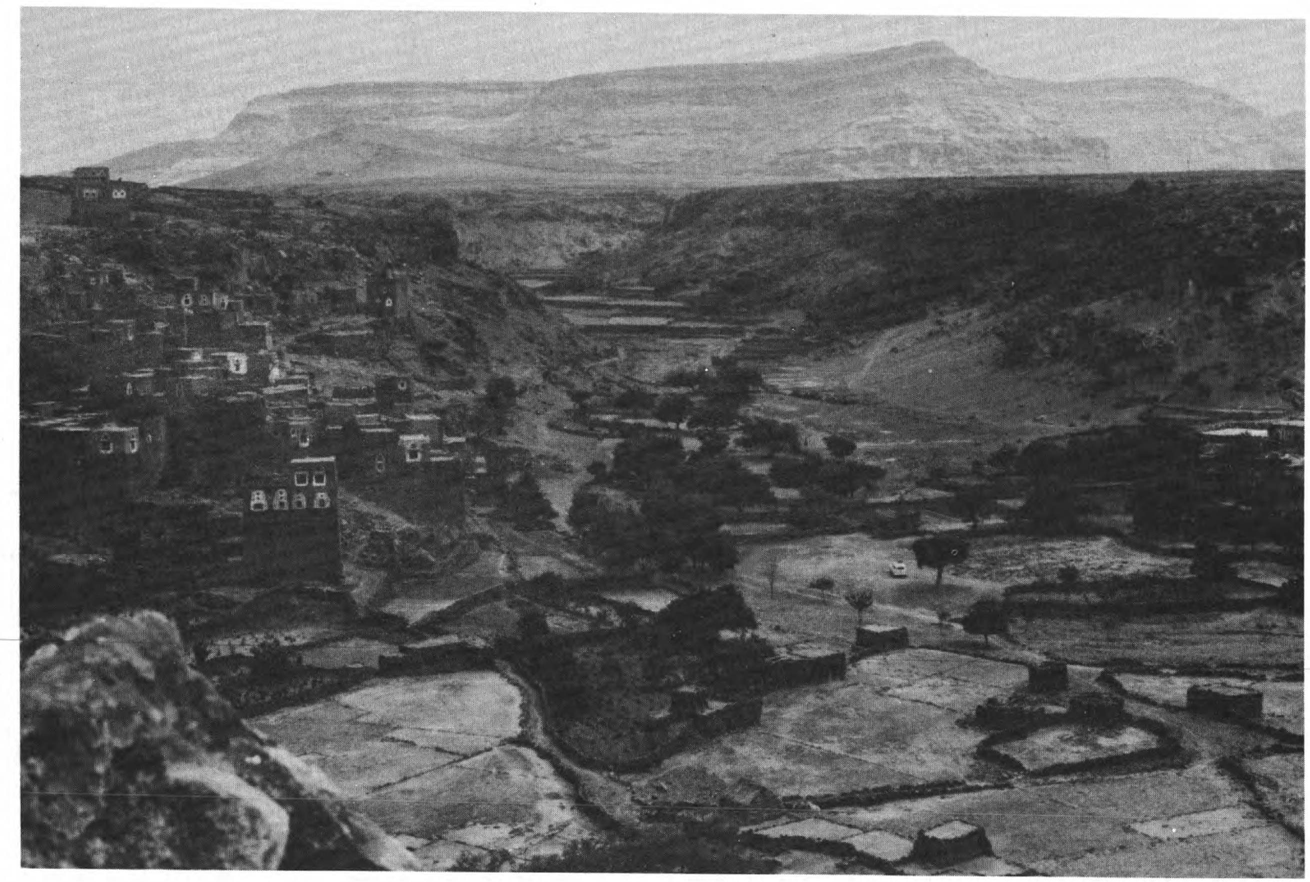

Figure 10.--A terraced valley northwest of Sanaa. The village is Al Hajer Saeed.

