A Qualitative Appraisal of the Hydrology of the Yemen Arab Republic from Landsat Images

By MAURICE J. GROLIER, G. C. TIBBITTS, JR., *and*
MOHAMMED MUKRED IBRAHIM

CONTRIBUTIONS TO THE HYDROLOGY OF AFRICA AND THE MEDITERRANEAN REGION

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CONTRIBUTIONS TO THE HYDROLOGY OF AFRICA AND THE MEDITERRANEAN REGION

A QUALITATIVE APPRAISAL OF THE HYDROLOGY OF THE YEMEN ARAB REPUBLIC FROM LANDSAT IMAGES

By MAURICE J. GROLIER, G.C. TIBBITTS, JR., *and* MOHAMMED MUKRED IBRAHIM[1]

ABSTRACT

Landsat 1 and Landsat 2 images were analyzed in June 1976 to describe the flow regimens of streams and the regional distribution of vegetation in the Yemen Arab Republic (YAR). The findings provide a factual basis for planning a surface-water data collection program and for preparing maps of plant distribution and agricultural land use. They lay the foundation for modernized water development and for effecting a program of countrywide water management in the YAR. The work was undertaken as part of the program of the U.S. Agency for International Development, with the cooperation of the Mineral and Petroleum Authority, Ministry of Economy, YAR.

Nine Landsat scenes cover the entire YAR. A false-color, composite mosaic of nine corresponding images was prepared using Landsat 1 images taken at a relatively low sun-angle in the winter of 1972–73. Catchment areas and the major drainage basins of the country were delineated on this mosaic. Additional Landsat 1 images taken in fall 1972, spring 1973, and fall 1973, together with Landsat 2 images taken in spring 1975, fall 1975, and spring 1976, provide repetitive coverage of these nine scenes. A hydrological and ecological analysis of this array of imagery shows many kinds of streamflow regimens and, along the reaches of some streams at least, yearly and seasonal fluctuations or changes in streamflow. Similar fluctuations in soil moisture and possibly in groundwater supply were inferred from variations in the site of vegetated areas and the apparent (spectral) vigor of plant growth.

In order of increasing water availability, the four catchment areas of the YAR are: Rub' al Khali (Ar Rab' al Khālī)[2], Wādī Jawf (Arabian Sea), Red Sea, and Gulf of Aden. Most streams are ephemeral. No lakes were detected during the period un-

[1]Mineral and Petroleum Authority, Ministry of Economy, Sana (Şan'ā'), Yemen Arab Republic.

[2]Geographic names in this report have been verified in the U.S. Board on Geographic Names (BGN) *Official Standard Names Gazetteer, Yemen Arab Republic, 1976*, as approved by the Board on Geographic Names, Geographic Names Division, Defense Mapping Agency, Hydrologic/Topographic Center, Washing-

der investigation, but sebkhas—salt flats or low, salt-encrusted plains—are common along the *Red Sea coast. In spite of the 80-meter resolution of Landsat images and the additional constraint of carrying out this hydrologic analysis at the 1:1,000,000 scale, streamflow was interpreted as perennial or intermittent, wherever it could be detected on several Landsat images covering the same scene at seasonal or yearly intervals. Much of the land under cultivation is restricted to valley floors and to valley slopes and irrigated terraces adjacent to stream channels. Little or no vegetation could be detected over large regions of the YAR.

The relatively advanced state of water development, as evidenced by irrigation from wells or by diversion of streamflow into irrigation canals, already warrants a quantitative evaluation of water resources and land under cultivation in some parts of the Tihāmah (the coastal plain inland from the *Red Sea coast) and in some of the interior valleys. Computer enhancement and photographic enlargement of perennial and intermittent streams and of the farming areas observed on available Landsat images, and large-scale thematic mapping of surface water and vegetation by hand-ratioing performed on computers will constitute a first step toward effective countrywide management of water resources and agricultural production. Systematic mapping of regional fractures, especially of intersecting fractures, on Landsat images may lead to the discovery of new sources of ground water.

INTRODUCTION

PROGRAM OBJECTIVES AND SCOPE OF THE REPORT

Agriculture in the Yemen Arab Republic (YAR) is critically dependent on irrigation from ground water or from diverted streamflow and sheetflow. In addition, the water supply of cities and individual farming communities is everywhere dependent on water pumped from wells, water from springs, or rain collected in cisterns during torrential showers. Further development of ground- and surface-water resources is a key element in developing agricultural resources in the YAR.

The qualitative appraisal of surface- and ground-water resources contained in this report is a service rendered by the U.S. Geological Survey (USGS) under Participating Agency Service Agreement (PASA) ASIA (IC) Yem-925-22-74 between the U.S. Agency for International Development (USAID) and the USGS, in cooperation with several agencies in the YAR—the Central Planning Organization (CPO), the Ministry of Agriculture, and the Minerals and Petroleum Authority (MPA) within the Ministry of Economy. The results of two segments of a Water and Minerals Survey of the YAR, called for in the PASA, namely (1) a ground-water survey of the

ton, DC 20315. Other processing of names, compilation, review, and editing, for cartographic and report use, was done in the Office of International Hydrology, 470 National Center, Reston, VA 22092. (See appendix III.)

Spellings of geographic names in the report are approved by the BGN. Names preceded by an asterisk (*) have no BGN recommendation. Previous reports used a transliteration of the native name, that is, Al Mukhā, San'ā', and Ar Rab' al Khālī, in preference to the conventional name spelling approved by the BGN. In this report, the conventional name is used, followed by the native name in parentheses, for example, Mocha (Al Mukhā), Sana (San'ā'), and Rub' al Khali (Ar Rab'al Khālī).

YAR north of the 15° N. parallel and (2) an ERTS (Landsat) satellite survey of the country, are presented in the report.

The Water and Minerals Survey of the YAR is a subproject of the Pre-Development Studies Project of USAID and YAR. One goal of the subproject has been to produce mosaics of Landsat scenes covering the YAR. Early versions were delivered to USAID and to the cooperating YAR agencies in 1975 and 1976. An improved version was prepared later by the USGS and used as the base for a geographic map of the country (U.S. Geological Survey, 1978b). A geochemical report (Overstreet and others, 1976) was released to the open file of the USGS, the CPO, and the MPA in February 1976, in partial fulfillment of the third segment of the subproject, a minerals survey north of 15° N. latitude. A preliminary geologic map of the YAR at the 1:500,000 scale and in nine separate sheets was released by Grolier and Overstreet in 1976, in partial fulfillment of the second segment of the subproject. They later prepared a more complete geologic map at the same scale (Grolier and Overstreet, 1978), transferring previously compiled geologic information to a single Landsat image mosaic of the YAR. The purpose of preparing the later geologic map was to bring together, at a convenient working scale, previously known geologic information and recently acquired data from Landsat scenes.

The objectives of the appraisal of the hydrology of the YAR are (1) to provide sufficient data for planning the development of water resources in some areas, (2) to make recommendations to the Government of the YAR as to projects and programs for evaluating the water resources of the YAR, and (3) to assist the YAR in developing plans and priorities for several studies of ground-water resources (PASA 22–74).

In this study, the spectral reflectances of surface water, wet or moist land, and vegetation, taken at successive times, were used to identify and locate surface water and to draw inferences concerning the occurrence of ground water at shallow depth. The study differed from the task originally called for in the PASA in two ways. First, surface water was included because it was considered impractical to describe the occurrence of ground water alone. In addition, the hydrogeological survey was expanded to include surface-water resources throughout the YAR, inasmuch as the Landsat survey covered the whole country.

The presence of ground water in the YAR can be inferred from the regional distribution of vegetation, as described in this report. However, any discussion of ground-water systems in the YAR, beyond such generalizations as alluvium, sandstone, and some lava flows being good aquifers and granitic and metamorphic rocks being poor ones because of lower porosity and permeability, is excluded from this report because data are not available.

Likewise, evaluating the status of ground-water and surface-water exploration and development in the YAR presupposes an *effective*, systematic, countrywide collection of hydrologic data and a repository (such as a library) where these data and pertinent reports by government agencies and consulting firms are maintained for safekeeping and analysis. Our efforts to procure such data and reports when this report was being compiled proved unsuccessful. However, ground-water development in the YAR has a long history, spanning several thousand years. Since time immemorial, water wells have been dug by the thousands in valley and coastal plain alluvium, and many are known to have been excavated by hand out of hard rock. In the last 20 years, many modern wells have been drilled and equipped with pumps under the foreign aid programs of many countries, including USAID. Well drilling by private enterprise has been very successful in the south-central part of the Tihāmah, so much so that indiscriminate ground-water withdrawal has resulted, locally, at least, in overdevelopment. Development of water resources in major river basins, such as those of Wādī Mawr and Wādī Zabīd, are in the planning or early stages. Clearly, however, an analysis of the long history of water exploration and development in the YAR and the many accomplishments of the last 20 years are beyond the scope of this report.

In contrast to most previous hydrological investigations in the YAR, the scope of this analysis is countrywide rather than regional or site-specific, and thus the survey is a reconnaissance rather than a detailed study of the water resources of the YAR. Nonetheless, on the strength of its results, several recommendations are made for future surface-water surveys and hydrogeological investigations.

TOPOGRAPHY

The YAR occupies an area of about 200,000 square kilometers (km^2) in the southwestern part of the Arabian Peninsula. On the north and northeast the country borders the Kingdom of Saudi Arabia, on the southeast and south, the People's Democratic Republic of Yemen, and on the west, the Red Sea. Its seacoast, from the mouth of Wādī Maydī on the north to the strait of Bab el Mandeb on the south, is about 460 kilometers (km) long. The capital, Sana (San`ā´), is in the north-central part of the *Yemen highlands. The major cities of the country—Bājil, Al Ḩudaydah (Ḩudaydah), Zabīd, and Ḩays (Ḩais) on the west, Ma`bar, Dhamār, Yarīm, Ibb, and Ta`izz on the south, and `Amrān (`Umrān) and Al Ḩarf on the north—are linked to the capital by paved highways (fig.

1.). Gravel roads permit travel to most populated places in the YAR, but in the extreme eastern part of the country, in Ramlat as Sab`atayn, these roads yield to desert tracks. Provincial subdivisions (fig. 1) are termed "governorates."[3]

The YAR has a total relief of more than 3,000 meters (m) and can be divided into five major regions (fig. 2). From west to east, these are: (1) a coastal plain, called At Tihama (or siimply the Tihāmah or Tihama), which borders the Red Sea; (2) a west-facing, mountainous escarpment (*Red Sea escarpment); (3) the *Yemen highlands; (4) the *Wādī Jawf valley; and (5) the southwestern fringe of Rub`al Khali (Ar Rab`al Khālī). The first three regions extend from north to south and are parallel to the *Red Sea coast. The *Wādī Jawf valley trends southeastward toward Ramlat as Sab`atayn, a sandy wilderness that separates it from the valley of Wādī Ḩaḑramawt (fig. 3) in the People's Democratic Republic of Yemen. Rub`al Khali lies north of the *Wādī Jawf valley.

The coastal plain (the Tihāmah) is a strip of land 25 to 50 km wide which slopes gently from the base of the foothills (at an altitude of 400 m, except in the north) to the *Red Sea coast. The channels of many transverse seasonal streams are incised a few meters below the colluvial, alluvial, and eluvial surfaces of the Tihāmah. Cultivated fields, irrigated with water pumped from wells, lie adjacent to many wadis. Drifting sand and some dune fields alternate with cultivated fields in the interfluves, and salt-impregnated flats (sebkhas) are common along the coast. Coral reefs fringe the coast, particularly in the southern part of the Tihāmah.

The coastal plain rises eastward to the foothills, and in its upper reaches it can be traced to an altitude of 1,000 m. The intermontane part of the Tihāmah is commonly referred to as upper Tihāmah mountain Tihāmah.

The mountainous slope, which rises from the floors of the valleys in the upper Tihāmah to the divide between westward-draining and eastward-draining streams in the interior, is referred to as the *Red Sea escarpment. Total relief along the *Red Sea escarpment averages 1,500 m, but west of the cities of Sana and `Amrān it exceeds 2,000 m. The *Red Sea escarpment, which ranges from 40 to 90 km wide, is a major orographic obstacle to southwest monsoons and also to dust blown inland from the Tihāmah. South of Ḩays, the escarpment disappears and is replaced by lower mountain ranges that extend eastward and southward toward the People's Democratic Republic of Yemen. The *Red Sea escarpment is the catch-

[3]BGN sources indicate that the governorate of Ma'rib was divided into two governorates in 1980: the southern part retained the name Ma'rib, and the northern part was named Al Jawf. The 11 governorates were listed in the April 10, 1981, issue of the Yemeni newspaper *Ath Thawrah*. As of October 1, 1981, boundary information was not available.

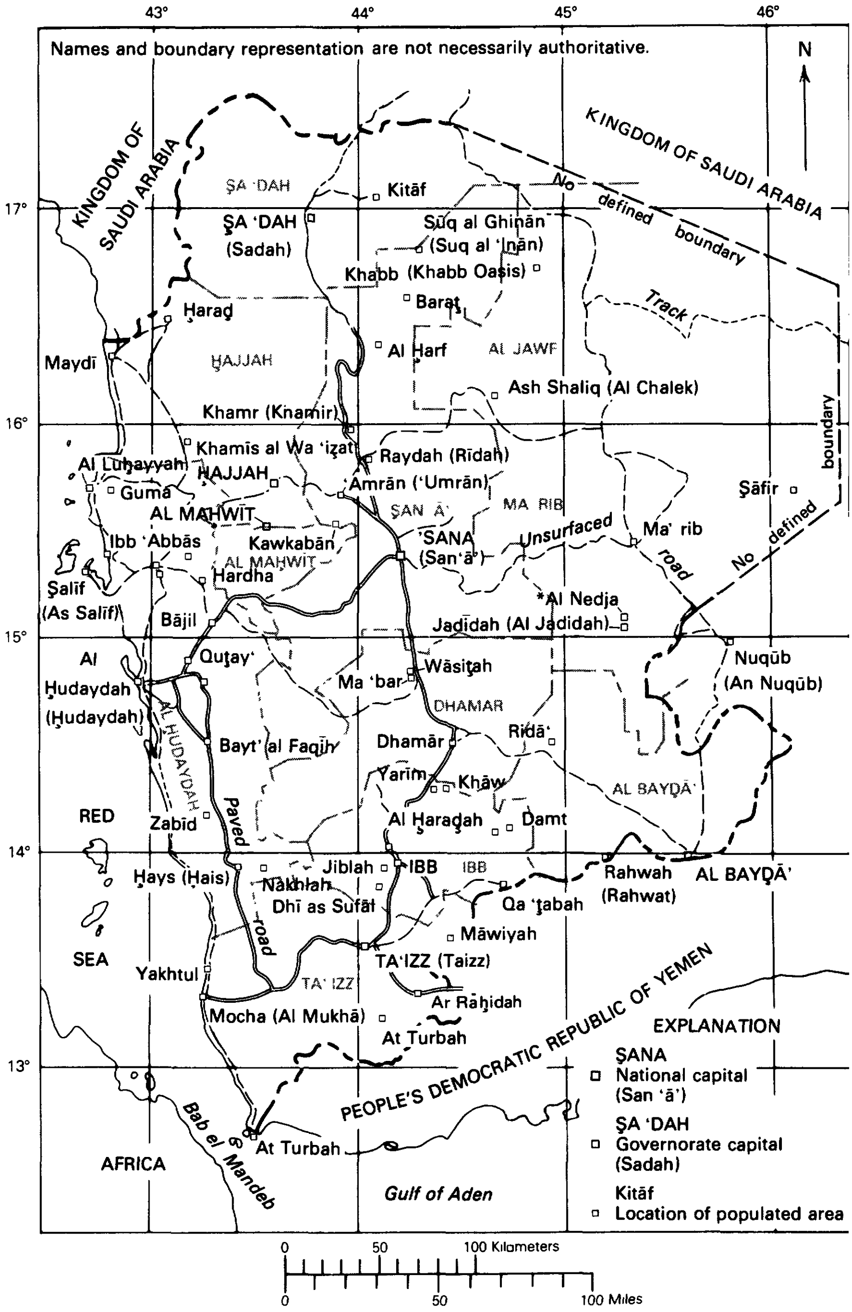

FIGURE 1.—Governorate boundaries and network of highways and other roads of the Yemen Arab Republic. Governorate names are short form names approved by the Board on Geographic Names.

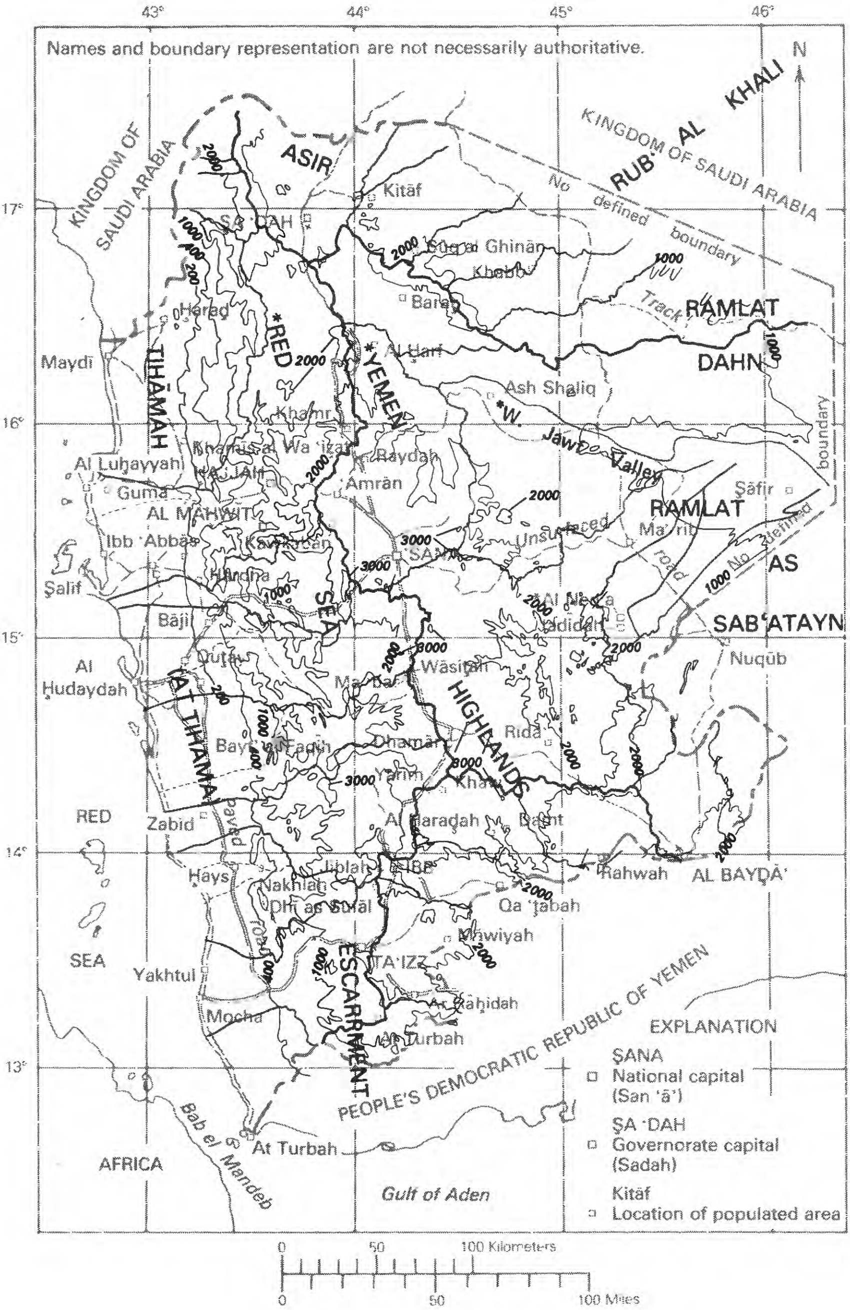

FIGURE 2.—Surface features of the Yemen Arab Republic, including catchment areas, generalized topography, and major physiographic provinces. Four catchment areas are delineated: Rub' al Khali, Wādī Jawf, Red Sea, and Gulf of Aden. Five major physiographic regions are shown: Tihāmah, Red Sea Escarpment, *Yemen Highlands, Wādī Jawf valley, and Rub' al Khali. Physiographic names having no Board on Geographic Names recommendation are shown preceded by an asterisk.

