Surface Water and Related Climate Features of the Sāhil Sūsah Area, Tunisia

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1757-F

Prepared in cooperation with the Sous-Direction de l'Hydraulique et l'Equipement Rural, Tunisian Secretariat of State for Agriculture under the auspices of the United States Agency for International Development

PROPERTY OF GROUND WATER BRANCH
OKLAHOMA DISTRICT

Surface Water and Related Climate Features of the Sāḥil Sūsah Area, Tunisia

By L. C. DUTCHER *and* H. E. THOMAS

CONTRIBUTIONS TO THE HYDROLOGY OF AFRICA AND THE MEDITERRANEAN REGION

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PREFACE

This report is the second of four being published by the U.S. Geological Survey, as chapters of Water Supply Paper 1757, on a project of technical assistance to the Government of Tunisia in hydrologic mapping and training. This project extended from January 1960 to August 1963. The first report (WSP 1757–E) was a detailed study of the ground-water resources in the vicinity of Ṭabulbah, in central Tunisia. Ṭabulbah has a productive agricultural economy based on irrigation by pumping or lifting water from hundreds of dug wells, but many wells are now more than 50 meters deep, water levels have been lowered as much as 30 meters below sea level, and the resource is being depleted. Furthermore, although there is stlll some water at greater depth, it is of poorer quality and is in less permeable sedimentary rocks, and the total amount is limited. Any replenishment is likely to be of saline water. Such a report inevitably raises the question: Where can these people turn for an assured supply of usable water?

In the hope of finding some answer to this question for the entire Sāḫil Sūsah area, the scope of the hydrologic studies was broadened to include all the drainage basin tributary to the Sāḫil Sūsah, and all phases of the hydrologic cycle within this broader area were considered. This comprehensive study of the Sāḫil Sūsah area will be reported in three chapters: the present chapter discusses the precipitation and evapotranspiration and the surface-water resources, the next will cover the geologic framework in which water occurs and moves, and the last will provide estimates of the quantities and qualities of the water involved in that storage and flow.

These reports will show that throughout most of central Tunisia the average precipitation, even during the winter "rainy" season, is less than the potential return of water to the atmosphere by evapotranspiration; thus the climate is one of prevailing water deficiency. All the water that can be of beneficial use to man must come from the momentary surpluses from rainstorms, and it must be stored somewhere until he needs it. Because soil moisture and all surface water are subject to loss by evapotranspiration, ground-water reservoirs constitute the prime places for any such storage over long periods.

Some ground-water reservoirs have a perennial yield because there is continuing or intermittent replenishment. Many of these perennial supplies are being used and have been used since ancient times; others are not of usable water or are so dispersed that suitable means have not been employed to collect them for use. All ground-water reservoirs contain stored water in quantities far greater than the average annual replenishment, and several of these, that have large volumes in storage, have a rate of replenishment so small as to be negligible. Another distinctive feature of ground water in the Sāḩil Sūsah is that much of it is in aquifers of very fine sand, and the development of large-capacity wells has been difficult. The special problems of well construction and development, however, are considered as another aspect of the technical-assistance program and are not within the scope of these reports.

Nevertheless, it is fundamental that the first stage of development of any ground-water reservoir involves some depletion. In a reservoir where replenishment is negligible, the water serves no human purpose until it is pumped out for use. True, once the water is pumped out, it is gone and unavailable for future generations. Perhaps ours is the generation that needs it most. Much of the ground water has been unavailable to previous generations because it was at depths too great for them to obtain it. It may be unwanted by any future generation that perfects the means for economical desalination of sea water, which is an inexhaustible supply bordering the Sāḩil. The water is of value to the present generation, with its technology in well drilling, pumping, and distribution facilities, if it helps develop an economy that can eventually afford the costs of desalination of sea water, particularly in the coastal communities where the Mediterranean is most accessible.

There is, of course, an element of risk in thus depleting ground-water resources: the risk that the economic productivity of the region will not rise fast enough, or the energy cost for desalination will not fall fast enough, to justify the changeover before the ground water has been exhausted. The element of risk, however, is introduced not by the hydrologist but by the people when they become so numerous that the fresh water provided perennially by Nature cannot suffice for their minimum needs.

As for Ţabulbah, depletion of the ground-water reservoir has been started and there is no choice but to continue because the removal of the water invites slow inflow of saltier water from all sides, which may eventually ruin the reservoir for further use. Desalination of sea water is still far too expensive to be undertaken by the existing economy; the risks of water shortage at Ţabulbah are therefore real and may create a crisis within a few years. Nevertheless, the depletion is probably justified because the ground-water reservoir for many years has been the prime basis of the subsistence of thousands of people. Thus in Ṭabulbah, population pressure for use of the water for minimum requirements has vitiated the alternative of husbanding the resource for the future. Similar conditions exist today in other parts of the Sāḩil Sūsah underlain by ground water.

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SURFACE WATER AND RELATED CLIMATE FEATURES OF THE SĀḨIL SŪSAH AREA, TUNISIA

By L. C. DUTCHER and H. E. THOMAS

ABSTRACT

This report discusses the water supplies available to the people of central Tunisia, of whom about 80 percent inhabit the Sāḩil Sūsah (coastal area) and the bordering Low Steppe, which together constitute plains generally less than 200 m (meters) above sea level. These lowlands receive water directly by precipitation and also by surface and underground flow from the High Steppe and the mountains of the Tell. This report thus embraces the entire drainage basin tributary to the coastal plain, called the Sāḩil Sūsah.

The median annual precipitation upon the Sāḩil and Low Steppe is about 280 mm (millimeters) which is less than one-fourth of the potential annual evaporation rate, and even in the winter "rainy" season precipitation is less than half the evaporation rate. Thus on the basis of averages there is a net water deficiency throughout the year. In about 10 percent of the past 60 years, precipitation has been great enough to sustain nonirrigated agriculture. In nearly 50 percent of the years, precipitation has contributed so little water to the soil that most crops not close enough to the coast to benefit from the nocturnal humidity there would fail without irrigation. The wide variations from average precipitation cause frequent droughts but also provide temporary surpluses which are essential for man's survival in the region. The temporary excesses in precipitation provide the occasional surpluses of water with which he can combat the normal water deficiency that characterizes the arid climate.

Available records indicate that the streams draining the mountain range on the northwest (Dorsale) in central Tunisia have high maxima and flash-flood runoff but negligible flow in rainless periods. These characteristics suggest that much of the rain falls on relatively impermeable surfaces because there is evidence of very little release from (and therefore of infiltration to) ground-water reservoirs. For example, the flood runoff of the Wādī Zurūd continues only a day or two after a minor or local storm and for as much as a week to 10 days after major general storms. At other times Wādī Zurūd has continuous flow that is very low for so large a drainage basin. The Wādī Nabhānah is exceptional in that its drainage basin includes a considerable volume of permeable limestone, and therefore as much as 35 percent of its total annual runoff may come from ground water; however, the ground-water reservoirs are small and require frequent replenishment, for without rain the base flow from them would diminish at a rate of about 90 percent every 4 months, or 99.9 percent in a year.

The significance of surface water is that it is an accumulation of the momentary surpluses from precipitation, which could be the basis for a perennial water supply

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if it could be stored and regulated. Water for irrigation could be provided for several months after runoff-producing rains ceased. The most efficient use of surface storage would be to hold flood water for only short periods to minimize evaporation losses. In the Sāḩil Sūsah area, however, high-evaporation losses, increasing salinity, sediment accumulation in reservoirs, and lack of suitable sites for dams or reservoirs are formidable handicaps to any such storage.

For perennial supply, the surface flow should be stored in suitable ground-water reservoirs from which it could be pumped out as needed.

INTRODUCTION

This report was prepared in the course of a project of technical assistance in hydrologic mapping and training extending from January 1960 to June 1963. The project agreement between the Governments of Tunisia and of the United States of America provided for three objectives:

1. Review of existing data in the office of the Subdivision Speciale des Sondages (SSS) of the Sous-Direction de l'Hydraulique et l'Equipement Rural (HER).
2. Study of the geology and the occurrence of ground water in Tunisia and to provide instruction in hydrologic techniques to Tunisian technicians.
3. Exploration and development of ground water.

It was planned that the second and third objectives would be pursued chiefly in the coastal plain area (Sāḩil) of central Tunisia, south of Sūsah [1].

Initially the area designated for hydrologic mapping was that covered by six topographic maps at the scale of 1:50,000: Sīdī al Hānī' (no. 64), Jammāl (no. 65), Al Muknīn (no. 66), Wadī Ash Sharīţah (no. 72), Karkar (no. 73), and Al Mahdīyah (no. 74). Each of these maps covers an area 16 km (kilometers) wide extending from the Mediterranean coast westward about 33 km nearly to the longitude of the city of Al Qayrawān. It was proposed that the hydrology of each quadrangle be depicted on six sheets: geological, hydrological, and geochemical maps and geological, hydrological, and geochemical sections, according to standards already in use by the Société Centrale pour l'Equipement du Territoire (SCET) and the Société Générale des Techniques Hydrauliques et Agricoles (SOGETHA) in mapping the hydrology of other areas in Tunisia. Several localities within this assigned area were selected for special consideration because of special problems of water supply: (1) The Ţabulbah area where water resources are being depleted; (2) the Az Zarāmidīn dome area near Banī Hassān as a possible source of increased supplies, (3) the south flank of Az Zarāmidīn dome as a source of water for Bū Mirdās and Sīdī Bū

[1] Geographic names used in this report conform to the usage of the U.S. Board on Geographic Names (1964).

Ṭubrīn, (4) the alluvium of the Wādī Glat as a source of water for Ṭuṣūr as Sāf, and (5) the 'Uglat ar Ramādah (Karkar Dome) as a source of water for Al Jamm.

Available information indicates that the area covered by the six quadrangles—and indeed the entire Sāḫil Sūsah—is not well endowed with water resources and that these resources may be inadequate for the needs of the existing population. The larger cities in the Sāḫil receive water by pipeline from the Wādī Marq al Layl drainage basin west of Al Qayrawān, and additional supplies will come eventually by another pipeline from the Wādī Nabhānah area. A detailed investigation of the Sāḫil, involving extensive exploratory drilling and geophysical prospecting for aquifers, will doubtless locate some fresh-water reservoirs not now known. It will also delineate more accurately the large areas where sedimentary rocks are impermeable or where ground water is of inferior quality, but in these areas it will beg another question by the residents: "Where, then, can we get water?"

PURPOSE AND SCOPE

The purpose of the investigation which is the basis of this report is to provide an answer to the question of where water for the Sāḫil Sūsah and the Low and High Steppes in central Tunisia can be obtained. The phase of the investigation discussed in this report pertains to climate and surface-water features. It is based largely on data collected before 1960. Other phases of the investigation are described in another report: "Regional Geology and Ground-Water Hydrology of the Sāḫil Sūsah Area, Tunisia" (Dutcher and Thomas, 1967).

Because geohydrologic data were insufficient to define the deeper aquifers and deposits, adequate geohydrologic maps and sections could not be completed where studies were undertaken in the area originally assigned by the Sous-Direction de l'Hydraulique et l'Equipement Rural (HER). Also, because there is only a limited potential for ground-water development within that area, the expenditure of a great deal of work to complete the maps was not warranted. Moreover, plans were being made for the construction of costly reservoirs and distribution systems in several places adjoining the six-map area without the benefit of an adequate preliminary survey of the overall water-resources potential of the region and of the average distribution of water in time and place. Thus, with the encouragement of the HER, the geohydrologic studies were broadened from the original plan, which was to complete six geohydrologic maps, to a hydrologic appraisal of the entire watershed tributary to the Sāḫil Sūsah. The more comprehensive plan included studies of precipitation, evaporation, runoff, surface water, ground water, and the chemical quality and use of water; however, only the climate and surface-water features are discussed herein.

ACKNOWLEDGMENTS

This report is based on work by "Mission Thomas," a subsection of the Sous-Direction d'Hydraulique et l'Equipement Rural, Secretariat of Agriculture, Tunisia. Mission Thomas was established as a part of a training project to introduce new geohydrologic mapping techniques in Tunisia, within the scope of the Technical Assistance Program of the United States Agency for International Development.

The work was under the direction of Lassaâd Ben Osman, chief of the Sous-Direction d'Hydraulique et l'Equipement Rural. During the first phase, the project was under the supervision of H. E. Thomas, geologist-in-charge of Mission Thomas and during the later phases under the supervision of L. C. Dutcher. Messrs. Thomas and Dutcher are geologists of the U.S. Geological Survey, Water Resources Division, who worked under the direction of G. C. Taylor, Jr., chief, Foreign Hydrology Section. The work in Tunisia was done under a participating agency agreement with the Agency for International Development (AID).

