ST/ESA/112

Natural Resources / Water Series No. 9

GROUND WATER IN THE EASTERN MEDITERRANEAN AND WESTERN ASIA

UNITED NATIONS

Via Wattman

1442

ST/ESA/112

Department of Technical Co-operation for Development

Natural Resources / Water Series No. 9

GROUND WATER IN THE EASTERN MEDITERRANEAN AND WESTERN ASIA

UNITED NATIONS
New York, 1982

NOTE

Symbols of United Nations documents are composed of capital letters combined with figures. Mention of such a symbol indicates a reference to a United Nations document.

ST/ESA/112

UNITED NATIONS PUBLICATION

Sales No. E.82.II.A.8

Price: $U.S. 17.00

FORWORD

The Economic and Social Council, by resolution 675 (XXV) of 2 May 1958, requested the Secretary-General to take appropriate measures for the establishment, within the Secretariat, of a centre to promote co-ordinated efforts for the development of water resources. It also singled out ground-water problems as one of the priority subjects in the development of a programme of studies. Large-scale Ground-water Development, published in 1960, 1/ was the first study prepared in this field by the Water Resources Development Centre (now the Water Resources Branch of the Division of Natural Resources and Energy, Department of Technical Co-operation for Development).

The Advisory Committee on the Application of Science and Technology to Development, in its World Plan of Action, 2/ gave priority to ground-water exploration and development. In fact, in the course of the First and Second United Nations Development Decades, more than 100 projects assisted by the United Nations Development Programme (UNDP) and other United Nations technical co-operation programmes were entirely or partially devoted to ground-water prospecting, assessment or pilot development. (A list of ground-water projects in the eastern Mediterranean and western Asia sponsored by UNDP is contained in the annex to the present report.)

While such operational activities were developing, the need for a comprehensive review of the results of the projects and for a dissemination of relevant information became more evident. As a result, the Economic and Social Council, by resolution 1761 B (LIV) of 18 May 1973, requested the Secretary-General to take the necessary measures, within the budgetary limitations, to improve and strengthen the existing United Nations services for the analysis, evaluation and dissemination of world-wide data on natural resources, including water resources.

With respect to ground water, a first comprehensive review of the African continent was published in 1972 and 1973 under the title Ground Water in Africa 3/ as a synthesis of material available in the records and files of the United Nations. The material of the second volume in this series, Ground Water in the Western Hemisphere, 4/ was drawn from country papers which were prepared by hydrogeologists and by ground-water engineers, specialists of the countries concerned. The material of the present volume (the third in the series), Ground Water in the Eastern Mediterranean and Western Asia, has also been drawn from

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1/ United Nations publication, Sales No. 60.II.B.3.

2/ United Nations publication, Sales No. E.71.II.A.18.

3/ United Nations publication, Sales No. E.71.II.A.16.

4/ United Nations publication, Sales No. E.76.II.A.5.

country papers prepared by ground-water specialists. Due to the abundance of interesting and specialized information obtained on a country basis and to the necessarily limited format of the publication, it has not been possible to present a broad overview of ground-water occurrence and development in the whole region, as was the case with part I of Ground Water in Africa.

It is hoped that the present publication, the first to provide a comprehensive view of the ground-water resources of the eastern Mediterranean and western Asia, will contribute to their development, especially in those areas where ground water is the only source of water supply and a key factor in economic and social development.

The United Nations wishes to acknowledge the valuable assistance provided by government organizations and by consultants and specialists who assisted in the preparation of the country papers, in particular W. R. Agha, M. Bergman, S. Bezirgan, R. L. de Jong, I. M. Elboushi, J. H. Johnson, J. Karanjac, J. Khoury, D. C. Kypris, A. A. Maleh, S. Mandel, S. Omar, A. A. Shata, A. Souresfil and M. Ubaid. The final draft was reviewed by Dr. P. E. La Moreaux, Professor of Geology at the University of Alabama, Tuscaloosa, United States of America, and President of the International Association of Hydrogeologist

CONTENTS

CONTENTS (continued)

LIST OF TABLES

CONTENTS (continued)

LIST OF TABLES (continued)

LIST OF FIGURES

LIST OF MAPS

LIST OF MAPS (continued)

Explanatory notes

The following symbols have been used in the tables throughout the report:

Three dots (...) indicate that data are not available or are not separately reported.

A blank indicates that the item is not applicable.

A full stop (.) is used to indicate decimals.

A slash (/) indicates a crop year or financial year, e.g., 1976/77.

Use of a hyphen (-) between dates representing years, e.g., 1975-1978, signifies the full period involved, including the beginning and end years.

Reference to "dollars" ($) indicates United States dollars.

Details and percentages in tables do not necessarily add to totals because of rounding.

The designations employed and the presentation of the material in this publication do not imply the expression of any opinion whatsoever on the part of the Secretariat of the United Nations concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries.

The term "country" as used in the text of this report also refers, as appropriate, to territories or areas.

INTRODUCTION

The region covered by the present publication is commonly referred to as the Middle East. Most of its boundaries are well defined (see map 1): to the north by the Black Sea, the southernmost ridges of the Caucasus Mountains and the Caspian Sea; to the west by the Aegean, the Mediterranean and the Red Seas; and to the outh by the Gulf of Aden and the Arabian Sea. Less well defined boundaries are to the west, across the Libyan desert and to the north-east and east of Iran.

The term "Middle East" does not express the fundamental character of the region in that its unique location is at the crossroads of three continents. It may be considered the fragile hinge of the eastern hemisphere, if not of the world. The cradle of monotheist religions, it is rich in culture and inhabited by a mosaic of peoples, with an eventful and turbulent history and an unstable political geography.

In the past 30 years or so, the region, which has always played a major role in world affairs, has gained a new importance owing in particular to the discovery of major oil deposits. It is estimated that two thirds of the known reserves of oil in the world are located in the region, which produced more than one fourth of the current world oil output in 1978. It is important to note, however, that most petroleum deposits are concentrated in a relatively small horseshoe-shaped area around the Persian Gulf and that only half of the countries of the region are oil producers.

Metallic ores have been mined in the region, but the deposits are not of international importance and do not give rise to significant ore exports, with the exception of chromium in Turkey and, to a lesser extent, copper in Cyprus, Iran and Turkey.

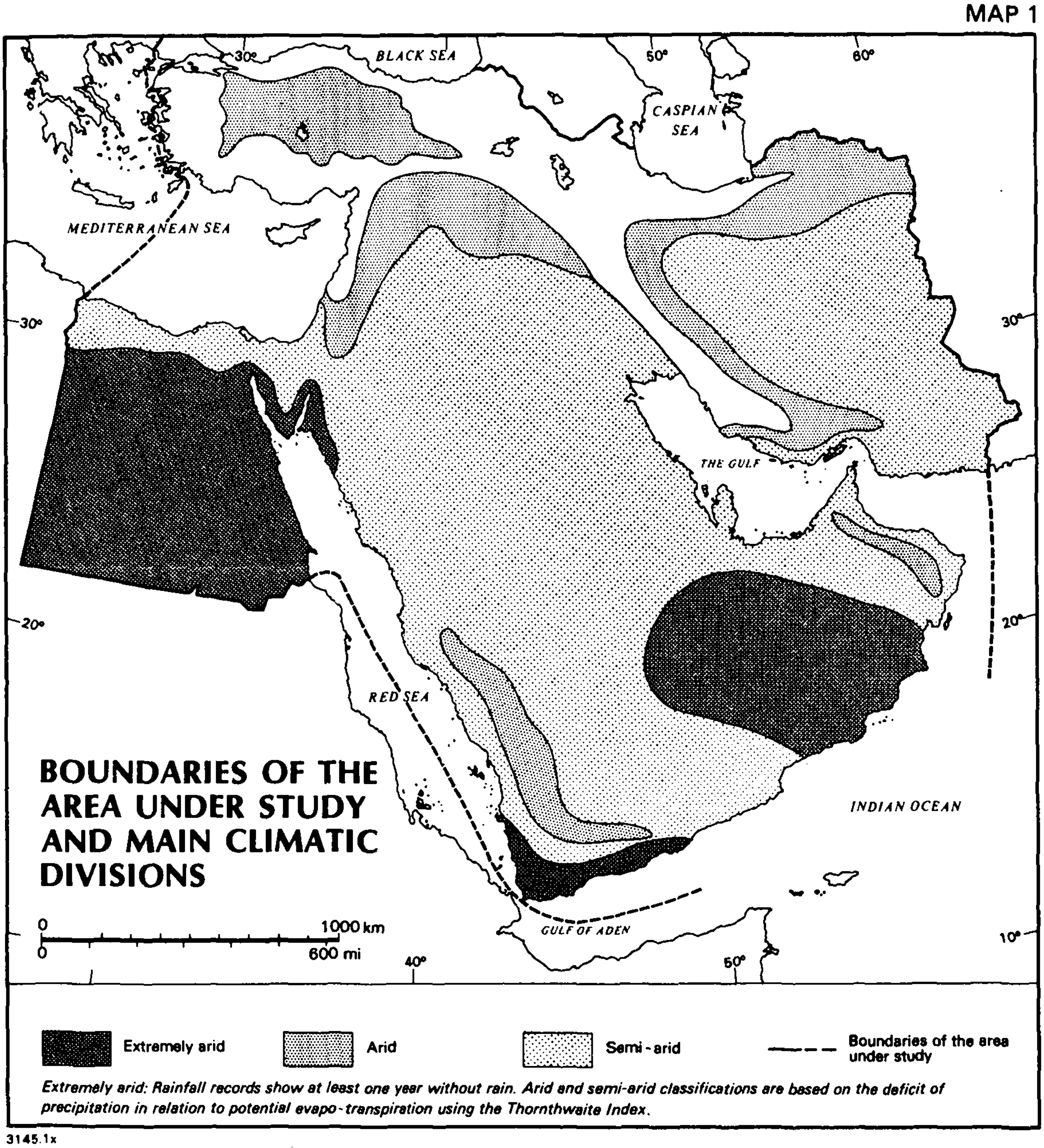
The vast majority (two thirds) of the population is engaged in agricultural or pastoral activities which are concentrated on 5 per cent of the land, mainly along the shores of the Mediterranean Sea, the Black Sea and the Caspian Sea, in the Nile valley, in Mesopotamia (the ancient civilization lying between the lower Tigris and the Euphrates rivers, now a part of Iraq), and in the highland areas of Turkey and Iran (see map 2). About 95 per cent of the land is part of the arid or desert zone (see map 1) and includes scattered oases.

One of the main agricultural areas of the region, known as the Fertile Crescent, stretches from the Nile delta along the shores of the eastern Mediterranean to the north and then to the east and the south-east through Mesopotamia to the northern end of the Persian Gulf. The Fertile Crescent itself is at the juncture of the three subregions of the Middle East: the platforms of Egypt and Arabia to the south, the plateaux bordered by folded mountains stretching to the north in Turkey and Iran, and the transition zone of the eastern Mediterranean countries, which corresponds to the central section of the Crescent.

Most of the land in Egypt, in the Arabian Peninsula northwards to the Euphrates River and in central and eastern Iran, is a desert, sparsely populated

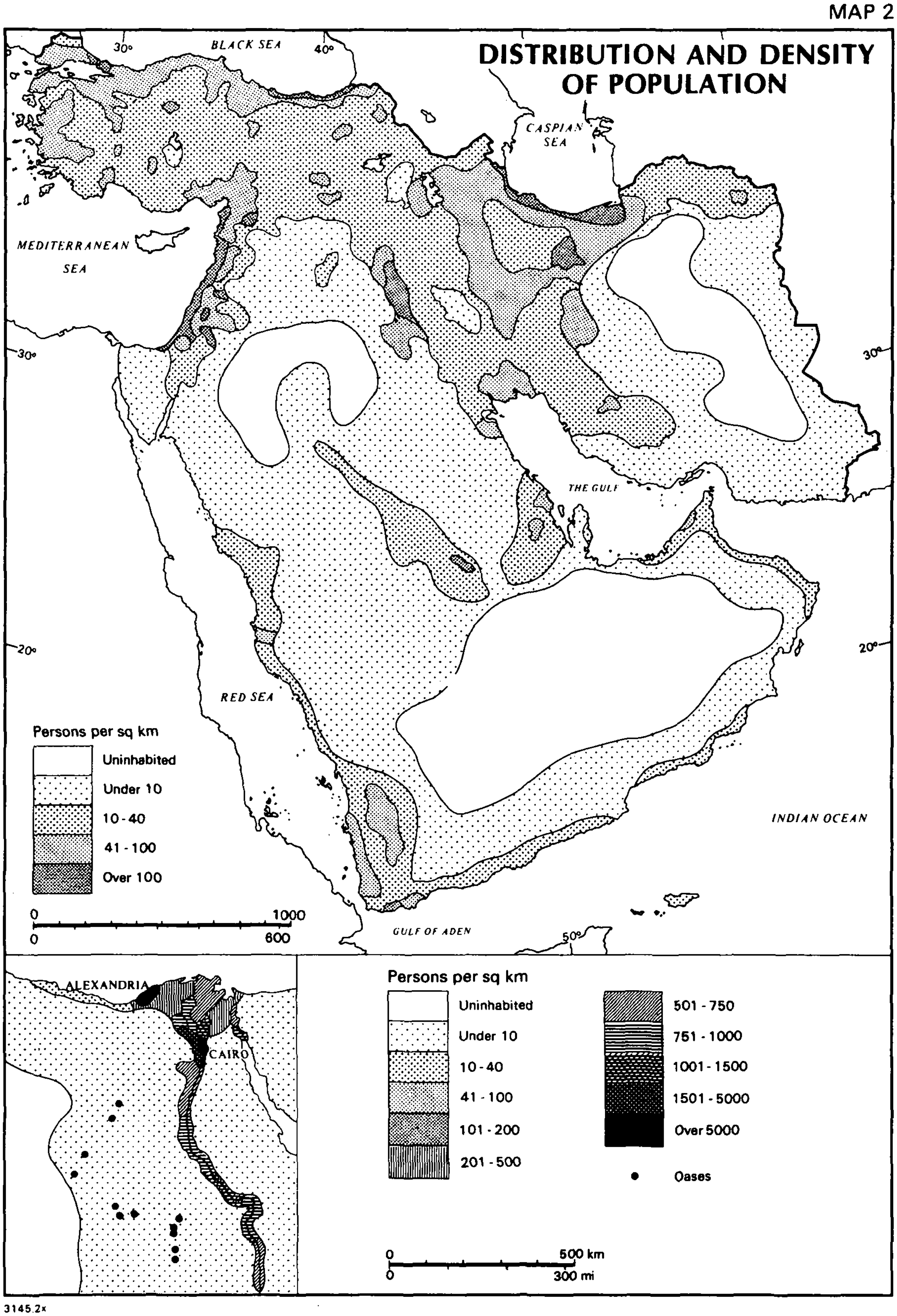
Map 1

Boundaries of the area under study and main climatic divisions



Map 2

Distribution and density of population



except in some mountain areas, valleys and oases. The total population is about 170 million, more than 55 per cent of which are Arabs. In the past 40 years, many movements of population have taken place, dramatically at times, which have affected millions of people; for instance, the movement of Jews to Israel and of Palestinians to various Arab countries, and the influx of manpower (including workers and professionals from countries outside the area, such as India, Pakistan and the Sudan) into oil-producing areas.

The development of industrial and urban areas, the need to increase agricultural production and, more generally, the over-all drive of the Governments and peoples of developing countries towards better socio-economic and living conditions, have resulted in a rapidly increasing demand for water, especially ground water, which is the only source of water supply in most of the region. In some countries, ground-water exploration and development, financed by the income from oil production have reached spectacular levels, but in many cases have proved costly.

A summary of the over-all natural conditions, that is, climate, morphology and geology, to which the occurrence of ground water is related, is given hereafter for the region, except for the desert areas of Egypt, the interior of the Arabian Peninsula and central and eastern Iran.

Climate

To the west, the climate is by and large of the Mediterranean type, with a rainy season in the winter and a dry season in the summer. Areas with the most rainfall are those facing the Black Sea and the Mediterranean Sea, the annual amount averaging 1-2/m. In the interior, rainfall is 250 mm or less (see map 3). Sharp contrasts in temperature on a daily or seasonal basis are experienced in many areas. Winters are cold in the mountains and the highlands of Turkey and Iran, but generally mild elsewhere. The Gulf area is extremely hot during the summer, with temperatures exceeding 40° C.

Physiography

Major relief features are shown in map 4.

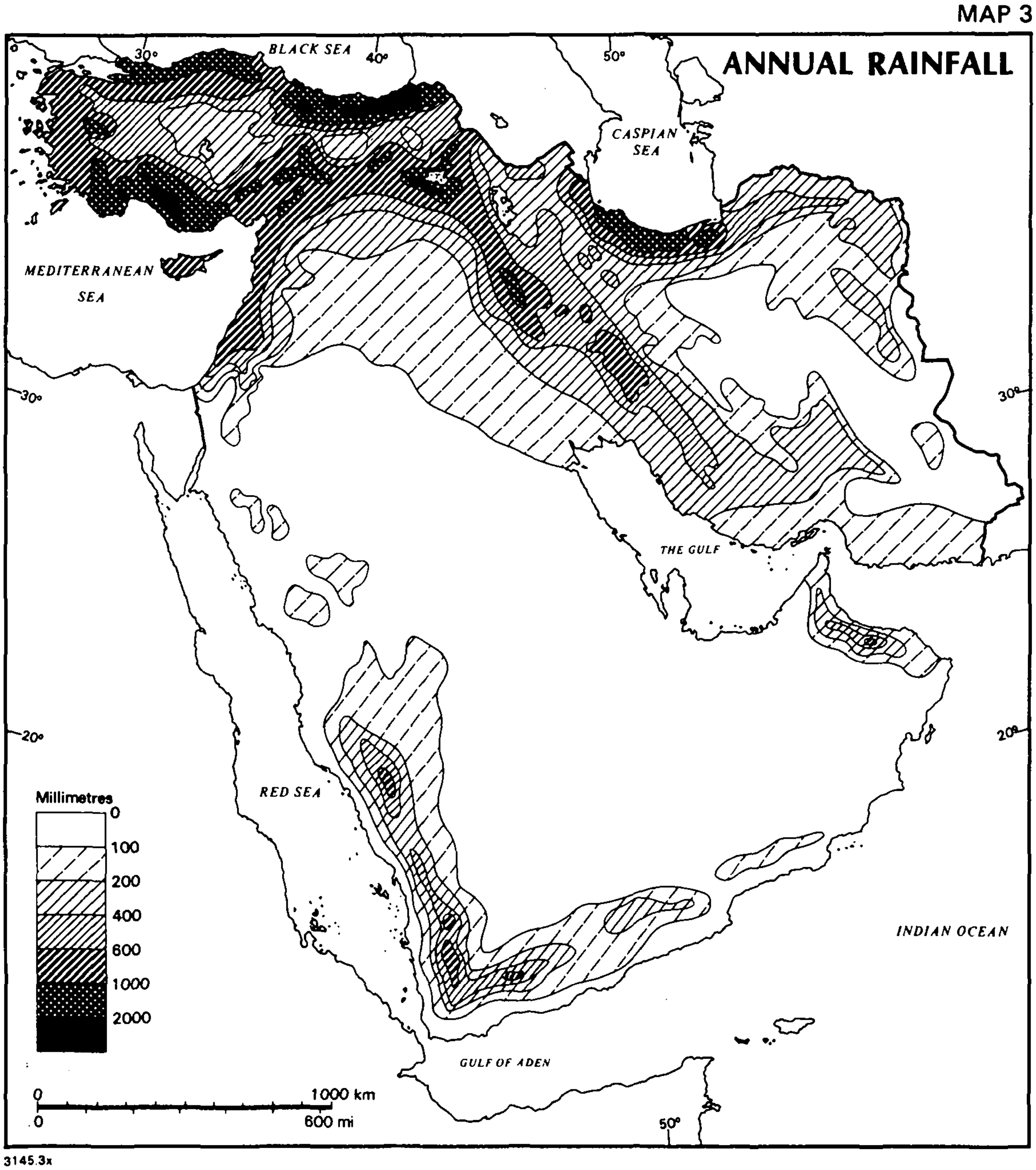
Based on the physiography and morphology, the area is divided into the following main units:

Mountains The Taurus mountains (3,700 m) and Pontine mountains (2,500 m to the west; up to 3,900 m to the east) in Turkey; the Alborz (up to 5,600 m) and Zagros (4,500 m) mountains in Iran; the ridges bordering the Red Sea in Egypt (up to 2,100 m); the Arabian Peninsula (2,500 m to the north near the Gulf of Aqaba; 3,200 m to the south, 2,500 m in the Hadramaw and 2,000 m in Oman) and the Lebanon mountains (3,000 m).

Plateaux are the morphological units prevailing in Turkey and Iran and the western part of the Arabian Peninsula. Most of these regions have little or no drainage to the sea. As a result, they contain a number of lakes, some of sizable proportions (in Turkey and Iran), sometimes with saline waters; in the arid desert areas of Iran, vast dry salt lakes can be observed.

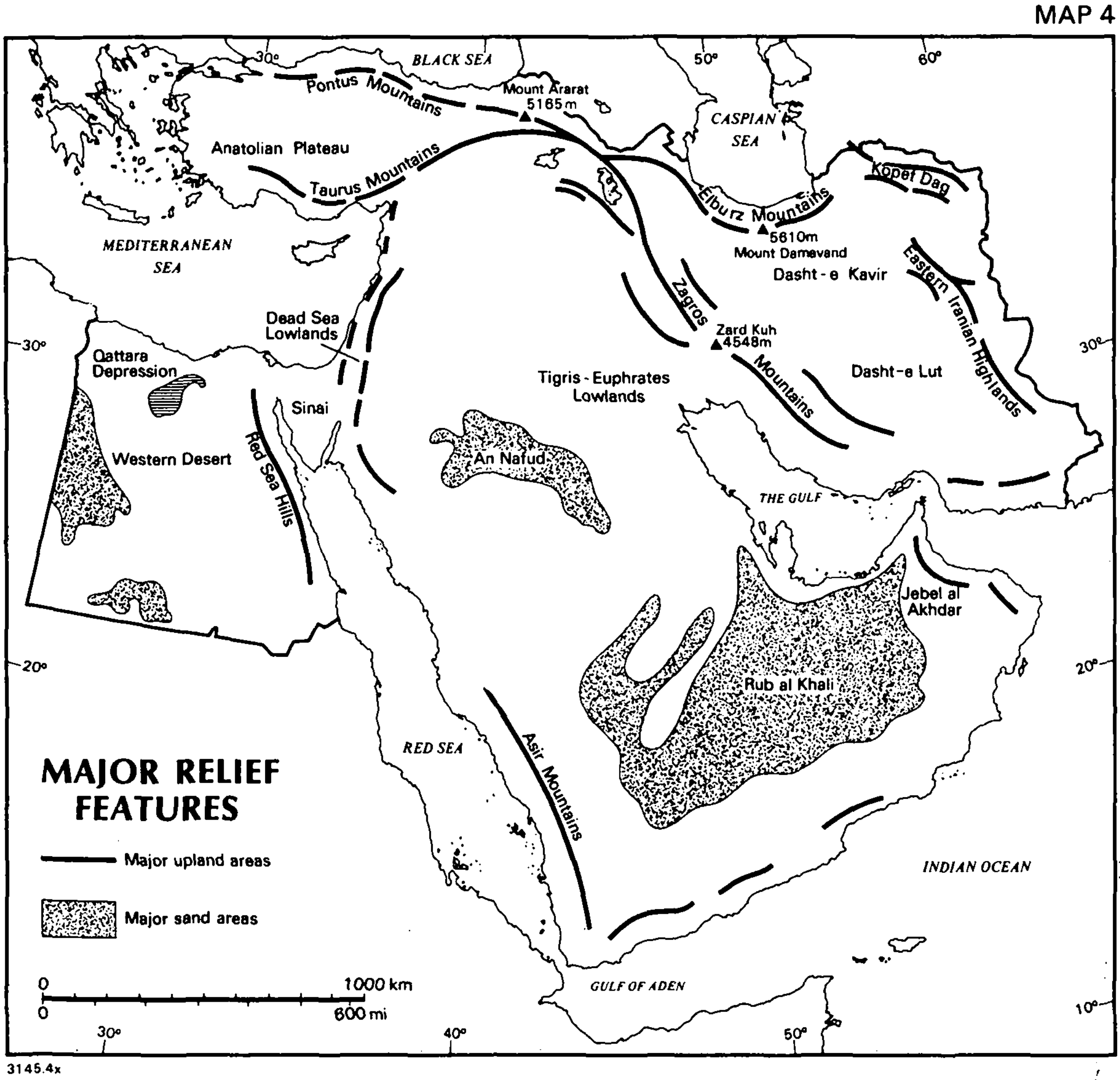
Map 3

Annual rainfall



Map 4

Major relief features



Plains The region includes two vast flat areas. In Egypt, the elevations decrease from 500 m in the south over a distance of nearly 1,000 km to the shores of the Mediterranean Sea, with depressions below sea level; and in the Arabian Peninsula, the elevations decrease from 1,000 m in the west (the mountain ranges parallel to the Red Sea) in an easterly direction through the An Nafud and the Ad Dahna to the Gulf, over distances of 400-600 km.

Shore-lines in general are rugged and dominated by cliffs. Main coastal plains are around the Caspian Sea and along the Gulf.

From the above general descriptions, it can be observed that with regard to climate, especially rainfall, and topography, (the mountain valleys and piedmont areas excepted), natural conditions are not favourable to the recharge of ground water by direct infiltration of rainfall or run-off for the following reasons:

(a) Direct infiltration of rainfall in flat areas under hot climates does not occur as water evaporates before it can infiltrate;

(b) Run-off occurs only during short periods; it is lost to the sea in coastal mountainous areas (Lebanon) or in saline depressions inland on the plateaux.

Geology

The geology of the area is shown in map 5.

In general, the main ground-water bearing formations are as follows:

(a) River alluvium in the Nile valley and delta, in the Tigris-Euphrates valley, in the Hadramaw valley and in various intermontane valleys, and in wadis of the Arabian Peninsula;

(b) Karstic Mesozoic limestones in the Mediterranean area (Turkey, the Syrian Arab Republic and Lebanon) and Iran;

(c) Extended and thick Mesozoic and Cenozoic sandstone aquifers in Egypt and the Arabian Peninsula. In the latter, a thick complex mass of sediments contains several aquifers, mostly confined, and sometimes wells flow at the surface when drilled.

The main problems experienced are those related to:

(a) The depletion of non-renewable ground water in artesian aquifers;

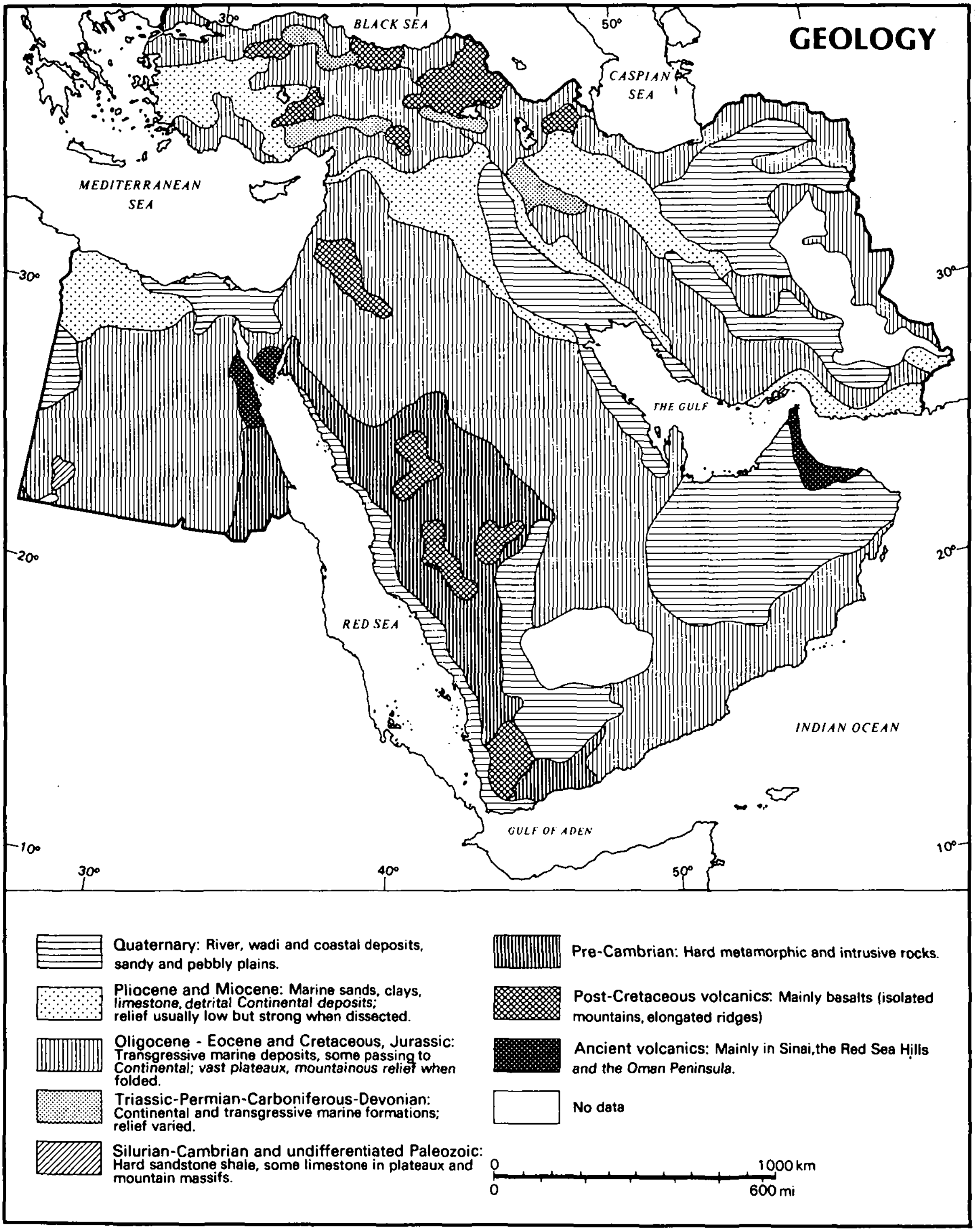
(b) The high dissolved solids of deep waters and shallow ground water in desert areas, including Mesopotamia; sea-water intrusion in coastal areas due to over-pumping;

(c) The irregular and low recharge in alluvium valleys and, in general, the disproportion existing between steadily increasing water needs and ground water availability.

Map 5

Geology

MAP 5



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For a time it was thought that desalinated water would help alleviate water shortages in some areas, especially the Gulf. Some large-scale desalination plants were built which used natural gas, the value of natural gas at that time being considered neglible. However, the cost of these large plants, their relatively short life, related high cost of amortization, and the value of exportable liquefied natural gas resulted in unit costs of desalinated water that precluded its use for irrigation.

Proper development and management of ground-water resources in this part of the world, more than in any other region appears, therefore, to be a matter of priority in socio-economic development, including the production of food and the improvement of living conditions, of a population that has strived for centuries, to survive against adverse natural conditions.

Area: 622 km^2

Population: 259,000 (United Nations estimate, 1976)

General

Bahrain comprises 33 islands the largest being Bahrain Island. The climate is hot and humid, with summer temperatures in September often rising to 45° and 50° C. Winter months are milder, with temperatures around 10°-20° C. Rainfall is irregular, occurring generally during the winter months of December and January. The average annual rainfall varies from 50 to 120 mm, though high-intensity convective storms can produce 60-70 mm of rain an hour. Due to its geographical location in the Gulf, Bahrain experiences a high relative humidity which often approaches 100 per cent. Evaporation averages 1.8-2 m per year. The prevailing Shamal winds from the north-west are diurnal, blowing at speeds up to 20 km/h. The hot humid Qaws blow from the south.

Bahrain's physiography has few distinctive features. An extensive relatively flat coastal plain rises imperceptibly to an elevation of about 60 m above mean sea level in the island's central southern area. Sabkhahs (depressed areas) are a feature of the coastal plain. They catch and evaporate much of the small surface-water run-off from the inland elevated areas by a poorly developed drainage system.

The first studies of the island's hydrogeology and the first recording of hydraulic and hydrochemical data were undertaken in the early 1940s by the Bahrain Petroleum Company (BAPCO). Data have been kept continuously since then and a gradual decline in water level and a deterioration in water quality have been recorded. In 1967 and 1971, extensive studies were carried out by engineering firms.

Bahrain's development of ground water dates from the remotest ages of antiquity when local inhabitants used the flow from springs to distribute the water either by surface canals or by underground aqueducts. Many of these springs and canals are now dry, as they probably were at the time of the first study in 1924. In 1953, BAPCO inventoried the island's 153 known springs and determined that 63 per cent had ceased to flow. In 1971, Italconsult inventoried the remaining 37 per cent and determined that 80 per cent of them had ceased flowing during the preceding 18 years.

Well-drilling began in the mid 1920s and accelerated during the 1940s to supply domestic and industrial water to make up for the loss of spring-flow and for new irrigation supplies. Drilling was generally continued through both the Alat and Khobar aquifers but, except for a casing collar, the holes were not cased. In 1971, more than 900 drilled wells existed. From 1971 until 1979, no further studies were made.

Geology

Bahrain Island is located on a structural dome on the crest of a north-south trending anticlinal structure. Strata dip away from the fold axis at an angle of 30 degrees. Important hydrogeological units overlie the Post-Cretaceous strata, as follows:

(a) Quaternary to Recent sands, sabkhah deposits, sandstones and foraminiferal limestones;

(b) The Neogene complex of chalky and detrital limestones, shales, grey marls, sandy limestones, silty sandstones, gypsum and chert;

(c) The Damman formation, composed of:

(i) The Alat limestone, consisting of porous, skeletal-detrital white to cream-coloured limestone which is commonly partly dolomitized;

(ii) A thin yellow and orange marl;

(iii) The Khobar limestone, which consists of porous, friable skeletal-detrital limestone and dolomitic limestone;

(iv) The Alveolina limestone, and Midra/Saila shale members;

(d) The Rus formation of hard limestone and dolomitic limestone which contains gypsum and anhydrite;

(e) The Umm er Radhuma formation composed of hard porous and vesicular skeletal and dolomitic limestone.

The deeper Cretaceous complex, the Wasia-Biyadh system, is oil-bearing.

Aquifers

On Bahrain, the aquifer system consists of the following:

System A: The Alat limestone;

System B: The Khobar limestone;

System C: The Umm er Radhuma formation with permeable sections of the Rus formation.

The Alat-Khobar aquifer is the most developed on Bahrain, as it also is in adjacent coastal Saudi Arabia. Owing to fracturing along the anticlinal axis, and te ineffective character of the separating confining bed, the strata possess hydraulic continuity. Their hydrology is difficult to interpret since both confined and unconfined conditions occur in the aquifer. It is believed that a hydraulic gradient in the range of 0.2 to 0.05 x 10^{-3}. This indicates a significant flattening from the average north-east trending mainland hydraulic grandient of 0.8 x 10^{-3}. The average piezometric elevation on southern Bahrain is 2-3 m above mean sea level, while in the northern part the water level attains an unconfined elevation of 6 m above sea level.

Geophysical logs in the Alat-Khobar aquifer show the Khobar strata to be highly porous and in places cavernous, with porosity ranging from 27 to 43 per cent. Pumping tests across both the Alat and Khobar indicate transmissivities in the range of 1.4×10^{-2} to 6.7×10^{-3} m^2/sec. Individual tests on the Khobar aquifer have given transmissivity results of 2×10^{-1} to 10^{-1} m^2/sec.

The Umm er Radhuma aquifer is not developed to any extent on Bahrain since the water is quite saline. As a result little is known of the piezometric surface. In a report prepared by Italconsult in 1971, however, it was indicated that the water-level elevation varies between 5 and 7.5 m above sea level. Transmissivity data are not available for Bahrain, but many pumping tests have been carried out in the mainland coastal zone which show transmissivity ranges from 6.4×10^{-1} to 7.5×10^{-2} m^2/sec for the Qatif Damman-Al Khobar area and 1.1×10^{-2} to 3.3×10^{-4} m^2/sec for the Hofuf area.

A source of water for Bahrain is flow through the aquifer from coastal Saudi Arabia. This flow is confirmed by the hydraulic gradients, the hydrochemistry and the absence of any known geological impediments to flow. Flow lines indicate that water moves towards Bahrain from the south-west with an average hydraulic gradient of 0.2×10^{-3} to 0.8×10^{-3}. Assuming an average transmissivity of 3.5×10^{-2} (averaged across the Khobar, the Alat and the Umm er Radhuma), it can be calculated than an average annual volume of water of about 140×10^6 m^3/year flows towards Bahrain. In 1971 it was estimated that Bahrain's overage usage ranged from 333×10^6 to 168×10^6 m^3/year.

Water quality

Water resources on Bahrain are complex mixtures resulting from contamination from an ancient high sea level, flushing by mainland open basin discharge or sulphate rich waters and recharge by local precipitation. As is the case with coastal Saudi Arabia, it is likely that the inland line of the main sabkhah belt was formerly a shore-line, and all waters down-gradient of this line are the result of ancient sea water being flushed by highly gypsiferous water. In parts of the island, a shallow aquifer, possibly analogous to a lens type of aquifer improves the pumped water quality owning to leakages. Table 1 shows selected hydrochemical analyses.

The total dissolved solids content covers a significant range, from about 300 to around 20,000 mg/l, the variation being the result of mixing of the main aquifer waters with recent fresh water. The recent fresh water has formed a shallow type of aquifer in response to coastal rainfall on the northern section of the island. Secondary aquifers such as this have formed in the Dhahran and northern Qatar regions, as the result of a particular coastal rainfall pattern and the formation of local high storage areas where storage has been enhanced by the formation of collapse structures resulting from dissolution of the Rus formation's gypsum and anhydrite with subsequent overburden collapse.

Table 1. Bahrain: selected hydrochemical analyses

(Parts per million, except where otherwise indicated)

Well	Total dissolved solids	Electrical conductivity (micro mho/cm)	Ca	Mg	Na + K	Cl	SO_4	HCO_3	pH
295 Difaz	1 841	3 460	212	53	360	670	360	186	8.0
1/C 20 Jurdah	2 590	4 740	244	86	611	1 100	370	179	8.3
24 Ras Rumman	3 076	4 760	284	72	875	1 350	449	184	7.1
1/C 95 Markh	3 366	5 970	433	135	582	1 130	910	176	8.2
HH-29 Ikur	3 574	6 540	281	131	888	1 700	370	204	8.1
36-Jau	4 889	9 050	309	106	1 432	2 590	300	152	8.1
454 Rifa Ash Sharq	6 003	10 840	405	176	1 710	3 190	370	152	8.1
1/C 16 Sanad	6 070	10 510	441	186	1 590	3 080	590	183	7.7
1/C 48 Alba	11 031	19 170	617	286	3 163	6 420	390	155	7.9
CWW 17 Refinery	16 975	...	714	273	3 771	7 308	589	225	7.6

Problems

Of most concern to Bahrain is the rapidly declining hydraulic head. At present, the Alat-Khobar aquifer's hydraulic head varies from 2 to 6 m above sea level; in 1971 it was falling at a yearly rate of 10 cm. The water-level decline appears to be linear, without any suggestion of approaching steady-state conditions. Associated with the declining hydraulic head has been a water-quality deterioration. Sea-water intrusion is noted around the island's perimeter and invasion from waters deep within the aquifer complex have been identified. While there is a good deal of controversy over the nature of the aquifer, it seems to behave as a lens type of aquifer supported by dense artesian water, with a total dissolved solids content probably as high as 60,000 mg/l.

Calculations based on a confined aquifer situation and the volumes of water pumped from coastal Saudi Arabia and Bahrain indicate that pumping interference, as much as 100 m or more, should have occurred on Bahrain. The actual draw-down, based on the best water-level evidence available, is about 3.5-4 m. At present, investigations are in progress in an endeavour to clarify the situation and to quantify the resource. If it is proved that the water-level decline is more symptomatic of a regional situation, Bahrain may be faced with the prospect of importing water.

Selected references

Food and Agriculture Organization of the United Nations. Survey and evaluation of available data on shared water resources in the Gulf States and the Arabian Peninsula. Rome, 1979.

Itaconsult. Water and agricultural studies in Bahrain. Unpublished report. 1971.

Wright, E.P. Report on the groundwater resources of Bahrain. Unpublished report. 1967.

CYPRUS

Area: 9,270 km^2

Population: 630,000 (1973 census)

Main Geographical Features

The dominant geographical features of the island are two mountain ranges: the Pendadactylos along the north coast, with the summit at 1,024 m (Kyparissovouno); and the Troodos, occupying almost the central part of the island, with the summit at 1,951 m (Mount Olympus). The Mesaoria plain, extends between the two mountain ranges with the city of Nicosia, capital of Cyprus, situated at about 180 m above mean sea level.

Since the mountains are high in relation to the size of the country, the topography offers sharp contrasts, relatively steep slopes forming narrow steep-sided valleys which restrict the coastal plains to narrow strips of irregular width. As there are no big rivers discharging large amounts of sediment into the sea, the coastal waters are clear. The shores are rocky where the hilly ground reaches the sea, but extensive sandy beaches are to be found in wind-protected bays.

Climate

Cyprus, lying in the eastern Mediterranean, has an intense Mediterranean climate, with mild rainy winters from November to February. Dry hot summers occur from June to August. Spring and autumn are short and transitional with intermediate conditions.

About 90 per cent of the rainfall in Cyprus, which averages about 500 mm, falls between November and March; nearly 50 per cent of that amount falls during December and January.

Owing to the rugged terrain, rainfall is quite unevenly distributed. In some low-lying areas rainfall on the average is less than 300 mm a year, while in the highest parts of the Troodos Mountains it exceeds 1 m a year, some of the precipitation falling as snow during the winter months.

The prevailing winds differ for different months. In general, from December to February they are south-west and west to north-west; from March to May they are west and north-west to north and north-east; from June to August they are west and north-west to north; and for the period September to November they are north-west and north to north-east. The winds rarely reach gale force.

The local winds are also very important, originating either from the orography of the island (anabatic and katabatic winds) or from local heating effects (sea and land breezes).

Mean evaporation rates, as measured from evaporation pans, range from about 1,200 mm per year in higher places on the Troodos Mountains to about 2,000 mm down on the central plains, with intermediate values along the coasts.

Surface water

River systems are numerous with high gradients and relatively small catchment areas. The most important rivers originate in the Troodos Mountains. The composition of the mountains (mainly igneous rocks) and the fact that they receive a relatively large amount of rainfall are conditions favourable to the presence of rivers. Most of these rivers would normally be perennial, but as a result of the upstream use of their base flow for irrigation purposes they are perennial in their upper reaches only.

The average run-off of the 17 most important rivers rising in the Troodos Mountains, which corresponds to an overall run-off coefficient totalling some 400 million m^3/year, was calculated by means of a calibrated mathematical model. The weighted average run-off coefficient was found to be around 23 per cent. The approximate average monthly distribution of the flow of those rivers and the monthly distribution of the average flow in two extreme cases are shown as percentages of the total flow in table 2.

Table 2. Cyprus: approximate monthly distribution of flow for the most important rivers originating in the Troodos Mountains

(Percentage)

	October	November	December	January	February	March	April	May	June	July	August	September
Approximate average for 17 rivers	1.5	2.0	14.0	22.0	24.0	16.0	8.0	5.0	3.0	2.0	1.5	1.5
Xeropotamos River	1.0	1.9	15.3	26.5	27.5	15.4	5.6	2.8	2.2	0.8	0.6	0.5
Karyotis River	3.1	3.3	10.8	16.4	18.3	14.3	9.7	7.5	5.4	4.4	3.7	3.1

As far as the peak flows are concerned, information on the most remarkable flood that occurred in selected rivers is set out below. (An analysis of the rainfall that occurred in the catchment of each river to produce such results cannot be presented here.)

Table 3. Cyprus: peak flows for the largest flood on record

River	Gauging Station	Catchment (km^2)	Peak Discharge (m^3/sec)	Date
Kourris	Khalassa	293	390	26.12.68
Dhiarizos	Kouklia	264	300	26.12.68
Yermasoyia	Phinikaria	110	290	26.12.68
Serrachis	Morphou Dam	457	260	26.12.68
Stavros	Evretou	93	250	12.10.65
Vathis	Athalassa	30	160	30.12.69

The silt content in river water is highly variable; it depends on a number of factors which cannot be detemined even within a reasonable margin of accuracy. The study that was made of the results of the sediment content analysis of samples obtained from various rivers at different stages and flows did not yield any useful conclusions. However, by studying the rate of silting up of the existing reservoirs, one could obtain some figures which would indicate the approximate order of magnitude of the suspended solids content. For example, for the rivers originating from igneous rocks with smooth slopes and good vegetative cover, an average of 3 grams of suspended solids per litre of run-off water would be considered a reasonable estimate. For rivers draining igneous rocks having a steeper relief and sparse vegetative cover, the suspended solids content might be 15 grams per litre. Since the silt content of the run-off originating from sedimentary rocks is much higher, it would have to be calculated to be about 40 grams per litre.

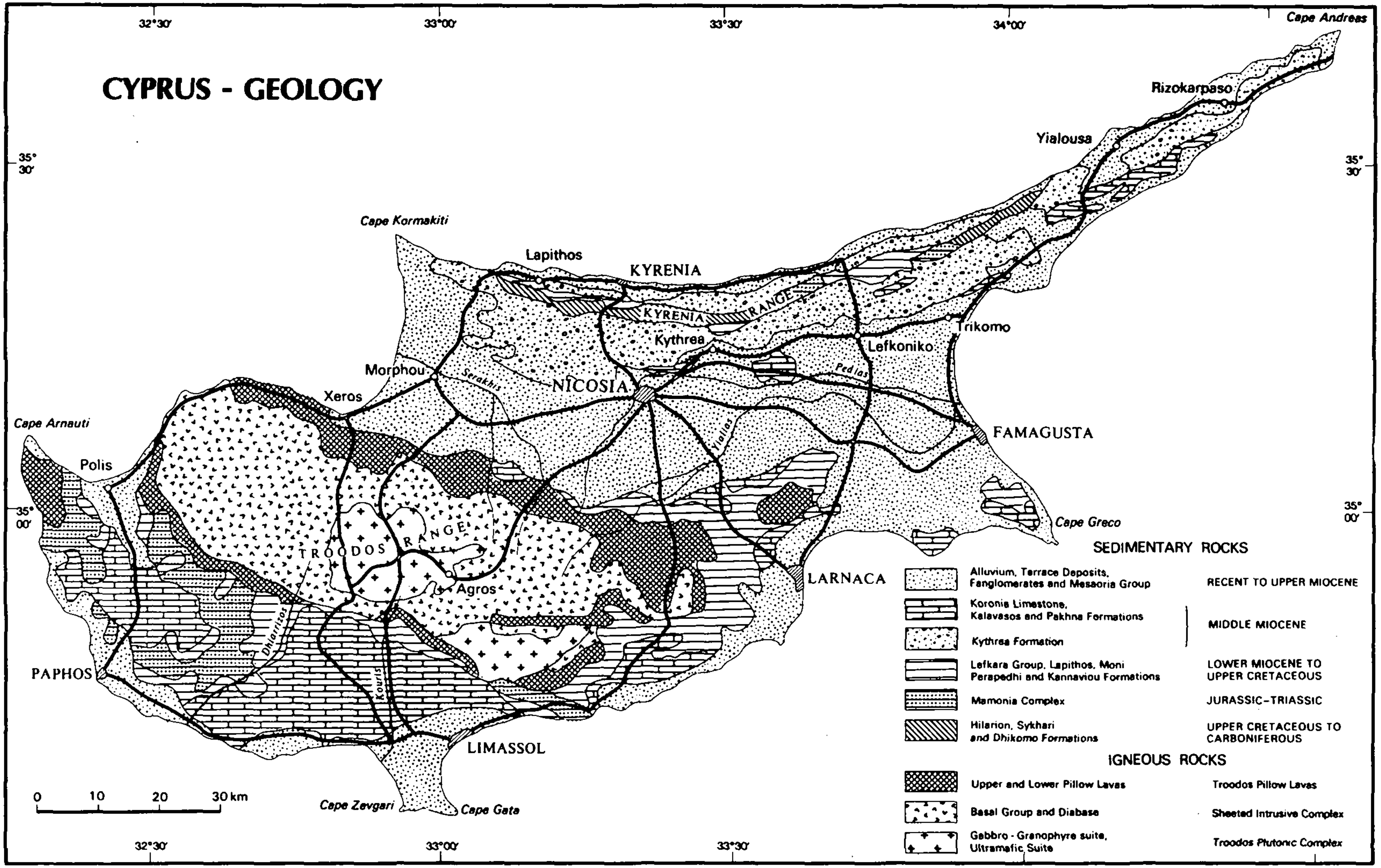
Geology

The geology of Cyprus (see map 6) is dominated by the Troodos massif, an ingeous complex occupying about one third of the island and composed of ultrabasic plutonics and extrusives of related composition, all arranged in a pattern of concentric rings.

The core of the complex is composed of dunite grading outwards to various types of peridotites and their serpentinized forms, encircled by a ring of gabroic rocks. A larger ring surrounding the above structure is called the sheeted

Map 6 Cyprus: geology

MAP 6



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intrusive complex and is composed of a series of dykes which have developed together in such a way that one is packed on the other. Their width generally ranges from 0.3 to 3 m having mostly an approximate north-south strike with steep dips to both east and west. Their composition is mainly microgobbros and microdiorites.

The outer ring of the complex is occupied by lavas, which have been extruded below the sea at two main stages and have formed what are called lower pillow lavas and upper pillow lavas. Sparse intercalations of shales and umbers found in the lavas have been identified as Campanian in age.

Although the above-mentioned ring structure is true in general for the Troodos igneous complex, the southern hills of the igneous massif are separated from the main mass by large faults trending east-west. Since their composition is to a great extend peridotitic and gabroic, they mark a departure from the general ring pattern.

Carbonated components prevail in the sedimentary rocks which occupy about two thirds of the island. The oldest sediments are the micaceous marbles, brecciated dolomitic limestones, and recrystallized limestone and marble, ranging in age from Carboniferous to Cretaceous, which compose the core of the northern range of the island, where they were emplaced and uplifted during the last facies of Alpine orogeny. The relation of these strata to other formations is complex and most geologists characterize them as allochtonous thrust plates and olistholiths. It is worthy to note, however, that these marbles and limestones are karstified well below the present water level in the area.

Another category of sediment which is considered allochtonous, is the Mamonia complex, the main outcrops of which occur in western Cyprus, while some exposures have been noted to the south-eastern part of the island. They are composed of bentonitic clays enclosing huge blocks of limestone, serpentine and quartzitic sandstone. They are characterized by erratic distribution and variations in thickness due to sedimentation on a buried relief.

The deposits that occurred from the Maestrichtian to the Lower Miocene are chalk (cherty in places) marl and limestone, but chalk predominates. Strata, having a thickness of as much as 600 m, crop out around the Troodos Mountains, dipping radially away from the igneous massif. Similar strata have been located along the Kyrenia range, highly deformed and structurally complicated because of the pressure that was exerted by the upthrust of this northern range. Some appearances of breccia, conglomerate and flysch of Oligocene to Eocene age, having a thickness calculated to be about 700 m are considered closely related to chalk in this area.

During the Middle Miocene, a rapid uplift of the northern range, together with a continuing process of deposition on the steep slopes plunging into the sea on either side of the Kyrenia range, was the main reason for the turbidity currents, which deposited the flysch, composed of interchanging layers for 3,000 m of greywacke, marl and calcareous sandstone. These beds are very tightly folded against the northern range, in the vicinity of which they restrict their appearance. At the same time, around the Troodos Mountains and most extensively on the southern part of the island, a series of chalks, marls and fine sandstones was deposited, characterized by abrupt facies variations and a maximum thickness of

450 m, dipping gently away from the Troodos massif. Very closely associated with this sedimentation is the deposition of gypsum in many areas of the island. A contemporaneous facies is also the development of reef limestones. Upper Miocene and Lower Pleistocene deposits are represented by beds composed mainly of marls and sandy marls, occasionally enclosing sandstones and conglomerates. In most areas the last stage of development of these beds formed calcarenites deposited in shallow water.

The main place where these beds developed, is a down-warped trough lying between the Kyrenia range and the Troodos Mountains forming the central lowland of the island, known as the Mesaoria plain. The greatest thickness of this deposit has been estimated for the centre of the basin to be about 800 m.

A rapid uplift of the island, or regression of the sea, in Pleistocene time resulted in the intensive weathering of the land into sand and gravel, which were spread by the rivers descending the Troodos Mountains, particularly to the north of the igneous massif, forming "fanglomerate" piedmont types of deposits. These, as has been said, consist of coarse material, part of which has been deposited under shore-line conditions and part as terrestrial deposits interfingering with the others. At their maximum development in western Mesaoria, they attain a thickness of about 60 m.

Ground-water resources

The development of the ground-water resources in Cyprus is the responsibility of the Water Development Department (under the Ministry of Agriculture and Natural Resources) which is responsible for the development of the water resources of the entire island. Another department connected with the development of ground water is the Geological Survey Department, which has a section that carries out hydrogeological surveys and drilling operations for ground-water exploration.

The development of the ground-water resources of the island has been a necessity since Roman times because there are few springs. In ancient times, underground drains, known locally as a chain of wells, were dug. These drains, consisting of a series of wells connected to a gallery, were planned with a low gradient so that the water could flow freely to the surface as the tunnel emerged from the ground. (These chains of wells are also to be found in Iran, where they are known as kanats.)

The digging of wells, from which water is withdrawn in buckets, has been a well-known art in Cyprus since ancient times. In those times also, the development of the system by means of which water is withdrawn using a chain of buckets (alakati) operated by animal power gave an impetus to the digging of more wells, the additional water being used to irrigate the land.

The real interest in the development of ground water came about in the 1940s, when the British authorities established the Water Supply and Irrigation Department and extended the drilling operations which had been carried out previously on a small scale by the Public Works Department.

The collection of systematic data and the study of ground water started in 1954, when the Water Supply and Irrigation Department was replaced by a Water Development Department, incorporating a new division called the Water Resources

Division whose responsibilities included the collection and evaluation of ground-water data. Ground-water surveys were believed necessary because in a number of places where the exploitation of ground water was intensive, ground-water levels had declined considerably and in coastal areas were even below sea level. Since then ground-water resources have been monitored for changes in water level and quality through specially drilled observation bore-holes as well as through a number of pumped bore-holes during periods when the wells were not being pumped.

The collection of data is carried out by technical assistants who are specially trained in the Department for that task. The preliminary processing and preparation of the hydrological maps is carried out by Inspectors of Work. The evaluation of the results and further processing to obtain water balances, or draw conclusions about the trends in the aquifers, is undertaken by professional geologists and hydrologists by means of mathematical modelling and digital computer operations.

The most usual methods applied involve geology, as far as prospecting for ground water and locating test wells are concerned. Geophysical methods, however, have also been used. For the location of a test well in the deepest part of a buried river valley, the seismic refraction method was applied. By means of the electrical resistivity method, layers of sand and gravel in marls have been located and the thickness of gravel deposits determined.

Most of the aquifers on the island have been entensively drilled and exploited. About 45,000 wells and bore-holes have been registered in the areas where the most important aquifers occur. Information about the main aquifers in Cyprus is presented in table 4.

Besides the main aquifers, there are many minor ones, either extending along the coasts or inland, scattered all over the island.

Most of the aquifers are over-exploited and in regard to the aquifers of western Mesaoria, south-eastern Mesaoria and Akrotiri, sea-water intrusion has occurred to the point that extensive plantations have been destroyed because of salination of the aquifer water.

The water in the main aquifers referred to in table 4 is considered good, with a total dissolved solids (TDS) content of 500-1,000 ppm. However, in the zones of sea intrusion and some isolated spots high salinity waters may occur. In some small aquifers inland, water with a TDS content between 1,000 and 3,000 ppm is quite common. In a number of gypsum aquifers the chloride content is low while the sulphate content is high.

The development of ground water followed the development of spring water, this being the second most economical source of water. The development of surface water received attention when the possibilities for the further development of ground-water resources became limited. The steep topography in Cyprus renders waterworks for developing surface water for perennial use quite expensive. While about 300 million m^3 of ground water are used throughout the year, the amount of perennial river water used is only about 30 million m^3. After flash floods, however, a large amount of river water is used for irrigation.

Table 4. Cyprus: information on principal aquifers

Name and location	Age	Lithology	Average depth of wells (m)	Specific capacity (l/sec/m/of draw-down)	Hydrogeological parameters K (m/day)	Hydrogeological parameters T (m^2/day)
Kyrenia limestone (along the northern range)	Carboniferous to Cretaceous	Karstified limestone, dolomite and marble	150-300 (Maximum drilled, 450 m)	1-100	...	...
South-Eastern Mesaoria (south-east Cyprus)	Upper Miocene to Recent	Calcareous sandstone intercalated with marl; in some locations reef limestone and gypsum	30-100 (some wells up to 200 m)	0.5-5	2-15	10-150
Western Mesaoria (western part of the plain between the two mountain ranges)	Pliocene-Pleistocene	Calcarenite, gravel, marl, sand, silt	50-100 (some wells 200 m or more)	3-15	2-20	100-1 000
Akrotiri (southern Cyprus)	Pleiocene-Pleistocene	Gravel, sand and clay lenses	20-60	2-20	5-50	100-3 000
River gravels (in valleys around the Troodos Mountains)	Mostly Recent	Gravel, sand, silt	15-50	1-100	5-50	300-4 000

Note: K = hydraulic conductivity or permeability.
T = transmissivity.

Ground-water development

Ground-water development through dug wells was given a serious impetus when the first drilling rigs were imported by the Government and operated as a part of the government service for drilling bore-holes for water, at first for both private individuals and government waterworks, but later for government projects only. Various drilling rigs owned by the Government are in operation. Twelve percussion drilling rigs, two rotary drilling rigs and one "down-the-hole hammer" rig are used for water. The drillers operating these rigs are well trained technicians with long experience, supervised by geologists and a mechanical engineer. In the private sector, the number of rigs drilling for water varies since some of those rigs may be engaged from time to time in contracts outside Cyprus. About 60 privately owned drilling rigs are in operation in Cyprus. One is a "down-the-hole hammer" rig and the remainder are of the percussion type.

The cumulative amount of drilling of bore-holes each year by government-owned rigs is about 15,000 m. An accurate estimate of the amount drilled by the private sector is very difficult to determine, but about 150,000 m per year would be considered reasonable.

Most of the water pumped from bore-holes and wells is used for irrigation. Of no less importance, however, is the use of ground water for community water supplies. For instance, Nicosia, the capital of Cyprus, draws 7 million m^3 of its water supply each year from bore-holes. The town of Limassol uses 5.5 million m^3 of water a year, 4 million m^3 of which come from bore-holes and 1.5 million m^3 from springs. The town of Paphos uses 1.5 million m^3 of water a year from bore-holes and the town of Larnaca uses 1 million m^3 a year from bore-holes and a further million from surface-treated water. Rural areas obtain most of their drinking-water supplies from bore-holes and the rest from springs. The use of water by sector and the contribution of ground water are shown in table 5.

Table 5. Cyprus: annual use of water

Sector	Water use (millions of m^3/year)	Ground water contribution (percentage)	Remarks
Agriculture	300	80	Irrigation of about 12 per cent of cultivated land
Domestic water supply	30	90	The rest is supplied by treating surface reservoir (spring water is considered ground water)
Industry	10	100	Main consumer's the mining industry

In Cyprus, water is the most important factor affecting development. Unfortunately, only about 12 per cent of the cultivated land is at present under perennial irrigation; the rest depends on rainfall. Every effort is being made by the Government to increase the water available for perennial use. The search for additional sources of ground water in new areas continues, and progress is being made in the design and construction of dams to store river water. Systems have also been worked out by optimization methods for the joint use of surface and ground water. However, a 50 per cent increase in the water supply, economically available at today's prices, would have excellent results. It should be noted that the main increase is expected to be in respect of surface water, the development of which is quite expensive compared with international standards, owing to the high relief prevailing in the country. Another source of water may be desalination plants. However, various studies undertaken indicate that desalination of sea water is still very expensive and is therefore not expected to have widespread application in the near future.

Conclusion

At present, about 80 per cent of the perennial water supply of the island comes from ground-water sources. Thus, the economic and social value of ground water is evident. Perennial surface water is expensive to develop owing to the topography of the country. For instance, the cost of ground water is about 5-25 Cyprus mils per cubic metre, while the cost of impounded water in surface reservoir distributed to the field, ranges from 19 to 56 Cyprus mils per cubic metre. The cost of desalted water is considered prohibitive at present.

As a result, ground-water development has taken place at an accelerating pace over the years with adverse effects on the environment in certain areas especially as regards sea-water intrusion and overpumping.

Selected references

Burdon, D. J. Groundwater in the Island of Cyprus. International Association of Scientific Hydrology. Publication No. 37. 1953.

Dixey, F. Recommended water boring sites in the Vasilikos-Tremithios area, Cyprus, Department of Water Development. Unpublished report. Nicosia, 1967.

Fink, M. Preliminary Report on the Hydrogeology of Akrotiri Peninsula, United Nations Special Fund Project. TAHAL (Water Planning) Ltd., Tel Aviv. Publication No. 473. 1975.

__________. Report on the Hydrogeology of the South-Eastern Mesaoria, United Nations Special Fund Project. TAHAL (Water Planning) Ltd., Tel Aviv. Publications Nos. 693 and 693A. 1967.

Grehan, M. Water Resources of Cyprus, Department of Water Development. Nicosia, 1958.

Hji Stavrinou, Y. Groundwater Resoruces of the Karstic Regions of Cyprus, Department of Water Development, Nicosia, 1963.

__________. Some Notes on Deep Drilling for Water in Cyprus, Geological Survey Department, Nicosia, 1964.

Lytras, S. The geology and hydroloy of the Avlona-Yerolakkos area, Cyprus, with a summary of the general geology and hydrology of the island. Unpublished M.Sc. thesis. London, 1964.

Mixius, F. K. and Kreysing. Hydrogeological Investigations and Groundwater Development in the Kyrenia Range of Cyprus, Bundesanstalt fuer Bodenforschung, Hannover, Federal Republic of Germany, 1965.

TAHAL Consulting Engineers Ltd. Interim Assessment of the Water Resources of the Island of Cyprus. Publication No. 682A. Tel Aviv, 1967.

Ward, I. L., D. P. McGregor and M. Grehan. Hydrology and Water Development in Cyprus. Institute of Civil Engineering, London. Paper No. 6256, 1958, pp. 233-280.

Area: 287,683 km^2

Population: 1,633,000

General

Democratic Yemen occupies the southern part of the Arabian Peninsula. The main physiographical units are a narrow coastal plain where most of the population is concentrated, a mountain ridge parallel to the coast and a vast desert plateau inland, deeply incised by the Hadramawt valleys.

The most densely populated areas are the coastal regions and the valley of wadi Hadramawt. The deltas of the coastal wadis are the arable lands. They receive flood waters from the catchment areas in the interior, which are mostly diverted to the fields before they reach the sea. These wadis are named: Tiban, Bana, Hassan, Ahwar, Maifa'a and Hajr (see map 7).

In the interior, there are several agricultural areas which wholly or partially depend on ground water; the most important are wadi Hadramawt, wadi Beihan, Nisab and its surrounding wadis, and wadis surrounding Lawder and Dathinah. These plateau lands vary in height between 650 and 1,200 m.

The highest peaks are Laboos (3,700 m) and Mukairas (2,600 m). The hills are mostly barren or have shrubs growing along their saddles. In the far north and north-east the desert extends through the Rub al Khali and the borders of Saudi Arabia, where only nomads are to be found. The area cultivated does not exceed 1 per cent of the whole area.

Climate

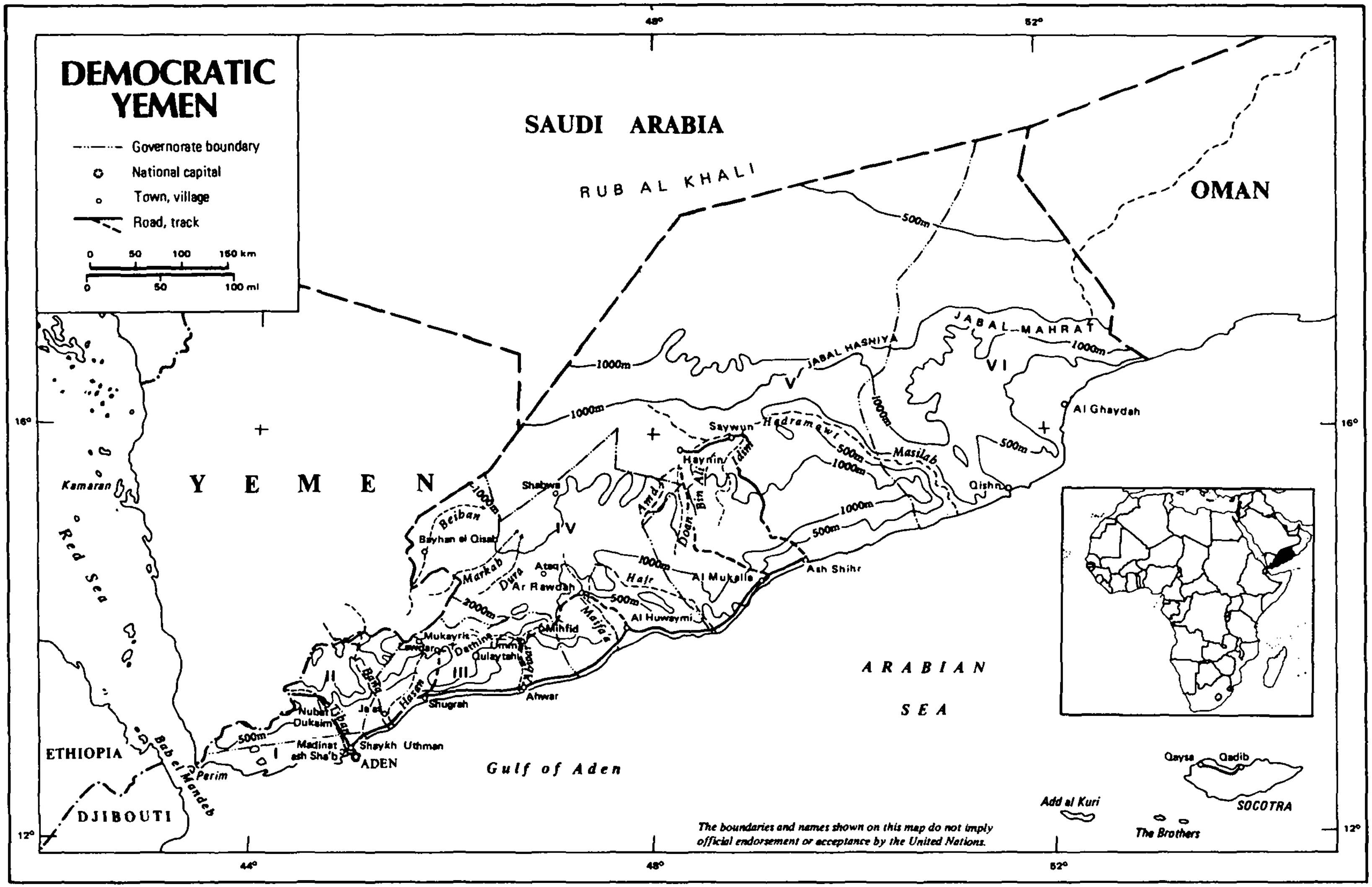
In the highlands over 2,000 m, the yearly rainfall may be as much as 600 mm (for example, Taiz, 610 mm; Malaki, 515 mm). Between 1,500 and 1,800 m (Dhala and Mukairas), the rainfall averages 180-220 mm. The coastal areas receive less than 50 mm rainfall. The rainy period is the summer monsoon (April to August). The rains are of short duration, not exceeding two to four hours and occur mostly in the afternoons. During winter, rains last longer but are not intensive.