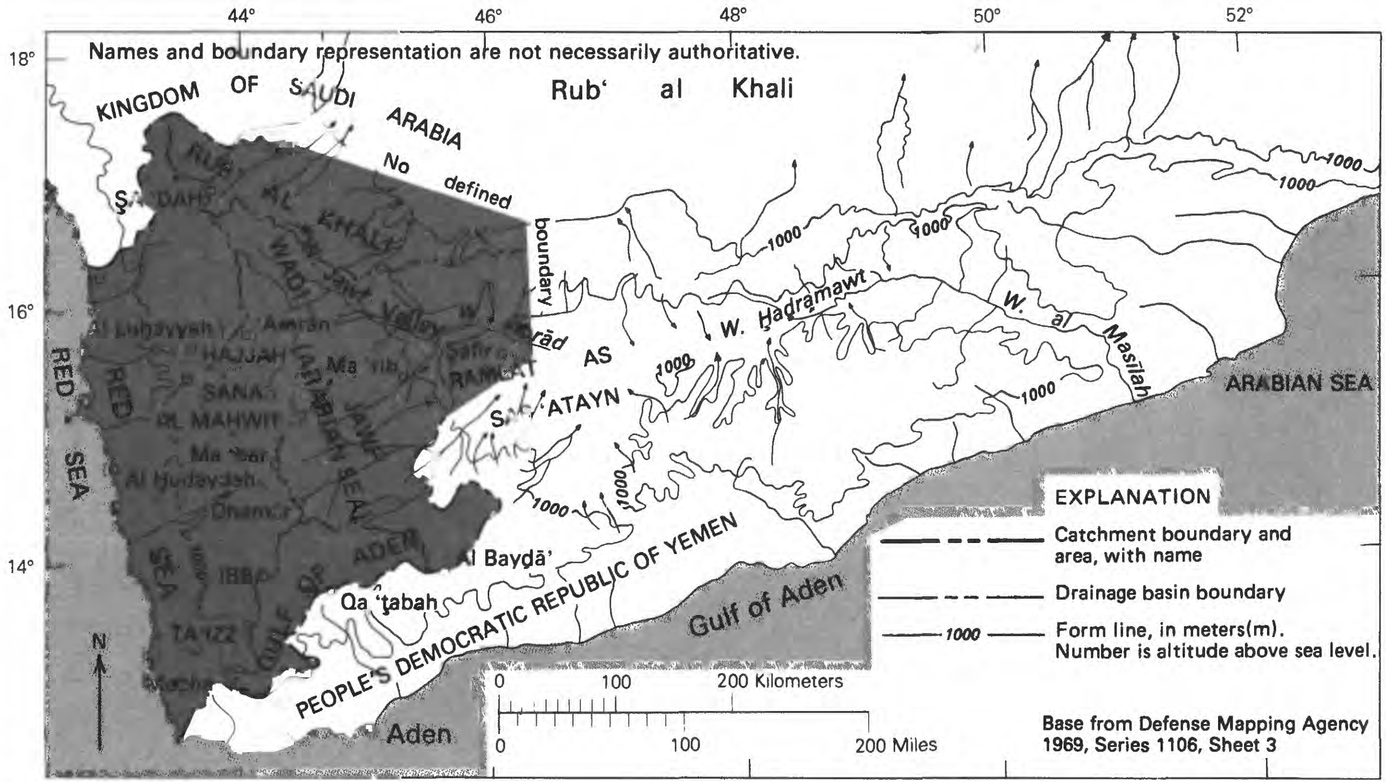

FIGURE 3.—Catchment areas of the Yemen Arab Republic (shaded area) eastward to the Arabian Sea. Names preceded by an asterisk (*) have no BGN recommendation.

ment area for many drainage basins, and stream erosion is vigorous. Euphorbia are the dominant vegetation up to an altitude of 2,000 m; terrace cultivation on slopes is the common agricultural practice, as it is through most of the YAR.

The *Yemen highlands occupy the center of the country, from the crest of the *Red Sea escarpment eastward to the *Wādī Jawf valley and Ramlat as Sab`atayn. The *Yemen highlands are about 190 km long and 140 km wide. The rugged and complex topography, including mountain massifs and peaks more than 3,000 m in altitude, reflects the wide variety of rock types exposed in the region. Eastward, the land surface gradually slopes to a general altitude of less than 2,000 m in the alluvial valley of the Wādī Jawf and the sandy wilderness of Ramlat as Sab`atayn. North of the *Wādī Jawf valley, a mountainous region above 2,000 m is the southern extension of the Asir (`Asīr) region of the Kingdom of Saudi Arabia.

The *Wādī Jawf valley occupies a 240-km-long structural trough (fig. 4) in the northeastern part of the country. Bare limestone and sandstone are exposed at the northwestern end of the trough, and its central and southern parts are covered by alluvium and windblown sand. Altitudes are generally less than 2,000 m, and less than 1,000 m along the lower reaches of Wādī Jawf, Wādī ad Dabīl, and Wādī Abrād at the northwestern end of Ramlat as Sab`atayn. The alluvial channels of Wādī Jawf are situated approximately along the axis of the trough. The flow regimen in most of these channels and tributary channels on the north and south banks of Wādī Jawf probably consists of ephemeral storm runoff only. East of the 45°30′ E. meridian, the course of Wādī Jawf ends abruptly in low sand dunes and drifting sand. Storm runoff occasionally flowing down the ephemeral channels of Wādī Abrād, northeast of Ma′rib, disappears because of high evaporaton and infiltration in permeable alluvium and windblown sand. These poorly defined channels have no obvious surface connection with those of Wādī Jawf, some 15 km southeast of Al `Alam al Aswad (a 1,210-m hill of Jurassic limestone at the northwest end of Ramlat as Sab `atayn).

The terrain in the extreme northeastern part of the YAR consists of granitic and metamorphic rocks; the region is characterized by low rainfall and an internal drainage network oriented toward Rub`al Khali. Altitudes range from 1,000 to 2,000 m.

GEOLOGY

The rocks of the YAR range from Precambrian (pC) to Quaternary age. They include metavolcanic, metasedimentary, granitic, and volcanic rocks, limestone, sandstone, evaporites, and unconsolidated colluvial, alluvial, and eolian deposits. The geology of the YAR has been described most recently by Geukens (1960, 1966). A

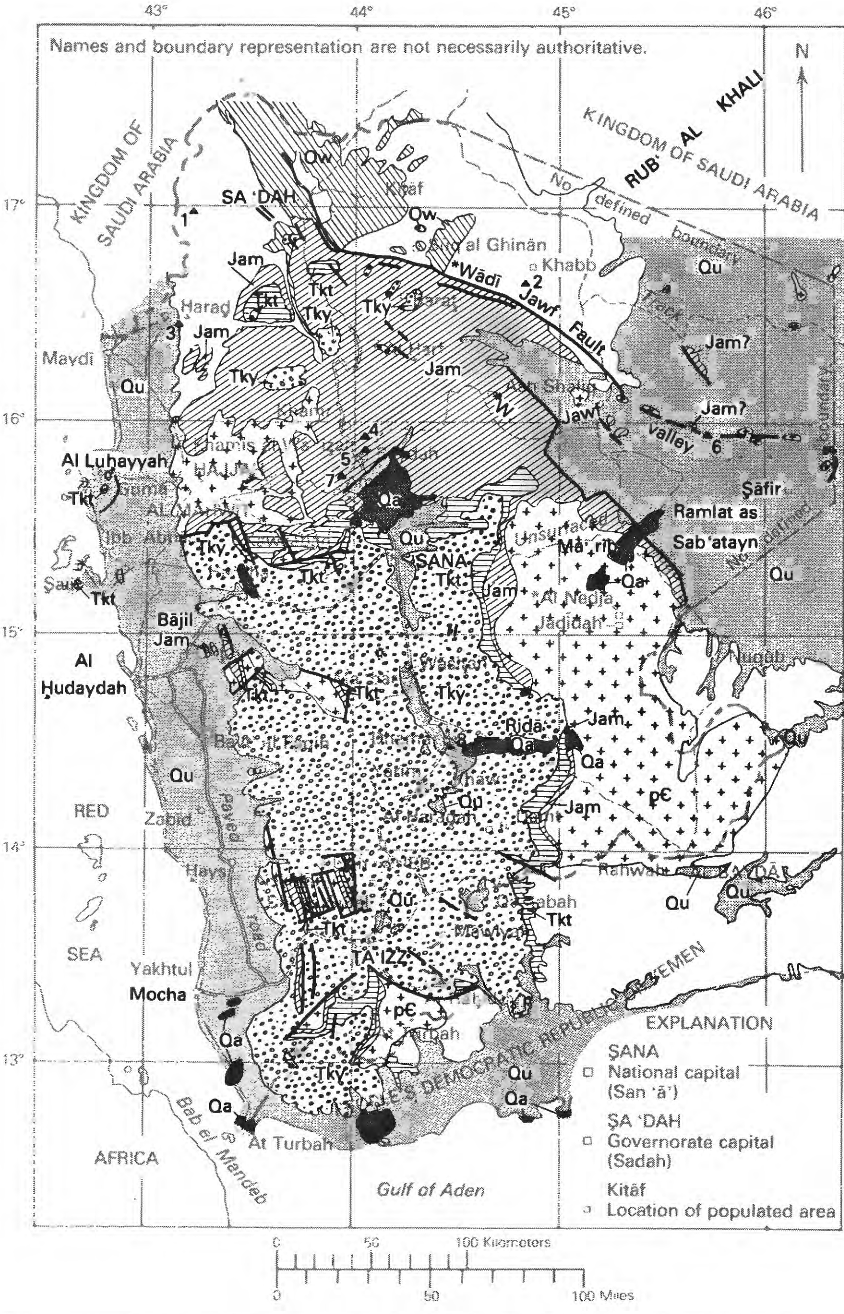

FIGURE 4.—Geology of the Yemen Arab Republic. Names preceded by an asterisk (*) have no BGN recommendation. Explanation on facing page.

EXPLANATION*

Quaternary

Qu — Quaternary undifferentiated
Qe, Eolian sand; Qu, alluvium and related surficial deposits

Qa — Aden Volcanic Series
May include rocks of Pliocene age

unconformity

Tertiary and (or) Cretaceous

Tky — Yemen Volcanic Series
Tla, laccoliths; Tgr, granite; TKt, Trap Series in places upper part overlies Medj-zir Series

unconformity

Tkt — Tertiary Sandstone
Tba, Baid (Baydah) Formation, Southern Red Sea Coast in Saudi Arabia near YAR border; TM, Medj-zir Series; Kt, Tawilah Group

unconformity

Jurassic

Jam — Upper Jurassic
Jam, Amran Series; JKo, Kohlan Series

unconformity

Ordovician

Ow — Ordovician Sandstone
Pw, Wajid Sandstone

unconformity

Precambrian

p€ — Precambrian rocks undivided
ur, Precambrian rocks undivided

Undifferentiated rocks (consists of sedimentary, metamorphic and granite)

Fault, dashed where approximately located

Collapsed caldera (crater)

Numbered features
1. Nadhīr
2. Khashiba Ridge
3. Khudhrayn
4. Qā' ash Shams
5. Qā' Hays
6. Al 'Alam al Aswad
7. Qā' al Bawn al Kabīr
8. Hamman al Lassī

*Rock-stratigraphic units shown on figure 4 are generalized. Symbols and geologic map explanation after U.S.G.S.--ARAMCO, 1963, Geologic Map of the Arabian Peninsula, scale 1:2,000,000.

FIGURE 4.—Continued

geological map of the YAR at the scale of 1:1,000,000 accompanies Geukens' memoir (1960). A modified version of this map was used as the base for the geology of the YAR in the 1963 compilation of the geologic map of the Arabian Peninsula at the scale of 1:2,000,000 (U.S. Geological Survey-Arabian American Oil Company) (fig. 4). Preliminary geologic maps of the YAR (Grolier and Overstreet, 1976) were prepared during the geologic phase of this program using nine Landsat 1 images as base maps.

Precambrian rocks are exposed along the outer fringe of the country, mainly in erosional windows in the *Red Sea escarpment (fig. 2) and in broad belts in the northern and southeastern regions. Metasedimentary rocks are common in the north, granitic rocks in the northeast and southeast, and metavolcanics in the south. Generally, the Precambrian rocks of the YAR form a southern extension of the Arabian Shield of the Kingdom of Saudi Arabia.

Northwest of the *Wādī Jawf valley, the Wajid Sandstone (Ow), a cross bedded, sugary sandstone of Ordovician age, unconformably lies above Precambrian rocks (pC). It also forms prominent outliers in the northern part of the *Red Sea escarpment and east of Ṣa`dah.

Conglomerate, shale, and sandstone of the Kohlan Series (Jko) unconformably overlie the Wajid Sandstone. The Kohlan Series (Jko) of Early Jurassic age is best exposed around the outer edge of the *Yemen highlands under the predominantly calcareous Amran Series (Jam) of Late Jurassic age. Four facies are recognized in the Amran Series (Jam) (Geukens, 1966, p. 9): (1) blue-violet fossiliferous limestone in the foothills marginal to the Tihāmah and in fault blocks farther east; (2) light-gray limestone and shale in the *Red Sea escarpment, west of Sana; (3) predominantly light-yellow marly limestone with thin beds of gypsum, north of Sana as far as the *Wādī Jawf valley; and (4) quartzite, oolitic limestone, shale, salt, and other evaporites at Ṣāfir, in the northeastern part of the country.

Sandstone of the Late Cretaceous-early Tertiary Tawilah Group (Kt) is exposed north of Sana along the outer border of the *Yemen highlands and also in the mountains southwest of Ta`izz.

Volcanic rocks were extruded during much of the Cenozoic era. The Yemen Volcanics Series (TKy) of Tertiary age cover the southern two-thirds of the country. This unit consists predominantly of felsic tuffs, interspersed with basalt layers, and is several thousand meters thick. Several granite plutons, which intrude the Tertiary volcanics, are slightly younger. Lava flows (Qa) of Quaternary age are exposed in four distinct lava fields: (1) northwest of Sana, (2) north and west of Ma′rib, (3) around Ridā`, and (4) in the southern part of the Tihāmah, inland from Mocha (Al Mukhā).

Late Quaternary gravel deposits are common near the drainage divide close to the western edge of the *Yemen highlands. Late Pleistocene loess also mantles the highest exposures of volcanic rocks in the southern part of the country. On the geologic map (fig. 4) both units are included in undifferentiated Quaternary deposits (Qu).

Precambrian metamorphic rocks in the YAR have been folded and faulted more intensely than have the younger rocks, and probably more than once. As pointed out by Geukens (1966, p. 19), basement rocks were faulted prior to the deposition of Jurassic rocks, but several large regional faults affect both the basement and the younger overlying rocks.

One of the most prominent faults is the *Wādī Jawf fault along the northern edge of *Wādī Jawf valley. The southern fault block of basement rocks moved downward with respect to the northern fault block, forming a structural basin in which deposition of Jurassic marine sedimentary rocks took place. Later reactivation of the fault resulted in vertical movement in the opposite direction. In the southern part of the YAR, the fault that controls the trend of the valley of Wādī Kaleyba (pl. 1), about 20 km southwest of Ta`izz, is another example of a fault that affects both basement and overlying sediments and volcanic rocks.

The traces of the faults that affect both basement and younger rocks at the eastern boundary of the *Red Sea rift are obscured by Tertiary marine deposits and overlying alluvium. Yet, Jurassic limestone of the Amran Series (Jam) crops out near Bājil in tilted fault blocks that are probably related to some stages of the formation of the *Red Sea graben. Emplacement of the many mafic dikes and granitic plutons and stocks intruding Jurassic sedimentary rocks and Tertiary layered volcanic rocks is probably related in time and space to sea floor spreading in the Red Sea and to the counterclockwise rotation of the Arabian Peninsula away from Africa. Aside from the many basaltic and granitic plugs in the northern part of the country, very few vents that were the sites of Tertiary volcanic activity have yet been identified. One that has been sited is an 8-km-wide collapsed caldera located about 50 km south of Sana. This circular feature probably formed during a very late phase of Tertiary volcanic activity (Grolier and Overstreet, 1976, Map IR(Y)–5). the gentle, regional, southernly and westerly dips of mid-Tertiary volcanic rocks in the central and southern parts of the *Yemen highlands probably reflect volcanic accumulation in tectonic basins and postdepositional tilting.

Monoclinal folding of the Amran Series (Jam) is common south of Şa`dah and west of Ma'rib. Piercement domes have brought Miocene-Pliocene evaporites (TKt) to the surface in the coastal Tihāmah between Al Hudaydah and Al Luhayyah, and Jurassic evaporites near Şāfir (950+ m), in the Ramlat as Sab`atayn. Quaternary marine shells strewn on the surfaces of terraces, several tens of meters above mean sea level at the sites of the Tihāmah piercement domes, suggest late epeirogenic movement, but the southward narrowing of the coastal plain and steeper regional slope of the Tihāmah south of Mocha may be construed as geomorphic evidence for subsidence.

CLIMATE

The YAR, with its land area contiguous to the Red Sea and also to the southwestern part of Rub` al Khali, is a country of many climates (Rathjens and others, 1956). Mean annual temperatures gradually decrease from 30 degrees Celsius (°C) in the Tihāmah to 18°C in the *Yemen highlands. The frost line at the latitude of Sana (appendix III) lies at 2,250 m, and temperatures in the *Yemen highlands may drop below freezing in winter.

The distribution pattern and amount of precipitation vary with altitude (fig. 5), latitude, and distance from the Red Sea and the Gulf of Aden. On the Tihāmah, rain falls in winter and amounts to less than 75 millimeters (mm) of precipitation annually. On the slopes of the *Red Sea escarpment, precipitation increases with altitude, to as much as 1,000 mm per year. The *Yemen highlands are characterized by two rainy seasons: (1) spring, from April to May or June and (2) summer, the more important of the two, from July through September. Much of the rain falls in torrential showers. Rainfall in the *Yemen highlands gradually decreases eastward; arid conditions prevail in Rub` al Khali and Ramlat as Sab`atayn.

The regional pattern of mean annual precipitation in the YAR is shown on an isohyetal map (fig. 5) prepared by Steward (*in* Beskök, 1971, map 2). This generalized, small-scale map, based on rainfall data collected in the early 1960's at a limited number of meteorological stations, shows that the southern part of the YAR, notably the region around Ibb, receives the greatest precipitation in the country.

NATURAL VEGETATION AND AGRICULTURE

Because of high topographic relief and variety of climatic environments, vegetation in the YAR has a marked zonal distribution. Vegetation also is a sensitive indicator of the local availability of surface water and shallow ground water. Generally, the Tihāmah is a salt-grass steppe along the coast and a prickly-grass steppe farther inland; water-loving trees, such as acacias, grow along the stream banks. The altitude zone (fig. 2) between 200 and 1,250 m is characterized by myrrh, palm trees, and many cultivated plants. Higher up, between altitudes of 1,250 and 2,000 m, is an evergreen zone where euphorbia are dominant. Above 2,000 m, grassland prevails. In the eastern part of the country, grass apparently is common in season; we observed grass in July 1975 from an airplane flying low over the lowlands between the seif dunes of Ramlat as Şab`atayn.