Records of precipitation at several selected stations in the area are included in a separate data report by Dutcher and Mahjoub (1963).

The writers acknowledge the field assistance of the Mission Thomas staff aids who included Mohammed Lahmar, Thamri Youssef, Abdelaziz el Ghali, Abderrazak el Ghali, El Aloui Tahar, Roland Guez, and others. The drafting was mainly done by Ben Abdallah Hamadi. Particular acknowledgment is given for the help and cooperation of Habib Zebidi, engineer-in-charge, of the Bureau de l'Inventoire des Ressources Hydraulique (BIRH) and the personnel of his staff who provided access to data and administrative support during the investigation. Acknowledgment is also given for the technical and administrative support of the staff of the U.S. AID Mission to Tunisia under the direction of D. C. Lavergne.

LOCATION AND EXTENT OF AREA

The Sāḩil area of central Tunisia is the plain bordering the Mediterranean Sea along the bulge between the Khalīj al Hammāmāt and the Khalīj Qābis. It extends from An Nafīḑah (100 km south of Tunis) southward to Al Maḩras. The part of the Sāḩil north of Ra's Kabūdīyah is designated the Sāḩil Sūsah and that to the south, the Şāḩil Şafāqis (fig. 1).

The Sāḩil Sūsah merges westward into the steppes that border the south flank of the Grande Dorsale of the Atlas Range. The wadis (ravines or watercourses, generally dry except in the rainy season)

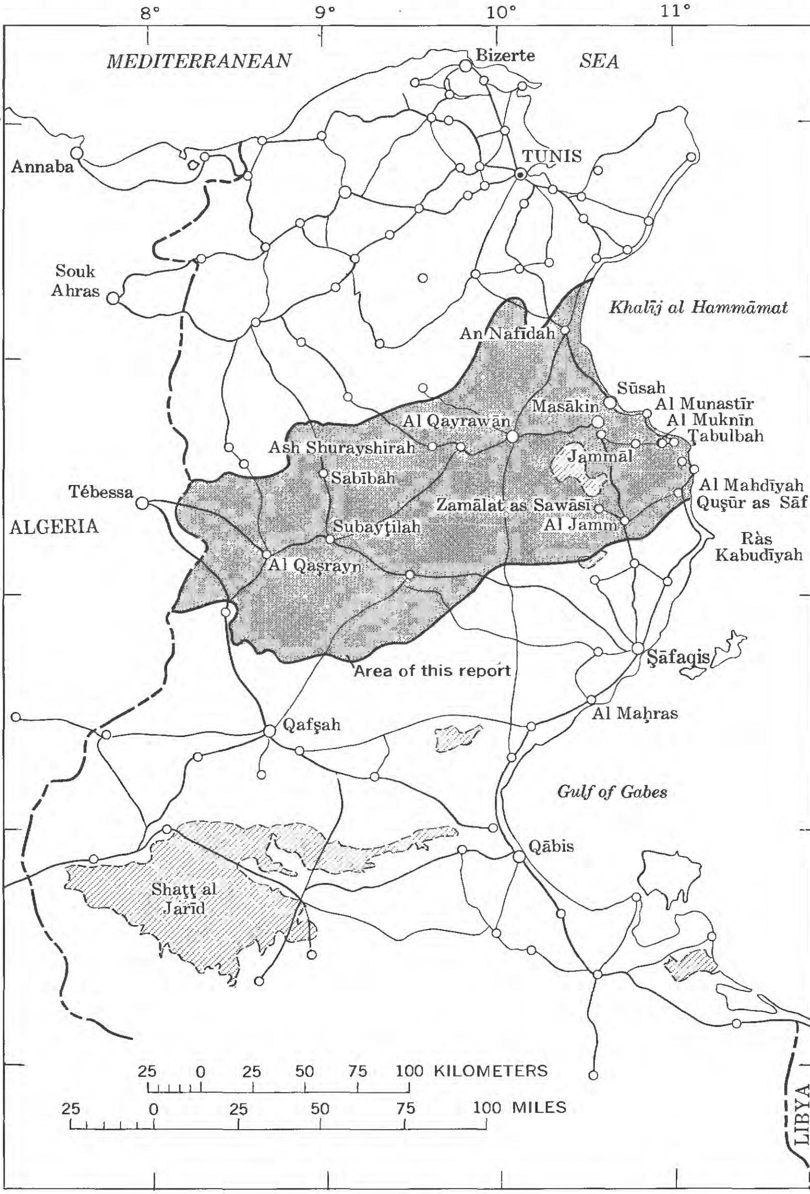

FIGURE 1.—Index map of Tunisia, showing roads and the region studied in this report.

draining this south flank flow generally southeastward and eastward toward the Sāḩil. Most of the wadis in the drainage basin tributary to the Sāḩil Sūsah flow only seasonally, but a few have small perennial flow. The Sāḩil Ṣafāqis to the south is similar in some respects to the Sāḩil Sūsah, but its bordering steppes are arid and not contiguous to the Dorsale. The wadis there are dry except following rare intense rainstorms.

The area described in this report, virtually the area that would be tributary to the Sāḩil Sūsah, is a rude rectangle of about 24,000 km^2 (square kilometers) whose northern limit extends along the crest of the Dorsale from the Algerian frontier east-northeastward about 200 km to the Mediterranean, and whose eastern limit is the 125 km of the Mediterranean coast between An Nafīḑah and Ra's Kabūdīyah. The southern and western limits of the area are formed by the ridges and hills that constitute the divide between wadis flowing, respectively, toward the Sāḩil Sūsah and toward the Sāḩil Şāḩfqis or the closed basins of southern Tunisia (pl. 1).

CLIMATE

Each year the climate of the Sāḩil Sūsah area ranges from dry subtropical in summer to temperate Mediterranean in winter, reflecting, respectively, the dominance of the broad Sahara to the South and the Mediterranean to the north. The Sāḩil is protected from the cold north winds by the Dorsale that lies north and west of it, and winters are therefore more mild than in most localities along the north African coast. Because of the Mediterranean along its eastern margin, the summer temperature is lower and the humidity higher in the Sāḩil than in most localities bordering the Sahara. Thus the opposing factors of a vast continental desert and a vast inland sea tend to ameliorate each other much of the time and to produce an overall climate that is attractive to human habitation. They also result in great climatic irregularity from year to year and from season to season. So dominant is this irregularity in all aspects of the climate that long-term averages alone are inadequate to describe the actual climatic pattern.

PRECIPITATION

Decreasing precipitation with increasing distance from the Mediterranean is an overall pattern in Tunisia, but this pattern is modified greatly by orographic influences which produce greater precipitation with increasing altitude. In central Tunisia the rains are commonly accompanied by winds from the northeast. Winds from the northwest are generally cool and dry after surmounting the Dorsale, and winds from the south are warm and dry after traversing the Sahara.

AVERAGE GEOGRAPHIC DISTRIBUTION

At seven localities within the Sāḩil Sūsah the average annual precipitation in the 30 years 1931–60 ranged from 380 mm (millimeters) at Ţabulbah to 275 mm at Quşūr as Sāf. Inland, on the

Low Steppe, the precipitation was somewhat less: 280 mm at Al Qayrawān and 215 mm at Zamālat as Sawāsī. On the High Steppe, and especially on the mountainous Dorsale, the average annual precipitation in the same period was notably greater, reaching 480 mm at Tālah, 510 mm at Makthar, and 660 mm at Bū Sa'dīyah. Tālah and Makthar are slightly beyond the north limit of the Sāḩil drainage area.

The map showing distribution of precipitation in central Tunisia (pl. 2) is based on the "Carte des Précipitations en Tunisie" (Gaussen and Vernet, 1940). The isohyets shown are based on available records for the period 1901–40 and constitute the effects of topography and exposure and evidence from the distribution of vegetation. Plate 2 shows (1) a northeastward-trending band along the Dorsale in which the average annual precipitation ranges from 400 to 800 mm within the part tributary to the Sāḩil, (2) a parallel band along the High Steppe and projecting southeastward along the Sāḩil in which there is precipitation of 300–400 mm, and (3) a broad area of the Low Steppe in which the annual precipitation is less than 300 mm but within which isolated hills and mountains probably receive somewhat greater rainfall.

AVERAGE SEASONAL DISTRIBUTION

The precipitation is negligible throughout central Tunisia, during the summer, but during the rest of the year it varies widely from place to place. In the Sāḩil, following the summer minimum (fig. 2), the precipitation increases to a maximum in October. Thereafter at Ṭabulbah, Al Mahdīyah, and Quṣūr as Sāf, there is a progressive decrease until the following June, but farther north (Sūsah and Masākin) there is a secondary maximum of precipitation during March and April which occurs also at Al Jamm.

Farther west, in the Low Steppe, the average precipitation in March at 'Ayn Ghrasesia and Al Qayrawān is equal to or greater than that in October. Moreover, in the Dorsale the long-term average precipitation at Makthar and Tālah is fairly uniform from September through May, although appreciably less in the summer.

Most of the monthly precipitation curves shown in figure 2 are based on averages for the 30 years 1931–60 but in several localities the precipitation records are long enough to give averages also for the years 1901–30. The differences between the monthly means for these two 30-year periods are indicative of the great variations in precipitation patterns that characterize the region.

VARIATIONS FROM THE AVERAGE

The average precipitation is a very poor indication of what a locality may expect in the next year, or in the next 5 years. At

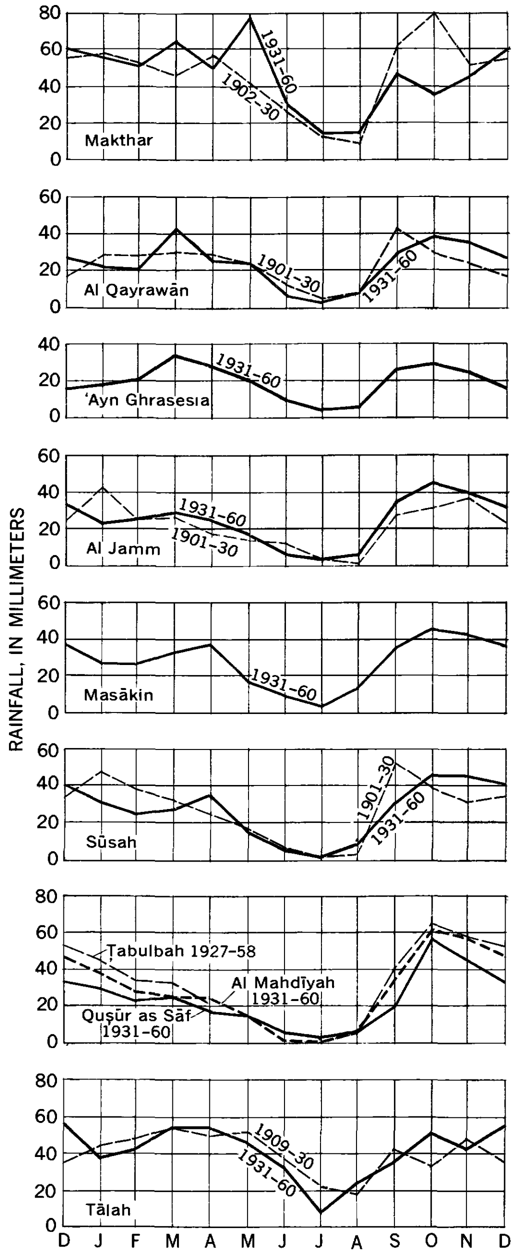

FIGURE 2.—Monthly precipitation for principal stations in or near the Sāḩil Sūsah, 30-year average.