The temperature also varies according to altitude. In the coastal areas it varies between 20° C and 45° C; in the interior, around Mukairas and Laboos, it might drop to 3° C. The differences between night and day temperatures might be as much as 20°-30° C.

The potential evaporation ratio is about 4 m. Most measurements were taken using a Penman evaporation pan. The minimum was 2,400 mm, at Elkod Station in 1965. The maximum values were recorded during the period April to July.

Democratic Yemen has no perennial rivers. The dry river beds of wadis convey floods of short duration (two to four hours) towards the sea or towards the desert

MAP 7



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AUGUST 1981

Map 7
Democratic Yemen

during rainy seasons. Wadi Hadramawt has the longest and widest catechment area with interconnexions with other subwadis, such as Masilah, Beihan and Markah. Wadis Tiban, Bana, Ahwar, Maifa'a and Hajr are also of major importance for their agricultural possibilities, as shown by the figures below.

Wadi	Catchment area (km^2)	Flood (millions of m^3/year)
Tiban	3 500	60-140
Bana	10 000	160-360
Ahwar	6 000	75
Maifa'a	5 500	30
Hajr	9 300	280
Hadramawt	114 000	144

Other wadis of less importance flow to the interior - some of them are in the catchment area of wadi Hadramawt, for example, Beihan, Dura, Abadan, Hanam, Markah, Kurah, Elgauf, Amd, Idm, Doan and Bin Ali. These wadis have discharges around 10 million m^3/year, with the exception of wadis Beihan of (about 50 million m^3/year) and Dura/Abadan (about 30 million m^3/year). Wadis between Madiah and Lawder have discharges around 30 million m^3/year and have interconnexion with wadi Ahwar.

Geology

The main structural features are the Hadramawt syncline and the northern and southern anticlines on both sides parallel to the Red Sea and the Gulf of Aden. There are some barren granites or abruptive lava cliffs directly at the sea shore, mostly on the eastern sides.

The whole area south of the Arabian Peninsula is characterized by fracture systems varying in depth, direction and age.

West and north of Aden, the geological structural history of the area is linked to the big tectonic movements along the Ethiopian rift system, associated with the formation of the Red Sea.

The main stratigraphic units are as follows:

Pre-Cambrian

Formations of the Arabian Peninsula Pre-Cambrian shield crop out in some areas north-east of Aden, in the north-west of the country and in areas north of Ataq to Beihan and the border. They mainly include granite-gneiss, meta-schists, quartz and calcite.

Jurassic formation: Amran group

These formations occur as small outcrops in northern areas of Giar, Shugrah and Ahwar. At Ayad and west of Hajr (Sifal) are some explosures. Salt hill accumulations of the Jurassic age occur in the Shabwa region.

Cretaceous: Tawila group

These outcroppings can be traced in the extreme western areas around Jebel Hawab (north of Ras el Arab) and around Museimer. Other patches occur around Kirsh, north-west Ahwar and along major wadis of Maifa'a, Beihan, Markah, Abadan, Hanam, Hadramawt and its tributaries. It is estimated that a volcanic eruption started during the Cretaceous and continued to late Miocene/Recent.

Paleocen/Eocene

Smaller patches crop out among granite/gneiss, metamorphic groups and around Mihfid and Ataq. The Paleocene hills are overlying Cretaceous sandstone around wadi Hadramawt and some northern wadis. Middle Eocene formations cover many areas in the Sixth Governote (Jebel Mahrat and Habshiya).

Quaternary formation

This includes valley-fill deposits and deltas where most of the agricultural activities are concentrated. Ground water is extracted from Quaternary aquifers which have different thicknesses according to location. They include boulders, loose pebbles, cobbles, sands and clays or conglomerates.

Ground-water resources

In Democratic Yemen, as in most arid, semi-arid and extremely arid regions, ground water is generally the only source of water for domestic, agricultural and other uses. Traditionally, agriculture depends on seasonal rains, mostly the short intensive summer monsoons. The rains fall in the catchment areas (mainly the interior highlands) and flow as floods through the wadis and lowlands, eventually reaching the sea. A limited amount of these flood waters percolates into the subsurface aquifers, depending on hydrological, hydrogeological and geomorphological conditions, such as higher inclinations of lands towards the sea or desert; shorter or barren highlands from which floods reach the sea before enough recharge to the aquifers; and, in some cases, the aquifers themselves being impervious. In order to increase recharge, diversion weirs have been built across the wadis. The building of surface and subsurface dams and local wadi-training measures have been proposed to increase the areas under irrigation by both surface and subsurface means. Serious actions are now being taken to establish a water management board from the ministries concerned. Two ministries have competence in drilling: the Ministry of Agriculture (Irrigation Department) and the Ministry for Local Administration. Any organization wishing to drill wells is required to contract with the Drilling Section of the Irrigation Department.

Throughout the country the people dig wells for both domestic and agricultural use. Only limited areas are irrigated by dug-wells. Optimal discharges range from 3 to 4 l/sec twice to three times a day and are of one to three hours' duration.

Such dug-wells do not penetrate more than 2-3 m through the aquifers. When pumped they may dry up quickly and it may be necessary to wait for some time before water levels recover. Therefore it has been the policy of the Government since the 1970 three-year plan, to drill wells by means of modern rigs. As a result, 25,000 hectares of land are under ground-water irrigation and measures could be taken within the next five-year plan to double that figure.

While exploratory wells were being bored, little precise data were collected. Some of the findings, however, are summarized in table 6.

Table 6. Democratic Yemen: summary of aquifer characteristics

Geological age	Geographical location	Depth of wells (m)	Specific yield (l/sec/m)	Hydrogeological parameters: Hydraulic conductivity (m/day)	Transmissivity (m^2/day)	Coefficient of storage
Recent Quaternary	Bir Ahmad a/	83.8	...	...	1 200	...
Recent Quaternary	Fiush a/	76	9	...	900-1 100	$3\text{-}3.5\times10^{-2}$
Quaternary	Lahej a/	61	8.5	...	1 300	3.2×10^{-2}
Quaternary	Intifadah farm b/	45	6	35	640	6.27×10^{-4}
Quaternary	Milicia farm b/	50	...	70	1 700	9.7×10^{-4}
Quaternary	Mayo farm b/	60	29	229	5 600	1.92×10^{-5}
Quaternary	Abyan Delta b/	40-60	4-20	35-180	620-1 860	...
Quaternary sediments	Ahwar Delta	40-50	2-10	...	900	...
Quaternary sediments	Maifa'a	55-80	6-12	...	1 000	...
Quaternary sediments	Maadin	45-65	7	...	1 800	...
Quaternary sediments	Lawder	40-65	4-8	...	1 200	...
Quaternary sediments	Mudiah	50-70	6	...	1 000	...
Quaternary with Pre-Cambrian basement	Nisab	45-60	5-8	...	1 000	...
Quaternary with Pre-Cambrian basement	Beihan	40-60	6-8	...	700-900	...
Quaternary with cretaceous sandstone	Baalal c/	186-295	2.5-46	...	2 200-3 600	2×10^{-3}
Quaternary with cretaceous sandstone	Bor c/	130-166	2.5-46	...	2 200-3 600	2×10^{-3}
Quaternary	Gaima c/	145-200	2.5-46	...	6 500	2×10^{-3}

Note: In the above evaluations, figures were mostly taken from drilled wells, depending on the availability of data.

a/ Figures collected for wadi Tiban.

b/ Figures collected for wadi Bana.

c/ Figures collected for wadi Hadramawt.

Water quality

The quality of water in Democratic Yemen is in general adequate but variable in salinity and pH. Depending on location, the pH value ranges from 7.5 to 8.2 (in a few cases it could be over 9).

Dissolved solids in drinking water from the wadi Tiban area average as follows:

Na	K	Mg	Ca	Cl	SO_4	CO_3	HCO_3	TDS	pH
310	1.65	56.90	58.50	275	330	38.40	322	1,232	8.5

Similar conditions occur in wadis Bana, Hassan and Ahwar.

In the interior and plateau lands, water quality is much better than in coastal areas, with the exception of wadi Hadramawt, where it differs in all respects. Along the banks of the wadi on both sides, the water contains less salt than in its middle portion, whether the penetration was through the Quaternary sediments or through the deeper Cretaceous sandstones. Along the banks, the salt content is between 0.6 and 1.2 g/l, but could increase up to 3 g/l. In the middle of the wadi it could reach up to 10 g/l or even more (mostly from the Quaternary sediments), in which case water could not be utilized for any purpose.

Assessment of ground-water resources

Hydrometerorological stations have been installed on the main wadis. Training of technical personnel in the Irrigation Department was started recently in meteorology, hydrology and hydrogeology, as well as in activities related to water management and land reclamation. Wadi Tiban flood water amounted to 60 million m^3/year for 1972 and 1973. Ground-water extraction approached 35 million m^3/year for irrigation and 22 million m^3/year for drinking. The continuous 10 cm/month drop in water level, the increase in salt content and sea-eater encroachment up-delta motivated the final decision to abandon drilling in the delta.

Wells have been drilled in wadi Tiban, 50-95 m in depth and 10-15 inches in diameter. In addition, it was planned to drill down to depths exceeding 300 m and to test the hydrogeological parameters of the lower aquifers.

Estimates for wadi Bana were also made for discharges and run-off, as well as for other wadis, including wadi Hadramawt, but no factual data could be obtained. However it has been considered possible to expand the present area in wadi Hadramawt under ground-water irrigation by 5,000 hectares and to replace the present dug-wells by tube wells without seriously affecting the aquifer. Detailed studies will be carried out for future development in wadi Hadramawt. From the confluence of wadi Hadramawt with wadi Masilah and downstream, surface water can be seen flowing along areas in wadi Masilah with variable but perennial discharges of up to 10 m^3/sec reaching the sea. The length of both wadis could be over 400 km. Problems that might arise in future would be in respect of the non-inhabited areas along wadi Masilah.

Ground-water development

Before 1968 there were some rigs owned by local drilling enterprises besides those owned by the Drilling Section of the Irrigation Department. Since 1970, however, drilling work throughout the country has been carried out by the Ministry of Agriculture (Irrigation Department). Some rigs are owned by the Ministry of Local Administration. There are about 40 rigs in the country, more than 20 of which are owned by the Irrigation Department, as follows:

(a)	Rotary:	Speedstar Kahering	2
		Failing 1250	1
		USSR rotary 16A15	10
(b)	Percussion:	Ruston Bucyrus 22 RW	4
		Ruston Bucyrus 60 RW	2
		Dando 800	3
		USSR percussion KCL 22	1

The USSR rotary rigs are in good condition. Among the newest rigs brought into the country was a Cyclone 39, supplied to the Ministry of Local Administration by the United Nations through an assistance programme for rural development. Both Ministries have problems with spares, complementary equipment and lack of qualified personnel in all fields, including geophysical investigation, maintenance, logistics and administration.

The total depth drilled in 1977 was 15,000 m. This may not seem much but, besides the difficulties mentioned above, drilling and transport conditions are quite severe.

Drillers have to be trained in the handling of rigs, especially when using rotaries. No major problems have been experienced in percussion drilling, since drillers can handle the rigs in a satisfactory manner.

Until recently, rural areas depended on dug wells for both domestic and agricultural needs. There are, for example, 1,800 dug wells in wadi Hadramawt alone. As of 1970, some 100 wells had been drilled. Most of them were in wadi Tiban, their main purpose being to supply Aden with water. The rest were drilled in deltas Abyan, Beihan, Maifa'a and Nisab.

From 1970 to the end of 1976, 650 wells were drilled for municipal and agricultural purposes, the depths ranging from 60 to 70 m and the diameters from 10 to 17 inches.

Municipal water supply is the responsibilioty of the Water Corporation Department, organized in 1970 within the Ministry of Local Government. Prior to that date the Ministry was in charge of the water supply of Aden only.

At present, Aden consumes some 22 million m^3/year for municipal and industrial purposes. In rural and desert (oasis) areas, the Ministry of Local Government drills wells to encourage nomads to settle with their animals. But the aquifers in those areas are not very productive and discharges from wells at depths up to 150 m do not exceed 3 l/sec.

The Irrigation Department of the Ministry of Agriculture has planned to drill 75 wells each year and irrigate 600 hectares of virgin land. Ground-water studies relating to the utilization of ground-water resources in the areas between Lawder and Mudiah are being carried out by Bulgarian teams with their own rigs. Drilling teams from the Union of Soviet Socialist Republics are drilling in wadi Hadramawt and reclaiming virgin land using ground water for irrigation.

It has been acknowledged that in the wadi Tiban area aquifer recharge is less than the discharge. A decline in water level and sea-water encroachment have been noted in some wells (those supplying Aden), so that an increase in water extraction is not being considered.

A few measures have been taken to recharge the aquifers, among which was the building of diversion weirs across the wadis. Subsurface barrages are now being considered for that purpose and for training wadis to have longer flow periods.

Artificial recharge through injection of coastal aquifers should be considered if sea-water encroachment endangers drinking water at Bir Nasser.

Conclusion

Ground-water development will be increased to meet the growing water demand for all types of uses.

A rural development programme has been initiated to settle nomads in cases where wells have been bored to provide water for domestic use and for irrigation of fodder and other crops. The objective of drilling enough wells to irrigate at least 600 hectares a year was accomplished in the course of the past few years.

With the assistance of teams from Bulgaria and the Union of Soviet Socialist Republics ground-water investigations and drilling are being carried out in the Lawder-Mudiah and western Hadramawt areas.

Water costs in Democratic Yemen vary widely, depending mainly on drilling conditions and location of the drilling sites. They may range from \$0.02 to \$0.10/m^3. In oases, they might be even more than that. The lowest costs are in wadi Bana, followed by wadi Tiban and then wadi Hadramawt. The wadi Bana aquifer is the easiest to penetrate: static water level at 15 m is quite shallow, dynamic water level is around 18-20 m and specific capacity might reach up to 20 l/sec/m of draw-down.

Municipal water from wadi Tiban costs a little more than \$0.03/m^3 at the well and is sold to households at 25 fils/100 gallons (\$0.16/m^3).

Selected references

Dar Al-Handasah Engineers and Architects, Shair and Partners. Countrywide Socio-Economic Study. Vols. 1-9. Beirut, 1974.

Hydrogeological studies for Wadi Hadramawt covering 900 km^2 and drilling 20 tube wells. Mission undertaken by the Union of Soviet Socialist Republics. Unpublished report. Aden, 1975.

Italconsult/United Nations Development Programme (Special Fund) Contract No. DP/PDY/71/508-1AGL. Soil and Water Utilization and Conservation in Wadi Tiban Watershed Area. Rome, 1975.

Tesco-Viziterv-Vituki. Survey of the Agricultural Potential of Wadi Zabid - Hydrology and Hydrogeology. Budapest, 1971.

Ubaid, M. Investigation on Groundwater Balance in Southern Arabia. Thesis. Budapest, 1973

United Nations Report to the Government of the People's Democratic Republic of Yemen (75/R 40). Groundwater Resources of the North Eastern Area. Aden, 1976. (Prepared by Mr. Wilson Iskander.)

Area: 1,001,000 km^2

Population: 37,200,000 (United Nations estimate, 1975)

General

Egypt, occupying a part of the arid belt of north Africa and western Asia, is subdivided into the following physiographical provinces (see map 8):

(a) The Mediterranean coastal areas (20,000 km^2), characterized by low topographic relief (rarely exceeding 100 m). Mean annual precipitation is 125 mm; so there is adequate potential water for agriculture, watershed management and range development.

(b) The Red Sea-Gulf of Suez coastal areas (10,000 km^2) which have a complex relief pattern and arid climatic conditions (winter rain and rare summer showers; the average rainfall is less than 25 mm). The ground elevation is about 200 m above mean sea level. The province is crossed by the downstream parts of many dry river beds and wide tracts are occupied by mudflats, which are subject to salinization. The agricultural potential of this province is therefore limited.

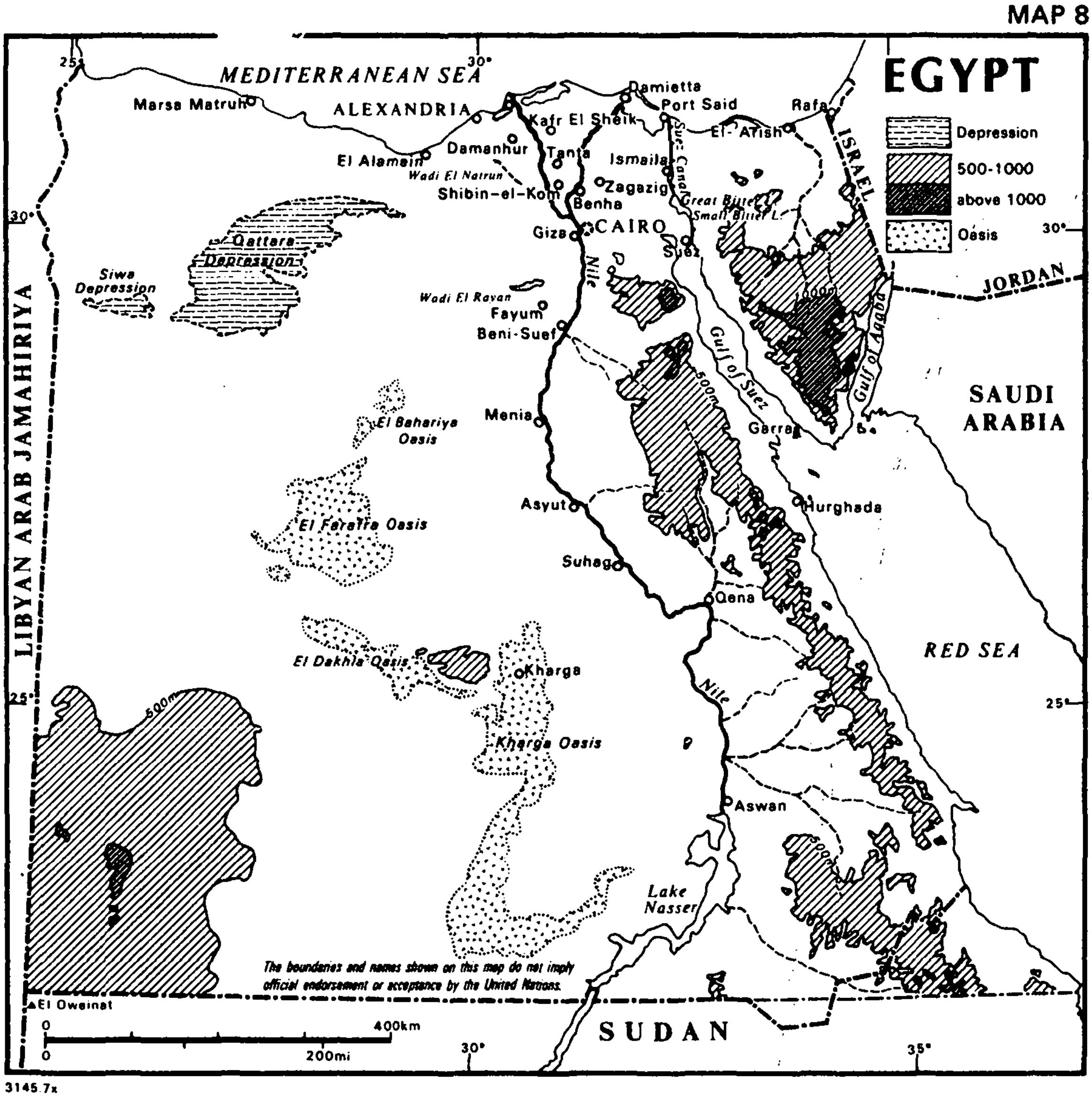
(c) The Nile Valley between the delta and the High Dam Lake (20,000 km^2), which is dominated by the main cultivated area of Egypt (flood plain) by flat areas suitable for land reclamation (terraces) and the great artificial water reservoir. The ground elevation rarely exceeds 200 m above mean sea level.

(d) The south Sinai-Red Sea granitic ridges (75,000 km^2), which form the backbone of the high mountain ranges of Egypt and rise to 2,600 m above mean sea level. This part of Egypt has very rugged topography and is dissected by many dry drainage valleys, which end at the Red Sea and Gulf of Suez or in the Nile Valley.

(e) The tableland areas (350,000 km^2), which are covered by carbonate rocks and recognized in central and northern Sinai, in the area between the Nile and the Gulf of Suez and in almost all the area west of the Nile from about the latitude of Aswan. In the Sinai and in the area to the east of the Nile, the surface elevation of the tableland rises to about 1,000 m above sea level, whereas in the area west of the Nile, the elevation averages 350 m above mean sea level. The surface of the tableland area is dissected by a dry hydrographical network, which ends either in the inland depressions or in the Nile Valley or in the sea. In the area west of the Nile Valley, the surface of the tableland shows the following different physical features:

Map 8

Egypt


MAP 8
EGYPT
Depression
500-1000
above 1000
Oasis
MEDITERRANEAN SEA
Marsa Matruh
ALEXANDRIA
Damietta
Port Said
Rafa
Kafr El Sheik
El-Arish
Damanhur
Tanta
Ismaila
El Alamein
Wadi El Natrun
Zagazig
Shibin-el-Kom
Benha
Great Bitter L.
Small Bitter L.
Giza
CAIRO
Suez
Suez Canal
ISRAEL
JORDAN
Qattara Depression
Siwa Depression
Wadi El Rayan
Fayum
Beni-Suef
Nile
Gulf of Suez
Gulf of Aqaba
SAUDI ARABIA
El Bahariya Oasis
Menia
Garra
Hurghada
El Farafra Oasis
Asyut
Suhag
Qena
RED SEA
El Dakhla Oasis
Kharga
Kharga Oasis
Aswan
Lake Nasser
LIBYAN ARAB JAMAHIRIYA
The boundaries and names shown on this map do not imply official endorsement or acceptance by the United Nations.
El Oweinat
400km
200mi
SUDAN
3145.7x

(i) Natural depressions, some of which are below sea level. Such depressions include, from north to south:

Wadi El Natrun	(- 20 m);
Qattara depression	(-134 m);
Siwa oasis	(- 18 m);
El Faiyum	(- 60 m);
El Bahariya oasis	(+100 m);
El Farafra oasis	(+100 m);
El Dakhla oasis	(+100 m);
El Kharga oasis	(+ 50 m);

(ii) Sand dune ridges and sand sheets, either in groups or in isolation;

(iii) Gravel plains south and east of the Quattara depression.

(f) The elevated sandy plains, which are located between the granitic slopes and the southern vertical edges of the carbonate tablelands (350,000 km^2). These extend southwards into the Sudan and westwards into the Libyan Arab Jamahiriya. The ground elevation is about 500 m above mean sea level, but locally it may rise to 1,000 m (El Gilf El Kebir). The surface of such elevated plains is dotted in places with volcanic cones, granitic ridges and ring dykes (El Oweinat, 1,600 m). The surface is also dotted with circular depressions filled with lacustrine deposits and is covered by sand sheets and Barkhan dunes.

In Egypt, cultivation is essentially restricted to the Nile Valley, the Mediterranean littoral, and to the oases in the depressions of the tableland area west of the Nile (3 per cent of the total area of the country). Attempts to reclaim the desertified areas of Egypt are under way and it is expected that by the end of the century the area cultivated will have increased to 5 per cent of the total area of the country (about 5 million hectares).

Geology

Egypt occupies a part of the "foreland structure" on the northern edge of the Arabian-Nubian shield. In south and south-eastern Egypt, Pre-Cambrian and Infra-Cambrian basement rocks are exposed or occur at shallow depths (south Sinai, Red Sea hills, Aswan and El Oweinat). They include igneous and metamorphic rocks and offer good prospects for mineral exploration.

Overlying the basement rocks is a predominantly sandstone sequence representing epicontinental environments of deposition. The thickness increases gradually from the south (500 m) to the north (in some bore-holes it is as much as 2,500 m) and locally marine facies can be observed. This section belongs to the Paleozoic and to the lower portion of the Mesozoic. The major ground-water aquifers of Egypt are associated with this complex, mostly known as the Nubian Sandstone.

Following the Paleozoic-Mesozoic sandstone section in a northward direction is a carbonate section (with interbeds of clay), which has an exposed thickness of about 2,500 m. This section, which belongs to the Upper Mesozoic (Jurassic and Cretaceous) and to the Lower Tertiary (Paleocene), displays classical examples of karst hydrology and occupies much of the tableland areas. The geographical distribution of this carbonate section in the subsurface and the variation in its lithology is controlled by the geological structure.

The landscape of Egypt attained much of its present shape in post-Paleocene times. Reference to the following geological events may be made:

(a) General rising of the land surface, retreat of the sea, development of terrestrial conditions with volcanic and hydrothermal activities in Oligocene and Lower Miocene times;

(b) Formation of the Red sea graben;

(c) Local ingressions of the sea from the north during Oligocene, Miocene and Pliocene (successive oscillations of the Mediterranean level);

(d) Development of the Nile basin, initially as a marine gulf during Pliocene time and then as a fresh water way flowing from south to north during Pleistocene time;

(e) Gradual changes in climatic conditions, ending with the development of aridity, which at present is indicated by sand-dune accumulation, degradation of most of the surface area with regard to soil and vegetation, domination of salinization processes, and lack of precipitation.

Ground water

The main aquifers are as follows (in decreasing order of productivity):

(a) The basal clastics (commonly referred to as the Nubian Sandstone portion of the basement rocks and the base of the carbonate rocks. This sandstone aquifer has a thickness varying between 100 m or less and 2,500 m, and water occurs generally under artesian conditions. Within the limits of Egypt, the piezometric level of this aquifer declines from 500 m in the south-western part of the vast area west of the Nile. This part of Egypt has developed into a common ground-water reservoir (or basis), which is hydraulically connected with other basins in north Sudan and in the south-eastern part of the Libyan Arab Jamahiriya, all of which form parts of what are known as the northeast-east African artesian basins. The chemistry of the water obtained from such basins shows a great similarity and the salinity of the water is generally less than 500 ppm (meteoric water). Dating of the water by means of the carbon 14 method, as well as by means of other radio isotopes, shows that, for the most part, the water accumulated in situ, during one or several pluvial periods. Its age ranges from 20,000 to 40,000 years (fossil water). It is accepted among hydrogeologists that the water is possibly recharged (at present) by small amounts from other sources located outside Egypt, including precipitation in equatorial Africa and the Nile in northern Sudan. The water is discharged, either naturally or artificially, into several locations in the vast region west of the Nile, which include the following:

(i) The Qattara-Siwa depressions in north Egypt (natural outlets), where the amount of water discharged exceeds 3 million m^3/day. The fresh-saline water interphase is located to the north of this depression area.

(ii) The El Kharga and El Dakhla oases, which are located in the south-eastern portion of the area (natural and artificial discharging area). In these two oases, some 400 relatively shallow bore-holes (not exceeding 100 m in depth) and deep wells (500-1,000 m) have been drilled. The amount of water extracted from El Kharga and El Dakhla exceeds, at present, 1 million m^3/day and it is expected that this amount will increase to 3 million m^3/day during the five-year period, 1979-1983. The water will be used for land reclamation, and it is expected that misuse of the water will not be permitted. The five-year plan includes improvements in well design and spacing as well as improvements in irrigation techniques. The total area to be reclaimed for cultivation during this period will be about 40,000 hectares;

(iii) The El Farafra and El Bahariya oases, located in the central part of the vast area west of the Nile Valley where natural and artificial discharge occurs. The amount of water discharged in this vast area is about 400,000 m^3/day; the number of deep wells is rather limited, but some are as much as 2,500 m deep. In the five-year plan, 1979-1983, the amount discharged will be increased to 1 million m^3/day and the area to be reclaimed will be increased to 15,000 hectares.

Very little is known about the amount of water seeping by vertical leakage into the fissured carbonate mantle from the underlying artesian sandstone aquifer. One can refer only to Siwa oasis, where there are about 200 natural springs in the Miocene carbonate rocks, with a daily output of about 200,000 m^3.

With regard to the area east of the Nile (excluding the Sinai Peninsula) the basal clastics also act as an aquifer, but the capacity is rather limited because of unfavourable topographical conditions on the western side of the high granitic ridges and because the sandstone section is rather thin compared with the area west of the Nile (many details are lacking). Some hot natural springs (Ain Sokhna) are reported to occur along the edge of the Gulf of Suez and are associated with block faulting. The water from these springs indicates a high amount of mineralization and is discharged as hot brines.

With regard to the Sinai Peninsula, during oil-drilling operations, high pressure water was encountered in the sandstone aquifer, which has a thickness of about 500 m. In some wells in central Sinai (for example, Nakhl well No. 1 of Esso), the water rises to about 200 m above mean sea level and the salinity is about 1,500 ppm. In western Sinai, the water in the sandstone aquifer flows to the surface at Ayoun Mosa to the south of Suez. Fewer than 20 wells tap the sandstone aquifer in Sinai. It is expected, however, that the aquifer can make an important contribution to the water supply of the Sinai. Water samples collected from the aquifer were analysed using the carbon 14 method, which revealed similarities with waters occurring in areas west of the Nile. On the other hand, it is generally considered that the sandstone aquifer of the Sinai is recharged from the vast watershed area located to the east of the Mediterranean (in Lebanon, the Syrian Arab Republic and Israel). Detailed studies, however, would be necessary to determine the pattern of ground-water flow.

(b) The sand and gravel section deposited in the Nile and delta depression (Pleistocene Nilotic deposits). This aquifer has a thickness of about 350 m and is underlain by Pliocene clays which may be considered as an aquiclude. This section is amlost saturated with water (salinity is in the range of 500 ppm) and depends for its recharge on the surface water of the Nile as well as on the complex of irrigation canals. It has been determined that in this part of Egypt, the water table is continuous and declines gradually from south to north. After the construction of the High Dam, the water table in the Nilotic deposits began rising, presumably as a result of the pronounced difference in head of the water in the High Dam Lake (+178 m) and the surface water in the river to the north (maximum level about +90 m). Because the deposits in the Nile Valley are not homogeneous from the lithological standpoint, disconnected clay lenses have been observed and account for the local development of subartesian conditions. The amount of water stored in this aquifer as a renewable resource is probably about 600 million m^3, and the discharging area comprises the following:

(i) Wadi El Natrun (-20 m) and possibly also the Qattara depression (-134 m) on the western side;

(ii) Wadi El Tumeilat, the Bitter Lakes and the Suez Canal on the eastern side;

(iii) The peripheral lakes along the Mediterranean coast on the northern side;

(iv) The large number of wells drilled in this long and narrow area. The water is used both for supplementary irrigation and for municipal purposes. The staff of the Groundwater Institute is making an inventory of the wells and carrying out a study of their yields.

At the northern edge of the delta, severe intrusions of saline water from the sea have been observed, which can be related to the overpumping of ground water. Again, mounds of saline water are locally developed in the new reclaimed areas (the west El Nubaria project) and are obviously related to the overuse of water for irrigation and to the lack of efficiency of the drainage systems.

(c) Fissured limestone aquifers have a broad geographical distribution in Egypt and are good examples of karstic features. Reference may be made to some important water sources tapping this limestone, which have not yet been studied:

(i) In the area west of the Nile, almost all the natural springs in El Farafra, El Kharga, Sitra, Arag, El Bahrein, Garra, Siwa, wadi El Rayan, etc. and almost all the wells in the calcareous plateau to the north of the Qattara depression;

(ii) In the area east of the Nile (including Sinai), a large number of natural springs along the Red Sea hills, at Helwan and adjacent localities to the east of Cairo (highly mineralized water); in the faulted area of west Sinai (Hammam Faraun sulphurous springs; hot brines); and at the edge of the carbonate tableland of east Sinai.

(d) The Mediterranean calcarenites which have developed in the coastal plain in the form of stranded ridges. Such deposits, of both shallow marine and terrestrial origin, form an important water-table aquifer all along 1,000 km of coastline at an elevation close to sea level. This body of water, the salinity of which is about 1,000 ppm floats on a saline water wedge resulting from the intrusion of sea water. Locally, however, subartesian and perched conditions occur and are attributed both to change in facies and to the geological structure. This aquifer is replenished through direct infiltration of local precipitation (winter rainfall averages 125 mm). The water is extracted from this aquifer by different types of wells:

(i) Drilled wells, to a depth of about 30 m, and use of centrifugal pumps (north-east Sinai). More than 100 wells of this type have been installed;

(ii) Wide-mouth open wells. These are hand-dug wells, lined, and equipped with ordinary suction pumps. Many wells of this type are also to be found in north-east Sinai;

(iii) Shallow hand-dug wells equipped with windmills. Depths range from 5 to 20 m. Such wells are to be found in large numbers in the coastal area west of the Nile delta;

(iv) Extra-wide open wells (diameter about 5 m), and having radial trenches excavated to the water table (galleries). A small number of such wells are located to the west of Alexandria;

(v) Horizontal wells (galleries), excavated to less than 1 m below the water table. Such horizontal wells are located at Mersa Matruh and between El Arish and Rafa in Sinai.

(e) The wadi fillings act as aquifers of limited importance in Sinai and along the Red Sea coast. Hundreds of shallow hand-dug wells are known to exist. The water of the wadi fillings depends on local precipitation and on surface run-off.

Ground-water investigations

Detailed studies of the different aquifers are now under way, both by means of traditional methods and by the application of modern techniques. These include the use of different types of models (analogue and mathematical), radio isotopes and remote sensing techniques. The ultimate goal will be the evaluation of the potential of such aquifers since the possibilities for exploitation have received much attention. The Desert Institute is involved in all activities of exploration and exploitation of ground water in Egypt.

IRAN

Area: 1,650,000 km^2

Population: 33 million (United Nations estimate, 1975)

General

Iran occupies a saline desert plateau covered with rocks and sand and almost entirely surrounded by mountain ranges (see map 9). There are four main physiographical areas in the country, each with a distinctive character.

(a) The Alborz and the Zagros mountain ranges to the north and the south-west

The Alborz and its associated ranges form a continuous wall among northern Iran from Ararat in Turkey to the north-western corner of Iran. This system consists of parallel ranges, increasing in elevation from north and south. In the middle ranges of the Alborz is Mount Damavand, the highest peak in Iran, at an elevation of 5,766 m.

The Zagros mountains begin with the ranges along the border with Turkey and consist of a number of ranges from north-west to south-east, almost parallel to one another. They form a continuous wall about 1,000 km in length and often more than 200 km wide. They attain heights of more than 4,500 m and play an important part in the climatology and soil formation of the country.

The Zagros system takes a south-easterly direction before reaching Khuzestan and goes through the provinces of Fars and Kerman for over 800 km.

South of Kerman, the Zagros splits into two branches. The north branch reaches the north-south chain of Sarhad, which runs along the eastern borders; the south branch runs parallel to the coastline of the Gulf of Oman and continues into Pakistan.

(b) The central plateau

The area within the "V" of the mountain ranges is a high plateau with its own secondary ranges; it gradually slopes down to become a desert which continues into southern Afghanistan and Pakistan. The plateau, with an elevation of 500-2,500 m above mean sea level, comprises four major physiographical units:

(i) The high plateau of north-west central Iran (elevation 1,200-2,500 m);

(ii) The Esfahan Saidbad basin (elevation 100-1,200 m);

(iii) The salt desert (Masileh-Kavir) (elevation about 600-1,000 m);

(iv) The Lut desert basin (elevation 500-600 m).

MAP NO. 3114 REV. 1 UNITED NATIONS
AUGUST 1981

(c) The region of Khuzestan and the low-lying southern coastal plains

The vast low-lying Khuzestan plain (30,000 km^2) in south-western Iran, is a continuation of the Mesopotamian plain. On the shores of the Persian Gulf and the Gulf of Oman coastal areas vary from a very narrow strip bordered abruptly by steeply sloping hills and mountains to wide deltaic or alluvial plains.

A narrow belt of low-lying plains on the eastern border of Iraq drains into the Tigris River which, together with the Euphrates, reaches the gulf by way of the Shatt-al Arab.

Large rivers in the southern coastal plains from west to east are the Shahpour River, which has built the Bushire and Barazjan plains, the Mard river which is building a large plain in Fars, and the Minab river near Bandar-e-Abbas which is building large plains of only minor agricultural importance because of the salinity of ground water and the soil.

(d) The Caspian Sea coastal area

The Caspian littoral is a narrow plain with an average width of about 50 km, produced by a withdrawal of the sea, which at one time probably extended as far as the foot of the Alborz mountains. Numerous rivers originate in the northern foothills of the Alborz, but they all cover only short distances before reaching the sea. There are, however, four rivers of importance that have their sources in the distant regions and discharge into the Caspian sea: Aras (Araes), Sefid Rud, Gorgan and Atrak. These rivers, respectively, have built the Moghan Plain, the Sefid Rud Delta (Rasht Plain) and the Gorgan and Atrek Plains. In addition, a group of rivers, Talar, Haraz-Babol and Tejan have built up the Mazanderan plain.

Climate

The major part of the country is arid or semi-arid. Except on the northern flanks of the Alborz mountains where it varies from 1,000 to 2,000 mm annually rainful is scarce, irregular and restricted to the winter months. On the plateau the average annual rainfall decreases to less than 120 mm in the south and south-east.

Most of the population of the country and the agricultural land are concentrated in the north (Azerbaijan, the Caspian Sea area and Khorasan), in the rich Khuzestan plain and at the foothills of the mountains. The eastern half of the country contains less than 10 per cent of the population.

There are considerable variations in climate from one part of the country to another. These variations, influenced by orography and physiography, are reflected in the climatic provinces of Iran.

The desert type of climate occurs along the coasts of the southern sea and in the interior.

Along the southern coastal areas, aridity is combined with high temperature and often very high humidity. Precipitation is very small, extremely variable, and limited to the cooler winter months.

The greatest extent of desert and the type of climate associated with it occurs in the interior of the country. There is a wide range in both the daily and the annual temperatures. Little rain falls, even less than in the coastal areas. Of the stations included in this section, Yazd has rainfall of about 67 mm and Nehbondan about 98 mm.

The semi-arid steppe, mostly a transition zone between the arid deserts and more humid areas, covering about half a million square kilometres of Iranian territory, occupies in most cases the foothills of higher mountains. It generally occurs between the 1,000 and 1,500 m contours except for the foothills of the Khuzestan plain, which are much lower in elevation. Precipitation is small and variable from 300 mm at Dezful to 140 mm at Esfahan. The rainy season coincides with the period of low sun and low temperature, so that the precipitation effectiveness becomes much greater. The winter rains, except when they are intense and produce considerable erosion, recharge ground water in storage, which can be utilized in the drier months of the year. The presence of springs and kanats as sources of underground water are a very important feature in the agricultural life of Iran.

About 400,000 km^2 (25 per cent of the total land area) is subject to the mesothermal group of climates.

The most densely populated areas of Iran are located in this climatic zone including the highest levels of the Zagros, a major part of Azerbaijan, and the coastal plains of the Caspian Sea.

In the highlands prevailing climatic conditions are similar to the Mediterranean type, especially in the south (Fars), while the north may be subject to cold waves during the winter period.

The coastal plain of the Caspian Sea, and the northern slopes of the mountains overlooking the Sea, are climatically very different from the rest of the country. The Caspian type of climate is best characterized by moderate temperatures, small annual and diurnal ranges, very high humidity, strong land and sea breezes and local winds, and very high precipitation (varying normally between 1,000 and 2,000 mm) spread over the different seasons.

Of the total land surface of Iran, probably 40,000 km^2 have a type of climate in which the coldest months are below 3° C and the warmest above 10° C. This climate normally occurs over higher lands, although it cannot be fitted into definite ranges of altitude. The type of climate in which the average temperatures during the warmest months are below 10° C, occurs where the higher mountain slopes are permanently covered with snow. Examples are the volcanic peaks of Damavand and Sabalan, and a certain area around Sabalan, on the plateau of Azerbaijan.

Hydrographical network

The country includes one million hectares of lakes and other bodies of water. All river basins of Iran have been defined and identified by a code number which includes four digits. The first digit (to the left) applies to one of six units, as follows:

1. Rivers flowing to the Caspian Sea;

2. Rivers flowing to the Gulf, the Karun (with the Mohammadrezashah Dam) and Karkheh rivers, which cross the Khuzestan, and the Mand and the Kul;

3. The closed basin of the Rezaieh lake in Azerbaijan (Zarineh rud river);

4. The desert center with two major rivers without outlet to the sea, the Zaende Rud (Shahabbas Dam) which crosses Esfahan and the Kor River, north of Shiraz;

5. To the east, the rivers flowing to Afghanistan;

6. To the north-east, the rivers flowing to the Kara Kum plains of the Union of Soviet Socialist Republics.

The second digit is for the designation of basin subunit; the third designates a river course; and the fourth designates an alluvial plain. A total of 233 alluvial plains (unit plain) contain the major ground-water resources of the country.

Geology

Iran can be divided into seven main structural units from the south-west to the north-east, as follows:

(a) The Khuzestan plain

This plain is covered by the deltas of the Karun, Dez and Karkheh rivers. It consists of alluvial deposits, which are coarser towards the mountains and very fine towards the plains, and silt and clay in large quantities deposited by the Karun and Karkheh (to the south-west of Ahvaz).

(b) The autochtonous folded zone of the Zagros system

The stratigraphic sequence in this zone starts with Cretaceous limestone and ends with the Miocene. The structures are a succession of regular features forming anticlines and synclines exposing Middle Cretaceous beds in the cores. A green and purple group some 400 m thick may be present near the base of the Eocene. Gypsum occurs at the top of the Eocene-Oligocene sequence. The desolate character of the southern fringe of Iran is due to Miocene-Pliocene sequence. At the base, this sequence is composed of Asmari limestone, which constitutes a hard layer nearly 300 m thick. Above the Asmari limestone are the thick Fars series of gypsum, anhydrite salt, marl, silt, and sandstone which are generally brick red in colour and form typical "badlands". They are several thousand meters thick, and show great lateral variations owing to the original conditions of deposition and to tectonic factors. Above the Fars series, the Bakhtiari series, several hundred meters thick, is composed of conglomerate, with clay and mudstone. The Bakhtiari conglomerate generally occurs on the outer edge of the folded zone. The folded zone sediments in some parts are cut through by Cambrian salt domes.

(c) The Iranides (thrust folded zone of the Zagros)

They include the radiolarite and ophiolite zone, made up of red and green chert, siliceous shale, and green eruptive ultrabasic rock (serpentines).

The Bisitun limestone zone consists of thick massive limestone of Cretaceous age. The Bisitun limestone zone wedges out between the radiolarite-ophiolite and the Hamadan zones west of Hamadan.

The Hamadan zone consists of dark shale and sandstone, dark phyllite and chlorite schist of Mesozoic age. In the Alborz range, southwest of Hamadan, biotitegranites have been intruded into phyllites. This zone is very broad (about 140 km) and in some cases tends to edge out.

The south-west limit of the Hamadan zone corresponds to an important geomorphological and climatic divide. South-west of this line drainage is towards the Persian Gulf and erosion is active. The mountain areas have more precipitation and the predominant limestone formations are good aquifers with numerous springs near the valley bottoms. North-west of this line, the original drainage is towards central Iran, with wide high plateaux and little erosion, less rainfall than towards the south-west, generally impervious bedrock, and steppe-like vegetation.

(d) The central plateau

A great tectonic event separates the zone of central Iran from the Iranides. In the upper Cretaceous and Tertiary deposits, eruptive rocks such as andesite occurred in different places on this tectonic line. Many springs with travertine deposits occur. In central Iran, Paleozoic, Mesozoic, and Tertiary sediments crop out.

The gypsiferous and saline series of Eocene to Miocene age characterize this unit and are made up of salt, gypsum, clay, mudstone, siltstone and sandstone. The erosion of gypsum has created the formation of salt lakes (Kavir). Marine Miocene deposits cover a large part of central Iran and the possibilities of locating adequate ground water may be related to these sediments (Qom area).

The volcanic activity in central Iran, which started in the Upper Cretaceous, developed fully in the Eocene and deposited eruptive material made up of tuffs and basaltic rocks. In Oligocene and Miocene time volcanic activity decreased considerably compared with the Eocene, and more acid rocks (andesite, deorite etc.) commonly associated with tuff were formed.

Pre-Cambrian metamorphic and volcanic rocks have been recognized in central Iran west of Kavir (130 km north of Tabas) and in southeast Kavar (Kerman).

(e) The Alborz range

The Alborz mountains are formed by a thick stratigraphic sequence of limestone, sandstone and tuff. The Gypsiferous and saline rocks are absent. The age of the formations ranges from Cambrian to Tertiary. In Alborz, Paleozoic formations cover a relatively large area.

In the Mesozoic period, the Jurassic has a great relative extension and the presence of coal has a great economic value.

Along the south slope of Alborz, the Eocene and probably the Lower Oligocene consists of 3,000 m of tuff with volcanic and intrusive rocks.

Metamorphic and eruptive rocks of Permian-Devonian age are more widespread in Alborz. Phyllite, quartzite, gneiss, biotite and granite occur in the Rasht area; schist, marble, amphibolite, and granitic rocks in central Alborz; and green schist and eruptive basic rocks in the Gorgan area.

(f) The Turmeman-Khorasan mountain ranges

These mountains, which are also called the Kopet Dagh mountains, occupy the north-east of Alborz and are mainly composed of Cretaceous limestone and marl.

(g) The Caspian littoral

In the Gorgan Mazanderan and Rasht plains in the north, alluvial materials, as well as younger Tertiary sediments of the Caspian type, occur, as well as some loose deposits, especially in the Atrak area.

Ground water

Institutional aspects

Consideration of ground-water development by the Government began in 1943 with the establishment of the Irrigation Corporation. Most of the hydrological activities consisted at that time in assistance to kanat owners. Regional aspects of ground-water hydrology became prominent in 1959 when a ground-water division was established in the Irrigation Corporation, with a view to undertaking a systematic study of Iran's ground-water resources. It became necessary to acquire trained personnel and for this purpose an intensive training and study programme began in 1961 with the technical assistance of international organizations, including the United Nations and the Food and Agricultural Organization of the United Nations. From 1961 regional ground-water studies were initiated in all provinces of the country.

Since then investigations have been carried out in three stages, the first being a reconnaissance for the purpose of identifying the aquifers, inventoring the points of ground-water discharge (wells, kanats and springs) and establishing an observation network.

The second stage consists of a semi-detailed investigation directed towards determining the quantitative aspects of the ground-water resources, including exploration drilling, hydrological tests, evaluation of the present state of exploitation, measurement of water levels, levelling and the computation of a water balance. In a third and final stage of the investigation, complementary data is collected and processed to assist in the setting up of a ground-water development plan.

Training of Iranian personnel has been provided by both United Nations and local experts. Training is also obtained by attending specialized courses abroad and by pursuing studies at the post-graduate level. Training is given in such subjects as ground-water hydrology, photogeology, drilling supervision, geophysics, discharge measurements, hydrological tests, geochemistry, land survey and levelling, cartography and drafting.

At the level of central government, all water resources matters are dealt with by the water unit of the Ministry of Energy and by regional authorities.

The work of the water unit of the Ministry of Energy, headed by an under-secretary for water affairs, includes project programming, water engineering, water production control and supervision of project implementation, surface water resources, ground water, and water-resources protection.

The ground-water bureau is responsible for the establishment, operation and maintenance of ground-water investigation networks, as well as for all ground-water data collection and ground-water resources evaluation at all levels of investigation (from reconnaissance to feasibility). The ground-water bureau establishes the ground-water balance of the country and evaluates the water still available for exploitation; it also advises the regional authorities on implementation of ground-water investigations throughout the country. Water resources problems are dealt with by 11 regional authorities, namely, the water and power regional authorities of Azerbaijan (offices in Tabriz), Shomal (Vasht), Khuzestan (Ahvaz), Kerman (Kerman), and Holmozgan (Bandar-e-Abbas); the water authorities of Teheran (offices in Teheran), Esfahan (Esfahan), Khorasan (Mashhad), and Djonub-Shanghi (Zahedan); and the development authority of western region (Kermanshah).

The regional authorities are responsible for the supervision and implementation of all water projects in the regions, for the disposal of domestic and industrial waste waters, for water distribution and management and for protection of water resources and water rights according to existing laws.

The activities of the ground-water specialists in the regional authorities are technically oriented and supervised by the ground-water bureau.

The ground-water bureau consists at present of five sections dealing with regional ground-water investigation, ground-water development, modelling, exploration drilling and geophysics, as well as research and development.

In the regional ground-water studies, the following prospection methods were used:

Photogeology and air photo-interpretation. This method was used in reconnaissance studies mainly to identify tectonic and geomorphological features to recognize the outcrops of the various aquifers and the boundaries of the alluvial plains, and for mapping existing water points. The scale of the air photographs was mainly 1:20,000 or 1:500,000.

Field geology. In reconnaissance studies, field geology was mainly utilized for obtaining a general background of the hydrogeology and in the complementary studies for outlining the boundaries of aquifers and locations of wells, exploration and exploitation and for a more detailed description of outcrops.

Geophysics. Geo-electric surveys were mainly carried out within the framework of the semi-detailed studies. These surveys were used to determine the thickness and composition of the alluvium, location of old river beds, location of areas of optimal permeability and also for determining the nature of the bedrock. In some cases, the surveys were used for determining the configuration of an outcropping formation that might be an aquifer. The seismic refraction method, when used, was only applied to complement the electrical method when the electrical parameters did not show sufficient contrasts and when it was difficult to differentiate the Quaternary overburden from the bedrock. In reconnaissance studies the density of electric measurements was 1 measurement for each 10 km^2. In semi-detailed studies it was 1 measurement for each 5 km^2.

Well logging. All exploration wells were logged. In each well, logging included self-potential and single-point potential, as well as gamma ray characteristics.

Main aquifers.

Alluvial aquifers. The main alluvial aquifers of Iran occur at the foothills of all mountains in the form of alluvial fans which cover most of the plains. They consist of boulders and gravel near the foothills and the material becomes more finely textured towards the center of the plains. Maximum thickness of such aquifers is about 600 m. Productive and extensive aquifers of this type occur at the foothills of the Alborz range around Ghazvin, Teheran, Varamin, Karadj, and some also occur in the south-east part of the country around Giroft.

Karstic limestone. The best karstic aquifers occur in Cretaceous limestone. The thickness of the formation ranges from 500 to 1,000 m. It occurs in Khorasan Province as well as in Kermanshah, where the thickness may be as much as 5,000 in Jurassic formations. Karstic limestone 3,000-3,700 m thick is also found in the Alborz range. In Fars Province the best karstic limestone belongs to the Asmari formation, the thickness of which varies between 50 and 600 m.

Dolomitic limestones. These rocks occur in every geological period and the thickness varies from a few metres to 1,000 m; typical dolomitic limestone formations occur in Nai Bandan in the south of Kerman.

Tuff andesite. These formations are of Eocene-Oligocene age. They occur in the Alborz range where they are referred to as "green beds". They are not a good aquifer but may yield ground water to the overlaying alluvial material because of the large area of contact. The thickness of these beds may range from a few metres to 3,000 m.

Sandstone. The most important sandstone formation is in the Devonian and Jurassic. Its thickness in the Alborz range varies between a few metres and 2,500 m.

The hydrological characteristics of the aquifers are summarized in table 7.

Table 7. Iran: hydraulic characteristics of aquifers

Aquifer	Geographical location	Depth of wells (m)	Discharge ($m^3/h/m$)	Specific capacity ($m^3/h/m$)	Hydraulic parameters: Hydraulic conductivity (m/day)	Trans-missivity (m^2/day)	Coefficient of storage (percentage)
Alluvial aquifer	Throughout Iran	25-400	50-300	2-15	3-20	100-4 000	5-25
Dolomitic limestone	Fars Province, Kermanshah, Khorasan Province	250	360	Very small	...	500	...
Karstic limestone	Fars, Semnan, Khorasan Province, Kermanshah, Alborz east	80-250	50-500	...	...	1 500-3 500	2-5
Tuff andesite	Southern flank of Alborz	50-200	10-50	0.5-1.5	Not tested	Not tested	Not tested
Basalt andesite	Azerbaijan, Alborz range	60-80	...	...	...	...	...
Schist sandstone	Alborz range, Kerman	Springs only	2-50	...	...	...	...

Ground-water quality

Coastal plain of the Caspian Sea. Water quality in the southern part of this plain near the northern flanks of the Alborz mountains is good owing to precipitation of more than 1,000 mm/year and the very restricted occurrence of continental Miocene formations. The aquifer is mainly recharged by precipitation falling on the plain and on the northern flanks of the Alborz range, which consist of limestone and igneous rocks. Water in these parts is mainly of the bicarbonate type. Near the coast and in other isolated locations, water also occurs having electric conductivities in the range of 3,000-5,000 micro mho/cm. Evaporation from a high water table also causes salinization of ground-water in low-lying areas. In large rivers such as Sefid, Gorgan and the Hazaz surface-water is of very good quality and conductivity is less than 1,000 micro mho/cm. Deep apparently fossil ground-water beds of 6,000 micro mho/cm also occur.

Rezaieh basin. This closed basin of some 40,000 km^2 is situated between the mountain chains of the Zagros and Alborz. Geological formations occurring in this area consist mainly of limestone and volcanic rock as well as continental formations that contain evaporite layers. Ground-water originating from precipitation on limestone and igneous rock is of the bicarbonate type and springs emerging from Cretaceous limestones have a total dissolved solids content of less than 300 ppm. The rivers west, south and south-east of lakes Nozlutchail Simineh rud, Zarine rud and others contain water having less than 1,000 micro mho/cm conductivity.

Saline ground-water occurs in the northern part of the basin and is caused by the contribution of the Adji Chai. This river is contaminated during its passage through continental formations of Miocene outcrops containing evaporative layers. Ground-water in the upper formation thus may have an electric conductivity of 10,000 micro mho/cm while fresh water of 600 micro mho/cm occurs in deeper units replenished from the Sahand mountains. Mineral springs are found at the border of the volcanic formations of Sahand and Sabalan. Springs at Vardjevi near Maraghe and other hydrothermal springs like Besonabad and Sarayne are sulphur bearing and also contain gases.

Central catchment basin. This catchment covers an area of about 700,000 km^2. It is bounded in the north by the Alborz range, in the south and west by the Zagros mountain and in the east by the small mountain chains of eastern Iran. It is a closed basin with the rivers and floods draining into saline lakes and marshes. The mountains surrounding this catchment mainly consist of carbonate and igneous rocks while in the center most of the formations belong to continental evaporite type of Eocene-Oligocene and Miocene-Pliocene age. Salt plugs are abundant. In the northern parts of the Sharoud-Varamin-Karadj-Ghazvin-Hamadan plains, as well as in the regions of Damghan-Firuzkuh, water is of the bicarbonate type and conductivity is about 1,000 micro mho/cm. The rivers that drain the catchments south of the Alborz carry fresh water at the foot of the mountains, but become saline after traversing the gypsosaliferous formations of the Miocene. The salinization of ground-water in the central catchment basin is attributed to the leaching of Oligocene-Miocene and Miocene-Pliocene saline formations especially in the northern parts of the plateau, in particular in the area surrounding the Dasht-i-Kavir desert. Also, the insufficient recharge by precipitation and the high evaporation in the southern parts of the individual northern plains cause salinization of the ground-water near the recharge areas of the plains. The water is mainly in the range of 1,000-2,000 micro mho/cm whereas near the discharge zones of the plains at the boundary of the Kavir, salinity increases to about 5,000-7,000 micro mho/cm.

Catchment basins of the Gulf. The coastal plain in the western part of the Gulf is fed by the Zagros mountains which consist mainly of limestone and locally of igneous rocks. In the southern and south-eastern parts, continental formations exist and evaporites and salt plugs can be seen (region of Bandar-e-Abbas); annual precipitation here does not exceed 150 mm. The rivers flowing into the western part of the Gulf, the Karvin River for example, carry water of good quality with a conductivity of 700 micro mho/cm; ground-water, however, becomes saline as a result of evaporation from a shallow depth and the existence of salt domes and evaporite formations. Some mineral springs that are sulphuric as a result of local volcanism occur south-east of the Khash area.

Ground-water resources assessment

Ground-water resources evaluation started in Iran 20 years ago. As a result, it was possible to arrive at an estimate, which, however, is still provisional, of the ground-water resources available in the alluvial plains. Investigations of water resources that can be made available by drilling in limestone and other hard rock formations have demonstrated the economic feasibility of exploiting ground-water from limestones, but no over-all quantitative assessment has yet been made.

The over-all assessment of ground-water resources in the alluvial plains is evaluated at 42 x 10^9 m^3/year, of which 20 x 10^9 m^3/year reach the plains as subsurface inflow from surrounding limestones and other hard rock formations; about 19 x 10^9 m^3/year are contributed to the aquifers by surface-water and only about 2 x 10^9 m^3/year (5 per cent) originate from natural replenishment of the aquifers by precipitation; 1 x 10^9 m^3/year are contributed to the aquifers as subsurface flow originating outside Iran. Ground-water resources evaluation studies at a semi-detailed level at present cover approximately 90 of the main catchment areas. Current investigation programmes include five semi-detailed ground-water resource investigations in alluvial basins per year. Investigative efforts are being directed towards the evaluation of ground-water resources and the proper exploitation of karstic limestones, basalt and tuff andesite.

Apart from the evident need to proceed in earnest with ground-water evaluation studies in limestone formations, there is a most serious lack of hydrogeological information and a need for further investigation with respect to artificial ground-water recharge of aquifers and management of ground-water resources by means of controlling spring and kanat flow, as well as a more serious study of the interaction of surface-water and ground-water in the various plains.

It is also believed that there is a need to utilize more sophisticated research tools, such as mathematical modelling, tracer studies and systems analysis applied to the conjunctive use of ground-water and surface-water resources. With regard to the urgent need for stock-taking and the processing of the immense amount of hydrogeological information that has so far been collected, an effort is being made to establish a central hydrological data bank to translate the results of the water-resources evaluation studies into ground-water development plans.

Comparative assessment of ground-water and surface-water resources

The available ground-water resources are about 42 x 10^9 m^3/year. The latest published estimate of the available surface-water resources is 107 x 10^9 m^3/year, of which 44 x 10^9 m^3/year are base flow and 64 x 10^9 m^3/year are flood flow. Some surface flow, estimated at 4 x 10^9 m^3/year, enters Iran through its boundaries with neighbouring countries. About 14 x 10^9 m^3/year originate from precipitation and drainage in the plains, and 19 x 10^9 m^3/year are lost by infiltration to the aquifers.

It is thus seen that surfac-water contributes to the available ground-water resources. Available surface-water resources also more than double the available ground-water. Total water resources in Iran are at present estimated at 149 x 10^9 m^3/year, of which about 28 per cent is ground-water and about 72 per cent surface-water.

Ground-water development

Water drilling in Iran has been carried out by one government company and by 190 private licensed firms. Most companies drill in alluvial formations and in limestones and own percussion and rotary drilling rigs. The total number of drilling rigs of licensed and government firms is about 250 of which 200 are percussion rigs and the remainder rotary. About 500 m are drilled per year by the percussion rigs whereas rotary rigs drill about 10,000 m per year. The number of experienced drillers is estimated to be 250-300 for percussion rigs and about 90-120 for rotary rigs. The professional experience of drillers may range from 2 to 20 years. Each drilling company is obliged to employ a drilling engineer for supervising the drilling from the hydrogeological site.

Ground-water is used at a rate of 29 x 10^9 m^3/year, of which 13.5 x 10^9 m^3 are pumped from some 21,000 deep wells and 54,000 shallow wells. About 9 x 10^9 m^3 are available from 28,000 kanats. The yearly discharge of 12,000 springs is about 6.5 x 10^9 m^3.

Problems

Ground-water utilization is limited by hydrogeological constraints. Kanats, which supply half of the ground-water developed in Iran depend heavily for their yield on the elevation of the water table.

Although the drilling of wells within a certain distance of kanats is forbidden by law, a growing number of wells pumping even at greater distances inevitably influence the water table and cause a decline in the kanat yield. Maintenance costs of kanats are very high, but despite the fact that the development of drilled wells is more efficient (kanats' winter and night flows are wasted), existing kanats are to be kept in operative condition for a variety of reasons, which does not make for rational development.

In some areas, for instance in Yazd, in the central catchment in Fahrum, in the south in Mashad, Varamin and other places, ground-water has been overpumped for some years causing a gradual decline in the water table. In some areas measures have been taken to increase the water resources by artificial replenishment, which at present is mainly at the experimental stage (Jaharum, Varamin). In Ghazvin, it is practised as part of a conjunctive use programme with river water. A solution is not available for all regions because saline water bodies also form constraints in many plains. These saline waters originate from the evaporation process acting upon high water table or from the flow through saline formations of the continental evaporitic type of Eocene-Oligocene and Miocene-Pliocene age (and gypsosaliferous formations of Miocene age). Sea-water intrusion also forms a constraint in the coastal plain of the Caspian Sea. However, saline water may also occur in deep wells as connate or fossil water.

Because of the high recharge rate by surface-water and the low permeability of the formations, water levels are high near the coast, causing drainage and evaporation problems. Some drainage problems occur in Marvdasht in Fars Province as a result of inundations of the Kor river. Drainage problems also occur in some of the plains in the Kermanshah area. Intensive pumping may improve that situation, but the agricultural character of the soils does not justify development. Grave drainage problems exist in the southern part of the Teheran urban area. The importance of water to greater Teheran has considerably increased in recent years. A large part of this amount infiltrates down to the water table and flows in a southerly direction raising the water table to a dangerous level in the southern part of the capital. About 30 million m^3/year are pumped from this area to prevent ground-water seeping into cellars and houses.

Selected references

Alamouti, A. M. Groundwater resources of Iran. CENTO Symposium on Hydrology and Water Resources Development, Ankara, 1966, pp. 415-430.

Amouzegard, K. Some statistical data about sources of water supply and water supply systems in Iran. International Conference on Water for Peace, Washington, D.C., 1967, vol. 8, pp. 821-827.

Azimi, M. A. Géologie et hydrologie des environs de Kermanschah, Iran occidental. Dissertation. Technische Hochschule, Aachen, Federal Republic of Germany, 1971.

Banihachemi, M. Climatologie et hydrologie de surface du bassin versant du Sefid-Roud (Iran). Analyse de l'ensemble des caractères climatiques et hydrologiques classiques du bassin de Sefid-Roud. Calcul du bilan d'eau, et tentative d'approche de la ration de variabilité sur les précipitations. Thèse doctorale, Université scientifique et médicale, Grenoble, 1971.

Beaumont, P. Qanat systems in Iran. Bulletin of the International Association of Hydrological Sciences, vol. 16, No. 1, 1971, pp. 39-50.

Bierschenk, W. H. and G. R. Wilson. The Exploration and Development of Ground Water Resources in Iran. International Association of Scientific Hydrology, publication No. 57, Symposium of Athens, 1961, pp. 607-627.

Engalenc, M. Contribution à l'étude géologique, géomorphologique et hydrogéologique de la région de Téhéran (Iran). Thèse doctorale, Université de Montpellier, novembre 1968.

Esfandiari, F. Procedure and results of groundwater pollution studies in Teheran area, Iran. Association internationale des hydrogéologues, Mémoires, t. 9, réunion de Tokyo, 1971, p. 3-7.

Fookes, P. G. and J. L. Knill. The application of engineering geology in the regional development of northern and central Iran. Engineering Geology, April 1969, vol. 3, No. 2, pp. 81-120.

Hariri, D. A study of interrelationship between surface water and ground water in the Karaj river basin. CENTO Symposium on Hydrology and Water Resources Development, Ankara, 1966, pp. 227-241.

__________ and P. Akbari. Contribution à l'étude hydrogéologique du bassin versant du Kordan-Rud, Iran. Thèse doctorale, troisième cycle, Université de Strasbourg, 1971.

Issar, A. The groundwater provinces of Iran. Bulletin of the International Association of Scientific Hydrology, vol. 14, No. 1, March 1969, pp. 87-99.

Kniul, J. L. and K. S. Jones. Ground-water conditions in greater Tehran. Quarterly Journal of Engineering Geology, December 1968, vol. 1, No. 3, pp. 181-194.

Kutchekpour, A. Contribution à l'étude hydrogéologique du basin versant du lac Rezaieh, Iran. Thèse doctorale, troisième cycle, Université de Strasbourg, 1971.

Laurent, H. Prospection hydrogéologique de la plaine de Karadj à l'Ouest de Téhéran, Iran. Thèse doctorale, troisième cycle, Université de Paris, 1967.

Mahdavi, H. Summary of water resources development in Iran. International Conference on Water for Peace, Washington, D.C., 1967, vol. 6, pp. 68-73.

Nadji, M. Gèologie et hydrogéologie de la région de Kashan, Iran. Dissertation, Technische Hochschule, Aachen, Federal Republic of Germany, 1971.

Rieben, H. Final report to the Government of Iran on groundwater investigations. Document No. 1324. Food and Agriculture Organization of the United Nations, Rome, 1961.

Sutcliffe, J. V. and W. R. Rangeley. An Estimation of the Long Term Yield of a Large Aquifer at Tehran. International Association of Scientific Hydrology, publication No. 52, General Assembly of Helsinki, 1960, pp. 264-271.