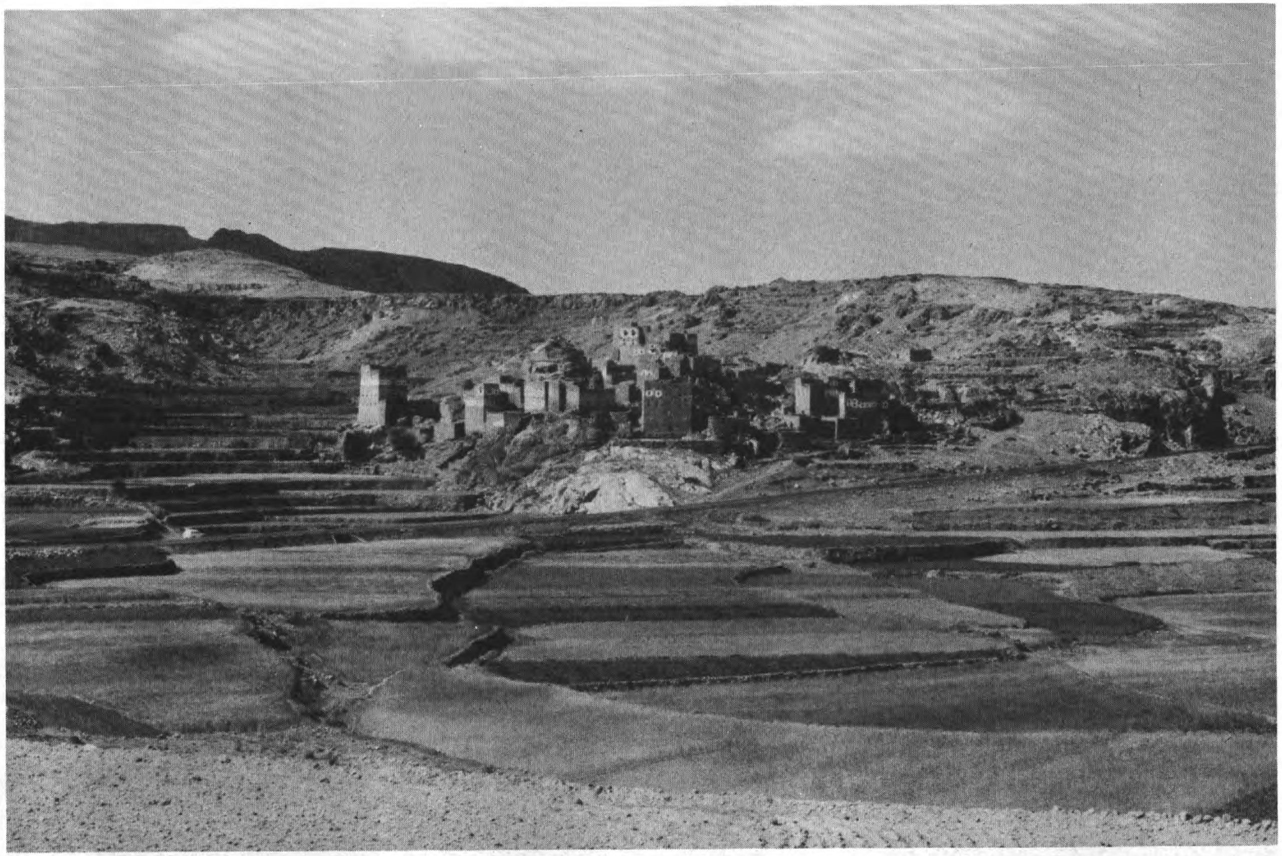

Figure 11.--Terraced valley on Sanaa-Hudaydah highway.

maximum use of available water. Consequently there is little need for definition of flow characteristics on such drainage basins (they are not streams in the usual sense).

Where stream channels are developed, the bed is usually subject to considerable movement (is unstable) as may be the banks, and streamflow carries a heavy sediment load. No measurements of sediment transport are known. But the combination of suspended-sediment and bedload movement would seem to preclude reservoirs as a means of regulating flow. Marib dam is an example of one which probably became ineffective because of silting. The dam and an irrigation system were built by the Sabaeans about 650 B.C. and the dam washed out during Ethiopian rule in the sixth century after years of neglect (Abercrombie, 1964).