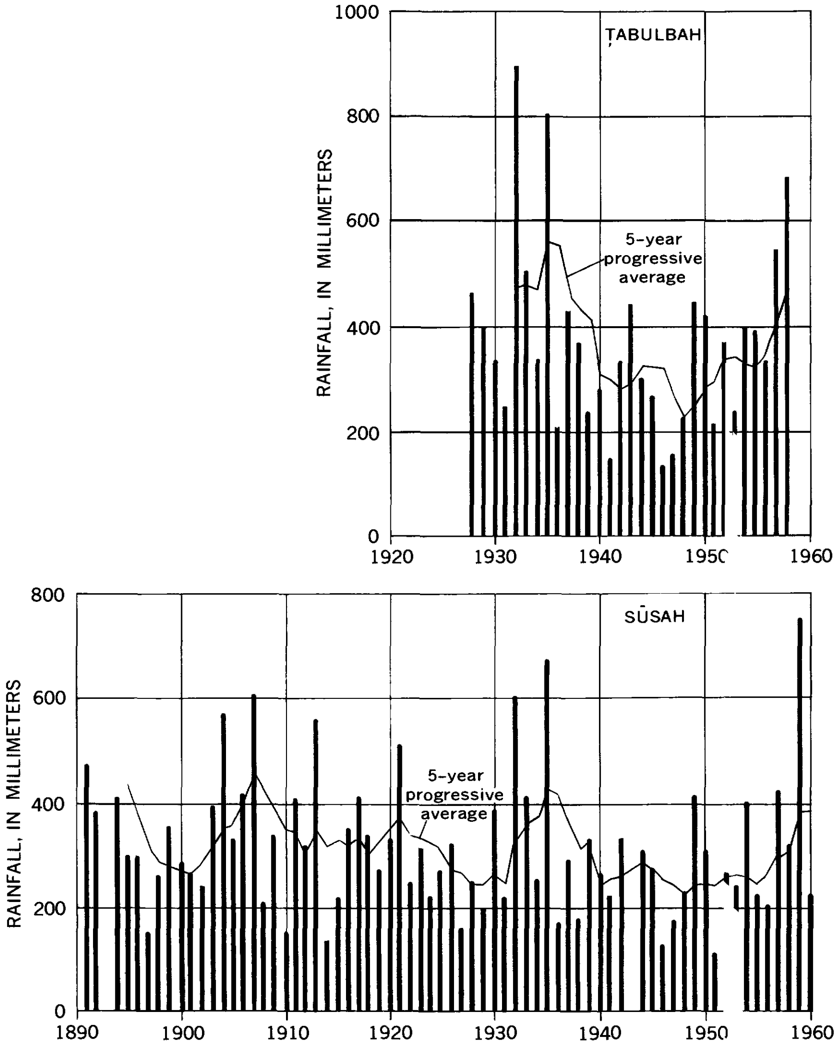

FIGURE 3.—Annual precipitation at Ṭabulbah and Sūsah, and derived averages.

Ṭabulbah, for instance (fig. 3), the average annual precipitation during the period 1928–58 was 380 mm, but in 2 years the annual rainfall was more than twice as great, and in three other years it was less than half the average. Actual precipitation was above the average in only 13 of the 31 years. A better index is the median of 345 mm, which is less than the annual rainfall in 15 of the years but

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greater than that in the other 15, although neither the average nor the median show the extent of the variation from year to year.

Within the Sāḩil there are seven stations whose records are fairly continuous for the 30 years 1931–60. In spite of the irregular geographic distribution of rainfall in individual storms, the annual totals measured at these stations correlate fairly well, and the average for the seven stations is probably representative of the annual total received in the Sāḩil. In the period 1931–60, the seven-station average ranged from 658 mm in 1932 to 128 mm in 1946, and the median was about 277 mm. In 50 percent of the years the seven-station average ranged from 213 to 366 mm—between 75 percent and 130 percent of the median. In the other 50 percent of the time, the precipitation was either less than three-fourths or more than four-thirds of the median.

In the same 30-year period, the annual precipitation at Sūsah ranged from 759 mm in 1959 to 116 mm in 1951, with a median of 267 mm. For the entire period of record (1889–1960), the median was 303 mm; in 25 percent of the years the precipitation exceeded 400 mm and in 25 percent it was less than 230 mm. At Al Jamm the median for the period of record 1896–1960 (247 mm) was almost the same as for the period 1931–60 (243 mm); in the upper quartile of the years the total ranged from 329 to 665 mm, and in the lower quartile the range was from 50 to 192 mm.

Available records indicate a tendency for wet years to occur successively, as in 1932–35 and 1957–59, and also a tendency for successions of dry years such as 1936–48, when precipitation exceeded the average in only 2 of the 13 years. At Ţabulbah (fig. 3), the average annual precipitation in the 5 years 1944–48 was only 220 mm, as contrasted with 560 mm in the 5 years 1931–35. The progressive 5-year average precipitation at six localities in the Sāḩil (fig. 4) shows trends similar to those at Ţabulbah: wet periods 1931–35, 1949–53, and 1956–60; dry periods 1937–42, 1946–48, and 1954–55. The curves representing the individual localities are more or less parallel because the 5-year averages have smoothed the local irregularities that are characteristic of each year, of each season, and of individual storms.

By the same smoothing technique it is possible to compare the major trends in the long-term records at Sūsah, Al Qayrawān, and Makthar in central Tunisia and to contrast these trends with those indicated by the records at Tunis and Tripoli (fig. 5). The Sūsah record suggests periods of drought in 1896–1901, 1908–12, 1922–28, 1937–41, and 1944–48; and wet periods in 1902–07, 1913–21, 1932–35, 1949–53, and 1956–59. Similar wet and dry periods are indicated by the record at Al Qayrawān. The record for Makthar also indicates

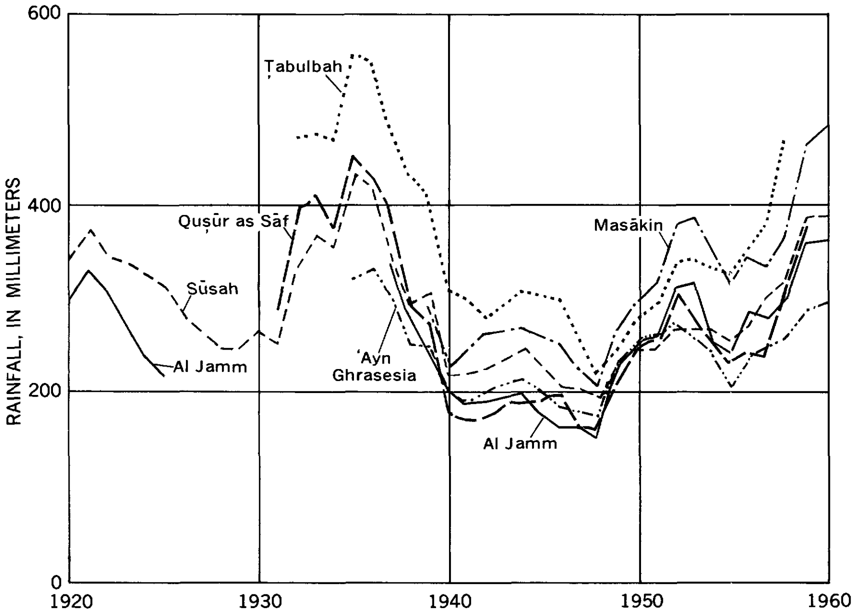

FIGURE 4.—Progressive 5-year average precipitation at six localities in or near the Sāḥil Sūsah.

a succession of alternating wetter and drier periods, although some are a few years prior to those indicated at Al Qayrawān and Sūsah.

Alternating wetter and drier periods are generally less pronounced at Tunis than at the stations in central Tunisia, although the drought of 1941–48 and the subsequent wetter period 1949–56 were more pronounced than those experienced in the Sāḥil. Nevertheless minor fluctuations appear in Tunis contemporaneously with the more pronounced fluctuations shown in the records for central Tunisia.

The record at Tripoli suggests a meteorological regime entirely different from that of the four stations in Tunisia. Indeed, the curves for Tripoli and Makthar are practically opposite in phase, that is, a wet period at Makthar corresponds to a dry period at Tripoli and vice versa. This lack of correlation raises questions beyond the scope of this report, but it may offer a partial answer to the question—where does the water go when it does not fall on Tunisia during periods of protracted drought?

EVAPORATION

Daily evaporation is measured at Sūsah and at Al Qayrawān by means of shallow open evaporating pans maintained near ground level. In 30 years of record, the measured evaporation at Sūsah averaged 1,330 mm a year and at Al Qayrawān about 1,800 mm. At Sūsah

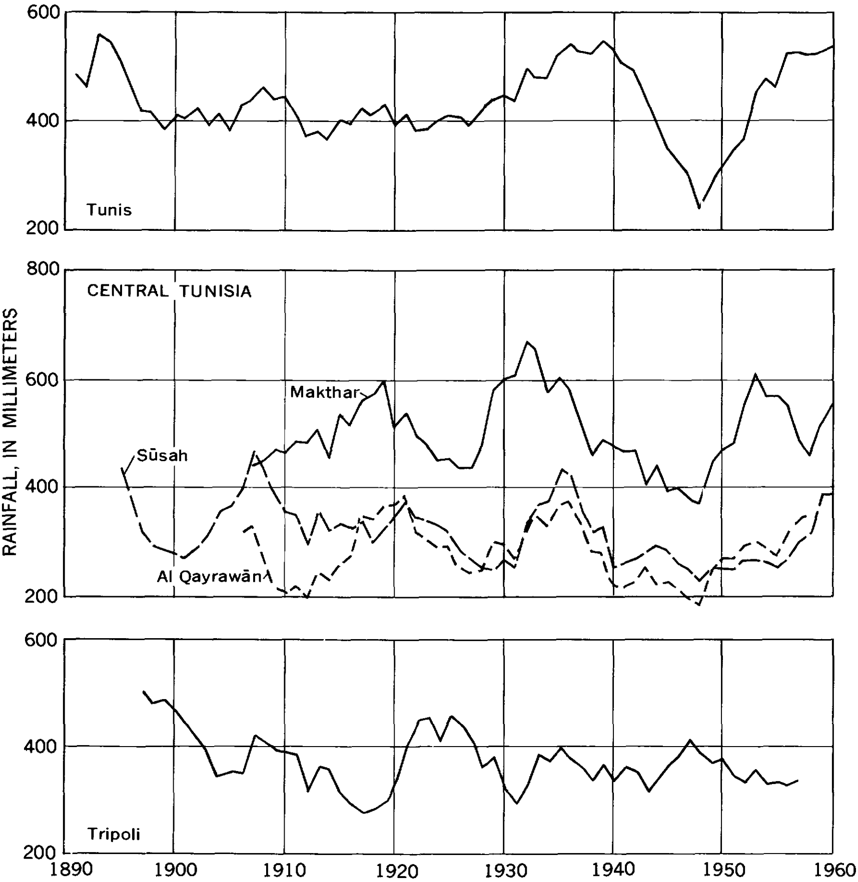

FIGURE 5.—Progressive 5-year average precipitation at Tunis, at three localities in central Tunisia, and at Tripoli, Libya.

the average monthly evaporation was a minimum of 92 mm in February, increasing to a maximum of 138 mm in July. At Al Qayrawān also, the minimum average monthly evaporation was 92 mm, reached in December, increasing to a maximum of 268 mm in July. Figure 6 shows the mean monthly evaporation as measured at both localities and also the range in rate of monthly evaporation as measured in 30 of the years 1926–60.

The evaporation from a shallow pan is greater than that from a lake, reservoir, or other free water surface in the same locality. The loss from such a free water surface is likely to be greater than that from moist soils and certainly greater than that from dry soils where water is unavailable, and this rate may be achieved in small pools and puddles. When they contain water, the evaporation from the sabkhas (ephemeral lakes, playas) and larger ephemeral ponds may

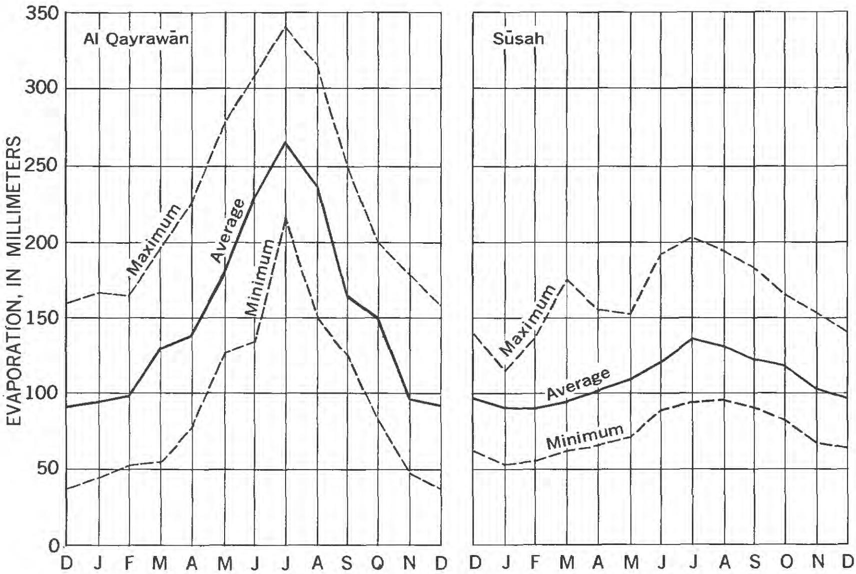

FIGURE 6.—Average monthly evaporation at Sūsah and Al Qayrawān, 30-year average.

constitute 65–85 percent of the total evaporation as indicated by the pans. From wet lands and moist soils, the rate of evaporation is commonly even less and diminishes quickly to a negligible quantity after the upper 30 cm of the soil is dried out.

