WATER RESOURCES ASSESSMENT YEMEN ARAB REPUBLIC

WATER RESOURCES OF THE SADAH AREA

main report

REPORT WRAY-3

YOMINCO
DEPARTMENT OF HYDROLOGY

TNO-DGV
INSTITUTE OF APPLIED GEOSCIENCE

WATER RESOURCES ASSESSMENT YEMEN ARAB REPUBLIC

Yemen Arab Republic
Yemen Oil and Mineral Resources
Corporation (YOMINCO)

Kingdom of The Netherlands
Ministry of Foreign Affairs
Directorate General of International Cooperation (DGIS)

WATER RESOURCES OF THE SADAH AREA

MAIN REPORT

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Report WRAY-3
November 1985

YOMINCO
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SUMMARY

A water resources assessment study of the Sadah area has been carried out by YOMINCO's Department of Hydrology, in collaboration with the TNO-DGV Institute of Applied Geoscience. Detailed information on the area's water resources is now available. Some important general characteristics are outlined below.

Rainfall in the area is low and may vary considerably from year to year. It contributes to crop growth, but is not a dependable direct source of water. Indirectly, it is of primary importance because it generates surface water run-off and groundwater recharge.

Neither permanent streams, nor surface water storage systems of significant size are present in the area. Most of the surface water used is intercepted rather than diverted. Agricultural lands are simply situated where surface water (e.g. sheet flows) tend to concentrate. Such 'run-off harvesting systems' are well adapted to local conditions and should be carefully preserved . There is only limited scope for additional development of surface water.

Large amounts of groundwater are currently being exploited in the Sadah area. Groundwater is a reliable source of water, fulfilling more than 50% of the area's actual water requirements. Total abstraction has increased dramatically since the introduction of drilling rigs and turbine pumps in the area around 1976; approximately 2000 wells (79% of them pumped) now jointly abstract some $76 \times 10^6 m^3$/year (1983 situation). Approximately 99% of all water is used for irrigation.

Most groundwater is pumped from sandstone aquifers. Of these, the Sadah sandstone aquifer (Sadah Plain and Abdin Valley) is the most important. It is several hundreds of metres thick, contains a large volume of stored groundwater and collects almost all the area's groundwater recharge. Wells drilled in this aquifer are usually successful and the quality of the groundwater they tap is generally good.

Fractured limestones and narrow zones of saturated alluvial deposits and weathered, fractured bedrock along wadi alignments offer additional, but less favourable possibilities for groundwater abstraction.
Water quality is poor at many locations in the partly salinized valleys of the wadis Marwan, Nushur, Akwan and Sadah (northern part) and locally where contamination from towns and villages occurs.

The most important constraint to groundwater development and abstraction in the Sadah area is the limited replenishment (recharge) of the groundwater reservoirs. The rate of recharge is now exceeded significantly by the strongly increased abstraction rate, and therefore there is severe over-exploitation. Its immediate effects are the depletion of stored groundwater and declining water tables (currently falling at an average rate of 1.5 m per year). As a result, wells are already falling dry and many more problems can be expected in the future, such as: the drying-up and diminishing productivity of existing wells, increasing costs and technical difficulties when constructing new wells, rising production costs of water and finally, exhaustion of the groundwater reservoirs or parts of them.

A model study was carried out in order to predict the occurrence and magnitude of these effects, and to analyse how they might be influenced by different water resources management strategies. Although some technical details of this study are still tentative, the main conclusions are considered to be reliable. It became clear that uncontrolled groundwater abstraction might exhaust the extensive Sadah sandstone aquifer in less than 60 years: the zones that are currently groundwater-irrigated then will be lost for agricultural production. Economic constraints may prevent this stage being reached, but in that case the profitability of the region's agriculture will have become minimal. The study demonstrates the extent to which selected management strategies may lead to more optimistic prospects for the future. It is concluded that groundwater abstraction in the Sadah area should be restricted and reduced as much and as soon as possible. An adequate water resources management strategy must be formulated and implemented.

1. INTRODUCTION

A water resources assessment study of the Sadah area (fig. 1) has been carried out as part of the project 'Water Resources Assessment Yemen Arab Republic, Phase 1' (WRAY-1). This report presents the major outcomes of the study; it summarizes and integrates information and results that are described in more detail in a number of technical annexes (reports WRAY-3.1 through 3.7). The reader should refer to these technical annexes for details of the data acquired, methodologies and interpretation.

The main objective of the Sadah study was to provide information on the area's water resources in order to promote adequate development and management of these resources. This implies that the information should be useful both at a local scale (e.g. for optimal siting and design of wells) and for matters of regional concern (water resources management).
A second objective of the study was to provide on-the-job training for employees of the Department of Hydrology of the Yemen Oil and Mineral Resources Corporation.