CHRONOLOGY OF FIELD INVESTIGATIONS BY AUTHOR

April 29 - Flow in 6-place Cessna with G. C. Tibbitts, Jr. (USGS), James Aubel (Peace Corps Geologist), L. L. Wagner (Assistant Director, U.S. Agency for International Development, Sanaa) and L. A. Maupin (Drilling Supervisor, AID). Purpose of the flight was to examine some geologic structures in order to assist in evaluation of ground-water potential. The author went along to obtain an overview of the topography, the stream channels, and other hydrologic features. Routing was from Sanaa to Thillah, Amran, Sadah, Wadi Jawf, Marib, Rida, Damth, Dhamar, Sanaa.

April 30 - Drove to Wadi Dahr about 15 km northwest of Sanaa with G. C. Tibbitts, Jr. to look at results of an extraordinary flood of August 1975. This site was revisited May 17.

May 3 - Drove to Amran Valley with Tibbitts and Aubel where USAID is drilling to determine ground-water availability.

May 5 - Drove to Hudaydah with Tibbitts and Aubel.

May 6 - Drove to Wadi Zabid, inspected gaging station, located site for survey of flood marks, and stayed at camp of Tihama Development Authority.

May 7 - Made slope-area survey of recent flood on Wadi Zabid using crew from Tipton and Kalmbach, Inc., advisor to Tihama Development Authority.

May 8 - Drove to Wadi Mawr Camp, measuring the widths of some channels enroute.

May 9 - Visited gaging station on Wadi Mawr and surveyed high water profile on left bank of a slope-area reach. Wadi was in flood and difficult to cross. Survey is to be completed by Tipton and Kalmbach, Inc.

May 10 - Returned to Sanaa

May 13 - Drove south through Mabar, Dhamar, Yarim, and Ibb to Taiz.

May 14 - Drove to Wadi Warazan (on main road to Aden); measured discharge of Wadi Warazan (0.128 m^3/s); measured channel widths; returned to Taiz and drove south on road to Naqil Hasus and back to Taiz.

May 15 - Returned to Sanaa, measuring some stream channels enroute.

May 17 - Revisited Wadi Dahr, surveyed a slope-area reach, and inspected stream channels as far north as the Amran Valley drainage.

VISIT TO TIHAMA, MAY 5-10

Purpose of this trip was to observe the hydrology of the coastal plain, to evaluate the flow records collected on Wadi Zabid and on Wadi Mawr, and to determine the suitability of stream channels for estimating the magnitude of the ten-year flood from channel width. See Riggs (1974) for description of method.

Wadi Zabid was gaged at Kolah from July 1969 to December 1970 by TESCO (1971). A later report by TESCO (1973), which the author has not seen, includes records for 1971 through 1973. Gaging is now being carried on by the Tihama Development Authority, advised by Tipton and Kalmbach, Inc.

Wadi Mawr and Wadi Laah have been gaged since early 1975 by Tihama Development Authority; records through December 1975 have been computed. A British team will have about a year of record on Wadi Rima by December 1976. No other continuous streamflow records in Yemen are available. No sediment data are known.

The gage locations appear to be as good as any available on these alluvial channels, but the stage-discharge relation probably changes with each rise in stage. In addition to the movable streambed, the stream carries a heavy load of sediment. A lack of high-stage measurements make some parts of these records of questionable reliability. Cable measurements are made with the operator on the bank. A 15-lb weight is usually used. Sounding lines are not tagged. Some earlier measurements by TESCO were made using floats.

To help define the upper ends of the rating curves on Wadi Zabid and Wadi Mawr I surveyed the high-water marks and channel cross sections of a recent flood on Wadi Zabid and high-water marks on Wadi Mawr (with the assistance of Tipton and Kalmbach, Inc.). Discharge will be completed slope-area method proposed by Riggs (1976) when the surveys are completed.

Another objective of the Tihama trip was to examine wadi channels to determine if there were reaches suitable for estimating the 10-year flood from channel width. For this purpose, we examined the gaged channels and some channels along the highway. Several channels were judged suitable and the width measured. All except the two gaged channels were dry.