The monthly evaporation varies considerably from year to year, as might be expected from the wide variation in climatic factors that influence evaporation: air temperature, wind velocity, and moisture in the atmosphere. For each month of the year the maximum evaporation recorded at Sūsah has been more than twice the minimum recorded. This relation of maximum to minimum evaporation has been true also at Al Qayrawān for the months October through May but not in the summer, when the climate is more uniform and many hot dry days occur each year.

NET WATER SUPPLY FROM THE ATMOSPHERE

Comparison of the average monthly precipitation and evaporation recorded at Sūsah and Al Qayrawān (fig. 7) reveals that in both places the average precipitation in every month is far less than the average recorded evaporation. Even in the winter rainy season, average precipitation is less than half the average pan evaporation. The graphs show also that the average monthly precipitation is less in each month than the minimum pan evaporation. Thus, at all times of the year the solar heat is sufficient to evaporate a greater quantity of water than is provided by the average precipitation. On the basis

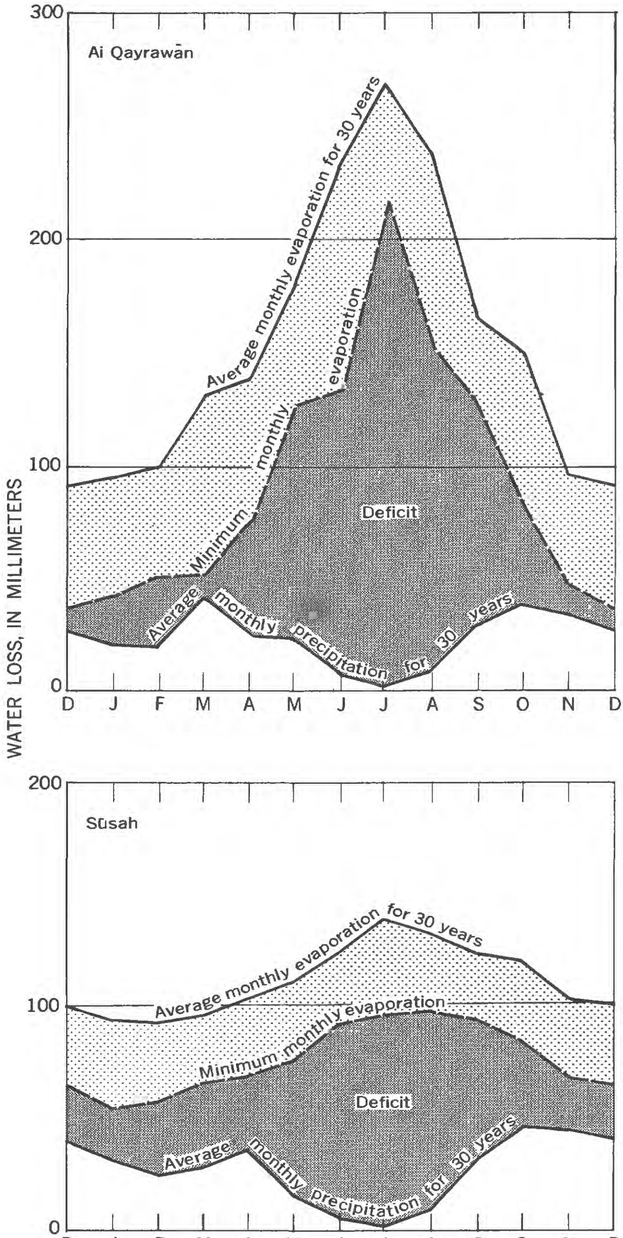

FIGURE 7.—Net water deficiency in the Sāḩil Sūsah, shown by 30-year monthly averages.

of averages, the water received is less than that which could be returned to the atmosphere and there is a net water deficiency.

In some individual months the precipitation is great enough to overcome this prevailing water deficiency. The graphs of figure 7 indicate that the monthly precipitation must exceed 50 mm to offset even the minimum monthly evaporation. At Sūsah, the rainfall has exceeded 50 mm in 4 or more months in about 10 percent of the agricultural years since 1900; these were the best years for nonirrigated agriculture. Of the remaining years, about half included 2 or 3 months when precipitation exceeded 50 mm, and if the soil had been able to store that water the needs of crops might have been met. In the other years—28 out of 60—the rainfall did not exceed 50 mm in more than 1 month; similarly at Al Qayrawān since 1900 there have been 27 years when the precipitation did not exceed 50 mm in more than 1 month. These were doubtless the years of greatest water deficiency in the soil, when most crops failed without irrigation.

In September and October when the fall rains begin, temperature is high enough that the potential evaporation may be in excess of 100 mm a month. After the land surface has had an entire summer to dry out, it is likely that the monthly rains must be considerably greater than 50 mm to replenish the soil moisture sufficiently for most crops. At Sūsah the rains in September and October have exceeded 100 mm in about 25 percent of the years of record. Many of these early storms, however, have been intense enough to cause overland flow and high runoff in the wadis but not of sufficient duration to permit much infiltration and replenishment of soil moisture.

The comparison of records of precipitation and evaporation suggests a water deficiency of such magnitude and frequency that one may wonder how the agricultural economy of the Sāḥil can persist as it has for so many centuries. Part of the answer may be in the atmospheric moisture that comes from the Mediterranean and provides some of the water requirements of olive trees and numerous other species of vegetation, although it is unmeasured as a contribution to the Sāḥil. The average humidity along the coast is indicated by the record from Ṣafāqis, based on readings three times daily (fig. 8). The noon reading is generally the lowest, and at that time the relative humidity is commonly 60 percent or more. By evening there is generally a rise to more than 70 percent, and during the night the relative humidity often exceeds 80 percent throughout the year. Inland from the Sāḥil, by contrast, as shown by the data for Al Qayrawān, the daytime humidity frequently drops below 50 percent

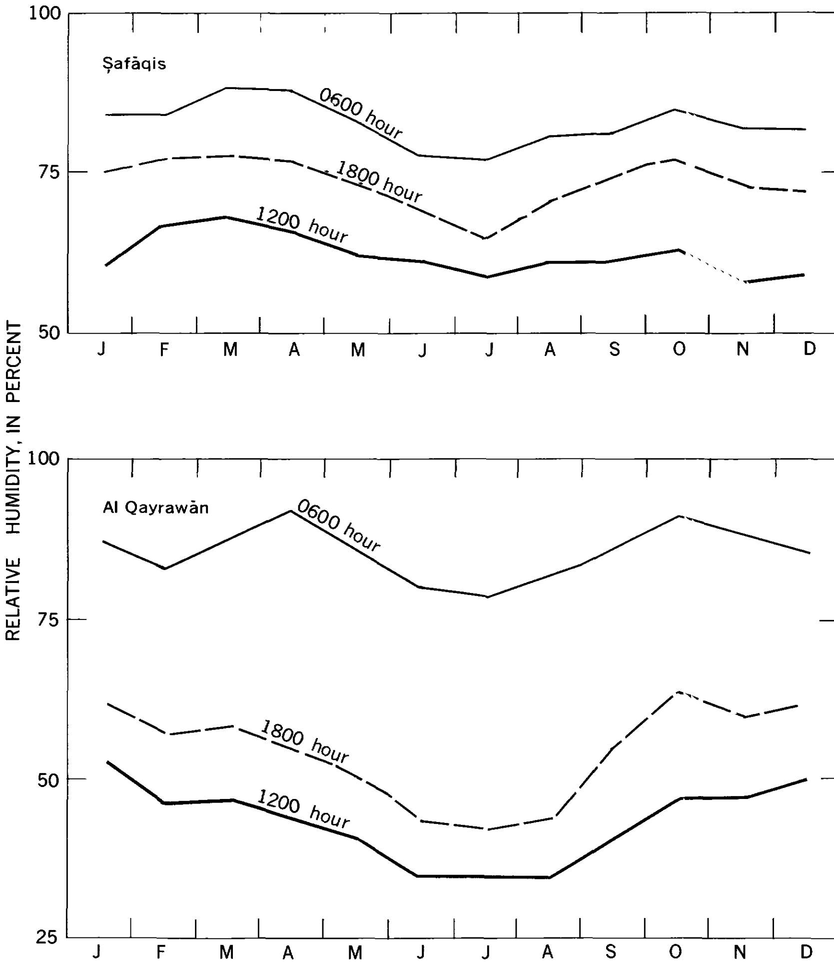

FIGURE 8.—Relative humidity at Şafāqis and Al Qayrawān, 40-year average.

and below 40 percent in the summer, and it does not ordinarily increase more than 10 percent by 6 p.m. The moisture, however, moves inland during the night, so that in the early morning the relative humidity at Al Qayrawān is often as high or higher than that at Şafāqis.

CHANGES OF CLIMATE

The large undrained basins of central Tunisia now contain sabkhas in their lowest parts which are generally dry most of the year. After rains, the sabkhas of shallow depth are perfect evaporators in the dry season, and thus concentrate the dissolved solids. Much of the salt, silt, and clay carried into the lakes by flowing water is removed later by wind action from the dry margins or bottoms of the lakes.

Many variants of sabkhas have been discussed by Tricart (1954a, b), but there is a noteworthy lack of evidence that the sabkhas in central Tunisia formerly contained larger and perennial bodies of water. Does this mean that, during the Pleistocene glacial stages and the contemporaneous pluvial periods, large perennial lakes were not established? Were Pleistocene lake deposits or erosion features later removed or covered by alluvium, and were old outlet channels completely covered by wind-drifted silt? Remnants of old Pleistocene lake features such as wave-cut terraces and beach bars or sandbars have not been found, and in most places old drainage channels to the sea do not exist.

Much evidence has accumulated that the glacial stages in Europe were represented by pluvial periods in North Africa. Capot-Rey (1945) has discussed terraces cut by large rivers that drained the Sahara during the Pleistocene. During and after the retreat of the last ice sheet in Europe, presumably beginning 15,000–20,000 years ago, the climate of central Tunisia was cooler and more humid than at present and large areas were forested. The last major pluvial period probably ended about 10,000–12,000 years ago, and the climate has become progressively more arid until very recent time. Studies made principally in North America and Europe suggest about 4,000 years ago there was another gradual worldwide change to a climate somewhat cooler and less arid. Re-advance of many glaciers support this belief, according to Matthes (1942).

Because remnants of old drainage channels or lake terraces are lacking in Tunisia and because there are only minor accumulations of salts on the sabkhas, it is postulated that these are young rather than old features. The sabkhas probably owe their present character to increased runoff during the minor glacial epoch and are probably not older than 4,000 years.

Capot-Rey (1953) depicted the large area of fixed dunes along the southern border of the Sahara as indicative of a relatively recent change to a more humid climate. In this regard, studies at carefully chosen sites might make it possible to estimate whether the present average water, sediment, and salt inflow to the sabkhas could account for the accumulation of the salt crust during a relatively short period. Perhaps plant remains also could be found in the sabkha deposits that would help to determine the recent climatic history.

In summary, forests in central Tunisia probably did not survive longer than the end of the last main pluvial period. During the ensuing 6,000–8,000 years the world climate was more arid than at present. Beginning, however, about 4,000 years ago there was a gradual change to a more humid climate and since then rainfall has

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been somewhat more abundant. The widely held belief that the Romans enjoyed a more humid climate during the height of their agricultural development of Tunisia cannot be proved by available geologic or climatic evidence. Great changes, however, have occurred in central Tunisia in historic time. Vegetation was formerly much more abundant, and locally in favorable places near the coast and in the mountains trees and shrubs were common. The grass cover was sufficiently abundant to support large numbers of grazing animals, reportedly including many types of antelope. These changes can be traced mainly to human activity and exploitation of the land during more than 2,000 years of human habitation. Erosion, which has been severe in many places, was caused principally by the removal of the natural vegetative cover from the soil, especially after the nomadic invasions of the post-Roman period.