Torabi Teherani, H. Étude hydrogéologique de la plaine de Kashan (Iran). Exploitation des eaux salées en bordure du désert. Thèse doctorale, troisième cycle, Université de Strasbourg, 1971.

Tscheltzoff, O. W. L'Institut d'hydrogéologie de Téhéran. Chronique hydrogéologique, mars 1967, No. 10, pp. 129-132.

Vistamehr, H. Contribution à l'étude géologique et hydrogéologique du bassin versant du Zaiandehrud (Zagros et Iran central). Thèse doctorale, Université des Sciences et Techniques du Languedoc-Montpellier, 1973.

Area: 434,924 km^2

Population: 12,171,480 (October 1977 census)

General

Iraq is mainly a flat country. The central part of the country is occupied by the vast Mesopotamian plain, bordered in the west and south by desert plateaux with elevations from 200 to 700 m above mean sea level and in the north and east by the range of folded mountains of the Zagros and east Taurus systems with heights up to 3,000 and 4,000 m above mean sea level. The high mountains and deep valleys in the north and north-east cover an area of 23,500 km^2 (6 per cent of the total area of Iraq). Their heights range between 750 and 3,600 m above mean sea level. This zone is flanked from north-west to south-east by a region of foothills which covers an area of 67,000 km^2 (15 per cent of the total area of the country), with elevations between 200 and 750 m above mean sea level. The area is cut by broad valleys of economic importance.

Throughout these regions are several rivers and streams which supply almost 65 per cent of the Tigris River water.

The great western plateau having a gradual upward slope westwards, constitutes the major part of western Iraq, covering an area of 263,000 km^2 (58 per cent of the total area of the country). The height of this plain ranges from mean sea level to 100 m.

The climate of Iraq is basically of the subtropical-continental arid type with dry hot summers lasting for nearly four and a half months, mild winters of about three months duration and two short transition seasons of spring and autumn. This general pattern is affected locally according to topography.

In the mountains in the north and north-east, the climate is characterized by low temperatures, cold winters, mild summers and abundant snow and rain.

In the foothill plateau and plain part, the climate is continental - subtropical with hot summers and cool winters. The area receives less rain than the high mountains. The western plateau has a tropical desert climate characterized by hot summers and receives very small amounts of rain in the winter. The influence of the Gulf on the climate of Iraq is very limited. Near the Gulf, the relative humidity is higher than in other parts of the country.

There is practically no rain during the summer. Snow falls only in the northern mountain regions where the annual precipitation ranges from 800 to 1,000 mm. Rainfall does not exceed 100-150 mm in the plains (see map 10).

Map 10

Iraq: mean annual rainfall

The mean annual temperature of the air varies from 15° to 16° C in the northern mountains and to 24° C in the middle and southern parts. The hottest month of the year is July with mean temperatures ranging from 30° to 35° C; the coldest month is January with mean temperatures from 2° C in the north to 12° C in the south. During the winter the air temperature is below zero, mainly at night. Absolute maximum temperatures reaching 50°-51° C are observed in July.

Evaporation is generally very high. Large amounts of surface and ground water are usually lost by this means. The evaporation ratio varies from one place to another, from 15 to 25 mm/day in the summer with yearly values exceeding 2.5 m.

The prevailing winds in all seasons blow in a north-westerly direction, the frequency of which is approximately 40 per cent. The total frequency of north, north-west and west winds is close to 70 per cent.

The Euphrates, one of the major rivers in the region, originates in Turkey from the confluence of the Karasu and Murat Su rivers. The total length of the river from the Murat Su River head to the confluence with the Tigris River is 3,065 km (1,213 km in Iraq); the catchment area is about 534,000 km^2. The Tigris River is second in importance in western Asia; the length of its course is 1,900 km (1,418 km in Iraq). The catchment area is 375,000 km^2 and its flow is far more important than that of the Euphrates. The Tigris receives its major tributaries downstream from the town of Mosul. The Shatt Al-Arab River originates from the confluence of the Tigris and Euphrates rivers at Qurna in the south and discharges into the gulf with a length of about 195 km and an average width of about 500 m. The total annual water supply of all rivers exceeds 69 billion m^3. Iraq contributes only 23 per cent of the total water supply of the basin.

Other water bodies include shallow lakes, swamps and marshes which are shallow depressions of flat-lying lowlands adjacent to the courses of the Tigris and Euphrates rivers in the lower region of Mesopotamia, and man-made lakes or reservoirs which are basically developed for flood control and irrigation.

Besides the above-mentioned rivers and lakes, many seasonal streams or wadis flow during the winter and spring in the northern parts of Iraq and also in the western desert.

Geology

The geology of the country is shown in map 11.

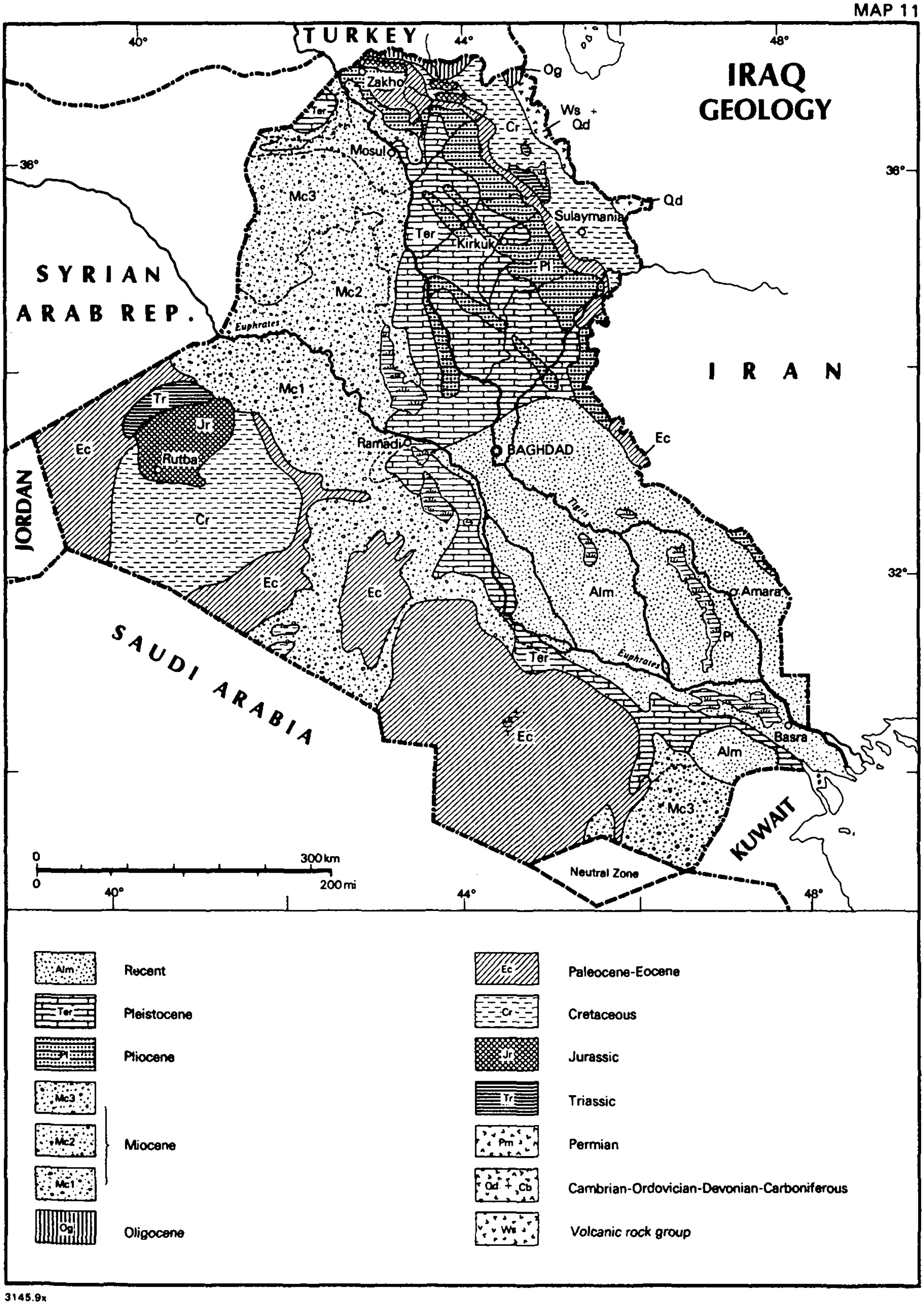
Paleozoic rocks are represented by a complex of three series of mostly Cambrian-Ordovician, Upper Devonian and Permian age. The Cambrian-Ordovician rocks are represented by quarzites, sandstones, siltstones, shales and micaschists and occur in the central parts of many anticlines in northern Iraq. The total thickness of these rocks is up to 600 m.

Upper Devonian formations include sandstones and shales with thin intercalations of limestones and micaschists. They occupy large areas in the vicinity of Amadiya and Zakho in northern Iraq.

Permian formations are discordant on the former. They are represented by highly differentiated deposits about 800 m thick. Near the border with Turkey, they include sandstone, shale and thin layers of dolomitic limestone.

Map 11

Iraq: geology



Triassic rocks occur in the northern part of Iraq as well as in the Gara depression in north-western Iraq. Lower Triassic rocks are represented by grey and yellow shale with thin inner beds of marls and limestones or by purple shales and marls which include thin beds of sandstones and limestones. Middle Triassic rocks consist of fine-grained grey-purple dolomites underlain by grey and yellow marly shales with limestone, marls and breccia. The thickness of these rocks is about 550 m. Upper Triassic rocks are developed mainly in the north of Iraq with dark grey dolomitic limestone and breccia. In the Gara depression, limestone prevails innerbedded with marls and bedded grey and reddish sandstones.

Jurassic deposits occur in the northern and north-eastern parts of Iraq and also in the southern part of the Gara depression. Lower Lias is represented by dark thin-bedded, fine-grained dolomites and dolomitic limestones interbedded with green shales and in some cases aggregates of anhydrites. Upper Lias is represented by massive, dark grey or black, bituminous dolomite and dolomitic limestones that are grey-blue in colour. Total thickness is 100 to 350 m. Deposits of Middle Jurassic age consist of black shale interbedded with thin limestone layers. Upper Jurassic rocks are represented by thin layers of dolomite and limestone interbedded with bituminous shales.

The contact between the Jurassic and Cretaceous rocks is not well defined. Lower Cretaceous rocks include marls, shales and limestones, while Upper Cretaceous rocks are represented by compacted and fine-grained (locally crystalline) dolomitic limestones (50-150 m thick) and rarely by marls.

Paleocene deposits occur in the north-eastern part of the country. They include lenticular grey-green bituminous sandstones with thin beds of marly limestone, shale and marls and detritic and organic limestones. The upper parts of the Paleocene are of volcanic series and occur in the thrust zone to the north-east of the country.

Eocene rocks are developed in the northern and north-eastern parts of Iraq, and also in the south-western parts. In the thrust zone, Eocene rocks are probably represented by the Kandil metamorphic series which occur near the border with Iran. Eocene rocks also include the red formations of Dohuk (limestones, conglomerates and shales). In other areas, Eocene rocks consist of sporadic conglomerates and limestones innerbedded with massive, locally dolomitic limestones overlying basal conglomerates.

In the western desert, formations considered to be Eocene include limestones commonly having marly or chalk-like innerbeds and numerous and diversified karst forms such as sink holes, funnels or uvalas.

In the north-western parts of the thrust zone, limestones and "red series" are Oligocene in age. They consist of alternating shales, sandstones, and conglomerates. Oligocene deposits near Anah in the west are represented by limestones.

The Middle and Upper Miocene are known as Lower and Upper Fars formations. Lower Miocene includes reef limestones called the Euphrates limestone. Middle Miocene (Lower Fars formations) is developed in northern Iraq with layers of clays, marls, shales, limestones and gypsum.

Upper Miocene (Upper Fars) formations occur everywhere within the thrust zone, and they can be observed on the slopes of many anticline ranges where they overlie the Lower Fars. They include continental deposits such as clays, sandstones, and fine-grained conglomerates.

Pliocene-Pleistocene deposits are known mainly in the northern and north-eastern part of Iraq as the Bakhtiari formation.

All conglomerates in the central part of Iraq are classified as Pleistocene. Only a narrow zone spreading out along the Tigris River valley has been called Pliocene while Bakhtiari in the mountainous area is characterized by the presence of abundant marly and shale intercalations among conglomerates.

Quaternary formations occur mainly in river valleys and in depressions. The following types of deposits can be distinguished: alluvial, deluvial-proluvial, alluvial-proluvial, alluvial-limnic, torrential, eluvial, aeolian, chemical and irrigations.

Ground water

Hydrogeological investigations in Iraq started after 1920 when different localities of the country were surveyed, for the purpose of defining the potential of ground-water use. Because of the increase in water requirements a better knowledge of aquifers was needed, especially in desert areas where permanent water-supply sources were not available. Ground-water areas are shown in map 12.

Around 1950 only a modest number of wells had been drilled in the northern, western and central parts of Iraq. In 1953-1957, on the basis of the data which were then available and at the request of the Government, the Ralph Parsons Engineering Company prepared an over-all description of the hydrogeological conditions in Iraq.

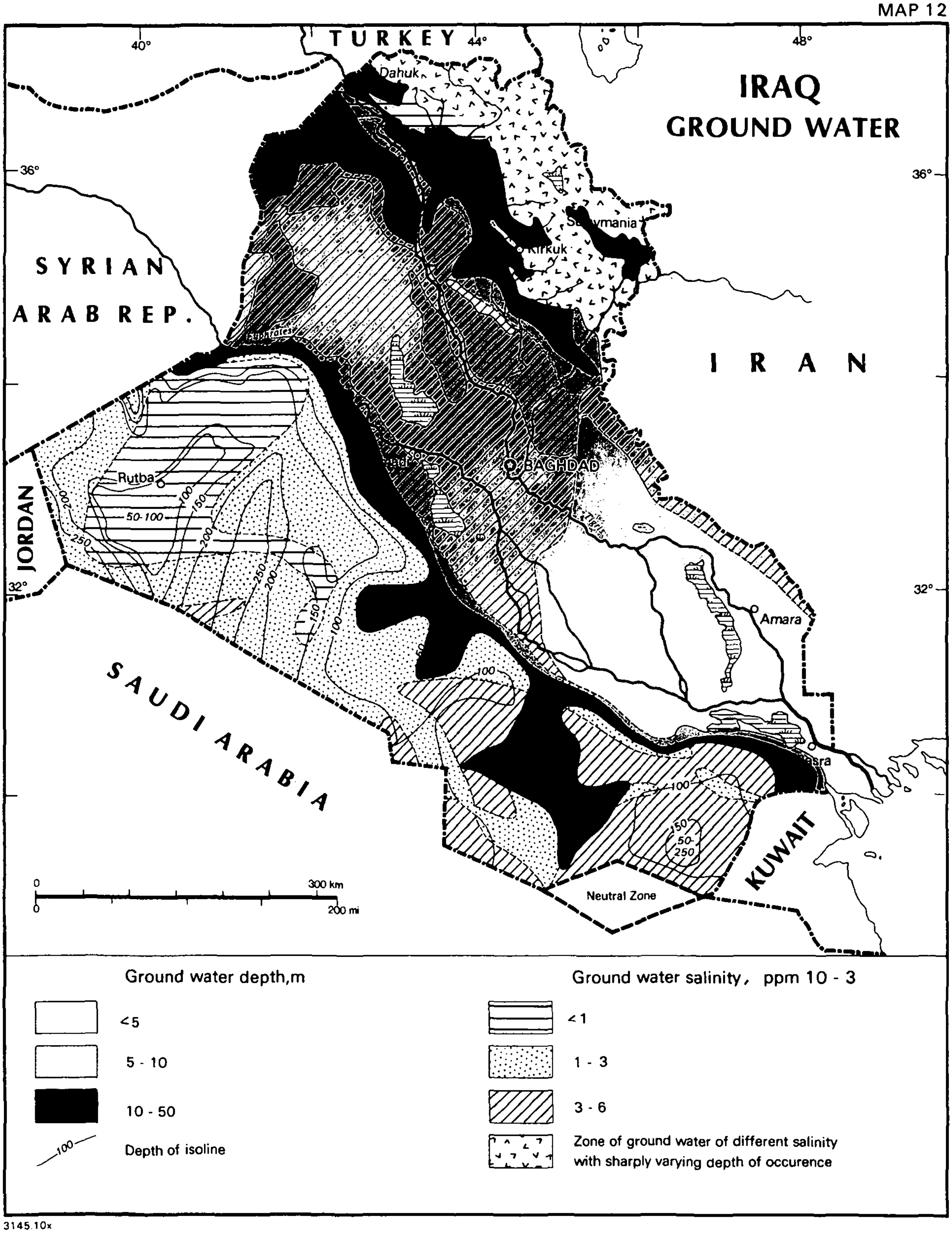
In the early 1960s, 110 wells were drilled in the northern and southern deserts. A statistical report was prepared on the hydrogeological conditions of the area. Other reports were also prepared using the drilling data and well logs available in the Ground Water Division of the Ministry of Agriculture. During the past 20 years, more than 2,500 wells have been drilled by different government organizations and foreign firms. The majority of the wells were suitable for exploitation. The number of hand-dug wells may be several times greater than that of drilled wells.

Prospecting methods

In Iraq, test drilling is the most common prospecting method used, together with geological mapping and photo-interpretation. Regional geological surveys are generally not used to locate wells. In recent years, systematic hydrogeological investigations in a few selected areas in the country were carried out by the Institute of Applied Research on Natural Resources, using such methods.

Map 12

Iraq: ground water



Hydrogeological characteristics and data such as coefficient of transmissivity, storage coefficient and hydraulic conductivity, specific yield, static and dynamic levels and chemical components of water were determined.

Results of ground-water investigations are summarized in table 8.

Table 8. Iraq: results of ground-water investigations

	Province	Geology	Depth of wells (m)	Specific field (l/sec/m)	Trans-missivity (m^2/day)
A	Northern Iraq				
A-1	Limestone	Cretaceous	20	...	...
A-2	Clastic	Cretaceous	3-5	1-1.5	...
A-3	Alluvium	Pliocene and Quaternary	...	...	...
B	Folded zone and terrace				
B-1	Bakhtiari	Pliocene and Pleistocene	10-40	7-20	1,000
B-2	Fars	Miocene and Eocene	5-20	0.1-0.3	70-80
C	Delta plain	Quaternary	1-5	...	...
D	Jezireh plain				
D-1	Lower Fars)	Miocene	20-50	...	...
D-2	Upper Fars)				
E	Desert				
E-1	Dibdiba	Miocene-Pliocene	70-100	...	...
E-2	Limestone	Eocene-Paleocene	(50-100)-(200-300)	2-5	300-500
E-3	Sandstone	Cretaceous and older	150-300	0.02-0.06	300-500

Main aquifers

The following artesian basins have been identified:

(a) East-Arabian artesian basin;

(b) Mesopotamian artesian basin;

(c) Zagros-Taurus group of artesian basins.

Since deposits of the same age occur in different basins, the description of water-bearing formations and groups of formations is given according to stratigraphical differentiation of water-bearing deposits.

Aquifers in Mesozoic deposits have not been studied thoroughly. Data obtained on several wells revealed the occurrence of ground water in Cretaceous rocks developed in the western desert plateau, where they lie at a depth of 150 m. Yield varies from moderate to low. Cretaceous artesian aquifers are related to fissured limestones in northern Iraq and in the western desert, and with sandstones in some other parts of the western desert. Salinity of the ground water discovered at a depth over 200 m in slightly fractured limestones and sandstones ranges from 1,000 to 1,500 ppm. Water hardness is high, water reaction is alkaline and specific yield of wells is rather low. In the east of Iraq, within the boundaries of the third group of artesian basins, Cretaceous aquifers are highly productive of good quality water.

The Paleocene-Eocene formations contain the major ground-water resources in the western plateau area. Precipitation within the boundaries of the complex extension is the recharging source and full discharge actually happens at the Abu Jir fault tectonic zone.

Eocene aquifers (sand or sandstone intercalations within dolomites and limestones) occur at various depths (40-130 m). Water capacity and yield of wells is small.

The Euphrates formation of Lower Miocene age represents the most important and the best potential source of ground water. Aquifers are confined with fissured limestones interbedded with marls and gypsum. The yield of wells is substantial and locally is relatively high. Occurrences are mainly along the Euphrates valley at shallow depths (20-75 m). Water quality is variable.

Lower Fars aquifers of Middle Miocene age are confined, with limestones interbedded with clay, marl, and gypsum. They occur in many areas of Iraq, at various depths (down to 50 m); water capacity and yield of wells are low. Waters are often highly mineralized.

Aquifers of Upper Fars (Upper Miocene) are confined with sandstone intercalations in clay and marls. They occur in many areas of Iraq at depths from 5 to 30 m. The aquifers are recharged by precipitation and by water originating from underlying layers. Artesian water occurs in some water-bearing sandstone layers. Almost everywhere, the piezometric level is between 5 and 20 m. Salinity increases generally with flow to a maximum in discharge areas from 500 to 3,500 ppm.

Pliocene-Pleistocene aquifers are represented in the north by the Bakhtiari deposits and coarse proluvium and in the east mainly by peripheral fine proluvium. The aquifers are recharged in the northern part of the country by precipitation and discharge as natural flow in valleys of the river. The ground-water depth in this zone seldom exceeds 40 m. Salinity ranges from 300 to 3,500 ppm.

The eastern zone of the Pliocene-Pleistocene aquifer has not been studied significantly. Ground water recharge is mainly from surface flow and discharge commonly in the form of springs and evaporation.

Alluvial quaternary aquifers are mainly related to recent deposits. They are moderately to highly productive when they include fine gravel and sand layers with a thickness of 10-25 m. Ground-water recharge and discharge are closely related to the régime of rivers as well as of aquifers for which terraces become the discharge area. Salt content ranges from 800 to 25,000 ppm.

Water quality

In general, ground water is acceptable for domestic use and for irrigation, but is generally mineralized. High carbonate content is the characteristic feature of water; next come sulphate and chloride. The most severe problem is salinity and sulphur intrusion, which locally may exceed 30,000 ppm. Such waters occur over the whole Mesopotamia plain up to Tharthar Lake.

High ion concentration of SO_4, Cl and NO_3 is normally associated with Lower Fars evaporites (anhydrite, gypsum, halite). Water with high nitrate content occupies relatively small areas and is recorded in some parts of the Jezireh plain and in the northern desert. Alluvial-proluvium and locally alluvial waters can be sulphuric or salty-sulphuric.

Ground water with concentrations up to 2,500 ppm is considered suitable for drinking in rural areas of Iraq where water with a total dissolved solids content up to 3,000 ppm is also acceptable for drinking provided that the nitrate content is less than 50 ppm. Bacteriological tests are not made for ground water in the country; therefore water considered potable in rural areas may not meet international standards.

Ground water development

The main source of water in the majority of the country is surface water, but ground water constitutes one of the most valuable water resources in Iraq, especially in foothill and desert plain areas.

The Administration of Ground-Water Utilization of the Ministry of Agriculture, with its well trained staff of hydrogeologists, engineers, technicians and drillers, is responsible for well-drilling and ground-water extraction. It is also responsible for the maintenance of existing wells through its regional divisions. A small number of local private firms are currently drilling some shallow water wells for irrigation purposes and domestic use. From time to time, foreign firms may carry out drilling programmes financed by the Government.

No other agencies deal with ground-water assessment and development. However, the Foundation of Scientific Research, the State Organization of Minerals and the Ministry of Irrigation, all carry out ground-water investigations for their own purposes, but not for ground-water development.

All the above-mentioned firms and organizations have their own trained staff of geologists, engineers, drillers, laboratory assistants and drilling rigs of several types and capacities.

Utilization of ground water

In Iraq, 52 per cent of the urban population but only 2.3 per cent of the rural population are provided with piped municipal water supplies. Approximately 15 per cent of the rural population uses water from drilled wells and dug wells.

Water consumption by the urban population for domestic use and by industry averages 90-100 l/day *per capita*.

Actual water consumption by rural population for domestic use (excluding needs of agricultural production) amounts to 30-40 l/day per inhabitant.

The analysis of data on the present state of water supply for the urban and rural populations leads to the conclusion that the supply does not meet the requirements (see tables 9 and 10).

Table 9. Iraq: water supply to towns, industry and rural settlements, 1975

(Thousands of m^3/day)

Water consumers and water sources	Zone			Total
	Northern	Central	Southern	
Towns				
Surface water	37	235	58	330
Ground water	30	9	1	40
Industry and thermal power stations				
Surface water	200	617	453	1,270
Ground water	20	5	...	25
Rural settlements				
Surface water	28	243	132	403
Ground water	80	30	2	112
TOTAL				
Surface water	265	1,095	643	2,003
Ground water	130	44	3	177

Table 10. Iraq: water consumption in towns and rural settlements, 1975
(Litres per day per inhabitant)

	Zone		
	Northern	Central	Southern
Averaged indices for all towns			
Domestic and drinking water supply	108	108	120
Water supply for local industry	5	5	6
Watering of gardens, streets etc.	11	23	26
TOTAL	124	136	152
Water supplied for agricultural needs			
Domestic and drinking water supply	49	54	60
Production zone	4	4	5
Animal husbandry	64	56	85
Watering of gardens, streets etc.	76	190	200
TOTAL	193	304	305

Rural water supply

There are nearly 10,000 settlements in rural areas of Iraq. The distribution of settlements over the country is uneven. In the north, the average land area related to one settlement is 18 km^2, in the central part as much as 120 km^2 and in the south 71 km^2.

In the north, 70 per cent of the settlements are supplied with water from wells and springs and 23 per cent from rivers and irrigation canals. The remaining 7 per cent of the water is brought in from more distant areas. Eighty-four per cent of the settlements in the central part and 91 per cent of the settlements in the south use surface water.

An analysis of the present water supply shows that an average rate of withdrawal from water intake posts is 42 l/day per capita. Water transported to the consumers in water tankers is distributed at the rate of 24 l/day per capita. During the summer, in the regions where water is supplied from dug wells, the rural population suffers great difficulties because of the sharp lowering of the water level in dug wells and the increase in water salinity. In many cases, dug wells become dry.

Only 93,000 people or 2.3 per cent of those living in 217 rural settlements are provided with a piped water supply. About 70 per cent of the population takes water directly from rivers, lakes, ponds, seasonal water courses, irrigation canals or uses rain water accumulated in natural depressions for domestic and drinking purposes. Fresh and saline ground water is obtained in modest quantities from dug wells of traditional construction equipped with traditional devices for water extraction.

After 1955, the construction of dug wells was undertaken on a large scale. The purpose of these wells is twofold: water supply and irrigation. In the vicinity of the wells used for water supply, water intake points comprise a pumping station and a storage basin with a capacity of up to 50 m^3. Technical data in water wells are shown in table 11.

Table 11. Iraq: technical data on water wells, 1978

	Zone			
	Northern	Central	Southern	Total
Number of wells	671	798	29	1,498
Depth (m)	10-339	10-481	17-203	10-481
Piezometric level	1.5-63	Flowing to 207	1.2-15	Flowing to 207
Dynamic levels (m)	13-138	Flowing to 290	1.2-84	Flowing to 290
Well yield (m^3/h)	1.14-263	1.1-177	2.18-18.2	1.1-263
Salinity (ppm)	190-9,950	246-10,000	1,400-10,000	190-10,000

Projected needs

Studies prepared by the Ministry of Planning show that by 1995, the situation will have improved considerably. It is expected that 95 per cent of the urban and 80 per cent of the rural population will be provided with a piped water supply. The water allocation is to be increased from 330 to 460 l/day per capita in urban areas and 315 to 525 l/day per capita in rural areas, taking into account agricultural production needs.

Water consumption by the population (urban and rural), agricultural production and industry, including thermal power stations, will increase from 2.2 km^3/year in 1975 to to 12.8 km^3/year in 1995 including 12.0 km^3/year of surface water and 0.8 km^3/year of ground water. The volume of ground-water withdrawal is in line with the explored resources of fresh and slightly saline ground water and, in 1995, it will constitute approximately 6 per cent of total water withdrawal (see table 12).

Table 12. Iraq: annual potable and industrial water withdrawals

(millions of m^3/year)

Water consumers	1975	1995
Potable water		
Urban and rural population (domestic needs) and small industries	541	1,982
Industry and thermal power stations	6	56
Subtotal	547	2,038
From surface sources	450	1,641
From ground sources	97	397
Industrial water		
Industry and thermal power stations	1,289	9,244
Irrigation of green plantations and gardens	344	1,541
Subtotal	1,633	10,785
From surface sources	1,553	10,425
From ground sources	80	360
TOTAL	2,180	12,823
From surface sources	2,003	12,066
From ground sources	177	757
Irretrievable water consumption	1,207	3,603

Problems

As shown by hydrometeorological data, the average rainfall decreases considerably from the north-east to the south-west. Ground-water flow also decreases in this direction. It could be increased by means of infiltration basins impounding the surface flow. Ground-water intake structures constructed in zones commanded by the basins could be exploited more intensively than under conditions of natural recharge.

Conclusion

Although surface water is the main source of water supply for about 50 per cent of the country, ground water is an essential source of supply in desert areas (which cover about 58 per cent of the country) and some parts of Jezireh and the foothills. Ground water represents the most important factor for the development of areas in the western desert in the future. Consequently, the main stress will be on the detailed recognition of hydrogeological conditions in this region and a reasonable development of the ground-water resources. It is planned to drill 160 deep wells over the whole western desert within a few years.

Generally, the cost of ground water (per cubic metre) is relatively high owing to the depth of wells and the cost of maintenance. It is emphasized that a large number of new drilled wells are dry or are characterized by a small yield. Many of these wells become dry after a period of time. The water is highly mineralized and has to be treated before use. Therefore, the supply of water for drinking and for industrial purposes should have priority over that for irrigation.

Large-scale surveys and development schemes for all aquifers of the country are being considered. They are elaborated by the Ministry of Agriculture and Agrarian Reform. According to these plans about 1,000 new deep wells were to be drilled each year between 1976 and 1980. At the end of 1980 about 4,500 new wells were made available for water production.

The problem of desalination of ground water has not been dealt with, but it should be solved in 10-15 years' time. Solving the problem would be of particular significance in respect of the vast region of Mesopotamia.

Selected references

Adnan, M. and W. Kraft. A contribution to the hydrogeology of the Western Desert. Journal of the Geological Society of Iraq, vol. V, July 1972.

Baghdadi, A. Ground Water in Iraq and its domestic use, supply and planned utilization. Report submitted to the twentieth International Geological Congress. Mexico, 1957.

__________. Ground water is Iraq. Bulletin of the College of Arts. Baghdad University. 1960.

__________. Ground water - an important resource of Iraq. Proceedings of the seventh Arab Engineers Congress. 1964.

Elerdashvilli. Hydrogeology and Engineering Geology of Iraq. Moscow, 1973.

El Kiki F., T. S. Al Din and H. A. Hassan. Hydrogeological conditions of Bakhtiari aquifer in Shari lake basin. Journal of the Geological Society of Iraq, vol. VII.

Haddad, R. H. and others. Ground water resources of Altun Kopri area. Foundation of Scientific Research. Technical Bulletin No. 69, 1974.

__________. Ground water resources of Erbil area. Foundation of Scientific Research. Technical Bulletin No. 70, 1975.

Hassan, H. A. Hydrological, Hydrogeological and Hydrochemical Investigations of Bahr el Najaf Area. M.Sc. thesis. College of Science, Baghdad University. 1973.

__________, A. El Obeidy and F. El Kiki. Hydrogeological conditions of Al Hamad area in Iraq. Institute of Applied Research on Natural Resources. Technical Report No. 3, 1974.

__________, C. Griolet and S. M. Ayob. Galal Badra Project area - Hydrogeological conditions Foundation of Scientific Research. Technical Bulletin No. 106, 1977.

Jabrael, N. An evaluation of ground water resources in Iraq. Institute of Applied Research on Natural Resources. 1973.

Khashab, W. Facts and speculations about the water supply of Iraq. Baghdad, 1960.

MacFadyen, W. Water Supplies in Iraq. Publication of Iraq Geology Department. 1938.

Nelson, J. Water resources in Iraq. 1938.

Parsons, Ralph, Engineering Company. Ground water resources in Iraq (13 volumes). Baghdad. 1955-1957. Supplemented with a geological map on a scale of 1:317,000. In 1957, the following maps were compiled on a scale of 1,2000,000:

Geological map;
Map of ground-water depth;
Isohyet map;
Nitrate-ion concentration map;
Ground-water salinity map;
Physiographical map;
Soil salinity contour lines map.

Sedow, A. W., H. A. Hassan and A. Al-Dakhil. Present state of knowledge on hydrogeology in Iraq and desired future development. Journal of the Geological Society of Iraq, vol. IV, 1971.

Selkhozpromexport. General scheme of water resources and land development in Iraq. Baghdad and Moscow, 1975.

ISRAEL

Area: 20,700 km^2

Population: 3,750,000

General

Israel is situated on the eastern shore of the Mediterranean Sea. The country forms a narrow strip about 500 km long in a north-south direction and comprises four major physiographical units (see map 13).

(a) Coastal plains

The coastal plains are undulating areas built of calcareous sandstone with a cover of light-medium soils.

(b) Hill region

The hill region rises to elevations of more than 1,000 m above mean sea level in the mountains of Galilee, Samaria and Judea and to only 550 m at Mount Carmel. The higher ranges are mainly hard limestone and dolomite; the lower hills are covered mainly by chalk and, in eastern Galilee, by basalt.

(c) Inland valleys

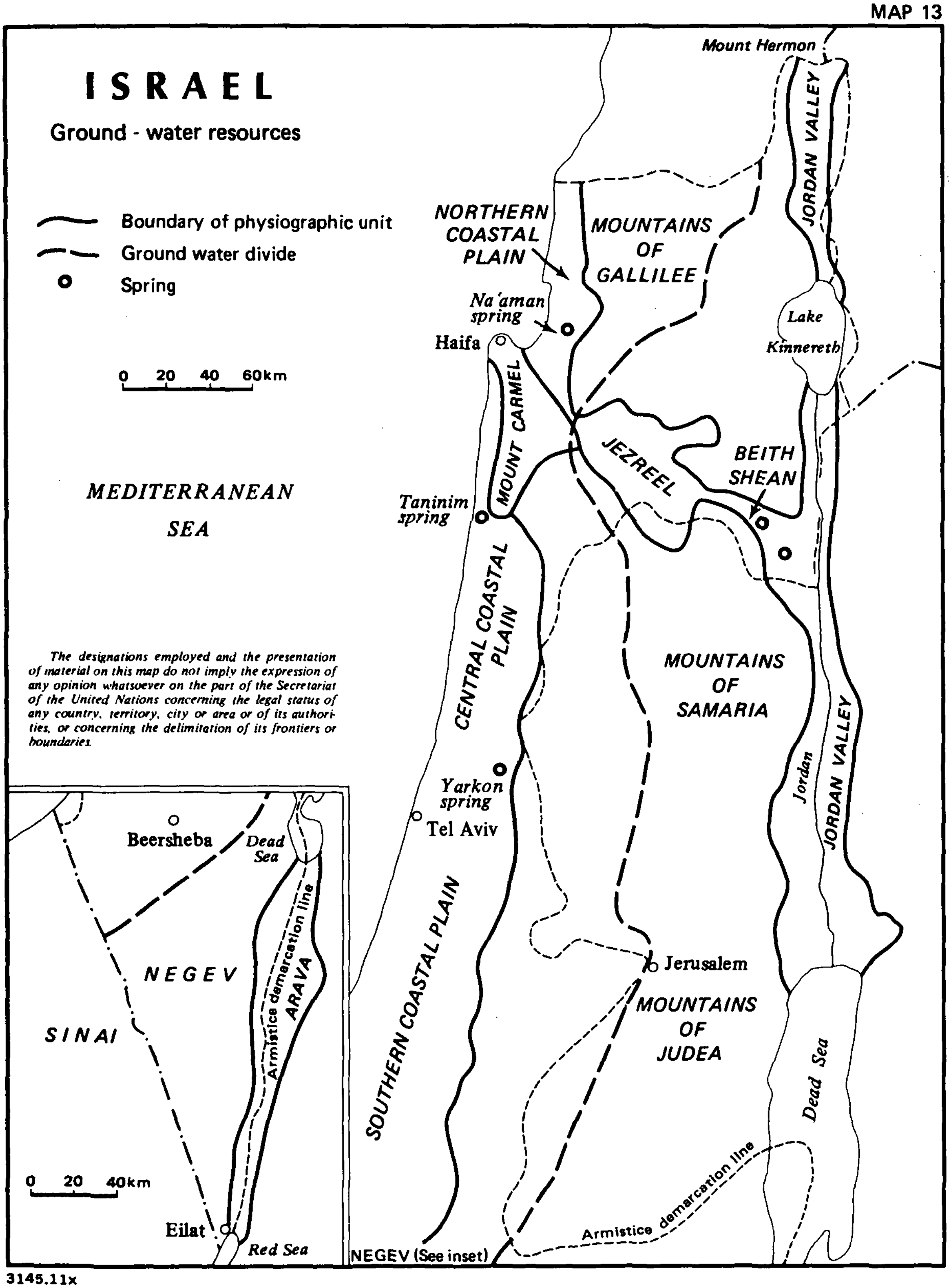
The inland valleys are plains hemmed in on both sides by steep mountain slopes. The Jordan Valley extends from the foot of Mount Hermon (2,800 m above mean sea level) in the north to the Dead Sea (400 m below mean sea level) in the south. Lake Kinnereth (210 m below mean sea level) is situated in its northern part. The floor of the valley is covered by deep alluvial soils in the north and by gypsiferous marls in the south. The Jordan river meanders in a deep canyon in the centre of the valley. The Arava is the southern continuation of the Jordan Valley from the Dead Sea to the Red Sea, a branch of the Indian Ocean. Detritic materials, sands and sandy silts, fill the valley to a depth of several hundred metres. On the mountain borders in the east and west there are large alluvial fans. A characteristic feature of this desert area is several salt marshes formed by the emergence of ground water at the surface. The valleys of Jezreel and Beith Shean extend from Mount Carmel to the Jordan Valley in a north-west to south-east direction. They are covered by heavy, deep, alluvial soils.

(d) The Negev

The Negev comprises two parts. In the larger southern part, rugged mountains rise to elevations of 800-1,000 m above mean sea level. The outcropping rocks are chalk, limestone, dolomite, multicoloured sandstone, and granite at the southern tip of the Negev. The smaller north-western part is an undulating area covered mainly by windblown sands and loess.

Map 13

Israel: ground-water resources



The climate of Israel is mainly semi-arid to arid. The rainy season lasts from October to April; about two thirds of the annual rainfall occurs during the winter months of November to February. The coastal plains and the western slopes of the hill region comprise less than half of the area of Israel but have a Mediterranean climate with an average annual rain between 750 and 500 mm/year. The north-eastern areas in the rainshadow of the mountains, and the northern fringes of the Negev have a steppe climate with rain decreasing from 400-250 mm/year. A desert climate prevails in the south-eastern half of the hill region, the Negev and the Arava. Precipitation ranges from 200 mm/year in the northern Negev to 15 mm/year on the shore of the Red Sea. Deviations of $\pm$ 25 per cent from the 30-year average are common in the Mediterranean region; even larger deviations frequently occur in the desert regions.

River flow is minimal. Apart from the Jordan there are only a few small perennial or seasonal streams fed through springs. Most river beds carry water for a few days each year only, if at all.

Geology

The folded structures composing the hill country started to emerge from the sea during the Senonian, and probably took final shape during early Miocene. The axes of the structures are aligned in a north-north-east to south-south-west direction in the northern half of the country and from north-east to south-west in the Negev. Limestones and dolomites of Turonian-Cenomanian age crop out in anticlinal positions with chalks of Senonian-Eocene age in synclines. In the Negev several anticlines have been eroded into terrestrial sandstones of Lower Cretaceous age and, in some places, even down to the Jurassic and Triassic.

A phase of faulting associated with the formation of the African Rift Valley created horsts, grabens and tilted blocks. The most intensive faulting took place towards the end of the Pleistocene and was witnessed by Early Paleolithic man. The Jordan depression, the Arava, and the Yezreel-Beith Shean Valleys are, essentially, down-faulted grabens. In the Carmel and in Galilee, pre-existing fold structures were broken up into series of tilted blocks. Magmatic effusions accompanying faulting deposited basalt sheets in eastern Galilee.

Eustatic changes of sea level during the Pleistocene, probably accompanied by some vertical crustal movements, caused repeated transgressions and regressions of the Mediterranean Sea and deposited sands and sandstones on the coastal plains. At the same time the inland valleys were filled up with detritic material and alluvial soils.

A summary of the aquifers is given in table 13. The geological ages are only indicative; local formation names are omitted.

Table 13. Israel: aquifers

Approximate geological age	Description	Hydrological importance
Pleistocene	Littoral sand and sandstones with intercalated layers of sandy silt; up to 150 m thick	Aquivers of the coastal plains
	Detritic material, sand and silt	Aquifer in the Arava
Neogene	Dark marine clays intercalated with thin sand beds	Bottom of the coastal plain aquifer in the southern part of Israel
Eocene	Chalks, locally siliceous	Confining bed in the hills
Senonian	Soft chalks with chert beds; locally bituminous	Confining bed above the Tertiary-Cretaceous aquifer
Turonian-Cenomanian	Dolomites and limestones up to 800 m thick; in some localities divided into an upper-limestone facies, middle chalky-marly facies, and lower dolomitic facies	Aquifer of the hill region
Albian-Aptian	Mainly marls	Bottom of all aquifers in the northern half of the country
Neocomian	Coarse grained, terrestrial sandstone	Aquifer in the Negev
Jurassic	Massive limestone in Mount Hermon; mainly chalky-shaly strata attested from bore-holes in Israel	Feeds the springs of the Jordan; otherwise hydrologically unimportant

Ground water

Ground-water replenishment and direction of drainage

In the northern half of the country, ground water is replenished by rain on the outcrops of the various aquifers. The water balance of the Mediterranean region is approximately as follows: 30-33 per cent of the average rainfall percolates into aquifers, 2-5 per cent forms surface run-off, and the rest returns to the atmosphere by evapo-transpiration. Yearly replenishment is subject to larger deviation from the mean than yearly rainfall, since a certain quantity, 300-400 mm/year, is invariably used by vegetation, and only the rest generates ground-water replenishment and surface run-off.

In the Negev and the Arava, ground water is replenished by partial infiltration of the rare floods. Isotope data indicate that the major part of the ground-water reserves, especially those in the Lower Cretaceous aquifer, are fossile, probably of Pleistocene age.

Ground water drains towards two base levels, the Mediterranean in the west and the inland valleys, which lie below msl over most of their length, in the east. Water level observations show that the ground-water divide generally coincides with the axes of anticlinal structures where Albian marls rise above the regional water table and thus constitute an impermeable barrier boundary. In the southern part of Galilee this pattern is disturbed by down-thrown fault structures and, as a consequence, the ground-water divide is shifted to the north-west.

In the mountain aquifers of the Negev, water levels are near or below mean sea level, thus indicating that small ground-water flow is directed towards the Arava from the east. The unconsolidated shallow aquifers of north-western Negev drain towards the Mediterranean Sea.

Ground-water regions

The aquifer of the central and southern coastal plain consists of calcareous sands and sandstones with interbedded layers of sandy silt. At the seashore it is 120-150 m thick and wedges out at the foot of the hill region.

Permeabilities calculated from pumping tests range from 10 to 60 m/day, average values obtained by calibration being 20-30 m/day. The specific yield is about 25-30 per cent.

Wells are 80-140 m deep and have specific capacities of 25-50 m^3/h/m of draw-down.

The Tertiary-Cretaceous aquifer of the regions of western Judea and Samaria drains towards two springs, the Yarkon spring near Tel Aviv and the brackish (750 ppm chloride) Tanninim spring, with a combined discharge of 300 million m^3/year. The concentration of ground-water flow from a large massif into two springs is attributed to the development of karstic solution channels.

The aquifer is developed by wells drilled mainly into its confined part all along the foothills. Specific capacities range from 50 to 300 m^3/h/m of draw-down. Calibration yielded enormous values, 50,000-100,000 m^3/day for the transmissivity of the aquifer, and a coefficient of storage of about 5 per cent. Owing to intensive ground-water withdrawals, spring discharges have markedly declined.

The Tertiary-Cretaceous aquifer of the Carmel Range is developed by wells 60-200 m deep. Natural drainage of ground water is effected mainly by direct seepage into the Mediterranean Sea, although a few small springs are also present.

The interface between sea water and fresh water is replaced by a zone of transition several hundred metres thick. Exploitation of all wells has to be carefully controlled in order to keep salinity at an acceptable level.

The Tertiary-Cretaceous aquifer of western Galilee is divided by an east-west fault line into two distinct parts. The lower southern part drains through the Na'aman spring which discharges in the natural state about 40 million m^3/year of brackish (700 ppm chloride) water. Spring flow has declined to a small trickle because of the intensive ground-water withdrawals from wells yielding fresh water.

In the higher northern part, ground water drains through several small fresh-water springs, by lateral overflow into the aquifer of the coastal plain, and by direct seepage into the Mediterranean Sea. There are two aquifers, an upper one and a lower one, separated by a marly horizon about 200 m thick. Wells are about 80 m deep in the upper aquifer and 300-800 m deep in the lower one. Water quality in both aquifers is excellent.

In the narrow coastal plain aquifer of western Galilee ground water is developed by shallow wells.

In eastern Galilee ground water is developed from the lower part of the Tertiary-Cretaceous aquifer and from basalt aquifers. Specific capacities are small, 2-10 m^3/h/m, except for one location near a karstic spring where discharges of 1,000 m^3/h/m were obtained.

Aquifers draining through the Yezreel-Beit Shean springs comprise Tertiary-Cretaceous limestones and dolomites, Eocene chalks, and Neogene-Pleistocene basalts. Most springs are brackish with salinities ranging from 300 to 1,000 ppm of chloride. Total spring discharge amounts to about 100 million m^3/year.

Ground water of good quality is developed mainly from wells drilled into the Tertiary-Cretaceous aquifer. The chalk and basalt yield minor amounts of water. Due to a succession of drought years and to intensified ground-water withdrawals spring discharges are gradually declining.

In the Negev, ground water is developed from the Tertiary-Cretaceous and the Lower Cretaceous sandstone aquifers. The wells are 500 to more than 1,000 m deep and pumping lifts are large, exceeding 200 m in several localities. Salinities range from 400 to 1,500 ppm of chloride.

A few shallow wells develop water from the sand dunes in the north-west corner of the Negev.

In the Arava, ground water is developed from three aquifers: detritic strata of the piedmont zone, Tertiary-Cretaceous limestone and Lower Cretaceous sandstone. The water tends to be brackish, with a chloride content between 400 and 3,000 ppm.

The traditional use of this mineralized water is for the irrigation of date palms. Drip irrigation and a scientifically controlled supply of fertilizers also makes it possible to grow vegetables and flowers for export. Intensified ground-water withdrawals have caused the saline swamps to shrink.

Ground-water administration and management

Ground-water withdrawals amount to about 1 billion m^3/year. This quantity constitutes approximately two thirds of the country's total water supply and is very near to the estimated limit of exploitation on a sustained basis. The need for a strict regulation of ground-water withdrawals is, therefore, evident.

According to the water law of Israel, all water resources are public property subject to control by the State. Executive authority is vested in the office of the Water Commissioner. Well-drilling and the withdrawal of ground water require licences, the latter licence being subject to yearly modifications according to the hydrological situation.

The majority of the wells belong to a state-owned water supply company which metres the water withdrawn from them. The production of privately owned wells is controlled on the basis of electricity consumption. Diesel-driven installations have practically disappeared.

Water levels, water quality and special parameters, such as the position of the interface in the coastal aquifer, are monitored by the Hydrological Service, a branch of the Water Commissioner's Office. Geological data of newly drilled wells are collected by the Geological Survey.

Data evaluation and hydrological research are carried out by the Hydrological Service, the Geological Survey, TAHAL (a state-owned company specializing in water supply planning) and by several academic institutions.

Ground-water management pursues three aims: (a) the efficient utilization of all water resources; (b) the provision of dependable water supplies, notwithstanding the seasonal and undependable rainfall; and (c) the substitution of usable water pumped from wells for brackish spring flow wherever possible.

Artificial replenishment and underground storage are used in order to achieve the first two aims. During the winter season, water from the Jordan conduit is recharged into the Pleistocene and Tertiary-Cretaceous aquifers in the central part of the country. Two installations recharge water from seasonal streams through spreading grounds into the coastal aquifer. A total of 80 to 170 million m^3/year, depending on the annual rainfall, is thus recharged into aquifers for seasonal and long-time storage.

The substitution of usable water for brackish spring flow has been mentioned in the regional discussion.

Selected references

Arlosoroff, S. Israel - a model of efficient utilization of a country's water resources (E/CONF.70/TP 150). Submitted to the United Nations Water Conference, Mar del Plata, Argentina, 1977.

Central Bureau of Statistics. Statistical Abstract of Israel, No. 29, 1978.

Mandel, S. The Turonian Cenomanian Aquifer in Western Israel. Haifa, Technion, 1961. Hebrew, English summary.

Ministry of Agriculture. Water Commissioner's Office, the Hydrological Service. Hydrological Yearbooks of Israel.

Ministry of Labour. Department of Surveys. Atlas of Israel, sections III-V.

Picard, L. Structure and Evolution of Palestine. Jerusalem, Hebrew University, 1944.

Prushansky, Y. Water Development. Fifth revised edition. Jerusalem, Israel Digest, 1967.

JORDAN

Area: 97,740 km^2

Population: 2,779,000 (United Nations estimate, 1976)

General

Most of Jordan, a land-locked country with the exception of a narrow coastal opening in the Gulf of Aqaba, consists of arid, rocky and sandy hills and plains with fertile uplands, west of the River Jordan. The country's present needs for water for agriculture are met from the annual rainfall, although this is scarce in volume and extremely variable in space and time. Schemes for the development of surface water and ground water are therefore receiving great emphasis to meet the increasing demands of agriculture and industry, as well as increasing municipal requirements.

Surface waters in Jordan are concentrated in the Jordan Valley region, the Dead Sea basin and the wadi Araba area, the average annual discharge being around 850 million m^3. Underground water is an important source of water in Jordan; it supplies much of the country's domestic and industrial requirements which, at the end of 1975, amounted to 421 million m^3 annually. By 1980 this requirement is expected to rise to 555 million m^3, distributed as follows:

Requirements	1975	1980
	(millions of m^3)	
Domestic	40	60
Industrial	6	30
Agricultural	375	465
Total	421	555

Jordan weather is often pleasant. In summer, the shade temperature seldom exceed 38°C and the nights are cool. In winter it is cold in the mountains. Winters in the Jordan valley, however, are warm and pleasant, although the summers are very hot.

Rainfall results from barometric depressions and cold fronts moving from the north-west. The cold fronts bring moist unstable air and precipitation of the frontal variety is activated by the country's western highlands. This rainfall is a highly seasonal winter event, being received from late October to March. It averages from 700 to 800 mm in the high mountain areas, and from 400 to 500 mm in the lower areas. The incidence and strength of cold fronts decreases eastwards and southwards causing a significant rain shadow in the lee of the mountains. In general, rainfall decreases gradually from north to south and rapidly from west to east. On an average, most of Jordan receives less than 200 mm per year, only 13 per cent of the country receiving more. In eastern Jordan, the rainfall decreases rapidly from 200 mm to 100 mm and 50 mm, and frontal events give way to the typical isolated desert storms. Rainfall intensities are generally low and not conducive to significant recharge. With regard to recharge, it is an interesting observation that ground-water levels, recorded over a 30-year period, are shown to be out of phase with the rainfall. As a general rule high ground-water levels are recorded in August, and low ground-water levels in February.

Winter humidities in the wetter months in western Jordan can often be as high as 90 per cent, though the average is around 55 per cent. In the summer months the average declines to around 35 per cent. However, in the eastern desert areas readings can be as low as 6 per cent, particularly when hot dry air masses move in from Iraq and Saudi Arabia. Evaporation is in line with other adjacent regions with readings averaging around 2 m or slightly above.

Geology

Jordan lies on the northern perimeter of the Arabian Shield. Rocks of the shield complex extend into southern Jordan and crop out along the top and sides of the Gulf of Aqaba, with northward occurrences in a thin strip to about 30 km south of the Dead Sea. The basement rocks include granite with basic intrusives, plus a Pre-Cambrian arkosic conglomerate known locally as the Saramuj conglomerate.

Shield formations are overlain by a thick series of lacustrine-terrestrial sediments; these are in turn covered by a a younger marine clacareous sequence. In time the sediments span the period from Cambrian to Recent. The older lacustrine-terrestrial complex has lateral equivalents in the Saq sandstone and Tabuk formations of Saudi Arabia, and in the Nubian Sandstones of north-eastern Africa. Lithologically the sandstone series is composed of sandstone, quartzide, grits and conglomerate. The younger marine sequence is subdivided into the older Ajlun group and the younger Belqa group. These are a complex of limestones, dolomites, cherts, chalks, marls and shales, which also have lateral equivalents in Saudi Arabia, in the Aruma Umm er Radhuma, Rus and Damman formations. Developments of sandstone in the lower Cretaceous (just prior to the Ajlun group) are laterally equivalent to the Wasias-Biyadh system of Saudi Arabia.

Up to the Middle Tertiary or Miocene period, the sediments were an intergral part of the Arabian basin. During the Lower Miocene there was a period of uplift accompanied by folding and faulting on a major scale. At this time the Lake Tiberias-Dead Sea rift was formed. In Late Pliocene/Early Pleistocene renewed movements along the rift fault deepened the Lake Tiberias-Dead Sea rift valley and formed for the first time the wadi Araba-Gulf of Aqaba rift. From Tertiary to Recent, lacustrine (Ghar) deposits and alluvial (Zhor) deposits were laid down in the rift valley overlying the Ajlun and Belqa groups.

Volcanic rocks, mainly basalts and tuffs dominate to the north-east of the eastern plateau. They range in age from Miocene to Pliocene in Jebel Druze in the southern part of the Syrian Arab Republic, the source area of the volcanism. In Jordan the flows occurred from the Oligocene to Pleistocene period and are thick, being in excess of 300 m.

Topographically and hydrogeologically, Jordan can conveniently be divided into three main provinces:

(a) The Jordan Valley-wadi Araba rift system comprising that portion of the country lying within the rift valley graben, and including the lacustrine and alluvial deposits;

(b) The east bank and west bank watershed to the Jordan River (the areas of rejuvenated and incised drainage) and the eastern watershed to the wadi Araba; this excludes the lacustrine and alluvial deposits of the valley bottom;

(c) The eastern plateau and the southern desert which comprise the areas of inland drainage and areas draining to wadi Sirhan in Saudi Arabia.

Aquifers

Aquifer characteristics are summarized in table 14.

Jordan Valley-wadi Araba rift system

The Tiberias-Dead Sea basins consist of a series of major-minor grabens within grabens, which have been infilled with Neogene conglomerates, Pleistocene marls and Recent alluvium. The Lisan Marls are a significant sequence, since, being composed of impermeable gypsiferous clays and marls, they play an important role in controlling local aquifer recharge. The Jordan River flows mainly on marl and it is believed that the alluvial aquifer does not possess hydraulic continuity with the river. However, the marl has a coarser and more permeable lateral equivalent that is in hydraulic continuity with the flanking/fluvial fans, and it is through these that the valley aquifers receive much of their recharge. Recharge to the valley aquifers comes essentially from wadi and spring flow and from deep basin leakage.

Water quality varies widely, especially since there is a rapid change in water type and total dissolved solids, both in area and in depth; in fact, this change is so rapid and the conditions are so complex that it is virtually impossible to predict success or failure for bore-holes when particular quality standards must be met. The water sampled from the Jordan's base flow is of the sodium chloride type. Marginal water, from the Yarmouk and Zerqa Rivers, are $CaNaHCO_3$ water and thus are probably mixtures of recent spring flow and deep basin leakage. In general, water higher in the marginal catchments $CaHCO_3$ waters. The total dissolved solids content of surface water ranges from 300 to 400 ppm.

Ground-water types include $CaHCO_3$, $CaMgHCO_3$, $MgCaHCO_3$, $CaSO_4$, $CaNaSO_4$, and NaMgCl, which covers alomost the entire metasomatic process for ground water from recharge to discharge. Interpretation is difficult since these types occur at random and present no sensible hydrogeological picture, apart from a complicated history of open and closed basin discharge and complicated flow régimes. The total dissolved solids content of the ground water ranges up to 7,700 ppm in the Ghar marls, though the average is around 1,800-2,000 ppm.

Table 14. Jordan: summary of aquifer characteristics

ERA	PERIOD	EPOCH			GROUP	FORMATION OR STAGE: WEST BANK	FORMATION OR STAGE: EAST BANK	Thick-ness (m)	WATER YIELD POTENTIAL	LITHOLOGICAL DESCRIPTION
CENOZOIC	QUATERNARY	RECENT			JORDAN VALLEY	ALLUVIUM	ALLUVIUM	0-300	Poor-excellent	Gravel, sand, clay
		PLEISTOCENE				LISAN	LISAN	0-300	Poor-good	Calcareous clays and gravels
						SAMRA	SAMRA	0-300	Poor	Calcareous-reddish clays and gravels
	TERTIARY	PLIO-MIOCENE				NEOGENE	NEOGENE		Poor	Conglomerate, indurated
		OLIGOCENE ?			BELQA	BASALT AND CONGLOMERATE	BASALT AND CONGLOMERATE	100	Moderate-good	Basalt and conglomerate
		EOCENE				EBAL	FALEJ (B4)	300	Moderate-excellent	Limestone, marl, chert, chalk
		PALEOCENE				GERIZIM NABLUS	RAMTHA	190	Poor	Limestone, chalk
MESOZOIC	CRETACEOUS	UPPER		DANIAN MAESTRICHTIAN		KHANAHMAR ZARQA	or MUWAQQAR (B3)	250	Moderate	Marl, chert, shale
				CAMPANIAN		AMMAN	AMMAN (B2)	100-150	Moderate-good	Limestone, chert, marl
				SANTONIAN CONIACIAN		ABU DIS	RUSEIFA (B1)	10-250	Poor	Chalk, marl and chert limestone
		MIDDLE		TURONIAN	AJLUN	JERUSALEM	WADI SIR (A7)	70-200	Good	Limestone, sandstone, marl
			CENOMANIAN	UPPER		BETHLEHEM	SHUEIB (A5-6)	70-150	Poor-moderate	Limestone, marl
				MIDDLE		HEBRON	HUMMAR (A4)	30-200	Good-excellent	Dolomite limestone
						YATTA	FUHEIS (A3)	80-150	Poor-aquiclude	Marl, chalk, limestone
				LOWER		BEIT (UPPER)	NAUR (A2)	120-300	Good	Limestone, marl, chalk
						KAHIL (LOWER)	NAUR (A1)	300	Excellent	Dolomitic limestone, marl
	LOWER ? JURASSIC ?					KURNUB	UPPER KURNUB	200	Poor	Fine sandstone, shale, limestone
							LOWER KURNUB	110	Moderate-good	White, coarse sandstone
	TRIASSIC					ZARKA	UPPER ZARKA	300	Good	Limestone dolomite, sandstone
							LOWER ZARKA	70	Poor	Shale, gypsum, marl
MAJOR UNCONFORMITY										
PALEOZOIC	SILURIAN ORDIVICIAN (UPPER)						KHREIM	0-400	Poor	Fine-grained sandstone, mudstone and shale
	ORDIVICIAN (MIDDLE)						DISI	250	Good	Bedded Brown — Medium to coarse grained sand-stone
	CAMBRIAN (LOWER)							130-350		Massive White
	(LOWER)							190-350		Massive Brown
	CAMBRIAN (LOWER)						UM SALEB	50-60	Moderate	Arkosic sandstone
PRE-CAMBRIAN							AQUABA	...	Poor	Granite and diabase

Source: Data compiled by John W. Harshbarger from published and unpublished reports in the files of the Natural Resources Authority and of the United Nations Development Programme, Amman, 1966.

Main sedimentary basin

Considerable work has been completed in the upper marine groups and the lower sandstones. Both the Ajlun and the Belqa groups have been studied in detail, and their main aquifers being designated A1 to A7 and B1 to B4, respectively (see table 14). The Ajlun group consists of interbedded limestones and marls, in which the limestones are essentailly the aquifers and the marls the confining beds. The main aquifers are:

Na'ur formation, A1 and A2

This, the lowermost part of Ajlun group, is composed of grey to pink, coarse-grained limestone, dolomite and marl. The limestone generally is karstic and fractured, while the marl within the formation serves as a discontinuous confinining bed. Useful quantities of water have been developed in this aquifer, particularly in the northern districts. In the central-south and the south of the country, the aquifer is not as productive as the other aquifers. Water quality is good.

Hummar formation, A4

This formation is composed of light to dark grey limestone with occasional pink strata; it is mostly a hard, crystalline, coarse-grained, dense, dolomitic limestone. It is highly fractured, cavernous, and honey-comb patterned. The typical outcrop section exists 16 km north-west of Amman, where the average thickness is about 40-50 m. The formation is a good aquifer in the northern central and western part of the country, and it is the source of many springs. Most wells drilled to the A4 have high water levels. In the Amman area most of the A4 wells flow with heads of up to 69 m above ground surface.

Wadi Sir formation, A7

This limestone is fissured and fractured throughtout; it is white to grey in colour, hard, semi-crystalline, fine-grained, occasionally with concentrations, and thinly bedded; it tends to be marly or chalky towards the bottom, and contains chert concretions towards the top. It ranges in thickness from 90 to 120 m. The formation is a very good aquifer and a major ground-water reservoir. Numerous springs and wells yield water from the A7 aquifer.

The main aquifers in the Belqa group are as follows:

Amman formation, B2

The Amman formation lies unconformably on the top of the wadi Sir formation. Its thickness ranges from 90 to 120 m. Broken and fractured Amman formation is highly permeable. It is a good aquifer throughout most of the country and tapped by numerous wells.

Ramtha formation, B4

This formation forms the uppermost aquifer in the Belqa group except in regions where it is overlain by a younger formation (B5). The B4 consists of a black and bituminous chert interbedded with chalky limestone and marl. In most areas the chert beds are thin, but they increase in thickness towards the east and south-east. The maximum known thickness of 287 m was penetrated in a drill hole in the north-eastern desert.

The B4 is a good aquifer, especially in the north-eastern plateau and eastern desert. Wells are productive from this aquifer in Azraq and the H4 areas. The quality of water is fair to good.

The sandstone aquifer

Palaezoic and Mesozoic sandstones occur mainly in the southern part of the country. The Jurassic and Lower Cretaceous sandstones crop out in the Zerqa River region in the north. Except for a few minor supplies in the southern area, sandstones generally have limited economic potential, though further investigatory work may prove otherwise.

During recent years many wells have been drilled into the sandstone aquifers in the southern desert and also in the north. Moderate to high yields were obtained from wells drilled in the south where pumping levels were about 100 m. In the northern part of Jordan, except those areas adjacent to the Zerqa valley, the sandstone aquifers are overlain by more recent carbonate rocks, and the depth to the sandstone is about 1,000 m. Water levels in the aquifers are about 300-350 m below land surface. Development at this depth would be uneconomic.

Other aquifers

Other aquifers include plateau alluvium and basalts. The wadi gravels on the plateau are considered good aquifers in some parts of the country, particularly along the major wadis such as wadi Yutum, wadi Amman Zerqa, and lower wadi Dhuleil. The Awajan area, 20 km north-east of Amman in wadi Amman-Zerqa, is an example of a typical plateau gravel deposit. Water in these gravels and wadi fills differs in depth, quantity and quality from place to place.

The basalts cover an area of about 11,000 km^2 in the northern and eastern plateaux. They have proved to be good aquifers in the wadi Dhuleil and Azraq areas. The main productive aquifer is a purple to grey-black-brown scorianceuos, sponge-like basalt which tends to be dense and amagdaloidal towards the bottom of the flow. In the Dhuleil area 30 wells have been drilled by the Natural Resources Authority. Some of these were high yielding, producing 450 m^3/h of excellent quality water. However, owing to the basalt's heterogeneous character, productivity is limited, and restricted to zones of significant fracturing and good permeability. Eleven wells have been drilled in the main productive aquifer, their total yield being about 3,000 m^3/h.

Ground-water investigation and development

Ground-water investigations in Jordan began about 20 years ago and since then the region has been the subject of continuous study. To implement the various studies, Jordan draws on resources of the United Nations Development Programme (UNDP) and organizations of the United Nations system including the International Atomic Energy Agency (IAEA) and the Food and Agriculture Organization of the United

Nations (FAO). The National Resources Authority administers the country's water resources. It is responsible for planning, designing, constructing, operating and maintaining water supply and irrigation projects, carrying out related works, settling disputes arising from the use of the water resources etc. It is also responsible for organizing and directing the construction of private and public artesian wells, and for registering and licensing owners of drilling rigs and groups which undertake the drilling of wells. The Natural Resources Authority comprises four departments: Water Resources; Mineral Resources and Geological Survey; Irrigation; and Petroleum.

The Natural Resources Authority operates the largest well-drilling organization in the country and is at present drilling around 40 wells per year by operating eight cable tool and four rotary rigs. In spite of the extensive practical training given to a large number of drillers in past years, Jordan is still short of trained drillers. This is mainly because of the migration of drillers to neighouring African, Asian and Arabian countries in pursuit of higher earnings. This problem was recognized in 1975-1976, and in 1976 a programme was initiated to train up to 30 drillers a year. It was expected that by early 1979, the Natural Resources Authority would have an adequate number of trained drillers.

Ground-water fields

There are many ground-water fields in the country, each of which has distinct characteristics. The most important developed ones, excluding the Jordan Valley are:

North	South	West bank of the Jordan River
Azraq a/	Hasa	Fawwar-Hebron
Dhuleil a/	Shaubak	Beit Fajjar
Sama Sdud	El Jafr a/	Shibtien
Amman-Zerqa a/	Basta-Arja	Dier Sharaf-Anabta
	Wadi Yutum	Qalailia
	Ram-Qa' Disi area	Qabatia (Jenin)

a/ Main fields.

Azraq ground-water field

Azraq gound-water field is located at Azraq Oasis about 85 km east-south-east of Amman. There are three aquifers systems in the area:

(a) The basalts, the B4 unit and the Quaternary deposits are hydraulically connected and form the upper aquifer system;

(b) The underlying B3 unit (a chalky, occasionally bituminous limestone) is a poor aquifer, although several wells do yield water from this formation;

(c) The B2 formation (chert and chalk), a good aquifer, owing to fracturing in the chert horizons.