No data are available in Yemen for defining the relation between 10-year flood and channel width. The relation developed from Utah-Wyoming data, figure 12, H. C. Riggs and K. L. Wahl, written communication, 1974, is proposed for use in Yemen. Based on previous channel morphology studies, the slope of the relation should be similar, but it is possible that a different flow regime would require a shifting of the relation. It was hoped that the 10-year flood was well enough defined at Wadi Zabid to assess the applicability of the Utah-Wyoming calibration but the few years of record are inadequate to define the 10-year flood. TESCO (1971) estimated the flood frequency curve for Wadi Zabid based on data for European rivers and on peak discharges of Wadi Zabid for a few years. Although this frequency curve, which shows the 10-year flood to be between 1,000 and 1,350 m^3/s, is largely speculative, it provides the only basis for testing the applicability of the Utah-Wyoming relation. Using that relation, the 10-year flood at Wadi Zabid based on channel width is about 740 m^3/s. In another check, the cross sectional area of the 10-year flood, according to TESCO (1971), is 200 m^2. Applying this area to figure 4 of Riggs (1976), relating discharge to cross-sectional area for mountain streams in western United States, gives a discharge of about 600 m^3/s. If these two relations defined by United States data apply to Wadi Zabid, then the velocity estimates of TESCO (1971) must be too high. They are much higher than maximum mean reach velocities observed in United States where few exceed 3 m/s; see p. 246, Leopold, Wolman, and Miller (1963). Consequently, the TESCO frequency curve

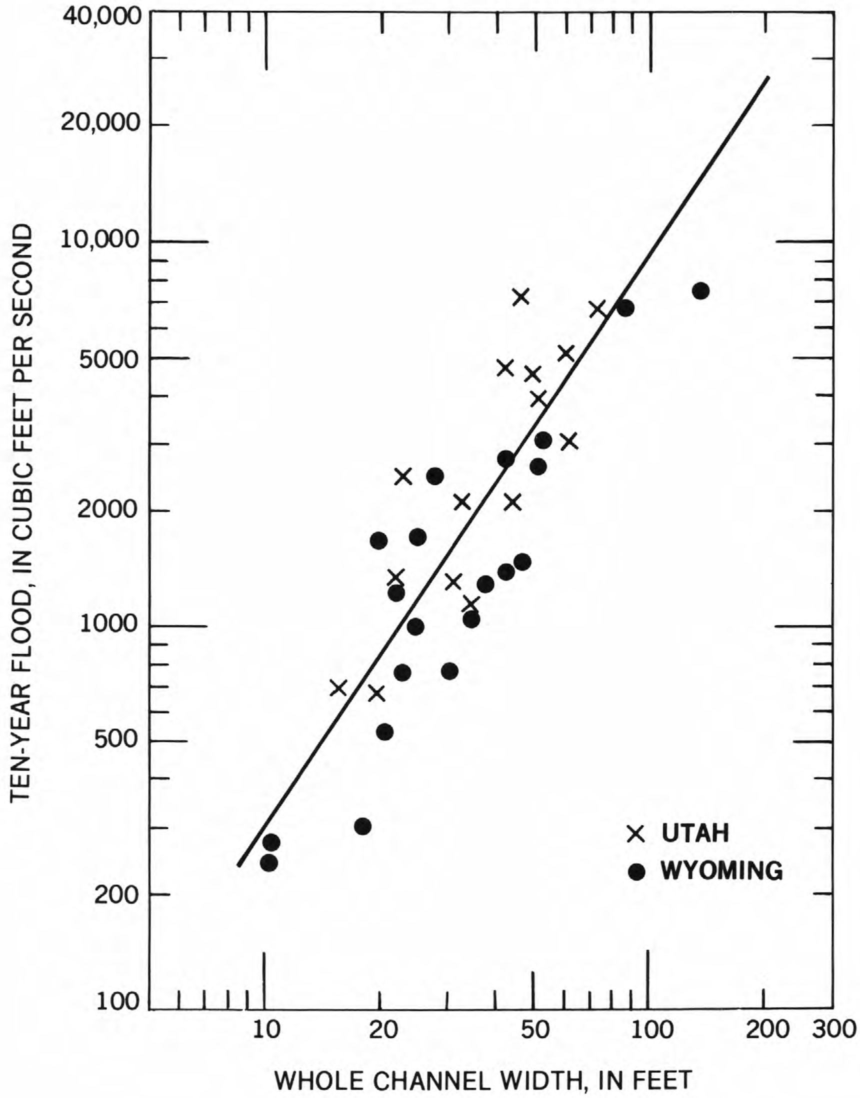

Figure 12.--Relation of 10-year flood to channel width for arid regions of Utah and Wyoming, USA.

is questioned and use of the Utah-Wyoming relation is suggested for Yemen streams.