Most glaciologists agree that since about the year 1850 most of the world's glaciers have undergone a recession which has proceeded at an accelerated rate since about 1920. This is the latest episode in the "little ice age" which has contained numerous cyclic advances and retreats of glaciers since about 1600 when the first data on advances of mountain glaciers were recorded. The latest general recession has lasted more than 100 years and may mark the end of the "little ice age," or it may not. Should the present period of increasing warmth and glacier recession continue, however, it would surely result in widespread deglaciation and increasing aridity over large areas. Conditions such as prevailed during mid-post-Pleistocene time might then return, and the arid parts of the world would face an era of water scarcity to which modern man would find it difficult to adjust.

RELATION TO HUMAN REQUIREMENTS

The people of central Tunisia are well aware that their agricultural economy remains at a meager subsistence level primarily because of insufficient water. Each new year begins with the hope that rainfall will again be as abundant as it was in the best years of the past, when crop yields were sufficient for a temporary prosperity. In most years, however, that hope must fade because these best years are no more numerous than years of extreme drought, and water deficiency is characteristic. Particularly in the densely populated Sāḫil and adjacent steppes, the average rainfall is less than the potential evapotranspiration in all months of the year, including the winter when evaporation is least and rainfall greatest.

Some people blame the irregularity of rainfall, from month to month and especially from year to year, for its inadequacy to meet human requirements, and they point to the failure of precipitation in most years to reach the totals that are characteristic of the best years for agriculture. Obviously such regularity could be attained only by a change in the climate from the present aridity to one more humid.

As long as the climate remains unchanged—with average precipitation remaining the same as that in the past half century and presumably for several centuries before that—the observed irregularity in precipitation is not necessarily bad for mankind, even though it results in periodic droughts and occasional disastrous floods. Indeed, this irregularity is essential for man's survival in the region, for the excesses in precipitation provide the momentary surpluses of water with which man can profit in spite of the normal water deficiency that characterizes the climate. Individual storms provide water for infiltration into the soil and deep percolation into ground-water reservoirs, as well as overland storm runoff in the wadis. If there are sufficient storms in a single year, that year becomes a good year for agriculture; if these storms contribute significantly to soil moisture, ground water, and surface water, agriculture also reaps benefits from this water in succeeding years.

Momentary surpluses of fresh water from storms are of value to mankind to the extent that they can be stored until they are needed and then can be recovered in adequate quantity and usable quality. In many parts of the Sāḫil and adjacent steppes there is natural storage of the water from precipitation, both above and below ground. Many of these natural facilities, however, are far from ideal for storage because of losses by evaporation, progressive accumulation of residual salts, and deterioration in the quality of the water remaining in storage.

The long-term trends in precipitation observed during the past 80 years impose a special requirement upon any water-storage facilities that must provide a firm supply of water for man's use, even though these trends are not clear enough to be termed cyclic and not regular enough to be useful in long-range forecasting. Throughout central Tunisia the long-term precipitation records show "wet" periods that include several years of greater-than-average rainfall, followed by "dry" periods in which rainfall was generally less than average for perhaps a decade. Water-storage facilities to match these fluctuations must have sufficient capacity to store the surpluses of a succession of wet years and then to hold that water with minimum loss by evaporation during the succeeding period of drought.

The problems of storage of water from precipitation, including the improvement of the natural facilities available and the development of supplementary facilities, constitute major aspects of the discussions of surface water in this report and of ground water in a following report (Dutcher and Thomas, 1967).

SURFACE WATER

"Surface water," as used here, includes primarily the water flowing in streams and the water in natural pools or artificial reservoirs along those stream courses; it also includes the large and small sabkhas and the small ponds of standing water that occur within the Sāḩil and adjacent steppes. Most of the wadis are ephemeral, and many of the sabkhas and other depressions contain water only in the rainy season, or perhaps during years when rainfall and runoff have been relatively abundant.

STREAMFLOW

The wadis of central Tunisia and their discharge characteristics are vividly described by Despois (1955, p. 75–88), who has also summarized (p. 75) in a single paragraph their limitations as to utilization:

> L'utilisation des eaux de ruissellement pourrait compenser très sensiblement l'insuffisance et l'irrégularité des pluies si le ruissellement lui-même ne dépendait pas avant tout des fantaisies de la pluviosité. Les oueds sont, de plus, soumis à une évaporation considérable, résultat des très fortes températures d'été et des vents de toutes saisons. Enfin les pentes sont faibles et la majorité des terrains—les deux tiers sinon les trois quarts—sont nettement perméables. Il en résulte que le ruissellement est tellement irrégulier qu'on peut le dire "accidentel" et que, dans cette région de bassins fermés, l'infiltration apparaît comme un fait plus important encore que l'évaporation.[1]

The drainage pattern of central Tunisia is poorly defined, particularly in the Sāḩil and Low Steppes where there are many dry channels, vaguely connected or separated by low divides (pl. 1). The drainage pattern is most clearly seen during general storms that produce flood flows. Then a few wadis in the Sāḩil carry water directly to the Mediterranean; many others in the Sāḩil and the Low Steppes discharge into sabkhas and are thus components in the centripetal drainage pattern of a closed basin; still others discharge on to alluvial plains where the water disappears by infiltration and evaporation.

Owing to an average annual precipitation exceeding 400 mm, the mountains of the Tell provide the greatest volume of streamflow in central Tunisia, and monthly and annual distribution is somewhat more regular than that in the Sāḩil and Steppes. The longest wadis and the wadis having the greatest volume and duration of flow are those that include water originating in the Tell. The easternmost of these, Wādī al Brek and Wādī al Bawl (Oued Khiarate), flow

[1] Translation: The use of streamflow could readily compensate for the inadequacy and irregularity of rainfall if the runoff itself did not depend above all on the vagaries of rainfall. The wadis are, moreover, subject to considerable evaporation, a result of very high summer temperature and of strong winds during all seasons. Finally, the slopes are gentle and most of the land—two-thirds if not three quarters—is quite permeable. Consequently the runoff is so infrequent that it might be described as accidental, and in this region of closed basins, infiltration seems to be a more important factor than evaporation.

eastward toward the Mediterranean near An Nafīḍah (pl. 1). Practically all the other wadis of the Tell flow toward the Sabkhat al Kalbīyah, but they form an integrated river system only during general storms that produce floods. At such times the Wādī Nabhānah (pl. 1) and several secondary wadis to the north of it utilize scores of distributary channels as they leave the mountains and flow out upon the Bilād Sīsab Plains; the channels coalesce in the lower part of the plain to form the Wādī al 'Ālim which flows into Sabkhat al Kalbīyah. To the south in the next major drainage area along the Tell, the Wādī Marq al Layl debouches upon the Al Qayrawān plains when it leaves the High Steppes (pl. 1).

At the lower end of these plains the water collects in the Wādī al 'Aṭf, which is joined by the Wādī al 'Ālim en route to Sabkhat al Kalbīyah. The Wādī Zurūd, which also debouches upon Al Qayrawān Plains (pl. 1), represents the runoff from a very extensive area of mountains and steppe lands. Its principal mountain tributaries, Wādī al Ḥaṭab (Oued Hathob) and Wādī al Ḥaṭab (Oued Hatab), flow across extensive plains where they lose much of their flow after leaving the mountains. In particular, the Wādī al Ḥaṭab (Oued Hatab) flows into the Wādī al Fakkah which in turn disappears in the vast Bilād Gamouda except during periods of exceptional floods. The Wādī al Ḥajal collects the surface outflow from the lower end of this plain, plus the flow of several tirbutaries that rise in the mountains, and then joins the Wādī al Ḥaṭab (Oued Hathob) to form the Wādī Zurūd. Thus the Wādī Zurūd, although it is a principal feeder of water to Al Qayrawān Plains, is also a collector of overflow from similar vast plains upstream, and in that respect is somewhat analogous to the Wādī al 'Aṭf which drains Al Qayrawān Plains.

The integrated river system tributary to the Sabkhat al Kalbīyah, which is formed in times of flood, disintegrates quickly after the rains cease and in fact is in existence for such a small part of the distance that there are no terms in common use to designate the entire drainage basin or the main stem that drains it. Characteristically the flood runoff from major storms decreases almost as rapidly as it begins, and thus continues for only a few days. Thereafter the water from wadis of the Tell, whether perennial flow or runoff from minor storms, diminishes and generally disappears as it flows out upon the plains, partly by evaporation but at a rate too great to be explained by evaporation alone. Thus, as Despois pointed out, infiltration must also be an important factor.

Several other factors are clearly involved in the pattern of streamflow in central Tunisia. The high maxima and short duration of flood runoff and the negligible flow in rainless periods, together suggest that much of the rain falls upon relatively impermeable surfaces where infiltration is negligible and where there is evidence of little percolation to and release from ground-water reservoirs. The development of distributary channels and of discontinuous channels results in part from the sediment that is carried by all wadis in flood and is deposited as the volume of water or the velocity of flow diminishes. The "rising water" which results in perennial flow in certain reaches of the principal wadis indicates that there has been infiltration into permeable materials somewhere upgradient from that point, and also that there may be some barrier to continued underground flow in the vicinity of the rising water.

Quantitative information as to streamflow in the major drainage basin tributary to the Sāḩil Sūsah is available from three gaging stations (pl. 1):

1. Wādī Nabhānah at Sīdī Mas'ūd, beginning September 1924 (no record for April–August 1927, September 1931–May 1932, February–May 1939, December 1942–August 1943, September 1947–August 1951).
2. Wādī al Ḩaţab (Oued Hatab) at Khanqat al Jāziah, beginning September 1946 (records missing for September 1956, January and April 1957, and February 1960).
3. Wādī Zurūd at Sīdī Sa'd, beginning September 1949 (no record for September 1954–August 1956).

WĀDĪ NABHĀNAH

The Wādī Nabhānah has a drainage area of about 855 km^2 above the gaging station at Sīdī Mas'ūd, which is at an altitude approximately 180 m (meters) above the sea. In 35 years of record, the mean annual runoff has been about 39 million m^3 (cubic meters) and the median about 20 million m^3. The runoff varies greatly from year to year, and even from month to month, as is indicated by plate 3. In every one of the 12 months, the mean discharge has equaled or exceeded 4 cu m per sec (cubic meters per second) in some years, and also in each month it has been less than 0.2 cu m per sec in one or more years.

The pattern of runoff follows closely the irregular pattern of precipitation, for it occurs chiefly during the rainy season and diminishes to a minimum during the rainless summer months. The greatest monthly runoff commonly occurs during the same months as the greatest precipitation. In each of the 5 months when the average rate of discharge exceeded 10 cu m per sec, the precipitation in the drainage basin exceeded 200 mm. The runoff diminishes quickly after the rains have ceased, so that even during the years of greatest runoff there are commonly one or more months when the average discharge is less than 0.2 cu m per sec.

Hydrographs of the mean daily discharge of Wādī Nabhānah (pl. 4) show several distinctive streamflow characteristics of which the most prominent are the sharp peaks representing the storm flow. In a single day, and commonly on the same day that heavy precipitation occurs, the rate of discharge may increase several hundred times. Minor storms also cause sharp peaks in discharge, but with lesser amplitude. A storm period of several days may produce several peaks in the hydrograph, corresponding to floods from individual storms.

After each storm peak the discharge declines, rapidly at first and then at a progressively decreasing rate until the next storm or, if there is sufficient time lapse between storms, until the trend of the hydrograph on a semilogarithmic scale approaches a straight line, having minor fluctuations. Such straight lines are characteristic of the hydrograph from May to August in 1956 and again in 1958, when there was no storm flow. During the same months of 1959 there was storm flow on several occasions, but after each storm the hydrograph resumed the trend—the recession curve—that had existed prior to the storm.