Manmade terraces built for thousands of years to bring steep hill and mountain slopes under cultivation are common throughout the YAR. Cultivated plants are watered either by diversion of sheet

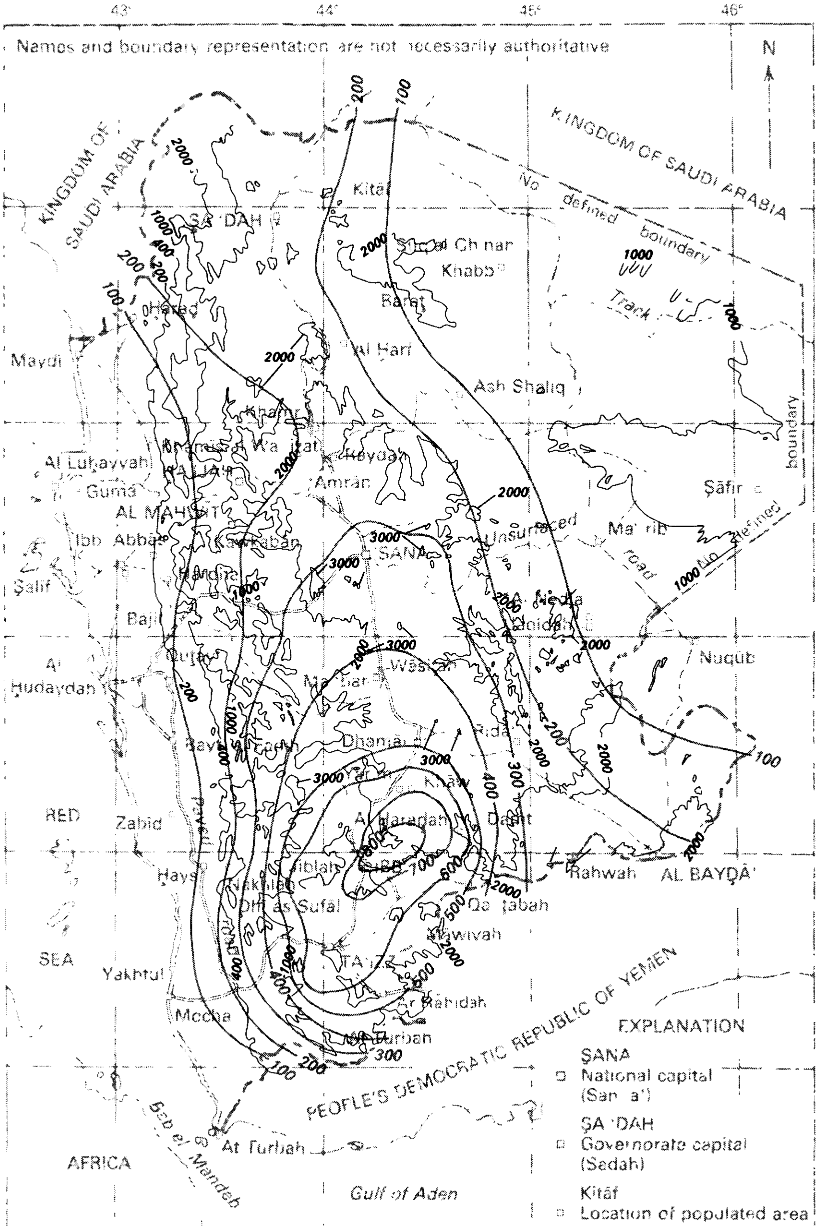

FIGURE 5.—Generalized mean annual precipitation (isohyets in mm), and generalized topography (contour lines in m) of the Yemen Arab Republic. Names preceded by an asterisk (*) have no BGN recommendation.

wash and streamflow into fields surrounded by manmade levees or by irrigation with water drawn from wells. In either case, water is retained in the terraced fields by low levees built of dried loam. Sorghum and quat, or khat *(Catha edulis)*, a shrub cultivated for its mildly narcotic leaves, are among the most common crops in the YAR.

WATER DEVELOPMENT AND PREVIOUS HYDROLOGIC INVESTIGATIONS

Water development in the YAR region goes back several thousands of years to the early stages of agriculture. There are tens of thousands of old water wells, many cisterns, and baths around some of the hot springs, as well as ruins of ancient dams. The most famous of these dams was built across Wādī Adhanah at a water gap west of Ma′rib more than 2,000 years ago (Wissman, 1953, p. 85–86; Bowen and Albright, 1958). It was breached by catastrophic floods about 575 A.D. The hot baths at the top of a well-preserved volcanic cone, Hamman al Lassī (Hayd al Asī; 2,870 m) (plate 1), about 15 km east of Dhamār, were visited and described by Niehbur (1774), and a cistern near hot springs at the top of a dormant volcano northwest of Sana has been described by Wissman (1953) and by Fricke (1959).

Although modern investigations of the surface- and ground-water hydrology of the YAR may be said to have begun with Botez (1912, 1925), who studied the region between Sana and Al Ḩudaydah, most subsequent hydrologic studies have remained regional in character. During the 1960's the hydrology of the central part of the Tihāmah was studied by several German investigators (Sawtschenko in 1965; Huth and Roxenberger in 1966; Quast and others in 1966; and Kraft and others, 1971). Only the last of these studies has been published to date (1976). During the early 1970's ItalConsult, an Italian consulting firm, made an extensive hydrological study of the Sana and Al Ḩudaydah regions for the World Health Organization (WHO) of the United Nations (ItalConsult, 1973). During that period, the Federal Republic of Germany also maintained a technical mission in the YAR staffed with hydrologists from the *Bundesanstalt für Geowissenschaften und Rohstoffe*. Beginning in mid-1974, hydrologists of the Land Resources Division of the Overseas Development Administration of the United Kingdom have investigated the montane plains near Dhamār and in Wādī Rima` for the Ministry of Agriculture of the YAR; their reports are unpublished.

In the last 15 years, WHO and agencies of many foreign governments, including the USAID, have worked in cooperation with the Yemeni government to improve water supplies in various parts of the country. Drilling programs have been initiated, and, along with

Yemeni personnel, foreign contractors and donors (German, American, Russian, Chinese, Iraqi, and Japanese) have drilled many modern water wells in an effort to improve municipal water supplies and irrigation or to supply water necessary for road construction. Some of this work has been documented (Ruiz, 1966), but most of the reports are unpublished and of limited access.

Acting for the Tihāmah Development Authority, Hungarian hydrologists (Tesco, Viziterv, and Vitok, written communs., 1971, 1973) and more recently, engineers from the American firm of Tipton and Kalmbach, Inc. (written commun., 1974), have investigated the ground-water potential of the region where Wādī Zabīd flows across the Tihāmah. Tipton and Kalmbach is currently active in developing the irrigation potential of Wādī Mawr in the northern part of the Tihāmah, North of Wādī Surdūd in the Tihāmah, a large industrial state farm, where modern irrigation farming with water drawn from wells was introduced by Russian specialists, has been in operation for several years. The German technical mission also maintains an experimental state farm near Sana and two others in the Tihāmah, near the road junction between the Al Ḩudaydah-Sana highway and the road to Mocha.

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James W. Aubel, a U.S. Peace Corps volunteer and geologist working with the second author on the USAID water-supply project in the YAR, guided the writers to many wells and helped in the collection of hydrological and related geological data.

Discussions in Sana with hydrologists and other specialists on the staff of several foreign technical missions that are engaged in water development or hydrologic investigations in the YAR were most helpful. These individuals included the following: Jamed Kahn, Tihama Development Authority; Dr. Joachim Thiele, party chief, mission to YAR of the *Bundesanstalt für Geowissenschaften und*

Rohstoffe, Federal Republic of Germany, Hanover, Germany; Dr. Karl-Heinz Schultze, chief, in replacement of Dr. Thiele; Michael Glaze, hydrologist, Tipton and Kalmbach, Inc., Denver, Colo.; Mikio Kurosaki, hydrologist-in-charge for YAR, Tone Boring Co., Ltd., Tokyo, Japan; John Chilton, hydrologist, Land Resources Division, British Ministry of Overseas Development; Rudolf Schock, Department of Geography, University of Zürich; and Peter S. Walczak, resident oceanographer at Al Ḩudaydah, U.N. Food and Agricultural Organization.

LANDSAT IMAGERY

DATA ACQUISITION SYSTEM

The territory of the YAR has been imaged repeatedly since 1972 by the multispectral scanners (MSS's) on board the first two orbiting Earth Resources Technology satellites (ERTS 1, and ERTS 2), now called Land Resources satellites (Landsat 1 and Landsat 2). ERTS 1, launched by the U.S. National Aeronautics and Space Administration (NASA) on July 23, 1972, is stabilized in a near-polar orbit at approximately 907 km above the earth. ERTS 2, launched on January 22, 1975, has the same orbital and imaging characteristics as ERTS 1. The imaging systems on ERTS 1 were described by Rowan and others (1974); their description is summarized below. ERTS 1 was officially retired (as Landsat 1) on January 6, 1978. Landsat 3 was launched on March 5, 1978, after compilation of this report, and therefore Landsat 3 images were not used in its preparation. The sensor systems of Landsat 3 were modified to include panchromatic cameras and an additional MSS band (band 8) that acquires nighttime thermal data with a temperature resolution of 1.5°C in the temperature range of −13°C to 67° and the the spectral range of 10.4 to 12.6 micrometers (μm) U.S. Geological Survey, 1978a). Because of a malfunction, the band-8 sensors on Landsat 3 were turned off a few weeks after launch, and band-8 data are not available.

The sun-synchronous orbit of the satellites allows coverage of the same area every 18 days at the same local solar time, which is 0942 hours at the equator. Data covering selected areas (including the YAR) acquired beyond the range of ground receiving stations are recorded on a tape carried aboard the spacecraft and transmitted at a later time to one of three NASA receiving stations in North America. A malfunction of the tape recorder on Landsat 1 made delayed transmission of the digital-data stream impractical after early 1975 but this function continued from Landsat 2.

LANDSAT NOMENCLATURE: BAND, IMAGE, AND SCENE

Solar energy reflected from the Earth's surface is measured in four spatially registered spectral *bands* through the same optical system.

Band	*Wavelength (μm)*
MSS 4	0.5–0.6
MSS 5	.6– .7
MSS 6	.7– .8
MSS 7	.8–1.1

Spatial resolution in each band averages about 80 m. Spectral resolution is 100 nanometers (nm) in bands 4, 5, and 6, and 300 nm in band 7.

The swath imaged simultaneously in each of the four spectral bands is 185 km wide. Coverage is continuous along each orbital track, but is framed into square pictoral *images*. Each image covers approximately 34,200 km^2. The total Landsat 1 coverage of the YAR numbers approximately 125 individual MSS images. As of June 1, 1976, the Landsat 2 coverage available amounted to 21 MSS images.

A Landsat *scene* is the area of the Earth's surface covered by a Landsat image. This area remains nominally the same during successive passes, as long as no change in orbital characteristics occurs with passage of time; in practice, some drift in framing the image along the orbital path does occur. The number of Landsat images available for a certain region may greatly exceed the number of corresponding scenes. NASA images scenes outside the borders of the United States upon request from investigators: when one Landsat satellite is in orbit, such scenes will be imaged once every 18 days; when both Landsat 1 and 2 were in orbit, scenes were imaged once every 5 and 13 days; while both Landsat 2 and 3 were transmitting, scenes were imaged once every 9 days.

It takes a total of nine Landsat scenes to cover the entire YAR; these scenes are imaged during three adjacent (but not consecutive) orbital paths. For ready reference, each Landsat scene mentioned in this report has been assigned an arbitrary number (scenes 1–7, 9, 10 on fig. 6). Numbers increase from north to south and from the westernmost of the three orbital swaths to the easternmost. These scenes are also referred to the worldwide index to Landsat coverage, which formalizes and uniquely identifies the geographic location over which repetitive images are centered when the satellite maintains normal positional tolerance (U.S. Geological Survey, 1975; World Bank, 1976). Nominal scenes are identified by three-digit orbital path and row numbers. The combined path-row number

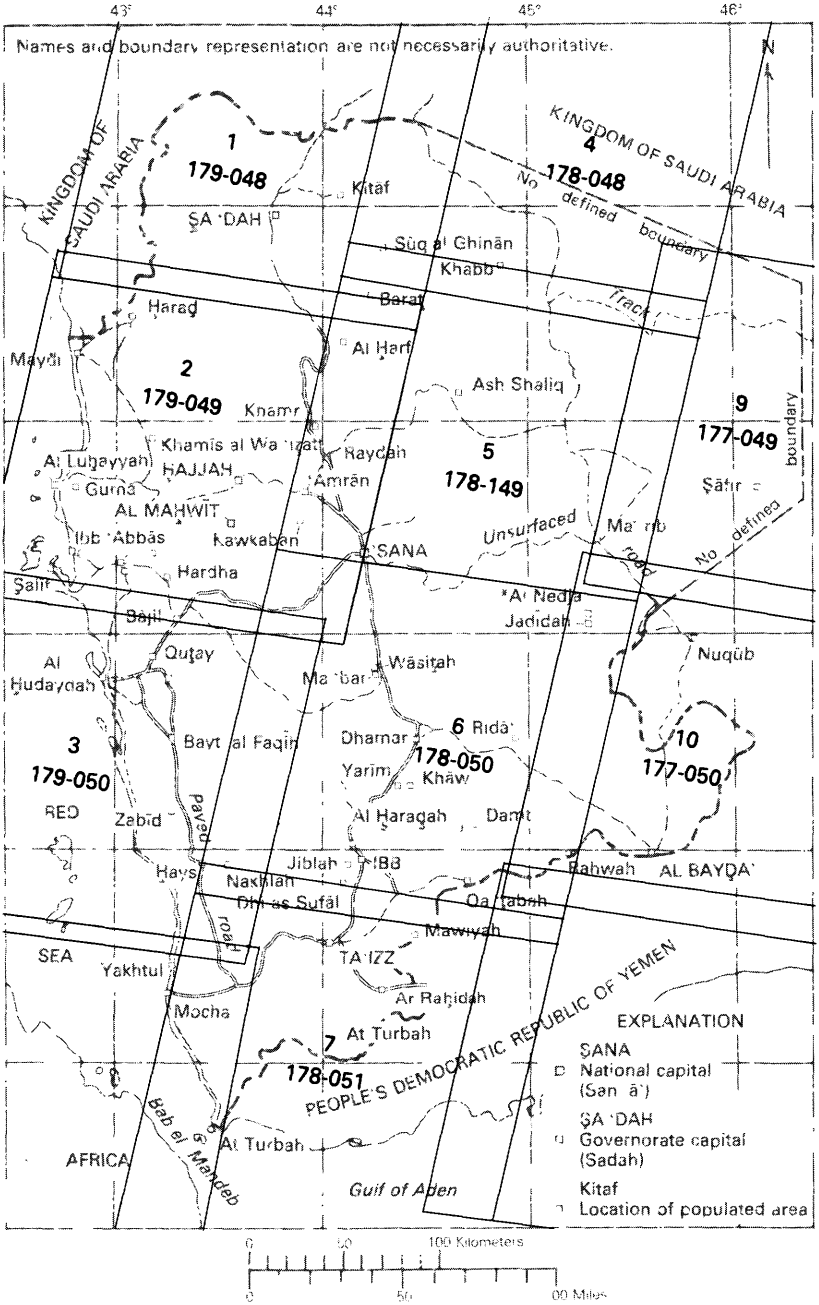

FIGURE 6.—Outlines of Landsat nominal scenes covering the Yemen Arab Republic. Landsat scene numbering keyed to tables 1 and 2 image data. Names preceded by an asterisk (*) have no BGN recommendation.

formally identifies the scene according to an arbitrary reference system first developed for Landsat coverage of Canada and extended to the whole world by the U.S. Geological Survey.

SELECTION AND PROCUREMENT OF LANDSAT DATA

The investigation was carried out in two separate, albeit related, steps: Geologic analysis preceded hydrologic analysis. The scope of the investigation controlled the selection of the types of Landsat data that were procured. In the planning stage of the investigation, it was decided that there was no need to use computer-compatible tapes (CCT's) to enhance Landsat data until specific geologic and hydrologic problems had been defined and mineral prospects located. This decision seriously limited the search for reflectance anomalies due to oxidized sulfide ore deposits, either exposed or lying at shallow depth, but it had no adverse effect on the hydrologic reconnaissance of the country. Therefore, both geologic and hydrologic analyses were made using prints and transparencies of Landsat images available from the EROS Data Center, Sioux Falls, SD 57198.

Distinctly different criteria are used to select Landsat images for geomorphic analysis and for lithologic and hydrologic analysis. Topographic detail and tonal contrast are critical for geomorphic and structural analysis; such detail is provided best by images procured when the sun is low above the horizon, because shadows are longest at that time. Of the 125 Landsat 1 images available, corresponding to the nine Landsat scenes covering the YAR, nine were selected for geologic analysis (see table 1). Selection criteria were time of imaging (close to the 1972 winter solstice in the period November 18, 1972, to February 14, 1973) and other factors such as absence of cloud cover and image quality. Preliminary geologic mapping was accomplished on transparent overlays placed over three-band, false-color composite prints of the Landsat 1 images at the scale of 1:500,000 (Grolier and Overstreet, 1976). While the nine Landsat 1 images were being mapped geologically, a black and white mosaic of Landsat images was hand-assembled by the Special Maps Center, Topographic Division, USGS, Reston, Va. for use as a geographic map base (U.S. Geological Survey, 1978b). This Landsat image mosaic of the YAR is also the base on which the geologic map of the YAR at the 1:500,000 scale was compiled (Grolier and Overstreet, 1978). Subsequently (1982), a black and white mosaic of digitally processed Landsat images which includes the territory of the YAR was prepared by the USGS Image Processing Facility, Flagstaff, Ariz., on behalf of the Office of International Geology (OIG), USGS, and the Directorate General of Mineral Resources (DGMR), Ministry of Petroleum and Mineral Resources, Kingdom of Saudi Arabia.

TABLE 1.—*Landsat 1 images used in the geologic analysis and geologic map compilation that preceded this hydrological investigation of the Yemen Arab Republic.*

Landsat scene outline No. (see fig. 6)	Path/row No.	Landsat ID No.	Date of image acquisition	Corresponding preliminary geologic map (Grolier and Overstreet, 1976)
1	179/048	1136-07012	6 Dec. 1972	(IR) Y–1
2	179/049	1136-07015	6 Dec. 1972	(IR) Y–2
3	179/050	1118-07021	18 Nov. 1972	(IR) Y–3
4	178/048	1117-06553	17 Nov. 1972	(IR) Y–4
5	178/049	1189-06555	28 Jan. 1973	(IR) Y–5
6	178/050	1189-06561	28 Jan. 1973	(IR) Y–6
7	178/051	1189-06564	28 Jan. 1973	(IR) Y–7
8	177/049	1152-06501	22 Dec. 1972	(IR) Y–9
9	177/050	1206-06504	14 Feb. 1973	(IR) Y–10
10				

In contrast to the relatively permanent character of landforms and rocks and the slow rate of change brought about by most erosional and depositional processes, the dynamic processes, which control surface and ground-water conditions, and the growth of vegetation are subject to seasonal changes and longer term climatic cycles. The repetitive character of the Landsat imaging system makes Landsat images taken at relatively short successive intervals of time ideally suited for analysis of yearly and seasonal fluctuations in the hydrologic regimen of streams and for monitoring the periodic growth and dormancy of vegetation. In addition, if hydrologic observations are to be meaningful, they must be timed to some elements of the hydrological cycle that are suitable for short-term as well as long-term comparison. In this context, the Landsat images chosen for hydrologic analysis were those that coincided as closely as possible with the two extremes of the yearly climatic cycle in the YAR: the end of the main rainy season in the late summer or early fall and the end of the dry season in early spring. It was hoped that these periods of the year would correspond to periods of high runoff in some stream channels and maximum vegetation growth on land on the one hand, and low flow and minimal vegetation growth on the other. The Landsat 1 and Landsat 2 images for fall 1972, spring 1973, spring–summer 1975, fall 1975, and spring 1976 used for the hydrological analysis are listed in table 2. For reasons stated previously, the Landsat images used for hydrologic analysis were not those used for geologic analysis or for the mosaic of Landsat images

TABLE 2.—*Landsat 1 and Landsat 2 images used in the analysis of yearly and seasonal fluctuations of vegetation, streamflow, and underflow (1972–76) in the Yemen Arab Republic*

Landsat scene outline No. (see fig. 6)	Path/row No.	Fall 1972 (high runoff)		Spring 1973 (low flow)		Fall 1973 (high runoff)	
		Landsat ID No.	Date	Landsat ID No.	Date	Landsat ID No.	Date
1	179-048	---	---	1244-07014	Mar. 24	1406-07000	Sept. 2
		---	---	---	---	1424-06593	Sept. 20
2	179-049	1010-07004	Aug. 2	---	---	1406-07002	Sept. 2
		---	---	---	---	1424-07000	Sept. 20
3	179-050	1010-07011	Aug. 2	---	---	1406-07005	Sept. 2
		1082-07013	Oct. 13	---	---	1424-07002	Sept. 20
4	178-048	1045-06545	Sept. 6	---	---	1423-06535	Sept. 19
		1063-06544	Sept. 24	---	---	1441-06533	Oct. 7
5	178-049	1045-06551	Sept. 6	---	---	1423-06542	Sept. 19
		1063-06551	Sept. 24	---	---	---	---
6	178-050	1045-06554	Sept. 6	---	---	1423-06544	Sept. 19
		1063-06553	Sept. 24	---	---	---	---
7	178-051	1045-06560	Sept. 6	1255-06570	Mar. 5	1423-06551	Sept. 19
		1063-06560	Sept. 24	---	---	---	---
9	177-049	1044-06493	Sept. 5	---	---	---	---
		---	---	---	---	---	---
10	177-050	1044-06495	Sept. 5	1206-06504	Feb. 14	---	---
		---	---	---	---	---	---

TABLE 2.—*Landsat 1 and Landsat 2 images used in the analysis of yearly and seasonal fluctuations of vegetation, streamflow, and underflow (1972–76) in the Yemen Arab Republic—Continued*

Landsat scene outline No. (see fig. 6)	Path/row No.	Summer 1975 (high runoff)		Fall 1975 (high runoff)		Spring 1976 (low flow)	
		Landsat ID No.	Date	Landsat ID No.	Date	Landsat ID No.	Date
1	179-048	---	---	2276-06475	Oct. 25	---	---
		---	---	---	---	---	---
2	179-049	---	---	2276-06481	Oct. 25	---	---
		---	---	---	---	---	---
3	179-050	---	---	2276-06484	Oct. 25	---	---
		---	---	---	---	---	---
4	178-048	2149-06434	Jun. 20	2257-06421	Oct. 6	---	---
		2185-06532	Jul. 26	---	---	---	---
5	178-049	2149-06440	Jun. 20	2257-06424	Oct. 6	---	---
		2167-06440	Jul. 8	---	---	---	---
6	178-050	2149-06443	Jun. 20	2257-06430	Oct. 6	---	---
		---	---	---	---	---	---
7	178-051	---	---	2293-06431	Nov. 11	---	---
		---	---	---	---	---	---
9	177-049	2130-06381	Jun. 1	2274-06364	Oct. 23	2400-06350	Feb. 26
		---	---	---	---	2418-06343	Mar. 15
10	177-050	2130-06384	Jun. 1	2274-06371	Oct. 23	2400-06352	Feb. 26
		2148-06385	Jun. 19	---	---	---	---

covering the YAR, with one exception: Landsat image 1206–06504, February 14, 1973, which covers scene 10 (fig. 6), was used for both geologic and hydrologic analyses because its quality is exceptionally good, and also because a Landsat image with a lower sun angle for that scene was unavailable at the time the mosaic was being assembled.