ESTIMATING 10-YEAR FLOOD FROM CHANNEL WIDTH

The reliability of a 10-year flood magnitude estimated from channel width depends on (1) applicability of the relation to the streams in the region, (2) availability of suitable stream reaches, and (3) judgment in selecting the cross section and the level at which the width is measured. Guidelines are given by Riggs (1974).

The previous section indicated the lack of data for calibration or even for verifying the applicability of the Utah-Wyoming relation to Yemen streams. However, the natural stream channels in Yemen appear similar to those in western United States so that relation (figure 12) is assumed applicable.

Reaches suitable for width measurements are not common on alluvial streams but some can be found on most such streams. This is also true in Yemen; it may be necessary to look at a kilometer or more of channel before finding a usable reach. The method applies only to natural channels. Thus, many small drainages in Yemen are excluded because terracing has modified or eliminated the channel. Nor does the method apply to small, extremely steep channels. But terracing in the headwaters of a basin would not preclude use of the method on an undisturbed channel downstream; it is assumed that the terracing has been in place for many years and that the downstream channel has adjusted to the modified flow regime. Thus, in spite of channel modifications, there are many stream channels for which a reasonable estimate of the 10-year flood could be made from channel width.

TABLE 3.--Ten-year flood estimates from channel width

Wadi and location	Measured whole channel width, feet	10-year flood cubic meters per second
Ain (left branch of Wadi Zabid) 6 km south of Zabid	60	120
Nasery (right branch of Wadi Zabid) 3 km south of Zabid	120	340
Unnamed (?) 2 km south of Wadi Rima	70	150
Rima 2 km south of Al Husayniyah	200	740
Unnamed (?) 9 km south of Bayt Al Faqih	62	130
Unnamed (?) 5 km south of Bayt Al Faqih	127	370
az Zullani 3.5 km south of Al Mansuriyah	55	110
Warazan 34 km from Taiz-Sanaa Highway on highway to Aden	63	130
Warazan Trib. 3.2 km toward Taiz from Wadi Warazan	65	140
Zuba Near Qaldah, between Taiz and Ibb	90	220
Nakhlan At As Sayani	126	360
as Sayl Near Jiblah	64	140
Al Jannat North of Jiblah, above highway and above big tributary from right	65	140
Dahr Above Thillah Road	75	170
Unnamed (?) At about long 44^{o} E., near Sanaa-Hudaydah Highway. Site known as Dobson's Falls	30	44

Channel size has also been used to estimate mean streamflow (Hedman, 1970; Hedman and others, 1972; Moore, 1968). But a relation of mean flow to channel size can be explained on a physical basis only if there is a good relation between mean flow and the channel-forming discharge. Mean flow does not affect the channel size. Therefore, a relation of mean flow to channel size is applicable only to a hydrologically-homogeneous region for which it was defined; such a relation is not transferrable areally as is the relation of 10-year flood to channel width. Since there are no streamflow data in Yemen suitable for defining a relation of mean flow to channel size, that approach is not possible.

Table 3 lists the streams on which were found suitable reaches for estimating the 10-year flood from channel width, and gives the widths and the estimated 10-year flood discharges. Of course only a few wadis were examined. Photographs of some of the channels are given in figures 13-15.

WADI DAHR FLOOD OF AUGUST 25, 1975

Wadi Dahr, about 15 km northwest of Sanaa, is perennial in a reach of 2 or 3 km. Consequently, that reach is heavily populated and intensely developed agriculturally. On August 25, 1975 a catastrophic flood occurred in this area. The following description of the flood is taken from hand-written notes (in USAID, Sanaa, office) made by Mohammed Lutf Al-Eryani (student assistant) who visited the area shortly after the flood and interviewed residents.

* * * * *

Flood started with a crest of 1 to 1.5 meters for about 30 minutes, then the stage rose to a height of 7 to 10 meters. High flow persisted for 7 to 8 hours, then started to decrease as a result of penetration of

Fig. 13.--Measurement of channel width on Wadi Warazan Tributary (Table 3).

Figure 14.--Channel width measurement of Wadi al Jannat (Table 3).