Two groups of springs issue from the upper aquifer. The first group, at the Shishan village, yields about 1,200 m^3/h. The second group, at Druze village, about 380 m^3/h. The quality of spring water is generally good. About 40 wells have been drilled into this aquifer complex; 23 of these are high yielding and produce good quality water. Ten wells have been drilled into the B3 aquifer. These wells are generally of low yield; the quality of their water is rather poor and classified as C3S2. The B2 formation which is about 450 m deep, is a good aquifer. Eight wells drilled into the aquifer indicate that it is artesian with a static water level ranging from 7 m above ground level to 85 m below the surface.

Dhuleil ground-water field

The wadi Dhuleil area lies on the edge of the eastern desert, 45 km north-east of Amman. The area is a gently rolling plateau, with several small wadis draining to the larger wadi Dhuleil. This joins the River Zerqa, 20 km west of the project area.

Hydrogeological investigations were carried out from 1962 to 1965. The main aquifer is the basalt. Six flows were identified during the investigation with the fourth flow from the top, the B3 grey to black-brown, scoriaceous, sponge-like basalt, being the main aquifer. The underlying formations, the wadi Sir, A7, and Amman, B2, are locally poor aquifers. To the south of the basalt aquifer, the limestones and cherts of the A7 and B2 formations are good aquifers, and many wells drilled into there aquifers have individual yields in excess of 120 m^3/h. In total, 21 wells were drilled in this zone, of which 11 were highly productive and six were of moderate yield.

The water quality is good. In most of the area the total dissolved solids content ranges from 230 to 430 ppm. Salinity increases towards the north and west.

Amman-Zerqa ground-water field

This field is one of the largest developed areas in Jordan, and new industries, farms, irrigation projects and municipal schemes are being directed to this area. The field extends from Amman, northwards along wadi Amman-Zerqa to about 30 km north-east of Amman. The area is mountainous, with wide open plains and several small wadis. These wadis drain the area into the Zerqa River. Outcrops in the area are mainly A7 and B2. In addition, the thick gravel deposits in the area form a separate unit. Main aquifers are the gravel deposits; Amman formation, B2; wadi Sir formation, A7; and Hummar formation, A4.

Two hundred wells are productive; most yield water from the gravel aquifer, while only a few penetrate the A4 aquifer. The depth of wells ranges from 10 m (in the gravel aquifer) to 350 m (in the A4 aquifer). Water in the A4 aquifer is under pressure and has a high static head ranging from 69 m above the ground surface (Amman municipality well No. 11) to 45 m below surface (refinery well No. 5). Recharge to this field was calculated to be about 45 million m^3/year; it is estimated that aobut 25 million m^3/year are used. The quality of the water is generally good.

El Jafr ground-water field

El Jafr is located in the southern desert, 50 km east of Ma'an town. The area is a basin-like structure and has an area of about 12,000 km^2 to the east in the Sirhan catchment area along the Saudi Arabian border. The main rock formations in the basin are the B4, the B3 and the A7. More than 20 wells have been drilled in El Jafr area, 14 of which are productive. The quality of water is generally good, the salinity ranging from 380 ppm to 1,200 ppm.

Selected references

Burdon, D. J. Groundwater in the Hashemite Kingdom of Jordan. 1958.

__________. Infiltration rates in the Yarmouk basin of Syria-Jordan. International Association of Hydrology, publication No. 37, 1958.

Harshbarger, J. W. Second review of the sandstone aquifers of east Jordan. United Nations Development Programme/Food and Agriculture Organization of the United Nations. Rome, 1968.

Lloyd, J. W. and others. The hydrogeology of the southern desert of Jordan.

Mudallal, U. H. Land and water use in the Hashemite Kingdom of Jordan, part II, ground-water resources. Natural Resources Authority, Amman, 1969.

Parker, D. H. and others. The hydrogeology of the Mesozoic-Cainozoic aquifers of the western highlands and plateau of east Jordan. UNDP/FAO. Rome, 1970.

UNDP/FAO. Development and use of ground-water resources of east Jordan. Rome, 1975.

UNDP/United Nations. Ground-water survey in the Azraq area. 1965.

Wilson, G. R. and D. H. Wozab. Chemical quality of waters occurring in the Jordan valley. International Association of Hydrology, publication No. 37, 1958.

Area: 17,818 km^2

Population: 929,000

General

The country has a flat topography with occasional hills and depressions. The land surface slopes gently to the north-east with an at large gradient of 2 in 1,000. Details of the topography are controlled to a large extent by tectonic structures. (see map 14 below.)

The Jal Az-Zer escarpment, one of the main geographical features of the country, extends along the northern shore of Kuwait Bay. This steep escarpment borders on the north-eastern shore of Kuwait Bay, rising to a maximum height of approximately 110 m above sea level. It slopes to the north-west at a gradient of 6 in 1,000. The only major depression is the broad, shallow wadi Al Batin which forms the western boundary of Kuwait. In central Kuwait the wadi is incised to a point 45 m below the level of the plateau but becomes more subdued near the border with Iraq. The average width of wadi Al Batin is 6-8 km. In southern Kuwait, Wara hill rises to a height of about 30 m. Ahmadi ridge also runs parallel to the coastline south of Kuwait separating the plain of Burgan from the Gulf coast; the eastern and western slopes of the ridge are very gentle. Sand dunes occur in a limited area only in the north-eastern part of the country near the border with Iraq. They are as much as 25 m high at Umm Nigga.

The climate is characterized by extremely hot dry dusty summers with an average maximum daily temperature of 45° C, and mild to cool winters with temperatures of 1° C.

Average annual rainfall is between 50 and 120 mm. Evaporation greatly dominates the whole climatic year, the highest rate occurring in June and July (approximately 15 mm per day). The country has no streams, rivers or lakes.

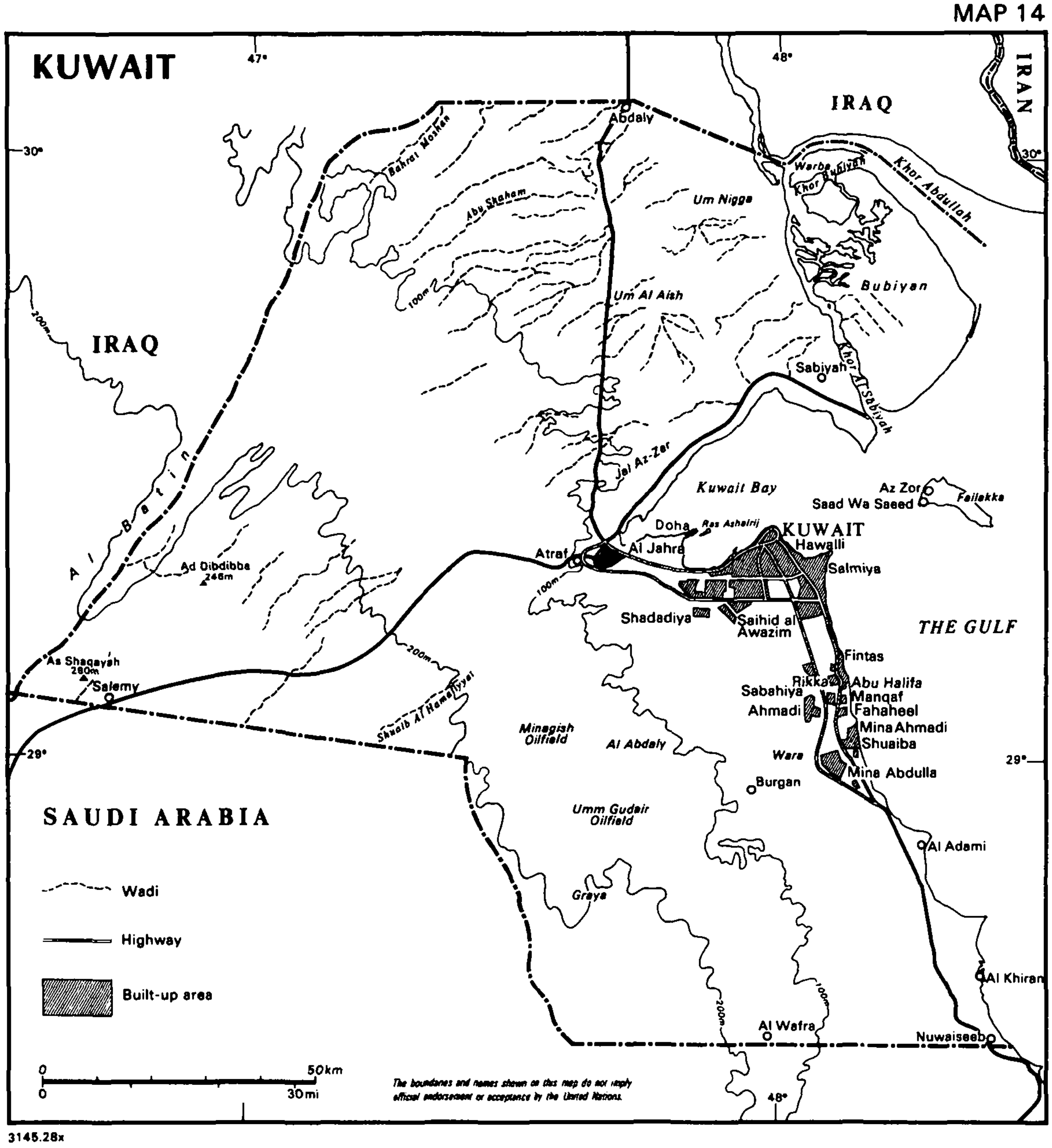
Geology

Kuwait lies at the edge of the Arabian foreland on the south-western flank of of the Gulf geosyncline. The regional dip is to the north-east at a gradient of about 2 in 1,000.

The regular dip surface is interrupted by the Kuwait arch and by other major structures which are present at Rawdatain, Umm Gudair and Minagish. These structures are very gentle and no dips over three degrees have been identified. Subsurface information indicates that the structures have been growing almost steadily since at least Middle Cretaceous times and possibly they are as old as Late Jurassic. The evidence indicates that the growth of structures is the result of vertical movement rather than horizontal compression, especially in Pre-Miocene times, but the exact cause of movement has not been determined. Formations exposed

Map 14

Kuwait



at the surface range from Middle Eocene to Recent. Similarity in lithology ranging from Middle Eocene to Recent, as well as the absence of any fossil evidence, makes correlation of formations regionally difficult.

Recent beds (Quaternary) consist of beach deposits, such as sandstone, sandstone cemented with calcium carbonate, oolitic limestones and shelly limestones. Deltaic and tidal mudflats which are composed predominantly of plastic clay and silt of high salt content occur in north-eastern Kuwait, Bubiyan Island and along the north shore of Kuwait Bay. Inland drainage basin deposits consist of very fine silt and clay with a variable percentage of sand.

Stratigraphic succession is naturally divisible into two main groups: an upper clastic unit, the Kuwait group, and a lower carbonate unit, the Hasa group. The Kuwait group is generally subdivided into three formations:

(a) Dibdibba formation (Pleistocene), the upper beds of the Kuwait group, consisting of sand, gravel with some clay, gypsiferous, and sandy clay beds; poorly to moderately stratified and cemented in some places with calcium carbonate and gypsum;

(b) Fars formation (Miocene to Pliocene), composed of alternating red and yellow sandstone, red and green clay and various sandstone and silty clay;

(c) Ghar formation (Oligocene to Lower Miocene), the lower part of the Kuwait group, consisting of coarse-grained to pebbly sandstone, some of which is firmly cemented and calcareous. Green clay beds are present in the lower part.

The Hasa group (Middle Eocene) is subdivided as follows:

(a) Dammam formation, which is subdivided into three members on the basis of lithological variation:

(i) Member III includes the upper beds of the Dammam formation which uncomformably underly the Kuwait group. It consists of shelly, chalky or granular porous limestone with hard siliceous cherty limestones at the top;

(ii) Member II includes chalky, locally shelly limestone with thin siliceous cherty limestone at the top and siliceous limestone with sand beds at base;

(iii) Member I includes dense dolomitic limestone with lower fossiliferous (Nummulitic dolomitic limestone), thin anhydrite beds and green shale in the lower part.

Dammam limestone is of economic importance being a main aquifer containing brackish water. Excavations in Ahmadi quarry (south of Ahmadi) exposed Dammam formation under a few metres of younger beds of the upper Kuwait group;

(b) Rus formation (Lower Eocene), underlying the Dammam limestone; it consists of hard, dense massive anhydrite with some unfossiliferous limestone;

(c) Umm Radhuma formation (Paleocene to Lower Eocene), which consists of anhydritic, dolomitic and marly limestone.

Ground-water resources

The first large-scale hydrogeological investigation in Kuwait was carried out in the early 1960s by Parsons Corporation for the Ministry of Electricity and Water. The objective was to explore ground-water resources in Kuwait, to evaluate and develop the Rawdatain fresh water field, and to evaluate the Sulaibiya brackish water field. Qualitative hydrological studies were carried out from 1960 to 1964 under the Ground Water Project.

During the period 1968 to 1974, hydrogeological investigations were carried out by the Ministry of Electricity and Water, Ground Water Section, to appraise quantitatively the yielding capacity of the Dammam aquifer beneath the western part of Kuwait and to look into the possibility of developing other areas for the purpose of increasing this brackish water supply. The investigation led to the Shagaya Project which resulted in the development of three water-well fields (1977).

In 1973 an evaluation of Rawdatain-Umm Aish Ground Water Project was made by the Ministry of Electricity and Water, Ground Water Section. Hydrogeological investigations were also carried out at Al Abdaly-Umm Nigga in northern Kuwait and in the Wafra-Graya area and Wafra from 1974 to 1976.

From 1976 to 1977 hydrogeological investigations for artificial recharge possibilities in Kuwait were also carried out by the Ground Water Section.

The management of ground water is based on mining the ground-water resources of the Kuwait group and Dammam formation. Water-level declines and water quality variations with time were forecast using analytical methods, while aquifer characteristics were determined by pumping tests.

The main aquifers in Kuwait are the Kuwait group and Dammam formation of the Hasa group. Silt and clay occur in different percentages in the Kuwait group which is unconsolidated, while Dammam consists of fissured limestone. The Kuwait group ranges in thickness from 60 to 300 m and overlies 120-200 m of the Dammam formation which, in turn, overlies the relatively impermeable Rus formation. In general, the aquifer system can be considered as a multilayered leaky aquifer system with variable boundary conditions. Based on the quality of water, there are two main ground-water resources in Kuwait: fresh ground water in the Rawdatain field and Umm Al Aish field and brackish ground water in Sulaibiya. Practically no guided or planned research is taking place at present. The Ground Water Section's activity is mostly concerned with development of ground-water resources. In this connexion, the existing knowledge, especially in the field of ground-water hydraulics, has been adequate to solve most of the problems that have developed. Aquifier characteristics are summarized in table 15.

Ground-water development

The Ground Water Section of the Water and Gas Department of the Ministry of Electricity and Water is responsible for the development of ground-water resources in Kuwait.

Activities of the Ground Water Section include exploration and special studies of certain areas of the country; drilling ground-water wells; development of water-well fields; and the operation and maintenance of water-wells.

Table 15. Kuwait: summary of aquifer characteristics

Geological age and depth (m)	Geographical location	Depth of well (m)	Hydraulic conductivity (m/day)	Transmissivity (m^2/day)	Coefficient of storage
Pleistocene (20-30)	Rawdatain-Um Al Aish	35-70	15-25	450-900	1.5×10^{-1}
Middle Eocene (120-150)	Sulaibiya	250-300	0.5-1.5	75-225	6×10^{-4}
Middle Eocene (180-250)	Shagaya	365-425	0.8-4.2	150-750	4×10^{-4}
Middle Eocene (60)	Wafra	225-250	0.8-12	75-1 200	1×10^{-4}

Staff

The professional staff includes nine geologists, one geophysicist and two operator-geophysicists (1979). It also includes drilling personnel and mechanical and production engineers supervising water-well fields and the operation and maintenance of water wells.

Four drilling rigs are operated, each of which could drill as much as 8,000 m/year.

Utilization of ground water

Fresh ground water from Rawdatain and Umm Al Aish well fields is being utilized after chlorination as drinking water for the nearby town of Jahra and surrounding areas. Fresh water is being produced at a rate of 10,000 m^3 daily from both fields.

Brackish ground water from Sulaibiya and Shagaya fields is used for mixing with distilled water to be used for drinking in Kuwait City and other parts of the country. The mixing is at a percentage of 120, during the summer, the production of Sulaibiya field increases to as much as 55,000 m^3/day owing to higher demand.

Sulaibiya water is used for municipal needs not requiring a low dissolved mineral content.

Problems

Overdraught

The magnitude of natural recharge has not been determined. Part of it comes from infiltration locally received through wadis and depressions scattered over the country. Another part is the underflow from Saudi Arabia under natural conditions through the Dammam formation. Total recharge is less than the level of present withdrawal.

Salt water intrusion

The water in Rawdatain basin ranges from fresh (about 200 ppm of total dissolved solids) to brackish (about 8,000 ppm of total dissolved solids). The fresh-water body overlies and is surrounded by more brackish water with the fresh-water surface in the upper aquifer. Ground water moves through the upper aquifer under water-table conditions and through the middle and lower aquifer under artesian conditions. Pumpage of the field at the high rate showed a deterioration in quality, especially when demands for water from Rawdatain reach the maximum in the summer.

Other problems have not been studied, but there is the possibility of subsidence in the future because of the high pumpage in the Sulaibiya field.

Artificial recharge

In August 1962, an artificial ground-water recharge project was undertaken by Parsons Corporation. The project was to recharge the underlying fresh ground-water basins in Rawdatain and Umm Al Aish by the naturally occurring ponded water which sometimes accumulates as a result of winter precipitation.

The purpose of the project was to drill recharge pits so as to recharge the excess water to the upper Kuwait group aquifer where the water table is shallow. The studies of artificial methods indicated that recharge pits with a gravel filter in the bottom of the pit would be successful. A recharge pit of 25,000 m^3 was constructed near the centre of the Rawdatain depression.

At present, the Ground Water Section is studying possibilities of recharging excess fresh water to the lower Kuwait group and the Damman aquifer.

Conclusion

If the quality is adequate, ground water is utilized for irrigation as is practised in the Sulaibiya and Shagaya fields. In the Wafra area, ground water contains about 5,000 ppm of total dissolved solids which is suitable for some plants.

Furthermore, ground water as mentioned above, is being used for mixing with desalinated water for domestic needs. Related production costs are much lower than those of desalinated water.

At present (1977) plans for the optimization of ground-water development from the point of view of quality, quantity and economics are being prepared. However, there are prospects for exploration in other areas when the need arises, although the expected quality and quantity will not be adequate. Furthermore, there are prospects for storing fresh water by artificial recharge in saline-water aquifers.

Selected references

Reports prepared by contractors

Compagnie générale de geophysique. Report to Ministry of Electricity and Water. Shagaya Geophysical Survey. 1968.

Parsons Corporation. Report to the Ministry of Electricity and Water. Ground-Water Resources of Kuwait, vols. I and II. 1963.

__________. Report to the Ministry of Electricity and Water. Ground Water Resources of Kuwait, vol. III. 1964.

Water Resources of Kuwait. Report prepared by experts of the United Arab Republic. 1964.

<u>Reports prepared by professional staff of the Ministry of Electricity and Water and other experts</u>

Abu S'ada, Said M. Studies and report on ground water in Kuwait. Ministry of Electricity and Water, Ground Water Section. 1973. Arabic.

__________. A short report on Al Qash'aniya ground water area including Al-Abdaly farms rectangle. Ministry of Electricity and Water, Ground Water Section. 1973.

__________ and Yacoub Al Haji. Wafra farms area: preliminary survey of ground water data and recommendations for further investigation. Ministry of Electricity and Water, Ground Water Section. 1973.

Ahmad, Moid Uddin. Ground water study in Kuwait. 1969.

Al Sumait, Abdul Aziz. Topography, stratigraphy structure and hydrogeology of Wafra area. Ministry of Electricity and Water, Ground Water Section.

Application of two-layer leaky aquifer theory to Rawdatain fresh water body bounded by brackish water. Ministry of Electricity and Water, Ground Water Section.

Burdon, D. J. and Abdulla Al-Sharhan. The problem of the Paleokarstic Dammam limestone aquifer in Kuwait. Journal of Hydrology, No. 6, 1968, pp. 385-404.

Hantush, Mahdi S. Memorandum on the Shagaya Ground Water Project. Ministry of Electricity and Water. 1971.

Omar, Sara Sayid. General report on ground water resources in Kuwait. 1974. Arabic.

Report on Dammam limestone aquifer, Wafra farms area. Ministry of Electricity and Water, Ground Water Section. 1975.

Roberts. Status of ground water studies and developments in Kuwait with comments on the drilling programme. United Nations Development Programme. 1972.

Shenay, Yilder. Brief preliminary hydrological report on Wafra Flowing Well I. Ministry of Electricity and Water, Ground Water Section. 1974.

__________ and Sara Sayid Omar. Ground water hydrology of Abdaly farms area. Ministry of Electricity and Water, Ground Water Section. 1975.

Area: 10,400 km^2

Population: 2,961,000 (United Nations estimate, 1976)

General

Lebanon is a mountainous country dominated by two parallel north-south mountain ranges: the coastal Lebanon range and the inland Anti-Lebanon range. The narrow coastal strip which borders the Mediterranean broadens in places producing the Akkar plain in the north and smaller alluvial areas in the Tripoli and Beirut localities. The inland elevated central Bekaa plain, lying between 650 and 1,000 m, is the source of the country's two major rivers, the Orontes and the Litani. Elevations up to 3,000 m along the Lebanon range and 2,300 m along the Anti-Lebanon range have a pronounced effect on the country's climate.

Lebanon's topographical configuration, with its orographical and geological structure, divides the country, into two major areas:

(a) The Mediterranean watershed (5,500 km^2) where numerous short costal rivers descend directly from spring sources on the western slopes of the Lebanon into the sea;

(b) An interior watershed (4,700 km^2), where the Orontes and Litani rivers eventually discharge into the sea.

The climate varies markedly across the country, owing to its unique physiography. The coastal mountain barrier intercepts both rain and humidity from the west; and the climate, vegetation and water resources graduate from a Mediterranean coastal environment to an inland Mesopotamian desert climate.

Rainfall is closely related to topography, elevation and distance from the coast, the coastal strip receiving annual rain of 900-1,000 mm; the coastal range, at 1,500 m, around 1,400 mm; the central Bekaa region, at Baalbeck, 400 mm; and the western flank of the Anti-Lebanon from 500 to 700 mm. Rainfall is essentially a winter event, with about 90 per cent being received during the period November to April; in general, January is the wettest month. Snow is frequently present above 1,500 m, melting snow being a valuable source of ground-water recharge. In general, the rainfall is not dependable, thus the cultivation of rainfed crops is a hazardous affair. For this reason irrigation is a most important factor, and the future development of agriculture requires that the investigation and development of ground-water sources has high priority.

Geology

Most formations are of a marine sedimentary origin and range in age from Jurassic to Quaternary. The Jurassic strata measure at outcrop more than

1,100 km^2 (600 in the Lebanon and 550 in the Anti-Lebanon), the Middle Cretaceous more than 4,200 km^2 (3,000 in the Lebanon and 1,200 in the Anti-Lebanon) and the Middle Eocene more than 200 km^2 in the central Bekaa region. The remainder of the country is covered by Quaternary alluvial and colluvial sediments, with basalts in the north.

Jurassic

This includes mainly dolomite, dolomitic limestone and reef limestone. The series has a thickness in excess of 1,600 m.

Cretaceous

Locally the Cenomanian-Turonian rocks range from 600 to 1,000 m in thickness and consist of limestone, marly limestone and dolomite. With respect to ground water, these are most important sediments and their widespread and interconnected karstic nature makes them the source of major springs in Lebanon.

Middle Eocene

These deposits occur only in the Bekaa plain region where they consist of a typical reef limestone formed in thickly stratified masses with inclusions of limestone breccia and some corals. The thickness varies widely but it is reported to be up to 1,000 m.

Vindobonian (Lower Tertiary)

These rocks have a very restricted outcrop area and occur only in the vicinity of Tripoli and at the mouth of the El Kelb river. They have a total thickness of about 250 m and include limestone and sandy marl.

The hydrogeology of Lebanon, together with the distribution of springs, their location and flow régime, is to a very large extent controlled by the geological structure imposed during the main rifting periods. In this respect Lebanon is notable for the density of its shearing and fracture network, which has had the effect of compartmentalizing wide areas of the aquifer and producing many simple overflow springs throughout the country.

The great Yammoune fault of the Lebanon range is hydrogeologically the most significant tectonic feature of the country. With a throw from 400 to 2,000 m, it possesses a thick 200-300 m zone of fault guage or breccia which acts as an impermeable barrier separating the karsts and aquifers of the east and west flanks of the Lebanon range.

Hydrogeological conditions and ground-water reservoirs

Apart from some coastal fan and plain deposits and the plains of the central Bekaa region, Lebanon's hydrogeology is determined by the distribution of the limestones and dolomites and their karstic features. The country can be divided into two distinct hydrogeological provinces: the karstic province and the province of porous formations.

Karstic province

The karstic province covers about 6,000 km^2, or about 60 per cent of the country. Throughout the province the land surface is characteristically of the karst type with sink holes, subterranean rivers, and spring seepage on the lower mountain flanks. Springs are classified according to the hydrological conditions that support them. Four types are identified:

(a) Those fed by perched unconfined aquifers;

(b) Those fed by unconfined aquifers which results from, for example, the filling and overflow of a compartment, or flow over an impermeable fault or stratigraphic barrier;

(c) Those fed by confined or artesian aquifers;

(d) Composite springs formed as a result of variations of the previous spring types.

The different régimes and localities of the karstic province can be summarized as follows:

Jurassic strata

Aquifer J I. In the north-western watershed of the Lebanon range, the springs are mostly of the overflow type, being caused by flow over a stratigraphic barrier;

Aquifer J II. In the western watershed of Lebanon, springs are caused by flow over stratigraphic barriers, although they are located at the lowest points of Jurassic outcrop and frequently in the valleys of the coastal rivers;

Aquifer J III. In the western flank of Mount Hermon, springs are again of the overflow type but, in this locality, are caused by flow over impermeable fault lines. Being on the Anti-Lebanon range, these springs are not permanent; their flow increases rapidly from April to July. The April to July period is sustained by contributions from melting snow;

Aquifer J V. Jebel Barouk-Niha. On the western and eastern watersheds springs are of the overflow type, caused by flow over a stratographic barrier and impermeable fault, respectively.

Cenomano-Turonian strata

Aquifer C I. In the western watershed of northern Lebanon, transverse fractures superimposed on fold structures produce several independent reservoirs or compartments. The springs are of the perched unconfined aquifer type and of the overflow type flowing over stratigraphic contacts. The submarine springs of the Chekka region are of the artesian type;

Aquifer C II. In the high plateaux of central Lebanon, these springs are the highest in Lebanon; they are of the overflow type caused generally by flow over an impermeable faulted barrier;

Aquifer C III. In the coastal plateaux of south Lebanon, the artesian springs occur because of the confining of the aquifer by the cover of marls and marly limestones of the Upper Cretaceous and Lower Eocene;

Aquifer C IV. In the western flank of the Anti-Lebanon, overflow springs of the stratigraphic contact type occur with some artesian sources in the Turonian-Senonian strata;

Aquifer C VI. In South Bekaa, localized river bed springs occur;

Aquifer C VIII. In the hills on the western border of Bekaa, localized overflow springs in the Yammoune fault compartment occur.

Eocene

Aquifer E I. In central Bekaa, minor artesian springs occur, which cease to flow in dry years;

Aquifer E II. In southern Bekaa, river bed springs occur where the Litani river cuts through a large synclinal formation.

Spring hydrology has been studied in detail. Conclusions are that all springs are seasonal and increase in flow following the main rains, particularly the January rains which are the heaviest. Where direct recharge exists instant response to rainfall is recorded, while those springs drawing on large reservoirs, and indirectly on recharge, show only gradual or delayed response. Some high altitude springs have a several months' delay due to water retention by the snow. This is released during the melting period in April-May. By October-November most springs have reached their lowest flow stage.

Province of porous formations

The province of porous formations covers about 4,200 km^2. Perhaps the most important area is the central Bekaa region, or the central valley, which contains the Orontes and Litani rivers. The plain is extensively developed for agricultural purposes, more than 31,000 hectares, 17,000 in the Orontes basin and 14,000 in the Litani basin, being irrigated. Water is pumped directly from the rivers and springs and from shallow wells. It is recorded that the Orontes River has regular monthly and annual flow, averaging 416 million m^3 per annum. By contrast, the Litani flow is not so regular and is most sensitive to pumping. It has a seasonally irregular average annual flow of 231 million m^3.

Aquifers in the central Bekaa region include:

(a) The Middle Cretaceous of the Lebanon range, a karstic limestone which is the source of three large springs, the Bordaouni, the Yammoune (in the mountains), and Ain Zarqa on the plain. This aquifer is very little exploited at present owing to the depth to water;

(b) The Middle Cretaceous of the Anti-Lebanon range, also a karstic limestone with important springs on the eastern edge of the plain (Anjar, Laboné-Ras el Ain Baalbek, Chemaine). These are at present exploited at 6 million m^3 per annum and there are plans to increase this to 21 million m^3;

(c) The Eocene of the Lebanon, a karstic limestone of limited extent and recharge, and little developed;

(d) The Eocene of the Anti-Lebanon, a karstic limestone with good recharge, at present developed to 21 million m^3 per annum with plans to increase pumpage to 30 million m^3 per annum;

(e) The Neogene-Quaternary aquifer of the plain, composed of conglomerates and alluvium and the most easily exploitable of all local aquifers. It is at present pumped at 36 million m^3 per annum and it is expected this could reach 60 million m^3 per annum.

In 1975, it was estimated that the total extraction in the central Bekaa was 63 million m^3 per annum. It is estimated that this yield can be safely increased to 111 million m^3 per annum.

The coastal plain of Akkar, with the Tripoli area, is the most important zone of the province of porous formations along the coast.

The plain of Akkar is located in the extreme north; it covers an area of 110 km^2 and is underlain by about 30 m of Pleistocene marine limestones, Quaternary talus, fan deposits and alluvium. Along the inland extremity of the plain there are occurrences of basalt interfingering with the sediments. Bedrock beneath the plain consists of Pliocene clays and marls from 30 to 198 m in thickness with Miocene evaporites, limestone and marl to 325 m. The plain contains both shallow and deep aquifer systems. The shallow aquifers receive recharge from the Nahr El Kebir and the Nahr Ostouene, and it is estimated that their safe yield is about 15 million m^3 annually, although an alternative estimate based on the amount of sub surface flow required to counteract sea-water intrusion is 34 million m^3.

The deep aquifer system is contained in the Turonian-Cenomanian limestone. This system has not yet been developed to any great extent in Lebanon, but it has been developed in the Syrian Arab Republic where it receives its main recharge. Beneath the plain of Akkar the aquifer is located between 495 and 547 m below land surface and is artesian. One typical test hole was tested at 95 l/sec free flow with a head pressure of 25 m above land surface.

The quality of water in the shallow aquifer is generally good, the total dissolved solids content ranging from 200 to 400 mg/l. Salinity increases towards the coast owing to a minor amount of seawater intrusion, with total dissolved solids in excess of 1,000 mg/l (3,000 mg/l near the mouth of the Nahr El Kabir). The deeper aquifer produces water of 3,725 mg/l. The water is sodium chloride in character and is believed to be contaminated with sea water.

The Tripoli-Koura-Zgharta region is the other important costal area. The main aquifer is the karstic Vindobonian reef limestone. The geology of the area includes a thin Quaternary surface veneer of conglomerates with a sandy marly matrix, overlying Upper and Middle Tertiary marls and conglomerates. The Lower Tertiary Vindobonian strata is mostly limestone, although it possesses numerous marly and sandy sections; it has a maximum thickness of 300 m though this is considerably reduced by erosion in places. The formation is karstic throughout, and in deep karsts it hosts the subterranean River Haab. Transmissivities in this aquifer vary widely as is characteristic for limestone. Best values of 10^{-2} to 10^{-3} m^2/sec are recorded in the Tripoli corridor area, whereas values recorded over the Koura-Zgharta plateau are generally in the range of 10^{-4} to 5×10^{-4} m^2/sec. In the latter region static water levels are deep at around 160 m; the aquifer is penetrated at a depth of 300-400 m.

The submarine springs of Chekka are estimated to flow at 10 m^3/sec from the Turonian-Cenomanian limestones at a depth of 120 m below mean sea level. Much investigatory work on the springs has been completed with the ultimate aim of onshore development. It has been shown that water moves to the sea via a complex of fault and karstic zones, and, like other springs, the Chekka springs show a season variation, the strongest flow being recorded in the late winter and early spring period.

Ground-water availability and use

Table 16 below gives a general evaluation of Lebanon's water balance, and shows the relatively considerable size of the water resource. It also shows that precipitation amounts to a total of 9,700 million m^3, or about 970,000 m^3/km^2 of the area of the country. Of this, about 5,400 million m^3 are lost through evapo-transpiration or go to ground-water storage, and 4,300 million m^3 run off. Of the run-off, approximately 510 million m^3 flow to the Syrian Arab Republic (415 million m^3 via the Orontes river and 95 million m^3 via the Kebir river) and 140 million m^3 to Israel (via the Hasbani river). Thus, the total amount of water available for use is approximately 3,375 million m^3, distributed as 820 million m^3 available in the dry season and 2,555 million m^3 in the wet season. The total amount at present stored, including the water in the Karaoun dam (across the Litani river) is around 500 million m^3.

Table 16. Lebanon: rainfall characteristics

(Millions of m^3/year, except where otherwise indicated)

Item	Mediterranean province	Interior province	Total (rounded)
Rainfall	6,396 (1.163 mm)	3,340 (711 mm)	9,700 (950 mm)
Total flow	2,942	1,351	4,300
Underground flow	1,980 (63 m^3/sec)	1,048 (33 m^3/sec)	3,000 (100 m^3/sec)
Streams	962	303	1,300
Flow deficit	3,454 (628 mm)	1,988 (424 mm)	5,400 (520 mm)
Run-off coefficient (percentage)	46	40	44
Underground flow coefficent a/ (percentage)	67	78	70

a/ Ratio of subsurface flow to total flow.

Ground water, theoretically utilizable, amounts to 600 million m^3 annually; of this, only 160 million m^3 are at present used, leaving a balance of 440 million m^3. Studies have shown that additional aquifer recharge during the humid season could increase the ground-water supply by 160 million m^3 as follows:

	Millions of m^3
Akkar Plain	15
Beirut area	10
Barouk/Nina mountains	50
Littoral (south)	20
South Bekaa	65

Therefore, total utilizable water resources amount to about 1,740 million m^3, as follows:

	Millions of m^3
Surface flow	820
Dam storage	500
Ground water	320
Submarine springs (Chekka springs)	100

The main planned irrigation schemes in Lebanon are as follows:

South Lebanon irrigation scheme

Eventually this scheme calls for irrigating 33,000 hectares in southern Lebanon. This includes an initial irrigation of 1,200 hectares near Saida and the reorganization of irrigation over 6,000 hectares already irrigated in the Qasmieh region. In 1972 a United Nations team prepared feasibility studies for this project.

Irrigation of south Bekaa

The irrigated area in south Bekaa was about 10,000 hectares in 1972. This project provides for normalizing and regulating the currently irrigated area, with the addition of 13,000 hectares, bringing the total irrigated area to 23,000 hectares. The water required amounts to 140 million m^3, of which 30 million m^3 will be drawn from the Karaoun lake, 74 million m^3 from ground water and 36 million m^3 from surface sources.

Hermel irrigation scheme

The project provides for irrigating 6,000 hectares in the Hermel area from the Orontes river waters in two phases. Phase one provides for the irrigation of

4,000 hectares by gravity, 2,500 hectares of which will be in the Kaa region and 1,500 hectares in the Hermel region. The second phase involves irrigating 2,000 hectares by pumping in the Kaa region and 500 hectares by pumping in Hermel;

Akkar Plain irrigation project

This project provides for irrigating 4,000 additional hectares in Akkar plus regularizing 6,000 hectares irregularly irrigated at present along with improving the irrigation supply for 2,300 hectares in the Bukaia plain (a smaller plain in Akkar near the border with the Syrian Arab Republic);

Koura Zgharta irrigation scheme

This project provides for the irrigation of 1,200 hecgares from a projected 40 million m^3 dam across the Asfour river in the Deir Beechtar area. The areas to be irrigated will be in the oases of Koura and Zgharta.

Selected reference

Burdon, D. J. and J. W. Harshbarger. The water components of hydro-agricultural development - LEB 13. Unpublished report. FAO, Rome, 1969.

Food and Agriculture Organization of the United Nations (FAO). World Conference on Agrarian Reform and Rural Development. Country review paper No. 10: Lebanon. Rome, 1978.

Guerre, A. Etude hydrologique préliminaire des karsts libanais. Revue libanaise de Géographie, vol. IV, Hannon. 1969.

UNDP/FAO. Etude hydrogéologique de la plaine d'Akkar. Unpublished report. 1970.

__________. Planification de l'utilisation des eaux dans le nord du Liban. Rome, 1976.

__________. Etude hydrogéologique de la région de Koura-Zgharta. Unpublished report 1972.

__________. Travaux de reconnaissance hydrogéologique dans la plaine de Bouqaie. Unpublished report. 1972.

__________. Projet de développement hydro-agricole du sud du Liban. Unpublished report. 1974.

__________. Projet de développement hydro-agricole de la Bekaa centrale. Unpublished report. 1974.

UNDP/United Nations. Liban: étude des eaux souterraines. 1970.

OMAN

Area: 213,000 km^2

Population: 743,000 (United Nations estimate, 1975

General

The northern part of Oman is dominated topographically by the Oman mountain range, an arcuate belt of deeply dissected terrain with a maximum elevation of 2,980 m above mean sea level at Jebel Sham, one of the peaks of the Akhdar range. The mountains are flanked to the east by a fertile coastal plain (the Batimah plain) and to the west by gravel plains and the desert. The province of Dhofar is separated from the mountainous north by 200 km of mainly desert land, the western continuation of which merges into the Rub Al Khali (the Empty Quarter), the major sand mass of the Arabian Peninsula. The geographical areas are identified in map 15 and are described below in some detail.

Capital area

The capital area, the most densely populated in the country, is composed of four regions: Muscat, Mutrah, Bawshar and Sib.

Musandam

The isolated northern region of Musandam consists of rugged mountains rising to 1,800 m in height from a deeply indented fjord coastline. The principal villages are Khasab, Bayah and Bukha.

Batinah plain

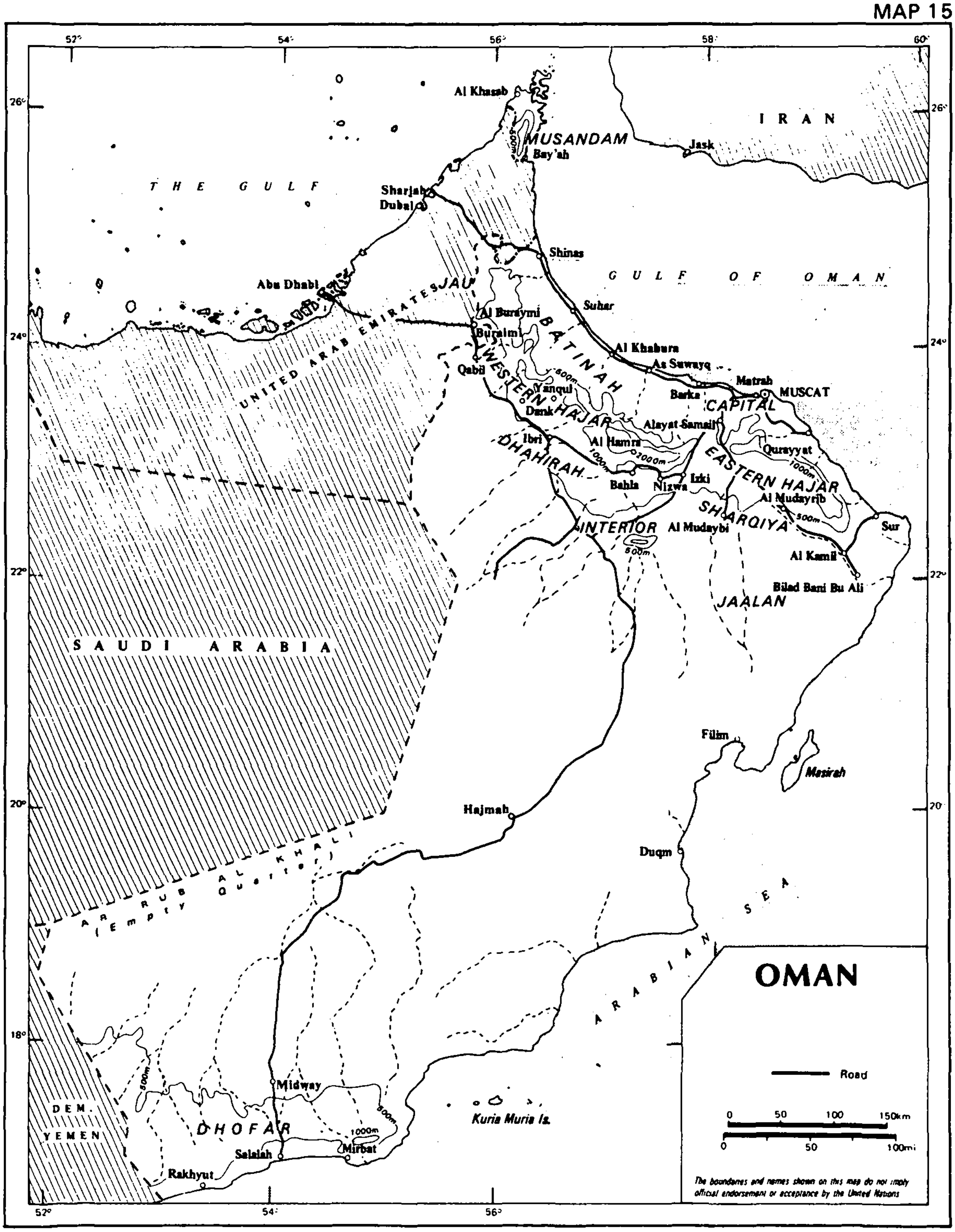
The Batinah plain runs from the border with the United Arab Emirates for a distance of some 270 km south-east almost to Muscat. It is situated between the coast and the western Hajar, varying from 10 to 30 km in width. Cultivation is limited to a narrow strip, seldom wider than 3 km, adjacent to the sea. The Batinah is one of the most populous areas of Oman, the main towns being Barka, Masnaa, Suwaiq, Khaburah, Saham, Sohar, Liwa and Shinas.

Western Hajar

The mountain range of western Hajar, parallel to the ... stretches from the border with the United Arab Emirates in the north to the ... gap in the south. The highest points are in the south-east, the Jebel al Akh... ...ving peaks approaching 3,000 m in height. There are groups of major se...ements on each side of the western Hajar. Those to the south make up the area known as Oman proper, while the main towns on the seaward side of the mountains are Rostaq, Awabi and Nakhl.

Map 15

Oman



MAP NO. 2993 REV. 1 UNITED NATIONS
SEPTEMBER 1981

Eastern Hajar

The eastern Hajar is the continuation of the main mountains of Oman from the Sumail gap to Jebel Khamis in the east, a distance of just over 200 km. To the north the mountains reach the sea and to the south they are bordered by the Sharqiya and the Jaalan. The highest elevation is 2,100 m. The principal towns on the seaward edge of the mountains are Sur, Tiwi and Qurayyat.

Dhahirah

Dhahirah is a semi-desert plain, sloping from the southern flanks of the western Hajar into the Rub al Khali. It is bordered to the north by Jau and Buraimi and to the south it is divided from Oman proper by Jebel al Kawr. The major settlements are on two principal wadis, wadi Dank and wadi al Ain, the towns being Dank, Ibri and Yanqal.

Jau

The northern extension of the plain of Dhahirah is known as Jau. In this small area between the border with the United Arab Emirates and the western Hajar, the population is concentrated around the Buraimi oasis where dates are grown under irrigation.

Oman interior

Oman interior is a central plateau sloping from the Jebel al Akhdar in the north towards the desert in the south. It is bounded in the west by the Dhahirah and in the east by the Sharqiya. There are four principal valleys: wadi Kabir, wadi Halfain, wadi Bahla and wadi Sumail. Wadi Halfain and wadi Sumail together form a natural gap in the main mountain range. This gap is a traditional route between Muscat and the interior, as well as being one of the most populous areas of Oman. The main towns are Nizwa, Bahla, Izki, Manah, Adam and Sumail.

Sharqiya

The Sharqiya is an area of sandy plains and valleys, lying on the inland side of the eastern Hajar, bordered to the south-east by the district of Jaalan and to the south by the Wahiba sands. The main towns are Inra, Mudaibi, Samad, Biddiyah and Mudairib.

Jaalan

The Jaalan is a sandy plain forming the southern extension of the Sharqiya and extending to the Arabian Sea. It is bordered on the northern side by the eastern Hajar and on the southern side by the Wahiba sands. The main towns are Bilad Bani Bu Ali, Bilad Bani Bu Hasan, Wafi and Kamil.

Masirah

The island of Masirah, almost 60 km long, is situated in the Arabian Sea. The other important islands, also in the Arabian Sea, are the Kuria Muria group, the largest of which is Hallaniya.

Dhofar

The southern region of Dhofar occupies almost one third of the area of the country. It is composed of two different climatic zones. The coastal plain, extending from Raysut in the west past Salalah, is nowhere wider than about 8 km but the fertile alluvial soil is well watered between June and September by the south-west monsoon. The monsoon also reaches the wooded hills which rise up to 1,500 m in elevation behind the coastal plain. North of the mountains and extending to the border with Saudi Arabia in the Rub al Khali there is very little rainfall and the area has desert vegetation. The main towns and villages are Salalah, Marbat, Taqa, Thamarit, Rakhyut and Mukhshin.

Monthly rainfall data and temperature averages are available for only a few stations in Oman. Rainfall figures for Muscat show an annual aggregate of 107 mm, of which 78 mm fall between December and April. Regional variations are indicated by rainfall figures for Sohar which receives a total of 38 mm a year, while in Dhofar about 115 mm fall mainly between May and November. Temperatures in Muscat range from an average maximum of 41° C in June to 27° C in January. Salalah, the regional capital of Dhofar, enjoys the more equable temperatures of 32° C maximum in June and 27° C in January. In spite of the arid climate, water is plentiful in many of the deeply incised wadis of the mountains and is present beneath the surrounding plains. Rain falls in short violent storms, which cause flash-flooding in the mountains, but cloud conditions without appreciable rain may persist for several days. Winds are light in clear weather, but may rise to gale force at night in the mountains. During stormy conditions high winds raise considerable amounts of dust.

A comprehensive network of meteorological stations is now being installed, which will generally improve the knowledge of climatic variations and phenomena, and also provide more complete data for navigation by sea and air.

Geology

In northern Oman mountains, Pre-Cambrian basement rocks are well exposed in Jebel al Akhdar, Sayh Hatat, and Jebel Jaalan. They include phyllite, green schist, granite and quartizite and are intersected by quartzoze veins. In the Dhofar region the basement is exposed in the area east of Salalah between Taqah-Mirbat and Al-Hasik. Here it includes gneisses, schists and pegmatic dykes. The basement rocks are unconformably overlain by thick beds of crystalline limestone with chert stringers and basal conglomerates. The limestones show solution textures and are cavernous. The age of these autochtonous rocks, which are well exposed on the flanks of Jebel al Akhdar and Sayh Hatat, ranges from Permian to Upper Cretaceous.

These series are unconformably overlain by an autochtonous unit called the Hawasina nappe. The contact is a thrust contact. The Hawasina nappe is composed of limestone, conglomerate, radiolarian chert and shale. The age of the Hawasina rocks ranges from the Permian to the Cretaceous. On top of the Hawasina rocks the Semail ophiolite nappe is in thrust contact with the lower rocks. The thrust contact is exemplified by metamorphic rocks and Oman melange which is a mechanical mixture of cherts, limestones, lavas and serpentinites, usually sheared. From the top to the bottom, the ophiolites are composed of basic extrusives, pillow lavas, dyke swarms, gabbros, banded gabbros, peridotites which are serpentinized in many places, and dunites and harzbergites. The ophiolites are unconformably overlain by the maestrichtian to Tertiary limestones, which are composed of reefal limestones that are crystalline at some places.

At the top of the geological column are the recent fluviatile sediments and fan deposits. These are formed of indurated well cemented conglomerates, wadi gravel and fanglomerate.

In general, the rocks of Oman reflect the effect of large-scale tectonism and thrusting and superposition of originally laterally equivalent units. This condition is well expressed in the Oman mountains. The nappes formation took place at the end of the Upper Cretaceous age. The Oman rocks were also subjected to the updoming and compression that took place in the early part of Tertiary. This resulted in the formation of the Sayh Hatat dome and the Jebel al Akhdar anticlines. All these events affected the rocks in Oman, so that they are all highly faulted and folded.

Surface water

Owing to the steep slopes, the low permeability of the rocks along the wadis and the intermittent rainfall of fairly high intensity, run-off in the mountains is high. Part of it comes down in the form of surface flows of short duration, while the remainder penetrates the gravel and sands of the wadis and is released as a perennial base flow. The Wadis Al Jizi, Al-Hawasina, Sumail and Bani Ummar in the northern Oman mountains provide a good example of this conditions.

Some streams tap the cavernous limestones, especially along the trust contact of the ophiolite rocks and the old shelf limestones. These are wadi Daiqua and wadi Bani Khlid. There are many other streams and springs especially at the base of Jebel al Akhdar, at Rustaq and at Tunnuf.

Ground water

Several large-scale resources surveys directed towards investigating the extent and availability of ground water to support further irrigation and urban development have been carried out. The main reports covering these investigations are identified in the list of references below.

In general, ground water in Oman is derived either from deep fossil aquifers extending over large portions of the Arabian Peninsula or from recent wadi deposits, alluvial fans and coastal plains along the mountain ranges. In view of the high cost of production from the deep aquifers and the scarcity of arable lands in the interior, the exploitation of this resource has to be limited to uses related to the development of petroleum and mineral resources. Most extraction takes place from the shallow acquifers, as described below for the three major regions.

Northern coastal plain

The aquifer system of the Batinah plain is contained in a wedge-shaped body of alluvial deposits which thicken from a feather edge adjacent to the mountain front towards the sea. The upper part of the system consists predominantly of gravel. Saturated thicknesses are as much as 100 m locally, but generally do not exceed 30 to 40 m and then narrow to a feather edge within 5 to 15 km of the coast. The lower part of the system is formed by clay gravels with maximum thicknesses in excess of 100 m adjacent to the coast.

The lower, essentially impermeable, boundary of that system is formed either by a thick unit of conglomerates and clays or by bedrock. However, with respect to ground-water development, there is a hydraulic boundary defined by the interface between fresh water and sea water, the position of which varies according to the head difference between the fresh water and sea level. Under transit conditions, the position of the interface is also dependent on the total porosity of that part of system in which the interface is moving.

The mean section permeability of the upper gravels is high, averaging about 50 m/day, though there is marked lateral and horizontal variation. The mean section permeability of the clay gravels is low, though lenses of clean gravel occur which will supply relatively high-yielding wells.

The hydraulic gradient is towards the coast. It averages about 1 in 100 where flow is predominantly in the clay gravels but slackens rapidly to less than 1 in 2,500 as the thickness of saturated upper gravels increases adjacent to the coast. Present extraction for irrigation is essentially concentrated in the coastal strip where water-level elevations are less than 2 m above sea level.

The studies show that, with local exceptions, the ground-water system is essentially in equilibrium. The outputs of the ground-water balance are consumptive use by irrigated agriculture; transpiration by natural vegetation; evaporation from the shallow water table (mainly in the sabkhah zone); and flow to the sea. A continuous cover of natural vegetation and palm trees, interspersed with irrigated gardens, extends to the coastal dunes. The presence of green vegetation at the heads of inlets to the sea indicates fresh water flow. However, the sabkhah zone is extensive. The economic and social values of the natural vegetation are not known but it must be accepted that the water it transpires forms an important part of the balance of the coastal aquifer system. It is likely that the flow to the sea is limited and that most of the underflow passing north of the cultivated zone is consumed by evaporation at the sabkhah.

Oman mountains and interior plains

The ground-water resources of the Oman mountains are developed in the narrow bottoms of deeply incised valleys which form line sinks for the ground-water discharge from the hills. The ground-water either discharges naturally as springs or base flows, or is developed by means of drainage galleries, known as falajs. Land limitations prevent any important extension of the irrigated areas and available water is often in excess of requirements. However, this excess should not be regarded as a loss as the valleys form closed systems and the water moves down-gradient to the benefit of users of lower aquifers on the plains. A major problem would appear to be maintenance of the falaj system, which can be the most efficient method of extracting the water under certain circumstances, but would be extremely expensive to replace.

The ground-water of the interior plains is contained in a relatively thin cover of coarse clastic materials overlying clay deposits which in turn overlie bedrock of low permeability. The coarse material consisting of gravel, sand and silt, forms aquifers when consolidated. Its thickness, however, is generally less than 10 m, though it may be up to 50 m in local depressions and along wadi channels. The exploitable ground water is therefore erratically distributed. Moreover, the irrigable land is also distributed, with few exceptions, in small areas which do not necessarily accord with the availability of water. An exception is the wadi Qurayyat plain where 2,900 hectares of new lands have been mapped, though the water resource to supply this land has not been identified.

Dhofar

The Salalah plain is about 50 km wide and a maximum of 15 km long. It is bounded to the south by the sea and to the north by mountains. Ground-water occurence is related to carbonate rocks and conglomerates. Recharge is by underflow from the mountain range and by springs which discharge at the foot of the mountains. Flood occurrences on the plain are extremely rare. The recharge appears to be very slight, although there is a fair amount of rainfall on the mountain catchment; much of this, however, occurs in the form of heavy mist. The ground-water quality is generally poor except in the central part of the plain behind Salalah.

In carbonate acquifers, low water levels, high cost of well construction and low yields combine to preclude the use of ground water for irrigation. In addition, the soils are patchy and thin, but development for domestic use and cattle watering appears feasible.

Little is known about ground-water conditions on the interior plateau (Nejd). The plateau is believed to be underlain by a carbonate aquifer system of regional extent. Artesian flows are obtained in some areas. Water quality is generally poor. The soils are structureless, highly permeable and of poor fertility.

The falaj system

In view of its historical importance the following discussion is devoted to a more detailed examination of the *falaj* and its role in water resources development in Oman. Viewed as an engineering system, it taps ground water in the coarse sediments of mountain-foot zones where the water is relatively close to the surface and has a low content of dissolved salts. Geological and geomorphological factors produce factors produce localized concentrations and channelling of ground-water flow. In most cases, a *falaj* is sited so as to tap such concentrations by means of "mother-wells". It then conveys ground water down-slope to areas of finer sediments more suitable for cultivation. The channel/tunnel gradient must be approximately uniform throughout and therefore differs from the varying surface gradients. Underground sections of a *falaj* have to be tunnelled through a variety of loose sediments (coarse and fine) and also through bedrock and cemented sediments. Underground sections may thus tap subsidiary ground-water flows also.

The main channel of the *falaj* is most vulnerable to mechanical damage when (*a*) underground sections are shallow or constructed in loose sediments; (*b*) it lies within wadis or crosses tributary wadis subject to severe floods; and (*c*) surface sections are embanked.

The rate of flow in a _falaj_ is determined by a relatively large rainfall catchment area feeding a relatively small channel concentration of ground-water. Fluctuations in flow are therefore fairly limited except during prolonged dry or wet periods. _Falaj_ construction is designed for equable flow conditions; if for some reason these conditions are not maintained major reconstruction becomes necessary.

Ground-water management

The fact that water has traditionally been relatively plentiful and was therefore developed in many scattered localities, has resulted in an absence of centralized control and regulation. Accelerated development, however, and the water problems that have arisen in the process, are beginning to create the need for government involvement and assistance. Problem areas include technical matters (salt-water intrusion, need for artificial recharge, interference of extraction patterns) and legal aspects (existing water rights, assignment of priorities).

In order to provide co-ordination in these matters the Water Resources Council was established as the supreme government body entrusted with the organization of co-ordinated water administration. Several measures are being implemented in that direction:

(a) A water resources law is being considered which will identify the co-ordinating functions, and will facilitate the procedures involved in the granting of permits and licences;

(b) The Government is studying alternative approaches to organizing a central administration;

(c) Several investigations are now being undertaken for the purpose of continuing or supplementing previous efforts. These include digital computer modelling studies of the coastal aquifers, and artificial recharge schemes for the more productive wadis;

(d) Long-term planning has been initiated for all major municipalities to cover needs and supplies.

The responsibility for these activities is at present shared by several government organizations, especially the Water Resources Council (co-ordination, legislation); the Ministry of Communications (urban water supply, meteorological data collection, desalination plants); and the Ministry of Agriculture, Fisheries, Petroleum and Minerals (hydrological data collection, irrigation, flood control).

Water drilling is carried out by a number of specialized firms, usually with broad experience in the region. At times, in response to specific emergency requests, the Government may assign its own equipment to assist villages or farmers in securing urgently needed supplies.

Problems

The main problems affecting ground-water resources are as follows:

(a) Saline (sea) water intrusion

This phenomenon is being monitored in several places, and is being countered by moving the extraction zone back from the coast;

(b) Net surface flow losses to the sea or the desert

Recharge schemes are being prepared which will not only minimize losses and recharge the alluvial fans, but will also help in the control of salt-water intrusion;

(c) Inefficient water use

To overcome this, educational efforts are being directed towards the introduction of water-saving techniques and practices. Results are expected from the publication of information on the subject and an efficient extension programme.

Conclusion

Ground water is one of the main natural resources in Oman and its availability is a limiting factor in many sectors of the economy of the country. It has received considerable development emphasis in recent years which is leading to an improved government role in co-ordination and the establishment of a proper infrastructure. On the basis of data and reports submitted as of 1977, it appears that cautious optimism is justified with regard to the adequacy of Oman's water resources to support planned economic development.

Selected references

ILACO, Arnhem, Netherlands. Water Resources Development Project, Northern Oman. Final Report. July 1975.

Sir Alexander Gibb and Partners, London, England. Water Resources Survey of Northern Oman. Final Report. June 1976.

Renardet-Sauti-ICE, Muscat, Oman. Water Resources Survey in North East Oman. Interim Report. March 1975.

Sir William Halcrow and Partners, London, England. Surveys and Investigations for Land and Water Resources Development in Dhofar. Final Report. August 1975.

QATAR

Area: 11,000 km^2

Population: 89,000

General

Qatar occupies a peninsula extending northwards from the land mass of the Arabian Peninsula into the Gulf. The length of the peninsula is approximately 190 km and its maximum width is 85 km. The average elevation does not exceed 40 m above sea level. Because of the gentle relief, no pronounced drainage system has been developed. The many depressions throughout Qatar act as individual catchment areas and the surface drainage which does exist is predominantly internal. Run-off is carried to the sea only along some of the coastal margins.

Qatar lies wholly within the northern hemisphere desert belt. Maximum temperatures exceed 40° C in summer, while the winter is cooler. The relative humidity is high. Mean annual evaporation exceeds 2,000 mm (Penman Eo). For a period of 13 years, the annual rainfall at Doha ranged from 2 mm to 190 mm with an average of about 75 mm per year. High intensity rainfall can occur over limited areas at any time during the period from December to May.

Since there are no surface-water resources in Qatar, the demand for water was met initially by the exploitation of the ground-water reservoirs. Increasing demands due to population growth and industrial and agricultural development have necessitated the construction of sea-water distillation plants, to provide an additional source of fresh water.

Geology

On most of the territory, large outcroppings of karstified limestones of Dammam formation (Middle Eocene) occur. They are covered locally by aeolian sands. The Lower Eocene red formation itself overlies the Umm er Radhuma formation (Paleocene dolomitic limestone). The geology of the country is shown in map 16.

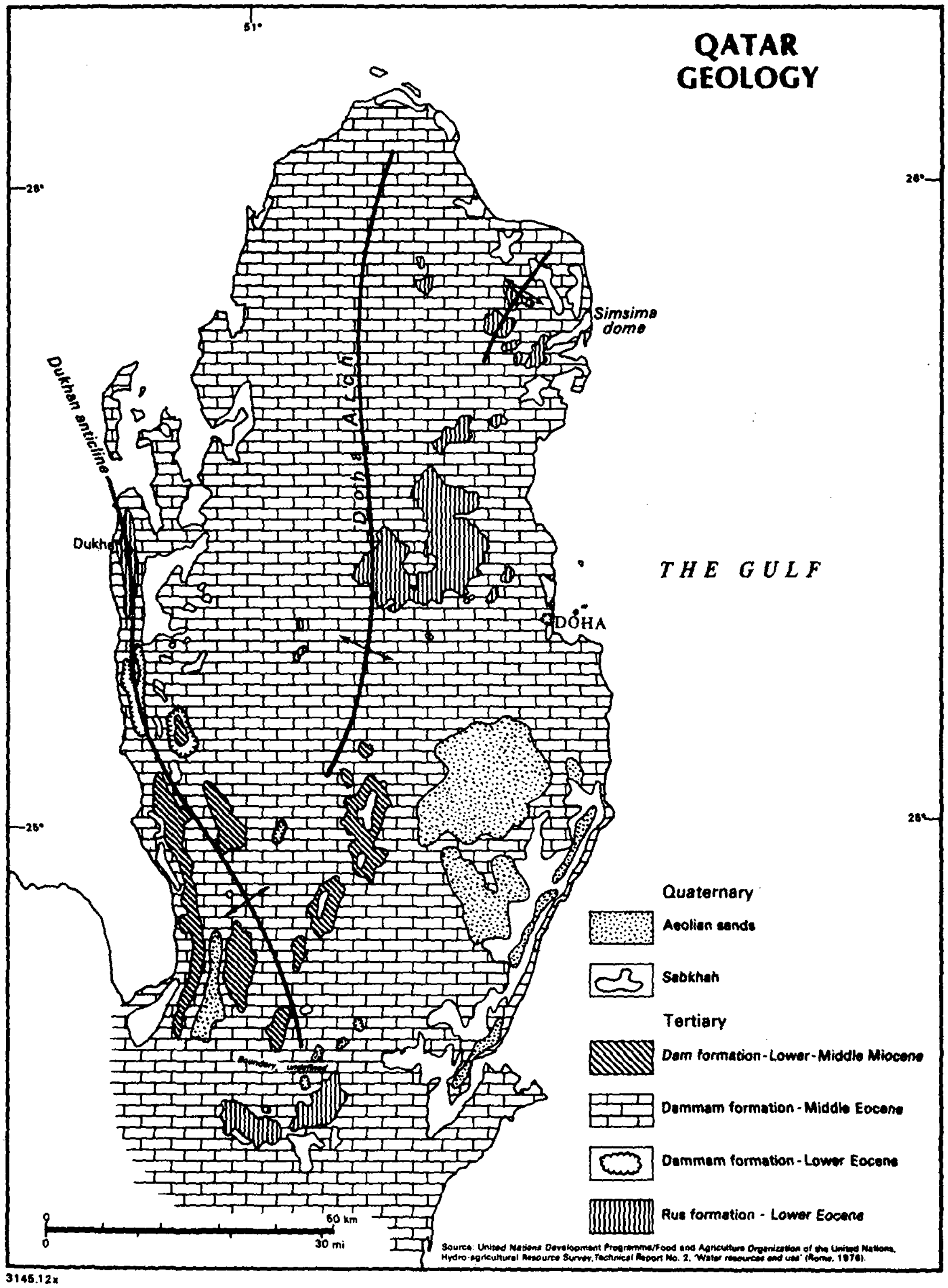
Ground water

The occurrence of ground water in Qatar is complicated by the regional geomorphology, fresh ground water (500-2,000 ppm of total dissolved solids) being generally limited to the northern half of the country. The northern ground-water province occurs as a typical fresh-water lens floating on a brackish and saline water base. The southern province is predominatly more saline with the exception of localized artesian conditions near the southern border.

Map 16

Qatar: geology

MAP 16



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Aquifers in Qatar can be subdivided into two units: the main limestone aquifers of the Rus and Lower Dammam formations and the deeper Umm er Radhuma aquifer. In northern Qatar the main aquifer yields fresh water to depths of about 100 m below sea level but in southern Qatar, wells drilled to that depth yield brackish to saline water. The Umm er Radhuma aquifer contains brackish water beneath the whole country.

The south-western corner of Qatar is the Abu Samra area. Wells tapping the Alat formation (Upper Dammam) at depths not exceeding 30 m are producing water under artesian pressure of suitable quality for irrigation.

During the period from May to June 1972, the surface of the fresh-water lens was at an elevation of about 4 m in the centre of the peninsula and tapered down towards the coastline (see map 17). It was estimated that the maximum depth of the lens was 100 m below sea level in the centre of the peninsula. The maximum tidal range is about 2 m.

The fresh-water lens is recharged naturally from the infrequent but heavy rainstorms of a relatively localized nature by means of internal drainage to collapse depressions. The recharge potential in areas outside the collapse depressions is low owing to the absence, or very limited extent, of vertical fractures except in the proximity of these depressions.

Over the past 15 years irrigated agriculture has developed in scattered areas mainly in the northern part of the country. Irrigation from ground water was negligible in 1956 but it has now increased to the point where the amount of ground-water withdrawal could exceed the natural recharge owing to the low rainfall (60 mm per year in Doha).

Under a UNDP project entitled "Hydro-agricultural Resources Survey", for which FAO was the executing agency, an extensive survey of the ground-water resources of the peninsula was carried out. In particular, a water balance was prepared for the years 1972-1975 (see table 17). It shows that in northern areas, estimated recharge covers only 50 per cent of water extraction and in the south, about 57 per cent. For the period 1958-1972 a growing decline in water levels in wells has been observed with a maximum of 10 m north-east of Doha (see map 18).

Distilled sea water is produced at a rate of 30 million m^3/year (1977).

Problems

Qatar faces serious problems in ensuring that there will be an adequate water supply in the next 20 years or so. It has been estimated that industrial and domestic demand will be met over the next 25 years by a combination of desalinated sea water and ground water requiring discharge rate of up to 20 million m^3/year by the year 2000. One of the main measures which is being considered in conservation/augmentation is the artificial recharge of the main northern area with desalinated sea water using excess natural gas as the energy source.