The water resources study in the Sadah region was carried out by the aforementioned Department of Hydrology of YOMINCO in collaboration with a Dutch team from the TNO-DGV Institute of Applied Geoscience, Delft. Appendix 1 lists the names of the personnel involved.

Most of the fieldwork was done during the period November 1982 - August 1983; an interim technical report was issued in October 1983 (Van der Gun, 1983). Of all field activities, only the hydrological network operation is still continuing.

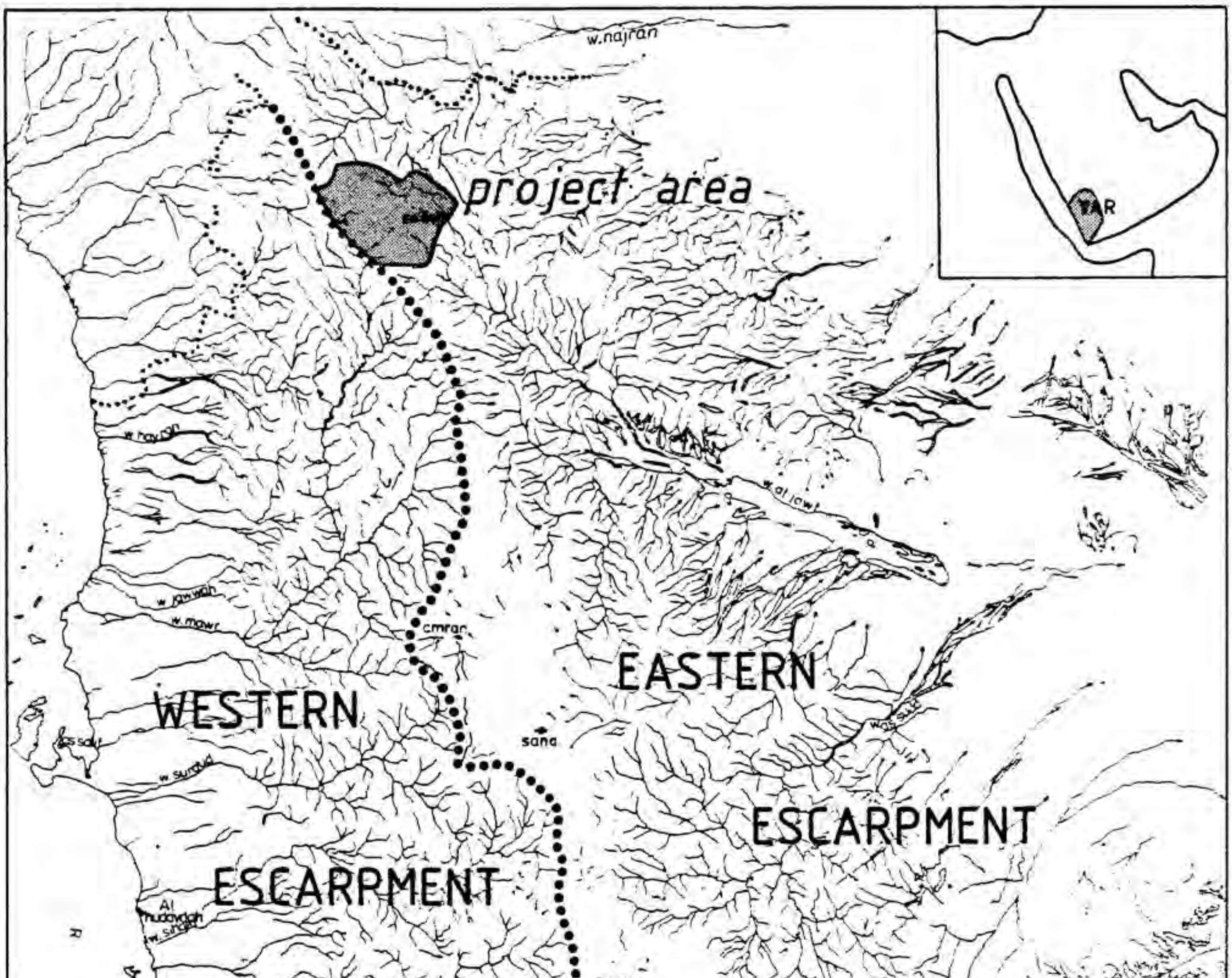


FIG. 1 LOCATION OF THE SADAH PROJECT AREA

2. REVIEW OF TECHNICAL ACTIVITIES

2.1 Inventory of information from previous investigations

No significant information related to Sadah's water resources was available when WRAY's activities started, except for the results of geological observations and surveys. These proved to be very useful and are summarized in section 3.2.