BASE FLOW

Recession curves similar to those of the Wādī Nabhānah have been observed in hydrographs of numerous streams in America (Kunkel, 1962). Analyses by various investigators have shown that a good approximation to the recession curve is given by the empirical recession equation:

$$\frac{\ln Q_t - \ln Q_0}{t} = k \tag{1}$$

or

$$Q_t = Q_0 e^{kt} = Q_0 K^t \tag{2}$$

in which Q_t is the stream discharge at time t after a given discharge Q_0, k and K, the depletion factors, are constants that are governed by the characteristics of the drainage basin, and e is the base of natural logarithms. $-Q_t$ is also the rate of discharge from storage S at time t, so that

$$\frac{dS}{dt} = -Q_t. \tag{3}$$

Substituting in equation (2),

$$dS = -Q_0 K^t dt. \tag{4}$$

Integrating,

$$S = Q_0 \int_0^t K^t dt = \frac{-Q_0}{\ln K} [K^t]_0^t = \frac{Q_0}{\ln K} (1 - K^t). \tag{5}$$

As t approaches infinity, K^t approaches O, because K is always less than 1. Thus, the total base flow after time t would be

$$S=\frac{Q_0}{\ln K}=\frac{Q_0}{2.30 \log K}. \tag{6}$$

The base flow in any period t is thus obtained by difference

$$S_0-S_t=\frac{Q_0-Q_t}{2.30 \log K}. \tag{7}$$

In the hydrographs of plate 4, the clearest and longest recession curves are those depicted during the relatively rainless spring and summer months of each year. During the rainy season, recession curves of the same slope are clearly apparent but of shorter duration because of the frequent periods of flood runoff. After many of these floods, the recession curve is displaced upward; this displacement indicates an increase in the ground-water increment to the stream and therefore increased ground-water recharge and storage from the same storm that caused the flood runoff. The dashed lines, all parallel, beneath the hydrographs represent our concept of the ground-water recession curve, in which K has a value of 0.982. At this rate of recession, the base flow diminished at the rate of about 90 percent every 120 days, or 99.9 percent in a year.

The hydrograph for some periods actually dropped below the projected recession curve, as for example in July and August 1957. Conversely the hydrograph for several rainless periods rose above the projected recession curve, as for example the hydrograph for December 1955, August 1956, January and April 1957, and September 1958. In all these periods the stream discharge was about 0.1 cu m per sec, when relatively small losses by evaporation or gains by recharge would be a significant part of the total flow. Nevertheless, these deviations indicate that the calculation of base flow on the basis of the selected curves is only an approximation.

On the assumption that the base flow of the Wādī Nabhānah is that part indicated by the dashed lines on plate 4 (that is, K=0.982), the ground-water contribution is estimated as follows:

Agricultural year	*Base flow ($10^6 m^3$)*	*Percentage of total annual runoff*
1956	8.76	16
1957	3.51	35
1958	10.33	32
1959	25.65	35

The depletion factor in the Wādī Nabhānah basin is so great that there can be relatively little carryover storage for base flow from one year to the next. Indeed, base flow is a significant proportion of the total runoff only because of frequent ground-water replenishment in the basin.

RAINFALL AND RUNOFF RELATIONS

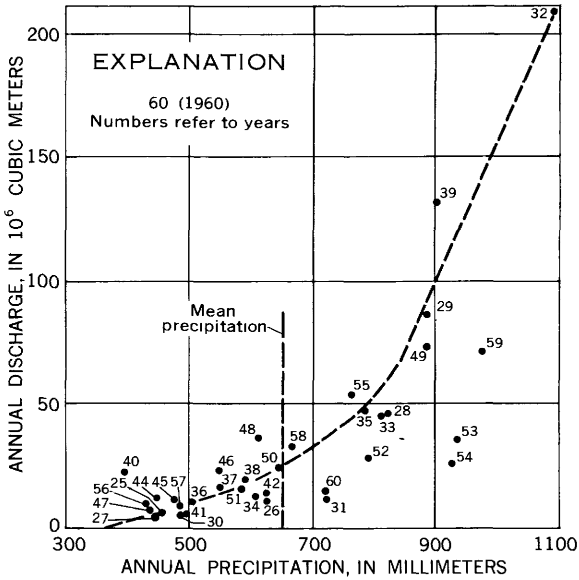
After identifying the base flow and storm flow in the daily hydrographs, as indicated on plate 4, comparisons of each were made with the rainfall in individual storms, as measured at Bū Sa'dīyah, which is at the base of Jabal Barqū in the western part of the Wādī Nabhānah drainage basin. Both base flow and storm flow increase generally with increased precipitation, as expected, but the relation varies so greatly that it cannot be closely defined; nor is it possible to determine from these records alone the magnitude of storms most favorable for ground-water recharge. Certainly the variation results partly from localized storms, some of which may have been centered over the rainfall station, whereas others were unrecorded because they occurred in other parts of the basin. Rainfall intensity also doubtless varied greatly, in some places greatly enough to produce significant overland flow, in some places little enough to permit much infiltration into the soil.

The relation between agricultural-year precipitation at Bū Sa'dīyah and annual runoff of Wādī Nabhānah (fig. 9) may be summarized as follows for the period 1925–60:

1. In every year when the precipitation was less than the mean of 660 mm, the runoff of the wadi was less than the average of 39 million m³. The runoff, however, was also less than this average in 5 years when precipitation was considerably greater than average and ranged from 710 to 920 mm.
2. In each of the 9 years when the runoff exceeded 39 million m³, the precipitation exceeded 760 mm. In four of those years, runoff of about 50 million m³ resulted from precipitation of about 800 mm. In the 5 years of highest runoff, the relation seems to be roughly that each 100 mm of rainfall above 800 mm produced an additional 50 million m³ of runoff.

The relation between monthly precipitation and mean monthly discharge for the period 1925–60 (fig. 9) varied somewhat according to season. In the first part of the rainy season (September, October, November, and occasionally August), the rainfall that caused runoff ranged from 50 to 200 mm per month. The corresponding runoff was at a mean monthly rate of 5–10 cu m per sec, rarely as much as 12 to 15 cu m per sec, and did not increase proportionally with precipitation. Clearly a varying part of the runoff in this period was absorbed by the terrain after the hot dry summer.

Later in the rainy season (December–April), the rainfall that caused significant runoff ranged from 20 to 470 mm per month. In



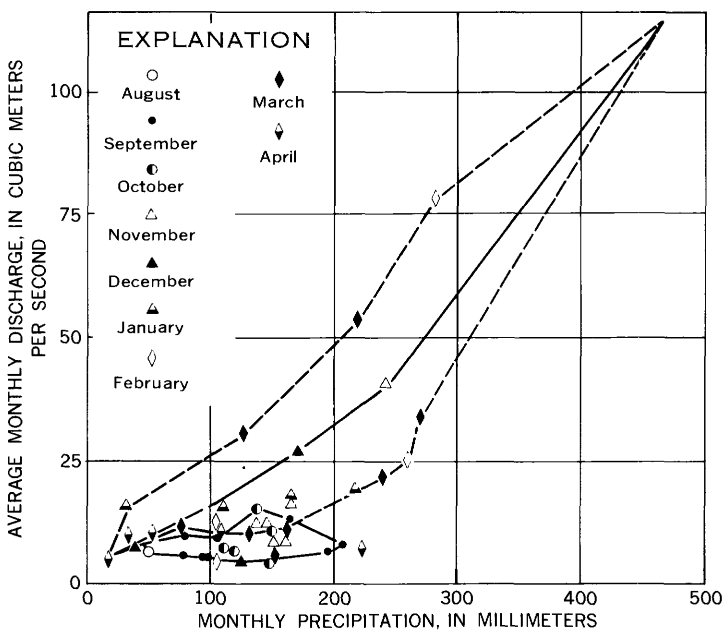


FIGURE 9.—Comparison of annual and monthly precipitation and discharge of the Wādī Nabhānah, 1925–60.

these months, widely varying amounts of rainfall have produced approximately the same runoff and equal amounts of rainfall have produced a wide range of runoff amounts. The general trend of the values shown in figure 9 suggests a rate of runoff of about 7–9 cu m per sec for each 50 mm of precipitation up to 250 mm in a month. Monthly precipitation of more than 250 mm apparently produces an accelerated rate of runoff.

WĀDĪ AL ḨAṬAB (OUED HATAB)

The flow on Wādī al Ḩaṭab (Oued Hatab) is measured at Khanqat al Jāziah where the gaging station measured an outflow from a basin of 2,283 km², above an altitude of 481 m. The drainage basin includes the Jabal ash Sha'nabī, which has a maximum altitude of 1,544 m, and several other ranges of the Tell that rise above 1,400 m; it also includes several broad mountain valleys. The Wādī ad Darb, which rises in one of these valleys and enters the Wādī al Ḩaṭab (Oued Hatab) north of Al Qaṣrayn, has sufficient perennial flow to be used extensively for irrigation in the vicinity of Al Qaṣrayn.

In 4 years of record the daily discharge of the Wādī al Ḩaṭab (Oued Hatab) has ranged from 0.003 to 143 cu m per sec with an instantaneous peak discharge of 492 cu m per sec. Flow-duration curves showing the percent of time various rates of daily discharge and the cumulative annual runoff have been equaled or exceeded are shown in figure 10.

In the 3 agricultural years 1957–59, the average discharge was about 1.65 cu m per sec. The mean daily discharge exceeded this rate in less than 8 percent of the time, but 86 percent of the total discharge in the 3 years occurred during that 8 percent of the time. In the 50 percent of the time when the mean daily discharge was less than 0.115 cu m per sec (the medium), the aggregate runoff was only 2 percent of the total runoff of the 3-year period.

More than half the total discharge of the Wādī al Ḩaṭab (Oued Hatab) during the 3 years 1957–59 occurred during and immediately after three storms: October 2–5, 1957, June 6–8, 1959, and August 22–25, 1959. Rainfall began October 2, 1957, at Tālah—about 10 km north of the boundary of the Ḩaṭab (Hatab) basin—and 17 mm had been recorded by October 4. On October 5, when 121 mm of rain was recorded at Tālah, the Ḩaṭab (Hatab) reached a peak discharge rate of 2,000 cu m per sec; the total runoff that day exceeded 32 million m³, dropping to 14.3 million m³ the next day and to 0.5 million

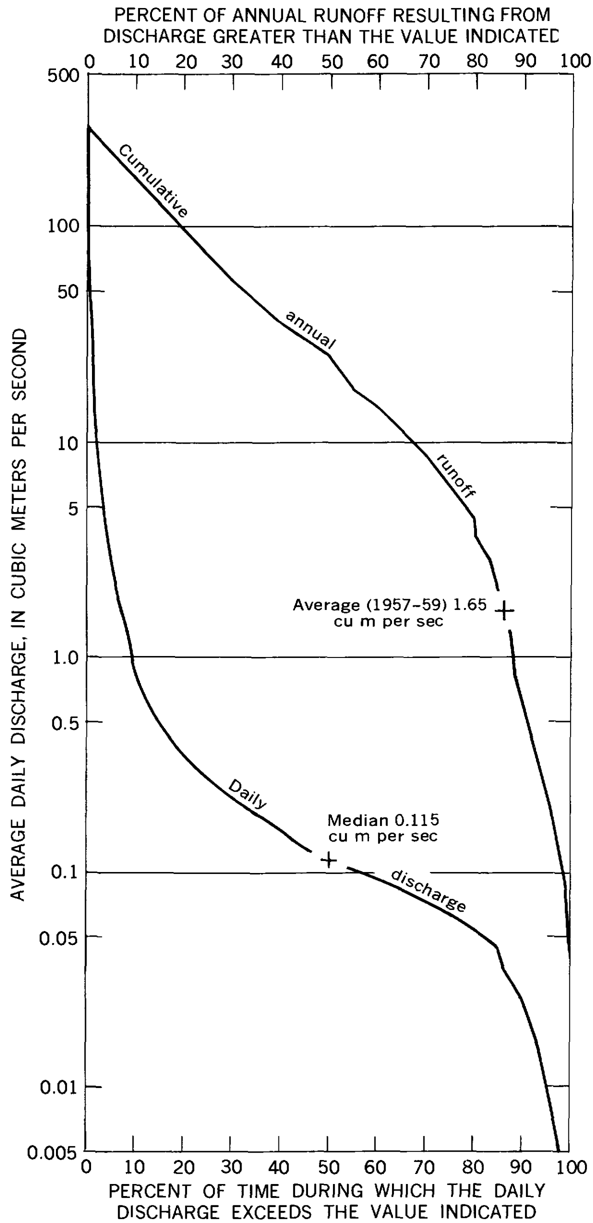


FIGURE 10.—Flow-duration curves of daily discharge and cumulative annual runoff of the Wādī al Ḥaṭab (Oued Hatab), 1957–59.

m³ the day after. In 8 days following this storm, the runoff was about 49 million m³, two-thirds of the annual total.

Rainfall at Tālah on June 6, 1959, was 76 mm, and an additional 23 mm fell in the next 2 days. The Ḩaţab (Hatab) discharge reached a peak of 492 cu m per sec on June 7, dropping to less than 1 cu m per sec within 4 days; the total runoff in the 4 days was nearly 15 million m³. Runoff was almost as great during the 4 days, August 24–27, 1959, when no major storms were recorded at Tālah, although light rains were reported beginning August 22.