METHODS OF ANALYSIS

The work procedure followed during both the geologic and the hydrologic analysis phases of the study consisted of bibliographic search, image interpretation supported by interpretation of available topographic maps, and reconnaissance field checking.

BIBLIOGRAPHIC SEARCH

The geologic and hydrologic literature covering the territory of the YAR is scattered through the scientific periodicals of several countries (mostly France, Germany, and the United States). An off-line computerized bibliographic citation list generated by GEOREF and originating with the System Development Corporation (SDC), Santa Monica, Calif. was most useful at the start of the investigation in identifying reports published during the last 10 years.

IMAGE INTERPRETATION

GEOLOGIC ANALYSIS

The base maps used for geologic mapping were three-band, false-color composite prints of each of the nine Landsat 1 images enlarged to the scale of 1:500,000. The geologic map was checked for accuracy against black and white positive transparencies (scale of 1:1,000,000) of band 7, the near-infrared (reflectance) band where tonal contrast between mafic and felsic rocks is greatest. Black and white positive transparencies of band 4, in which penetration of clear water by solar radiation in the blue-green portion of the spectrum occurs down to several fathoms, were used to check the extent of coral reefs observed along the *Red Sea cost. Even though the brightness and color of a Landsat image are modulated by topography and, therefore, are ambiguous parameters for distinguishing geologic materials, a preliminary geologic map of the YAR produced (Grolier and Overstreet, 1976) at 1:500,000 scale, showed more geologic data than had been possible before. This success was possible because of (1) the relatively small scale of the geologic map (1:500,000), (2) the vivid contrast between some of the more prevalent rock units in the country [for example, the contrast between limestone and volcanic rocks, between young and unweathered volcanic rocks and older and (or) weathered rocks, and between alluvium and eolian sand], (3) the relative sparsity of vegetation and the absence of thick, chemically weathered soils, and (4) the unusually high regional relief (more than 3,000 m) which, in some places, allowed three-dimensional structural analysis on a monoscopic image. The high quality and photographic fidelity of the color prints made of each image greatly facilitated the geologic analysis.

SURFACE WATER AND VEGETATION

The interpretations of the hydrologic features of the YAR given in this report are qualitative and preliminary. Some of the engineering characteristics of Landsat orbiting and imaging systems put definite constraints on an evaluation of the hydrologic features of any arid or semiarid land. The irregular repetitiveness of imaging Landsat scenes in the YAR and the frequent cloudiness over the country make the imaging of overland flow and surface runoff in ephemeral streams—processes that figure so importantly in the yearly renewal of water resources in an arid land—a matter of chance. Likewise, the spatial resolution of the system (approximately 80 m) is inadequate for detection of most ground-water discharges. Only very large springs or seeps can be detected on the Landsat 1 and 2 images. Numerous small seeps that occur close to one another can be detected as a group but cannot be discriminated as individual seeps or as springs by the interpreter.

A review of irrigation and drainage practices in the YAR, however brief, makes for a better understanding of water occurrence and the difficulties encountered in observing it. Flood irrigation is the traditional practice in the *Yemen highlands and on mountain slopes, as it is in many other arid regions. Regulated irrigation through diversion canals is practiced to some extent near perennial reaches in some wadis and at the head of the Tihāmah. In both environments, irrigation with surface water is supplemented by irrigation with water drawn from wells or diverted from springs. Where flood irrigation is practiced on terraced fields, advantage is taken of natural overland flow moving as sheet wash and in rills over valley slopes and valley floors. Overland flow is channeled and stored in terraced fields surrounded by levees of dried mud or by walls of roughly piled uncemented stones. Once the moisture capacity of the soil is reached, excess water is allowed to escape to the terrace below through a breach in the levee or through openings between stones in the walls. Excess water in the lowest terrace moves down toward the nearest wadi channel or evaporates. Recording such complex sequences of events on a Landsat image, and then detecting them through image analysis by visual means, are difficult and not always successfully accomplished tasks.

The water resources of any region, that is, the total supply of water available, depend on the annual water budget, which expresses the balance between the various components of the hydrologic cycle. The annual increment of rainfall can be viewed as a credit, while annual runoff, infiltration, percolation through soil, changes in storage of water in the ground, seepage of ground water to sea or interior basins, and evaporation and transpiration can be viewed as debits. In the YAR, only the input to this system, the annual rainfall, has been measured (to some degree). Evaporation is known to be high, but it has not been measured; infiltration does occur—and probably could be estimated—but has not been measured.

In this report, reaches where concentrated runoff takes place, areas of relatively high soil moisture content, and areas where ground water is stored at shallow depth (as indicated by growing vegetation) are identified and mapped. Then, in an indirect way, recommendations are made on how to measure the other elements of the hydrologic cycle. The report describes the occurrence (rather than the renewal) of soil moisture and of surface and shallow ground water. It also describes the direction of flow, water quality (to some extent), and yearly fluctuation in the occurrence of water between the two main periods of high runoff and low flow. The report does not give quantitative evaluations of the frequency and amount of seasonal and yearly water renewal, annual stream flow, or well yield; nor does it describe the chemical quality of the water. The year 1975 was a relatively "wet" year compared with the previous 3 years, although total precipitation was not much greater than the long-term average. It was selected as the temporal base of reference, during which "normal" surface water distribution and "normal" plant growth are compared with conditions during previous and subsequent years. On the basis of the hydrologic evidence shown on Landsat images, the years 1972 and 1973 were interpreted as being anomalously dry years and so were rejected as reference years. It is possible that these years are representative of the prolonged drought that affected a belt of the northern tropical zone extending at least from western Africa to southwestern Asia.

The initial step in this preliminary investigation of water resources in the YAR was to prepare a small-scale topographic map that would serve as a base map on which the boundaries of catchment areas and drainage basins as well as precipitation and geologic data could be overlain. The 200-m, 400-m, 1,000-m, 2,000-m and 3,000-m contours were traced off topographic maps at the 1:250,000 scale (United Kingdom, Ministry of Defence, Mapping and Charting Establishment, 1974) and reduced to an appropriate scale (fig. 5). The divides between drainage basins were delineated on a false-color mosaic of Landsat images covering the YAR at the 1:500,000 scale. Where regional relief was low and did not allow visual identification of divides on the mosaic, boundary lines between basins were transferred from topographic maps to the drainage basin map. The resulting drainage basin map, on which four catchment areas and the major drainage basins in the YAR are outlined (pl. 1), was then reduced (fig. 7) and overlain on the topographic base map (fig. 2). The isohyetal map of the YAR (fig. 5) is also superimposed on the small-scale topographic map. All these maps are at the same scale and can be compared with one another to investigate relationships between location; altitude, and shape and size of watershed on one hand, and precipitation and rock types on the other.

The next step was to identify, locate, and describe drainage channels where streamflow could be observed. The final step was to identify areas supporting vegetation, as a basis for inferring other hydrological conditions. Only two of the four bands available for each scene were used in this analysis: Band 7 was used because there is little or no reflection of incident solar radiation from water in this spectral region, and thus the water appears dark in a positive black and white print or transparency; and band 5 was used because, within the red region of the spectrum, chlorophyll and carotene absorption of incident solar radiation reduces reflectance intensity, and vegetation appears dark gray on a positive black and white print. Band 6, which can be used to identify wet and water-saturated soil (Deutsch and others, 1973), was not used, because identification of streamflow and vegetation was the principal objective of the analysis.

Although vegetation and water are directly mappable on black and white transparencies or prints of bands 5 and 7, two-band, false-color composites were prepared for each scene, using Diazo color foils, in order to enhance contrast by subtraction of color. By superimposing the two bands upon each other, using foils suitable for subtractive color techniques, water and vegetation appear on the false-color composite in the dark hue of the colored band in which their reflectance is least. This part of the analysis was accomplished at a scale of 1:1,000,000, to conform to available laboratory equipment.

Vegetation mapping is relevant to a regional survey of water resources because some plants (hydrophytes and phreatophytes) are excellent indicators of shallow ground-water during their growing season. Natural vegetation and agricultural crops were identified separately in some places, and lumped together where the size of cultivated fields is below the resolution of the Landsat imaging system and the geometric pattern characteristic of cultivation cannot be detected. Even where a definite pattern of cultivation does not

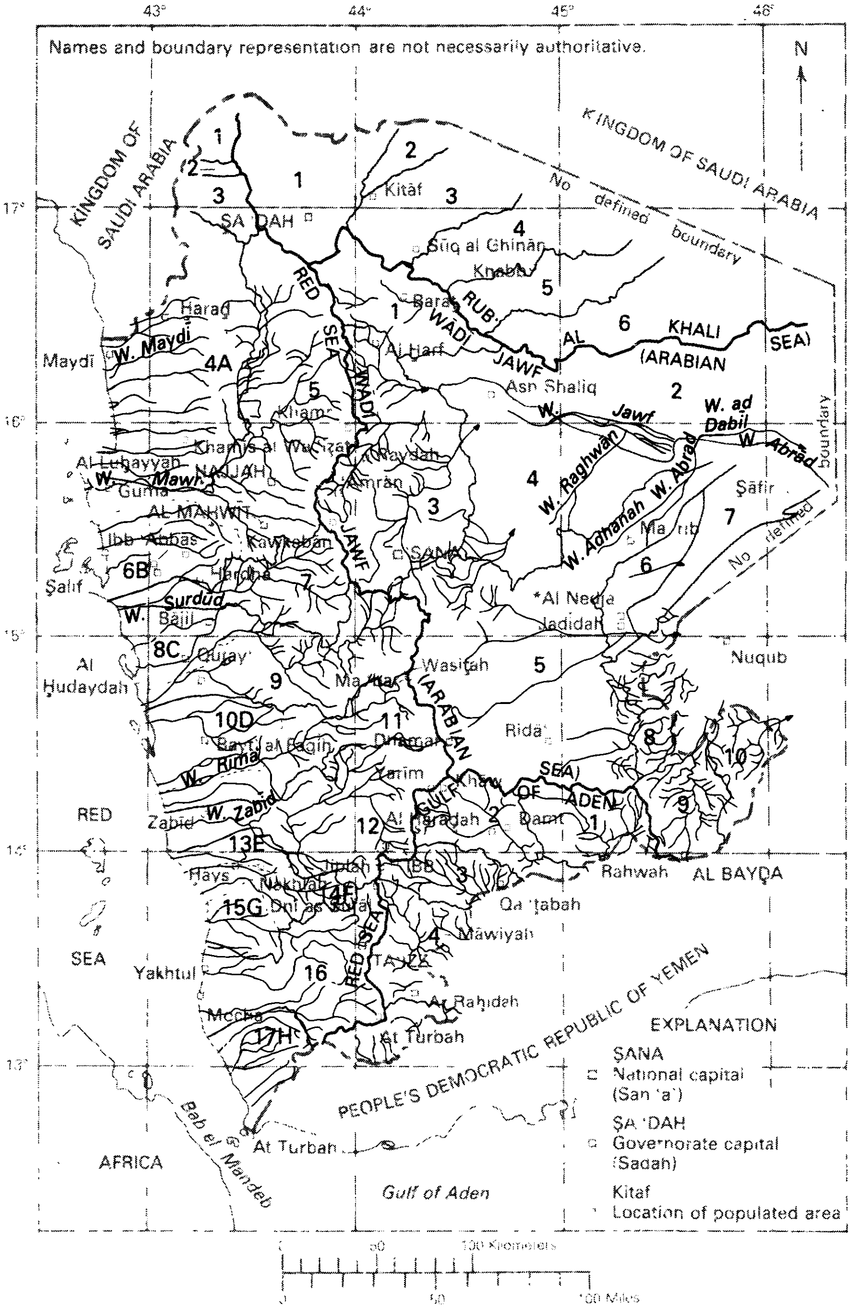

FIGURE 7.—Drainage features of the Yemen Arab Republic including catchment areas, the major basins, and the drainage network within each major basin. Catchment areas and drainage basin labels are keyed to table 3. Names preceded by an asterisk (*) have no BGN recommendation.

emerge from analysis of a Landsat image, some inferences can still be drawn from the environment in which plants grow. "Light forest" in the mountains can be generally inferred from the characteristically diffuse color value superposed on an otherwise drab, grayish, rugged terrain. Yet, there is no way at the scale of this visual analysis to state the percentage of terraced irrigated fields planted with quat (khat) or with sorghum, which is included with trees and succulents growing wild in the "light forest." Similarly, vigorous seasonal plant growth in alluvial valley floors takes on different meanings depending on site location, which in turn may reflect one of the many cultural, ecological, or economic patterns of human activities. In the valleys of wadis near the divides between catchment areas (where precipitation is relatively high because of altitude and and population density is also high), spectral evidence of vigorous seasonal plant growth implies agricultural crops. At lower altitudes in the *Yemen highlands, particularly in the basins of wadis draining Precambrian crystalline rocks, where aridity is greater than in the mountains and population density may be low, seasonal plant growth, particularly spot vegetation at times of low flow, may imply that phreatophytes are growing in alluvium, drawing water from shallow ground water, or simply that plants are thriving on soil moisture replenished by the last storm runoff or from seeps and springs too small to be detected.

In this reconnaissance survey of vegetation in the YAR, the objectives were to interpret the spatial distribution of plants as observed on Landsat images and to infer from it the sources of the water (soil moisture or surface or ground water) used by plants. The presence of soil moisture or ground water available for plant growth is inferred from the presence of vegetation. The plants themselves are described only in very general terms, even at the community level.

RECONNAISSANCE FIELD CHECKING

Two field trips were made in connection with this study. The first, which included aerial and ground reconnaissance, was made between June 16 and July 13, 1975, jointly with W.C. Overstreet, USGS economic geologist. During this trip it was possible to check the accuracy of the preliminary geologic map (Grolier and Overstreet, 1976) and to appraise several mineral prospects. A low-altitude aerial reconnaissance of the country was made during the first week in the field. It helped to relate erosional, textural, and tonal patterns to specific rock types, to observe stratigraphic relationships, and to prepare for the ground reconnaissance. Laterite, which occurs in the Asir region of the Kingdom of Saudi Arabia, was sighted for the first time in the extreme northern part of the

YAR. Darkening of limestone along contacts with lamprophyric dikes, which had been observed on Landsat 1 images, was confirmed from the airplane and later was verified on the ground. The ancient dam across Wādī Adhanah near Ma'rib was overflown, and observations were made of the ruined control gates and irrigation canal partly buried by drifting sand. Field checking on the ground was limited to a reconnaissance along the major road network of the YAR (Santa-Ta`izz-Mocha, Al Ḩudaydah, Sana), a round trip between Sana and Şa`dah, and a few side trips around Sana, Ta`izz, Şa`dah.

The second field trip, February 1–29, 1976, afforded an opportunity to collect rock and water samples in regions not visited during the first reconnaissance. It allowed close observation of several late Tertiary piercement domes on the Tihāmah near Al Luḩayyah and sampling of several water wells in addition to inspection of Precambrian rocks exposed in the southeastern part of the YAR, along the road between Ridā` and Al Bayḑā.' Rock and water samples collected during the second trip had not been analyzed as of this writing.

REGIONAL OCCURRENCE OF SURFACE WATER AND VEGETATION IN THE YEMEN ARAB REPUBLIC

Only streams, one spring, and several seeps were identified during the analysis. No lakes or ponds were detected at the 1:1,000,000 scale of the analysis. Although there are many kinds of springs, only a few are described in this report. The terms used to describe them and some of the phenomena and processes associated with springs and streams are explained in a glossary in appendix 1 at the end of this report.

There are four main catchment areas in the YAR. In order of increasing annual precipitation, they are: (1) Rub` al Khali, (2) Wādī Jawf (Arabian Sea), (3) Red Sea, and (4) Gulf of Aden.

The divides between catchment areas and those between smaller drainage basins need not coincide with ground-water divides. Only catchment area divides are described below. Detailed hydrologic investigations are required to locate ground-water divides accurately in a semiarid country such as the YAR. One divide at the top of the *Red Sea escarpment separates the basins draining toward the Red Sea from those draining eastward toward Rub` al Khali, Ramlat as Sab`atayn, and southeastward toward the Arabian Sea. This catchment area divide is parallel to the general orientation of the *Red Sea coast, and its closest approach to the coast, 110 km, is west of `Amrān. The highest altitudes in the YAR are along this divide, which rises about 3,000 m at several locations—southwest of

`Amrān near Jabal Ḩaḑūr ash Shaykh (3,350 m), southwest of Sana at Jabal an Nabī Shu`ayb (3,620 m), and northeast of Ibb at Jabal Manār (3,350 m). Altitudes along the divide are in excess of 2,000 m except at the northern and southern ends. The lowest pass at the northern end is located 6 km south of Jabal al Khaţţārīn (2,130 m); there, the divide between the Wādī Mawr and *Wādī Jawf valley drainage basins is below 1,750 m. At the southern end, 30 km northeast of Ta`izz, the divide is as low as 1,650 m.

The divide between the Rub` al Khali and Wādī Jawf catchment areas forms a triple-point junction with the Red Sea catchment divide, 17 km south of Şa`dah, and stays a few kilometers north of the fault zone, which borders the northern side of *Wādī Jawf valley (figs. 2 and 3). The Gulf of Aden–Wādī Jawf (Arabian Sea) catchment divide also forms a triple-point junction with the Red Sea catchment area divide, about 10 km south of Dhamār; it trends eastward for about 50 km, generally above 2,000 m. The four main catchment areas in the YAR and the drainage basins within them are shown on figures 2 and 7 and on plate 1, which is based on a mosaic of nine Landsat 1 images covering the Yemen Arab Republic at the 1:500,000 scale.

The Rub` al Khali catchment area receives the least precipitation, between 100 and 250 mm per year in the western part and less than 100 mm per year in the eastern part. Similarly, the eastern part of the *Wādī Jawf valley drainage basin gets less than 100 mm rainfall per year. However, in the higher and westernmost part of the basin, between the cities of Sana, Dhamār, and Ridā`, annual rainfall ranges from 350 to 550 mm. Annual rainfall in the northern part of the Red Sea catchment area (fig. 5) is generally less than 300 mm, but south of the Wādī Surdūd drainage basin, rainfall gradually increases from 300 mm to as much as 700 mm in the *Red Sea escarpment, southwest of Ibb. The catchment area draining toward the Gulf of Aden in the extreme southern part of the country (plate 1 and fig. 2) receives 600 to 800 mm of rainfall per year.

In this report, all descriptions of surface water—and ground water, indirectly through the distribution of vegetation—were obtained from analysis and interpretation of Landsat images. The occurrence of water and vegetation in each of the drainage basins that make up the four catchment areas of the YAR is described in the order of increasing annual rainfall for each region. A list of the drainage basins in that order is shown in table 3.