Map 17

Qatar: ground-water contours, May-June 1972

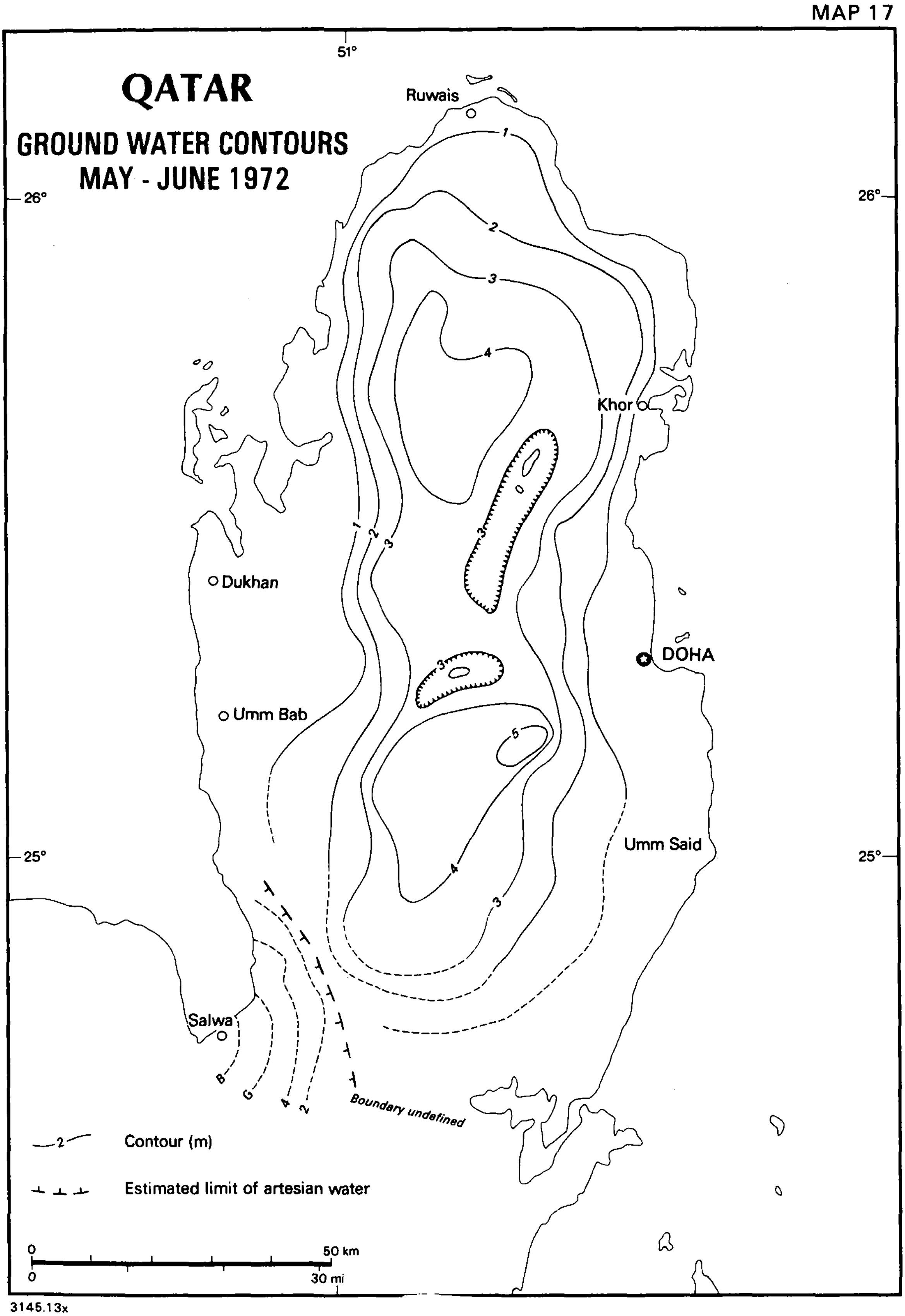


Table 17. Qatar: water balance assessment for the years 1972-1975

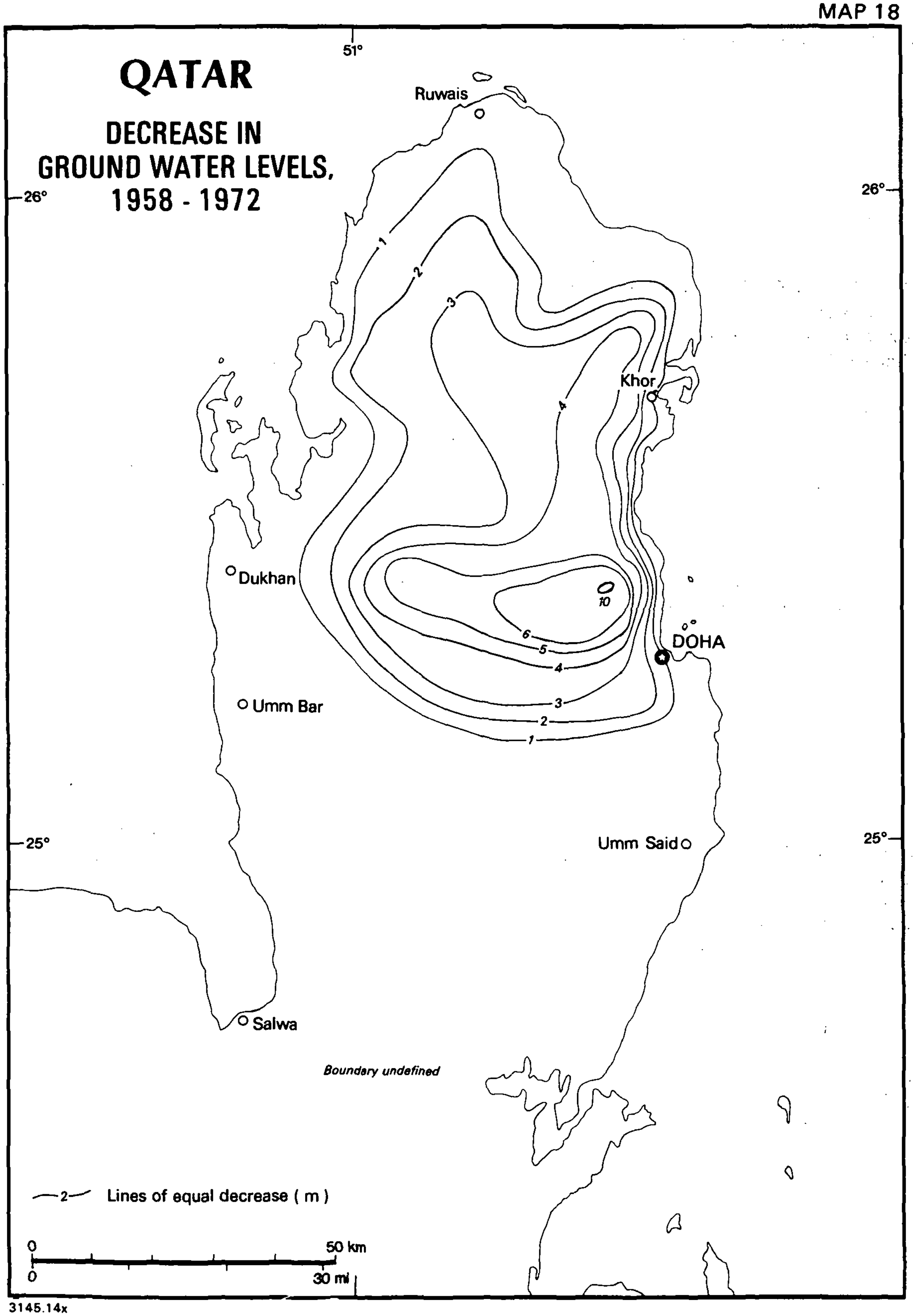
(Millions of m^3/year)

Ground-water province	Estimated recharge	Net extraction			Depletion or increment to storage
		Agriculture	Domestic/ Industrial	Outflow	
Northern area					
A	4.12	10.99	...	0.3	-7.17
B	1.48	0.36	0.14	0.3	+0.78
C	5.20	3.77	2.89	0.3	-1.76
D	2.43	0.20	0.10	0.3	+1.83
E	2.40	5.14	1.48	0.3	-4.52
F	1.38	6.24	0.02	0.3	-5.18
Subtotal	17.01	26.60	4.65	1.8	-16.02
Southern area					
G	1.59	0.07	...	0.3	+1.22
H	1.74	0.02	...	0.3	-0.58
I	0.25	...	...	0.3	-0.05
J	0.33	...	...	0.3	+0.03
Subtotal	3.91	2.09	...	1.2	+0.62
TOTAL	20.92	28.69	4.63	3.0	-15.40

Source: United Nations Development Programme/Food and Agriculture Organization of the United Nations, Hydro-agricultural Resources Survey, technical note No. 34 (Rome, 1976).

Map 18

Qatar: decrease in ground-water levels, 1958-1972



SAUDI ARABIA

Area: 2,149,000 km^2

Population: 9,240,000 (United Nations estimate, 1976)

General

The Arabian Peninsula may be divided into six physiographical units: the mountainous zones, the elevated plains, the escarpment belt, the central plateau, the coastal regions and the aeolian sand areas.

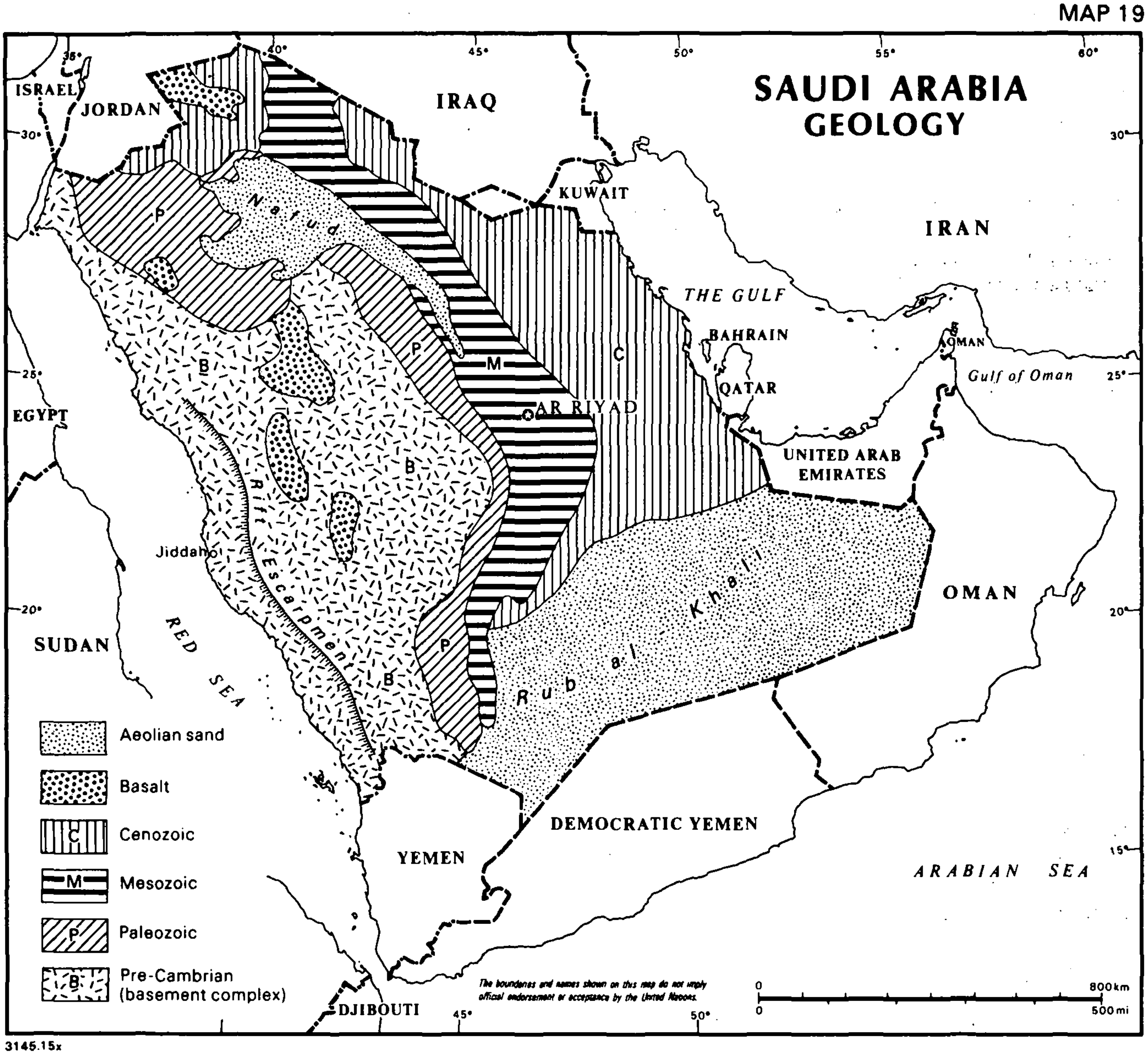
The mountainous zones include the Oman mountains in the east, the mountains along the Gulf of Aden, the Hadramawt plateau, and the mountains of Yemen and the Red Sea coastal ranges. The elevated plains include the wide gravel plains and numerous granite inselbergs of the shield. The escarpment belt includes the region of westerly facing scarps, one of which, the Tuwayq mountain scarp, is continuous for 800 km. The scarps are retreating hog's back features related to the easterly dipping Paleozoic strata. The central plateau, which is a region of Tertiary sediments between the escarpment belt and the coastal plain, is mainly a flat calcareous rock area with widespread karstic development and calcareous duricrusts. The Gulf coastal plain is a flat area of sabkhahs, thin gravel plains, small marine terraces and strand lines. It is an area rich in evaporites (though deposits are poor due to aeolian deflation) since the present-day ground-water basin discharges through this zone. The aeolian sand areas cover approximately one half of the peninsula: the Rub al Khali, the Great Nefud, the Ad Dahna and the Al Jafurah. The Rub al Khali (the Empty Quarter) contains vast areas of mountainous sand dunes, broad interdunal plains and sabkhahs. The Great Nefud in northern Saudi Arabia is another area of vast dunes, with scarcely any vegetation and no oases. The Ad Dahna is a curious strip of sand stretching continuously from the Great Nefud to the Rub al Khali and covering the outcrop of the Umm er Radhuma strata.

The major easterly flowing wadis have all cut through the escarpment belt, flowing strongly because of the non-recharging character of the Paleozoic strata. In general they cease flowing over the younger recharging aquifers where they have left major gravel deltas as witness to the vast flows of a pluvial period. It is interesting that the ancient wadi courses do not reach the sea, which suggests that in former times the sea level may have been higher or the land surface considerably depressed. There are suggestions by several writers that the line of sabkhahs, which is continuous from Iraq to Oman along the 125 m topographic contour, could have been an ancient shore-line.

The geological history of the Arabian Peninsula (see map 19) is dominated by the Red Sea rifting in Late Cretaceous and Early Tertiary times, when the Afro-Arabian shield was parted by rift faulting. Prior to this event, erosion in the shield produced a Paleozoic perimeter of clastic sediments through the Cambrian, Ordovician, Silurian, Devonian, Carboniferous and Permian periods.

Map 19

Saudi Arabia: geology



However, in the region of Riyadh, from latitude 20° N to 24° N, erosion over the central Arabian arch has removed all Pre-Permian strata, so that at present the Permian lies directly on the crystalline basement. This has produced a somewhat anomalous stratigraphic picture in which the north and south outcropping Paleozoic strata, though almost certainly laterally equivalent, have been mapped separately and have received different formation names. The Permian and Post-Permian strata are continuous in outcrop from north to south.

In Lower Cretaceous time the sedimentation was still of a clastic nature, but from Middle to Upper Cretaceous the sedimentation changed to a shallow marine facies. This continued through Tertiary time to the present day. Aquifers occur throughout the sedimentary sequence and are described in figures I-III, which present the stratigraphic and hydrogeological columns.

Saudi Arabia is a hot dry country. The absence of surface water and the scarcity and irregularity of rainfall make it almost entirely dependent on ground-water. As a result, the Government, through its Ministry of Agriculture and Water, has invested heavily in ground-water investigations and development. Studies commenced in 1953 in the wadi Jizan area and continued until the mid 1960s. In 1967, regional studies covering eight areas, numbered I to VIII, began (see map 20). Other specific areas and problems were studied as time permitted. At present, there is a good regional knowledge of ground-water in the country and an excellent local knowledge in the more populated areas.

For ground-water purposes, Saudi Arabia can conveniently be divided into three principal regions:

(a) The Tihama coast and the Red Sea catchment;

(b) The Arabian shield;

(c) The eastern Arabian sedimentary basin.

The last-mentioned region may be subdivided into depleting and non-depleting aquifers (see figure IV). Depleting aquifers are those Post-Jurassic aquifers with a normal recharge, aquifer underflow and discharge régime, whereas non-depleting aquifers are those Pre-Cretaceous aquifers which do not discharge, have no normal underflow régime and hence reject recharge. In a depleting aquifer a water supply can be pumped either from, or jointly from, aquifer underflow, storage, and recharge. In a non-depleting aquifer the yield comes from storage and, as in the case of Riyadh's pumping from the Minjur aquifer, the cone of depression will assume vast dimensions.

Tihama coast and the Red Sea catchment

The Tihama coast extends for 1,700 km from Yemen in the south to Jordan in the north and varies in width from 40 km in the south to zero in the north. Its inland boundary is the north-south drainage divide between the Red Sea and Gulf catchments, giving it an area of 190,000 km^2. The region was studied by SOGREAH in 1967 (see map 20, area VI) and by Italconsult in 1969 (the Jeddah, Mecca and Taif area). Two geological environments are included. The inland areas contain the western raised perimeter and scarp of the Arabian shield. In the north the shield is covered with a thin capping of Paleozoic and Mesozoic sandstones and

SAUDI ARABIA: SUBSURFACE SEQUENCE -- AREA I (EXCEPT WADI AS SIRHAN)

Figure I

AGE			FORMATION		LITHOLOGY	GENERALIZED LITHOLOGY DESCRIPTION	MAXIMUM THICKNESS		MAJOR STRATIGRAPHIC DIVISIONS	AQUIFER CHARACTERISTICS
CENOZOIC	Quaternary		Surficial deposits & basalts			Unconsolidated gravels, sands and silts. Basalt beds in N.W.				Low to moderate yields; mineralization low to high, generally highly mineralized when there is return flow from irrigation.
CENOZOIC	Tertiary	Miocene – Pliocene	Undifferentiated			Sandstone and sandy lithologies of limestone, marl, and clay. Basalt beds locally.	100 m		Late Tertiary sandy carbonates and clastics	In Wadi as Sirhan Region, limestone and marls yield very little water; moderate yields from fine grained sandstone; locally quality is very poor but used in many places.
CENOZOIC	Tertiary	Paleocene – Eocene	Umm er Radhuma			Tan and brown, soft, argillaceous limestone with marly beds.	100 m		Late Cretaceous – Early Tertiary carbonates	No wells.
		—— disconformity? ——	—— disconformity? ——							
MESOZOIC	Cretaceous	Maestrichtian – Campanian	Aruma			Cream limestone and dolomite with minor shale.	410 m			Principle aquifer in Tapline region, very high lifts, static water level below 300 meters at 'Ar'ar, low to moderate yield; quality is useable, highly mineralized.
MESOZOIC	Cretaceous	Turonian (?) – Cenomanian	Sakakah ss. (Wasia)			Fine and medium grained sandstone with shale stringers.	244 m		Middle-Lower Cretaceous sands and sandy carbonates	
MESOZOIC	Cretaceous	Barremian – Aptian	Biyadh			Fine and medium grained sandstone.	267 m			Moderate yields in Sakakah Region; quality range from moderate to very high salinity.
MESOZOIC	Cretaceous	Hauterivian	Buwaib			Limestone, calcarenitic limestone and dolomite, in part sandy.	30 m			
MESOZOIC	Jurassic	Tithonian	Arab			Tan calcarenite and aphanitic limestone.	100 m		Jurassic carbonates and clastics	
MESOZOIC	Jurassic	Kimmeridgian	Jubaila			Tan dolomite and aphanitic limestone.	75 m			No wells
MESOZOIC	Jurassic	Kimmeridgian	Hanifa			Tan aphanitic limestone with calcarenitic limestone and some calcarenite.	70 m			
MESOZOIC	Jurassic	Oxfordian Callovian	Tuwaiq Mtn.			Buff, hard, aphanitic, occasionally cherty limestone.	165 m			
MESOZOIC	Jurassic	Callovian (?) Bathonian Bajocian	Dhruma			Olive and brown shale with thin calcarenitic and aphanitic limestone beds and sandstone stringers.	353 m			No wells
MESOZOIC	Jurassic	Toarcian	Marrat			Buff, hard, fine-grained limestone with a red, silty shale bed in the middle.	129 m			No wells
MESOZOIC	Triassic	Upper	Minjur			*Poorly sorted, reddish sandstone with subsidiary shale beds at top and bottom.*	150 m		Permo-Triassic clastics *and carbonates*	Present only in limited area, moderate yield; quality poor to very poor.
MESOZOIC	Triassic	Middle	Jilh			Gray-tan, in part sandy dolomite with minor gray, calcareous shale beds, sandstone stringers and evaporites.	375 m			Low to moderate yields; quality is generally poor; in a few places yields acceptable water.
MESOZOIC	Triassic	Lower	Sudair			Green and brick red shale with sandstone and minor dolomite.	188 m			Aquiclude.
PALEOZOIC	Permian	Upper	Khuff			Gray shale, dolomite and limestone with some calcarenite, and evaporites at top.	340 m			Low to moderate yields, several wells flow, water quality is usually poor to very poor, fair quality in scattered locations.
PALEOZOIC	Permian Carboniferous	Lower Upper	Pre-Khuff*			Gray, red, occasionally yellow, in part silty shale and fine to medium grained, occasionally coarse, micaceous sandstone.	822 m		Early Paleozoic and carboniferous clastics	
PALEOZOIC	Carboniferous	Lower	Berwath*			Gray and vari-coloured shale, in part pyritic and micaceous, and fine to medium grained sandstone.	104 m			
PALEOZOIC	Devonian	Upper Middle Lower	Jauf			Poorly sorted, micaceous sandstone with interbeds of vari-colored, pyritic, micaceous shale, and impure dolomitic limestone beds toward bottom.	653 m			Sandstones are good aquifers at Al Jawf, Sakakah, Tapline ('Ar'ar deep test), and Turabah deep test; moderate flows in Al Jawf, static water level 140 meters at 'Ar'ar; quality excellent at Al Jawf to acceptable at 'Ar'ar.
PALEOZOIC	Silurian		Tawil	Tabuk		Fine to medium grained, micaceous sandstone alternating with gray and gray-green, micaceous, silty shale.	303 m	1030 m		Sandstone units yield low to moderate quantities, quality is good in Tabuk Region and variable to very poor at places in the Qasim. Wells in Tabuk Region and in Qasim near Buraydah will flow. Hanadir shale acts as confining bed between Tabuk sandstone and Saq.
PALEOZOIC	Silurian		Qusaybah	Tabuk			220 m			
PALEOZOIC	Silurian		Mid. Tabuk ss.	Tabuk			162 m			
PALEOZOIC	Ordovician	Upper	Ra'an	Tabuk			80 m			
PALEOZOIC	Ordovician	Middle	Lower Tabuk ss.	Tabuk			180 m			
PALEOZOIC	Ordovician	Lower	Hanadir	Tabuk			80 m			
PALEOZOIC	Cambrian		Saq			Coarse and medium grained sandstone with thin shale stringers.	928 m			Yields are moderate to high. Quality is generally good although highly mineralized water occurs locally. Wells in eastern part of Qasim have high heads, large flows. Wells in Tabuk area encounter low head, moderate flow in Saq-equivalent sandstone. Best potential of all aquifers in Basin.

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Figure I. Saudi Arabia: subsurface sequence - area I (except wadi as Sirhan)

Figure II. Saudi Arabia: stratigraphic sequence in area II

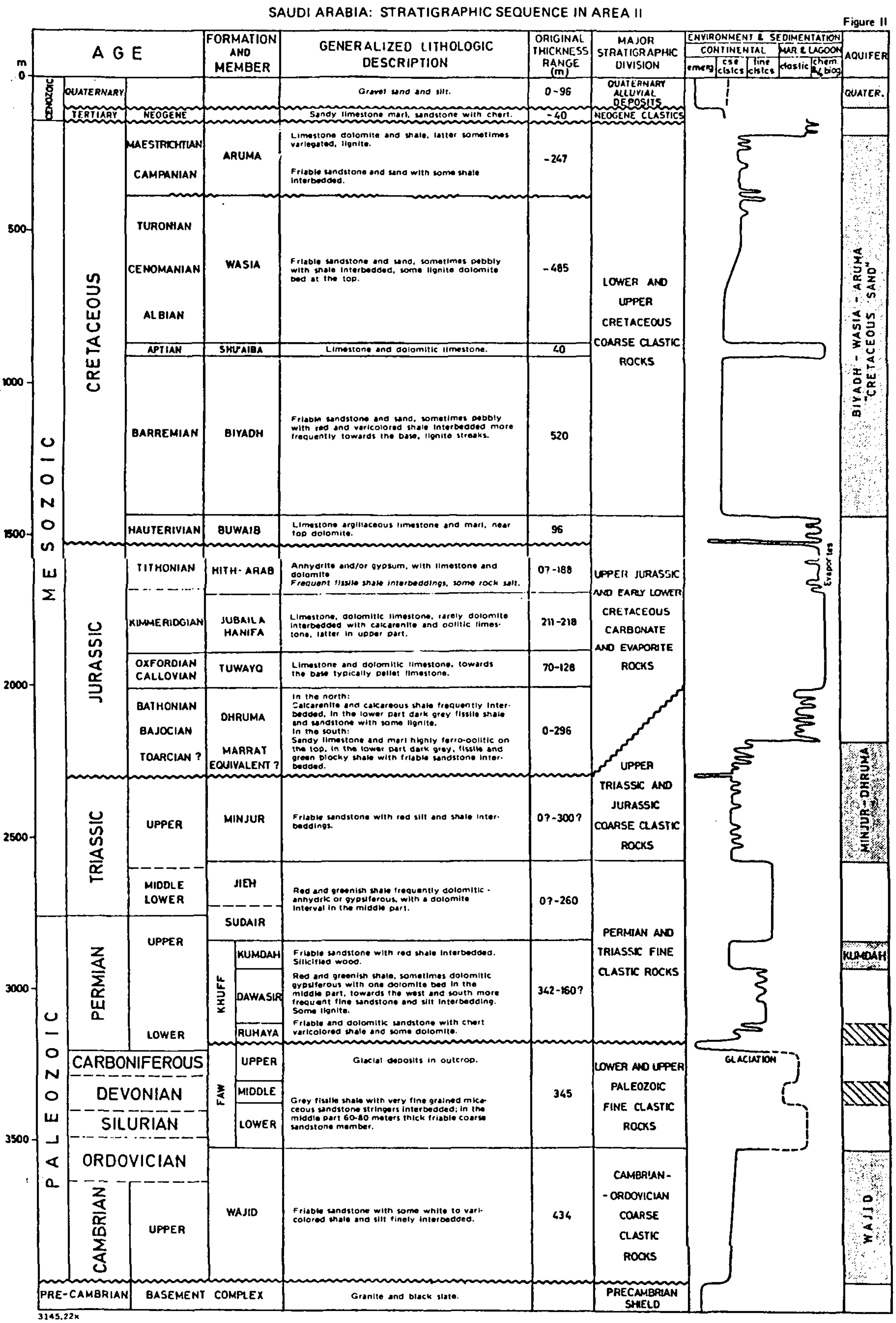
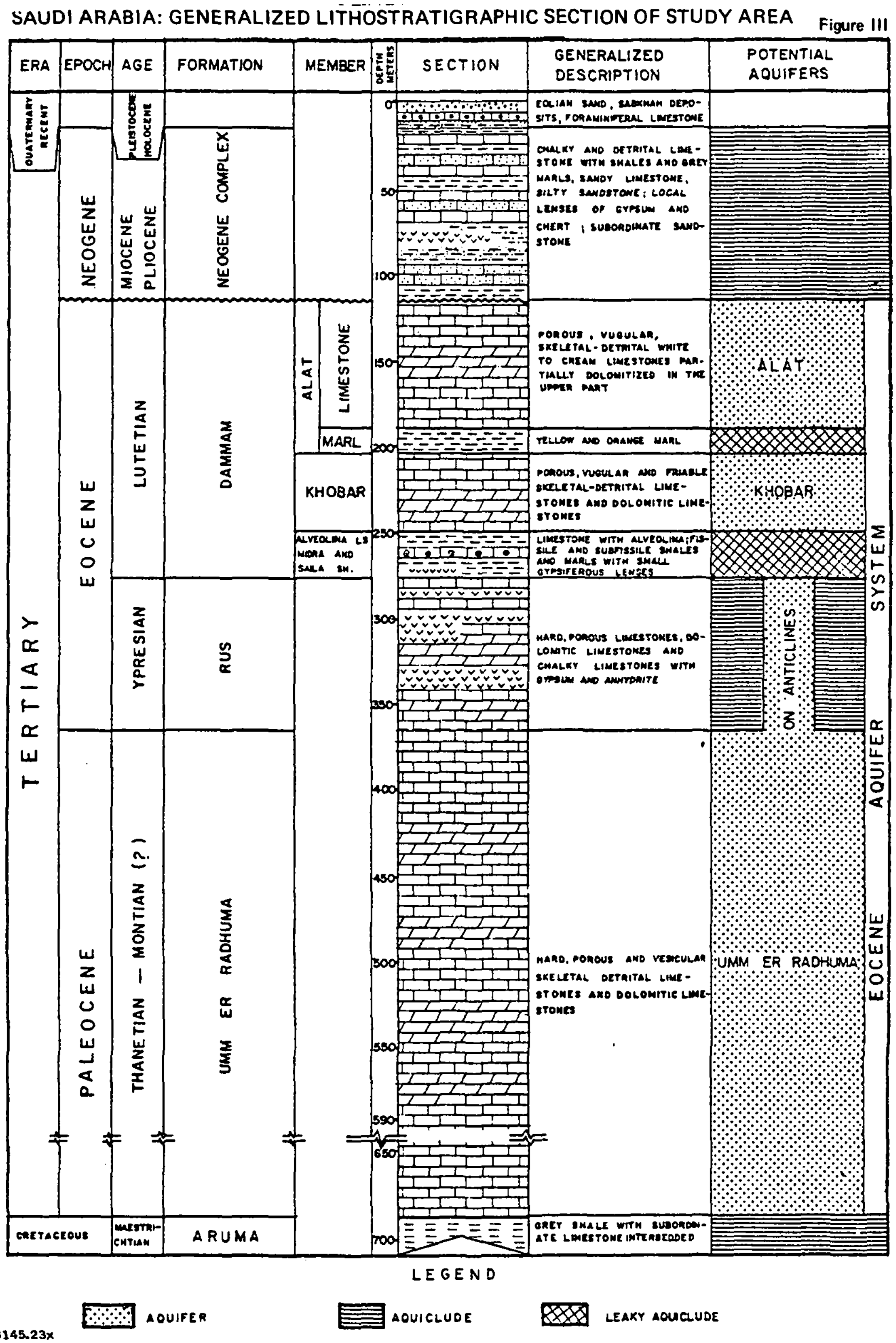


Figure III. Saudi Arabia: generalized lithostratigraphic section of study area



Map 20

Saudi Arabia: location of the eight areas surveyed

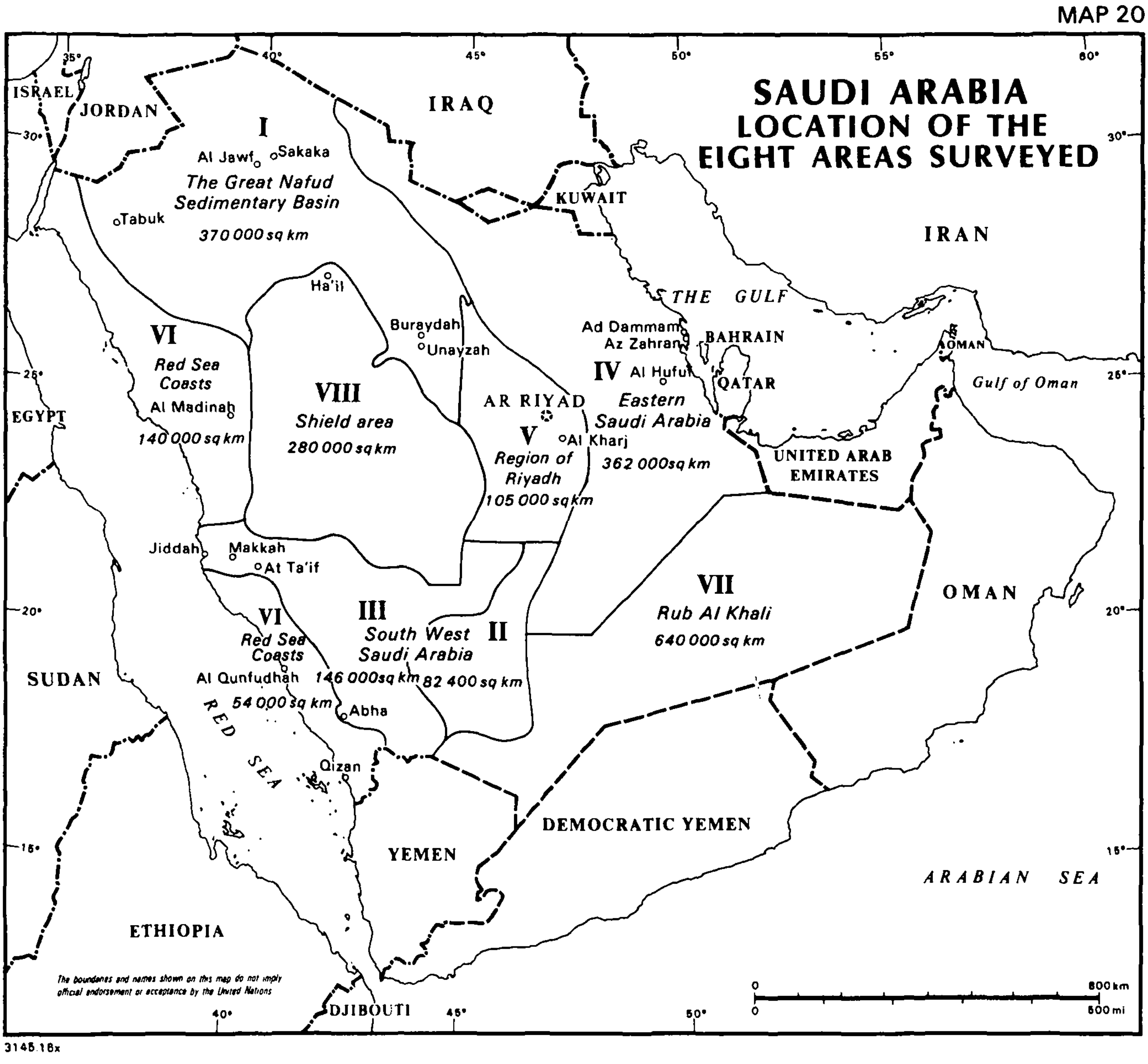


Figure IV

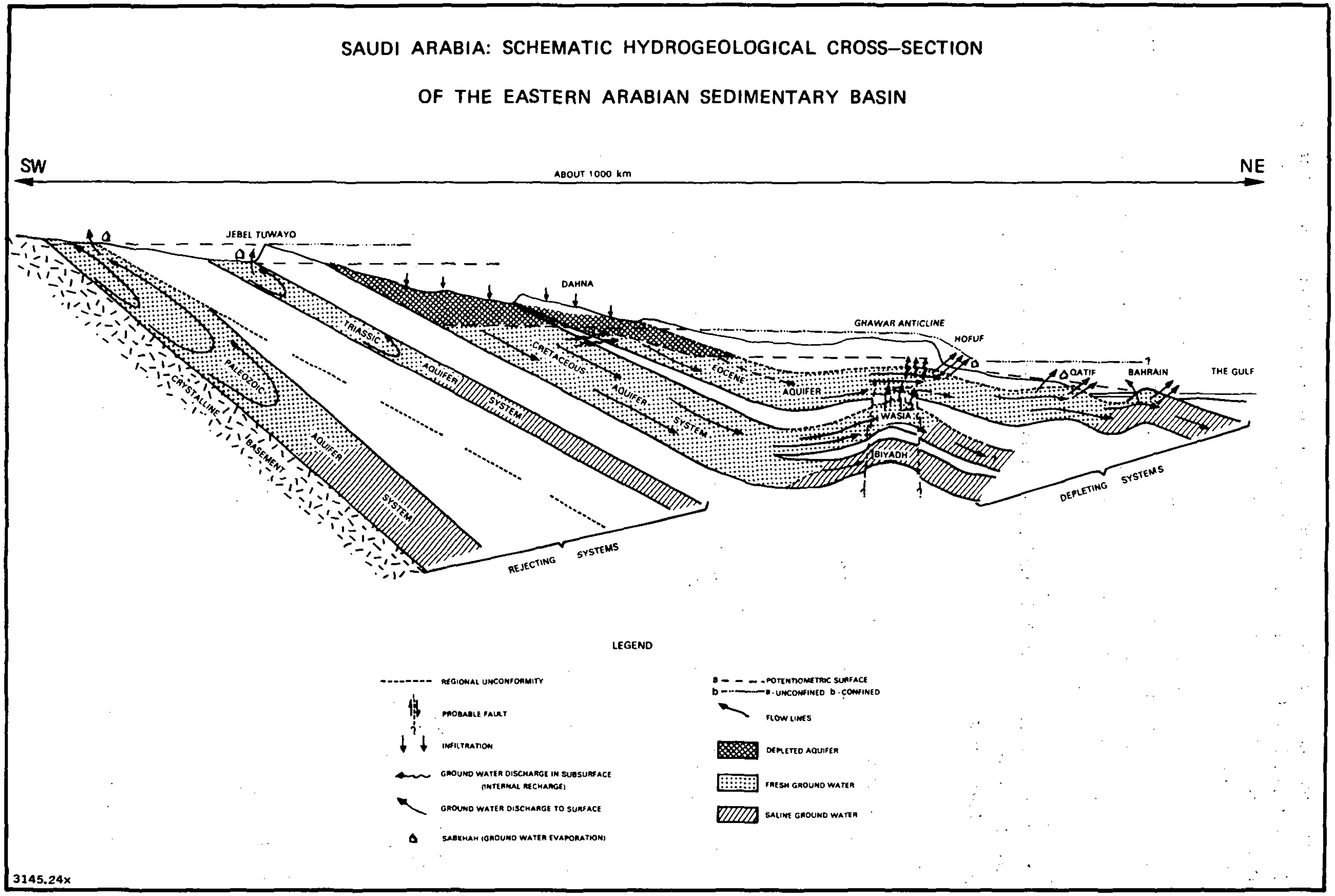


Figure IV. Saudi Arabia: schematic hydrogeological cross-section of the eastern Arabian sedimentary basin conglomerates with Recent basalts. The plateau area is characterized by a thin soil cover where dry wadi courses are entrenched in old structural lines, fault zones, joints etc. The face of the scarp is characterized by deep boulder-filled valleys. The coastal strip or Tihama plain is essentially a wedge of unconsolidated sediments, varying from an average of 12 m thick in the south to over 80 m in the north. The plain overlies an undulating Tertiary bedrock of clay, marl, limestone and evaporite.

The region experiences a wide range of climatic conditions with contrasts from north to south and from inland to the coast. Inland and coastal temperatures are high, though they are more extreme inland where average summer temperatures for Medina are around 36° C. Humidities are high along the coast, but low inland, for example, 75 per cent for Jeddah compared with 26 per cent for Medina. Rainfall varies from an average of 22 mm per year for Medina to 215-300 mm in the monsoon-affected south. Most beneficial rain comes from high-intensity storms which cause torrential wadi flows in the scarp area. Potential evaporation is generally in the range of 2-3 m.

Resources

There are potentially good resources in the surface flows of the wadis, but only limited use is made of the waters owing to their short duration and torrential flow.

Aquifers in the Tihama are of two types: wadi fill and coastal plain sediments. In general the wadi gravels are thin and shallow and since they are highly permeable, ground-water levels rise and decline quickly in response to stream flow. However, zones with access to continuous recharge give small reliable supplies. In the northern inland zone, areas of alluvium and old wadi courses are blocked and covered with basalt, creating substantial spring zones.

The coastal plain sediments are a typical heterogeneous colluvial complex. With the exceptions of wadi Jizan and the Tihama Ash Shaur there is limited alluvial development. In general, coastal plain colluvial aquifers are only local and low yielding.

The top of the Tertiary bedrock contains a permeable coralline limestone, and via this stratum it may be possible to develop the reasonable storage characteristics of the overlying material, though salt-water intrusion could be a problem if unrestricted development were to take place.

Water use

Water is mostly drawn from springs, underground drainage galleries 1/ and wells. In the past, these galleries were used extensively along the entire coast, but they have largely fallen into disrepair owing to lack of maintenance.

1/ These underground drainage galleries are known as ayuns and kanats in Iran and as falajs in Oman.

In general, ground-water is not used to its maximum extent in this region, although there are good aquifers in the wadi Jizan and Tihama Ash Shaur areas. At present good rains and flood-water spreading schemes with wells supply sufficient water for irrigation.

Future development will require more detailed studies of the ground-water situation, in particular problems of bore-hole design, since the development of the Tihama ground-water will most probably have to use bedrock transmissivity to utilize the storage of the thin overburden.

Arabian shield

The shield area is a vast peneplain of broad shallow wadi beds, barren scree slopes, wide gravel plains, granite inselbergs, broad basalt plateaux (harrats) and aeolian sands. Winds are incessant, heat haze and frequent dust storms being characteristic. In general the shield is a desert region although in the south, owing to the penetration of the monsoons, it becomes subhumid and quite fertile.

In the northern and inland areas the rainfall varies between 50 and 100 mm. In the south it averages around 400 mm. Rain is reliable only in the southern areas where it generally falls in April and May. Elsewhere, and during the summer months, thunderstorms are the main source of rainfall. Run-off is most unpredictable, as it depends on the storage available in the wide wadi bed sands and their ability to absorb surface flow. Potential evaporation varies from 1.8 to 2 m in the south to over 3 m in the north and inland regions. Humidity varies from 60 per cent in the highlands and mountains to 20 per cent in the lower and inland desert regions. Temperature relates more to elevation than to latitude, with extreme temperatures in the low desert regions frequently reaching 48° and 50° C. At elevations up to 2,000 m, temperatures fall to an average of 10°-18° C. In winter months frost and ice occur frequently on the higher peaks.

Essentially, the shield is a complex of granite, granodiorite, diorite, gneisse, schist, with such sediments as feldspar, quartz, breccia and arkose, and in the south, remnants of the Cambrian-Ordovician Wajid sandstone. Parallelling the Red Sea and coincident with the inland north-west to south-east trending fault system is a series of Cretaceous-Tertiary basalt. These form broad slightly elevated plains littered with joint blocks and rubble. In the north, the basalts frequently cover alluvial deposits, blocking drainage lines and giving rise to numerous spring zones. In ancient times, the Ayn Zerka, now dry, was the water supply for the city of Medina.

A most complex structural pattern is recorded from major crustal movements in the Archean and Proterozoic, and the Red Sea rifting era. This has imposed a prominent north-west to south-east fault and joint pattern on the shield which now largely controls the run-off pattern, as it formerly controlled the volcanic outpourings of the Cretaceous to Tertiary periods. A less prominant north-east to south-west fault system is also evident.

In the elevated areas, wadis are limited to their narrow valleys. On the plains they reach enormous widths with wide spreads of gravel and rubble, often several hundred metres to several kilometres on either side of the wadi courses. The alluvial plains are shallow features, frequently no more than 5 to 10 m thick and are composed of stable, sometimes partially cemented, silts and clays. The wadi bed material is unstable, and consists of coarser material, sands, gravels etc. In general, alluvium is thin and enormous areas of bare rock outcroppings occur throughout the shield area.

Ground-water in the region is restricted to the wadi bed alluvium or to jointed or weathered zones where crossed by wadis. Important jointing, especially in the wadi headwaters, is a feature of the Asir region in the south and this, together with the higher rainfall and recharge, produces better ground-water potential in the south. The basalt harrats in the west act as collectors of rainfall, and these waters find their way through interflow boundaries and lateritic or limonitic beds to peripheral spring zones. Where the basalt overlies alluvium, water is often tapped by wells which penetrate the basalt and pump from the alluvium. These enormous areas of basalt are interesting sources of ground-water.

As in other shield areas, the waters are mostly unconfined. Confined conditions, however, have been revealed by pumping tests in deeper wadi alluvial aquifers. In these aquifers, horizontal permeability values appear to be higher than vertical permeability values.

The quality of the water is typical for arid areas; in fact there is no consistent pattern. In the wadi headwaters, the ground-water is of a low total dissolved solids (TDS) bicarbonate type. As a general rule, water in the lower wadi reaches becomes chloride dominated, with increasing TDS. Bicarbonate is the dominant ion up to 1,000 ppm, with chloride becoming more and more dominant as TDS increases. Sulphate waters of gypsum contaminated waters are sampled from closed and small basins and are mostly in the range of 3,000-6,000 ppm.

The water is used for livestock and domestic purposes, although there is always limited irrigation development along the principal wadis. Most of the major wadis have been studied in detail. Geophysical, drilling and hydraulic studies are included in the major regional studies.

Eastern Arabian sedimentary basin

Throughout eastern Saudi Arabia climatic conditions are remarkably similar. Rainfall everywhere averages between 50 and 100 mm, although high intensity storms, which are not infrequent, are the main source of aquifer recharge. Inland summer temperatures range up to 50° C, while winter temperatures drop to a milder 10°-20° C. Gulf coast temperatures range up to 37.5° C. Inland humidities vary widely depending on the penetration inland of saturated air masses and figures ranging from 5 per cent to 90 per cent are quoted. Gulf coast humidities are extreme, being normally between 95 per cent and 100 per cent. Coastal potential evaporation averages between 1.8 and 2 m, while inland figures range up to 4 m. The prevailing shamal winds blow from the north, while the qaws blow from the south-east. The shamal winds are diurnal and blow at an average of 20 km/h. Both the shamal and the more humid qaws move great volumes of sand and are the cause of the peninsula's great dust storms.

The scheme suggested by Italconsult (1967) of non-depleting or recharge-rejecting systems and depleting or recharge-accepting systems best describes the eastern basin's aquifer systems. Thus, on a regional basis there are the non-depleting Paleozoic aquifer systems: the Saq sandstone in the north, the

Wajid sandstone in the south, and the Minjur system. The depleting systems begin with the Cretaceous Wasia-Biyadh system and include the younger shallower Eocene aquifers, namely, the Umm er Radhuma, the Damman (including the Alat and Khobar formations) and the Noegene. 2/ The last-mentioned depleting systems are dynamic aquifers with active recharge, aquifer underflow and discharge régimes. Figure IV illustrates this aquifer concept, and figures I-III present the stratigraphic and hydrogeological columns - figures I and II the non-depleting aquifers north and south of the central Arabian arch, respectively, and figure III the depleting younger or post-Jurassic aquifers.

The strata dip radially away from the Arabian shield basement complex contact at gentle angles, and are thus seen to be draped around the central core of the shield. The central Arabian arch to the west of Riyadh and the Hail Arch to the north are two areas in which the strata achieve their maximum curvature, as seen on a geological map.

The main structural features in the basin are the folding of the coastal zone, and the faulting, graben and basin structures west of Riyadh, where down-thrown basement faults on a line though Majina'ah to Dhruma and wadi Nisah cause the basin sediments to thicken to 12,000 m. The important Ghawar anticlinal structure, with its associated minor anticlines and gentle folding, dominates the coastal region and affects local flow patterns in the Al Hassa to Haradh region. The Ghawar anticline is also the main oil structure in Saudi Arabia, and the Arab and Hith formations are the oil reservoirs.

Non-depleting aquifers

The principal aquifers in the northern non-depleting sector are the Saq sandstone and the Tabuk aquifer.

The Saq sandstone in outcrop covers 16,000 km^2 in the northern region; the confined areas are much more extensive and can be followed from the village of Khuff into Jordan. The aquifer thickness varies between zero and 900 m. On samples, it is seen to be a coarse- to medium-grained friable sandstone, made up essentially of well-rounded to subangular quartz grains. Both argillaceous and calcareous cements are present, but are not abundant. High porosity of the rock is the characteristic feature.

The aquifer's piezometry is not yet clearly defined, though indications suggest movement to the south-east and north-east away from the contact with the shield. In the outcrop area the aquifer is unconfined, and unconfined conditions seem to persist to depths around 350 m. Below this depth the aquifer becomes confined. Elsewhere, away from the outcrop area the aquifer is confined and hydraulic heads of 150 m above ground level occur. Recent recharge to the aquifer has not been fully ascertained.

2/ Recent studies (FAO, 1979) place the boundary between the depleting and non-depleting aquifers at the Shu'aiba shale, which commences down-dip from the Wasia-Biyadh outcrop and divides the two strata into an upper active Wasia aquifer and a lower stagnant Biyadh aquifer.

Ground-water temperatures are characteristically high in the Saq sandstone and increase with depth. In the confined areas they range from 50° to 80° C. In the unconfined areas they average from 27° to 32° C.

Numerous pumping tests have been performed and transmissivity values are in the range of 25.7×10^{-3} to 0.19×10^{-3} m^2/sec with an average of 12×10^{-3} m^2/sec. The average coefficient of storage is 8.9×10^{-4}.

The water in the outcrop zone is of a predominantly sodium chloride type although some low TDS bicarbonate waters occur along the wadi courses. Isotopic evidence dates the water between 20,000 and 28,000 years, but along the wadis dating shows that the water is of distinctly modern origin.

The quality of water is generally good in the Saq aquifer and certainly ranks with the best in the country. Average TDS values range between 400 and 1,200 mg/l, but quality deteriorates with depth. For example, the Qiba bore-hole, which is 2,400 m deep, produces a strongly sodium chloride dominant water containing 32,800 mg/l of TDS.

Water is used in the Qasim region for irrigation of wheat, alfalfa, vegetables and fruits, including dates, grapes and citrus fruits. Elsewhere the water is used for livestock. Although water is being mined from the aquifer, its high porosity and unconfined storage factor will ensure water supplies for an extremely long period of time.

The Tabuk aquifer is an aquifer of less importance than the Saq sandstone. It crops out over a small area and is relatively undeveloped, although it supplies domestic and irrigation water supplies to the towns of Tabuk and Bureidah. The waters are confined but the aquifer has a lower hydraulic head than the Saq aquifer, water levels being plus or minus a few metres with respect to ground level. Chemical characteristics are similar to those of the Saq, and isotopic analyses suggest that the water is not of modern origin.

In the southern sector, the Wajid sandstone aquifer lies directly on the crystalline basement. Its entire outcrop area is not known but it is not less than 50,000 km^2. Also, the aquifer thickness is not known with certainty but it is said to increase to the south and to decrease to the east. In the stratigraphic column (see figure II) it is shown to have a thickness of 434 m.

The Wajid sandstone is a white to light red or brownish coarse-grained friable quartz sandstone. The grains are well rounded, of even size, and the rock has a high porosity. In outcrop the sandstone is frequently bedded with occasional bands of siltstone, claystone and ferruginous quartzite, typical of a continental deltaic fluvio-lacustrine environment.

The direction of ground-water movement is not known in detail but the general suggestion is that water moves from south to north. Flowing wells are widespread in the confined areas, with heads of up to 91.4 m above ground level.

Numerous pumping tests have been conducted and substantial transmissivity has been shown. Transmissivity values are in the range of 5.7×10^{-4} to 2.1×10^{-2} m^2/sec, and the coefficient of storage varies from 2 to 4×10^{-4}. Although not determined, unconfined storage values will be high, marking mining of the aquifer as a likely prospect for a long period of time.

Like the Saq sandstone, water qualities in the Wajid aquifer are very good, the TDS content averaging between 500 and 800 mg/l. Again bicarbonates dominate at the lower TDS values, and increasing TDS is associated with increasing sodium chloride. Although sulphate waters are present, they are rarely dominant. The unconfined waters are generally of a higher TDS, and sulphates are proportionately higher in the unconfined waters.

There is little data on recharge to the aquifer, although it is an important observation that only major wadi flows cross the Wajid outcrop. Isotope determinations show that the water samples taken during pumping are complex mixtures, the mixing possibly being due to leakage. In the deeper wells, the waters are around 20,000 years old.

Although there is little development of the Wajid sandstone aquifer, it is generally regarded as an excellent mining prospect.

The Triassic Minjur formation, together with adjacent parts of the Dhurma and Jilh formations and their sandstone layers, are the next major aquifer in the basin. The Minjur, which has an average maximum stratigraphic thickness from 300 to 350 m, is an alternating complex of sandstones and shales. The sandstones are thick bedded, coarse to very coarse subrounded and pebbly, and are typical of a continental deltaic facies. They are highly porous, with porosities recorded in the range of 10-25 per cent. They are commonly cemented with iron and silica. The interbedded shales are typically variegated red and purple. The Jilh formation is similar to the Minjur, though its sandstones are less well developed. Where they occur they are composed of coarse subrounded sand grains, with silica cement and good porosity.

In the Riyadh deep exploration well the sandstones occurred as follows:

Upper Minjur	1 352-1 432 m
Lower Minjur	1 569-1 653 m
Upper Jilh	1 752-1 798 m
Lower Jilh	1 905-1 977 m

The Minjur-Jilh aquifer, along with the Wasia-Biyadh aquifer system, supplies water to the city of Riyadh. Like the aquifer previously discussed the Minjur-Jilh system is one of the non-depleting/recharge-rejecting aquifers and water is therefore pumped from storage. As a result, the Riyadh pumping programme has produced draw-downs of 70 m and a cone of depression almost 200 km wide. At this width it now intersects the wadis Shaba, Hainfah and Nisah. The shape of the cone of depression is modified by graben faults to the west of Riyadh.

Bore-hole transmissivities for the Upper Minjur are recorded in the range of 1.3 to 7.2×10^{-3} m^2/sec, with aquifer permeabilities in the range of 2×10^{-5} to 1.6×10^{-4} m/sec. At Riyadh typical storage values average 1×10^{-4}.

The water is sulphate-dominated in the aquifer's outcrop area, though in many places the sulphate and chloride contents are equivalent. TDS values of 2,000 mg/l, 1,500 mg/l and 5,000 mg/l are recorded in the aquifer outcrop area, at Riyadh and at Khurais, respectively. In general the Upper Minjur water is of better quality than the Lower Minjur and Jilh sections of the aquifer.

Isotopic dating of the Riyadh water suggests ages from 25,000 to 30,000 years.

The Minjur-Jilh formations are not generally developed owing to their deep static water levels, which at Riyadh are about 100 m.

Depleting aquifers

The first of the depleting or recharging aquifers is the Cretaceous Wasia-Biyadh system, or the Cretaceous sands as they are often called. These crop out east of Riyadh as a narrow belt over a north-south extension of 1,400 km. At the type section in the Khashm Wasi area, the formation is 42 m thick. In the south at wadi Dawasir it is from 25 to 30 m thick, while to the north at Sakakah (where it is also called the Sakakah sandstone) it attains a thickness of 285 m. Thus, as with most other formations, the Wasia-Biyadh increases in thickness from south to north and from west to east. In the coastal region near southern Kuwait, stratigraphic holes drilled for oil exploration reveal thicknesses of 750 m.

In its outcrop area the formation is a fine to very fine brown to yellow continental cross-bedded quartz sanstone with scattered quartz pebbles. The rock is poorly cemented and in general quite friable. It contains intercalations of red and purple shale, lenses of red sandy dolomite and frequent nodular limestones.

Down-dip the Wasia-Biyadh system becomes parted by the introduction of the Shua'iba Shale formation. This formation is a most significant layer since the aquifer's hydrochemistry shows the Biyadh strata from this point to be non-depleting. The Wasia-Biyadh is notable also for its gradual down-dip facies change, the sandstones changing imperceptibly to clays east of the Ghawar structure and to shales in Qatar.

Between the Wasia-Biyadh and the overlying Umm er Radhuma aquifer is the Aruma formation aquiclude. The Aruma consists of shales, limestones and dolomites, and behaves generally as an efficient aquiclude, though it does sustain an upward leakage from the Wasia-Biyadh aquifer due to widespread minor fracturing and the high hydraulic head relationships between the Wasia-Biyadh aquifer and overlying aquifers. The thickest Aruma section encountered is 685 m.

The Umm er Radhuma aquifer because of its high transmissivity is potentially Saudi Arabia's most important aquifer. It is of Paleocene to Upper Eocene age and varies in thickness between 110 and 450 m. It crops out over a wide area extending from the western desert in Iraq, through central Saudi Arabia into the Yemen region. It extends from the wadi Hadramawt area, through Dhofar into western Oman.

It is relatively uniform marine sequence of light grey to tan and orange partly dolomitized chalky limestone with interbeds of yellow finely crystalline dolomite and chalky aphanitic siliceous limestone. From the bottom to the top of the sequence there is a gradual change to a more dolomitic limestone. On the whole, the lithological characteristics remain fairly constant throughout the Peninsula.

Between the Umm er Radhuma aquifer and the Damman aquifer is the conformable Rus formation aquiclude. At its type section the Rus is 56 m thick, though it is seen to vary from 20 to 100 m elsewhere. It consists of soft, chalky, pink to cream, friable limestones and dolomitic limestones with frequent lenses of anhydrite. In regional terms it is an inefficient aquiclude as it is frequently eroded and missing over structural highs. In areas outside Saudi Arabia it becomes an aquifer owing to facies changes. It is, however, probably the most important geological horizon and stratigraphic marker bed in the entire region.

The Damman formation and the overlying Neogene formation are the most important aquifers along the Gulf coast and in the countries neighbouring Saudi Arabia. The Damman formation contains two major aquifers, the Khobar and Alat members. The Khobar member is mainly a friable skeletal detrital marine limestone, sometimes slightly argillaceous and with some marl intercalations. The Alat member has a similar lithology. The Neogene complex is a sequence of fine to coarse clastics, which lies unconformably on the Damman formation, though the two are in hydraulic continuity.

The piezometric contours of the upper depleting aquifer system indicate that it can be regionally divided into two separate hydraulic or aquifer systems, the Wasia-Biyadh system and the Umm er Radhuma-Damman-Neogene system. Piezometric maps show a drastic head difference between both systems, the Wasia-Biyadh aquifer having a hydraulic head of 150 m above sea level at the coastline and about 145 m in excess of the heads of the overlying aquifer system.

The Wasia ground-water movement, which is known in detail only in the Riyadh to Dhahran area, confirms that ground-water flows towards the Gulf under the influence of a consistent hydraulic head of 0.25×10^{-3}. This small hydraulic head is interpreted as being indicative of a small aquifer underflow and possibly diffuse vertical leakage through the confining Aruma aquiclude. It is thought that the Wasia-Biyadh facies change from sandstone to shale precludes any significant aquifer discharge to the Gulf.

As with the Piezometric surface, the hydraulic aquifer coefficients are known only in the same area. Transmissivities in the Wasia segment range from 1.4×10^{-3} to 2×10^{-1} m^2/sec, the average transmissivity being around 5×10^{-2} m^2/sec. This suggests that the average sub-surface flow per kilometre of flow front is 0.39×10^6 m^3/year.

For practical economic purposes, though the regional piezometric surface indicates they are one aquifer, the Umm er Radhuma-Damman-Neogene aquifer complex is regarded as two aquifers, the Umm er Radhuma being treated separately.

The Umm er Radhuma's regional piezometric surface indicates flow to the north towards the Euphrates valley, to the east towards the Gulf in central Saudi Arabia, and north to the Gulf from the Rub al Khali region. The over-all average gradient for the Umm er Radhuma is 0.8×10^{-3} though it is as high as 5×10^{-3} in its intake beds in central Saudi Arabia. Again knowledge of transmissivity is restricted to the central region where the figures are generally high, coastal values being as high as 1.6×10^{-1} m^2/sec. Values further inland are lower, averaging 6.7×10^{-2} m^2/sec. It is the general opinion that the change in transmissivity is indicative of a change from laminar flow to turbulent flow in the aquifer.

As is the case with the overlying aquifer segments, the line describing the suggested change in flow régimes corresponds to an inland continuous line of sabkhahs which stretches from Iraq through Kuwait, central Saudi Arabia and central Rub al Khali from where it swings north running past the foothills of the Oman mountains. The significance of this line is not fully understood though it is known as an ancient shore-line, a major discharge horizon and the inland limit of ancient sea-water contamination of the coastal aquifer systems.

A re-examination of the aquifer underflow situation above and below the sabkhah line, shows that a transmissivity of 6.7×10^{-2} m^2/sec and a hydraulic gradient of 0.5×10^{-3} gives a per kilometre flow of 1.05×10^6 m^3/year above the sabkhah line, while a transmissivity of 1.6×10^{-1} m^2/sec and a hydraulic gradient of 3×10^{-3} gives a per kilometre flow of 15.12×10^6 m^3/year. Such a situation is clearly anomalous, perhaps owing to insufficient data or its interpretation since the piezometry of the Wasia-Bivadh system, the only source of additional water, is unaffected by this horizon.

The ground-water movement of the upper Damman-Neogene aquifer is generally identical to that of the Umm er Radhuma aquifer in both hydraulic head and gradient.

Transmissivities, being the sum of the transmissivity of the component aquifers, are of an average order of 3×10^{-2} to 4×10^{-2} m^2/sec, with 4×10^{-3} m^2/sec the average above the sabkhah line and 5×10^{-2} m^2/sec below the line. Again steeper gradients are recorded below the sabkhah line than above, that is, 1.4×10^{-3} as against 0.5×10^{-3}, and these produce flow values of 2.2×10^6 m^3/year per kilometre below the line, as against 0.063×10^6 m^3/year per kilometre above the line.

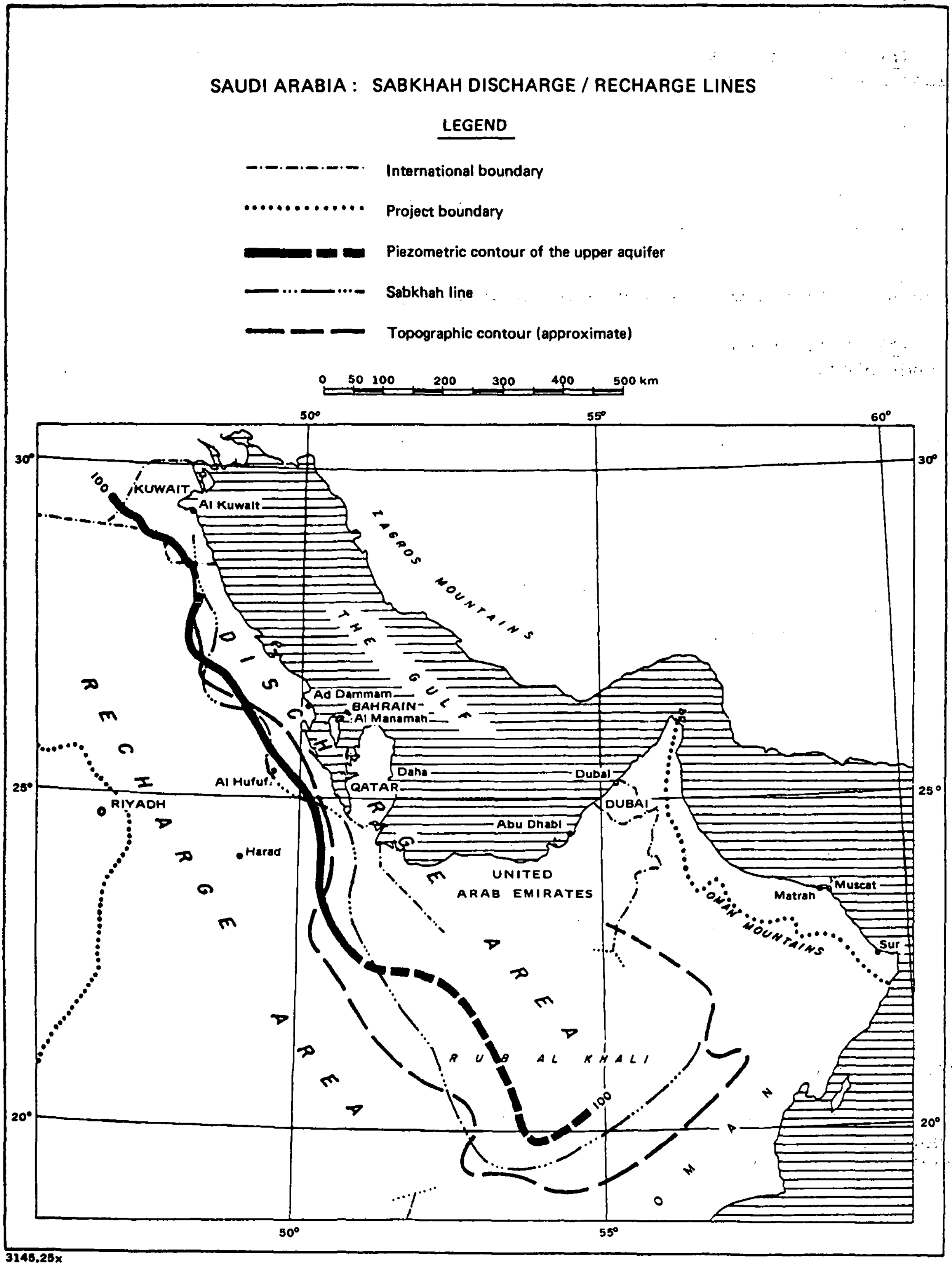
Considering that the total flow above the sabkhah line is currently producing no water level decline in the depleting aquifers' unconfined or intake bed areas, it is estimated that recharge amounting to 6.9 mm per year is being received. However, both hydrochemical and isotopic observations suggest that modern recharge waters do not occur in the outcropping or potential recharge zones of the Umm er Radhuma or Damman-Neogene aquifers. Thus to satisfy the aquifer underflow component it can be recalculated that the Wasia-Biyadh system must receive 17 mm of recharge for a stable steady state system. Satellite imagery studies show that a multitude of minor wadis discharge into and are absorbed by the Wasia-Biyadh outcrop. They also show that the major wadis suffer a significant diminution in size across this hydrogeological horizon.