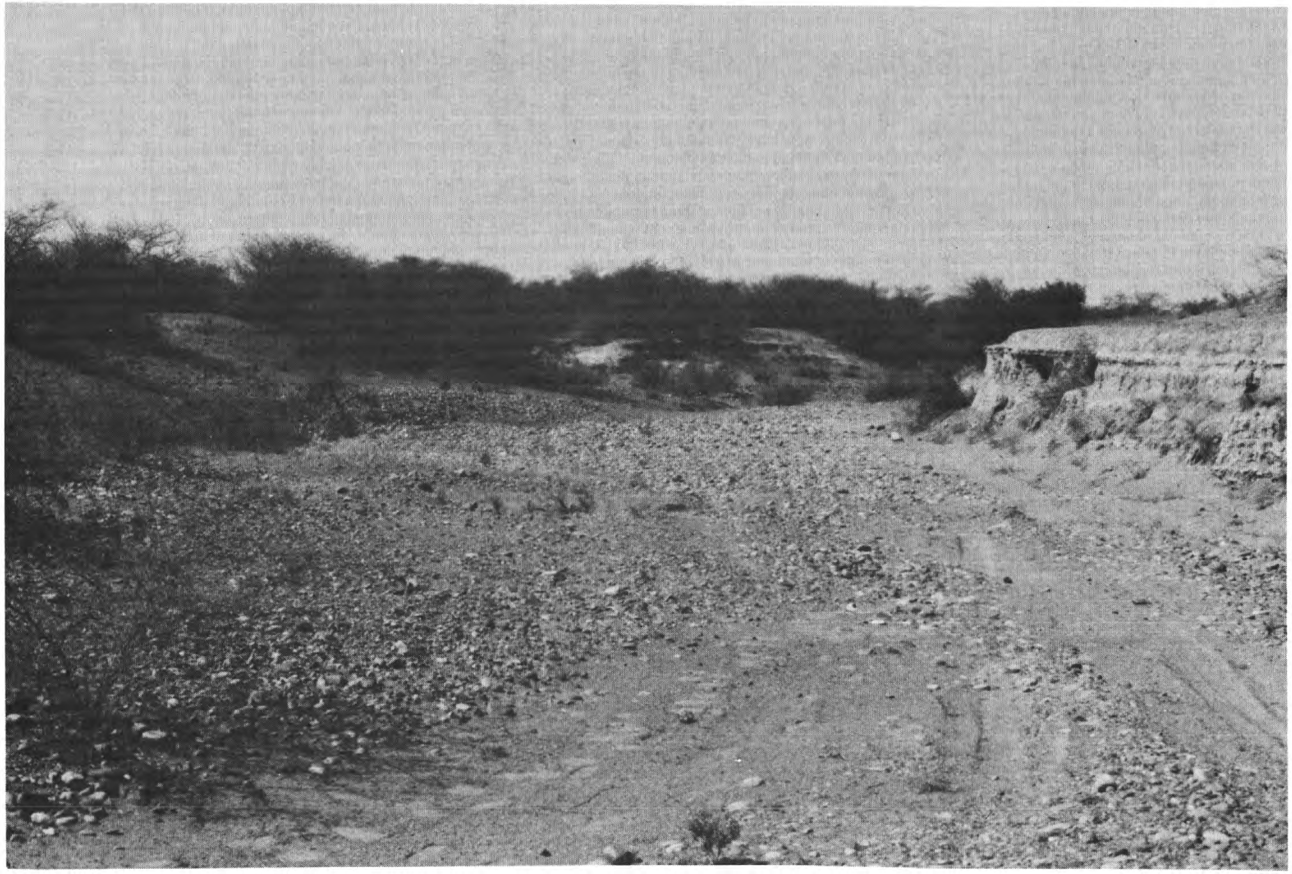

Figure 15.--Unnamed Wadi in the Tihama 2 km south of Wadi Rima.

flood through farms, around houses, etc. The valley, about 250 meters wide, was covered with water. Generally, unusual flow persisted for 36 hours, then usual high flow continued for 3 more days. Total flood flow was for approximately 5 days.

Thirty-five people were killed; 36 houses completely destroyed; 48 other houses damaged; almost all wells which supply water for farming were buried; about 75 percent of the land was damaged; main water path was scoured a meter or so.