RUB` AL KHALI (AR RAB` AL KHĀLĪ) CATCHMENT AREA

Surface water.—Surface water was found in only two of the six drainage basins identified in this catchment area, namely in the Wādī Khadwān and Wādī `Imārah-Wādī Amlaḩ drainage basins. All

TABLE 3.—*Catchment areas and drainage basins (in order of increasing rainfall) in the Yemen Arab Republic, as shown on plate 1*

[Names of catchment areas and drainage basins have been made to conform to associated features that have been approved by BGN]

Catchment area	Drainage basin (from North to South)
Rub`al Khali (Ar Rab`al Khālī)	1. Wādī Najrān[1]
	2. Wādī Khadwān
	3. Wādī `Imārah (W. Imara) and Wādī Amlaḩ
	4. Wādī Qa`if (W. Qu`ayf) and Wādī Silbah (W Silba)
	5. Wādī Khabb (W. Khubb)
	6. Wādī Amwāḩ and Wādī Khalifayn
Wādī Jawf (Arabian Sea)	1. Wādī Madhāb
	2. Wādī Jawf valley
	3. Wādī al Khārid
	4. Wādī al Furdah, Wādī al Jufrah, and Wādī Raghwān (W. al Mukhaynia)
	5. Wādī Adhanah
	6. Wādī al Khāniq (W. Manqai)
	7. Small unnamed wadi drainage basins northeast of Jabal Omrikha
	8. Wādī Ḩarib[2]
	9. Wādī Bayḩan[3]
	10. Wādī Markhah[3]
Red Sea	1. Wādī Difā`ah (W. ad Dafa) and Wādī Hanabah
	2. Wādī Ḑamad
	3. Wādī Jizān (W. Qizān) and Wādī Ma`bār
	4. Coastal stream drainage basins A
	5. Wādī Mawr
	6. Coastal stream drainage basins B
	7. Wādī Surdūd
	8. Coastal stream drainage basins C
	9. Wādī Sihām
	10. Coastal stream drainage basins D
	11. Wādī Rima
	12. Wādī Zabid
	13. Coastal stream drainage basins E
	14. Coastal stream drainage basins F
	15. Coastal stream drainage basins G
	16. Wādī al Gayl and Wādī Rasyān
	17. Coastal stream drainage basins H
Gulf of Aden	1. Wādī Ḩamrā' Wādī Ḩarib, and Saylat Siḩ
	2. Wādī Banā
	3. Wādī Tuban[2]
	4. Gulf of Aden coastal stream drainage basins[2]

[1] The lower part of this basin is located in the Kingdom of Saudi Arabia.
[2] The lower part of this basin is located in the People's Democratic Republic of Yemen (PDRY).
[3] The lower part of this basin is located in the PDRY; the uppermost part is along the undefined border between the YAR and the PDRY.

streams in this catchment area are ephemeral, with the exception of the short intermittent reaches of Wādī Khadwān and the tributary to Wādī ʿImārah described below.

Vegetation.—Some vegetation was detected in all drainage basins, but there is appreciably less vegetated area in the northeasternmost basins than in the others. As expected, there were wide seasonal fluctuations in growth, but yearly differences occurred also.

WĀDĪ NAJRĀN DRAINAGE BASIN

Surface water.—None.

Vegetation.—Vegetation is limited to valleys in the Ṣaʿdah region: in the valleys of Wādī Dammar (W. Dammer) and Wādī Abdī, south and southeast of Ṣaʿdah; in the valley of Wadi ʿIlāf, southwest of Ṣaʿdah; in the valley of Wādī Agnām; and, sporadically, in the valley of Wādī Ṣubr. Vegetation also grows far from wadis, in spots on the Wadjid Sandstone. Vegetation growth was most vigorous in October 1975 and less vigorous in September 1973.

WĀDĪ KHADWĀN DRAINAGE BASIN

Surface water.—Wādī Khadwān is an intermittent stream that had some water at the surface or ground-water underflow in October 1973, June 1975, and October 1975. Yearly and seasonal variations are great: There was no water in September 1972, and less water in July 1975 than in June 1975.

Vegetation.—There are some irrigated fields in the upper (southern) part of the valley of Wādī Khadwān. Plant growth was most vigorous in October 1975.

WĀDĪ ʿIMĀRAH (W. IMARA) AND WĀDĪ AMLAḤ DRAINAGE BASINS

Surface water.—In the drainage basin of Wādī ʿImārah, water was at the surface, or occurred as underflow in the short reach of an intermittent tributary draining into Wādī ʿImārah, at the following times: September 1972, September 1973, June 1975, and October 1975. Yearly and seasonal variations are prominent: Streamflow was most obvious in September 1972 and October 1975. Water in the reservoir upstream from a dam across the headwaters of Wādī Aẓlah, a south-bank tributary of Wādī Amlaḥ, was not detected at the scale and resolution of the Landsat images analyzed.

Vegetation.—Vegetation is restricted to (1) the valley floor in the northeast-trending valley 8 km north of the village of Kitāf and also in the plain near Kitāf (the valley joins the upper part of the valley of Wādī ʿImārah) and (2) the valleys of Wādīs al ʿAqīq, Amlaḥ, and Aẓlah. Irrigation farming is probable in the latter valleys. Vegetation was most vigorous in 1973 and 1975, particularly at the mouths of Wādīs al `Aqīq and Aẓlah, where both wadis enter the large alluvial plain at the edge of the desert.

WĀDĪ QA `ĪF (W. QU `AYF) AND WADĪ SILBAH (W. SILBA) DRAINAGE BASINS

Surface water.—None.

Vegetation.—There is vegetation in valley floors within a distance of 10 km north and east of the village of Sūq al Ghinān (Sūq al `Inān). Discontinuous patches of vegetation grow at the base of the foothills in the valley of Wādī Qa `īf. There was a marked seasonal change in the vigor of plant growth between July and October 1975 and a marked increase in plant growth between 1972 and 1973.

WĀDĪ KHABB (W. KHUBB) DRAINAGE BASIN

Surface water.—None.

Vegetation.—Vegetation is restricted to Khabb (Khabb Oasis), in the valley of Wādī Khabb, and to the valley floor of a northeast-trending tributary to Wādī Khabb, about 4 km west of Khashiba Ridge (1,770 m). There are also faint traces of vegetation in small valleys in the western part of this drainage basin.

WĀDĪ AMWĀḤ AND WĀDĪ KHALĪFAYN DRAINAGE BASINS

Surface water.—None.

Vegetation.—Some vegetation was present in the valley floor of an unnamed wadi west of the 45° E. meridian in September 1972 and October 1973; there was less vegetation in June 1975. This vegetation occurred in discontinuous patches ranging from a few hundred meters to 3 to 4 km long. In October 1975 there were some faint traces of vegetation in the valley of Wādī Shuqbān.

WĀDĪ JAWF (ARABIAN SEA) CATCHMENT AREA

The Wādī Jawf catchment area, the largest in the YAR, includes all the drainage basins tributary to Wādī Jawf and its southeasterly extension across Ramlat as Sab`atayn. It is characterized by the extreme asymmetry of long south-bank tributaries and short north-bank tributaries. This catchment area undergoes great yearly and seasonal fluctuations. Therefore, its hydraulic regime, its groundwater hydrology, and its vegetation are sensitive indicators of climatic fluctuations in the YAR.

WĀDĪ MADHĀB DRAINAGE BASIN

Surface water.—The Wādī Madhāb drainage basin is interpreted as containing the headwaters of Wādī Jawf. In October 1975, there was surface water in two wadis tributary to Wādī Madhāb and in pools between riffles in the lower course of Wādī Madhāb; in June 1975, there was water in the lower course of Wādī Madhāb but not in the two tributary wadis. No surface water was present in September 1972. No streamflow in any of the other wadis was detected on any of the Landsat images examined.

Vegetation.—Vegetation is present in the valley of Wādī Madhāb 7 km in extent southeast of Jabal aş Şafrā (2,030 m) and also near the city of Baraţ, in the valleys of wadis tributary to Wādī Madhāb.

WĀDĪ JAWF VALLEY DRAINAGE BASIN

The Wādī Jawf, the main watercourse of the Wādī Jawf (Arabian Sea) catchment area, is ephemeral. In the north-bank tributaries to Wādī Jawf, neither surface water nor vegetation was evident; all streams there probably are ephemeral. In contrast, three south-bank tributary wadis to Wādī Jawf—Wādī al Khārid, Wādī Adhanah, and Wādī Ḩarīb—are perennial or inermittent along some reaches, although they are ephemeral for tens of kilometers upstream from their junction with Wādī Jawf.

WĀDĪ AL KHĀRID DRAINAGE BASIN

Surface water.—Wādī al Khārid is the westernmost of the south-bank tributaries to Wādī Jawf. Wādī Ḑahr and Wādī as Sirr, which debouch in the *Sana basin, possibly a closed interior basin, are included within the Wādī al Khārid basin for descriptive purposes only.

Water was flowing in Wādī Ḑahr in October 1975, but not in June and July 1975, nor in 1972 and 1973. In Wādī as Sirr, water flowed in October 1975, in September 1973, and to a lesser extent in September 1972 and June 1975. At the 1:1,000,000 scale of this analysis, it was difficult to discriminate between streamflows in Wādī Ḑahr and Wādī as Sirr and flows in irrigation ditches diverting water from them. There appears to be a strong seasonal and yearly variation in runoff as well as in the flow of Wādī al Khārid. Wādī al Khārid is an ephemeral stream in the upper part of its course, but for 12 km upstream from the 90° bend, where it enters the *Wādī Jawf valley, it is an interrupted stream with intermittent stretches of water in pools between dry reaches. In this part of its course, Wādī al Khārid is alternately a gaining and losing stream. Water was flowing or standing there in October 1975 and September 1973, but there was much less water in July 1975 and none at all in June 1975 and September 1972. In October 1975, surface water flowed in the channel of Wādī al Kharid for 48 km downstream from the 90° bend to where it enters the *Wādī Jawf valley. There were strong annual and seasonal fluctuations in surface flow there. Wādī al Khārid was an intermittent and interrupted stream in June 1975 and in September 1972. It flowed for only 5 km downstream from the bend in July 1975, but in September 1973 it flowed as far downstream as the junction with Wādī al Jufrah.

Vegetation.—Farming is widespread in the *Sana plain and in the valleys adjacent to it. The largest of these farmed areas are in the valleys of Wādī as Sirr northeast of Sana and Wādī Ḍahr northwest of it. The plains of Qā`Hays and Qā`ash Shams, northeast of Raydah (Rīdah), and the valley of Wādī Aṭṭāf (Ghayl Hirran) also are intensively farmed. Other valleys farther north are intensively farmed, and seasonal plant growth is prominent there. These are: the *`Amrān valley, in the Qā`al Bawn al Kabīr (Beni Awni al Kabir), and adjacent valleys such as those of Wādī Ḥayḍān, Wādī Mansib, and the lower reaches of Wādī Qumāmah and Wādī Salab. The plains in the district of Al Ḥarf also show evidence of vigorous seasonal plant growth, as follows: (1) the plain and valley of Wādī Harrīnah (W. Harrine) 10 km south of Al Ḥarf and (2) the valleys of Wādīs Khayrah and Birkah, 5–10 km north of Al Ḥarf. The widest seasonal fluctuation in plant growth occurred between June 1975 and October 1975. In September 1972 vegetation was scarce.

WĀDĪ AL FURḌAH, WĀDĪ AL JUFRAH, AND WĀDĪ RAGHWĀN (W. AL MUKHAYNIA) DRAINAGE BASINS

Surface water.—No surface water was apparent on any image. All streams in these basins are ephemeral.

Vegetation.—There was no vegetation apparent on images showing the drainage basin of Wādī al Furḍah. No vegetation was present in the valley along the lower reaches of Wādī al Jufrah in September 1972, but there was some in September 1973 and in June and November 1975. Plant growth was most vigorous there in October 1975, and vegetation covered a much enlarged area then. Vegetation also occurs in a zone about 10 km by 3 km, east of the gravel terraces that border the valley of Wādī Raghwān (W. al Mukhaynia) on the south slope of the *Wādī Jawf region. It was most vigorous in June 1975, less vigorous in October 1975, and dormant in February and March 1976. Wide seasonal and yearly variations in plant growth were also detected in the channels of Wādī Jawf, upstream from its junction with Wādī Raghwān, and in small reaches of Wādī Ḥalḥalan. Likewise, vegetation is prominent in the valley floor of an unnamed wadi south-southwest of the city of Ash Shaliq (Al Chalek). At all these locations, there are large annual and seasonal fluctuations in plant growth. Vegetation there did survive the 1972 drought.

WĀDĪ ADHANAH DRAINAGE BASIN

Surface water.—The Wādī Adhanah drainage basin is the largest within the Wādī Jawf catchment area. It is underlain by Precambrian crystalline rocks, by Tertiary bedded sedimentary rocks, and by Tertiary and Quaternary volcanic rocks. The only surface water detected outside Wadi Adhanah was in a short wadi that winds across the plain (Qā`al Fayd) near Ridā` and in an unnamed south-bank tributary to Wādī Adhanah, near 15°00′N. latitude and 44°59′E. longitude. Wādī Adhanah is intermittent in a reach extending for 38 km, from a point about 15°13′N. and 44°59′E. to the water gap 9 km upstream from the city of Ma′rib. Surface flow ceases at the water gap, and the stream, north of the water gap and downstream from the site of the ancient dam built across it, is ephemeral. Seasonal and yearly runoff of Wādī Adhanah varies widely: in September 1972 there was only a trickle of water in two reaches of Wādī Adhanah west of the water gap, each about 2 km long, one just upstream and the other 9 km southwest from the water gap. Runoff fluctuations in Wādī Adhanah and in Wādī al Khārid are among the most spectacular in the YAR.

Vegetation.—Vegetation grows on the valley floors of many wadis that drain the eastern Precambrian terrain of the YAR, with tremendous variation in plant growth. There was only spot vegetation in these valley floors in February 1976, at a time of low flow, whereas plant growth was vigorous in long reaches of these valley floors in October 1975. Plants in irrigated fields near Ridā` were growing vigorously in February 1976. Natural vegetation and irrigated fields are present on terraces and on the flood plain of the unnamed south-bank tributary to Wādī Adhanah, 10 km upstream from the ancient *Ma′rib dam.

Downstream from the dam, natural vegetation and irrigated fields are sporadic along Wādī as Sudd (Wādī Saba) and downstream from Ma′rib along Wādī Abrad. There was no discernible vegetation in September 1972. The most vigorous plant growth in irrigated fields northeast of Ma′rib occurred in June 1975; farther downstream, near the junction of Wādī Abrad and Wādī ad Dabīl, the most vigorous growth occurred in October 1975. This 3-month time lag between vegetation peaks along two distant reaches of the same wadi is worth investigating further, as it might suggest either different seasonal fluctuations of the water table or plant growth being restricted to mid-autumn as a result of increasing aridity in the lower part of the basin.

WĀDĪ AL KHĀNIQ (W. MANQAI) DRAINAGE BASIN

Surface water.—All streams in this basin are ephemeral. Ground water may occur under the channel of Wādi al Khāniq west of Jabal Sama` (1,990 m).

Vegetation.—Cultivated fields are present only in the upper valley of Wādī al Khāniq and near the cities of Jadīdah (Al Jadidah) and *Al Nedja. Strong seasonal variation in plant growth is indicated: Vegetation observed in June 1975 reached a peak in October 1975 and had faded away by February 1976.

SMALL UNNAMED WADI DRAINAGE BASINS NORTHEAST OF JABAL OMRIKHA (1,490 m)

Surface water and vegetation.—All streams are ephemeral in these basins, and no vegetation could be identified at any time. Farther north, aerial observations in 1975 revealed grass growing in the intervening lowlands between long seifs, but no grass could be detected on Landsat images.

WĀDĪ ḤARĪB DRAINAGE BASIN

Surface water.—A trickle of water was identified in the lower courses of Wādī Ablaḥ and Wādī Jirādhah, and channel darkening in some reaches suggested near-surface ground-water underflow in June and October 1975. Annual and seasonal fluctuations are prominent: Some water was present in February 1973, but none was apparent in September 1972 and February 1976.

Vegetation.—Vegetation is confined to valley floors and to the alluvial plain of Wādī Jirādhah. Annual and seasonal variations in plant growth are great in the alluvial valley of Wādī Jirādhah, but less marked in the valleys of other wadis. Even in February 1976, at a time of low flow, plant growth persisted there in spots.

WĀDĪ BAYḤAN DRAINAGE BASIN

Surface water.—All streams in this basin were ephemeral, except in a reach of Wādī at Ghayl near the border with the People's Democratic Republic of Yemen and at 14°30′N. latitude in September 1972 and October 1975. Flows fluctuate seasonally.

Vegetation.—Vegetation is restricted to the valley floors of wadis. Plant growth is prominent in the valley of Wādī al Ghayl and in tributaries in its upper course. Variation in plant growth is great. Plant growth was good in September 1972, but there was little vegetation in 1973. Plant growth was vigorous in October 1975 and persisted, to a lesser extent, until February 1976.

WĀDĪ MARKHAH DRAINAGE BASIN

Surface water.—All streams in this basin are ephemeral with the following exceptions: In late June 1975 and also in February 1976, there was streamflow in reaches of Wādī Markhah and Wādī Quwah, and in a reach of Wādī Jumhūri (W. Gumhuri), near the People's Democratic Republic of Yemen border. A wide-ranging seasonal and annual fluctuation is indicated by the spectral evidence.

Vegetation.—Vegetation is restricted to the land adjacent to wadis, particularly to the valley floors of Wādī al Qawl and Wādī Laylān and in reaches of small tributaries near the junction of Wādī al Qawl and Wādī Laylān. There is a marked seasonal variation in plant growth: The vigorous growth observed in October 1975 had all but faded away by February 1976.

RED SEA CATCHMENT AREA

The Red Sea catchment area, the second largest in the YAR, includes the drainage basins of the two largest rivers in the country: Wādī Mawr and Wādī Zabīd. The headwaters and middle courses of all major streams in this catchment area are in the *Red Sea escarpment; their lower courses traverse the coastal plain, the Tihāmah, although surface flow generally ceases a long distance from the coast. The drainage basins of all streams except coastal streams are almost entirely east of a high range of foothills facing the Tihāmah. The shape of many of the drainage basins is strongly controlled by geologic structure, Wādī Mawr, for example, and the stream network may be unusually asymmetric, as in Wādī Surdūd. Streams arising in the *Red Sea escarpment enter the Tihāmah through a narrow water gap across the high range of foothills and follow a course incised a few meters below the surface of the Tihāmah. From the northern border between the YAR and the Kingdom of Saudi Arabia to the entrance of Wādī Mawr onto the Tihāmah, Precambrian metamorphic and granitic rocks predominate in the *Red Sea escarpment; from Wādī Mawr south, volcanic rocks predominate. Colluvium and alluvium, from sand to gravel size, and windblown sand and silt are the Quaternary deposits commonly at or near the surface of the Tihāmah. Lateral hydrologic continuity in these deposits, from the channel of one transverse stream to another, is undetermined.

WĀDĪ DIFĀ`AH (W. AD DAFA), WĀDĪ HANABAH, AND WĀDĪ ḌAMAD DRAINAGE BASIN TRIBUTARIES

The streams in the two northernmost basin areas in the YAR are tributaries to Wādī Difā`ah (W. ad Dafa), Wādī Hanabah, and Wādī Ḍamad. They all flow down the *Red Sea escarpment into the Kingdom of Saudi Arabia, and all are ephemeral streams. These minor features were not studied.

WĀDĪ JĪZĀN (W. QĪZĀN) AND WĀDĪ MA`BĀR DRAINAGE BASINS

Surface water.—Wādī Ma`bār, east of the border with the Kingdom of Saudi Arabia, is a perennial stream in its middle course. Flowing water was detected in it in October 1975 and in September and March 1973. Other streams are ephemeral.

Vegetation.—There is some diffuse vegetation on mountain slopes, but little or none on the valley floors. Plant growth was most extensive in October 1975, but it was also detected in March and September 1973.