Discharge from the basin is accomplished by evaporation from sabkhahs, spring flow (both onshore and offshore in the Gulf) and pumpage to town water supply, irrigation and industrial complexes. Until recently the Wasia system was pumped in the vicinity of the Ghawar structure for oil reservoir flooding operations. The natural discharge conditions are analogous to open basin or sulphate discharging conditions, and considerable thicknesses of gypsum and anhydrite have been desposited (provided they are syngenetic with their host strata) through the Tertiary, Quaternary and up to the present. Evidence of similar open basin discharge conditions is seen throughout the basin in the red bed occurrences, and in the laterite, silcrete and calcrete horizons. The sabkhah discharge line (see figure V) is thus an important line the basin's hydrogeology, dividing the up-gradient recharge areas from the down-gradient discharge areas.

The total significance of the sabkhah discharge line to the basin's hydrogeology is not fully understood, and future studies will be directed towards

Figure V. Saudi Arabia: sabkhah discharge/recharge lines

Figure V



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understanding its various functions, particularly its effect on down-gradient ground-water developments. However, it is known that:

(a) The hydraulic picture down-gradient is anomalous;

(b) The sabkhahs evaporate or discharge increases in subsurface flow from the inland recharge areas;

(c) While the sabkhahs remain active hydraulic features they allow only a constant metered amount of ground-water to pass;

(d) The inland limit of the sabkhahs, i.e., about the 125 m topographical contour, was an ancient shore-line;

(e) The interval from the 125 m contour to the present coastline, including Bahrain and Qatar, was subjected to an ancient phase of sea-water intrusion;

(f) This intruded water is at present being flushed by a sulphate rich ground-water; and

(g) Flushing is most efficient in the more highly permeable sections of the aquifer, and much less efficient in the less permeable sections, the aquitards and the aquicludes.

The basin's hydrochemistry is influenced to a large extent by the desert's evaporative environment where much of the surface sands and dust are composed of gypsum crystals. Sulphate-dominant waters occur generally in all aquifer intake bed or recharge zone waters, in all perched aquifers, along all wadi courses (especially along the border with Iraq) and in the basin's underflow régime as it approaches the sabkhahs. Water in the underflow régime can be either chloride- or sulphate-dominated, though downstream of the sabkhah line the water becomes strongly sodium chloride. The total dissolved solids content is regionally consistent (though with some local anomalies) throughout the basin, being in the range of as much as 3,000 mg/l above the sabkhah line (but with anomalies between 3,000 and 6,000 mg/l where the water is highly gypsiferous) and from 6,000 to 50,000 or even 100,000 mg/l and over below the sabkhah line.

Of particular significance is the change in the Wasia-Biyadh aquifer system down-dip from the commencement of the Shu'aiba Shale. From this horizon the Biyadh segment stagnates and its TDS values rise rapidly from 4,000 mg/l to 80,000 mg/l and above. The Wasia segment carries on with TDS waters of 4,000-5,000 mg/l. Thus the Wasia's water quality is consistent with a discharging system, whereas the Biyadh's is not. Although there is scant evidence of a regional diffuse leakage and discharge from the Waisa system to the overlying aquifers, definite evidence exists at Haradh, around the southern Ghawar structure generally and in the Rub al Khali, particularly in the region of latitude 21° N and longitude 49° E. In both regions, hydrochemical and thermal evidence confirms widespread vertical flow from the Wasia.

Once the basin's ground-water bypasses the sabkhah discharge line it possesses a definite and final sodium chloride character. However, in Bahrain and in the coastal strip around Dhahran there are zones where the TDS content of the water, while still maintaining its sodium chloride character, is in the range of 500-1,500 ppm. In this region the upper series of aquifers, the Damman-Neogene system, hosts a series of shallow fresh-water lenses formed as a result of coastal rainfall infiltration or as a result of gypsum dissolution in the Rus formation and shallow horizons, with subsequent overburden collapse and storage enhancement. Recharge of rainwater then collects in the small closed depressions and gradually percolates to the water table. The lenses stretch discontinuously across coastal Saudi Arabia, Bahrain, Qatar and possibly into the Liwa area of Abu Dhabi. They are partially supported by an artesian "substratum" of saline Umm er Radhuma water. Thus, within the lens areas there are isolated cases of artesian flow from bore-holes. The waters pumped in the lens area are mixtures of basin water and lens water low in TDS.

The inland alluvials, generally upstream of the Wasia-Biyadh outcrop, have provided many traditionally important sources of water. Oases exist in shallow water-table areas where grasses and palm trees have drawn water by subirrigation. These areas have been developed by shallow hand-dug wells and the water is used for live-stock and for irrigating small private plots.

In general, the wadis and their alluvials can be classified as those which rise on the crystalline basement formations of the shield area, and those which rise in the sedimentary areas to the east. Those of shield origin possess coarse erosion-resistant boulders (in the upper reaches), gravels and sands. Those rising in sedimentary catchments possess fine sandy, silty and clayey alluvium, and generally ill-defined aquifers. Though storage is significant in the latter type, the permeability is low, so that they have not been developed beyond small wells or bore-holes to supply stock needs.

The main wadis, of which wadi Dawasir is a good example, deposit their alluvium in V-shaped symmetrical valleys in which three depositional zones can be identified: the centrally located wadi bed and adjacent alluvials, the marginal flood plain material and the flanking colluvial plains. In general the main ground-water potential is associated with the wadi bed alluvials which can vary from 60 to 100 m in thickness. Transmissivities can be high and values from 1.3×10^{-1} m^2/sec to 5×10^{-3} m^2/sec have been recorded; the aquifers are unconfined.

Just as there is a lateral definition of sedimentary conditions, there is also a downstream differentiation, with thick coarse material in the upstream higher gradient areas leading to thin layers of fine sands, silts and clays in the east. In the east the alluvium forms broad alluvial fans or deltas; in the Rub al Khali, broad alluvial corridors through the dunes, all of which are downstream of the Wasia-Biyadh outcrop, are essentially dry. In fact the wadi Dawasir provides an excellent example of the communication between the basin's up-dip non-depleting aquifers and the down-dip depleting aquifers. Where wadi Dawasir crosses the Wajid sandstone, the wadi alluvium is replenished by artesian leakage from the sandstone. The same wadi alluvium loses almost its entire water content to aquifer recharge at the Wasia-Biyadh outcrop.

The wadis to the south of Riyadh, including those that flow from the Yemen area and north from the Peninsula's southern watershed, possess some alluvium and associated water supplies of varying amounts. To the north, the wadis have generally cut down through the alluvium into the underlying rock strata and the alluvials are generally dry.

It is an interesting observation that of the multitude of stream courses seen on satellite imagery, all but the few main existing wadis cease at the sabkhah line. This suggests that the 125 m topographical contour, or thereabouts, may have been the base level of erosion in the past.

Apart from the wadis, major oases form another source of water. The major oases are Al Hassa, Qatif and Jabrin. These derive water from vertical leakage from the main basin aquifers and, as with most major springs throughout the world, there is controversy over the source of the water and the safe yield. Many wells have been drilled around the Qatif and Al Hassa oases and pumping has caused a reduction in artesian pressures and water levels; it is noted that the yield from the Al Hassa spring system decreased from 12.4 m^3/sec in 1966 to 9.7 m^3/sec in 1974. The Qatif area has similar problems, but in this case it is certain that the declining water level was due to the lack of control of free-flowing wells and bore-holes. In 1962 there was an upsurge of bore-hole drilling around Qatif. Many holes were completed uncased, so that a problem now exists where aquifers are still discharging and leaking into each other. Jabrin oasis is little developed by comparison but studies in this area are in progress.

Ground-water exploration and development

When established in 1954, the Ministry of Agriculture and Water was involved mainly with agriculture and only in a minor way with water. In 1966, by special decree, the Ministry took over the role of custodian of water affairs, and became responsible for water-resource studies and development in the country. The Ministry of Defence and the Ministry of Petroleum and Minerals are also concerned with water, as is the National Guard.

In 1964, the Ministry of Agriculture and Water signed an agreement with FAO for the provision of an advisory team to assist in supervising studies to be carried out by selected consulting firms. The areas studied were those outlined in map 20. During 1976 and 1977, additional major studies of the Wasia aquifer and the Al Hassa springs were completed and, during 1979 and 1980, of the Umm er Radhuma aquifer. The Umm er Radhuma study has been extended to cover Bahrain, as was the area IV study in 1969. Results of these investigations are unpublished; they are available for perusal only in the library of the Ministry in Riyadh.

Future investigations will involve the accurate quantification of water resources in the more highly developed areas, in particular those areas in which water levels are declining and spring flows decreasing. The coastal Dhahran region is of particular concern and studies, jointly with Bahrain and Qatar, will be undertaken to quantify accurately the resources available and, with mathematical modelling, to plan future developments and pumping programmes.

Utilization of water in Saudi Arabia is mainly for irrigation and livestock, a percentage being used for town and village water supplies. Until recently, ground-water was pumped from the Wasia aquifer to flood the deeper oil reservoir. This practice was terminated late in 1978, when sea-water was piped to the Gharwar region for that purpose.

It is the aim of the Ministry to bring to full utilization the main resource areas, and studies will commence directed towards a fuller utilization of the storage waters in the non-depleting Pre-Jurassic aquifer. Such a study is at present taking shape with respect to the Wajid sandstone aquifer in the wadi Dawasir region.

In summary, Saudi Arabia has at its disposal very significant ground-water resources. Some resources are dynamic, as in the Post-Jurassic eastern regions; others are static, as in the Pre-Cretaceous areas of the eastern region. On development, these resources would be mined, but the storages available are considerable. The shield area has small but useful water resources which are sufficient for irrigation on a small scale, especially along the main wadis, and for range land purposes. The Tihama plain is perhaps the least studied, though the present water requirements are met by flood flows from the mountains and ground-water from wells in the main wadi alluvials.

Selected unpublished references

Aramco. A study of the water resources of the Rub al Khali in southern Saudi Arabia. 1961.

Bureau de Recherches géologiques et minières (BRGM), Orleans, France. Hydrogeological investigations of the Al Wasia aquifer in the eastern province of Saudi Arabia. 1976.

__________. Al Hassa development project. Groundwater resources study and management programme. 1977.

El Khatib, A. B. Seven green spikes, 1965-1972. 1974.

Food and Agriculture Organization of the United Nations. Survey and evaluation of available data on shared water resources of the Gulf States and the Arabian Peninsula. 1979.

Italconsult. Land and water surveys on the Wadi Jizan. Report on geo-electrical investigations. 1965.

__________. Water and agricultural development surveys for Areas II and III. 1969.

__________. Water and agricultural development studies for Area IV. 1969.

MacDonald, M. and Partners. Riyadh additional water resources study. 1975.

Oktun, G. Paleozoic sandstone aquifers in Saudi Arabia. 1971.

__________. Observations on Mesozoic sandstone aquifers in Saudi Arabia. 1972.

__________. More about Paleocene karst aquifers in Saudi Arabia. 1975.

Parsons, Basil. Agricultural and water resources of the Great Nafud sedimentary basin, Kingdom of Saudi Arabia. 1968.

SOGREAH. Riyadh deep exploratory water well. 1969.

__________. Water and agricultural development studies, Area V. 1968.

SYRIAN ARAB REPUBLIC

Area: 185,100 km^2

Population: 7,200,000 (United Nations estimate, 1974)

General

The territory of the Syrian Arab Republic can be divided into three main physiographical units: the western mountain ranges, the southern plateaux and the eastern plains. The highest peak (2,814 m) occurs in Jebel Esh-Sheikh in the south-western part of the country. Ground-surface elevation at Lake Tabaria is 212 m below mean sea level. The amplitude of relief thus exceeds 3,000 m.

In the northern part of the country, the western mountains stretch northwards along the Mediterranean coast. They include Alaween mountain (1,520 m), the Bassit hills and Jebel El Aqraa. In the extreme north-west of the country, the Kurd-Dagh (1,200 m) and the Amanos chain of mountains (1,800 m) extend in a north-easterly direction.

The southern part of the western mountain ranges includes the Anti-Lebanon mountains (2,600 m) and Jebel Esh-Sheikh. A system of low mountains and ridges, the Palmyrian mountains branch off from the Anti-Lebanon north-eastwards. The mountains terminate on the right bank of the Euphrates (Al-Furat) river by Bishri mountain. The northern and southern Palmyrian mountains are separted by an extensive closed basin named the Dawwa basin.

The southern plateaux include the Hauran volcanic plateau in the south-west and the Namad plateau in south-east. The Hauran plateau, deeply dissected by the Yarmouk river and its tributaries, rises eastward to a volcanic ridge, Jebel-El-Arab. The Namad plateau is composed of carbonate rocks. It slopes gently towards the north and includes several desert drainage basins having no outlet to the sea.

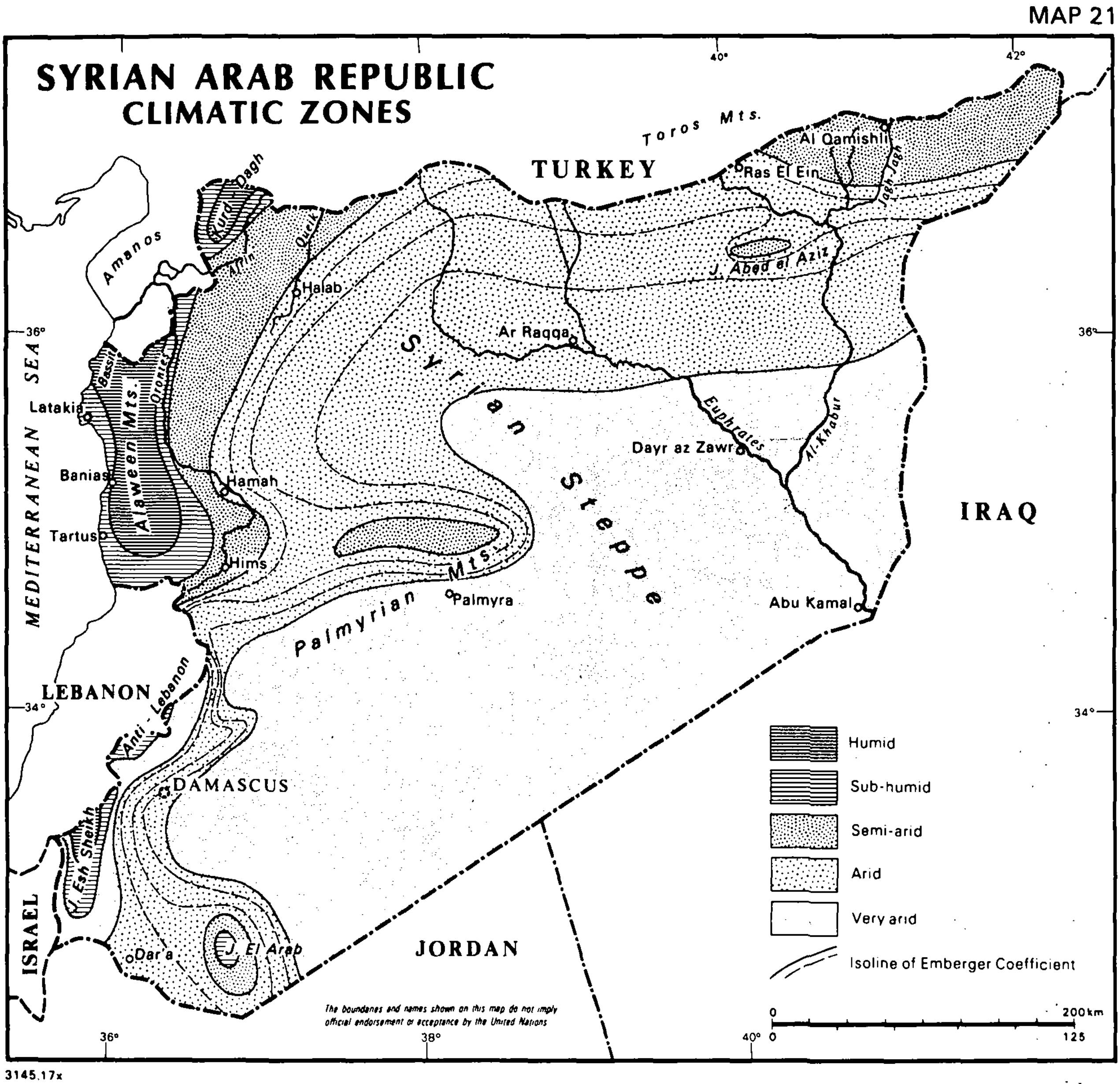
The eastern plains include an arid steppe, and also a semi-arid region with the most fertile land in the country. The steppe includes Badiet-Esh-Sham and Badiet-El-Rasafe, south of Al-Furat river, and Badiet-El-Jezireh, north of the Al-Furat river. The semi-arid region includes the Homs-Hama plains, the Edleb-Halab plain and the norther Jezireh plains.

Climate

The climate of the Syrian Arab Republic is of the Mediterranean type, characterized by a cold rainy winter and a dry hot summer with two transitional periods in spring and autumn. The precipitation pattern is influenced mainly by two mountain belts: the western mountain ranges which run nothward along coastline and the Taurus mountain ranges which extend along the northern boundary, mainly beyond the limits of the country. Climatic zones in the country are shown in map 21.

Map 21

Syrian Arab Republic: climatic zones



The rainy season usually begins in September and ends in April with the possibility of heavy showers in May. Snowfall occurs on the western highlands. Rainfall decreases from north to south and from west to east. High intensities are usually recorded in winter in the northern regions and in spring or autumn in the southern and south-eastern regions. The rainfall distribution in the country is summarized in table 18.

Evaporation rates range from 1,000 to 3,000 mm per annum (Lamb-recht evaporimeter).

Table 18. Syrian Arab Republic: rainfall distribution

(Millimetres)

Region	Annual Rainfall	Maximum rainfall within 24 hours
South-eastern region	Less than 200	20-40
Northern region and Jebel El Arab	200-400	40-70
Al Jawlan and the extreme north-east	400-600	60-90
Coastal plains	800-1,000	90-120
Western mountain region along the coast	1,200-1,600	235

During a period of about six months, between September and April, temperatures drop below zero in most regions except in the coastal plains. The coldest part of the country is the north-eastern area where temperatures drop to between 10° and 15° C below zero.

The absolute maximum temperature rises above 40° C in the interior region, starting from May. The temperature rises above 45° C in the east and north-eastern regions in July. It is usually below 35° C in other parts of the country.

Surface water

The longest rivers are the Al-Furat (Euphrates) river, which flows across the eastern part of the country and the Nahr El-aasi (Orontes) which originates in the Lebanon-Anti-Lebanon mountains and flows northwards across the western part of the country. The second largest river of Mesopotamia, the Dijleh (Tigris), flows along the north-eastern border with Iraq.

The Al-Furat river drains the Jezireh plain. The length of the river in the Syrian Arab Republic is 675 km and its catchment area covers 20,000 km^2. The average discharge is 830 m^3/sec. The Orontes river drains the western calcareous massifs.

In the south-western part of the country, the Barada, Aawaj and Yarmouk rivers drain the eastern parts of the Anti-Lebanon, Jebel Esh-Sheikh and the Hauran volcanic plateau. These rivers have discharges that very from about 2.5 to 14 m^3/sec. The coastal area is characterized by a high density of river systems. Their water courses are short and they usually have small drainage areas.

In the north-western region of the country, three water courses, the Queik, Aafrine and Sajour rivers, originate on the southern slopes of the Taurus mountain ranges and drain the major part of the Halab plateau. The average discharge of these streams ranges from 3 to 8 m^3/sec (see table 19).

The Syrian steppe, which covers 60 per cent of the country, is characterized by closed desert basins. Some of the large wadis in Badeit-Esh-Sham and smaller wadis in Badiet-El-Rasafeh drain into the Al-Furat river. The river beds of several ephemeral streams and major wadis cut into the southern slopes of the Palmyrian and Jebel El-Arab mountains.

Table 19. Syrian Arab Pepublic: rivers

River	Discharge (m^3/sec)			Total length (km)	Length in the Syrian Arab Republic (km)	Catchment area (km^2)
	Minimum	Maximum	Average			
Al-Furat (Euphrates)	250	2,500	830	2,230	675	350,000
Aafrine	2	450	8	149	85	2,780
Queik	...	60	2.5	124	100	4,214
Jagh-Jagh	1	8	3	124	100	...
Northern Kabir	0.8	150	3	80	56	1,040
Yarmouk	7	100	15	57	47	6,990
Sajour	...	25	3	108	48	2,372
Orontes	10	400	...	571	325	...
Khabour	35	300	52	460	...	31,800
Belikh	5	12	6	105	...	13,088
Es-Sinn	8.5	22	12	6	...	150
Barada	5	25	7	71	...	748
Aawaj	0.7	12	2.5	66	...	262
Southern Kabir	...	...	...	90	...	992

Geology

The Syrian Arab Republic is situated in the northern part of the Arabian platform. The Pre-Cambrian basement rocks are exposed in the Gulf of Aqaba. The Pre-Cambrian basement in Jordan is composed of metamorphic rocks and represents the northern outcrop of the Arabian-Nubian shield. The shield passes northwards into the platform slope and, in the Syrian Arab Republic, is composed of Paleozoic, Mesozoic and Cenozoic sediments.

The following geological regions are recognized:

Southern Syrian platform

The southern areas of the country are occupied by a relatively stable part of the platform slope that has a shallow basement and flat or gently dipping sedimentary strata.

In this region the Hamad plateau, underlain by Cretaceous and Paleocene sediments, separates two major depressions: the Damascus depression in the south-west and the Euphratian depression in the north-east. The former is underlain by thick basaltic flow, marl and gravel of Neogene and Quaternary age. The latter is filled up with thick marine, lagoonal and continental rocks of Neogene age.

Palmyrian folded zone

This is an elongated zone of intensive folding which is morphologically expressed by the Palmyrian mountains and ridges. The folded zone is highly faulted and is bounded on two sides by systems of deep faults. The rocks consist of limestone, dolomite, marl and chert of Cretaceous and Paleocene age. Intermontane depressions are filled with Neogene and Quaternary continental deposits.

Halab uplift

A large block bounded by deep faults, the largest part of the Halab plateau is underlain by Paleocene marl and limestone. Neogene basaltic lava flows are widely developed in the Halab area. They occur in the centre of the uplift covering Paleocene and Lower Miocene carbonate rocks.

Western mountain ranges

The most distinctive feature of the region is the Lebanon-Syrian fault system which is the northern extension of Jordan rift system. In the Syrian Arab Republic, the rift valley is represented by the Ghab graben. The coastal mountains, the Anti-Lebanon, Jebel Esh-Sheikh and Jebel Az-zawiyeh are made up mainly of Jurassic and Cretaceous limestones and dolomites. Paleocene and Neogene beds composed mainly of marls and conglomerates lie transgressively at the limbs. The uplifted carbonate complex extends in a northerly direction. In the extreme north, the north-easterly trend of the Bassit region corresponds to the trend of the adjacent Alpine orogenic belt. The Bassit region is composed mainly of aphiolitic and carbonate rocks.

Mesopotamian trough

The Mesopotamian trough was formed during the final phase of the Alpine mountain-forming movements which were very strong in the Pliocene-Quaternary time within the adjacent geosynclinal area of Zagros and Taurus.

The Mesopotamian trough is underlain by gravels, conglomerate, sandstone and clay of Pliocene and Quaternary age. Basaltic lava flows also occur in this region.

The stratigraphy of the country can be summarized as follows:

Mesozoic

Limestone and dolomite predominate in succession. Towards the upper Cretaceous a considerable lithological variation is noted. Thus, chert, phosphate beds, limestone and marl characterize the Campanian, and the Maestrichtian is represented by clay, marl and marly limestone.

Paleocene

Marls and clays predominate. The uppermost beds of the Lower Eocene are interbeded with chert. Nummulitic limestone and calcarenite characterize the Middle and Upper Eocene.

Neogene

This is represented by marine, continental and volcanic rocks. The marine sediments occur in the north-western part of the country. They include marl and reef limestone. In the north-east, the Mesopotamian basin was to a certain extent isolated from the open sea in Neogene time. The sediments of the basin include gypsum, salt, limestone, marl and clay.

Neogene continental sediments are present in the southern and central parts of the country. They comprise conglomerate, sandstone and clay. Volcanic rocks cover extensive areas in the south-western part of the country (the Hauran plateau). They occur also in Homs, Halab and in the Jezireh and are represented mainly by basalt with occasional pyroclastic deposits.

Quaternary

Quaternary formations are quite varied. They include alluvial, marine and lacustrine sediments. Volcanic rocks of Quaternary age are also common. The alluvial sediments consist of sand, gravel, clay and conglomerate. Relatively thick deposits occur in the Damascus, Dawwa and Radd areas.

Ground-water resources

Several government agencies are entrusted with water resources investigations and development. The Department of Irrigation and Hydraulic Power of the Ministry of Public Works and Water Resources has both a Ground Water Bureau and a Surface Water Bureau. The former is responsible for ground-water investigations and latter for the measurement of the flow of streams. Other bureaux of the Department of

Irrigations are responsible for the development and management of surface-water resources. The Major Project Administration is responsible for the construction of large dams. It undertakes studies in hydraulics and hydrology related to the design, construction and operation of these dams. The Ministry of Euphrates Dam is in charge of similar work in the Al-Furat basin. The Department of Sanitary Engineering of the Ministry of Municipalities, and the Geology Department of the Ministry of Defence are responsible for the domestic water supply.

Investigations

Systematic geological work was conducted during the period 1924-1945 by French geologists. The geological and lithological maps of the country, published in 1933 and 1945, formed the basis for later hydrogeological work. in January 1952, the newly created drilling section in the Ministry of Public Works had one Syrian geologist and an FAO hydrogeologist who was on a technical assistance assignment to the country, from 1952 to 1960. The drilling section carried out local hydrogeological studies and supervised the drilling of 259 bore-holes for irrigation and domestic water supplies. Some 95 unpublished reports summarized the knowledge obtained during those eight years. Seven papers on the hydrogeology and hydrochemistry of the country were published.

A systemic geological survey was initiated in 1958 by geologists of the Union of Soviet Socialist Republics in close co-operation with Syrian geologists. The results of the survey, which included reconnaissance hydrogeological work, served for the compilation of a 1:1,000,000 hydrogeological map of the country.

In 1961, Technoexport carried out geo-electrical prospecting work over an area of approximately 50,000 km^2 in the Syrian steppe. On the basis of this work several hydrogeological zones were recognized. A detailed investigation of ground-water resources of the Jezireh of the Syrian Arab Republic (50,000 km^2) was carried out during the period 1961-1963 by UNDP, in co-operation with the Major Project Administration. The project included geophysical (electrical) prospection and hydrochemical, hydrological and water-balance studies.

Regional hydrogeological and hydrochemical investigations were conducted by a geological mission from the Federal Republic of Germany in 1966 and 1967. Electronic computers were then used to prepare a synthesis of the regional hydrogeological studies.

A project directed towards the appraisal of surface- and ground-water resources of the Damascus, Orontes, Alab and coastal hydrographical basins was initiated in 1974. The investigations are being carried out by Soviet and Syrian surface- and ground-water hydrologists. During the period 1972-1977 the Arab Centre for the Studies of Arid Zones and Dry Lands conducted detailed hydrogeological research work in the Dawwa basin, an arid environment. The Dawwa basin project also included surface-water studies of a representative basin west of Palmyra.

From 1964 the Ground Water Bureau of the Ministry of Public Works and the Hydrogeological Department of the Ministry of Municipalities have been carrying out detailed hydrogeological studies in areas located in the populated western and northern parts of the country. The management of ground-water resources and the water supply of towns and villages are based on these studies.

Methods of investigation

Conventional methods are used in ground-water exploration. They commonly include geological surveys, hydrogeological reconnaissance and air photo-interpretation. Geological maps are not normally prepared within the framework of hydrogeological reconnaissance. Comparatively recent 1:200,000 geological maps are available for the whole country and maps on a scale of 1:50,000 or even larger maps are available for some highly populated or industrialized areas. Geological work is usually directed towards obtaining further details pertaining to the joint and fracture systems or facies variation in Neogene and Quaternary sediments. The objective of these studies, which are usually carried out locally, is to locate drilling sites for domestic supply or for irrigation purposes. Drilling is supervised by the hydrologist who conducted the reconnaissance work. Valuable information is usually obtained from drilling of exploitation bore-holes, with regard to subsurface geology, water quality, ground-water temperature, specific capacity and other aquifer characteristics.

Hydrogeological studies of large karstic springs in the country (Ras El Ein: 40 m^2/sec; Ein El Fijeh: 8 m^3/sec) included the use of artificial tracers and environmental isotopes. Electrical resistivity methods were used to study the aquifers and aquicludes in the vicinity of their discharge points. Underwater exploration techniques have been employed in the cavernous discharge area of the Ein El Fijeh spring. Geo-electrical methods have been widely used in water-resources investigations of extensive hydrogeological regions or large ground-water basins. Vertical electrical sounding (VES) is used for the subsurface investigation of alluvial and carbonate aquifers. Electrical profiling (EP) is currently used for the study of fault and fracture zones which border the Palmyrian and western mountain ranges. Radial electrical sounding has been used in the Palmyra area for investigation of fractured zones underlying wadi alluvium. Electical well logging was first used in 1973. Complex geophysical logging (resistivity, spontaneous potential, gamma ray, temperature, caliper) is now widely used.

Investigations on rhegmatic systems of faults and fractures have been carried out by using air photographs. Work on hydrochemical models and mathematical models began in 1976. The use of digital computers for the storage, processing, retrieval and statistical analysis of hydrochemical data started in 1970. Computer techniques are utilized in a systematic manner in research being conducted by the Arab Centre for the Studies of Arid Zones and Dry Lands in the Dawwa basin and other regions.

Ground-water regions

The western and northern regions are characterized by limestone and basaltic aquifers. The capacity of these aquivers to store and transmit water is usually relatively high. The western mountain ranges of the country are endowed with abundant precipitation. They are generally composed of karstic limestone and fissured basalt and act as excellent recharge areas for the highly productive aquifers which occur in the coastal plains, in the Homs-Hama regions and in the Hauran and Damascus plains.

The interior arid regions are relatively poor in ground water. They include mainly geological formations which can be considered as aquicludes or aquitards. Ground water occurs in alluvial plains and valleys. Minor aquifers of relatively modest dimensions are to be found in cherts and siliceous limestones which occur intercalated with the thick marly series.

The geological succession consists mainly of carbonate rocks. It includes several major and minor aquifers.

In the Mesozoic, limestone and dolomite of Cenomanian and Turonian age constitute one of the major aquifers. Jurassic limestones are very permeable, but they are not exposed to a significant extent. The upper Maestrichtian and the Paleocene consist mainly of marl and clay and constitute one thick impermeable hydrogeological unit. In the upper part of the Eocene, chert and limestone, alternating with marly beds, form minor aquifers in the south of the country. In the extreme north-east, Paleocene limestones are highly productive artesian aquifers. The great springs of Ras El Ein (40 m^3/sec) and Ain El Arous (6 m^3/sec) discharge from these limestones.

The Neogene and Quaternary rocks include two groups of major and minor aquifers. The first group includes fractured and cavernous formations while the second group consists of porous formations. Fractured basaltic aquifers occur in the Homs area and in the south-western part of the country. The lower Fars aquifer, which extends north of the Euphrates into the lower Jezireh, is composed of fractured and cavernous gypsum and anhydrite. Clastic porous formations comprise sandstones, gravels and conglomerates. They form highly productive aquifers in the coastal and the interior regions. Prominent among these are the Damascus, the Dawwa and the Radd alluvial basins.

The Syrian Arab Republic can be divided into four hydrogeological regions (see map 22). In defining these regions, lithology, geological structure and climate are the most important factors. Several regional ground-water flow systems have been delineated. In the humid and semi-humid calcareous massifs of the western part of the country, a complex pattern of ground-water flow can be identified.

In the Syrian steppe a relatively deep regional system occurs. The depth and length seem to be clearly related to aridity. The hydrogeological characteristics of each of the regions are briefly outlined below.

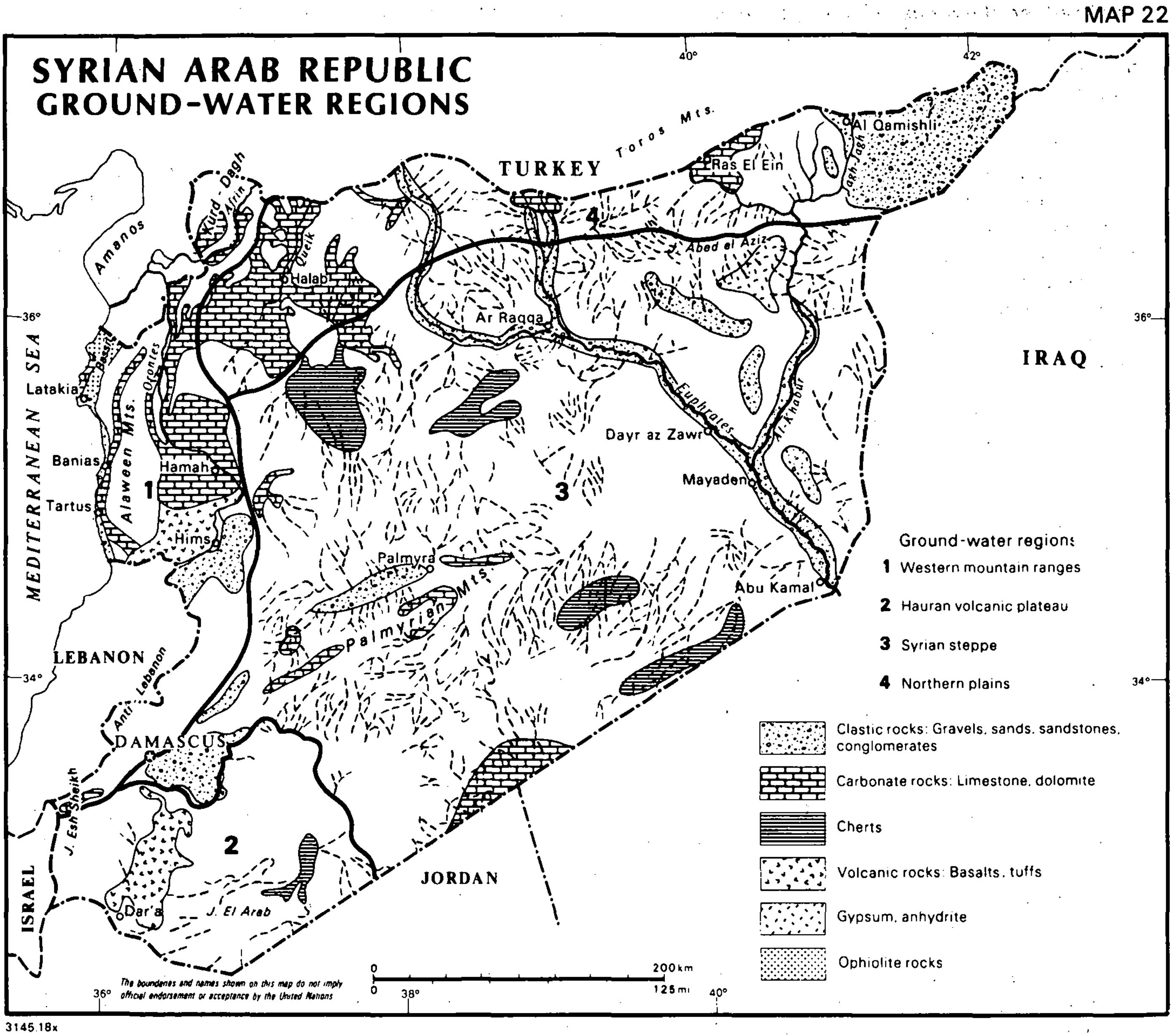
Western mountain ranges

Hydrogeology

The western mountain ranges are composed mainly of carbonate rocks. Limestone, dolomite and dolomitic limestone of Jurassic, Cenomanian and Turonian age crop out in the cores of these mountains. The Bassit block in the extreme north is made up mainly of ultrabasic and basic rocks. The western calcareous massifs receive abundant precipitation. Karstic surfaces which are extensively developed in these mountains favour infiltration and innumerable springs surge along the north-south fault zone in the Aarneh area, in Jebel Esh-Sheikh and in the Zabadani and Serghaya areas. Larger springs issue from the rift faulted zone in the Ghab graben. Thermal springs (Hemeh, Sheikh Eissa) are evidence of deep

Map 22

Syrian Arab Republic: ground-water regions



ground-water circulation in certain parts of the rift fault system. Ground water flowing westwards discharges mainly in the central part of the Syrian coast. Submarine springs occur in several locations near Tartous and Banias. Satellite images indicate the possible existence of significant submarine discharge in these locations.

In certain areas karstic and cavernous zones have developed at various depths underground. In the Anti-Lebanon and Jebel Esh-Sheikh the calcareous massifs are drained southwards along permeable zones, which run parallel to their axes, and the water discharges in the form of large springs. The great springs of Ein El Fijeh and Barada issue from the southern end of the Anti-Lebanon and Jebel Esh-Sheikh massifs, respectively.

In some areas, the uplifted limestone blocks are faulted down on one side only or the fault displacement may be small. The limestone dips gently beneath the Maestrichtian-Paleocene marly aquiclude forming major aquifers. In the Hama area, the confined Cenomanian-Turonian aquifer yields up to 50 l/sec of water to individual wells. In western areas, artesian water has been tapped in the Jezireh of Arouad. The productivity of confined aquifers in the Syrian coastal plains ranges from low to moderate. The carbonate rocks are sometimes overlain by alluvial or basaltic aquifers. These are particularly significant in the Jableh, Ghab and Homs areas.

In the northern part of the western mountain ranges, ground water occurs in fractures in ultrabasic and basic rocks, from which low-yield springs (2-3 l/sec) discharge.

Serpentine, the most widespread type of rock in this area is a completely altered rock, forming a poor aquifer.

Water quality

The ground water of the western region is low in mineral content, total dissolved solids ranging from 250 to 500 ppm. Throughout the major part of the western limestone ranges, the ground water contains mainly calcium and magnesium bicarbonate.

Upper Miocene gypsum deposits out crop at the north-western flank of the Alaween mountains west of Haffe which causes an increase in the sulphate content of the ground water in the gravel filling of the Nahr el Kish valley. Several springs at the western border of the Ghab graben, which indicate an increased content of SO_4 and Ca, can be related to interbedded gypsiferous beds in the Middle Jurassic of the Alaween mountains.

In the Hama region where the confined Cenomanian-Turonian aquifers are covered by Upper Cretaceous marls, the influence of these marls can be observed in the Na, Cl and SO_4 content of the ground water.

Sea-water intrusion has occurred at Hamidiyeh on the southern part of the Syrian coast and north of Latakia. Overpumping for irrigation and domestic uses is the main cause of sea-water encroachment.

Hauran volcanic plateau

Hydrogeology

In the south-west, volcanic rocks of Neogene and Quaternary age form an undulating plateau which extends beyond the border of the Syrian Arab Republic into Jordan and Saudi Arabia. Jebel El Arab rises to an elevation of 1,700 m along its western edge. The thickness of the basalt in this volcanic massif exceeds 800 m. The volcanic plateau is deeply dissected in the south by the Yarmouk valley. The Hauran plain, which is one of the most fertile parts of the country, is underlain by Quaternary basalts and constitutes the main aquifer in the plateau. Joints caused by cooling and lavatubes and some tectonic fractures are responsible for the formation of permeable zones in the Hauran aquifer. Coarse pyroclastics constitute minor aquifers that may be hydraulically connected with the main aquifer. The western and eastern regions of the plateau, where Neogene basalts crop out extensively, are poor in ground water. Furthermore, the fine-grained tuffs which occur in these areas impede ground-water movement towards the main hydrological system. Local ground-water flow patterns are formed and numerous small springs emerge at different levels in Jebel El Arab. Well yields are extremely variable. Maximum yields, usually ranging from 5 to 15 l/sec, have been obtained in the Mzerib area and in areas which lie towards the southern part of the central Hauran plains. Production wells range in depth from 120 to 200 m. Deeper exploration bore-holes (200-300 m) have been unsuccessful.

In the Hauran hydrogeological region, the Al Jawlan highlands and Jebel Esh-Sheikh in the west and Jebel El-Arab in the east are the main recharge zones. Precipitation exceeds 450 mm in the east and 1,000 m in the west and a significant part of the precipitation infiltrating into these highlands flows eastwards and westwards towards the Hauran plain which is underlain by Quaternary basalts. The Hauran aquifer is drained by the Yarmouk river and the Mzerib springs which are located in the extreme south-western part of the country. Along the deep wadis of the south-west several springs and waterfalls also occur. The topography and lithology of the underlying sedimentary rocks and the deep wadis which occur in the discharge zone are important factors which influence ground-water flow in the basalt and seem to limit the saturated thickness of the basaltic aquifer in the Hauran region. The central and eastern areas are underlain by impermeable Paleocene marl and clay. In the western areas, however, limestone may occur under the basaltic flows creating a multilayered aquifer. These aquifers will require further exploration in order to assess fully their ground-water potential.

Water quality

The Hauran volcanic plateau is characterized by fresh bicarbonate water. The total dissolved solids content ranges from 155 to 500 ppm. Water from the bore-holes drilled in the Qneitra area contains 154 ppm and represents the least mineralized of the water analysed in the country. In the Mzerib discharge area the salinity of ground water increases to 600 ppm. Ground water is of a calcium bicarbonate type in the western and eastern recharge zones. Towards the lower part of the hydrological system and in the Mzerib discharge zone ground water is primarily sodium bicarbonate. A sharp increase in salinity is noted locally. In the Mesmyeh region total dissolved solids are as much as 2,300 ppm. In this area, overlying lacustrine marl is the main cause of salinity.

Syrian steppe (Badiet-Esh-Sham)

Hydrogeology

The Syrian steppe comprises the Hamad plateau in the south and extensive desert plains in the north. The central part is occupied by the Palmyrian mountain chain.

In the areas lying south of the Al-Furat river, ground water occurs in carbonate rock, chert, and clastic deposits. Classic formations occur in alluvial plains which flank highlands or in intermontane basins. North of the Al-Furat river ground water occurs in abandoned valleys and in cavernous gypsum deposits. Great variations in yield of aquifers occur in the Syrian steppe. Production from drilled wells varies from 0.5 to 1 l/sec in Paleocene aquivers to 50 l/sec in alluvial aquifers.

In the Palmyrian area, the Cenomanian-Turonian limestones and dolomites form aquifers of relatively modest dimensions. These aquifers usually occur in intermontane basins and valleys. They have been tapped in the Nasseryeh and Sawaneh areas by wells ranging in depth from 100 to 200 m. The production from wells at these locations ranges from 6 l/sec to 12 l/sec.

In the desert plains which extend to the east and north of the Palmyra mountains, the Cenomanian-Turonian aquifer has been faulted down by the south Palmyrian fault zone. In the Tenf uplifted area, however, a Jurassic limestone aquifer has been tapped by relatively deep bore-holes. The top of the Jurassic aquifer lies at a depth of 400 m below the surface. Further deep exploration bore-holes are needed in order to delineate the Jurassic and Cretaceous limestone aquifers in this area. Ground water which has been tapped in the Cenomanian-Turonian, Campanian and Lower Eocene aquifers occurs under confined conditions. Water-bearing chert rocks of Campanian age occur extensively in the Khanasser basin and the wadi El Miah basin. Campanian aquifers also occur in Tadmor, El Bardeh, Arak and several other intermontane areas in the Palmyrian mountain belts.

The water-bearing formation of Lower Eocene (Acarinina Pentacamerata zone) age includes chert and silicified limestone. It is overlain by impervious marls of Middle Eocene age. The Lower Eocene aquifers occur widely in the Syrian steppe, but have very low yields. Specific capacity of wells which completely penetrated the aquifer normally ranges from 0.15 to 0.3 m^3/h/m of draw-down. Lower values, 0.02-0.04 m^3/h/m of draw-down are not uncommon.

Neogene and Quaternary deposits form several important aquifers in the Syrian steppe. The Ghouta plain which extends east of Damascus is one of the most productive and heavily developed areas in the country. This extensive plain which flanks the Anti-Lebanon mountains is underlain by gravel, conglomerate, basalt, lacustrine limestone and marl. It is characterized by a high water-table and the aquifer is hydraulically connected with the Barada and Aawaj rivers; ground-water pollution is therefore one of the main problems in the Damascus Ghouta. The Ghouta aquifer is replenished from surface water and wadi run-off which originates in the western highlands. Discharge from wells drilled to a depth not exceeding 50 m ranges from 10 to 25 l/sec. Discharges of 40-50 l/sec occur in the areas underlain by thick gravel facies.

The Dawwa plain extends west of Palmyra and is underlain by sand, sandstone, gravel and conglomerates. The detrital rocks represent the final stage of a complex sedimentation which started with the deposition of thick carbonate sediments in a huge depression bounded by deep faults. The grain size of clastic sediments decreases north and south towards the central area of the basin, which is composed of clay and marl. Gravel beds which may occur underneath the clay and marl reflect periods of higher rainfall during the Pleistocene.

The complex multilayered carbonate-detrital aquifers of the Dawwa basin have been investigated recently by the Arab Centre for the Studies of Arid Zones and Dry Lands. In the eastern area of the basin several confined water horizons have been identified in the Turonian, Santonian and Campanian carbonate rocks. Ground water in the deeper water-bearing calcareous formation is exceptionally fresh (350-400 ppm of total dissolved solids). In Tadmor the higher detrital aquifers are replenished from the confined silicous limestone (Campanian) aquifer along fault and fracture zones. In the western areas (the Dawwa plain) confined ground is relatively deep, more saline and in several locations high temperatures (55° C in Zamlet El Maher and 100° C in Abou Rabah) have been recorded. Higher detrital aquifers are recharged mainly from surface run-off originating in the northern and southern highlands. Relatively fresh ground water occurs in several areas in the southern part of the Dawwa plain, while saline aquifers occur in the northern part of the desert plain.

Water quality

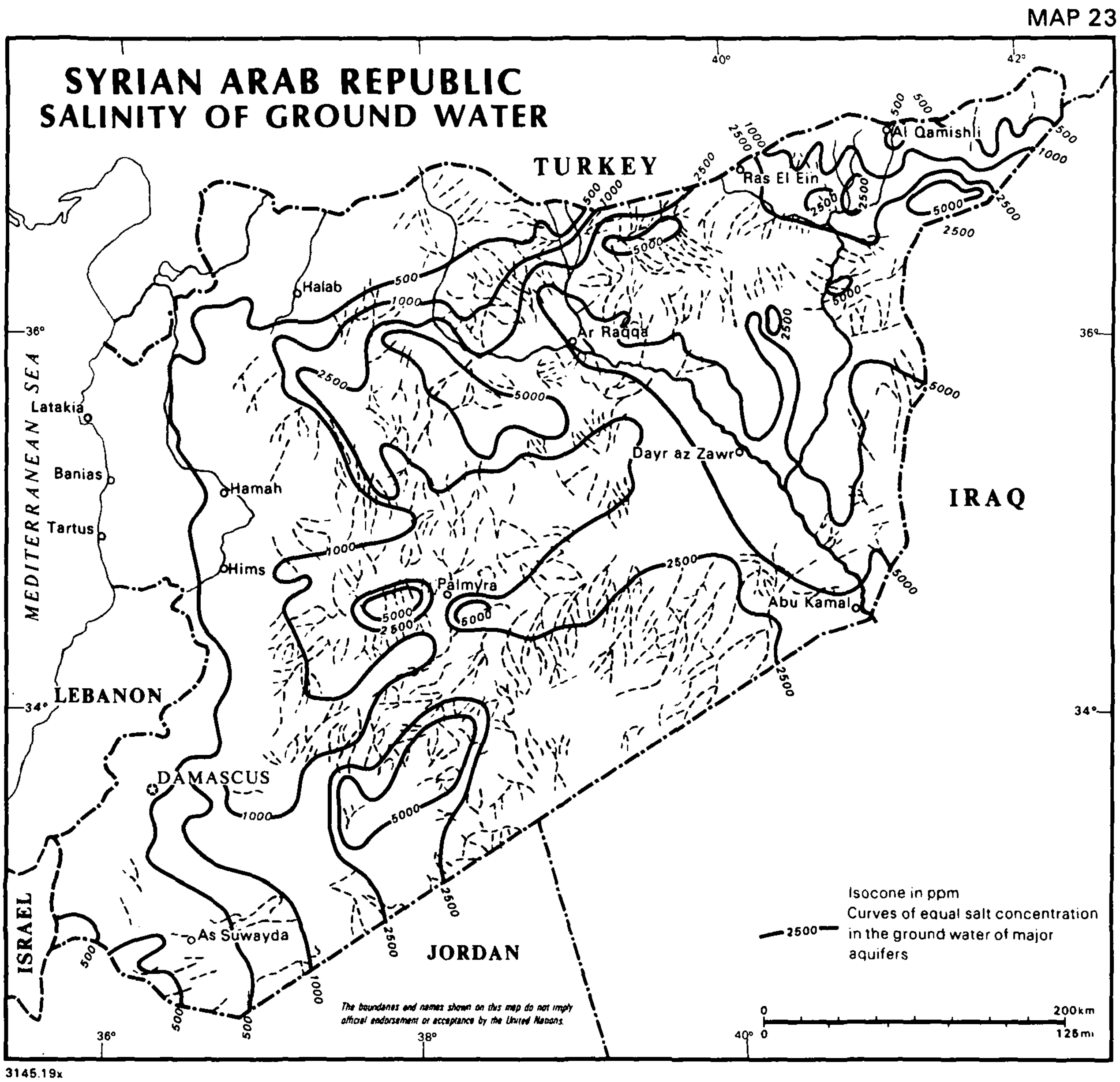
Fresh ground water containing 400-600 ppm of total dissolved solids occur in carbonate aquifers in Nasseryeh, Qariatein, Arak and wadi El-Miah. Ground water low in mineral content also occurs in clastic sediments in the Damascus Ghouta, in the Jeiraud basin in the flood plain of the Al-Furat river and in the alluvium of several wadis in the northern desert plains. The aquifers that yield ground water low in mineral content in the Syrian steppe are of paramount importance, since they supply several urban, mining, industrial and rural areas with drinking water. The majority of these aquifers are of relatively modest dimensions. Aquifers occurring in the Palmyrian area yield ground water containing from 200 to 1,100 ppm of total dissolved solids. Such ground water is considered a good quality water in the Syrian steppe. It characterizes a ground-water flow system of intermediate type. Confined aquifers in the wadi El-Miah basin and Khanasser basin yield water containing about 3,000 ppm (see map 23). Saline ground water occurs in Lower Fars gypsiferous formations and in the discharge points of the confined and unconfined aquifer systems of the Syrian steppe. Hydrochemical sections across the Al-Furat river have revealed that salinity of ground water below the alluvium exceeds 8,000 ppm. Saline ground water discharges in the alluvial flood plain, and several hydrochemical zones have been recognized.

Ground water of the closed ground-water basins normally discharges into sabkhahs. Salinity of ground water in sabkhah areas may exceed 100,000 ppm. Overpumping of ground water from aquifers which eventually discharge into sabkhahs may result in salt water encroachment. The phenomenon has been identified in the Ramadan area north-east of Damascus and in the Beida area west of Tadmor.

The chemical content of ground water reflects characteristics such as rock type, transmissivity, climate and the distance from recharge areas to points of discharge.

Map 23

Syrian Arab Republic: salinity of ground water



Ground water of the calcium bicarbonate type occurs in limestone aquifers in the Nasseryeh and Arak areas and in clastic formations in the Damascus Ghouta. All these areas are flanked by highlands and receive an appreciable amount of rainfall. Calcium bicarbonate water also occurs in wadi El-Swab and wadi El-Miah which are the longest wadis in the extremely arid areas of the eastern part of the country. Fresh bicarbonate water of the Syrian steppe originates from infiltration of rainfall into the alluvium of major wadis and from direct infiltration from precipitation in the higher parts of the Anti-Lebanon and Palmyrian carbonate mountains.

Calcium sulphate water occurs in the Lower and Upper Fars aquifers of the lower Jezireh which include gypsum, marl, and sandstone. They also occur in the chert artesian aquifers of the Khanasser basin. The relatively low content of sulphate in the Campanian aquifers of the Palmyrian area is brought on by sulphate reduction. In this area, the Campanian is represented by bituminous marl and chert. The oxidation of organic matter is accompanied by the reduction of sulphate. Thermal water containing variable amounts of H_2S and SO_4 is yielded by springs which issue from the Campanian aquifers of the Palmyrian basin. Sodium chloride water occurs in detrital sediments in the major part of the Dawwa plain and in parts of the Palmyrian and Damascus plains. Concentration by evaporation in sabkhahs and desert depressions is the main controlling factor. Other important factors include the slow movement of ground water in lacustrine marls in which gypsum and salts of sodium and magnesium may occur. Highly mineralized ground water of sodium chlorids type occurs also in Paleocene marl and chert in the Rassafeh and Hama areas. Limited recharge and the very low transmissivity of these aquifers are among the main factors which affect the composition of ground water in these areas.

Northern plains

Hydrogeology

The northern plains are one of the most highly productive ground-water regions of the Syrian Arab Republic. Clastic and basaltic rocks occur in the east and carbonate formations in the west. Several important aquifers have been identified: the Radd aquifer; the Ras El-Ein aquifer; Tel Abiad aquifer; and the Halab aquifer.

In addition to these major aquifers minor aquifers occur in the region. They occur in weathered marl, limestone and chalk. The principal recharge areas occur in the extreme north-west and north-east of the country. They extend northwards beyond the boundaries into the southern part of the Taurus mountain range. Annual rainfall averages 400 mm in the north-western and north-eastern parts of the area. It increases in a northerly direction to 1,000 mm in the Taurus highlands. In the plateau flanking the highlands, it averages 550 mm.

Infiltration of precipitation into fissured limestones and basalts in the plateau areas is relatively high. Recharge from surface run-off occurs along small rivers and wadis which originate in the northern highlands.

The Radd aquifer includes gravel, conglomerate sand and sandstone of Upper Miocene and Quaternary age. Several permeable zones of substantial width and thickness and moderate-to-high permeability occur between Kamishly and Karatchock. Recharge from precipitation and run-off along the wadis of Jagh Jagh, Brebitch, Jarah, Khneizir and Roumeilan amounts to 350 x 10^6 m^3 per annum. Discharge by evapo-transpiration from the extensive Radd marshes in the south is estimated to be 270 x 106 m^3 per annum.

The Ras El-Ein artesian aquifer is the most productive aquifer in the country. It includes cavernous limestone and dolomite of Eocene and Miocene age. The major recharge area, located in the north, comprises basalt and Eocene limestone and is estimated to extend over 7,500 km^2. Average annual precipitation over this region amounts to 450 mm. The annual recharge is estimated to be 1.6 billion m^3.

The spring of Ras El-Ein which issues from the artesian limestone aquifer is one of the largest karst springs in the world. The discharge of Ras El-Ein spring averages 40 m^3/sec. The spring is located in a collapsed area which occurred as a result of dissolution of deeper formations by ground-water flow. The Ras El-Ein artesian aquifer extends southwards to Tel Tamer. To date, the southern boundaries of the aquifer have not been clearly determined.

The hydrogeological characteristics of Tel Abiad limestone aquifers are similar to those of Ras El-Ein aquifers. These aquifers form a belt of limited width. The discharge of the Ain El Arous spring which issues from the aquifers averages 6 m^3/sec.

In the Halab area ground water occurs mainly in chalk and marly limestone of Eocene age. The base of the aquifer is impervious marl of Paleocene and Upper Cretaceous age. Shallow ground water occurs in unconsolidated clastic deposits of Pliocene and Quaternary age in the Jaboul and Madekh lowland areas. Neogene limestone forms multilayered aquifers in several areas west, north and south-west of Halab.

Ground water is recharged by infiltration of local precipitation and surface run-off in the Queik river basin. The Madekh and Jaboul depressions are among the most important discharge points for the shallow ground-water bodies.

Water quality

Ground water in the northern part of the Radd area is of the bicarbonate type. The predominant cation changes from calcium in the north-east to magnesium and sodium in the south. Ground water is low in total dissolved solids. Throughout most of the southern Radd, salinity of ground water ranges from 500 ppm to 1,000 ppm. Bicarbonate waters change southwards, in the direction of ground-water flow, into calcium sulphate water and sodium chloride water in Sabkhet El Radd. In that area, ground water becomes mineralized. Salinity ranges from 5,000 to 55,000 ppm.

Bicarbonate water areas occur in the north owing to high rainfall. They extend southwards along the wadis of Jarah, Khneizir and Roumeilan because of recharge from surface run-off in these wadis.

The Eocene limestone aquifers of Ras El-Ein and Tel Abiad are characterized by calcium bicarbonate water of low mineral content. Total dissolved solids range from 250 to 510 ppm. Ground water occurring in limestone and chalk aquifers of the Alab area is of the calcium bicarbonate type or the calcium magnesium bicarbonate type. Salinity is usually low. In some parts of the Halab area, the thickness of Cretaceous-Paleocene marls exceeds 300 m and deep ground water is highly saline. Salinity of deep aquifers decreases as the recharge by fresh water from the surface or from shallow ground-water bodies increases.

Assessment of available water resources

It would be unrealistic to give exact and definite figures about available surface- or ground-water resources. The estimates given below will serve to provide some information about the relative importance of surface- and ground-water resources in the country.

Previous studies included a computation of water balances in the Radd, Ras El-Ein, Damascus, and Hauran areas. When investigations were conducted in those areas available hydrological or hydrogeological data were insufficient with regard to length of record or density of observation networks. However, discharge in the areas studied can be accurately measured, since it is limited to a small number of large springs which emerge from fissured, cavernous and karstified formations. The following table summarizes available information pertaining to ground-water recharge and discharge. It can be seen that recharge is approximately equal to discharge. The Radd area is exceptional since it is one of the few areas in which significant evapo-transpiration takes place. On the basis of such results average annual ground-water recharge in the country has been estimated to be about 5 billion m^3. This figure includes the estimated discharge of offshore submarine springs.

Ground-water region	Ground-water area	Average annual recharge (Millions of m^3)	Average annual discharge (Millions of m^3)
Northern plains	Radd	350	65
	Ras El-Ein	1,640	1,450
	Tel Abiad	...	...
	Halab	...	334
Hauran volcanic plateau		314	...
Syrian steppe	Damascus	501	518
	Dawwa	...	...
	Jebel Abdel Aziz	75	60
	Badiet-El-Jezireh	15	...
	Badiet-Esh-Sham	...	...
Western mountain ranges	Ghab	...	800
	Edleb	...	66
	Coastal	...	375
	Plains off-shore	...	...
	Submarine springs	...	...

The average annual flow of perennial and intermittent rivers in the Syrian Arab Republic is estimated to be 30 billion m^3. Thus, although present estimates indicate that the ratio of renewable surface resources to ground resources is 6:1, this result should be examined with great caution. Only towards the end of the present decade will reliable estimates on water resources be made available. New estimates will be based on the results of current water resources investigations in the coastal area and in the Halab, Orontes, Damascus, Belikh and Badiet-Esh-Sham areas.

Ground-water development

Abou El Fawares and Aamy kanats (infiltration galleries) were excavated for the water supply of the Kingdom of Palmyra (A.D. 260-272). The Romans and later the Arabs maintained the older kanats and excavated new ones in the Qalamoun area and in other arid regions. Some of these kanats are still in use in the Qalamoun and Quteifeh intermontane areas. Recent studies have shown that the kanats, which intercept and collect shallow ground water, are well suited to the hydrogeological conditions prevailing in these areas.

Between 1925 and 1952, about 25 bore-holes were drilled and records of this drilling were maintained. No records are available in the country of the 81 bore-holes drilled during the Second World War, although some information on these bore-holes can be obtained from a publication which appeared in 1947. Some 150 dug wells were excavated during the period 1935-1945 by the Department of Irrigation and Hydraulic Power. In 1952, the drilling section of the Department was created and between January 1952 and March 1960, 243 bore-holes (53,000 m) were drilled.

Between 1957 and 1977, drilling and other activities relating to ground-water development were carried out as follows:

(a) Fifty-seven exploration and exploitation bore-holes were drilled during the period 1959-1961 for the improvement of pastures and animal production in the Syrian steppe;

(b) The Jezireh ground-water project (UNDP/FAO) included the drilling of 33 exploration and 8 observation bore-holes (1961-1962);

(c) Several hundreds of bore-holes were drilled by private firms for the domestic water supply of towns and villages;

(d) Several thousands of wells were drilled by private construction and drilling firms and by individuals for irrigation and industrial use. They include dug wells and bore-holes. Dug wells are excavated in the shallow clastic or carbonate aquifers. Several horizontal galleries are often driven from these wells. They are the local equivalent of collective wells, but differ from them in that they are generally excavated in aquifers characterized by limited thickness and small transmissivities.

The government drilling service operates about 30 drilling rigs. Approximately 150-200 wells (20,000 m) a year are drilled, mainly for domestic supplies and livestock. It is likely that drilling will be substantially increased in the near future.

In 1977, 18 rotary rigs were being used for ground-water exploration in the western part of the country. Some 10 drilling rigs, with capacities up to 200 m, belonging to private firms or individuals are in operation. These small drilling companies use mainly cable tool equipment which seems to be a satisfactory and economic solution for the development of ground water for irrigation in shallow alluvial or carbonate aquifers. Difficulties are encountered when bore-holes are drilled in basaltic or relatively deep artesian aquifers.

A two-year course is offered by the Ministry of Petroleum to qualify drillers for government organizations concerned with well-drilling. About 25 per cent of the private drilling firms are manned by skilled drillers. Most of them need further training and knowledge pertaining to well design, pumping tests, and other areas of water-well technology.

The perennial water courses originating in or flowing through the country are large. It has been estimated that the total annual flow of all the perennial rivers is 30 billion m^3. With such relatively large resources of surface water, it might seem that ground water would be of secondary or even minor importance. However, the fact that in several cases ground water occurs far from any supply of surface water gives special importance to this resource. Individual water supply systems are required to meet the needs of the small dispersed villages in semi-arid and agricultural areas and of the nomad populations all over the steppe. Ground water can be developed and utilized in small but complete individual units. Total investment in money, time, man-power, equipment and organization is usually within available resources. It is evident that the development of ground water for irrigation is within the competence and financial resources of private farmers.

The mode of life, the social and financial conditions and the technical and economic considerations combine to make the development of ground water of paramount importance in the overall picture of the future development of the country.

Water use

The total irrigated area in the Syrian Arab Republic from both surface- and ground-water resources, amounts to 578,000 hectares. According to recent reports ground water is utilized for the irrigation of about 39 per cent (227 thousand hectares) of total irrigated land. Current withdrawals in the country amount to 3.5 billion m^3 a year. By 1985, total withdrawals are expected to reach 7 billion m^3 a year.

Water consumption for irrigation, domestic and industrial use is summarized in table 20. The table also shows projected needs. The consumption of water by tourism is small at the present time, but is expected to rise to 24 million m^3 a year by 1985.

Large springs issuing from cavernous limestone and fissured basalt are the main source of water for the city of Damascus and for other large towns in the western part of the country, namely, Daeraa, Suweida, Hama, Homs and Latakia. Large towns in the north, Halab, Al-Thoura, Dier Ez Zor, Raqqa, Hasakeh and El Kameshly, obtain domestic water supplies from the Asad lake, the Euphrates River and its tributaries. Small towns and rural communities depend mainly on ground water for their domestic supplies. Of all these large towns and small communities, it is the city of Damascus which is expected to face major water problems with regard to its domestic supply and the needs of its industrial areas.

Table 20. Syrian Arab Republic: approximate classification of present water use and projected needs for 1985

(Millions of m^3/year)

Area	Present use, 1976					Projected needs, 1985		
	Irrigation		Municipal and industrial water supply			Irrigation	Municipal and industrial water supply	
	Surface water	Ground water	Surface water	Ground water	Total	Surface- and ground-water	Surface- and ground-water	Total
Damascus	260	250	...	80.0	590.0	795	140.0	935.0
Orontes	580	105	...	26.0	711.0	1,015	118.0	1,133.0
Coastal	81	71	4.0	12.2	168.2	487	49.6	536.6
Halab	50	200	33.0	7.8	290.8	450	110.7	560.7
Jezireh	1,340	240	21.0	4.0	1,605.0	3,580	68.9	3,648.9
Hauran	...	60	...	13.3	73.3	110	38.0	148.0
Total	2,311	926	58.0	143.3	3,438.3	6,437	525.2	6,962.2

The municipal and industrial water use in the Mohafazats of the Syrian Arab Republic is shown in table 21. In each Mohafazat the per capita use of water and total use in rural areas is relatively low in comparison with municipal use in urban communities. In the Mohafazats of Damascus, Homs, and Halab, industrial use is relative high and may exceed domestic use.

Table 21. Syrian Arab Republic: present municipal and industrial water use in the Mohafazats and projected needs for 1985

(Millions of m^3/year)

City or town	Present use, 1976			Projected needs, 1985		
	Surface water	Ground water	Total	Surface water	Ground water	Total
Quneitra	...	3.9	3.9	...	11.4	11.4
Daeraa	...	5.9	5.9	...	16.9	16.9
Suwaida	...	3.5	3.5	...	9.7	9.7
Damascus	...	80.0	80.0	...	140.0	140.0
Homs	...	15.5	15.5	...	90.0	90.0
Hama	...	10.5	10.5	...	28.0	28.0
Edleb	...	7.8	7.8	...	20.7	20.7
Halab	33.0	...	33.0	90.0	...	90.0
Tartous	1.0	6.3	7.3	...	23.0	23.0
Latakia	3.0	5.9	8.9	...	26.6	26.6
Raqqa	6.1	...	6.1	16.9	...	16.9
Deir Ez Zor	7.3	...	7.3	20.0	...	20.0
Hasakeh	7.6	4.0	11.6	32.0	...	32.0
Total	58.0	143.3	201.3	158.9	366.3	525.2

Future development

For future ground-water development, the following aquifers are the most important:

The Radd clastic alluvial aquifer (Neogene-Quaternary);

Ras El-Ein artesian limestone aquifer (Eocene);

Tel Abiad artesian limestone aquifer (Eocene);

The Hama limestone aquifers (Turonian-Cenomanian);

The Ghouta alluvial aquifer (Neogene-Quaternary);

The Hauran basalt aquifer (Neogene-Quaternary).

Most of these major aquifers are characterized by high storage capacity (see map 24). In the northern part of the country, the karstic springs which issue from the Ras El-Ein and Tel Abiad aquifers feed the Khabour and Belikh Rivers, respectively. When such aquifers are highly developed, the flow of these springs will diminish. Integrated development of surface- and ground-water resources would thus lead to full and rational development of available resources. It is particularly needed in the Belikh and Khabour basins, because topographical, climatic and hydrogeological conditions do not favour surface storage in reservoirs. Induced recharge is practised in the Jaghjagh and Queik valleys. It provides underground storage for water which otherwise would be lost by evapo-transpiration in the Radd and Madekh discharge points. By inducing an artificial variation in yield, it is also possible to increase the discharge of some springs during the summer and reduce the flow during the winter.