Previous floods occurred in 1873, 1895, 1913, and 1934 (all dates converted from Moslem calendar). All were of much lesser magnitude than the present one.

* * * * *

On May 17, 1976, the author visited the site with James Aubel and Jamal Ahmed Zaifallah. The party drove and walked upstream in the Wadi to above the major tributary from the north. Because of the extensive damage, depth of overflow, and rebuilding of some walls, it was not possible to determine flood height, nor was there a confined section suitable for a slope-area measurement of peak flow. The main channel, which is also the main road in the Wadi, has been eroded a meter or more. Many gullies drain into the Wadi in this reach. It appeared that these gullies must have contributed substantially to the flood. A high-water mark painted on a building shortly after the flood is shown in the photo of figure 16.

The party then drove to Wadi Dahr at the Thillah Road crossing (above the canyon) and walked down the canyon to where perennial flow starts. The channel in the canyon is much too rough for a slope-area reach, and there were no high-water marks. However, just above Thillah Road an

Figure 16.--Channel of Wadi Dahr in May 1976 showing high-water level of flood of August 25, 1975 (paint mark on next to top course of building).

acceptable reach was found with fairly good high-water marks on the left side which were surveyed. Discharge computed by the simplified method (Riggs, 1976) was 153 m^3/s. This is a little less than the 10-year flood as defined from channel width and figure 12 (see table 3). The tributary from the north did not appear to have had an unusual discharge where Thillah Road crossed it; there is extensive terracing in the basin above that point.

The moderate peak discharge of Wadi Dahr at Thillah Road and the apparently moderate discharge of the north tributary at Thillah Road reinforce the conclusion that the flood in the developed reach of Wadi Dahr must have been generated mostly by an intense storm over that immediate area. Rainfall at Sanaa at that time was only about 15 mm per day on each of 3 successive days.

RECHARGE TO GROUND WATER

Recharge from large perennial wadis may be substantial in the upper part of the Tihama. Most of this recharge is thought to be through the channel bed. TESCO (1971) gaged Wadi Zabid at Kolah, near the mouth of its canyon and at Maath, about 9 kilometers downstream. From October 1, 1969 to September 30, 1970 the flow at Kolah was 99 Mm^3 of which 59 Mm^3 was determined to be recharge based on the flow at Maath and on irrigation diversions in the reach. Changes in ground-water levels for the period confirmed the general magnitude of that estimate. Apparently little or no recharge occurs in this region except through the channel bed. Tipton and Kalmbach, Inc. (1975) state that estimates of total recharge for 1971, which they credit to TESCO, are too low because the streamflow record on Wadi Zabid probably did not include all the floods that occurred. The TESCO recharge estimates for 1970-73 are substantially higher than 59 Mm^3 and their average-year recharge estimate is higher than that for any individual year.

Another estimate of recharge was made in the basin of Wadi Jizan in the Tihama of southern Saudi Arabia. According to ITALCONSULT (1964) the average ground-water recharge was 0.315 m^3/s from 1,100 km^2. This is much less than the 1.9 m^3/s (59 Mm^3) recharge for Wadi Zabid but the latter drains 4,630 km^2 and may flow over more permeable material as it enters the Tihama. The occurrence of substantial ground-water recharge in the Tihama if further supported by the large number of wadis that flow to the Tihama but rarely reach the Red Sea (although much of this attenuation of flow is the result of irrigation diversions).

In contrast to the recharge from the largely perennial wadis as they enter the Tihama, recharge to ground water upstream in those basins, and in other basins, is difficult to define. Obviously, there must be some recharge because these wadis and a few others are perennial. For example, Wadi Dahr mean discharge was estimated at 60 L/s by ITALCONSULT (1973); and a kanat built by the Turks 400 or 500 years ago and located a few kilometers south of Sanaa was producing an estimated 15 L/s on May 18, 1976. ITALCONSULT (1973) considers Wadi Dahr is fed from a perched water table. The kanat obviously drains a limited ground-water source because it has been dry in years of low precipitation.

The vast majority of streams in Yemen are ephemeral. As a rule the streams either have steep slopes or they are terraced. Runofff from the steep channels is rapid and of short duration with little opportunity for recharge. Terraced areas (see figures 10 and 11) store runoff as soil moisture but it seems unlikely that the infrequent wettings of the terrace soils are sufficient to produce appreciable recharge. This opinion is supported in the report by ITALCONSULT (1973, p. 30) which says that arable land cannot be expected to allow recharge; recharge may only be expected through undeveloped land.