COASTAL STREAM DRAINAGE BASINS A

Surface water.—At least four streams flowing into the Kingdom of Saudi Arabia are perennial for short stretches east of the border with the YAR. From north to south, they are: (1) an unnamed south-draining wadi south of Nadhīr (Mt. Nadhīr; 2,300 m), (2) Wādī Khulab, (3) Wādī Liyyah, and (4) Wādī Ta`ashshar. Other perennial streams are: Wādī Ḩaraḑ, perennial in its middle course down to the water gap where it debouches into the Tihāmah, 6 km northeast of the city of Ḩaraḑ, and north of Khudhrayn (Mt. Khudharain, 320 m); Wādī Ḩayrān, for a short stretch of 2 to 3 km, upstream from its entrance onto the Tihāmah; Wādī Ḩabl, along a southeast-trending reach in the Tihāmah and close to the foothills; Wādī Bawḩal and Wādī al Qūr (W. al Our), in short stretches east of the first range of foothills; and Wādī Banī Nāshir and an unnamed wadi south of it, on the Tihāmah close to the foothills.

Vegetation.—Vegetation is sparse in the mountains of the *Red Sea escarpment but denser along the base of the foothills on the Tihāmah and on land adjacent to wadis on the Tihāmah, including cultivated fields. Some annual variation in plant growth is indicated on the images: Vegetation was denser and more vigorous in October 1975 than in September 1973.

WĀDĪ MAWR DRAINAGE BASIN

Surface water.—The Wādī Mawr drainage basin is the largest in the Red Sea catchment area. Except in the headwaters, where all streams are ephemeral, high-order streams and some tributaries are perennial. Wādī Mawr is perennial in a 16-km-long, northeast-trending reach upstream from the junction with Wādī Lā`ah and may be intermittent farther upstream. Two east-bank tributaries to Wādī Mawr, Wādī Lā`ah and Wādī Warū (Wādī Husayb), are perennial along most of their courses, and a third one, Wādī Dhubāwah-Wādī Sharas, is an intermittent stream. The headwaters of these tributaries to Wādī Mawr are in the vicinity of Jabal Miswar (3,240 m), above an altitude of 3,000 meters. In addition, Wādī Lā`ah has four intermittent tributaries: Wādī Sam`, a south-bank tributary, and, farther east, Wādī Rummān (W. Roman), Wādī `Iyal`Alī, and Wādī Ḩijlah. Wādī Mawr is perennial for 25 km of its incised course across the Tihāmah, and yearly fluctuations in runoff and extent of surface flow are common. Wādī Mawr flow in the Tihāmah was 3 km longer in September 1973 than in October 1975, and in August 1972 there was only a thin trickle in this 28-km-long channel.

Vegetation.—Vegetation is lighty scattered throughout the foothills of the *Red Sea escarpment. Agriculture is practiced on land adjacent to the channel of Wādī Mawr across the Tihāmah, from the base of the foothills to a distance about two-thirds of the way down to the coast and the city of Al Luḩayyah. Cultivated fields near Wādī Mawr are grouped into two clusters, which assume the shape of two conical sections, with the apex of each cone oriented toward the foothills. Plant growth was relatively vigorous in September 1973 but was most vigorous in October 1975, when it approached within 7 km of the *Red Sea coast.

COASTAL STREAM DRAINAGE BASINS B

Surface water.—Water was detected in the following wadis during September 1973 and October 1975: from north to south, Wādī `Ayyān, Wādī `Ulaysī, Wādī Tabāb, Wādī Ḩaţab, and Wādī Shebe. Little or no water was present in these wadis in August 1972.

Vegetation.—Vegetation is dense on Jabal Manābirah (850 m) and in the foothills to the south of it. The Tihāmah plain is cultivated along the base of the foothills and also between Wādī Tabāb and Wādī Shebe. There was little or no vegetation on the Tihāmah in August 1972, but there was in September 1973, and plant growth was at its best in October 1975.

WĀDĪ SURDŪD DRAINAGE BASIN

Surface water.—In October 1975, Wādī Surdūd contained water for 24 km upstream from the water gap, where the stream enters the Tihāmah. Farther upstream, Wādī Surdūd was intermittent in October 1975 and September 1972. In September 1973 and October 1975, surface flow extended across the Tihāmah as far as the city of Hardha and the Russian Industrial Farm; in August 1972, it extended hardly beyond the water gap near Jibāl Dahnah (1,050 m). Most, perhaps all, tributaries are ephemeral streams.

Vegetation.—There is sparse, diffuse vegetation in the mountains. Vegetation also occurs on valley floors, and the upper reaches of the Tihāmah are under general cultivation, especially near the city of Hardha. The state farm, managed by Russian agronomists, is easily recognized as the largest development of irrigated land on the Tihāmah. It lies along the north bank of Wādī Surdūd, west of Hardha. Seasonal variation in plant growth in the farmed areas is easily recognized. There were large annual fluctuations in plant growth, with little vegetation in September 1972 and more in September 1973; plant growth was at its best in October 1975.

COASTAL STREAM DRAINAGE BASINS C

Surface water.—Water was detected in an unnamed, incised wadi, winding around the north end of Jabal adh Dhāmir (1,100 m), which is located approximately 6 km northeast of Bājil, in a stretch extending for 6 km east of Jabal adh Dhāmir. Water was present there in October 1975 and in September 1973, but not in August 1972. In an unnamed wadi south of Jibāl Dahnah (1,050 m) there was water close to the surface in October 1975 and September 1973, but none in Agusut 1972.

Vegetation.—Vegetation is most prominent in the upper Tihāmah, in cultivated fields extending from the base of the foothills to the banks of wadis, on valley floors, and on the Tihāmah plains northwest of the city of Bājil. The two state farms in this drainage basin, both located near the road junction between the road to Mocha and the Al Ḫudaydah-Sana highway and both managed by German agronomists, were not identified on the images, as was the Russian industrial farm in the Wādī Surdūd drainage basin, despite their irrigated orchards and crops. Yearly fluctuations in plant growth follow the same temporal pattern elsewhere in the YAR, with little or no vegetation in August 1972, more in September 1973, and most in October 1975.

WĀDĪ SIHĀM DRAINAGE BASIN

Surface water.—Water was detected in Wādī Sihām in its course through the mountains of the *Red Sea escarpment and also across the Tihāmah. Yearly change in runoff is appreciable, but there was still water in the wadi in September 1972. Seasonal fluctuations appear more widely ranging than yearly fluctuations: There was little water in the wadi in June 1975.

Vegetation.—Most of the diffuse vegetation in the mountains is on Jabal Bura` (2,270 m), close to the Tihāmah. Vegetation on the Tihāmah is light. Seasonal increase in plant growth between June and October 1975 was great.

COASTAL STREAM DRAINAGE BASINS D

Surface water.—There was water in an unnamed wadi only in September 1973. All streams in this region probably are ephemeral.

Vegetation.—The foothills in the upper reaches of these drainage basins form the most densely vegetated region of the *Red Sea escarpment. Growth of vegetation on the Tihāmah is also vigorous. A large seasonal change is indicated by the spectral data.

WĀDĪ RIMA` DRAINAGE BASIN

Surface water.—In the mountains of the *Red Sea escarpment, Wādī Rima` is alternately a losing and gaining stream. It carried water in October 1975 and in September 1973, but there was little water in the course of Wādī Rima` across the Tihāmah in September 1972, and none in June 1975. Wide annual and seasonal fluctuations in runoff are indicated.

Vegetation.—Vegetation is diffuse on mountain slopes and mountain peaks of the *Red Sea escarpment; plants also grow on alluvial plains, and on land adjacent to Wādī Rima`, where the stream enters the Tihāmah. Seasonal and annual fluctuations in vegetative cover are evident.

WĀDĪ ZABĪD DRAINAGE BASIN

Surface water.—Wādī Zabīd is the second largest drainage basin in the *Red Sea escarpment. After Wādī Mawr and its tributaries, Wādī Zabīd and its network of tributaries have the longest reaches of perennial streams. In October 1975, water was flowing in Wādī Zabīd, both in the mountains of the *Red Sea escarpment and in the Tihāmah, in Wādī Ḫammān, and in Wādī `Annah. There was also water in the headwaters of two tributaries to Wādī Suḫul, north of the city of Ibb. In September 1972, Wādī Zabīd had become intermittent along some stretches.

Vegetation—Vegetation is diffuse on mountain slopes and on wide valley floors northwest of the city of Ibb. Tree growth and cultivated fields are typical of this region. Vegetation is sparse also in the mountains northeast of the city of Zabīd. On the Tihāmah, plant growth is vigorous on alluvial fans and on land adjacent to wadi channels. Little vegetation grows on the narrow valley floors of most wadis. Some yearly and seasonal change in plant growth on the Tihāmah is indicated.

COASTAL STREAM DRAINAGE BASINS E

Surface water.—Water was detected in Wādī al Fawwahāh and in unnamed tributaries to the north, both in mountain valleys and across the Tihāmah, in October 1975. Less water was present in September 1973, and none was apparent in June 1975. There are large annual and seasonal fluctuations in runoff.

Vegetation.—Plant growth is vigorous on the valley floors of most wadis and extremely vigorous on alluvial cones at the base of the foothills in the upper part of the Tihāmah. There was little vegetation in September 1972 and 1973, some vegetation in June 1975, and abundant plant growth in October 1975.

COASTAL STREAM DRAINAGE BASINS F

Surface water.—As in the E basins just described, there are large annual and seasonal fluctuations in stream runoff in the F basins. There was water in the course of Wādī Nakhlān through the mountains and across the alluvial plain at the head of the Tihāmah in October 1975, and the same condition applied to Wādī Suwayhirah. Water was also detected in September 1973, but there was none in June 1975.

Vegetation.—There is diffuse vegetation in the mountains north of Wādī Nakhlān. Plant growth in cultivated fields is vigorous on the flood plains of two unnamed wadis near Ḩays, in the upper part of the Tihāmah. Seasonal change in plant growth is indicated. There was little vegetation on the flood plains and valley floor in September 1972, September 1973, and June 1975, but plant growth was more abundant in October 1975.

COASTAL STREAM DRAINAGE BASINS G

Surface water.—All streams in these basins are ephemeral.

Vegetation.—There is diffuse vegetation in the foothills with some cultivation on land adjacent to wadi channels and on alluvial cones at the base of the foothills. Little vegetation was detected prior to October 1975.

WĀDĪ AL GHAYL AND WĀDĪ RASYAN DRAINAGE BASINS

Surface water.—Water was detected in Wādī Rasyan in March 1973, September 1973, and September 1972. In March 1973, there was water only in the channel of Wādī Rasyān, which extends part way across the Tihāmah. In September 1972 and October 1975, water was detected in the upper channels of Wādī Tānif. In November 1975 and September 1972, there was water in the lower courses of Wādī Maksab and Wadi al Ghayl (Wadi al Kabir) (plate 1), upstream from their confluence in the Tihāmah. In March 1973, there was little water in Wādī al Ghayl and Wādī Maksab and little or no water in Wādī al Ghayl's upstream reaches. Seasonal and yearly fluctuations in these wadis are not as great as those farther north in the Red Sea catchment area.

Vegetation.—Diffuse vegetation is plentiful on Jabal Şabir (3,006 m), particularly on its western slopes, and on the mountains to the west of it. Plants, mostly cultivated fields and orchards, grow at the upper and lower ends of the valley floors of Wādī Kaleyba and in the upper part of the valley of Wādī al Ghayl. Except in the valleys of these two wadis, seasonal and yearly fluctuations in plant growth are not obvious.

COASTAL STREAM DRAINAGE BASINS H

All streams in these basins are ephemeral, and vegetation is very scant.

GULF OF ADEN CATCHMENT AREA

The Gulf of Aden catchment area receives the greatest amount of precipitation in the YAR. Surface water was detected in four of the five drainage basins in the area. Yearly and seasonal fluctuations in streamflow do occur, but they are not as marked as in the other three catchment areas of the country. Most streams are ephemeral.

WĀDĪ ḤAMRĀ', WĀDĪ ḤARĪB, AND SAYLAT SĪḤ DRAINAGE BASINS

Surface water.—Some water was present in the headwaters of Wādī Yahir (W. Yislam), and possibly in Wādī Zaydān, in October 1975, and a lesser amount was noted in September 1972 and February 1976. No water could be detected in those streams in February 1973 or in June 1975.

Vegetation.—Vegetation is confined to the valley floors in the upper reaches of Wādī Ḥamrā, north of Rahwah (Rahwat), of Wādī Yahir (W. Yislam), and, possibly, of Wādī Zaydān. The presence of growing vegetation in September 1972 and October 1975, and its absence in February 1973 and June 1975, indicate wide seasonal variations in plant growth.

WĀDĪ BANĀ DRAINAGE BASIN

Surface water.—The Wādī Banā basin, which drains south from near Ibb, receives the greatest amount of precipitation in the entire country (fig. 4). In October 1975 and September 1973, there was water in the headwaters of Wādī Banā and also southeast of its junction with Wādī Ajlub. Water could also be detected in the headwaters of two unnamed north-bank tributaries to Wādī Banā, northeast of Damt. Wādī Ajlub is an intermittent interrupted stream northwest of its junction with Wādī Banā. Seasonal and annual fluctuations in surface flow occur. Little, if any, surface water could be detected in June 1975, and it probably occurred only in pools between dry reaches in September 1972. A thermal spring at Al Ḥaraḍah issues from a mound of tufa and travertine; this spring, the largest of several mound springs near the city of Damt, can be identified on the Landsat image taken in October 1975.

Vegetation.—Vegetation in the basin of Wādī Banā occurs in the narrow valley floors of Wādī Ajlub and in the valleys of the north-bank tributaries to Wādī Banā mentioned in the preceding paragraph. It also occurs, more diffusely, on mountain slopes south of the upper course of Wādī Banā and north of its lower course. There is little or no apparent seasonal fluctuation in plant growth on valley floors, but some seasonal and yearly fluctuations in the vegetation growing diffusely on mountain slopes were detected on the Landsat images.

WĀDĪ TUBAN DRAINAGE BASIN

The lower part of the Wādī Tuban drainage basin is outside the YAR; only the headwaters of the wadi, herein referred to as the upper drainage basin, and the upper courses of its west-bank tributaries are within the YAR. They are described separately below.

Upper drainage basin surface water.—Salabat as Sayyidah is an intermittent stream, probably gaining and losing water for 15 km downstream and southeast of the city of Ibb. There was also streamflow in an unnamed tributary southeast of Jabal Bārid (2,500 m) in October 1975, September 1972, and September 1973. Seasonal and yearly fluctuations in streamflow are not obvious.

Upper drainage basin vegetation.—Vegetation grows in the valley floors of wadis, but the dip slopes west of Ibb are lightly forested. The mountain range north of Ibb and the slopes of Jabal Khaḑra′ (2,600 m), 10 km south of Ibb, are also forested, but more lightly. Seasonal and yearly changes in plant growth are not evident.

West-bank tributary drainage basin surface water.—Streamflow was detected in Wādī Dhī as Sufāl (W. Zuba), south of the village of Dhī as Sufāl, in Wādī Nakhlān, and in Wādī Amid, downstream from its junction with Wādī Nakhlan, in October 1975, September 1972, and September 1973. Streamflow in shorter reaches in June 1975 suggests seasonal fluctuation.

West-bank tributary drainage basin vegetation.—Vegetation grows in the valleys of Wādī Saram, Wādī Warazān, Wādī Khadir, Wādī Dahr, Wādī Dabbah, and Wādī Shamera, and in a valley 5 km southeast of the town of Māwiyah and Jabal `Amā′ imah (2,230 m). Vegetation also grows on the step valley slopes and the valley floor of Wādī Amid. Except in the northern part of the basins, plant growth was most vigorous in September 1972 and less vigorous in March 1973 and November 1975. Some seasonal change is indicated. Plants grow on the valley floors of Wādī Tis`ān and its main tributaries; seasonal and yearly variations are not obvious there.

GULF OF ADEN COASTAL STREAM DRAINAGE BASINS

Surface water.—All streams in these drainage basins are ephemeral.

Vegetation.—Vegetation is diffuse on the high plain near At Turbah. Otherwise, plant growth is confined to the very narrow valley floors of Wādī Fawān, Wādī Ukayyān southwest of At Turbah, and Wādī al Adīr and Ghayl Dabāb, about 18 km east of At Turbah. Plant growth reached a peak in September 1972, and was less vigorous in March 1973 and November 1975.

CONCLUSIONS

The following conclusions concerning the occurrence of surface and ground water in the Yemen Arab Republic may be made from the analysis of selected Landsat images:

Landsat imagery can be used to delineate large regional drainage areas and to map the boundaries between major drainage basins (pl. 1).

Periodically repetitive Landsat imagery can be used to identify, tentatively, ephemeral, intermittent, and perennial streams and to determine where streamflow starts and ceases. This information can be transferred to existing topographic maps or mosaics of Landsat images (pl. 1). Most streams in the YAR are ephemeral streams.

The repetitive Landsat image coverage available provides a graphic portrayal of the seasonal and yearly fluctuations in streamflow that occur in the arid and semi-arid regions of the YAR. The seasonal rainfall pattern varies from one region to another in the YAR; thus, besides storm runoff, spring-fed streamflow occurs at different times in different regions of the country. Generally, however, streamflow is greatest (in terms of both wet channel length and color value on a false-color composite Landsat image) in the summer and early fall of each year, and least in late winter or early spring.

The imagery for Rub `al Khali and the *Wādī Jawf valley and the northern half of the Red Sea catchment area suggests that the lower the annual precipitation, the greater the seasonal and annual fluctuations in stream runoff. Conversely, fluctuations in stream runoff, and also variations in the vigor of plant growth, are smaller and less obvious in the Gulf of Aden catchment area and in the southern part of the Red Sea catachment area, where annual precipitation is relatively high.

There is a direct relationship between total length of perennial stream reaches in a drainage basin and basin area; also, the higher the elevation of headwaters, the greater the number of small-order tributaries. In this respect, the drainage basins of Wādī Mawr and Wādī Zabīd in the Red Sea catchment area, and those of Wādī Tuban and Wādī Banī in the Gulf of Aden catchment area, may be said to hold the largest surface- and ground-water resources in the country.

Streamflow in the lowest reach of any stream in the Wādī Jawf (Arabian Sea) and Red Sea catchment areas contributes to the recharge of the ground water in valley and coastal plain alluvium or, at least, is diverted into canals to replenish soil moisture. However, the percentage of these contributions as against water loss through evaporation is likely to be low.

The lower valleys of Wādī al Khārid and Wādī Adhanah in the Wādī Jawf catchment area, and to a lesser extent those of Wādī Ḥaraḍ in the Red Sea catchment area, appear underdeveloped. Irrigation farming downstream from the point where streamflow ceases in the lower valleys of these streams is at a minimum, perhaps because diverted streamflow is insufficient to replenish soil moisture.

RECOMMENDATIONS

This countrywide survey of the hydrologic features of the YAR has resulted in tentatively identifying perennial and intermittent reaches and areas where soil moisture is available for plant growth or where the water table is at a shallow depth. This new information greatly expands what is known of the hydrology of the YAR, especially the surface-water hydrology. Even when accurately known, however, the occurrence of surface and ground water, by itself, hardly constitutes an adequate basis for hydrological forecasting and sound management of water resources. The following recommendations for future hydrological investigations in the YAR are made after considering the need for institutional innovation; they represent a sound methodological approach to network design, site selection, data collection, processing, and analysis, forecasting, and logistical support. Some studies and investigations are recommended.

INSTITUTIONAL RECOMMENDATIONS

1. The Landsat imagery program should be continued and expanded to cover the entire YAR at least once a month for several years. The expanded and more frequent coverage is needed to monitor the change in water occurrence and to verify the extent of plant growth. The imagery would also permit periodic inventories of agricultural land use.
2. An effective countrywide program of surface- and ground-water hyrological studies should be initiated to meet the present and

future needs of the YAR for irrigation, rural, livestock, and municipal supplies in the short term, and for industry in a longer range program. From the regional reconnaissance framework provided by the imagery system of an orbiting spacecraft, which was adopted in the present report, the program should evolve toward qualitative and quantitative studies in the hydrological and ecological fields, using direct and indirect methods. These studies may be site-specific or regional in scope, but the more localized ones need to be put within the broad regional framework dealt with in first-priority investigations.

3. Permanent, countrywide networks for gaging streams and for measuring water levels in wells should be initiated. In organizing these networks and locating gaging stations and observation wells, prime consideration should be given to the hydrological and agricultural evidence shown on Landsat images, as described in this report.
4. Topical studies should be undertaken to observe and analyze sheet flood processes. Our brief ground reconnaissance of the YAR in June–July 1975 showed that sheet floods are a common occurrence but of uncommon magnitude in the YAR, and that they occur on steep mountain slopes as well as on gentler valley slopes. Vast amounts of weathered rock debris, particularly in the silt-size range, are transported during sheet flooding; traditionally, this debris has been trapped by Yemeni farmers in their irrigation terraces, possibly as means of periodically building, adding to, or renewing, their soil resources. One study in sedimentology particularly applicable to the building of dams and their life expectancy in the YAR should deal with the ratio of sediment loads in overland flow to sediment loads in stream channels.
5. The present meteorological network should be expanded to include at least one weather station in each major vegetation zone in each drainage basin. Air temperature should be monitored, so that ground-water temperature can be related to its mean annual value. Latitudinal variation of the frost line in the mountains needs investigation, as freezing in winter affects streamflow and discharge of ground water to springs and seeps. Rain gages should be equipped with automatic recording equipment so that each of the 20 or 30 annual showers may be quantified, and so that the extent of the rainy seasons may be determined accurately.