The Damascus Ghouta area is favourable to artificial recharge. Several rivers and wadis flow into the alluvial plain from the highlands which lie to the west and north. As they cross the plain these permanent and ephemeral streams flow over coarse alluvial deposits. The gravel becomes finer-grained eastwards where lacustrine marl and limestone also occur.

In the Hauran area in the south-western part of the country, and in the Dawwa plain, water spreading would permit the storing of (a) moisture in the soil for summer crops, and (b) some of the winter flow of the wadis in the underlying aquifers.

Ground-water development problems

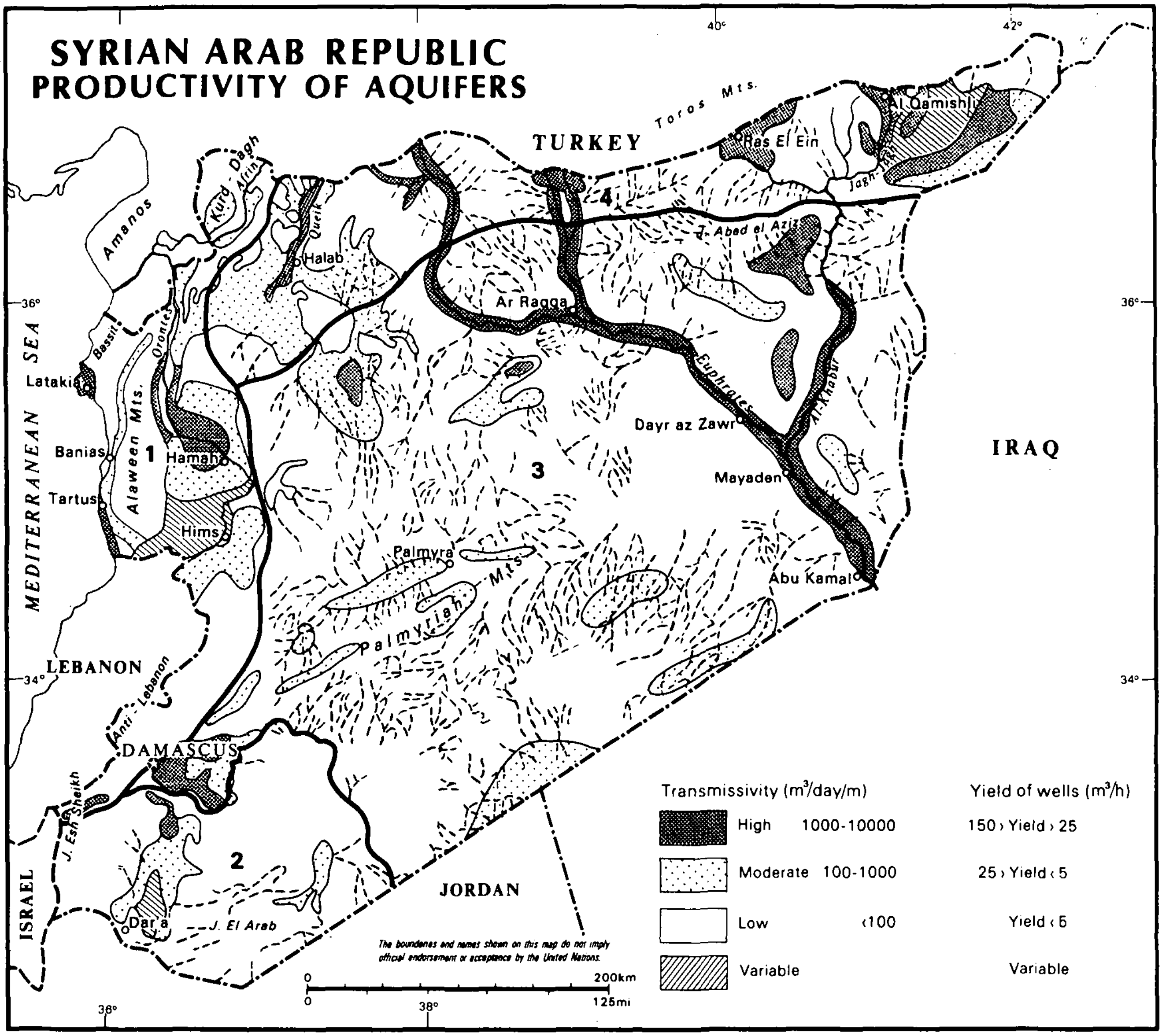
In regions having the problem of aridity or frequently affected by drought conditions, ground-water development may create serious problems in respect of the environment. The lack of sufficient knowledge pertaining to resource management practices is also cause for concern.

The development and exploitation of ground water has gained momentum in the country. Such success has brought problems caused mainly by overpumping. Salt-water intrusion has become a serious threat in the Syrian coastal plains (the Hamidyeh and Latakia areas) and some arid regions (the Ramadan and Beida areas) in which extensive saline aquifers occur.

Map 24

Syrian Arab Republic: productivity of aquifers

MAP 24



Measures are needed for the control and conservation of water resources particularly in areas in which ground-water quality deteriorates as a result of salt-water intrusion. Deterioration in quality also occurs in areas irrigated by brackish water and in multilayered aquifers when fresh water is underlain or overlain by saline ground water (the lower Radd area). Salt-tolerant crops are grown in some areas. Eventually, however, the soil will deteriorate as a result of salt accumulation.

In the semi-arid regions of the country several shallow ground-water reservoirs were overpumped during the past decade. These include the Qalamoun, Salamyeh, Mouselmyeh, El Bab, Menbej and Jeiroud aquifers. They are characterized by a limited thickness, high water table, and medium to high transmissivity. Most of these shallow aquifers occur in areas where the land resources are eminently suitable for agricultural development. In the early phases of their development the aquifers gave good or excellent economic returns. Overpumping and drought conditions caused storage depletion, so that measures had to be taken, which included reduction of pumping, from wells, prohibition of further development and artificial ground-water replenishment from surface run-off. Small dams have been constructed in many areas and an integrated use of surface- and ground-water has proved to be advantageous.

In some areas, however, the problem of overpumping can be solved only by importing water.

Current and future investigations

In spite of recent progress and the regional work already done in the fields of geology, geophysics, climatology, hydrology and hydrogeology, the country needs further investigations in respect of, for example:

(a) Water balance studies;

(b) Ground-water and surface-water observation networks;

(c) Hydrogeological modelling for highly developed areas;

(d) Determination of the interface between salt water and fresh water in coastal and arid areas;

(e) A computerized system for storage, processing and retrieval of hydrological and hydrogeological data;

(f) A revision of water legislation;

(g) Ground-water exploration of deep aquifers;

(h) Artificial recharge of aquifers in semi-arid regions;

(i) Desalination of brackish ground-water resources.

Ongoing investigations include five major projects:

(a) Water resources investigation of four hydrographical basins: the Dawwa, Orontes, Halab and coastal basins;

(b) Surface-water study of the Belikh river basin;

(c) Water resources appraisal of the Syrian steppe;

(d) Hydropastural investigation of the Hamad basin (a regional project involving the Syrian Arab Republic, Iraq, Jordan and Saudi Arabia);

(e) Surface-water investigations in the Nahr El Kabir Esh Shimali and Aawaj river basins.

Conclusions

Desert lands prevail in the Syrian Arab Republic. Areas in which annual precipitation exceeds 250 mm form a crescent extending along the western and northern parts of the country. This fertile semi-arid land, whose area constitutes about 40 per cent of the country, is inhabited by about 80 per cent of the population.

Problems arising from variability in time and location of precipitation can be solved only by supplementary irrigation.

Social and economic conditions combine to give the development of ground water in this semi-arid country paramount importance in plans for future development.

The average annual flow of all perennial rivers is estimated to be about 30 billion m^3. The Government has made great strides in developing surface-water resources. Total reservoir capacity has risen to 12.6 billion m^3. This includes the Assad reservoir which was completed recently on the Al-Furat River, with a storage capacity of 11.9 billion m^3.

The cost of production of ground water from major aquifers ranges from 0.34 to 3.41 United States cents per cubic metre. The cost of production of ground water from the highly productive zones of Hama, Ghouta and Jezireh ranges from 0.34 to 0.61 cents per cubic metre. The cost is high when the production from wells does not exceed 5 l/sec or the total pumping head exceeds 75 m.

Great variations exist in the cost of ground water in the marginal zones of some major aquifers. This is caused by the predominance of fine clastic material or poor development in fissure systems.

The recent increase in labour costs has aggravated the situation and rendered the exploitation of ground-water resources uneconomic in several parts of the country unless modern irrigation methods and improved agricultural practices are utilized. Previous ground-water investigations have shown that the country has ground-water reservoirs in almost every stage of development, from those capable of considerable development to those capable of very little sustained perennial use and seriously overdeveloped.

In the northern part of the country, the base flow of the Al-Furat River and its tributaries is fed by large springs issuing from major artesian aquifers. Integrated development of the surface- and ground-water resources would have several advantages in this region. In the south-west, artificial recharge of the alluvial and volcanic aquifers would be a practical and economic solution to problems that already exist and those expected to arise in the near future.

Current investigations cover the western region and the Syrian steppe. They include ground-water inventories, water-balance studies, ground-water exploration and a quantity and quality assessment of available resources. The results of these hydrological surveys and investigations would render existing ground-water legislation more effective, since the policy makers would have a more accurate knowledge with regard to quantity and quality of ground-water resources. The water code may then be revised in line with past experience and recent developments.

Further research is needed in several areas pertaining to the development and management of water-resources investigations. Important topics include ground-water movement in fissured and cavernous formations, salt-water encroachment, submarine discharge of ground water, surface storage of run-off, well design, and mathematical modelling for highly developed or overdeveloped ground-water areas. It is desirable that these matters and others that may arise in the course of future developments should be integrated into long-term programmes which may include research, training, exploration and development planning.

Selected references

Papers and reports

Boeckh, E. Geological mission in the Syrian Arab Republic, 1966-1970. Final report. Hannover, Federal Republic of Germany, 1970.

Burdon, D. J. The location, the amount and the future development of the underground water resources of south-west Syria. Unpublished report. Damascus, 1954.

Burdon, D. J. and S. Mazloum. Some chemical types of ground water in Syria. Proceedings of the Teheran Symposium. 1958.

__________. Ground-water development and conservation in Syria. FAO Report No. 1270. Rome, 1961.

Dubertret, L. L'hydrologie et aperçu sur l'hydrographie de la Syrie et du Liban dans leur relations avec la géologie. Revue de Géographie physique et de Géologie dynamique. No. 6, Paris, 1933.

FAO. Etude des ressources en eaux souterraines de la Jezireh Syrienne. Report Final, FAO/SF: SYR. Rome, 1966.

Kawasmi, Y. Climatological conditions in the Dawwa basin. Water Resources Report R-4. ACSAD, Damascus, 1977.

Khouri, J. Chemical characteristics of ground water in the Syrian Arab Republic. Arab Engineer, No. 27. Damascus, 1969.

__________. Occurrence of ground water in the Syrian Arab Republic. Arab Engineer, No. 28. Damascus, 1969.

__________. Hydrochemical investigations in some arid and semi-arid zones in the Syrian Arab Republic. Proceedings. Seminar on ground water. UNESCO and the Foundation of Scientific Research. Baghdad, 1973.

__________. The cost of ground water in the Syrian Arab Republic. FAO Report. Rome, 1977.

__________ and W. Rasoul Agha. Salt water intrusion in the central region of the Dawwa basin. A hydrogeological and a geophysical study. Water Resources Report P-5. ACSAD, Damascus, 1977.

Rasoul Agha, W. Geophysical prospecting for searching ground water in the Syrian Arab Republic. Unpublished doctoral dissertation, State University, Moscow, 1973.

__________. Use of geophysical methods for the study of the ground water resources of the Dawwa basin. Water Resources Report P-6. ACSAD, Damascus, 1977.

Safadi, C. Hydrogéologie des terrains volcaniques de la Syrie meridionale. Thèse. Nancy, France, 1956.

Selkhozpromexport. Programme of hydrogeological and hydrological surveys and investigations in three areas of the Syrian Arab Republic. Damascus, 1971.

Technopromexport. Report on water supply of pastures in the Syrian Arab Republic. Moscow, 1962.

Hydrogeological maps

ACSAD. The International Hydrogeological map of the Arab World. Sheet Cl. Damascus, 1977.

ACSAD. The International Hydrogeological Map of Europe. Sheet F6. Halab. UNESCO, Paris.

Khouri, J. A hydrogeological map of the Syrian Arab Republic. Damascus, 1969.

Technoexport. Schematic map of the first below the surface water bearing formation of Syria. Moscow, 1961.

Area: 780,576 km^2, including lakes; 774,815 km^2, excluding lakes

Population: 40,197,670 (1975 census)

Conditions of ground-water occurrence

Physiography

The country may be divided into four major physiographical structural units: (1) the central massif, (2) the northern folded zone, (3) the southern folded zone, and (4) the Arabian platform (see figure VI). Each has its own characteristic relief, land forms and drainage patterns.

Central massif

The central massif extends inland from the Aegean Sea, passes south of Ankara and terminates near Sivas, where the northern and southern folded zones converge. Throughout this region relief is a good deal less strong than in the zones to the north and south. In spite of the lack of fold structures, the term "Anatolian plateau" is somewhat misleading. The central massif is not uniform in structure or relief. In addition to the large high-level plains which dominate the central part of the region, there are also numerous elevated plateaux and mountain ranges of varied origin and rock types.

Northern folded zone

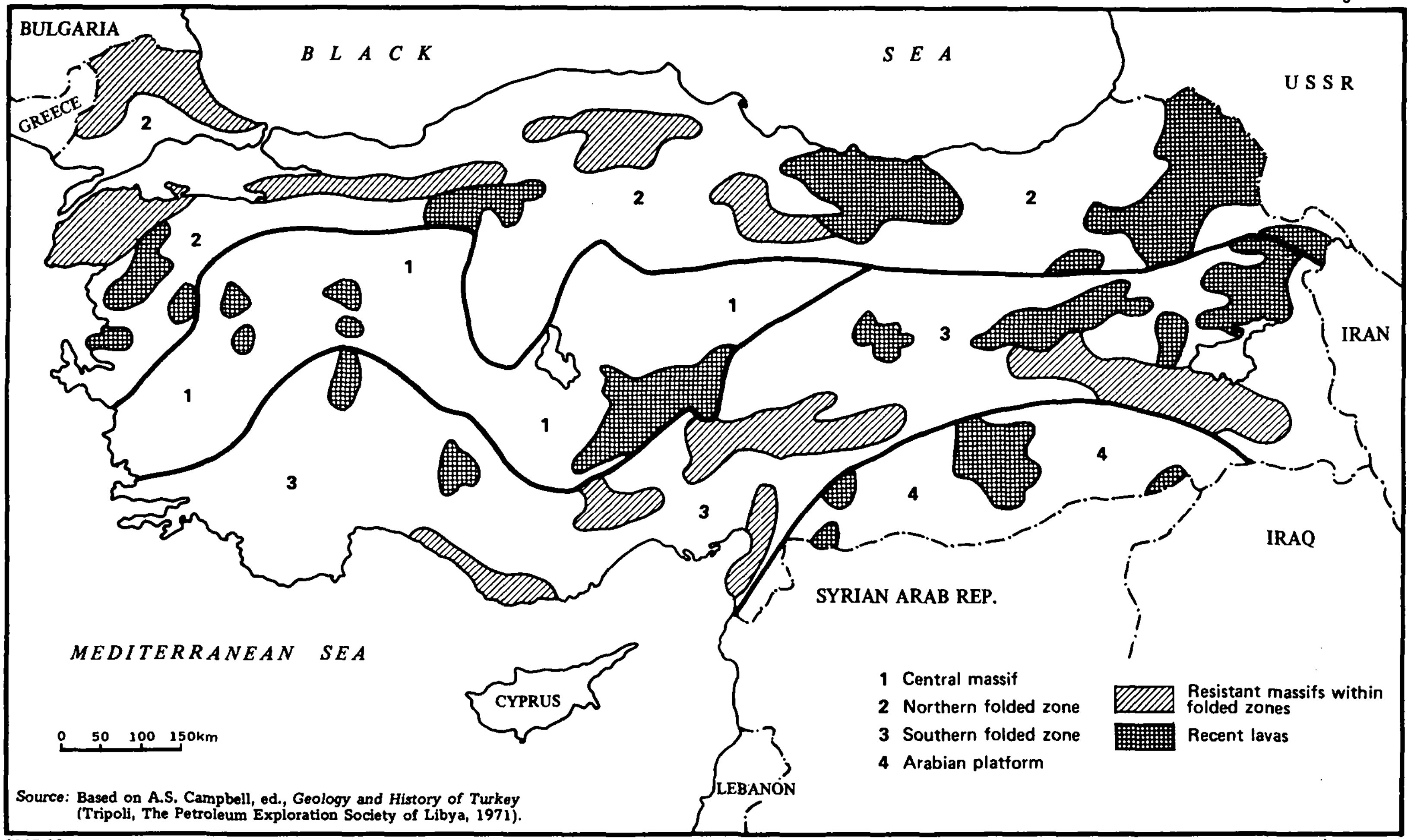
The northern folded zone occupies the whole of northern Turkey for a distance of 150-200 km inland from the Black Sea. Throughout most of this zone, the dominant structures are younger faults composed largely of Mesozoic and Tertiary rocks, but there are also a number of metamorphic blocks and Paleozoic materials and an extensive spread of Tertiary volcanics. The whole mountain system, referred to generally as the Pontic range, has a strongly pronounced west-east trend. Long, narrow mountain chains and broader, fault-bounded high plateaux are separated by deep-set valley troughs. The Pontic range constitutes a formidable barrier between the Black Sea and the interior which is broken in only three places where the Kizilirmak, Yesilirmak and Coruh rivers have cut gorges to the sea.

Southern folded zone

The southern folded zone, known as the Taurus, occupies much of southern and eastern Turkey. The western half of this system separates the central massif from the Mediterranean Sea, while in the east it converges with the northern folded zone and is bounded on the south by the stable block of the Arabian platform. Along the Mediterranean coast, the Taurus ranges rise abruptly from the sea to heights of 2,500-3,000 m above sea level. In the east, a common feature is the presence of

TURKEY: MAJOR STUCTURAL DIVISIONS

Figure VI



Source: Based on A.S. Campbell, ed., *Geology and History of Turkey* (Tripoli, The Petroleum Exploration Society of Libya, 1971).

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Figure VI.
Turkey: major structural divisions

down-faulted basins whose flat floors are covered with Neogene sediments. The highest peaks occur along the northern edge of the zone, especially where volcanic features rise above the general level as in the case of Büyük Agri Dagi (Mount Ararat) which, at 5,165 m, is the highest mountain in Turkey.

Arabian platform

The Arabian platform, a stable massif lying to the south of the eastern Taurus, is an area of relatively gentle relief in the form of a series of broad plateaux at heights of 400-700 m above sea level. The whole area is drained into Iraq by the Euphrates (Firat) and the Tigris (Dicle) rivers.

Climate

The basic factors of relief, altitude and distance from the sea combine to bring about considerable climatic contrasts between the various regions of Turkey. Six climatic regions may be distinguished.

The Black Sea coastlands are strongly affected by maritime influences throughout the year. The region is characterized by a relatively mild, moist climate. January mean temperature at sea level is 6° or 7° C and summers are hot. Rainfall over the whole region is well over 1,000 mm. In Thrace and Marmara winter depressions bring rain, but the northerly winds of summer are drier. Much of lowland Thrace records less than 600 mm. Winters are quite cold in Thrace, and summers are hot, with the July mean temperature approaching 25° C.

The Aegean coastlands have a typical Mediterranean régime. Winters are mild, with the January mean temperature between 7° and 9° C, and summers are hot, with average temperatures above 25° C in July and August. Annual precipitation is between 600 and 700 mm at sea level, rising to more than 1,000 mm in the mountains.

The Mediterranean coastlands have the warmest winters of any region, with the January mean temperature between 9° and 10° C. Summers are very hot, particularly in the Antalya plain, where the July average temperature exceeds 28° C. There is a marked summer drought but winter precipitation is quite heavy, particularly in the west, where Antalya has an annual total of 1,030 mm. Annual rainfall decreases towards the east, Adana recording a total of only 611 mm.

The South-east is another summer drought area. Precipitation falls mainly in winter, but annual totals are low, varying between 300 and 600 mm. Summers are very hot, with a July mean temperature above 30° C over most of the region.

The Anatolian interior is characterized by a semi-continental type of climate. January mean temperatures are below freezing throughout the region. Summer temperatures vary with altitude, the July average ranging from about 23° C in the Konya basin to 15° C in the eastern mountains. Annual precipitation also varies with elevation. While some of the higher mountains receive more than 1,000 mm, totals fall below 400 mm over large areas of the central plains, and barely exceed 300 mm in the Konya basin.

Surface water

Since the average annual precipitation for the entire country amounts to about 670 mm, or to an equivalent water input of about 518 billion m^3, it could be concluded that Turkey is rich in water resources. Slightly less than one third of that amount or approximately 166 billion m^3 is estimated to be surface runoff. The largest surface-water potential is in the eastern part of the country in the Firat (Euphrates) and Dicle (Tigris) river watersheds. The major rivers, their drainage areas, and average annual discharge in millions of cubic metres are shown in tables 22 and 23. Additional information on flow data (daily, monthly and annual), on floods and peak flows, on silt content and run-off-coefficient are contained in the Yearbook on Stream Flow, published by the State Hydraulic Works (Devlet Su Isleri), Ankara.

Geology

The geological style of Turkey is widespread tectonism. Paleo-geographical reconstruction is extremely difficult in some areas. About one sixth of the country is covered by alluvium and terrace material and one third by metamorphic rocks.

In Devonian time, Turkish marine waters are presumed to have been split by a large land mass. By Permian time marine waters are likely to have flooded most of the country. Regression occurred during the Triassic period, with the result that several major blocks emerged, one south of the Black Sea and the other in western Turkey. The Jurassic witnessed greater transgression. From the Jurassic into the Cretaceous and Upper Cretaceous, marine waters are judged to have engulfed Turkey almost completely. The Upper Cretaceous interval is characterized by large areas of clastic deposition. The clastics, both coarse and fine, are interpreted as flysch. Sudden regression followed the powerful Upper Cretaceous transgression. By Eocene time the country was engulfed once again by marine waters, which retreated during the Oligocene. In areas of known Oligocene deposition, a common component is evaporite, especially in north-central and north-west Turkey. The Miocene time was a period of transgression. Pliocene and Quaternary time was essentially a time of uplift and even of revolution, especially folding.

The Alpine nature of much of the territory of Turkey, intensely deformed and faulted, has been emphasized by many authors. Fault blocks and thrusts are common. The major thrust enters Turkey from Iraq, separating the Alpine portion of the country in the north from the folded belt in the south. The country has been divided into four provinces: a northern Paleozoic and Mesozoic tectonic province; a central Middle Alpine tectonic province; a southern Early Alpine tectonic province; and a south-eastern folded belts tectonic province.

Hydrogeology

Almost all lithostratigraphic formations have significant hydrogeological implications. Water-bearing units are spread throughout the entire stratigraphic column, that is, from Paleozoic marbles (as in the Konya closed basin) to Quaternary alluvium.

Table 22. Turkey: major rivers

River	Drainage area (km^2)	Average annual discharge (millions of m^3)
Firat (Euphrates)	128 428	...
Kizilirmak	78 180	5 172
Dicle (Tigris)	57 614	...
Sakarya	58 160	5 898
Yesilirmak	36 114	5 898
Büyük Menderes	24 976	2 649
Göksu	22 048	...
Asi	21 790	5 425
Ceyhan	21 982	...
Seyhan	20 450	...
Coruh	19 872	...
Gediz	18 000	More than 2 460
Meric (Maritza)	14 560	1 482
Aksu	6 472	1 262
Dalaman	5 230	1 303
Köprücay	2 062	3 659
Manavgat	928	4 889

Table 23. Turkey: international rivers

River Basin	Total drainage (km^2)	Drainage in Turkey (km^2)	Percentage in Turkey
Firat (Euphrates)	400 000	105 000	26.3
Dicle (Tigris)	378 834	48 000	13.0
Kura-Araks	225 000	57 000	25.3
Meric (Maritza)	56 000	14 600	26.1
Coruh	21 000	19 300	91.1
Asi (Orontes)	13 300	2 000	15.0

In south-western Anatolia the Comprehensive limestone formation is a prominent lithological unit that spans the period from Jurassic to Upper Cretaceous, but is mostly of Upper Cretaceous age. It receives the precipitated water over the Taurus mountain range, transmits it, and discharges it at large karstic springs. The underlying flysch barrier is almost always present near the discharging points. Another barrier to ground-water flow from Cretaceous limestone is the Miocene molasse formation, a mixture of predominant marl, siltstone and sandstone, with interlayers of limestone and conglomerate. The molasse occupies most of the coastal plain in the Antalya region. Its thickness is over 1,000 m in the lower Köprücay River watershed. The Cretaceous and younger limestones are karstified and discharge large volumes of water through the springs. The Miocene conglomerates, which are more than 1,000 m thick in the Köprücay valley, are also karstified.

In the Antalya region an extremely prominent formation occupies an area of about 600 km^2 between elevations of 0 and 300 m. This is the Antalya travertine formation of Quaternary age. Numerous features of karstification are developed in Antalya travertine. Karstification is characteristic for almost one third of Turkey.

The water-bearing formations in the huge Konya-Cumra plain are Paleozoic marble, Mesozoic limestone, Neogene limestone, Pliocene unconsolidated layers, and sandy gravelly layers of alluvium. In another huge plain, the 7,000 km^2 Ceylanpinar plain in south-east Anatolia, the Eocene limestone is the only water-bearing formation. In many plains, however, the most important aquifers occur in Quaternary and Pliocene alluvial deposits (see table 24 below).

Ground-water resources

Government services

In Turkey, the history of ground-water development by means of drilled wells spans a period of only 50 years. In ancient times, the villages and towns of Anatolia were built in the vicinity of springs or streams. In other villages, water for domestic use was obtained from cisterns, kanats, and shallow wells. In the years following 1923, in which the republican régime was established, it became evident that the surface-water supply was not sufficient to meet the domestic water needs of many villages and towns. The first deep wells were drilled in 1932 to provide the domestic water supply to the cities of Istanbul and Samsun. In the period between 1932 and 1949, several government institutions, including the Bank of the Provinces (Iller Bankasi), the Electric Resources Survey Department (EIE) and the Mineral Research and Exploration Institute (MTA), made sporadic studies of ground-water resources and drilled a limited number of wells.

In 1952, a small ground-water office was formed in DSI (Devlet Su Isleri, State Hydraulic Works) which, since then, has developed into the major government agency in the ground-water sector. Between 1952 and 1956, 194 exploration and water wells were drilled in various regions of Turkey, mostly by DSI. The ground-water investigations were accelerated in 1956, during which the Ground Water Division of DSI was established and equipped with 22 Failing SS drilling rigs.

According to the Ground Water Law, a legal instrument numbered 167 and enacted in 1960, the ground-water resource is the property of the State, DSI being legally responsible for investigations, evaluation, use and protection of this resource. Permission is required from DSI on behalf of the Government for opening bore-holes, drilling the wells, constructing water-supply galleries, tunnels etc. The Law holds DSI responsible for carrying out ground-water studies in all plains and basins within Turkish territory.

The Geotechnical Services and Ground Water Division of DSI is at present the single largest government agency active in ground-water exploration, evaluation and development. In 1977, the Division had a staff of 188 at its Ankara headquarters, 88 of whom were professional and 100 non-professional. There are 15 Ground Water Branch Offices under DSI Regional Directorates. The budget for 1977 envisaged expenditures of about one billion Turkish lira (approximately $50 million) in respect of ground-water development. Although these figures apply to both the geotechnical and ground-water sections, the major share is allocated to ground-water sustained irrigation. Two other government agencies are active in the ground-water sector: Iller Bankasi (Bank of the Provinces) and the General Directorate of Roads, Water and Electricity (YSE). They are both legally responsible for the water supply of the population: Iller Bankasi for cities with between 3,000 and 100,000 inhabitants and YSE for the villages with fewer than 3,000 inhabitants. Their major role is to construct the water-supply systems, mostly based on surface water and springs, without undertaking a systematic and complex programme of ground-water investigations and assessments. YSE, in addition, drills the wells for some of its water-supply systems.

Mode of operation of DSI in ground-water investigation

Investigations of ground-water resources in Turkey are done by the Ground Water Division of DSI in two stages: (1) Systematic coverage of Turkey (mostly the plains), the reconnaissance stage; and (2) Detailed investigations in selected areas, the planning stage. Individual hydrogeological studies are also undertaken.

Hydrogeological investigations at the reconnaissance stage are made to assess the depth, thickness, boundary, geological and lithological characteristics, water quality and yields of aquifers occurring in the plains and basins. The studies tend to give a preliminary appraisal of development potential of the plains and basins. Generally, classical methods are used, including an inventory of water wells, surface geology, very limited drilling data, water level observations and water sampling. Maps on a scale of 1:100,000 are used in investigations. This systematic coverage of the plains of Turkey was nearly completed by the end of 1969. It is claimed that 342 plains, with a total surface of about 596,527 km^2 have been investigated at the reconnaissance stage.

Hydrogeological studies at the planning stage are made in selected areas, according to the priorities determined on the basis of the preliminary development appraisal. At this stage the investigation is complex. It integrates geological, hydrogeological, geophysical and drilling activities. Water sampling and reporting on water quality is extensive. The scale of the topographical maps used in the investigations is 1:25,000, and the results are reported on maps on a scale of 1:100,000 and occasionally on a scale of 1:50,000. By the end of 1976, detailed hydrogeological studies had been completed for 139 plains covering a total surface of about 103,701 km^2 (see map 25).

MAP NO. 3088 REV. 1 UNITED NATIONS
AUGUST 1981

Turkey: ground-water investigations

Map 25

The programme of investigation and evaluation still relies heavily on classical methods. However, in DSI, modern methods are slowly becoming routine practice. The first electric analogue model (R-C) was constructed in 1970 for the Ergene Basin in Thrace (Trakya) and the first mathematical model in 1976 for the Elâziğ-Uluova plain in eastern Turkey. The mathematical modelling training of DSI staff was provided through the recent, ongoing UNDP assistance programme. Isotype hydrology also plays a part in the complex evaluation of ground-water resources, as does remote-sensing methodology. Although the DSI laboratory is not yet self-sufficient in implementing the isotope data evaluation programme, but has to rely on assistance from the International Atomic Energy Agency (IAEA), the remote-sensing services of DSI, are expected to be fully equipped for complex programmes in the near future.

Technical capabilities of DSI

The technical capabilities of the most active government agency, DSI, are such that it can carry out the various programmes of investigation, quantification and assessment of ground-water resources throughout the country. Difficulties may be experienced in the evaluation of aquifers in karstic carbonate rocks and in coastal regions where there is the prospect of salt-water intrusion or contamination, and where submarine springs discharge large quantities of fresh water into the sea.

The major drilling equipment of DSI includes about 70 large-diameter well drilling rigs, 20 of which are less than two years old. In addition to DSI, YSE operates about 40 drilling rigs, and many private companies have one or more rigs each. It is estimated that each year about 1,200 new water wells are drilled.

Although DSI is, by law, the central agency and should have a complete record of all drilled wells and other information on ground-water resources, it has failed to establish a modern, automated data-processing system. Assistance has been offered by UNDP and it is to be hoped that in the next few years an appropriate system will be established. The Ground Water Division of DSI has access to the inhouse IBM 370/145 computer.

Hydrogeological maps

Maps on scales of 1:50,000 and 1:100,000 accompany each report made at the planning stage. There is no complete and systematic coverage of Turkey in its entirety by hydrogeological maps on scales of 1:100,000 or greater. With the present completed reports, about 200,000 km^2 of Turkish territory have been covered by hydrogeological maps on scales of 1:100,000 and 1:50,000. The territory of Turkey has been divided into 18 sheets of hydrogeological maps on a scale of 1:500,000. Twelve sheets had been published by 1973 and the remaining six by 1977. The 1:1,500,000 hydrogeological maps of Turkey, as a part of the Hydrogeological Map of Europe, are completed in three sheets: E6, E5 and F6. The maps follow the instructions contained in the International Legend for Hydrogeological Maps, established by the United Nations Educational, Scientific and Cultural Organization (UNESCO).

Training of DSI staff

The technical personnel training programme was initiated by the Institute of Hydrology sponsored by UNESCO and annexed to the Technical University of Istanbul in the period 1959-1962. Many ground-water personnel have benefited from fellowships sponsored by, for example, the United States Agency for International Development (USAID), the North Atlantic Treaty Organization (NATO), UNESCO and UNDP. Since 1975, training has been provided by the United Nations through the following UNDP-financed projects: Strengthening the ground-water capability of DSI; Assistance for utilizing isotopes in hydrology; and Training and support for DSI personnel.

Examples of advanced methods utilized in Turkey

Isotopic studies in the Manavgat basin (southern karst region of Turkey) have been conducted since 1963 by IAEA in co-operation with FAO, DSI and EIE. Follow-up studies in the same region were carried out by IAEA during 1970 to 1972 in co-operation with EIE. The major concern of the follow-up isotopic studies was to have a more detailed interpretation of the selected systems and possible sinkhole-spring connexions in the Manavgat River basin, which is of particular importance for the engineering decisions to be taken in the planning of the Oymapinar Dam project. The samples collected from the major springs, sinkholes and the Manavgat River were analysed for oxygen 18 (^{18}O), deuterium (^{2}H) and tritium (^{3}H) content. Furthermore, the environmental isotopic composition of precipitation is being regularly monitored on a monthly basis at Antalya station (one of the IAEA/WMO Global Network Stations being operated for that purpose).

Isotopic studies in the Niğde-Misli plain, in the Konya closed basin, and in the Ergene Basin of Thrace were completed in 1976. The ongoing UNDP project to strengthen DSI ground-water investigative capabilities includes a continuous isotope data sampling and interpretation programme.

Tracing ground-water flow is a well-known technique used in Turkey for investigations of regional hydrogeological features in karstic aquifers, and in solving the problems in dam engineering. Several tracing tests were made using the rhodamine family of dyes and fluoroscein dyes in the Antalya region, the Eynif polje-Manavgat system and the Kirkgözler springs-Düdenbasi spring in 1976 and 1977; in the Ovacik submarine springs area in 1972; and in the Keban Dam and Lake leakage studies in 1975. At present DSI is equipped with three Turner 111 fluorometers that are routinely used for quantitative tracing.

Mathematical model. Only one mathematical model has been made in Turkey. This is the model of the elazig-Uluova plain. It covered an area of 555 km^2 and simulated the system's behaviour under stress in the period 1976-1985. The model integrated the influence of Lake Keban which floods one part of the plain.

Electrical analogue model. One electrical analogue model was constructed in 1970. The R-C (resistor-capacitance) model of the Ergene Basin (Thrace) modelled the response of the 6,000 km^2 ground-water system. The calibration phase covered the period 1957-1969, and the prediction phase the period 1970-1990.

Remote-sensing techniques are being utilized in defining the fracture traces in the Taurus mountain regions to correlate them with the main ways of subsurface drainage. For that purpose ERTS and LANDSAT images are available in DSI.

Results of ground-water investigations

The results of ground-water investigations are summarized for selected plains only in table 24. Each of the reports follows a pre-arranged format with regard to presentation of information. Most reports have a bilingual version or an English summary. The "safe yield" concept is, in the Turkish version, an arbitrary percentage of total water input to a ground-water system. This percentage in most cases is between 60 and 70. The hydrogeological parameters are obtained from numerous pumping tests. However, whereas the range of transmissivity values is quite acceptable, the values shown as storage coefficients are misleading. The short-term pumping tests yield values of storage coefficient that are always much lower than would be expected from continuous pumping conditions. One will notice that even the Quaternary alluvium aquifers, completely unconfined, will have a short-term test value of storage coefficient in the artesian range, that is, 10^{-3} and 10^{-4}.

Major aquifers

According to the hydrogeological studies carried out at both the reconnaissance and the planning stages, about 9 billion m^3 of ground-water can be developed annually without having any adverse effect on ground-water systems.

Several huge aquifer complexes contain the greater part of that resource. The huge Ceylanpinar plain in south-eastern Anatolia has an area of about 7,000 km^2 in Turkey and extends into the Syrian Arab Republic. The recharge to the aquifer is in Turkey, but it is drained by huge karstic springs with a total of about 42 m^3/sec outflowing into the Syrian Arab Republic. It is estimated that about 852 million m^3 can be safely developed annually from the Eocene limestone aquifer. The aquifer system of Konya-Çumra and Karapinar plains in central Anatolia covers an area of about 5,000 km^2. The Neogene limestone is the most prolific aquifer, but ground-water occurs in many formations from Paleozoic marbles through Pliocene-Quaternary alluvium. The area has a semi-arid climate, and the thick Pliocene cover prevents in situ infiltration of precipitation, so that the annual safe yield is estimated at 318 million m^3. The sandy complex of Pliocene in the Ergene basin in Thrace extends over an area of about 5,855 km^2. Its safe yield was evaluated at 184 million m^3. There are other huge aquifer systems in the plains of Turkey. Yet the major ground-water resources are in the coastal area on the southern flanks of the Taurus mountain ranges. Large karstic springs, such as Dumanli, Olukköprü, Kirkgözler, Göksu, Göldeğirmeni and Sarikiz, produce between 300 and 1,500 million m^3 of water annually. This water is the result of rainfall that penetrates into the limestone formations of the Taurus mountains, flows rapidly through the subsurface system and is released through the springs. The total combined outflow from all these springs is more than the total ground-water potential in the plains, at present estimated at 9 billion m^3.

Table 24. Turkey: summary of results of ground-water investigations

Year of report	Geological age and depth of aquifer	Geographical location	Depth of wells (m)	Hydrogeological parameters: Specific capacity (l/sec/m)	Hydraulic conductivity (m/day)	Transmissivity (m^2/day)	Coefficient of storage	Annual safe yield (millions of m^3)	Mean annual precipitation (mm)	Mean annual evaporation (mm)	Remarks
1969	Neogene and Quaternary fill (350-400 m)	KAYSERI-SARIMSAKLI plain (central Anatolia), 355 km^2	10-317	3-5 (average)	...	200-3 000	0.001-0.004	77	371	...	
1971	Volcanic Neogene (250 m)	MISLI plain near Nigde city (central Anatolia), 347 km^2	37-100	1-18	...	1 000-3 000	0.21 (one test)	45	356.6	1 524	
1970	Quaternary alluvium	AFYON-SUHUT plain (central Anatolia), 125 km^2	36-300	0.6-3.8	...	130-190	...	21	461.3	983.3	
1970	Quaternary alluvial fill (including Neogene) (200-250 m in east 100-150 m in west)	DEVELI-YESILHISAR plain (central Anatolia), 800 km^2	10-300	1-10	2-10	100-1 900	0.00004 (artesian well)	65	390	...	
1970	Pliocene-Quaternary (150-400 m)	ELAZIG-ULUOVA plain (eastern Anatolia-Euphrates Basin), 400 km^2	28-300	0.8-46.6	1-10	300-3 000	0.003-0.014	74	431	...	
1975	Paleozoic marbles, Mesozoic limestone, Neogene limestone, Pliocene-Quaternary (more than 250 m)	KNOYA-CUMRA-KARAPINAR plain (central Anatolia), 5 000 km^2	23-409	8-81 (Neogene limestone)	...	576-5 130 (Neogene) 800-3 000 (near Cumra)	0.001-0.0001 (Cumra)	318	250-350	...	
1970	Eocene limestone (more than 1 200 m), basalt (30-50 m)	CEYLANPINAR plain (south-eastern Anatolia), 7 000 km^2 RESULAYN springs	12.5-306.6	From 1 to over 100 in limestone; 0.1-20 in basalt	...	...	...	852	500	...	Huge karst springs (over 42 m^3/sec in the Syrian Arab Republic

Table 24 (continued)

Year of report	Geological age and depth of aquifer	Geographical location	Hydrogeological parameters								Remarks
			Depth of wells (m)	Specific capacity (l/sec/m)	Hydraulic conductivity (m/day)	Transmissivity (m^2/day)	Co-efficient of storage	Annual safe yield (millions of m^3)	Mean annual precipitation (mm)	Mean annual evaporation (mm)	
1972	Quaternary alluvium, volcanic Neogene (100 to over 300 m)	CÖL plain (western Anatolia), 100 km^2	30-300	1-44	...	169-5 170	...	15	534	611	
1972	Miocene-Pliocene sand, Eocene limestone	HARRAN plain (south-eastern Anatolia), 1 500 km^2	10-400	1-36 (very large in some limestone wells)	...	10-3 600	...	190	452	...	
1972	Neogene sand and gravel (over 500 m)	EREGLI-BOR plain (central Anatolia), 2 170 km^2	29-400	5-10	...	1 000-2 100	0.005 (short-term test)	122	299 (W) 384.4 (E)	...	1 000 dug wells; salinity problems
1971	Pliocene-Quaternary sand and gravel (about 200 m)	PASINLER plain (eastern Anatolia), 350 km^2	24-340 (most about 200 m)	Up to 24	...	1 000-2 000	0.001-0.0001	82.5	431.9	...	
1973	Pliocene-Quaternary sand and gravel (up to 300 m)	MARAS plains (middle Ceyhan basin), 785 km^2	Up to 349 m	0.5-50	...	200-4 000	...	156	690	...	
1970	Pliocene-Quaternary talus and conglomerate (about 100 m)	MARDIN-KIZILTEPE plain (south-eastern Anatolia), 600 km^2 in Turkey	25-268 (generally 100 m)	0.01-1	...	340-2 000	0.03-0.13	13	437	...	
1977	Quaternary alluvium (10-240 m), basalts	VAN-ERCIS plain (eastern Anatolia), 114 km^2	18-200	0.2-8.9 (generally 1.0)	...	113-489	...	26.5	497	...	
1971	Pliocene-Quaternary basalt tuff, Miocene and Eocene limestones	SURAC plain (southern Anatolia), 387 km^2	10-270	0.4-16.8	...	900	0.02	50	338	...	
1971	Miocene limestone, Pliocene-Quaternary sands	CIHANBEYLI-YENICEOBA-KULU plains (central Anatolia, Salt Lake basin) 3 600 km^2	95-337 (45 wells)	0.01-4.6	...	20-650	...	...	295	682	

Table 24 (continued)

				Hydrogeological parameters							
Year of report	Geological age and depth of aquifer	Geographical location	Depth of wells (m)	Specific capacity (l/sec/m)	Hydraulic conduc-tivity (m/day)	Trans-missivity (m^2/day)	Co-efficient of storage	Annual safe yield (millions of m^3)	Mean annual precipi-tation (mm)	Mean annual evapo-ration (mm)	Remarks
1973	Pliocene-Quaternary (up to 400 m)	MERZIFON-GÜMÜSHACI-KÖY plain (Black Sea region), 470 km^2	16-470	0.07-28	...	34-1 710	...	22	373	143	
1973	Quaternary (100-200 m) Neogene limestone, conglomerate, volcanic tuff (more than 400 m)	KÜCÜKMENDERES plain (western Anatolia), 3 470 km^2	20-339 (51 wells)	0.1-68	...	100-3 300	...	148	711	...	
1973	Quaternary alluvium (80-200 m, Bursa) (30-50 m, Cayirköy)	BURSA-CAYIRKÖY plain (Marmara Sea region), 290 km^2	20-300 (Bursa) 12 wells; 54-378, (Cayirkoy), 3 wells	0.4-8 0.07-2.3	...	15-6 800	...	80	709.3	...	
1973	Miocene limestone (30-130 m) under Pliocene-Quaternary (50-70 m)	ALTINEKIN plain (Konya district), 1 350 km^2	27-250 (14 wells)	1-33.3	...	560-8 000	...	30	...	...	
1976	Quaternary alluvium (100-250 m)	IGDIR plain (at the border with the Union of Soviet Socialist Republics), 770 km^2	68-343 (26 obser-vation wells); 90-160 (46 water wells)	4-26 5	...	700-3 000 (21 tests)	0.0018-0.00083 (deep aquifer) 0.01-0.1 (shallow aquifer)	144	253	...	Salinity problems
1976	Quaternary alluvium (25-30 m)	MÜRTED plain (Sakarya basin, central Anatolia), 320 km^2	11-315 (1 well, 700 m)	0.1-30.2	...	25-4 938	...	...	439	...	

Table 24 (continued)

Year of report	Geological age and depth of aquifer	Geographical location	Depth of wells (m)	Hydrogeological parameters Specific capacity (1/sec/m)	Hydraulic conduc-tivity (m/day)	Trans-missivity (m^2/day)	Co-efficient of storage	Annual safe yield (millions of m^3)	Mean annual precipi-tation (mm)	Mean annual evapo-ration (mm)	Remarks
1975	Quaternary alluvium (10-95 m)	ESKISEHIR and INÖNÜ plains (central Anatolia), 410 km^2	10-100 (42 wells)	4-7	...	100-300	...	88.5	480	...	
1976	Pliocene-Quaternary (100 m), Neogene limestone and conglo-merate, Upper Creta-ceous limestone (80-140 m), extension unknown	ATTABEY plain (Isparta, central Anatolia), 211 km^2	44-250 (16 wells)	0.6-2 (Quaternary wells)	...	4 040-7 850 (Upper Cretaceous)	...	5	555	...	
1976	Quaternary alluvium (20-30 m), Miocene conglomerate and limestone (60-240 m)	USAK, BANAZ and SIVASLI plains (central Aegean), 228 km^2	16-296 (14 wells)	0.1-4.8 (17 in limestone)	...	130-300 (continental Neogene); 160 (alluvium)	...	27	540.6	...	
1977	Tertiary sand and gravel, limestone (more than 50 m)	KORKUTELI, BOZOVA and KESTEL plains 565 km^2	35-300 30 wells (Korkuteli); 50-292 41 wells (Bozova)	0.5-1 (Korkuteli) 0.5-4.5 (Bozova)	...	400 (Korkuteli); 400-1 600 (Bozova)	...	10	440	...	
1975	Permian-Triassic limestone (10-80 m), Jurassic-Cretaceous limestone (250 m), Pliocene (150 m), Alluvium (10-300 m)	ANKARA-HATIP plain 1 223 km^2 drainage area	24-330 (248 wells)	1-5	...	500 (alluvium); 10 (Pliocene)	...	33	359.3	1 316.9	
1974	Pliocene-Quaternary alluvium (70-150 m)	IZNIK, ORHANGAZI and GEMLIK plains (south-east of Marmara Sea), 173 km	10-270 (29 wells)	1-4	...	120-2 500 (Iznik) 200 (Orhangazi) 200-500 (Gemlik)	...	30	534-765	...	

Table 24 (continued)

Year of report	Geological age and depth of aquifer	Geographical location	Depth of wells (m)	Hydrogeological parameters							Remarks
				Specific capacity (l/sec/m)	Hydraulic conductivity (m/day)	Transmissivity (m^2/day)	Co-efficient of storage	Annual safe yield (millions of m^3)	Mean annual precipitation (mm)	Mean annual evaporation (mm)	
1975	Quaternary alluvium (50-100 m)	OSMANIYE plain (Mediterranean region), 105 km^2	25-206 (17 wells)	0.05-27.7	...	500-3 400	...	...	739.5	...	
1974	Pliocene Quaternary alluvium (20-100 m)	HARUNIYE plain (Mediterranean region), 90 km^2	175-275 (10 wells)	...	...	97-1 481	0.027	...	998.6	...	
1975	Pliocene-Quaternary, Miocene limestone and conglomerate, basalt	ASI basin (south-eastern Turkey), 4 755 km^2 drainage area	21-363 (69 wells) 1 774 (oil well)	0.1-4	2 (sand)	450-1 250 (W-E); 100-200 (SE-N)	...	96.5	533-1 183	...	
1975	Neogene limestone (75 m) Paleozoic marbles (25-225 m)	KARAMAN-AYRANCI and AKCASEHIR plains (central Anatolia, near Konya), 1 065 km^2	34-300 (38 exploratory wells, 49 producing wells, 6 water wells)	8 (Neogene) 10-25 (Paleozoic)	...	1 300-3 000 (Neogene) 2 250-3 000 (Paleozoic)	...	52	345	1 175	
1977	Limestone Paleocene, Quaternary	North of ERGENE (Thrace), 600 km^2	15-60 (21 wells)	...	...	...	...	38	632-864	...	Numerous springs
1976	Pliocene-Quaternary (50-325 m)	AGRI-ELESKIRT plain (eastern Anatolia), 4 500 km^2 drainage area	10-324 (61 wells)	1-9	...	186-1 250	...	27	434-533	...	
1977	Pliocene Quaternary (20-50 m) Neogene limestone (100-150 m)	ESKISEHIR-ALPU plain (central Anatolia), 525 km^2	30-300 (34 wells)	0.5-2.0	...	200-3 900	0.003-0.11	33.5	327	...	
1976	Quaternary sand (5-20 m) Neogene limestone (Over 400 m)	ALTINTAS plain (central Anatolia), 262 km^2	13-302 (25 wells)	1-5	...	15-1 738 (Quaternary) 3-2 528 (Neogene)	...	15.5	430	...	

Table 24 (continued)

Year of report	Geological age and depth of aquifer	Geographical location	Depth of wells (m)	Specific capacity (l/sec/m)	Hydraulic conductivity (m/day)	Transmissivity (m^2/day)	Co-efficient of storage	Annual safe yield (millions of m^3)	Mean annual precipitation (mm)	Mean annual evaporation (mm)	Remarks
			Hydrogeological parameters								
1976	Neogene limestone (150-180 m)	KÜTAHYA-CAVDARHISAR plain (central Anatolia), 160 km^2	41-261 (24 wells; 160 dug wells)	0.4-21	...	151-3 466	...	36	572	...	
1977	Quaternary alluvium (25-150 m)	TOKAT-KAZOVA-TURHAL plains (eastern Black Sea), 380 km^2	30-280 (19 wells)	3-6.6 (one part) 8-133 (?)	...	345-895 1 456-3 000	...	78	461-484	1 075.6	
1976	Quaternary (100 m) Permian-Triassic limestone (400 m)	BAKIRCAY plain (near Izmir), 700 km^2	30-300 (32 wells)	Up to 28	...	About 500 (2 wells)	...	About 110	602-750	...	
1970	Pliocene sandy complex, Eocene-Pliocene limestone, Quaternary, Sandy complex (maximum 350 m)	ERGENE basin (Thrace) 5 855 km^2 in sandy complex	Drilled 75 012 m (371 wells) 8-450 m, mostly 200-250 m	4.9 (mean value for 73 wells)	12.9 (mean value in sandy complex)	115-2 803 (generally about 1 000)	0.10 (sandy complex) 0.001 (short test)	184	565-607	...	Inventory of 5 366 water points

Water quality

Each investigation programme contains the results of chemical analyses of ground-water samples. Throughout most of Turkey the ground waters are of good quality. Salinity is generally less than 500 ppm. In semi-arid provinces, such as the closed basin of Konya near the large salt lake (Tuz Gölü), and in some areas in the south-east, there is a problem of secondary salinity from evaporation from the leaching of salt. Numerous coastal springs and submarine springs have brackish or salty water. A programme is under way to capture the fresh water inland of submarine springs in the Ovacik area near Silifke.

In semi-arid areas the shallow aquifer dug wells have higher salinity - over 1,000 ppm, and much more locally. But the huge karstic springs of Ceylanpinar plain, which is a typical semi-arid region with about 500 mm mean annual precipitation, yield water with 300-500 ppm of total dissolved solids. The karstic springs in the Mediterranean region, which drain the Taurus mountains, have less than 200 ppm mineralization.

The personnel of the Ground Water Division of DSI process the ground-water quality data by computer in the form of STIFF or PIPER diagrams. This practice is a sporadic rather than a routine one, and the computer-processed diagrams are not synthesized into a publication. On the other hand, each of the 139 reports on hydrogeological units explored at the planning stage contains numerous water quality data.

Assessment of ground-water resources

According to DSI's appraisals, about 9 billion m^3 of ground water can be developed annually from the plains. If the same volume (a conservative estimate) can be developed from the karstic springs draining the Taurus Mountain range, about 18 billion m^3 will be available for development each year. This amounts to about 10 per cent of the total surface run-off in Turkey. With an average agricultural demand of about 1.1 l/sec/hectare or about 6,000 m^3 per hectare per season, a total of 3 million hectares could be irrigated with ground water. Thus ground-water resources might be sufficient to sustain irrigation of about 36 per cent of the total economically irrigable area in Turkey. 1/

The water supply of many cities and villages in Turkey is sustained by ground water. With an average *per capita* daily consumption of 100 litres and on the assumption that 50 per cent of the population get their supply from ground water, the total consumption of ground water would be about 730 million m^3 annually.

In many cases ground water resources have already been developed but in many more the utilization percentage is still much inferior to the optimum value.

1/ The Government has estimated that about 8.5 million hectares are capable of being irrigated economically.

Ground-water development

Drilling capacities

The drilling capacity of DSI is far greater than that of all other firms and organizations active in this sector. DSI has 72 drilling rigs, including 24 Failing 1500 and 20 Speedstar. The drilling lot comprises 5 Davey, 4 Franks, 2 Portadrill, 2 Failing JED, 1 Failing 2500 and 2 Ingersoll-Rand, among others. Drilling capacity is from 100 m (some cable-tool rigs) to 750 m (Failing 2500 and Davey). On average, DSI drills about 130,000 m/year.

Some 20 drilling companies are active in ground-water investigations. These are private enterprises with one or two drilling rigs each. Together they operate about 30 drilling rigs, and drill between 30,000 and 40,000 m/year.

YSE operates about 40 drilling rigs. With such drilling capacity, it should produce about 500 wells and drill at least 50,000 m each year.

Present status and future plans for ground-water utilization

Irrigation

At the end of 1975, the total area irrigated from ground water in the public sector amounted to 120,000 hectares. About 50 per cent of the irrigated area in the private sector probably used ground water as the source, so that the total area dependent on ground-water irrigation would amount to about 620,000 hectares. The DSI ground-water irrigated area, which was 120,000 hectares in 1975, is expected to expand at a rate of 20,000 hectares each year, so that by the end of 1982 (the end of the fourth Five-year Development Plan) the total DSI area irrigated from ground water should be about 260,000 hectares.

The Master Plan for development of the Konya-Çumra Basin envisages irrigation of 283,000 hectares with known sources of water, out of which 46,700 hectares will be from ground water. In the same basin an additional 500,000 hectares could be irrigated if there were enough water. The lower Euphrates (Firat) project anticipates irrigation of about 80,000 hectares from ground water. The Master Plan and Preinvestment Reports for the Ergene basin, Thrace, show that the ground-water resources are sufficient for irrigation of 30,000 hectares. Elâziğ-Uluova plain in eastern Turkey, one of a number of plains, can develop enough ground water to sustain irrigation of about 10,000 hectares. The ground-water resources of Ceylanpinar plain near the Syrian border (which discharge through huge karstic springs) are sufficient for irrigation of over 100,000 hectares.

In the coastal Mediterranean plains, where irrigation is practised utilizing surface water, it is not easy to distinguish which percentage comes from surface water and which from ground water. Almost all the water that issues from Kirkgözler springs north of Antalya, about 600 million m^3 annually, is consumed for cotton irrigation. The Köprüçay and the Manavgat rivers in the same region draw one third of their total annual discharge from the karstic springs Olukköprü and Dumanli, respectively. Numerous derivation projects exist for irrigation of lands adjacent to both rivers.

Water supply

The long-term target of the country's development policy is that by 1982 all rural and urban communities should have piped water. At the present time only about 60 per cent of the population have a sufficient water supply. For rural water supply, ground water is given preference over surface water mainly because the latter requires treatment which rural communities cannot afford. To satisfy the domestic consumption of about 50 per cent of the entire population, about 730 million m^3 of ground water should be supplied annually. If half the rural population (about 12 million people) were to obtain their water supply from ground water in the next six years, the result would be an increase in ground-water consumption of about 200 million m^3 per year, based on a per capita consumption of 50 litres per day. For heavily populated cities, such as Istanbul and Izmir, the trend in water supply will be on the combined use of surface and ground water, including artificial recharge of aquifers with surface water.

As one illustration, the table below contains the programme of YSE for the construction of new water-supply units until 1982 when, it is to be hoped, an estimated 90,000 rural settlements will be supplied with piped water for domestic use.

Year	New units
Up to 1975	48,516
1976	4,000
1977	5,000
1978	6,513
1979	7,500
1980	7,500
1981	6,000
1982	5,000
Total existing and new units	90,000

YSE has identified several problem areas that hinder progress and affect the quality of service. Excluding the problem of financial resources in relation to the political pressure to supply water to villages without an adequate source of water, some of the technical problems are as follows:

(a) Water supply systems may be designed with little or no attempt to survey available water resources. If the source is a spring or a well, observations of at least one year are needed to define the quality and quantity of the source. YSE is working under pressure to construct several thousand units each year and cannot give the necessary attention to each source. Better co-operation with DSI would help, but strengthening YSE with additional geological and hydrogeological staff is also needed. Depletion of ground-water resources, unsuspected at the beginning of construction, would result in either an inadequate system or a need for reconstruction.

(b) The number of drilling rigs used by YSE is inadequate and spare parts are lacking. The rigs are old and spare parts are often needed. Only 62 per cent of YSE's 1975 drilling programme to construct 400 water wells was achieved. The expected arrival of 13 drilling rigs will alleviate the situation.

(c) YSE has to cope with an inadequate supply of well screens, in respect of both quantity and design. Screens of improper design result in clogging of wells, decreased well capacity, and final failure of the water supply system after a short time in service. YSE also reports shortages on the local market of large-capacity electrical motors, diesel engines and all kinds of submersible pumps.

Research and development

The Government of Turkey has long recognized that orderly development of ground water requires proper programmes of investigation, quantification and assessment and in this respect DSI has embarked upon a long-term major ground-water investigation and development programme throughout the country, giving priority to those areas in which demand is the greatest. Studies carried out by DSI to date indicate that the prospects for ground-water development are considerable.

However, as the shallower aquifers are tapped and brought into full use, for the rest of ground-water resources (karstic regions, coastal and submarine springs, semi-arid areas), the more specialized and sophisticated investigative techniques are required for proper quantification and assessment. In addition, the work of DSI is hampered by insufficiency of equipment and instrumentation. This situation has improved, however, owing to United Nations assistance to DSI over the past two years. Additional training may be needed in the following areas:

(a) Study and application of artificial recharge of ground water. Only several small-scale schemes have been implemented so far in Turkey, and none through the wells.

(b) Development of karstic spring. Each large spring requires a well-defined programme of investigation, evaluation and assessment. In some cases (those considered to be of primary economic importance), studies have been completed and the springs developed. A striking example of what has been achieved is the several cubic metres per second water supply system of the city of Izmir designed to utilize the ground water of the springs Göksu, Göldeğirmeni and Sarikiz, among others, not directly from the springs, but from deep wells intersecting the primary ground-water reservoir. One part of the system has been successfully completed.

(c) Investigation of water leakage and seepage through dams and from reservoirs in karstic areas. The largest dams, both newly constructed and future ones, are located in karstic areas. The Keban Dam, the largest in Turkey, has severe leakage problems. A treatment programme is under way but additional cases may be expected in the future. The new Oymapinar Dam is located in the midst of the karst. There are huge springs (several cubic metres per second) a few hundred metres downstream of the dam axis.

(d) Development of submarine springs, and brackish coastal springs. An infra-red thermal survey of the Mediterranean coast may help in locating additional submarine springs; at present, however, a programme in respect of capturing the fresh water in the Ovacik area is under way. The results are not yet conclusive, but the problem is definitely very grave.

(e) Management of water resources. Appraisal of development potentials by computer modelling is not practised in Turkey. The combined use of surface and ground water, and management of over-all water resources should be given much more attention if the results are to match the growing economic expectations.

(f) Pollution control of ground water. Criteria and anti-pollution measures and monitoring systems must be developed and potential dangers must be evaluated in rural areas (where modern sanitation does not exist and the supply of water is from underground), industrial areas, urban developments, major mines, karst areas etc.

(g) Inauguration of a modern (computer-based) data processing (storage and retrieval) system. Data on over 20,000 water points are at present stored in the DSI files. In the light of the specific legal status of DSI in the ground-water sector, all users, including other agencies, universities and the private sector, benefit from the wealth of information collected by DSI. However, access to information is no longer easy without a modern automated data-processing system.

Conclusion

Ground water has considerable economic and social value to Turkey for the following main reasons:

(a) In many regions annual precipitation is less than 400-500 mm. It is unequally distributed in space and time. Irrigation water demands cannot be met entirely by surface water. In many semi-arid plains the ground-water source is the major resource for domestic and agricultural use;

(b) In the limestone areas off the Taurus mountain range, surface water is relatively scarce owing to poor development of surface drainage on the limestones. Karstic springs discharging huge volumes of water are the alternatives;

(c) Several rivers whose waters are expected to be harnessed for energy development depend heavily on the karstic springs (Manavgat, Köprüçay);

(d) Ground water is a more economical and a more convenient source, because minimum treatment is required and the supply is closer to the points of utilization. This mostly applies to small rural water supplies currently being provided by YSE to the whole rural population of Turkey.

The importance of ground water is gaining momentum in Turkey. The more accessible sources of both surface and ground water have been developed. The demand for water is constantly growing.

The third largest city in Turkey, Izmir, depends completely on ground water for its water supply. At present, a group of 16 wells (Halkapinar) producing about 1,000 l/sec are the only source of the municipal water supply. Additional development of springs will contribute up to 3,000 l/sec. The importance of that contribution is clearly evident from the fact that projected needs of Izmir call for a 5-6 m^3/sec supply by 1985, and a 9.5-11 m^3/sec supply by the year 2000.

The municipality of Antalya plans to increase its present water supply by about 2 m^3/sec; that amount is expected to be obtained from Duraliler springs and from caisson wells (horizontal collectors). The present source of supply is ground water.

At least 1.5 million hectares of fertile land could be irrigated with ground water. The Government is aware of this possibility. For the purpose of promoting the utilization of ground water, DSI, the government agency, runs a continuing programme of detailed hydrogeological investigations. One of the problems Turkey is facing in relation to the development of its ground-water resources is a shortage of trained personnel at the intermediate or technical level. The number of geologists and engineers who have specialized in hydrogeology is still relatively small. Both the headquarters of DSI and the field offices are understaffed in respect of personnel trained in hydrogeology. Yet the results that Turkish hydrogeologists have achieved so far are encouraging and, in some cases, outstanding.

Selected references

Brinkman, R. Geology of Turkey. Stuttgart, Federal Republic of Germany, Elsevier Scientific Publishing Comapny, 1976.

Campbell, A. S., ed. Geology and History of Turkey. Tripoli, The Petroleum Exploration Society of Libya, 1971.

DSI. More than 150 individual hydrogeological survey reports with detailed small-area maps, inventories, chemical analyses etc. Ankara, 1963-1977.

________. Statistical Bulletins, with maps. Ankara, 1968, 1973 and 1975.

________. More than 50 published Hydrogeological Investigation Reports, with hydrogeological maps on a scale of 1:100,000 or 1:50,000. Ankara, 1969-1977.

________. Geotechnical Services and Ground Water Division activities. Ankara, 1973.

________. Altinkaya Dam Project. Prefeasibility report. Ankara, 1975.

________. Hydrogeological Map of Turkey on a scale of 1:500,000. Eighteen published sheets.

EIE, Electrical Survey Department. Publications on the geology and hydrogeology of potential dam sites. Ankara.

Eroskay, O. Geological investigation of the Beskonak Reservoir area. EIE, Ankara, 1968.

Ilhan, E. Geology of Turkey. Ankara, Middle East Technical University, 1976. Turkish.

Istanbul Technical University and the Mineral Research and Exploration Institute (Maden Tetkik ve Arama (MTA)), Ankara. Periodic publications on the geology and hydrogeology of selected areas.

Italconsult. Ergene Basin (Thrace) Ground Water Development Project. Complete hydrogeological coverage of almost the whole of Thrace.

Keban Dam Project, Euphrates River. Numerous publications by EIE, DSI and foreign consulting companies, 1964-1974.

Linsley, R. and K. Anderson. Sections on ground water in the Master Plan of Development of Konya-Cumra Closed Basin. 1967.

Oymapinar Dam Project, Manavgat River. Numerous publications by EIE, DSI, Coyne et Belier (France) and Energoprojekt (Yugoslavia), among others 1965-1977.

United Nations Development Programme/United Nations. Report of Mission on Energy, Minerals and Water Resources. Ankara, 1976.

_________. Strengthening ground-water capability of DSI, phase II (TUR 77-015). Project document. Ankara, 1976.

_________. Strengthening ground-water capability of DSI, phase II (TUR 77-015). Technical reports. Ankara, 1976 and 1977.

Water resources of the Lower Dalaman River, The. Overseas Technical Co-operation Agency. Japan, 1966.

UNITED ARAB EMIRATES

Area: 100,000 km^2

Population: 653,000 (1975 census)

General

Five of the seven emirates lie on the southern coast of the Gulf, from Qatar in the west, to Munsandam Island in the east. One emirate lies on the coast of the Gulf of Oman and one opens on both gulfs (see map 26).

Most of the country is included in the hot arid desert climate zone. Rainfall is extremely irregular and in most cases less than 100 mm a year in the plains, which constitute most of the country. It is more abundant on the mountain ranges which extend north-south from Jebel Harim (2,043 m) to Jebel Hafit (1,189 m). Shade temperatures exceed 45°C.