Drainage areas of many streams are indefinite due to the topography and the terracing of land.

ITALCONSULT (1973) made an estimate of hypothetical recharge in the Sanaa basin based on recorded significant rainfall events, estimated evapotranspiration, and an estimated 50 mm soil-moisture capacity. Result was 200 mm of possible recharge in 9 years, or about 20 mm/yr, equivalent to about 3 percent of the annual input. It is doubtful if a better estimate of recharge can be made at this time using the hydrometeorological approach. Recharge would seem to be particularly sensitive to the frequency of significant storms. A significant storm is one that extends over several days and produces substantial runoff for several days or a week. Storms for shorter periods would only replenish the soil moisture. The high variability of annual rainfall at Sanaa (figure 4) indicates a high variability of annual recharge, ranging from perhaps none in dry years to a relatively large amount in a year having several significant storms.

In the Amran basin, about 200 km^2 are farmed out of a total drainage area of about 800 km^2, as interpreted from 1:250,000 scale maps. Assuming that (1) the annual rainfall is 400 mm, (ITALCONSULT, 1973, map), (2) the recharge is about 3 percent of the annual rainfall, and (3) recharge occurs only on the undeveloped land, the average annual recharge would be 0.03 (400) = 12 mm on 600 km^2, equivalent to 7.2 Mm^3/yr. If all this recharge moved to the 200 km^2 of flat agricultural area, the recharge would be $\frac{600}{200}$ (12) = 36 mm and this might cause an average rise in the water table on the order of 150 mm, assuming a porosity of about 0.25.

Recharge in the Amran basin can be estimated from water levels in wells, well logs, and pumping tests. These estimates, and rainfall records, should provide some guidlines for estimating recharge in other basins using hydrometeorological data.

CONCLUSIONS AND RECOMMENDATIONS

Streamflow data in Yemen consist of about 5 years of record on Wadi Zabid and a year of record on three other large wadis. These data are neither adequate to define the flow characteristics at those sites nor to verify the applicability to Yemen of hydrologic relations derived elsewhere. Nor can useful estimates of ground-water recharge be made by hydrologic-meteorologic methods in the absence of streamflow data.

Needs of surface-water information in Yemen are:

1. Continuous flow records on large wadis for project planning and design.

2. Streamflow data on other wadis for use in estimating ground-water recharge.

3. Flood-frequency characteristics for use in highway-crossing design.

4. Base-flow characteristics of perennial or near-perennial streams, especially the variation among years.

5. Adequate data at gaged sites to define relations for estimating flow characteristics at ungaged sites.

For the great majority of wadis whose flow is modified by terracing and generally consumed, collection of flow data is not justified.

Until some streamflow data are available, information needs must be met by:

1. Estimating mean flows of large wadis as they enter the Tihama, from available short records or from the relation with drainage area and precipitation (figure 7). Estimating flood frequency characteristics of these wadis from channel width using the relation of figure 12.

2. Estimating 10-year flood on other natural channels from channel width (figure 12).

3. Measuring springs and perennial streams during baseflow periods to estimate dependable flow and base-flow recession characteristics.

Presently, there is no acceptable basis for estimating mean flow of the smaller wadis and of the easterly-flowing wadis.

In order to meet needs in the future, I recommend a streamgaging program on a national basis. Such a program should be designed and directed by a surface-water specialist with experience on alluvial streams and in reconnaissance methods. The data collection points need not be numerous but some streams should be gaged for 10 to 20 years so as to provide a better basis for estimating flow characteristics of ungaged ones. Imagery from satellites will be useful in identifying the channels which flow much of the time and thus in selecting representative wadis to be gaged. Applications of information received through satellite technology are presently emerging and expanding (Owen and Shown, 1976). Flood and base-flow measurements should be made at other representative sites where a continuous flow record is not needed. The sediment-transport characteristics of a few streams should also be assessed. Advantages of a unified gaging program are (1) better records, (2) continuity of records, (3) adaptability of the program to changing needs and (4) more efficient operations.

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