Only by expanding and upgrading the meteorological network can the probability of storm runoff and flooding in a given drainage basin or in part of a basin be determined. In the YAR, sheet wash and overland flow are modified by either natural or manmade ponding, evaporation, and replenishment of soil moisture by diversion. These modifications are important aspects of the hydrologic regimen in the YAR. Because of them, the occurrence of storm runoff in stream channels and recharge to the water table probably are even more erratic events than the occurrence of rainstorms and cannot be predicted from the knowledge of storm frequency distribution alone. Not only should observations be made to calculate by direct or indirect means the annual runoff of major streams, but methods should be devised to quantify the amount of surface water, particularly overland flow, that is put to agricultural use *before* it reaches stream channels. For planning purposes, there is the further need to relate storm frequency and magnitude within each of the two annual rainy seasons and also to find out whether there is a second period of base flow in perennial reaches during the short intervening period beween the two rainy seasons.

Floods and drought are hazards familiar to hydrologists and planners. The intricate pattern of irrigation terraces, which is a striking feature of the Yemeni landscape, represents community efforts to control floods and overland flow that were initiated thousands of years ago. The ruins of the *Ma'rib dam on Wadi Adhanah in the eastern part of the YAR are a reminder of successful ancient efforts at flood control and irrigation farming. Nevertheless, Yemeni agriculture seems as vulnerable to drought as it has ever been.

The recent continent-wide drought, which affected the north tropical zone (including the YAR) for a span of several years, from 1968 to 1973, suggests a climatic (but necessarily periodic) cycle, the duration of which remains to be determined. As described earlier in this report, the effects of this drought on the environment are well documented on Landsat 1 images of the YAR that were obtained in August–September 1972 and also in 1973. The Landsat 1 evidence shows that these effects were widespread and not restricted to the valleys of the main wadis. Besides reducing the length of perennial and intermittent reaches in streams, the drought reduced plant growth throughout the YAR. The Landsat 1 images provide overwhelming and indisputable evidence that in the YAR the fluctuations in length of the perennial and intermittent reaches of streams, together with fluctuating ground-water levels, may provide data that can be used as sensitive indicators of the climatic threshold below which human settlement in the YAR is impaired.

It is not clear how hydrologic investigations aimed at evaluating maximum floods and annual runoff in some wadis of the YAR will improve countrywide flood-control practices; nor is it clear how water stored in surface reservoirs can be beneficial to agriculture in lands adjacent to the Red Sea, where the annual potential evaporation is reported to approximate 2 m. On the other hand, an intensive study of the hydrologic regimens of perennial and intermittent reaches of streams in the YAR, monitoring of water levels in water wells, and ecological investigations aimed at continuous monitoring of plant growth will provide basic data that should be of considerable value for regional or countrywide planning.

METHODOLOGICAL RECOMMENDATIONS

1. Network design: To the extent possible, the location of gaging stations and observation wells, as well as the selection of equipment and methods, should have multipurpose objectives, so that measured or calculated surface-water data will be of maximum use to an analysis of ground-water hydrology, and vice versa. This is necessary for an effective, all-encompassing hydrological program, particularly in a country where satellite data show that both effluent and influent streams are common.
2. Site selection: Sites for gaging stations and observation wells should be selected with consideration for the following factors:
   a. The spatial distribution of rainstreams in the YAR depends largely on the ratio between the dimensions of the storm and the area affected by it on one hand, and the size of the region being studied on the other. One meteorological and ecologic problem along the *Red Sea escarpment concerns orographic control of precipitation. Along the *Red Sea escarpment (the mountain front just east of the Tihāmah), there are wide seasonal and yearly variations in plant growth on some slopes but little variation on nearby slopes of the same orientation. Further studies may show that greater vigor in plant growth on some slopes is not due to greater rentention of soil moisture because of favorable rock types and joint pattern, but rather that these mountain slopes lie across the tracks of major regional storms.
   b. Measurement of the runoff of a drainage basin may give quantitative meaning to the perennial and intermittent reaches identified on Landsat images.
   c. The influence of the major rock types in the YAR (alluvium, colluvium, granitic and metamorphic rocks, carbonates, sandstone, and volcanic rocks) on streamflow, sediment load, ground-water storage, recharge and discharge, and quality of water is not well known. A large area in the *Yemen highlands north of Sana is underlain by limestone of Jurassic age included in the Amran Series (fig. 3); yet large-scale karst topography is either poorly developed or not obvious in the field. Why not? A chemical analysis of

samples of Amran (Jam) limestone to determine its dolomite content and measurement of the percentage of solids actually dissolved in surface and ground water originating in this area may help solve this hydrologic, geomorphologic, and, possibly, climatic riddle. Likewise, the storage characteristics and permeability of the Yemen volcanics (fig. 3) require study.

3. Data collection: Perennial and intermittent streams should be mapped on Landsat images enlarged to an appropriate working scale, and the information should be transferred to existing topographic maps at 1:250,000 scale.

   Collection of some hydrologic data should be timed to coincide with low flow (ideally base flow) and flood stages in streams. In this way, it may be possible to relate and compare specific image data with quantitative hydrologic data, to determine the occurrence of a stage of summer low flow that might eventually be identified spacially on Landsat images, and ultimately to make long-term, low-flow forecasts for the YAR.

4. Computerized data bank: It is not too early to contemplate establishing a computerized water resource data bank for the YAR and implementing a data storage and retreival system, possibly after the model followed by the Kingdom of Saudi Arabia since 1978 (Marsh and others, 1981).

FORECASTING

Some redundancy should be built into the methods used to measure or calculate hydrological data. In no way should the general approach to surface- and ground-water investigations in the YAR be confined to only one method of hydrological forecasting. Conventional hydrological and meteorological observations must be made concurrently with indirect methods in which stream hydraulics are related to channel geometry. Over the years, only an adequate data base will substantiate or negate the validity of the results obtained by the mathematical-statistical approach to stream dynamics. Further, some of the other methods employed in hydrological forecasting, particularly those used to calculate evapotranspiration rates, should also be considered in the formulation of an overall water resources program in the YAR (World Meteorological Organization, 1975, p. 5).

LOGISTICAL SUPPORT

In the selection of sites for gaging stations and observation wells, the type of logistic support the field hydrologist will get in servicing stations and monitoring wells should receive priority attention. Similarly, in determining the optimal frequency of observations, accessibility and availability of trained technicians, rather than the general level of economic development in the country, should be the overriding factors. At present, the YAR is characterized by a scarcity of good roads and a surplus of high-salaried but untrained technical labor. In any case, sandy wastes, lack of population, tremendous topographic relief (2,500 meters over a 10- to 20-km belt in the *Red Sea escarpment), valley dissection, and terraced irrigation farming will limit easy road access to many regions in the foreseeable future.

The sites of gaging stations and observation wells should be selected with the understanding that they will be serviced from a helicopter; for this reason, space should be allotted for a landing site near some, or perhaps most, gaging stations and observation wells. Helicopter service, with or without a simple radio alert network, will also make it possible to perform occasional as well as regular monitoring of hydrological processes and meteorological phenomena. Flash floods, flows in ephemeral streams, torrential downpours accompanied by sheet wash and tremendous rates of erosion and sediment transport and deposition, then, can be monitored on an emergency basis. In turn, these monitored events take on added meaning if their effects on the ground can be identified on Landsat images. Water is the most valuable mineral in the agricultural economy of the YAR, so the cost of using and maintaining a helicopter for hydrologic fieldwork can be fully justified in terms of countrywide benefits returned when the helicopter is used jointly with a geological survey of the country.

RECOMMENDATIONS FOR FURTHER STUDIES

1. The present remote-sensing program should be expanded to include routine acquisition and analysis of weather satellite images, so that regular precipitation data collected at weather stations can be related to nephanalysis.
2. Theoretical and actual evaporation rates in each of the four catchment areas should be determined, possibly by taking advantage of the thermal data routinely acquired in the thermal infrared band of existing weather satellites.
3. A quantitative evaluation of the consumptive use of water by plants in at least one of the major drainage basins should be made. In the YAR, natural soil moisture is replenished and augmented by diverted overland flow, streamflow, and water from wells. The proportions of these sources of water available for agricultural crops should be estimated, so that their relative importance in the national economy can be known. Total acreage under cultivation and in light forest can be derived

from Landsat images, using computer compatible tapes and existing land-use computer programs.

4. Other types of data needed to interpret Landsat images in greater detail should be collected, specifically:
   a. Data on natural plant cover and on types of crops grown in irrigated and nonirrigated fields. In this context, pollen traps should be set up in the vicinity of each gaging station and some of the observation wells, to monitor the pollen rain, and should be serviced at least once a year. This recommendation recognizes that subsistence agriculture has assured human survival in the YAR for thousands of years and is still the mainstay of the Yemeni economy. The present pollen rain, therefore, can be used as a data base against which past and present changes in natural vegetation and cultivated plants growing in the YAR can be estimated. In turn, changes in plant distribution over time may be useful in inferring cyclic rainfall fluctuations and, therefore, short-term and long-term climatic change in the YAR.
   b. Data on distribution of soil types.
5. Analysis of repetitive Landsat coverage should continue:
   a. To define basins or areas where withdrawal of water exceeds replenishment from all combined sources, as evidenced by diminishing vegetated acreage;
   b. To map wetlands where brackish water is known to be present at shallow depth, as under the sebkahs that dot the coastal areas along the Red Sea or down valley from irrigated farms where drainage is ineffective;
   c. To map the areal extent of coral reefs along the coast, as an aid to navigation and fisheries; and
   d. To map pollution of seawater along the coast.

Given the ability to use Landsat imagery in these specialized ways, it is clear that in a later phase of a countrywide hydrological program, remote sensing of the YAR may be a powerful tool, first in modernizing, and later in enforcing water laws, assuming that current riparian practices and customs, as well as local ground-water law, are codified into a modern unified system of laws.

Additional remote-sensing programs also should be considered, including a thermal infrared aerial survey to detect possible ground-water discharge offshore which may be reflected in small temperature differences between Red Sea water and fresh ground water. Such an aerial infrared survey should be undertaken with the objective of locating presently untapped ground water and intercepting it by drilling wells at critical locations on the coastal plain of the Red Sea. The aerial survey should be supported on the ground by a survey of existing wells in the Tihāmah and a water sampling program aimed at determining the chemical quality of ground water. A countrywide thermal infrared survey would allow the systematic mapping of thermal springs, which traditionally have played an important part in the cultural life of the Yemenis, and also might help locate hot spots related to volcaniam. Some hot spots might warrant further exploration in the seach for geothermal energy. More advanced remote-sensing techniques such as those for estimating moisture content through the dielelectric constant of materials should not be considered, however, until radar imagery has become widely available in the YAR.

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APPENDIX I: GLOSSARY OF SELECTED TERMS USED IN THIS REPORT

GROUND-WATER AND SURFACE-WATER TERMS

[Summarized from Meinzer (1923, p. 54–57) and from Lanbein and Iseri (1960).]

GROUND-WATER TERMS

Ground water. Water in the ground that is in the zone of saturation, from which wells, springs, and ground-water runoff are supplied.

Ground-water outflow (underflow). That part of the discharge from a drainage basin that occurs through the ground and that is not measured at a gaging station.

Ground-water runoff. That part of ground water which has been discharged into a stream channel as spring or seepage water.

Mound spring. A spring that may be produced wholly or in part by the precipitation of mineral matter from the spring water.

Thermal spring. A spring having water at a temperature appreciably above the mean annual temperature of the atmosphere in the vicinity of the spring.

SURFACE-WATER TERMS

Discharge. The actual flow of a stream, whether or not subject to regulation or underflow.

Drainage divide. The rim of a drainage basin.

Overland flow. The flow of rainwater over the land surface toward stream channels.

Runoff, with respect to source:

- **Base runoff.** Streamflow composed largely or wholly of effluent ground water.
- **Surface runoff.** That part of rainwater that appears in streams.
- **Direct runoff.** Overland flow entering stream channels shortly after a rainfall.

Stream. Water flowing in a natural channel.

Relation to time:

- **Perennial stream.** A stream that flows continuously.
- **Intermittent or seasonal stream.** A stream that flows only at certain times of the year, when it receives water from springs or from some surface source such as melting snow in mountainous areas.
- **Ephemeral stream.** A stream that flows only in direct response to precipitation and whose channel is at all times above the water table.

Relation to space:

- **Continuous stream.** A stream that does not have interruptions in space.
- **Interrupted stream.** A stream that contains alternating reaches that are either perennial, intermittent, or ephemeral.

Relation to ground water:

- **Gaining (effluent) stream.** A stream or reach of a stream that receives water from the zone of saturation. It is said to be effluent with respect to ground water.
- **Losing (influent) stream.** A stream or reach of a stream that contributes water to the zone of saturation. it is said to be influent with respect to ground water.

Streamflow. The discharge that occurs in a natural channel; may be applied to discharge whether or not it is affected by diversion or regulation.

Underflow. The downstream flow of water through the permeable deposits that underlie a stream.

VEGETATION TERMS

Plants are grouped into three ecologic classes according to the relative wetness or dryness of their habitats: **hydrophytes, xerophytes,** and **mesophytes** (Warming, 1895, 1925); they grow in wet, dry, and moist habitats respectively (Daubenmire, 1959, p. 138).

Plants also have been classified in a way that expresses the relationship of their roots to the water table (Meinzer, 1923, 1927; and Robinson, 1958). **Phreatophytes,** a term proposed by Meinzer in 1923, require large quantities of water for growth and habitually transpire water either directly from the zone of saturation or through the capillary fringe. **Xerophytes,** in contrast, have roots well above capillary fringe and therefore transpire soil water only. **Mesophytes** neither grow in water nor endure prolonged drought.

Phreatophytes, indicative of a relatively shallow water table and therefore of particular interest in this study, may be either natural or domesticated. Tamarisk *(Tamarix gallica)*, a tree growing wild in clumps along the banks of many wadis in the YAR, was frequently observed by the writers. Alfalfa, widely cultivated in the YAR in fields irrigated with surface water or ground water, is a domesticated phreatophyte having long-root penetration (Robinson, 1958, p. 60).

Halophytes are plants having great tolerance for salt and alkali in the soil water; they generally are xerophytes. Their inward zonation by species around the outer fringe of a playa or around a natural sump at the end of a losing stream is a reflection of the increasing salt tolerance of each species. Mangroves, a familiar sight along some stretches of the Red Sea landscape, are rooted on the seafloor in the intertidal zone and therefore fit the definition of a hydrophyte.

Consumptive use is the quantity of water absorbed by crops and transpired or used directly in the building of plant tissue, together with the water evaporated from natural vegetation and cropped areas.

GEOLOGIC TERMS

[from Gary and others, ed. (1972)]

Catchment area. As used in this report, one of the four large regional drainage areas toward the Rub `al Khali, the Arabian Sea, the Gulf of Aden, and the Red Sea. Each catchment area includes many smaller individual drainage or river basins.

Escarpment. A long, more or less continuous cliff or relatively steep slope facing in one general direction, breaking the general continuity of the land by separting two levels of gently sloping surfaces and produced by erosion or by faulting.

Facies. A term used to refer to a distinguishing part or parts of a single entity, differing from other parts in some general aspect; for example, any two or more significantly different parts of a recognized body of rock or stratigraphic unit, distinguished from other parts of the same rock or unit by appearance or composition.

Felsic rock. Igneous rock having light-colored minerals in its mode; opposite of mafic rock.

Mafic rock. Igneous rock composed chiefly of one or more ferromagnesian, dark-colored minerals in its mode.

Massif. A massive topographic and structural feature in an orogenic belt, commonly formed of rocks more rigid than those of its surroundings. These rocks may be protruding bodies of basement rocks, consolidated during earlier orogenies, or younger plutonic bodies.

Metasedimentary. A metamorphic rock of sedimentary origin.

Metavolcanic. A metamorphic rock of volcanic origin.

Piercement dome (diapir). A dome whose overlying rocks have been ruptured by the squeezing out of the plastic core material.

REMOTE SENSING TERMS

[from Reeves and others, eds. (1975) and from Sabins (1978)]

Band. A wavelength interval in the elecromagnetic spectrum; also the spectral image taken in that particular wavelength interval.

Band ratioing. A process for making images. An image can be produced by processing digital multispectral data; in ratioing, the value for each pixel of one band is divided by the value of the corresponding pixel of another band, and the resulting digital values are displayed as an image.

Computer enhancement. The process whereby a computer alters the appearance (or contrast) of an image so that the interpreter can extract more information. Enhancement can be done by digital or photographic methods.

Dielectric constrant. Electrical property of matter that influences radar returns.

False-color composite. A color image prepared by superposing black and white images of individual spectral bands of the same scene, using different color filters for each band. To produce a Landsat false-color composite, which approximates a color infrared (or false-color) photograph, a blue filter is assigned to band 4, a green filter to band 5, and a red filter to band 6 or 7.

Image. The representation of a scene as recorded by a remote-sensing system. Image is a general term, but it is commonly restricted to representations acquired by nonphotographic methods.

Mosaic. An image or photograph made by piecing together individual images or photographs covering adjacent areas.

Multispectral scanner. A scanner system that simultaneously acquires imges of the same scene in various wavelength regions.

Near-infrared. The shorter wavelengths of the infrared region, extending from about $0.7 \mu m$ to $1.3 \mu m$. The term emphasizes the solar radiation reflected from plant materials, which peaks around $0.85 \mu m$ and can be recorded by photographic means as well as by multispectral scanners.

Orbital track. Path of spacecraft travel.

Pixel (contraction of "picture element"). In a digitized image, a pixel is the area on the ground represented by each digital value. Because the analog signal from the detector of a scanner can be sampled at any desired interval, the picture element may be smaller than the ground resolution cell of the detector.

Radar imagery. Image obtained through the use of radar (radar is an acronym for radio detection and ranging, an active form of remote sensing that operates at wavelengths ranging from 1 mm to 1 m).

Resolution. The degree to which closely spaced objects on an image or photograph may be distinguished.

Scene. The area on the ground, sometimes called footprint, that is covered by an image or photograph.

Spectral band. An interval in the electromagnetic spectrum defined by two wavelengths, frequencies, or wave numbers.

Spectral reflectance. The reflectance of electromagnetic energy at at specified wavelength intervals.

Sun-synchronous orbit. An earth satellite orbit in which the orbital plane is near polar and the altitude is such that the satellite passes over all places on earth having the same latitude twice a day at the same local sun time.

Swath. That portion of the Earth surface scanned in a cross-orbital track direction. The multispectral scanners aboard the Landsat spacecraft scan a swath 185-km long, imaging six scan lines in each of the four spectral bands simultaneously.

Thematic mapping. Mapping done according to themes, or elements of interest. Any photograph or image contains data pertaining to a variety of themes: land, water, vegetation, rock types, land use, and so forth. In thematic mapping, image data are extracted selectively (by specific wavelengths, for example), one theme at a time, and re-imaged separately so as to produce maps that emphasize vegetation, geologic features, land use, or other aspects.

Thermal infrared. That portion of the infrared region, from approximatley 3 to 13 μm, that corresponds to heat radiation. This spectral region spans the radiant power peak of the Earth.

APPENDIX II: SHEET NUMBERS AND NAMES OF TOPOGRAPHIC MAPS AT THE 1:250,000 SCALE COVERING THE YAR

The following is a list of geographic maps prepared for the Yemen Arab Republic by the Director of Military Survey, Ministry of Defence, United Kingdom (1974), at the scale of 1:250,000.