The country can be divided into six physiographical areas:

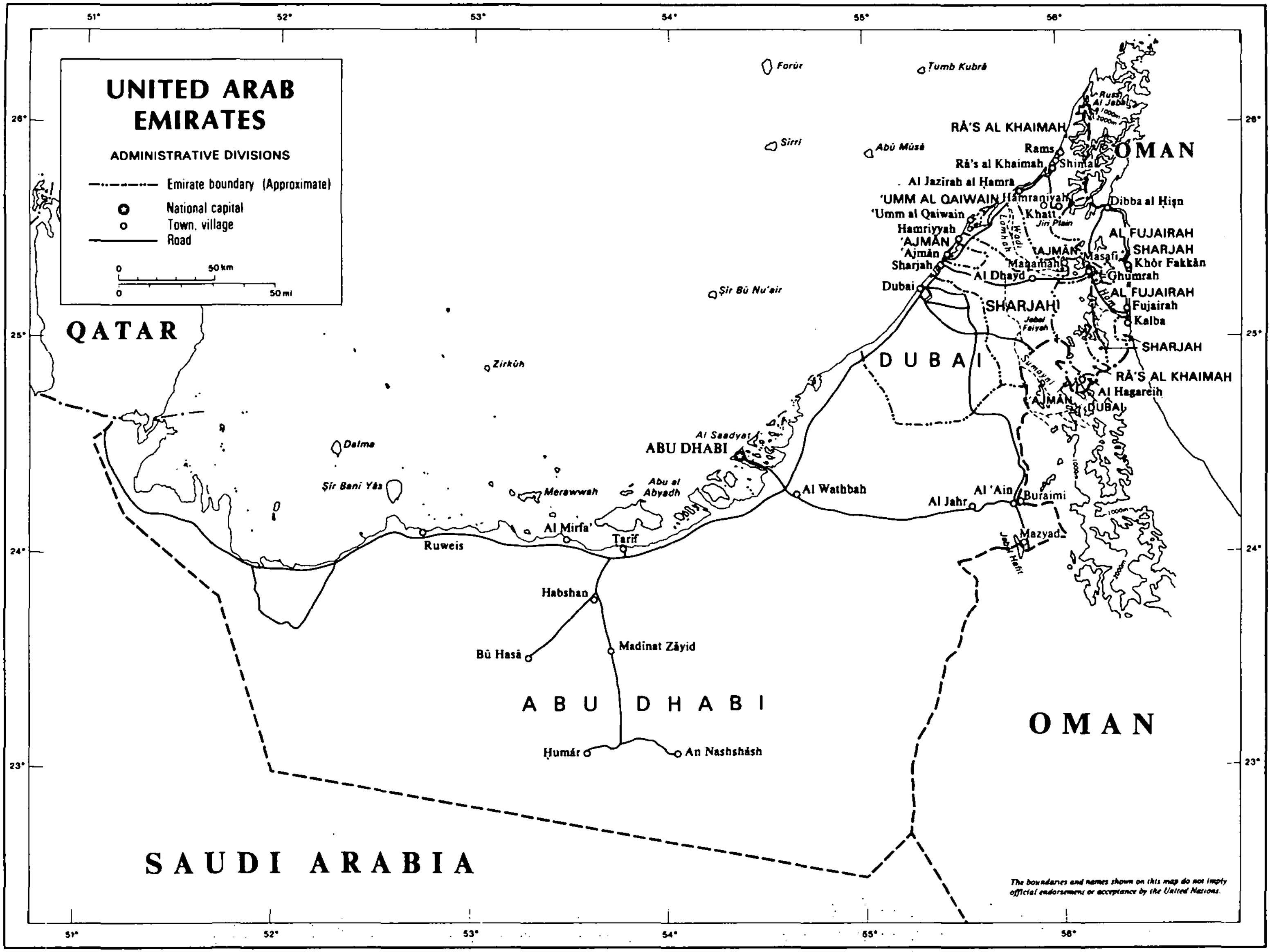
(a) Russ Al Jabal. This is the mountain area at the north end. The mountains comprise limestone, dolomite and marl of Permian to Upper Cretaceous age totalling over 3,000 m in thickness. Aerial photographs show few signs of karst development, but the limestone may contain relic karst inherited from previous erosion periods, which may add to its aquifer potential. High permeability of the limestones is indicated by the relatively small number of drainage channels.

(b) Central mountains. This is the main range of mountains south of Russ Al Jabal. The topography of the central mountains is less pronounced than that of Russ Al Jabal, having gentler slopes and fewer scarps. In spite of varied lithologies the area tends to weather homogeneously and the many drainage channels suggest low permeability. The rocks are schists and other metamorphic rocks, cherts and serpentinites with gabbro and other intrusions. They are predominantly of the Hawasina and Semial formations of Upper Cretaceous.

(c) Gravel plain deserts. The deserts extend from Ras Al Khaimah in the north to Buriami in the south. The topography is flat and featureless. The run-off from the mountain catchment is disgorged from the mountain wadis on to the gravel plain and the sediment deposited at the foot of the mountains gives rise to a coalescing series of gravel fans, one of the most distinctive being that of wadi Al Bih near Ras Al Khaimah. Deposits are of Quaternary age. The plain forms the main reservoirs of ground water.

(d) Sandy desert. This area forms a triangle bordered by coastal sabkhahs to the north-west, by the desert of Saudi Arabia to the south and by the gravel plain to the east. Generally consisting of dunes separated by deflated plains, the area is crossed by wadi Lamhah and wadi Yudayyah.

MAP 26



MAP NO. 3064 REV. 1 UNITED NATIONS
AUGUST 1981

(e) West coastal strip. This is the area of tidal flats and sabkhahs bordering the Gulf. The large sabkhah flats are a feature of the eastern coastline. They comprise sandy silt-sized carbonate sediments with anhydrite and halite, probably formed in tidal lagoons.

(f) East coast. Along the northern part of this coast a series of alluvial flats fill in the embayments between projections of rock spurs into the Gulf of Oman. South of Khor-Fakkan, the flats and wadi fans coalesce to form an almost continuous littoral strip between the mountains and the sea. As on the gravel plain, to the west of the main mountain range, the fans near the mountains comprise rock and coarse gravel which become progressively smaller in size as the distance from the mountains increases. Although some wadis bring coarse gravel and sometimes boulders almost to the sea, the wider flats are of sandy alluvium and are extensively cultivated. Stretches of sabkhah occur along the coast. The gravels and sands contain relatively fresh ground water which drains from the wadi fans towards the sea. Major wadis (dry river beds) ares Ham, draining eastwards to the Gulf of Oman; Al Bih and Lamhah, draining westwards to the Gulf; and Sumayni, which drains westwards on to the gravel plains. The floods in these wadis are very sporadic, flash floods being typical of very arid zones. They generally do not last longer than a few hours. During this period, however, very heavy damage and occasional loss of life may be experienced. These floods are sometimes strong enough to overturn loaded lorries. The flow in the wadis is as variable and unreliable as the rainfall. It is recorded at eight automatic gauging stations. Some flow values are given in table 25.

Geology of aquifers

The desert foreland and gravel plain consist mainly of quartz sand, some silt, and occasional thin gravel lenses. The sands are underlain by conglomerate and gravel, in places entrenched in long hollows in the underlying bedrock. Thickness of the conglomerate and gravel does not appear to greatly influence the yields of wells, although tongues of water with low salinity do seem to be associated with their presence. Deposits of gravel have been penetrated within the Quaternary sands in nearly all bore-holes drilled in the gravel plain and in the desert at depths up to 60 m below ground surface and at distances of up to 70 km from the mountain range.

Along the coast, sabkhah and other carbonate sediments consist of gypsum, anhydrite, halite and other evaporites. The results of two tests indicate a low permeability in spite of the sandy silty texture. Ground water is very saline, containing up to seven times the salt content of sea water.

Formations of Miocene to Oligocene age occur below the Quaternary up to about 30 km from the coast. They consist of thick marl, limestone, dolomite and evaporite including gypsum. Ground water occurs under artesian conditions in these formations but is very saline in all the bore-holes drilled so far.

Up to 250 m of marl and limestone occur in Jebel Hafit and the mountains to the east. These yield large quantities of water in the Faqqabuya area to the west of Hafit.

Table 25. United Arab Emirates: peak discharges of wadis

Stream flow gauging site	Date of observed flow	Peak flow (m^3/sec)	Probable duration (hours)	Probable volume (m^3)
Wadi Qor near Jebel Faiyah	9.12.68	0.2	2	Very small
	7. 1.69	25.2	8	363 000
	10. 1.69	42.5	20	1 530 000
Wadi Ham near Bithna	7. 1.69	29.4	2	106 000
Wadi Siji near Siji	6.12.68	50.5	4	364 000
	9.12.68	10.5	5	95 000
	9.12.68	5.6	5	51 000
	7. 1.69	62.0	3	335 000
	9. 1.69	13.0	3	71 000
Wadi Lamhah near Falaj al Mu'alla	9.12.68	0.7	2	Very small
	10. 1.69	87.4	20	3 140 000
Wadi Lamhah near T. Qaran	10. 1.69	54.7	12	1 180 000
Wadi Al Bih near Burayrat	9.12.68	47.3	12	1 020 000
	3. 1.69	Small	Localized	Flow in wadi
	7. 1.69	190.5	54	17 440 000
	10. 1.69	Small	Localized	Flow in wadi
	11. 1.69	Small	Localized	Flow in wadi
Wadi Sumayni below T. Dahuth	1. 1.69	25.2	8	363 000
	10. 1.69	76.5	20	2 760 000
Wadi Al Bih near Al Fulayyah	9.12.68	34.1	6	570 000
	7. 1.69	58.4	15	1 580 000

In the Maestrichtian formation, limestone, marl, conglomerate and boulder beds with chert, dolomite and serpentinite are transgressive eastwards and crop out at Jebel Faiyah and up the west flank of the main range. The limestone has weathered in places to form fairly thick localized beds of clay which probably act as aquicludes. The limestone also contains water of variable salinity.

The Seminal formation comprising serpentine, serpentized ultra basic rock and gabbro, forms most of the mountain zone. Along the western flank of the mountain it is generally overlain by the Maestrichtian Formations.

The Hawasina formation consists of low-grade rocks, radio-larian chert with some limestone, marl, shale and conglomerate. There are serpentine sills and some volcanic rocks. There are two main outcrops in the area; the first occurs just south of the Dibba line and the second along the west flank of the mountains south of Jebel Sumayni. The ground-water potential of this formation is unknown but is unlikely to extend beyond weathered zones. A marine facies, consisting of marl and thin limestone, has been found underlying Quaternary formations in bore-holes west of an imaginary north-south line linking Faiyah and Sumayni. It is usually an aquiclude.

The Musandam limestones (Jurassic to lower Cretaceous) are mainly grey and compact, but can be marly, dolomitic and chalky in places. They form part of the Russ Al Jabal peninsula and crop out along its western flank between wadi Al Bih and wadi Batha Mahani. There are also outcrops near Jebel Sumayni.

Permian to Triassic formations include mainly limestone and dolomites that are increasingly arenaceous towards the top of the succession.

Hydrogeology

Falajs and springs

Of the 37 falajs in the United Arab Emirates only 19 are in operation. The major springs are Khatt springs, Habhab, Ayn Massafi and Ayn Bu Sukhanah.

It is difficult to make a clear distinction between springs, wadi seepages and falajs. There are several sites which in fact may be considered as part of the wadi base flow, but have become a falaj in local terminology by virtue of excavation at the source and diversion of the flow. The most interesting of these springs is Khatt spring, which has a high temperature of about 39° C, compared with a range of 27°-32° C for all other ground-water in the Emirates.

Yields have varied considerably during the period of observation. The trends have not been uniform over the country, the yield having improved at some sources and deteriorated at others (see tables 26 and 27).

Table 26. United Arab Emirates: falajs or springs in the central mountain area

Reference number, name and location	Date of observation	Electrical conductivity (micro mho/cm)	Flow (l/sec)
ZONE 1. CENTRAL MOUNTAINS			
105 Wadi Siji	22.11.68	600	47.2
	4. 3.69	590	44.4
108 Ayn Massafi	24.11.68	395	11.3
	26. 3.69	400	7.1
111 Bithna (irrigation channel upstream of dam on right bank)	26.11.68	715	8.0
	23. 5.69	600	5.4
112 Bithna (irrigation channel on left bank of dam)	24. 5.69	64	39.4
114 Falaj Howeilat	30.12.68	1 260	16.6
	15. 3.69	1 300	6.1
118 Falaj Masfut (irrigation channel on right bank)	28.12.68	615	16.1
	15. 3.69	700	3.3
121 Falaj Warrah, Masfut	27.12.68	500	36.3
	13. 3.69	525	31.12

Table 27. United Arab Emirates: falajs or springs in the Katina coastal area, the central gravel plain and the Ras Al Khaima-Jiri plain

Reference number, name and location		Date of observation	Electrical conductivity (micro mho/cm)	Flow (l/sec)
ZONE 3.	KATINA COAST			
341	Falaj Awaina Saqamqam	28.11.68	1 050	1.5
		23. 5.69	1 020	0.8
ZONE 4.	CENTRAL GRAVEL PLAIN			
402	Falaj al Mu'Alla	23.11.68	1 405	11.3
		22. 3.69	1 280	13.1
404	Falaj Shaik	25.12.68	1 180	17.2
		4. 5.69	1 220	15.8
408	Falaj Manama	1.11.69	630	71.1
		5. 5.69	600	2.8
ZONE 6.	RAS AL KHAIMA-JIRI PLAIN			
616	Khatt Spring, north	12.11.68	2 270	13.1
		5. 3.69	2 200	7.5
617	Khatt Spring, south	12.11.68	2 220	16.9
		5. 3.69	2 150	9.7
618	Falaj Al Usayli	13.11.68	2 300	9.9
		15. 3.69	2 190	4.5

Configuration of the water table

Ground-water table contours in general are parallel to the mountain front, north-south; proceeding downstream the bend veers in a west-east to south-west direction near and parallel to the coastline of the Gulf. The water table is generally unconfined and its configuration closely reflects the surface topography.

In Jiri plain, it appears that the ground-water contours are parallel to the coast rather than to the mountain front and are dominated by the proximity of the sea and topography of the ground, which falls steeply towards the north, rather than by the apparently limited recharge from the limestone range.

In the Al Ain area the water-table gradient appears to be 1 in 38 in some places where exploratory bore-holes have been drilled.

In the gravel plain the water table configuration suggests that below ground level there are some obstructions in a few places near Jebel Faiyah.

About 25 km from the coast of the Gulf the backwater effect of the sea in the sabkhah becomes noticeable. The gradient of the water table flattens rapidly and the topography ceases to exert a substantial influence on the slope of the water table.

Near the sea shore, especially in sabkhah areas, the water table slope tends towards the horizontal but a slight draw-down has been noticed in the vicinity of lagoons and creeks, which reflects the drainage of ground water to the sea.

Along the sabkhah flats the water table is near the surface which means that evaporation through capillary action increases the deterioration in water quality. The total dissolved solids content is as much as 220,000 ppm.

In some cultivated areas the water table is declining because of overpumping.

Quality of ground water

As the ground water moves from the mountains to the sea, the quality of water changes.

In some bore-holes at Massafi and Manama two aquifers were penetrated. Water in the lower serpentinite aquifer, underlying the weathered formation and gravels above, has a relatively high proportion of sodium chloride the source of which is unknown. Ground water within the serpentinite gravels acquires an increasing sodium and chloride content as it passes towards the coast. This may be derived from marl aquiclude and probably to a greater extent from the flushing of salt, the relic of previous marine intrusions. Some sulphate, probably derived from gypsum crystals within the Quaternary gravel is also present. A relatively high proportion of calcium occurred where there is limestone, as on the Jiri Plain. The magnesium and bicarbonate water is metasomatised, that is, some salt radicals are replaced by others during its passage towards the coast through a magnesium-sodium and sulphate-chloride water and finally, near the coast, to a sodium and chloride water.

The Jebel Faiyah and Jebel Hafit ranges act as barriers to the flow of ground water and create local occurrences of less saline water.

Along the western coast, the quality of ground water is usually poor due to the very high salinity, and the occasionally excessive fluoride content, as at Sharjah, and the frequently excessive boron in some wells in Dubai.

In the gravel plain, the ground water is for the most part satisfactory for drinking and agriculture. Between the plain and the sea the quality is variable. It has been observed that after recharge of ground water by wadi flow infiltration, the rise in ground-water level was accompanied by a reduction in the total dissolved solids content.

It has been observed also that in some cultivated areas the salinity of water has increased without any decline in ground-water level. This is explained by the fact that recirculation of irrigation water leaches the salts and takes them back to the ground water.

Water balance

Water balance was established on the following basis:

(a) The total transpiration losses for natural vegetation was assumed to be equivalent to open water evaporation over full green which is 70 per cent of class "A" pan evaporation;

(b) The recirculation of pumped water back into storage was estimated on the basis of field trials;

(c) Forty per cent of the abstracted water was considered lost through direct evaporation;

(d) Runoff was estimated from the rainfall data available from 20 rainfall stations.

The storage capacity of the gravel plain and desert upstream of the salinity hazard boundary is 5,280 million m^3. It was estimated that the total ground-water outflow of this plain is 157 million m^3/year. If by any means that amount of outflow is reduced sea-water intrusion will occur. However, the storage capacity is ample and should no be affected either by short-term deficiencies in rainfall or by pumping of water.

The east coast is a narrow strip of land between the sea and the mountains. Natural impervious barriers are very few along that coast, which means that sea intrusion will take place if there is any overpumping, Saqamqam has already faced sea intrusion in the cultivated area near the foot of the mountains. Therefore, many of the wells on the east coast are under tidal effect. Most of the water supply for cultivation and urban use on the east coast is from open wells except for Kalba, Fujairah and Khorfakkan. The only area safe as a source of continuous good quality water is upstream of the wadi Ham fan and upstream of wadi Shimal near Dibba.

Ground-water development

In ancient times, water was provided by open wells and *falajs*. Open wells were dug by hand and in the mountain areas the water was extracted by the *shadouf* (a stick tied to a rope attached to a bucket). The *yazri* (an animal-powered rope-and-pulley system) was another method of extracting water for irrigation and drinking purposes. Traditional drains, *falajs*, include open channels cut into the sides of hills, covered aqueducts and tunnels. They are the equivalent of the Iranian *kanats*. Such *falajs* are found throughout the United Arab Emirates; in the Burami they yield a continuous supply of over 340 l/sec of good quality water. In most of the *falajs* there is no evidence of any form of lining or strutting except downstream where water is close to the land surface. The length of the *falajs* in the United Arab Emirates ranges from about 1 to 6 km. It is claimed that the practice of excavating *falajs* was developed in pre-Achaemenian (640 B.C.) Persia and suggested that it was introduced to Arabia in Achaemenian (640-320 B.C.) times.

In the course of the past 20 years or so, water drilling programmes have been carried out at an accelerating pace and the use of mechanical means for the extraction of ground water has been widespread. This progress was rendered necessary to cope with the increasing demand for water as a result of expansion in the agricultural, industrial and domestic sectors. The consumption of urban water increased from 33 million m^3 in 1973 to 140 million m^3 in 1975/76. The *per capita* demand is nearing 700 l/day in the most developed of the Emirates.

Water resources in the United Arab Emirates are handled by five organizations: the Ministry of Agriculture and Fisheries; the Ministry of Electricity and Water; the Dubai Water Supply Department; the Abu Dhabi Water Supply Department and the Sharjah Water Supply Department. The Ministry of Agriculture and Fisheries has suggested a framework for the creation of a central authority to control the water resources of the country.

The activites of the Ministry of Agriculture and Fisheries are limited to rural areas; it is responsible for domestic water supplies to villages and for irrigation. The Ministry owns seven rigs, which are assigned to drilling for water for the farmers free of charge. Loans are available to farmers for pumps and engines. The farmer pays half the cost of the engine and pump. As a result of encouragement by the Government the cultivated areas are expanding very rapidly.

Furrow and basin irrigation systems are dominant. Irrigation channels are not lined and infiltration losses are high. The soil is especially highly permeable in many of the irrigated areas. A series of tests was carried out at the trial station at Digdaga in June 1966 and at Kalba in August 1966, to determine seepage losses in unlined canals. The highest rate of loss, 28.3 cm/h, was recorded in a new channel in sandy soil near Meleiha. In the older channel at Kalba and Digdaga, silting and gleving of the soil had reduced the permeability of the channel bed. The losses were considerably lower at Kalba, where a mean infiltration rate of 4.7 cm/h was observed and at Digdaga, after initial absorption, the rate of percolation declined to 6.2 cm/h and may have been expected to reach a steady state at about 4.4 cm/h. The conveyance losses were determined to amount to two thirds of the net consumptive use. These systems of irrigation are causing an increase in the salinity of ground water due to the cycle of irrigation. The Government has no control over ground-water extraction.

In recent years new systems of irrigation have been introduced into the area by using drip irrigation in the forests which are being grown along the Abu Dhabi-Al Ain road. Drip irrigation is being tested on an experimental basis at Meziad, at the Government Trial Station Al Saadyat, at Abu Dhabi and at Hamraniyah in Ras Al Khaimah.

The Ministry of Electricity and Water is in charge of the urban water supply obtained from wells drilled by both government and private rigs.

A UNDP mission which visited the United Arab Emirates in 1972 suggested that ground water shoud be left for irrigation, since the quantity is limited, and that urban water should be supplied through desalination plants.

The total dissolved solids content of the water for urban use varies from one Emirate to another:

Emirate	Total dissolved solids (ppm)
Abu Dhabi	200
Dubai	1 260
Sharjah	1 340
Ajman	1 400
Umm Al Qaiwain	800
Ras Al Khaimah	2 100
Fujairah	840

The sources of water for urban use for the Emirates are the following well fields, some of which are being overpumped:

Emirate	Source of water for urban use
Abu Dhabi	Desalinated water mixed with ground water from Al Ain
Dubai	Awir and Wahoosh well field
Sharjah	Bidaat well field
Ajman	Tawi Rashid well field
Umm Al Qaiwain	Zarka well field
Ras Al Khaimah	Burirat well field
Fujairah	Fujairah well field

Trends in water policy

Aquifers are recharged by the run-off from the moutains on rainy days. Since floods are of short duration and high intensity, the infiltration rate cannot compensate for the decline in water levels in some areas. In the wadi Al Bih area, there is only a short strip of land where water may infiltrate before it reaches mineralized ground water near the shore-line; the quality of flood water will consequently deteriorate. The Government has planned to control the water from floods and recharge it to the ground water so as to raise water levels and improve water quality. The Government of the United Arab Emirates has obtained the co-operation of the Bureau of Land Reclamation of the United States of America in a feasibilitly study for the erection of recharge dams or reservoir dams

The Ministry of Agriculture and Fisheries plans to control and minimize the consumption of water and the pumping rate, which will result in saving more water for areas under irrigation. Drip irrigation and sprinklers together with lined channels or pipes will be used for central irrigation. The master plan will make the best use of national water resources. The country is in need of a central water authority to control its water resources.

Selected references

Food and Agriculture Organization of the United Nations. Technical Advisory Mission. Agricultural Development in the United Arab Emirates.

Sir Alexander Gibb and Partners. Survey of Water Resources at Al Ain.

Hunting Technical Service, Ltd., in association with Sir Alexander Gibb and Partners. Falaj Dhaid Feasibility Study. November, 1975.

Khalil, Ataya. The ground water and agriculture expansion in the United Arab Emirates. 1974.

Ministry of Agriculture and Fisheries. Yearbook, 1973.

Morton, D. M. The geology of Oman. 1959.

Trucial States Council, Water Resources Survey. Hydrological Yearbook, 1968/69. Water Division, Public Works Department. Dubai, 1970.

Area: 200,000 km^2, approximately

Population: 4,700,000 (1975 census)

General

The country can be divided into five physiographical units.

The Tihama coastal plain, 30-60 km wide, with an average width of 45 km, extends over an area about 440 km along the Red Sea and rises to a maximum altitude of 400 m. The total surface is about 1,800,000 hectares.

The plain is flat to slightly undulating and sparesely intersected by mainly east-west running, wide and shallow wadis which, during the rains, can carry enormous floods from the western mountain slopes to the Red Sea. So in some places the range in particle size varies from clay and silt to gravel and boulders, which has a direct influence upon the vegetation, hydrology and agricultural potential.

The foothills and middle height western mountain slopes of the central mountain range cover the area between the altitudes of 400 and about 2,000 m. This is the most rugged part of Yemen where wadis have cut very deep gorges with sometimes almost vertical slopes. It is also the only region where rainfall is abundant and good crops can be grown all year long.

The central highlands comprise the upper parts of the central mountain range with altitudes varying between 2,000 and 3,000 m and peaks often exceeding 3,500 m. Yemen's highest mountain, Nabi Shu'ayb, rises to a height of 3,760 m. This area is much less indented than the western slopes; the eastern slopes of the central highlands are gentle and terminate in the high tablelands. Rainfall in the highlands is less abundant than on the western slopes.

The high tablelands (montane plains) are interspersed with volcanic inselbergs and lava flows (Warternary). These highland plains are concentrated around the cities of Sana'a, Mabar, Dhamar and Yarim; they vary in width, much as does the altitude (2,200-2,700 m).

The depth of alluvium exceeds 5 m; so the only limit to agricultural expansion is the rainfall, which is sufficient only in the most southern part of the plains.

In the rest of the area rather poor and highly labour-intensive crops are grown. For most of the year the area has an almost desolate appearance. Only in those parts where irrigation from hand-dug wells or drilled holes can be applies does this situation change positively. The area has the best potential water resources, apart from the western mountain slopes where extension is impossible owing to the lack of alluvium.

The eastern mountain slopes rise gently towards the eastern desert (the two areas comprising the largest part of Yemen) and end at an altitude of 1,000 m in the Empty Quarter (Rub al Khali), one of the most desolate parts of the world. The rainfall, though minimal, renders agricultural activities possible, but only in a couple of very broad wadis draining the high tablelands.

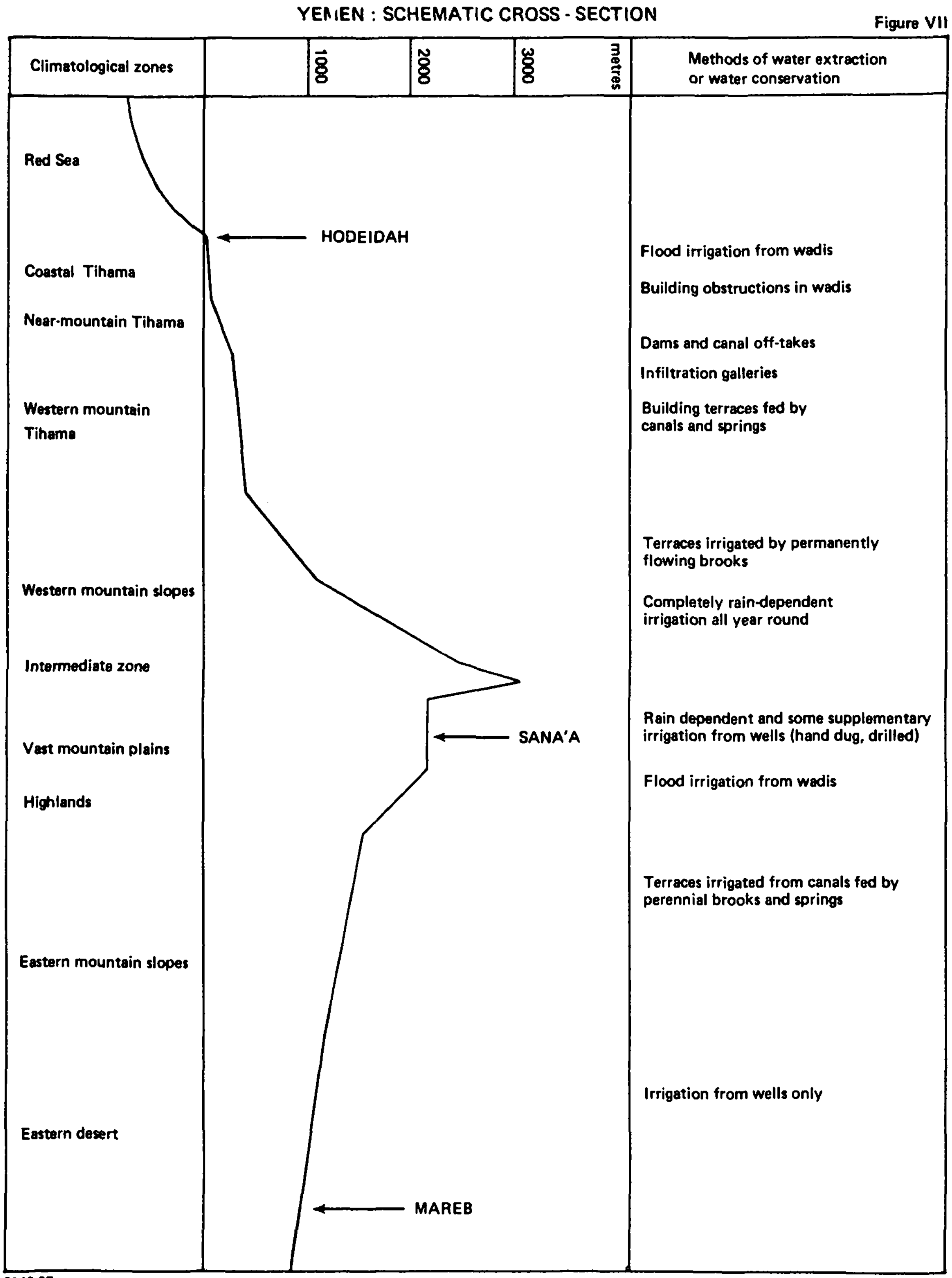
The main features of the climate are described in table 28.

Table 28. Yemen: main climatic features

Climatological zones	Altitude (m)	Climatological Character	Maximum average temperature (°C)	Precipitation (mm/year)
Red Sea	0	Tropical	30.5	80
Coastal Tihama: low rainfall; damp	0-50	Tropical	28.5	80
Near-mountain Tihama: low rainfall; dry	50-250	Tropical	27.0	120
Western mountain Tihama	250-400	Tropical	25.0	300
Western mountain slopes	400-1800	Subtropical	22.0	400-1,000
Intermediate zone	1,800-3,700	Moderate	16.0	1,000 (average)
Highlands	1,800-2,500	Moderate	16.5	300-400
Vast mountain plains	2,200-2,400	Moderate	16.5	300-400
Eastern mountain slopes	1,200-1,500	Subtropical	22.0	100-250
Eastern desert	800-1,200	Desert subtropical	24.0	80-100

A simplified cross-section is given below in order to (a) indicate the resemblance of the climatological zones and the physiographical units; (b) present the natural existing possibilities for the population to irrigate their crops; and (c) make it clear that with extended drilling techniques in all areas of the country, efforts are being made to increase the amount of available water, primarily for a continuous supply of drinking water and, when possible, for irrigation (see figure VII). New methods are also being investigated to improve the existing surface-water supply systems.

Figure VII. Yemen: schematic cross-section



Surface water

Surface water is available from a limited number of springs and from short-life floods which occur in the wadis (dry river beds). The most important perennial springs are the hot and warm water springs occurring at several places throughout the country, but in some cases the salt content only permits a limited use.

The Kharid springs have an average discharge of 200 l/sec and the temperature is 34° C; the quality is excellent.

The Damth hot springs have a temperature of 50°-60° C and the almost over-saturation with carbonates makes them unsuitable either for drinking or for irrigation.

The wadi Dahr, some kilometres north of Sana'a, seems to have a minimum discharge of 60 l/sec at the end of the dry season.

Some main wadis in Yemen have a continuous discharge. Most of them originate on the western mountain slopes; their water infiltrates very quickly into the alluvium of the Tihama coastal plain, recharging the alluvial aquifer.

The hydrological stream pattern in Yemen is determined by the watershed line in the intermediate part of the central mountain range. The most important wadis draining the western slopes to the Red Sea and those draining the high tablelands and the eastern mountain slopes into the eastern desert are listed below:

(a) Draining to the west: wadi Hairan, wadi Mawr, wadi Surdud, wadi Siham, wadi Rima, wadi Zabid, wadi Haydan-Hamili and wadi Al Ghail;

(b) Draining to the east: wadi al Ard, wadi Marwan, wadi Atfayn, wadi Hishwash, wadi Khablu, wadi al Qadim-Jauf, wadi Rugwan, wadi Denne and wadi Harib;

(c) The wadis in the south discharging into the Gulf of Aden are wadi Choban, wadi Bana, wadi Tiban and wadi As Shar.

The nature of the discharge mechanism of those wadis with very high peak floods and almost non-existent base flows makes it difficult, if not impossible, to utilize even a small percentage for irrigation and drinking water supply. For centuries the people have built terraces, small dams and other streamflow-delaying constructions in order to increase infiltration. Without high capital investment other possibilities are not availabe.

The expression that in Yemen perennial surface water is practically non-existent is heard mainly in conexion with the hydrological system, because most of the villages are for a great part of the year totally dependent on their surface-water supply systems. These include mostly cisterns with a certain catchment area in or near the villages and for a certain time the villagers can depend on a supply of drinking water, usually of very bad quality. The amount of time during which they can use this source of drinking water depends on the amount of rainfall, the number and size of their cisterns, the extent of the catchment areas and, of course, on the size of population.

Methods are being studied to improve the quantity of these surface-water supply systems and the quality of the collected water, but only when possiblities of developing ground-water extraction are non-existent.

Stream-flow in the wadis is ephemeral and depends on the concentrated high intensity rainstorms on the western mountain slopes; all these wadis discharge into the Red Sea and the Gulf of Aden in the south. Very few discharge data are available, except for a couple of wadis where irrigation schemes have been studied.

An impression of the annual differences of total discharge (in millions of cubic metres) is given by measurements carried out over six years at different places on wadi Zabid:

Period	Zabid at Kolah	Zabid at Ma'ah
1970	111.7	67.7
1971	125.3	91.3
1972	124.0	94.2
1973	120.1	80.3
1974	145.9	118.8
1975	230.4	184.0

Differences between the two are caused by recharge of the alluvial aquifer in the Tihama through the stream bed and offtakes for irrigation.

Monthly totals were also measured at those stations and at one on wadi Mawr. In 1975, wadi Zabid discharged 75 per cent of the yearly total during the period of July to September, which coincides with the so-called great rainy season. Wadi Mawr had high discharge values around April, which is known as the small rainy season (see the table below).

1975	Zabid at Kolah	Zabid at Ma'ah	Mawr
January	2.4	0.1	3.9
February	2.2	0.4	3.5
March	3.2	1.5	6.3
April	8.5	7.0	46.7
May	5.0	2.9	11.7
June	10.2	7.4	15.0
July	35.3	29.1	17.8
August	83.5	72.1	43.1
September	49.5	41.1	25.6
October	17.0	13.5	9.6
November	7.7	5.5	6.0
December	5.9	3.4	7.0

Catchment areas in Yemen

Until the present time, only qualitative studies have been carried out in approximately 30 main catchment areas in Yemen. As has already been stated, stream-flow occurs in violent floods of short duration in the big wadis.

The wadis flowing through the Tihama to the Red Sea are the best known because of their some time great irrigation potential.

Of the wadis discharging into the eastern desert, the wadi Jauf is the largest and has a catchment area of 9,500 km^2. The ground-water level in the flat region is at about 50 m, which opens up many possibilties for development. The total annual amount pumped into the wadi is estimated at about 15 million m^3 a year. The water quality in the area varies the TDS content ranging from 500 to 2,000 ppm.

For the rest of the wadis in Yemen no quantitative information is available. Silt content has never been measured and no hydrological parameters can be given.

Geology

Pre-Cambrian formations are observed only in isolated places in Yemen, so that differentiation into structural units is not possible. A continental period of long duration converted the area after long erosion into a peneplain. During a Paleozoic transgression deposits were laid down which were almost completely removed during another continental period in the late Paleozoic. In Permian times this peneplain was warped and the old surface was eroded and redeposited as a delta in the west and as dunes in the north (Wajid sandstones). Mesozoic was characterized by a warm climate in which secondary basins formed in most parts of Yemen in which red sandstones were deposited followed by dark green and gray-black shales of fluviolacustrine origin (Kohlan series). In isolated bays or near the coast, short periods of emergence resulted in the formation of gypsum lenses.

During the Malm the most important transgression extended over the entire country, forming shallow-water calcareous deposits (Amran series). In some places this transgression took place directly over the Pre-Cambrian basement. After this transgression a lagoonal stage occurred in the centre of the depression where gypsum and salt were deposited while the margins of the basins remained above sea level and were subjected to erosion. Continental sandy conglomerates of Cretaceous age (Tawilah formation) are laid down and occur where protected by the Yemen volcanics.

During the Paleocene a narrow sea spread over most of the country and neritic facies of the deposits attest to the nearness of the land mass.

Tectonic movement, resulting in faulted domes, affected the central part of the country, where Jurassic and Cretaceous beds were removed by erosion at the beginning of the Tertiary. During this period intense volcanic and intrusive activity became widespread in the country. Calm intervals during the Oligocene and Miocene produced fluviolacustrine deposits intercalated with the Yemen volcanics. Very intensive volcanic activity characterized by normal faulting continued to the end of the Tertiary.

In the Quaternary, volcanic materials were deposited over the whole country. Large areas of basalt flows and craters characterize the main part of Yemen.

As a result of wind activity, major loess deposits extend widely over the plateaux, limited in extent by Recent faults.

Afterwards, structural deformation strongly modified the drainage pattern in the country and more than one example of stream capture has been noted.

Present geomorphology is mainly the result of recent volcanism in the country.

Major geological formations are as follows:

(a) The basement rock, consisting of Pre-Cambrian formations, such as granites, gneisses, slates, schists, quartzites. They are widely distributed in the south-eastern and north-eastern parts of the country, especially east of Radah and around Sadah in the north, and occur intermittently as outcrops in the foot-hills and in the midland belt. The formations demonstrate a general north-south folding.

(b) Wajid sandstone, a formation of mostly well sorted and often cross-bedded quartz sandstone, with conglomerates in places, is of Ordovician age. North of Sadah these sandstones cover the Pre-Cambrian formations.

(c) Kohlan series, a Mesozoic-Jurassic formation with green shale, sandstone and conglomerates in the basal parts and conglomerate and sandstone forming the upper parts. This series is distributed in the foot-hills and midlands. It directly covers the basement and the contact with the overlying Amran series is gradational.

(d) Amran series, consisting of limestone, marl and shale. This series is Jurassic; it is widely distributed on the highlands in the Sadah-Jebel, Musawar-Amran and Mareb region and appears as intermittent outcrops in other parts of the country. It is overlain by a less widespread Upper-Jurassic transition, one of gypsum, marl, clay, sandstone and some limestone.

(e) Tawilah group and Medj-Zir series, consisting of undivided continental-type coarse cross-bedded sandstones with lenses of conglomerate and gravel and interbedded shale in the lower part. They are overlain by sandstones with locally fossiliferous calcareous sandstone and shale, and cover rock of Jurassic age or the basement. They are distributed in the highlands especially in the midland area.

(f) Yemen volcanics, composed of bedded alkalic flows and pyroclastic rock, including basalt, andesite, trachite, riolyte, and vari-coloured tuffs and porphyry. The stratum is very thick and can exceed 1,200 m. It covers an extensive area south of Sana'a.

(g) Recent volcanics, consisting of conical volcanoes, basalt flows and dykes, at places covered with tuff and volcanic bombs. The whole sequence is at least 2,000 m thick.

(h) Recent alluvial, aeolian and other deposits, including silt, clay and muddy sand mostly saturated with brine, along the Red Sea coast.

(i) River terrace deposits and alluvial fans, including gravel, sand and silt.

(j) Loess deposits in the mountain plains.

Ground-water resources

It was not until recently that government services have been involved actively in planning and implementing water supply projects, most projects having been carried out by consultants and foreign contractors.

Within the Ministry of Public Works and Municipalities, the Department of Rural Water Supply is in charge of the planning, design and execution of the water supply system for villages all over Yemen in respect of both surface and ground water.

Within the Ministry of Agriculture, the Irrigation Department is actively involved in several irrigation schemes.

In the large cities, drinking water supply systems are under the responsibility of the National Water and Sewerage Authority as follows:

Sana'a: construction of a water supply system, including wells, pumps, generators, distribution pipes, chlorination, tanks and other engineering services, as well as staff training;

Hodeidah: construction of water supply and sewerage systems;

Taiz: installation of a well-pumping station, clear water reservoirs, main waterline, power plant, storage tanks and a distribution system.

Hydrogeological investigations started as early as 1912 with investigations in the area between Sana'a and Hodeidah. During the 1960s the hydrology of the central part of the Tihama was investigated by specialists from the Federal Republic of Germany. An extensive hydrogeological study of the Sana'a basin and the Hodeidah area was carried out in 1970-1973 by the World Health Organization (WHO).

Several hydrologists from the Federal Republic of Germany and the United Kingdom of Great Britain and Northern Ireland have worked in Yemen in recent years. Drilling itself has been executed by local firms, foreign contractors and donor organizations, based in the Federal Republic of Germany, the United States of America, Iraq, China and Japan, and hundreds of wells have been completed. In particular, wells for irrigation have been drilled in the Tihama by the Tihama Development Authority. Ground-water potential has been investigated for the regions of wadi Zabid, wadi Mawr and wadi Surdud by specialists from Hungary and the United States. Hydrogeological work (mainly inventories) has recently been carried out by a consulting firm in the wadi Jauf area in the north-eastern part of the country.

Co-ordination of all ground-water activities in Yemen is necessary and the Department of Rural Water Supply has recently taken action to gather as much drilling information as possible. Private companies, however, are not yet obliged to make their logs public.

Aquifers

Six major aquifers can be distinguished in Yemen, namely, alluvium, recent volcanics, tertiary volcanics, sandstones, limestones and basement rocks (see map 27). A brief description is given below of the characteristics of these aquifers to indicate possibilities for development of ground-water extraction or storage of surface waters.

Alluvium

Among the extended alluvial aquifers the following may be singled out: the Tihama coastal plain, the montane plains and the eastern desert. The wadi Jawf system is in places 75 km wide and has a length of more than 150 km before ending in the eastern desert regions.

Aquifer characteristics in these alluvial areas are different owing to geological origin, climatological conditions, age and, of course, the topographical conditions of the formations.

The Tihama coastal plain consists of alluvial fans and flood plains composed of gravel, sand and silt. The lithology becomes finer towards the coastline and sometimes interbedded salt deposits are encountered.

Mobile sand dunes can be found locally but these are mostly not higher than a few metres. Along the coast mudflats occur, composed of clay, silt and muddy sand; they are saturated with brine and encrusted with salt.

Permeability in the plain is good and high yields are obtained from hand-dug wells and from drilled bore-holes. Water quality near the mountains and the main wadis is excellent but deteriorates in places near the coast owing to sea-water intrusion or the presence of salt lenses. In some villages along the coast the water has to be pumped from 20 to 30 km inland, to ensure good quality.

The alluvium in the montane plains consists of much finer loess components and alluvial silt mixed with a variable amount of colluvial gravel. At little depth calcareous concretions and caliche layers occur which are evidence of only shallow infiltration and consequent evaporation of the precipitation. Infiltration has been estimated at 3-5 per cent of annual rainfall and recharge of the alluvial aquifer through the alluvium itself at only 1 per cent.

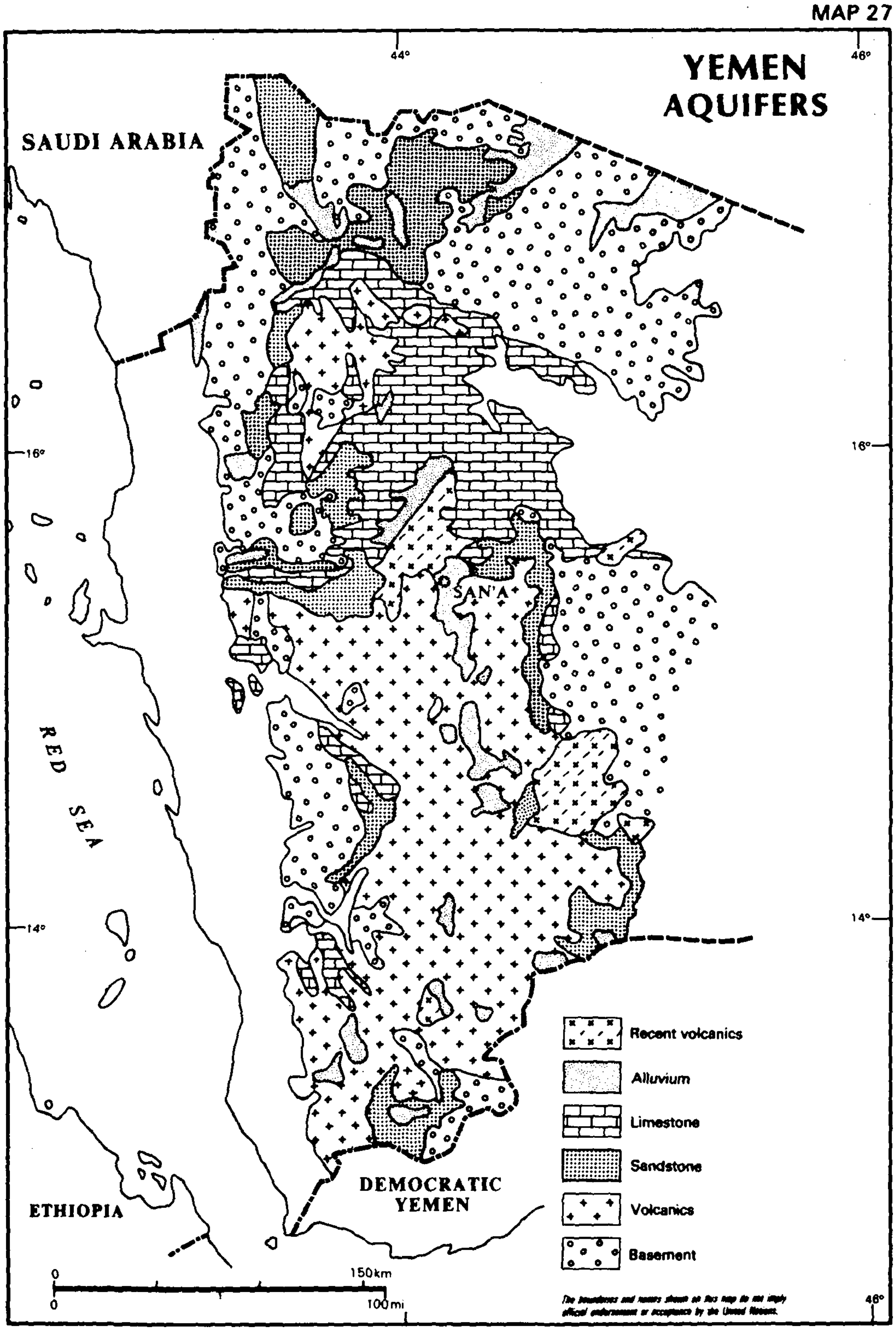
Permeability is much less than in the Tihama and only moderate yields can be pumped from hand-dug wells and bore-holes. Water levels in the different plains vary considerably, from a few metres below the surface near Dhamar to more than 60 m near Sana'a.

The total thickness of the alluvium also varies between a few metres to more than 400 m. In this area where hand-dug wells are utilized in great numbers for irrigation, many bore-holes are being drilled. Because of low recharge figures in most places, mining of the ground water already occurs and ground-water levels go down yearly. All hand-dug wells in Sana'a have to be deepened every month. Some have been deepened to about 60 m.

The alluvium aquifers in the montane plains are responsive to pumping and special care has to be taken to prevent serious mining.

Map 27

Yemen: aquifers



The alluvial gravel, sand and silt in the channels and flood plains of the wadi Jawf system are deposited on large river terraces and have a reasonable permeability. In places the ground-water levels are rather high, at 10-20 m below the surface, but the quality of the water is in many cases bad, which makes it unsuitable for drinking. It is likely that quality improves with depth. In the future, deep bore-holes may provide drinking water to parts of the area.

In the eastern desert, the depth and lithology of the alluvium is unknown except for some limited areas around a few settlements. Mobile aeolian sands commonly occur on the surface.

Since more than half of the total surface of Yemen drains to the east, the drainage pattern concentrating in a couple of areas, recharge in these areas is adequate. Much of the available water evaporates leaving salt in the topsoil, thereby endangering possibilities for future agriculture. Old dams in these areas indicate that water resources were developed more in the past than at present.

<u>Tertiary (or Yemen) volcanics</u>

This aquifer has very heterogeneous characteristics as a result of the complex nature of the deposits. Alkaline lava flows alternated with various pyroclastic rocks, locally interbedded with lenticles of lacustrine and fluviatile sediments and volcanic paleosols make up the bulk of this geological formation. The felsic and tuffaceous conglomerates and the multi-coloured tuffs function almost as aquicludes throughout the formation and only the shallow weathered zones can act as aquifers. Interbedded volcanic ash layers, sediments and paleosols sometimes provide small quantities of good quality water. The basalt flows mostly have a high primary porosity specially at their periphery. Cooling fractures are commonly vertical, so horizontal ground-water movements are restricted. The basalt flows are mostly covered by mesa-like gravel plains and fine silts which lower infiltration capacity and recharge.

Wells with yields of up to 5 l/sec can be drilled in areas where ground-water levels are not too deep, but drilling in these very hard rocks is difficult.

Total thickness of the Yemen volcanics exceeds 2,000 m. They form most of the mountainous area in Yemen. Deep gorge-like valleys lower the drainage base, so that ground-water levels are mostly very deep in the mountains.

Recent volcanics are mainly dark to very dark basalt flows and dykes, which sometimes measure only a few metres in thickness, covered with scattered volcanic cones and craters and thin layers of tuffs and ashes. As an aquifer these recent volcanics do not play a significant role in the ground-water hydrology of Yemen, mainly because of their often modest dimensions, their topography and their mediocre aquifer characteristics.

Little or no karstification has been observed in Amran limestone of Jurassic age which provides a poor aquifer even in topographically suitable places, such as deep-cut wadis where ground-water levels can be reached within reasonable depth. Bore-holes can give medium yields in recent fracture areas.

Drilling in limestone is not especially difficult although loss of circulation has to be taken into account within the more suitable fracture areas.

Sandstone formations

Three different sandstone formations occur in Yemen. Because of variations in topography, volcanic influences and lithological composition, the related aquifer characteristics differ, sometimes considerably.

Wajid sandstone, the oldest of these formations (Ordovician) is well sorted and often cross-bedded. Conglomerates are good potential aquifers. Many small springs may be found near the contact with the underlying basement and metamorphic rocks. Development of these springs may have to be considered as an alternative to drilling. Often highly fractured by even slight tectonic movements, this series will give good bore-hole results depending only on the depth of the ground-water level. Total thickness exceeds 200 m.

Kohlan series (Lower Jurassic) underlie the Amran limestones. They consist mainly of siltstone and shale interbedded with conglomerates and sandstone. Vertical permeability is much lower and aquifer characteristics are marginal. Only in concentrated fracture areas can reasonable yields be expected from bore-holes when the ground-water level is not too deep. Total thickness is about 300 m.

Tawilah sandstone (and Medj-Zir series) is of Tertiary age and the best sandstone aquifer in Yemen. Weathered and in places highly fractured, the aquifer yields between 20 and 30 l/sec from a bore-hole. In the future, the drinking water supply, especially around the capital, Sana'a, will depend on the Tawilah sandstone aquifer. Total thickness is between 200 and 250 m. The Tawilah sandstone overlies the Amran limestones which in some cases form an impervious layer. Springs originate near the contact between the two geological formations.

Basement rocks

In Yemen a multitude of basement rock components occur with fairly comparable hydrological characteristics. Infiltration rates are very low owing to an almost non-existent effective porosity. Intensive surface run-off results in a high degree of erosion with some alluvial accumulation in the valleys. Ground water is to be extracted there by means of dug-wells. The building of small dams (even underground) may store water on the impervious rock in selected steep valleys. In the eastern desert, Pre-Cambrian formations are mostly covered by a considerable alluvial blanket.

Ground-water development

The most exploited aquifer in Yemen is the alluvium, the water being obtained mainly by means of hand-dug wells. In the mountain plains, drilled wells provide water only in and around Sana'a. In the Tihama, wells have been drilled with yields of up to 50 l/sec, mainly for the purpose of irrigation. Most wells drilled in the mountain plains do not yield more than 10-15 l/sec.

In volcanics, yields of 1-2 l/sec may be obtained. Sandstones are productive if drilled down to a depth of 200 m. The limestones in Yemen have so far not shown good yields. The main reason could be the lack of karstification due to climatic circumstances.

Water-well drilling has been carried out mainly by:

(a) The United States Agency for International Development (USAID), which has been the most important contributor to exploration and exploitation drilling. The equipment consists of seven Ingersoll Rand rigs, operated by the Department of Rural Water Supply. However, a lack of functional spare parts is delaying drilling activities.

(b) British, Danish and Japanese firms which operate about 12 rigs, mainly rotaries.

(c) Two private Yemeni firms drilling with percussion rigs.

(d) The Yemeni Army, which operates rigs for irrigation projects, two of which are of the cable-tool type.

(e) The Ministry of Argiculture, with two rigs in operation for irrigation projects.

According to priorities, several development projects have involved drilling operations but no country-wide experience has been gathered about aquifer characteristics, so that wildcat drilling is often the only solution, with, of course, the risk of failure.

Prospection for ground water has so far been limited to a couple of areas which were the subject of specified projects. For example, USAID has carried out an extensive investigation in the Amran-Graben, 45 km north of Sana'a, but only with exploration bore-holes. A British firm has been investigating the area around Mabar with geo-electrical equipment and results seem promising. A Netherlands project on rural water supply in the Radah area has also done geo-electrical surveys in several places and they seem encouraging. Both surveys are concentrated in alluvial deposits. Elsewhere, only surface geology and air photo-interpretation can determine the optimal location for drilling.

Salt-water intrusion seems a big problem in the coastal area but often the reason for the bad quality of the ground water is the presence of salt deposits in the alluvium.

Overdraught of ground water is a major problem all over Yemen especially in well fields supplying major urban areas such as Sana'a, Mabar and Dhamar, where a steady lowering of water levels has been noted over the years, from .052 m (minimum) to 3.75 m per year in Sana'a, with an average of about 1.80 m.

A limited number of major water resources development projects have been carried out by the Government, especially in respect of supply to the main urban areas.

The water supply system for Sana'a needed improvement and a feasibility study in 1972 by UNDP/WHO proved positive. Four producing wells were drilled. The Hodeidah water supply system should be adequate to supply 70 per cent of the population by 1985, at a cost of $31 million. The Taiz water supply system, started in 1962, provides 4,000 m^3/day to 6,400 households.

Water supply projects in other towns, for instance, Dhamar, Radah and Sadah, are being started. These projects can be divided into three categories:

(a) Rural water supply projects directed towards providing villages having the most urgent drinking water needs with an adequate supply from surface-water and/or ground-water bodies. Such projects include the Dhamar project and the Radah project. The Department of Rural Water Supply and some aid programmes also provide villages and institutions with water supply systems.

(b) Urban water supply projects, such as the Sana'a, the Hodeidah and the Taiz drinking water projects, which are under construction or are being improved.

(c) Irrigation projects under study at present are the wadi Surdud, wadi Rima, wadi Mawr, wadi Zabid and wadi Jawf projects, the last one being only in the pre-feasibility phase.

Most of the promising areas are currently under study. After detailed investigations, however, other areas may be singled out as suitable for ground water development.

Tourism could become an important factor in the national economy. Health risks as a result of inadequate water supply conditions are great at present, so that in this field exploitation of ground water with protection against pollution will be one of the first steps to be taken.

A ground-water quality data bank has recently been set up in the Department of Rural Water Supply. Generally speaking ground water quality in Yemen is good, although in some places wells have been abandoned because of an unpleasant odour and/or taste, mostly owing to the presence of hydrogen sulfide.

Furthermore, near rain-fed cisterns and hand-dug wells, environmental conditions are unsatisfactory in most cases, so that all these nonflowing surface waters are more or less polluted. The people have to be informed about hygiene and the water-borne causes of most of their illnesses. Even nowadays they may pump clean ground water into their polluted cisterns. No amelioration of the situation has been achieved by drilling deep bore-holes to obtain safe drinking water. The design of so-called "closed systems" is the only possible solution.

The necessity for drilling as many bore-holes as possible is generally clear but country-wide surveys will have to be carried out and steps will have to be taken regarding costs: small villages can no longer pay for even one medium-depth bore-hole. In 1978, unit prices from $50,000 to $100,000 were being paid for bore-holes.

A national five-year plan which includes rural and urban drinking water supply schemes has been established. In the rural sector, the goal of providing 15 villages with bore-holes and another 40 with the complete design of a surface-water supply system or improvements to an existing one each year should easily be reached.

Surface systems, such as rain-dependent cisterns with a catchment area, do of course provide water but the quality will always be doubtful. Attention should be focused on drilling bore-holes as much as possible. If more drilling programmes are undertaken it is likely that unit prices will be lowered.

Centralization of drilling activities through a national ground-water authority may be helpful in facilitating future planning and control. Water extraction laws will have to be enacted to protect the meagre water resources and hydrological balances will have to be established in order to calculate exploitation possibilities and to study the future development of the country. Since ground water will have a very important role in the future of Yemen, a careful approach will be necessary.

The price of the ground water varies widely from season to season and from place to place. For instance, the price of municipal water in Sana'a ranges mostly from 2 to 4 Rials (1/2 to 1 United States cent) a cubic metre, but buying water from a pulled cart can sometimes cost up to 10 times as much and prices of water during the dry seasons in badly located villages can go up to almost 300 Rials ($7.50) a cubic metre. Most of the villages were built on hilltops for security reasons and, as a result, are not easily supplied with water. Villages with a population of less than 500 need water supply systems costing sometimes up to 500,000 Rials ($20,000).

At present the major sources of water for the daily needs of most Yemeni people are hand-dug wells (2-4 m in diameter and of variable depth, up to 40 m), rain-dependent cisterns and small springs. Because of the improper use of these mostly inadequate water resources, they are highly contaminated. The supply of pure water would considerably reduce most of the water-borne diseases which are the main reasons for the high infant mortality and the average low life span.

Most of the water resources used are subject to great seasonal fluctuation. In many places water resources become completely exhausted at the end of the dry season, which means carrying the water over distances of sometimes 10 km. The women fetch the water and often a complete day is lost in doing so. Supplying a village with a modest but sufficient amount of constant and pure drinking water is therefore essential to the social and economic development of the country. Improvement of surface-water supply systems, in a way, only increases the amount of contaminated water. Drilling wells, despite the expense, is the only solution for guaranteed safe drinking water.

In 1978, many wells were drilled in Yemen with depths up to 250 m, depending on the topographical and geological conditions. For the most part, obtaining ground water of good quality from deep wells presents no difficulty, provided that measures are taken to prevent pollution from surface water. In the coastal areas, however, intrusion of sea water can create difficulties if water-supply operations are not carefully executed.

The Government of Yemen, recognizing the importance of the development of water resources, has assigned high priority to it in the five-year plan, along with transport, communications, education and agriculture. Eleven per cent of the total development budget has been allocated to the water-supply sector. Many plans are being made for water-supply schemes, drinking-water supplies for the larger cities, irrigation projects in the coastal plain and in the highlands. However, no comprehensive country-wide knowledge of water resources is available, which would make possible the proper planning and co-ordination of water development projects.

Selected references

Ballaeu, W. P. Observation and evaluation at Sana'a well field. American Institute of Professional Geologists. 1976.

Benfield, A.C. Notes on the hydrogeology of the Montane Plains, Yemen Arab Republic. Montane Plains and Wadi Rima Project. London, Institute of Geological Sciences, 1975.

Botes, G. Rapport définitif sur les études géo-hydrologiques faites en Yemen. Bucharest, Universala, 1912. Includes two topographical maps.

Brief investigation of the surface-water hydrology of the Yemen Arab Republic. United States Geological Survey, open-file report 77-150. Reston, Virginia, 1977.

Geukens, F. Geology of the Arabian Peninsula, Yemen. United States Geological Survey. Professional Paper 560-B, 1955. Includes 17 figures and one table.

Grolier, M. J. and others. Data from geologic investigations in the Yemen Arab Republic. 1976. Includes nine preliminary maps made from LANDSAT images.

Geophysical surveys to assist hydrogeological investigations in the Yemen Arab Republic. London, Institute of Geological Sciences, 1977.

Initial Development Prospects, vols. I and II. Montane Plains and Wadi Rima Project, Yemen Arab Republic. Ministry of Overseas Development of the United Kingdom of Great Britain and Northern Ireland, Land Resources Division. 1976.

Italconsult. Land and water surveys on the Wadi Jizan: hydrological report II. Prepared for UNDP/FAO. Rome, 1964.

__________. Sana'a basin ground water studies: water supply for Sana'a and Hodeidah. Prepared for UNDP/WHO (YEM 70-507, WHO Yemen 3202). Rome, 1973.

Rathjens, C. Exploration au Yemen. Journal asiatique, vol. 215, No. 1, 1929.

__________. Zum Klima von Mittel-und Sud-Arabien. Annalen der Hydrography und maritimen Meteorology, vol. 63, No. 9, 1935. Includes tables and figures.

__________. Beobachtungen in Yemen. Geologische Rundshau, vol. 33, 1942.

Robbins, N. S. Results of groundwater drilling. Montane Plains and Wadi Rima Project. London, Institute of Geological Sciences, 1976.

Ruiz, Adelmo. Efforts of the United States Agency for International Development to supply water to the people of Yemen. American Water Works Association Journal, vol. 58, No. 10, 1966.

Statistical Yearbook, 1974-1975. Central Planning Organisation, Statistics Department, Yemen Arab Republic.

Statistical Yearbook, 1976. Central Planning Organisation, Statistics Department, Yemen Arab Republic.

Tesco-Viziterv-Vituki. Survey of the agricultural potential of the Wadi Zabid, Yemen Arab Republic. Technical Report No. 10. Budapest, 1972.

Tipton and Kalmbach Inc. Wadi Zabid groundwater potential: Tihama Development Authority, Yemen Arab Republic. 1956.

ANNEX

Ground-water projects in the eastern Mediterranean and western Asia
sponsored by the United Nations Development Programme

Country and project	Symbol	Agency	Duration	Ground-water component: Exclusive or major	Substantial (30-50 per cent of project)	Minor
Cyprus						
Survey of mineral and ground-water resources	CYP 2	United Nations	1963-1969		x	
Surveys, demonstration and planning of water resources utilization	CYP 66-506	Food and Agriculture Organization of the United Nations	1966-1974	x		
Feasibility study for irrigation development in the Morphou-Tyllizia area	CYP 71-513	Food and Agriculture Organization of the United Nations	1971-1974		x	
Paphos irrigation project	CYP 75-016	Food and Agriculture Organization of the United Nations	1976-1980	x		
Democratic Yemen						
Soil and water irrigation and conservation in the Wadi Tuban watershed area	PDY 71-508	Food and Agriculture Organization of the United Nations	1971-1979			x
Development of Northern areas (Hadramaout)	PDY 72-R40	United Nations	1972-1980		x	

Country and project	Symbol	Agency	Duration	Ground-water component: Exclusive or major	Ground-water component: Substantial (30-50 per cent of project)	Ground-water component: Minor
Egypt						
Pilot project for ground-water utilization, New Valley, Western Desert	EGY 71-561	Food and Agriculture Organization of the United Nations	1972-1978			
Master plan for water resources development	EGY 73-024	International Bank for Reconstruction and Development	1977-1982			
Iran						
Geological survey institute	IRA 1 and 28	United Nations	1962-1968			x
Co-ordination of water resources development	IRA 73-015	United Nations	1974-1978			x
Water resources development	IRA 77-029	United Nations	1978-1979		x	
Iraq						
Rural water supply programme Phase I	IRQ 71-527	World Health Organization	1971-1973			x
Rural water supply programme Phase II	IRQ 73-016	World Health Organization	1974-1979			x
Israel						
Experimental ground-water coastal collectors	ISR 3	Food and Agriculture Organization of the United Nations	1960-1965	x		
Underground water storage study	ISR 9	Food and Agriculture Organization of the United Nations	1962-1969	x		

Country and project	Symbol	Agency	Duration	Ground-water component: Exclusive or major	Ground-water component: Substantial (30-50 per cent of project)	Ground-water component: Minor
Jordan						
Ground-water survey of the Azraq area	JOR 4	United Nations	1961-1964	x		
Investigation of the sand-stone aquifers of East Jordan	JOR 9	Food and Agriculture Organization of the United Nations	1965-1970	x		
Investigation and use of ground-water resources of East Jordan	JOR 71-525	Food and Agriculture Organization of the United Nations	1971-1976	x		
Ground-water irrigation of East Jordan	JOR 74-004	Food and Agriculture Organization of the United Nations	1975-1978		x	
Lebanon						
Ground-water survey	LEB 7	United Nations	1962-1969	x		
Adviser in ground-water and connected subjects	LEB 70-014	United Nations	1970-1974	x		
Hydro-agricultural develop-ment of Northern Lebanon	LEB 71-524	Food and Agriculture Organization of the United Nations	1972-1978		x	
Irrigation of Khoura Zgharta	LEB 73-004	Food and Agriculture Organization of the United Nations	1973-1978		x	
Hydro-agricultural develop-ment of Central Bekaa	LEB 74-001	Food and Agriculture Organization of the United Nations	1974-1977		x	

Country and project	Symbol	Agency	Duration	Ground-water component		
				Exclusive or major	Substantial (30-50 per cent of project)	Minor
Oman						
Water Resources Centre	OMA 73-009	Food and Agriculture Organization of the United Nations	1974-1978		x	
Soil and water management	OMA 73-010	Food and Agriculture Organization of the United Nations	1974-1978		x	
Qatar						
Hydro-agricultural resources surveys	QAT 71-501	Food and Agriculture Organization of the United Nations	1971-1976		x	
Integrated water and land use planning	QAT 73-007	Food and Agriculture Organization of the United Nations	1974-1978		x	
Saudi Arabia						
Land and water survey in the Wadi Jizan	SAA 1	Food and Agriculture Organization of the United Nations	1961-1964		x	
Irrigation development in Wadi Jizan	SAA 66-518	Food and Agriculture Organization of the United Nations	1966-1981			x

Country and project	Symbol	Agency	Duration	Ground-water component: Exclusive or major	Substantial (30-50 per cent of project)	Minor
Syrian Arab Republic						
Survey of ground water resources of the Jezireh	SYR 8	Food and Agriculture Organization of the United Nations	1959-1964	x		
Turkey						
Strengthening ground-water capability of DSI Phase I	TUR 74-042	United Nations	1975-1977	X		
Phase II	TUR 77-015	United Nations	1977-1980	X		
Assistance for utilizing isotopes in hydrology	TUR 74-053	International Atomic Energy Agency	1975-1979		X	
Training and support for DSI personnel	TUR 77-006	United Nations	1977-1980	X		
United Arab Emirates						
Water resources management for agricultural purposes	UAE 73-008	Food and Agriculture Organization of the United Nations	1973-1982		X	
Yemen						
Water supply of Sana'a and Hodeida	YEM 70-507	World Health Organization	1971-1976		X	
Rural water supply	YEM 73-017	World Health Organization	1974-1980		X	

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