Several other storms recorded at Tālah have caused storm flow of short duration in Wādī Ḩaţab (Oued Hatab), as for example on September 26, 1956, when rainfall at Tālah was 37 mm. Discharge of the wadi rose to a maximum of 43 cu m per sec the same day, although the mean daily discharge was less than 3 cu m per sec and dropped to 0.7 cu m per sec within 48 hours. The irregularity of geographic distribution of rainfall during individual storms is attested by the fact that there have also been several days of storm runoff in Wādī al Ḩaţab (Oued Hatab) when little or no rainfall was recorded at Tālah.

In contrast to the Wādī Nabhānah, the Wādī al Ḩaţab (Oued Hatab) record shows no indication of progressive and regular depletion of ground water during the intervals between the storms that produce flood runoff and no indication of significant buildup of ground-water storage during these storms. Throughout the year, the low-flow hydrograph fluctuates irregularly, perhaps in response to changing rate of diversions, and is lowest in summer, probably because of loss by evaporation. The perennial flow is an indication of some discharge of ground water to the stream, but the low rate of flow in rainless periods is an indication that such contibution is not significant.

WĀDĪ AD DARB

The Wādī ad Darb (pl. 1) has a ground-water drainage area of about 500 km² in the area of the Al Qaşrayn syncline south of Al Qaşrayn, but the surface-water drainage area is much smaller. It is a minor tributary of the Wādī al Ḩaţab (Oued Hatab) in point of drainage area but is important because it is one of the few perennial streams in central Tunisia. Wādī ad Darb cuts into the water table throughout a reach that extends from Al Qaşrayn for 8 km upstream. A dam constructed in 1945 near the ruins of an ancient Roman dam about 2 km west of the town intercepts this flow, which is then diverted for irrigation. The outflow from ground water is at a rate reportedly ranging from 240 to 340 lps (liters per second) and data supplied by HER shows that the average annual discharge from rising ground water is 292 lps. At times the stream flow is increased by rain in the drainage basin, but systematic measurements of storm runoff have not been made.

WĀDĪ ZURŪD

The Wādī Zurūd has a drainage area of about 8,950 km² above the gaging station at Sīdī Sa'd (pl. 1), which is at an altitude of 233 m. Excluding the part of the basin above the gaging station on the Wādī al Ḩaţab (Oued Hatab), the Zurūd drainage basin covers 6,670 km². In 8 years of record the mean daily discharge of Wādī Zurūd has ranged from 0.043 to 829 cu m per sec, with an instantaneous maximum of 4,864 cu m per sec. The annual runoff has ranged from 26.8 million m^3 in 1949 to 166.7 million m^3 in 1953.

In nearly every month when the runoff of Wādī Zurūd has exceeded 2 million m^3, rainfall of 50 mm or more has been recorded in some part of the basin, and in most of those months the rain has been distributed widely enough to be recorded both at Maktḩar or Tālah as representative of mountainous areas and at Al Qayrawān or 'Ayn Ghrasesia as representative of the lowlands. Some storm flows have resulted from rainfall recorded chiefly at the lowland stations (as in July 1952 and September 1956), and other storm flows occurred when the lowlands received very little rainfall (as in May and July 1951 and August 1952).

A comparison of the monthly runoff of the Wādī Zurūd with concurrent precipitation at Al Qayrawān and 'Ayn Ghrasesia indicates that there are rarely any major increases in runoff in months when the total precipitation is less than 50 mm. In months when precipitation exceeds 50 mm (about 1½ months a year), there is likely to be flood runoff, and in months with more than 75 mm of precipitation (less than 1 month per year), flood runoff is almost certain—presumably because so high a total of monthly rainfall generally includes at least one storm during which there is rainfall of 50 mm or more. Some increase in daily discharge, however, is likely to occur even with precipitation of a few millimeters, and the rainfall records thus serve as indicators of storm conditions within the drainage basin, even when the gage is near the edge of the storm area.

The mean daily discharge of the Wādī Zurūd fluctuates markedly in most months in response to major and minor storms, some of which may be general and may produce runoff throughout the large basin. Others are localized so that the increased flow in the Zurūd comes from tributaries that drain only a small part of the basin. Flood runoff from minor or local storms ordinarily continues only a day or two, and that from major and general storms may continue as long as a week or 10 days. After the storm runoff the discharge generally diminishes to approximately the rate prior to the storm. Because of the minor fluctuations that characterize the discharge during periods of low flow, the recession curve for the Wādī Zurūd is not clearly defined, although it appears that the base flow may diminish at a rate of about 50 percent every 3 months. If so, the numerous ground-water reservoirs within the drainage basin that contribute this base flow must be replenished frequently, because the low flow is ordinarily in the range 0.5–0.8 cu m per sec except in the hot summer months, when it may decline to 0.1 cu m per sec owing to losses by evaporation.

The hydrographs of plate 4 compare the fluctuations in daily discharge of the Wādī al Ḩaţab (Oued Hatab) at Khanqat al Jāziah and of the Wādī Zurūd at Sīdī Sa'd, about 70 km downstream, for the agricultural year 1959. Some of the flood peaks recorded on the Zurūd, as for example those of April 26 and August 4, 1959, have no counterpart on the hydrograph of the Ḩaţab (Hatab) and indicate that the runoff came entirely from tributaries other than the Ḩaţab (Hatab). Some floods on the Ḩaţab (Hatab), as for example on December 7, 1958, and April 14, 1959, may have been recorded at the Zurūd station as smaller rises two days later.

The fact that several of the flood peaks on the Zurūd occur on the same day or very shortly after those recorded on the Ḩaţab (Hatab) suggests response to the same storm by independent wadis rather than measurement of the same flood at two points on the same wadi. A more pronounced indication of independence of the two wadis is the record for August 13, 1958, when an increase in discharge of 10 cu m per sec in the Ḩaţab (Hatab) produced no increase in the Wādī Zurūd. This flood runoff was obviously dispersed entirely in the Bilād Gamouda Plains. In several periods of flood runoff the discharge of the Wādī Zurūd has been less than, or very little greater than, that of the Wādī al Ḩaţab (Oued Hatab), another indication that the flow in the Ḩaţab (Hatab) may not reach the Wādī Zurūd.

The low flow on the Wādī al Ḩaţab (Oued Hathob) between Sabībah and the Wādī Zurūd ranges from 0 to more than 250 lps, depending on the permeability of the stream bed and the geologic structure of the area traversed. The chemical quality of water is variable with about 1,200 ppm (parts per million) or less of dissolved solids at Sabībah and 2,000–4,000 ppm near Jabal al Halfā'. In the reach between Jabal al Halfā' and the fault along Jabal al Abeïd, the flow disappears in the sandy channel deposits but at the fault about 150 lps, having about 2,500 ppm dissolved solids, reappears in the wadi. The flow remains fairly uniform for several kilometers downstream, but opposite Hājib al 'Uyūn the low flow generally is very small, and the dissolved solids average about 3,000 ppm. Just upstream from the gaging station the low flow increases slightly.

The low-flow discharge of the Wādī al Ḫajal at its confluence with the Wādī Zurūd probably averages about 50 lps, and the low-flow discharge of the Wādī Zurūd to the Al Qayrawān Plain probably averages about 800 lps according to long-time residents of the area. The dissolved-solids content may average about 4,000 ppm.

OTHER WĀDĪS

Runoff in several important wadis has not been measured. The largest and most important of these is the Marq al Layl which has a drainage area of about 1,396 km² between the Wādī Zurūd and Wādī Nabhānah, above the 100-m land-surface contour of the Al Qayrawān Plain (pl. 1).

There are numerous other wadis whose flows are not gaged. Some have small perennial flows which are diverted for irrigation, and water from others is sometimes diverted during floods to inundate croplands temporarily. The Sabībah, Al 'Aṭf, Al 'Ālim, Al Fakkah, An Niqādah, Subayṭilah, Al Bawl, and Al Brek wadis (pl. 1) are in the latter group.

SABKHAS, PONDS, AND POOLS

Natural bodies of standing water are widely and irregularly distributed in the Sāḥil and adjacent steppes. Most of these are ephemeral, and they are thus most numerous after rains and especially during periods of abundant rainfall. Also, their water-surface areas and volume of water in storage vary markedly from season to season and from year to year. These bodies of standing water include sabkhas, the largest of which are Sīdī al Hānī', altitude 29 m, with a maximum water-surface area of about 350 km², and Kalbīyah, altitude 20 m, with a maximum area of 160 km² but which range downward in size to a few square kilometers; smaller ponds, which occur chiefly in the steppes, and pools, which may range in size from a fraction of a hectare to several hectares, are found in stream channels.

The pools include the small bodies of water that are left in the channels of the wadis as streamflow ceases, and the pools remain until the water evaporates. This evaporation occurs especially in the summer and leaves saline residues which are redissolved by the first flood runoff of the following rainy season. Thus in many wadis the runoff in early autumn may be more highly mineralized than that later in the rainy season. Pools also develop along the stream courses in places where infiltration has been sufficient to saturate the alluvium practically to the land surface. This high water table appears at the surface to form pools in slight depressions. Here, too, there may be a gradual increase in the mineral content of the water because of evaporation.

The sabkhas and ponds occupy closed depressions whose positions reflect in part the regional geologic structure. The Sabkhat Saqānis, along the coast near Al Munastīr, Sabkhat Sīdī al Hānī', and Sabkhat Ash Sharīṭah inland occupy a broad southwest-trending trough, separated by highlands to the north from a similar broad trough which contains the Sabkhat Ḥalq al Manzil and Sabkhat al'Assah al Jarībah along the coast and Sabkhat al Kalbīyah inland. The Sabkhat Matā 'al Muknīn and the Sabkhat al Kotaia south of the Sāḥil area shown in plate 1 are within a third broad trough to the south of the others. Still farther south, extending southwest from the Sāḥil Ṣafāqis, is another broad trough which contains the Sabkhats Al Jamm, Matā 'al Ghurrah, Bū Jamal, and Mashāqīq. West of the Sāḥil and lower steppes, the Sabkhat al Buḥayrah and Qar 'at Majdūl are in a separate structural basin along Tunisia's central north-south structural axis (Dutcher and Thomas, 1967).

The water in the sabkhas is derived in part from direct precipitation, in part from inflow of tributary wadis, and in part from ground water. Thus the sabkhas constitute areas of evaporation of water from all phases of the hydrologic cycle, although the amounts derived from the individual phases have not been measured and cannot yet be estimated. Nevertheless, it is clear that the sabkhas constitute areas of natural disposal and return to the atmosphere of water that has fallen as precipitation upon an area far more extensive than that of the sabkha. Such disposal areas are characteristic of many arid regions, and characteristically there is accumulation of saline residues, or evaporites, as water is evaporated.

A more humid climate—that is, an increase in the volume of precipitation and (or) decrease in the rate of evaporation—would not eliminate the sabkhas, but would induce greater accumulation of water and eventually overflow from the closed depression, perhaps to another closed depression, perhaps to the Mediterranean. With continuity of outflow, the saline water and saline residues in the underlying bed of the sabkha would be flushed out and the body of water would become a fresh-water lake.

In the past century the inflow to Sabkhat al Kalbīyah from the combined Nabhānah-Marq al Layl-Zurūd basin has been sufficient to fill that basin (capacity about 450 million m^3, or 375,000 acre-ft) to the point of overflow several times. In 1932 the outflow from the northeast corner of the basin toward the Mediterranean continued for 6 months, during which time the outflowing water was fresh enough to use for irrigation. The lake formed by the floods of 1932 and sustained by additional inflow in subsequent wet years such as 1935 continued to exist in gradually diminishing size until 1938.

SEDIMENT LOADS IN STREAMS

The runoff in the wadis that drain the Tell and High Steppes is usually highly charged with sediment, and erosion is severe in nearly the entire area west of the Bū Dīnār-Shurayshīrah-Sawāṭīr structural zone (Dutcher and Thomas, 1967). The sediment load transported during periods of low flow from ground-water discharge is negligible in a few streams, principally the Wadis al Darb, Barqū, and Nabhānah, but also at times on a few small wadis tributary to the Marq al Layl, Ḥaṭab (Hatab), and Zurūd. Even these streams, however, are relatively free of suspended sediment only during periods of little or no precipitation.

Systematic measurements have not been made of the sediment loads carried by most streams. The HER recognizes the importance of sediment studies, and a program for collecting data is being considered. The data available were collected during short preliminary studies and are adequate only for making approximate estimates at a few gaging stations. Nevertheless, these studies indicate the magnitude of the sediment loads transported by some of the wadis.