		Coordinates of sheet boundaries			
		North latitude boundary		East longitude boundary	
Sheet No.	Sheet name	North	South	West	East
1	Ṣa`dah	17°45′	16°00′	42°40′	44°00′
2	Al Ḩasm	17°45′	16°00′	44°00′	45°30′
3	Rayyān	17°45′	16°00′	45°30′	47°00′
4	Ḩudaydah	16°00′	14°15′	42°40′	44°00′
5	Ṣan`ā′	16°00′	14°15′	44°00′	45°30′
6	Ḩarib	16°00′	14°15′	45°30′	47°00′
7	Ta`izz	14°15′	12°30′	43°00′	44°30′
8	Qu`tabah	14°15′	12°30′	44°30′	46°00′

APPENDIX III: GAZETTEER

Published sources listing Yemen Arab Republic place names in original Arabic are few. Entries in the gazetteer include names approved by the U.S. Board on Geographic Names (BGN) and unapproved variant names.

As far as possible, Arabic names in the gazetteer have been romanized from Arabic script according to the transliteration system used jointly by the BGN and the Permanent Committee on Geographical Names (PCGN) for British Official Use (the BGN/PCGN 1956 System as revised in 1972).

SPELLING: FORM AND USAGE

BGN-approved names are categorized as long form names, short form names, and conventional form names; conventional form use is preferred by BGN. Both long form and conventional form names have been used in this report. Short form names are used on figure 1 because of its small scale. Use of the conventional form name with the native name following in parentheses (see footnote 2) identifies a feature name of a previous report.

Additionally, geographic names having no BGN recommendation or not located in BGN available sources are categorized as "no BGN recommendation" and "edited names." Edited names are applied to hydrologic and some physiographic (topographic) features described in this report. These two name categories were necessary to retain the report's geographic references (locations).

EXPLANATION OF NAME FORMS

BGN (report) name	*BGN name forms, with unapproved name categories*
1. Al Bayḍā'	Approved name
2. <u>Kamaran</u> Island (Conventional) (Kamarān) (Arabic)	Long form name (the complete name)
3. Kamaran	Short form name (the underlined portion of the long form)
4. Asir (Conventional) (ʿAsīr) (Arabic)	Conventional form name (use of the native name in parenthesis is optional)
5. *Al Nedja	No BGN recommendation
6. *ʿAmrān valley	Edited BGN name (no BGN recommendation)

LETTER SYMBOL ABBREVIATIONS OF NATIONAL NAMES

1. (Y/S) Yemen (Sana)
2. (Y/A) Yemen (Aden)
3. (Y-S/A) Yemen (Sana and Aden)
4. (SA) Saudi Arabia
5. (UAE) United Arab Emirates
6. (Oman) Oman

GEOGRAPHIC FEATURES

	English	Abbreviation	Generic
1.	dam	dam	---
2.	depression	dpr	qā`
3.	desert	dsrt	rub`
4.	gulf	gulf	---
5.	escarpment	escar	---
6.	hill	hil	ḩayd, jabal
7.	island	isl	jazīrat
8.	saltmines	mnn	---
9.	mountain	mt	`alam, jabal
10.	mountains	mts	jibal
11.	oasis	oas	---
12.	independent political entity (republic)	pcli	---
13.	plain	pln	jawl, gā`
14.	populated area	ppl	---
15.	ridge	rdge	ḩayd
16.	region	rgn	---
17.	sand area	sand	ramlat
18.	sea	sea	---
19.	stream	stm	saylat, wādī, ghayl
20.	strait	strt	bab
21.	valley	val	---

GLOSSARY OF GEOGRAPHIC NAMES

[The glossary is arranged in four columns. The BGN (report) names are in column 1. These names are converted from source names. When applicable, the conventional name is indicated (conv.) and the native name follows in parentheses. Where shown in column 1 near a name, letter symbols in parentheses indicate that the named feature extends into an adjacent country (or countries) or is located in another country (or countries) (see "Letter Symbol Abbreviatons of National Names," this appendix). The geographic feature descriptions applied to BGN names are in column 2. The geographic coordinates are in column 3. Coordinates are given to the nearest degree and minute for: (1) populated places and other entities occupying limited sites, (2) the mouth of a wadi or its junction with another wadi, (3) the highest point of a mountain or hill, (4) the extremities of points, or (5) near the center of midpoints of a region or area. The sheet numbers given in column 4 refer to the topographic quadrangle in which a named geographic feature is located (see appendix II)]

BGN (report) name[1]	Feature description	Coordinates N lat	Coordinates E long	Sheet No. (app. II)
Al `Alam al Aswad	mt	15°56′	45°46′	6
Al Baydā′	ppl	13°59′	45°34′	8
Al Ḩaraḑah (location of spring)	ppl	14°05′	44°40′	8
Al Ḩarf′	ppl	16°22′	44°06′	2
Al Ḩudaydah (Hudaydah)	ppl	14°48′	42°57′	4
Al Luḩayyah	ppl	15°43′	42°42′	4
*Al Nedja	ppl	15°04′	45°17′	5
`Amrān (`Umrān)	ppl	15°41′	43°55′	4
*`Amrān valley	val	15°40′	43°51′	4
Arabian Peninsula (SA)	rgn	25°00′	45°00′	off
Arabian Sea	sea	18°00′	71°00′	off
Arabian Shield (SA)	rgn	25°00′	45°00′	off

BGN (report) name[1]	Feature description	Coordinates N lat	Coordinates E long	Sheet No. (app. II)
Ar Rāḩidah	ppl	13°22′	44°18′	7
Asir (ʿAsir) (conv.) (SA)	rgn	19°00′	42°00′	off
Ash Shaliq (Al Chalek)	ppl	16°06′	44°41′	2
At Turbah	ppl	13°13′	44°07′	7
Bab el Mandeb	strt	12°35′	43°25′	7
Bājil	ppl	15°04′	43°17′	4
Baraţ	ppl	16°36′	44°15′	2
Bayt'al Faqīh	ppl	14°31′	43°19′	4
Damt	ppl	14°06′	44°43′	8
Dhamār	ppl	14°33′	44°24′	5
Dhī as Sufāl	ppl	13°50′	44°07′	7
Ghayl Dabāb	stm	13°13′	44°18′	7
Gulf of Aden	gulf	12°00′	48°00′	7
Guma	ppl	15°41′	42°49′	4
Hamman al Lassī (Hayd al Asī)	mt	14°33′	44°32′	5
Ḩaraḑ	ppl	16°26′	43°05′	1
Hardha	ppl	15°15′	43°15′	4
Ḩays (Ḩais)	ppl	13°56′	43°29′	7
Ibb	ppl	13°58′	44°11′	7
Ibb ʿAbbās	ppl	15°23′	42°47′	4
Indian Ocean coast	---	---	---	off
Jabal adh Dhāmir	mt	15°02′	43°23′	4
Jabal al Khaţţārin	mt	16°44′	43°49′	1
Jabal Amā' imah	mt	13°34′	44°25′	7
Jabal an Nabī Shuʿayb	mt	15°17′	43°59′	4
Jabal aş Şafrā'	mt	16°44′	43°56′	1
Jabal Barid	mt	13°55′	44°11′	7
Jabal Buraʾ	mt	14°54′	43°29′	4
Jabal Ḩaḑūr ash Shaykh	mt	15°35′	43°50′	4
Jabal Khaḑrā'	mt	13°51′	44°12′	7
Jabal Manabirah (J. Manabira)	mt	15°29′	43°15′	4
Jabal Manār	mt	14°02′	44°17′	7
Jabal Miswar	mt	15°37′	43°41′	4
Jabal Omrikha	mt	15°09′	45°25′	5
Jabal Şabir	mt	13°30′	44°03′	7
Jabal Samaʾ	mt	15°10′	45°19′	5
Jadīdah (Al Jadidah)	ppl	15°03′	45°17′	5
Jazīrat Jabal Zuqar (Jazīrat Zuqar)	isl	14°00′	42°45′	off
Jazirat al Ḩanīsh al Kabīr (Hanish Kabir)	isl	13°43′	42°45′	off
Jibal Dahnah	mts	15°09′	43°20′	4
Jiblah	ppl	13°55′	44°09′	7
Kamaran Island (Kamarān) (conv.) (Y/A)	isl	15°21′	42°35′	off
Kawkabān	ppl	15°30′	43°54′	4
Khabb (Khabb Oasis)	ppl	16°43′	44°54′	2

BGN (report) name[1]	Feature description	Coordinates N lat	Coordinates E long	Sheet No. (app. II)
Khamīs al Wa`iẓat	ppl	15°52′	43°12′	4
Khamr (Khamir)	ppl	15°59′	43°58′	4
Khashiba Ridge	rdge	16°37′	44°51′	2
Khāw	ppl	14°18′	44°25′	5
Khudrayn (Mt. Khudharain)	hll	16°26′	43°09′	1
Kitāf	ppl	17°02′	44°06′	2
Ma`bar	ppl	14°48′	44°17′	5
Ma′rib	ppl	15°26′	45°20′	5
*Ma′rib dam	dam	15°27′	45°23′	5
Māwiyah	ppl	13°35′	44°21′	7
Mocha (Al Mukhā) (conv.)	ppl	13°19′	43°15′	7
Maydī	ppl	16°19′	42°48′	1
Nadhīr	mt	16°58′	43°16′	1
Nakhlah	ppl	13°55′	43°34′	7
Nuqūb (An Nuqūb) (Y/A)	ppl	14°59′	45°48′	6
Perim Island (Barīm) (conv.) (Y/A)	isl	12°39′	42°35′	7
Qā`al Bawn al Kabīr (Beni Awni al Kabir)	dpr	15°45′	44°00′	4
Qā`al Fayd	dpr	14°25′	44°50′	5
Qā`ash Shams	pln	15°55′	44°05′	5
Qā`Hays	dpr	15°51′	44°06′	5
Qa`tabah	ppl	13°51′	44°43′	8
Quṭay`	ppl	14°54′	43°12′	4
Rahwah (Rahwat) (Y/A)	ppl	13°59′	45°13′	8
Ramlat as Sab`atayn (Y-S/A)	dsrt	15°30′	46°10′	6
Ramlat Dahn	sand	16°25′	45°45′	3
Raydah (Rīdah)	ppl	15°50′	44°03′	5
Red Sea	sea	25°00′	35°00′	7
*Red Sea coast	---	14°45′	42°56′	1, 4, 7
*Red Sea escarpment	escar	---	---	4
*Red Sea graben	---	25°00′	35°00′	off
*Red Sea rift	---	14°30′	43°30′	off
Ridā`	ppl	14°25′	44°50′	5
Rub`al Khali (Ar Rab`al Khāli) (conv.) (Y-S/A, SA UAE, Oman)	dsrt	21°00′	51°00′	3
Sa`dah (Sadah)	ppl	16°57′	43°46′	1
Sāfir	mnn	15°39′	46°06′	6
Sana (Ṣan`ā′) (conv.)	ppl	15°21′	44°12′	5
*Sana basin	---	15°29′	44°15′	5
*Sana plain	pln	15°22′	44°41′	5
Salabat as Sayyidah	stm	13°57′	44°11′	7
Ṣalif (As Salīf)	ppl	15°18′	42°41′	4
Saylat Sīḩ (Y-S/A)	stm	13°52′	45°07′	8
Sūq al Ghinān (Suq al`Inān)	ppl	16°43′	44°19′	2
Ta`izz (Taizz)	ppl	13°34′	44°01′	7
Tihāmah (At Tihama) (Y-S/A, SA)	pln	22°00′	40°00′	4

BGN (report) name[1]	Feature description	Coordinates N lat	Coordinates E long	Sheet No. (app. II)
Wādī `Abdī	stm	16°57′	43°46′	1
Wādī Ablah	stm	14°58′	45°28′	5
Wādī Abrād	stm	15°51′	46°05′	5
Wādī Adhanah	stm	15°24′	45°16′	5
Wādī al Adīr	stm	13°12′	44°18′	7
Wādī al `Aqīq	stm	17°03′	44°27′	2
Wādī Agnām	stm	17°00′	43°47′	1
Wādī Ajlub	stm	14°06′	44°40′	8
Wādī `Annah	stm	14°04′	43°44′	7
Wādī Amid	stm	13°42′	44°11′	7
Wādī Amlaḩ	stm	17°10′	44°33′	2
Wādī Amwāḩ (Y/S, SA)	stm	17°00′	45°40′	2
Wādī Aţţāf (Ghayl Hirran)	stm	16°02′	44°12′	2
Wādī `Ayyan	stm	15°28′	42°46′	4
Wādī Aẓlah	stm	16°57′	44°19′	2
Wādī Banā (Y-S/A)	stm	13°03′	45°24′	8
*Wādī Banā basin	---	13°40′	45°06′	8
Wādī Banī Nāshir	stm	15°52′	43°13′	4
Wādī Bawḩal	stm	16°05′	43°03′	1
Wādī Bayḩān	stm	15°11′	45°51′	6
Wādī Birkah	stm	16°25′	44°06′	2
Wādī Dabbah (W. Shamera Dabbah)	stm	13°31′	44°25′	7
Wādī Dahr	stm	13°31′	44°15′	7
Wādī Ḑahr	stm	15°27′	44°08′	5
Wādī ad Dabīl (SA)	stm	15°51′	45°54′	6
Wādī Ḑamad (SA)	stm	16°59′	42°33′	1
Wādī Dammar (W. Dammer)	stm	16°53′	43°48′	1
Wādī Difā`ah (W. Ad Dafa)	stm	17°47′	42°54′	1
Wādī Dhī as Sufāl (W. Zuba)	stm	13°46′	44°09′	7
Wādī Dhubāwah	stm	15°52′	43°34′	4
Wādī Fawān	stm	13°05′	44°05′	7
Wādī al Furḑah	stm	15°51′	44°45′	5
Wādī al Fawwahāh	stm	13°55′	43°12′	7
Wādī al Ghayl (W. al Kabir)	stm	13°17′	43°15′	7
Wādī al Ghayl	stm	14°35′	45°39′	6
Wādī Ḩabl	stm	16°10′	42°52′	1
Wādī Ḩaḑramawt (Y/A)	stm	16°00′	48°53′	off
Wādī Ḩalḩalan	stm	15°55′	45°11′	5
Wādī Ḩammān (W. Anman)	stm	14°13′	43°53′	7
Wādī Hamrā′ (Y-S/A)	stm	13°59′	45°09′	8
Wādī Hanabah	stm	17°24′	43°18′	1
Wādī Ḩarīb (Y-S/A)	stm	15°30′	45°58′	6
Wādī Harrīnah (W. Harrine)	stm	16°16′	44°07′	2
Wādī Ḩaraḑ (Y-S/A)	stm	16°25′	42°46′	1
Wādī Ḩatab	stm	15°26′	43°02′	4
Wādī Ḩatib	stm	13°50′	45°06′	8

BGN (report) name[1]	Feature description	Coordinates N lat	Coordinates E long	Sheet No. (app. II)
Wādī Ḩayḑān	stm	15°37′	43°58′	4
Wādī Ḩayrān	stm	16°16′	42°53′	1
Wādī Ḩijlah	stm	15°32′	43°38′	4
Wādī `Iyal`Alī	stm	15°33′	43°41′	4
Wādī `Ilāf	stm	16°57′	43°44′	1
Wādī `Imārah (W. Imara)	stm	17°12′	44°37′	2
Wādī al Jufrah	stm	15°53′	45°04′	5
Wādī Jawf	stm	15°50′	45°30′	5
*Wādī Jawf fault	---	16°26′	45°00′	5
*Wādī Jawf region	rgn	16°00′	45°15′	5
*Wādī Jawf valley	val	16°05′	45°15′	5
Wādī Jumhūrī (W. Gumhuri) (Y/A)	stm	14°35′	46°07′	6
Wādī Jirādhah	stm	15°00′	45°32′	5
Wādī Jīzān (W. Qizān) (SA)	stm	16°57′	42°33′	1
Wādī Kaleyba	stm	13°20′	43°48′	7
Wādī Khabb (W. Khubb) (Y/A, SA)	stm	17°00′	45°30′	2
Wādī Khadir	stm	13°30′	44°16′	7
Wādī Khadwān	stm	17°17′	44°10′	2
Wādī Khalīfayn	stm	16°27′	45°10′	2
Wādī al Khāniq (W. Manqai)	stm	15°17′	45°18′	5
Wādī al Khārid	stm	16°07′	44°44′	2
Wādī Khayrah	stm	16°25′	44°05′	2
Wādī Khulab (SA)	stm	16°38′	42°44′	1
Wādī Lā`ah	stm	15°37′	43°19′	4
Wādī Laylān (SA)	stm	14°05′	45°55′	8
Wādī Liyyah (Y/S, SA)	stm	16°34′	42°55′	1
Wādī Ma`bar	stm	17°05′	43°15′	1
Wādī Madhāb	stm	16°27′	44°20′	2
Wādī Maksab	stm	13°18′	43°34′	7
Wādī Mansib	stm	15°37′	43°57′	4
Wādī Markhah (Y-S/A)	stm	14°59′	46°36′	6
Wādī Mawr	stm	15°41′	42°42′	4
Wādī Maydī	stm	16°21′	42°49′	1
Wādī Najrān (SA)	stm	17°33′	45°00′	2
Wādī Nakhlan	stm	13°47′	44°10′	7
Wādī Qa`if (W. Qu `ayf)	stm	17°00′	44°56′	2
Wādī al Qawl	stm	14°14′	45°55′	8
Wādī Qumāmah	stm	15°39′	43°52′	4
Wādī al Qūr (W. al Our)	stm	16°00′	43°06′	1
Wādī Quwah (Y-S/A)	stm	14°34′	46°06′	6
Wādī Raghwān (W. al Mukhaynia)	stm	15°46′	45°06′	5
Wādī Rasyān	stm	13°35′	43°17′	7
Wādī Rima`	stm	14°15′	43°05′	4
Wādī Rumman (W. Roman)	stm	15°32′	43°39′	4
Wādī Salab	stm	15°39′	43°52′	4

BGN (report) name[1]	Feature description	Coordinates N lat	Coordinates E long	Sheet No. (app. II)
Wādī Sam`	stm	15°33′	43°28′	4
Wādī Saram	stm	13°24′	44°12′	7
Wādī Shamera (W. Shamera Dabbah)	stm	13°32′	44°23′	7
Wādī Sharas	stm	15°51′	43°40′	4
Wādī Shebe	stm	15°22′	42°58′	4
Wādī Shuqbān	stm	16°32′	45°15′	2
Wādī Silbah (W. Silba)	stm	16°58′	45°01′	2
Wādī Sihām	stm	14°42′	42°58′	4
Wādī as Sirr	stm	15°34′	44°17′	5
Wādī Şubr	stm	17°02′	43°40′	1
Wādī as Sudd (W. Saba)	stm	15°26′	45°21′	5
Wādī Suḩūl	stm	14°13′	43°58′	7
Wādī Surdūd	stm	15°10′	42°52′	4
Wādī Suwayhirah (W. Suwarhira)	stm	13°49′	43°15′	7
Wādī Ta`ashshar (Y/S, SA)	stm	16°31′	42°44′	1
Wādī Tabāb	stm	15°27′	43°02′	4
Wādī Tānif	stm	13°45′	44°05′	7
Wādī Tis`ān (Y-S/A)	stm	13°36′	44°32′	7
Wādī Tuban (Y-S/A)	stm	13°07′	44°51′	7
Wādī Thu`bān (W. Tha`bān) (SA)	stm	17°25′	43°45′	1
Wādī `Ukayyān	stm	13°03′	44°05′	7
Wādī `Ulaysī	stm	15°24′	42°48′	4
Wādī Warazān (Y-S/A)	stm	13°26′	44°21′	7
Wādī Warū (W. Husayb)	stm	15°44′	43°25′	4
Wādī Yahir (W. Yislam)	stm	14°15′	44°53′	5
Wādī Zabīd	stm	14°07′	43°06′	7
Wādī Zaydān	stm	14°16′	44°53′	5
Wāsiţah	ppl	14°49′	44°17′	5
Yakhtul	ppl	13°27′	43°16′	7
Yarīm	ppl	14°18′	44°23′	5
Yemen (Sana)	pcli	15°00′	44°00′	8
Yemen Arab Republic (conv.)				
Al Yaman (Arabic short form)				
Al Jumhūriyah al Arabīyah al Yamanīyah (Arabic long form)				
Yemen (Aden)	pcli	14°00′	46°00′	8
People's Democratic Republic of Yemen (conv.)				
Al-Yaman (Arabic short form)				
Jumhūrīyat al Yaman ad Dīmuqrāţīyah ash Sha`bīyah (Arabic long form)				
*Yemen highlands	mts	15°25′	44°15′	5
Zabīd	ppl	14°12′	43°19′	7

[1] From Official Standard Names Gazetteer, Yemen Arab Republic, (U.S. Defense Mapping Agency, 1976) or map sources in accordance with the BGN/PCGN (Board on Geographic Names, U.S. and British governmental bodies) system.