According to Tixeront (1958, table 4), the sediment load transported by the Wādī Zurūd during 4 years of record at Sīdī Sa‘d was about 500 metric tons (500,000 kg) per km^2 per year. Thus, for this basin of about 8,950 km^2 the annual sediment load may exceed 4,400,000 metric tons, or about 50 kg (kilograms) of sediment per cubic meter of water. On the average, about 500 g (grams) of soil and mantle rock is removed from each square meter each year, or about 1 cm of the surface materials is eroded in approximately 30 years, but the erosion is not uniform and in some places is more severe than at others.

It appears likely that the average sediment load transported by the Wādī Marq al Layl may also be about 500 metric tons per km^2 per year. Estimates by J. H. Johnson, U.S. Soil Conservation Service (oral commun., 1962), indicate that the sediment load carried by some small wadis trubutary to the Wādī Marq al Layl may exceed 1,000 metric tons per km^2 of drainage area per year. The Wādī Nabhānah may transport relatively less sediment, but the amount is undoubtedly high compared to streams in humid climates.

Climatic factors, topography, geology, and land-use practices combine to create an environment conducive to extreme soil erosion, because: (1) the summers are hot and virtually without rain, (2) the rains of early fall are often of short duration but very intense, (3) the texture of the soil enhances runoff, (4) the geologic formations which crop out in much of the area are easily eroded, (5) the topography is dominantly irregular, and (6) overgrazing and other abusive land-use practices commonly remove almost all the natural cover from the soil each summer—a condition which is particularly damaging during September and October.

Undoubtedly erosion would be reduced and the production of beneficial crops and forage could be increased if appropriate soil- and water-conservation and land-management practices were followed throughout each stream valley. Studies on the Wādī Marc al Layl drainage basin are being carried out by HER within the scope of the program for technical assistance by the Agency for International Development (AID) following the procedures and practices of the U.S. Soil Conservation Service. An effective plan for land use and soil and water conservation should be completed for each watershed.

Basinwide soil- and water-conservation programs in each stream basin should make it possible to build inexpensive structures to control the runoff in the wadis. It would be possible to build dams, flood channels, and other structures to control floods, to store the water temporarily, or to increase ground-water recharge, and these could even be completed prior to correcting the abusive practices of land use or before good soil conservation programs are implemented. It is probable, however, that the building of additional large dams and other structures would not be profitable unless erosion is reduced first because the cost would be great and sediments would soon fill or reduce the capacity of most reservoirs or recharge basins.

Detailed engineering studies to determine whether or not designs for dams are suitable, and if the costs of construction and operation are less than the expected benefits, also are needed prior to construction of large dams or flood-control works. Under present conditions only limited expenditures can be justified for flood protection because there are virtually no developed urban areas or lands endangered by the uncontrolled floods.

Rather than planning to construct large and expensive dams it might be more practical to control the flood flows by building small dams and structures to divert flows into off-channel recharge basins where large volumes of flood water could be used to recharge shallow aquifers. Any such programs would logically follow the implementation of basin-wide soil-conservation practices. Choosing these recharge sites and designing diversion dams and canals to withstand the floods will require further studies. Experiments should be carried out to test each proposed type of structure before large-scale projects are undertaken. Any type of reservoir will probably require frequent cleaning or flushing with water to remove the sediments because erosion will remain a serious problem.

An expanded program should be started to measure the sediment load carried by the larger wadis. Suitable sites for making the measurements must be selected, and sediment sampling should be carried on as a part of an expanded program of stream gaging. Streams selected for such studies should include the Wādī Nabhānah at a site upstream from the dam under construction, the Wadis Zurūd, Marq al Layl, Ḩaţab (Hatab), al 'Aţf, al 'Ālim, and others where data are required.

UTILIZATION AND QUALITY OF WATER

A dam under construction on the Wādī Nabhānah at Sīdī Mas 'ūd was scheduled for completion in 1965 at which time the entire flow, except for losses due to evaporation from the reservoir and minor losses from seepage and during transport, will be available for public supply at Sūsah and in other coastal towns and for irrigation. The long-term average annual amount of water available for use on the basis of the mean annual runoff, will be about 39 million m^3 (less the losses), according to data supplied by HER. This average is equal to a constant flow of about 1,240 lps. Thus, the use of water from the Wādī Nabhānah will soon far exceed the average annual use of water from all other surface sources in the area. This condition will undoubtedly continue indefinitely unless studies show that it is feasible to construct dams or other diversion structures on the Wādī Zurūd or the Wādī Marq al Layl.

Present use of surface water is limited mainly to diversions of low flow from the Wadis ad Darb and Sabībah (and, locally, from a few other wadis where the supplies are less certain) and to the spreading of the uncertain and highly silt-laden flood flows on crop lands near the streams where they cross the alluvial plains near Al Qayrawān, Sīdī Bū Zayd, An Nafīḑah, and the Bilad Sīsab. The use of surface water is limited by the flow characteristics of the streams. The torrential flows are difficult to divert from the stream channels for use, but nevertheless the flows from the flooded channels of several streams are successfully diverted and spread on nearby crop lands. This form of irrigation has been practiced in the region for many centuries, and although the average volume of water supplied per hectare of land is small, the practice contributes to the agricultural economy during years when flood runoff is available for such use.

Earthen diversion dikes have been built on the Wādī Marq al Layl near Al Qayrawān which in some years divert water to sheetflood about 4,500 hectares of land that usually is planted to cereals. Similar structures on the Wādī Zurūd are used, when runoff is sufficient and can be controlled, to irrigate about 1,200 hectares. The rustic earthen dikes need constant repair and are often destroyed by the torrential floods; they seem unsuited to their task, but in view of the conditions, the braided-stream channels, and large volumes of water which the floods bring, one wonders whether the fragile nature of the diversion structures is not their most valuable quality.

Similar dikes are used to divert flows from the wadis tributary to the Wādī Nabhānah north of Al Qayrawān. The flows are used for the irrigation of small gardens. Near An Nafīḍah, flood flows of the Wādī al Brek and Wādī al Bawl (Oued Khiarate) are diverted, as are those of the Wādī al Ḩaṭab (Oued Hatab) and its tributaries near Sīdī Bū Zayd.

According to HER, surface water from the Wādī ad Darb, which has an average flow of about 290 lps, is used to irrigate about 500 hectares. A small dam has been constructed on the Wādī Sabībah about 4 km west of the town, and surface water and well water are used to irrigate about 500 hectares, but plans are complete to place an additional 1,500 hectares under irrigation in the area. Surface water is used in the Sāḩil Sūsah area to irrigate more than 1,500 hectares under intense cropping and to flood a maximum of about 15,000 hectares of land during the most favorable seasons. On the average, however, surface water is sufficient to irrigate much less than 15,000 hectares annually.

The quality of the surface water in each wadi is highly variable with time and place. Analyses of surface waters are given in table 12 of the separate data report (Dutcher and Mahjoub, 1963). These analyses show that the dissolved-solids content of the flows of the Wādī Nabhānah ranges from less than 300 to more than 3,000 ppm, depending on the time of year, the stage of the wadi, and the location of the sampling point. Samples of water from the Wādī Zurūd were analyzed, and these show variations which are even more remarkable and which are also related to stage, time, and place—dissolved solids as low as 440 ppm and in excess of 19,000 ppm have been recorded. The water of the Wādī Marq al Layl has a much smaller range of dissolved solids and generally contains about 1,000–2,500 ppm. The water of the Wādī Ḩaṭab (Oued Hathob) generally contains from 500 to 2,800 ppm, but the quality of the water in the Wādī ad Darb is more uniform and generally contains only 800–900 ppm of dissolved solids. The quality of the Wādī al Ḩaṭab (Oued Hatab) water generally ranges from about 2,000 to 4,000 ppm of dissolved solids.

In general, the flood flows have a much lower content of dissolved solids than do the base flows from ground-water discharge—the low flows are subject to intense evaporation and other factors which tend to increase the dissolved-solids content of the water.

RELATION TO HUMAN REQUIREMENTS

Practically all the water that flows in the wadis of central Tunisia remains in the Sāḫil or adjacent steppes until it is returned to the atmosphere by evaporation, for there is negligible runoff to the sea. Much of this water, whether it is stored on the surface or underground while awaiting return to the atmosphere, becomes too highly mineralized to be utilized by man.

The base flow of the perennial wadis—released naturally from ground-water reservoirs—is the surface water most readily available for use by man, for it requires only diversion from the low-flow channel at places where the water is of usable quality, and it flows at relatively uniform rates. Few of the wadis in the region flow perennially, and in these few the base flow constitutes only a small proportion of the total flow.

The storm flow in the wadis is not naturally regulated in form appropriate for diversion for beneficial use. This water can be salvaged for use by man only after it has accumulated in reservoirs, either on the surface or underground, where it can be stored and subsequently released under control. The reservoirs on the surface include the sabkhas, where the water accumulates naturally, and artificial reservoirs to be formed by dams. Similarly, underground reservoirs might store water received naturally by seepage from the wadis or artificially in recharge projects that might be developed

The sabkhas generally contain water that has gone beyond the limit of salt concentration suitable for salvage and use. Only when the outflow from the sabkha is sufficient to carry out excess salt is there a possibility for the stored water to become fresh enough for use. Without outflow, the water in the sabkha becomes increasingly saline as its quantity is reduced by evaporation, and this evaporation may continue until the water disappears and leaves a salt crust. The salt remains as a potential contaminant for any fresh water that subsequently enters the sabkha.

Artificial surface reservoirs that might be created by dams would be subject to substantial water losses because of the high evaporation, and where the inflowing water carries a moderate content of dissolved solids, such losses would cause deterioration in quality of the water remaining in the reservoir. Because of the high rate of evaporation and the consequent deterioration in the quality of standing surface water, the opportunities for developing a firm water supply by means of dams and surface reservoirs are negligible in the Sāḫil and adjacent steppes. A reservoir capable of storing all the flood inflow during a wet period would lose most of that water by evaporation during the subsequent dry period, which is generally of greater duration than the wet period. Water stored in surface reservoirs during wet years, therefore, should not be expected to supplement the annual runoff for more than the first few years of an extended drought.

Artificial reservoirs, however, would have an advantage over sabkhas in that the water diverted from a reservoir would carry its proportionate share of the mineral matter; furthermore, reservoir management could provide for flushing out of the water when its mineral content became excessive. The best reservoir sites for the arid climate of central Tunisia would be those in which the water-surface area is small in relation to the volume of water stored, but unfortunately such sites do not exist within the Sāḩil and adjacent steppes.

The storage of water in underground reservoirs and the development and utilization of this water by man are discussed in other Water-Supply Papers (Dutcher and Thomas, 1967). It is worthwhile to note here, however, (1) that existing ground-water reservoirs underlying or adjacent to the wadis may derive replenishment from surface water, especially from storm flow, and (2) that if projects are undertaken for artificial recharge of certain ground-water reservoirs, the water used for recharging will probably be surface water derived from the wadis.

To those seeking to salvage water for beneficial use, the ground water in the broad valley plains along the major wadis poses problems similar to those presented where water accumulates on the surface in sabkhas. The Bilād Gamouda, which receives the flow of the Wādī al Ḩaţab (Oued Hatab), and Al Qayrawān Plains, which intercept the flow of the Wadis Zurūd, Marq al Layl, and several other wadis, are examples. The water contributed to these plains from the tributary streams may be of usable quality, at least in some seasons and especially during major storms. However, because this water is dispersed over a broad area and at a shallow depth below the land surface, a large proportion is returned to the atmosphere by evapotranspiration and the remainder deteriorates in quality because of accumulation of saline residues. Unlike the sabkhas, these plains have continuous ground-water outflow from their lower limits (collected, for instance in the Wadis al Ḩajal, al ‘Aţf, and others), but the outflowing water is too highly mineralized for most uses.

The problem posed by artificial storage of surface water and recharge of ground water are somewhat similar to problems involved in use of natural storage and recharge. Such artificial storage and recharge sites require sites where the inflowing stream water is of usable quality and where the proposed reservoir can store the water and subsequently yield it in a condition suitable for use. A related problem is the difficulty of finding such suitable sites in central Tunisia.

In summary, development of the surface-water resources of central

Tunisia presents numerous problems, but there appear to be conditions and places where considerable quantities of water can be stored, on the surface or in the ground, and recovered in quantity and quality usable for some purposes.

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