2.2 Photo-interpretation and preparation of base-maps

When fieldwork started, the only available topographic maps covering the project area were at scale 1:250 000 and smaller. Aerial photographs (flown 1980) were used during fieldwork for orientation and for fixing locations. At the office hydrography, geology, topographic features and land use were interpreted from photo sets. After the Ministry of Public Works had provided four uncontrolled photo-maps at approximate scale 1:50 000, a base map at the same scale was prepared for the project area. Final draughting and photographic reduction were done at TNO-DGV Headquarters in Delft.

2.3 Well inventory

More than 1750 wells have been identified and their location and elevation recorded. Water level, yield, electrical conductivity and water temperature were measured, certain characteristics of well and pump were observed and well-owners were interviewed about well construction, aquifer rocks, well performance and water use. The resulting data give a general impression of the groundwater conditions in the area and are described in Annex 1 (Gamal et al., 1985a).

2.4 Geo-electrical survey

In all, 241 vertical electrical soundings have been carried out in the Schlumberger array, most of them by project crews equipped with TNO GEA-51 direct current resistivity meters, and some by YOMINCO's Geophysical Section using Italian-manufactured equipment. The main result of this survey is a map of the depth to basement under the Sadah Plain sandstone; this map suggests that a complicated tectonic system controls the sandstone aquifer thickness in the Sadah graben. The survey and its outcomes are described in Annex 2 (Van Overmeeren, 1985a).

2.5 Hydrological network

By the end of 1982, five rainfall recorder stations, eight ordinary (manual) rain gauge stations, one meteorological station and one stream gauging station had been installed by the project. At the beginning of 1983, four water-level recorders were installed on private wells and another 65 wells were selected for monthly monitoring. Water-level recorders were also installed on WRAY's exploration wells, during 1984. Although they cover a short period only, the data collected enable the main hydrological characteristics of the area to be identified, and demonstrate wide-spread groundwater storage depletion, as described in Annex 3 (Danikh and Van der Gun, 1985). The network is still operating, in particular in order to monitor the groundwater levels.

2.6 Exploratory drilling

A contracted drilling firm drilled two deep boreholes (422 m and 470 m, respectively), through the Sadah Plain sandstones until basement. The first objective was to confirm the geo-electrical interpretations made; secondary objectives were to obtain additional information on lithological variations, aquifer characteristics and groundwater levels. Annex 4 reports on this drilling programme (Van Overmeeren, 1985b).

2.7 Geophysical well-logging

Many private boreholes that were being drilled during the project's intensive fieldwork season (1982-1983) were traced; permission was obtained to run a geophysical well-log in a large number of wells, upon completion of drilling. In addition, geophysical logs were made in completed private boreholes that had not been equipped with pumps and in WRAY's exploratory boreholes. In total, 63 geophysical well logs were obtained, including LN and SN resistivity, gamma, caliper and SP logs. During 1982 and early 1983 an old well-logger was used, until a new B-1000 well-logger came available; both were manufactured by the TNO-DGV Institute of Applied Geoscience at Delft.
Analysis of the logs yielded information on lithological characteristics, resistivity and porosity of the sandstone units and is summarized in Annex 5 (Elewaut, 1985).

2.8 Aquifer tests

Drawdown and/or recovery tests of short duration were carried out at 32 locations. With one exception, all the pumped wells tested were private production wells. The results, presented in Annex 6 (Gamal et al., 1985b), revealed the hydraulic behaviour of the Sadah Plain sandstone unit.

2.9 Groundwater flow modelling

A numerical groundwater flow model (PLASM) was used to analyse the consistency of the collected information, to estimate recharge and to predict future groundwater levels. Relevant aspects of this study are reported in Annex 7, which deals with the availabilty of groundwater (Elderhorst and Van der Gun, 1985).

2.10 Miscellaneous

Various other technical activities were carried out in order to support and supplement the work mentioned above. They include:

- altimetry: 35 km of topgraphic levelling (along the asphalt road) and intensive altimeter field traverses in order to produce a reliable elevation map;
- groundwater sampling for chemical analysis (15 samples);
- development of software for the processing and graphic output of data on an HP-85 microcomputer;
- draughting and word-processing.

Most of the processing and interpretation of field data was done at DOH's office at Sana'a.

3. GENERAL CHARACTERISTICS OF THE PROJECT AREA

3.1 Location and topography

Figure 1 shows the project area's location; its main topographic characteristics and some local names are indicated in figure 2. The area is situated in the northern part of the YAR, between the meridians 43°29' and 43°57' East and the parallels 16°47' and 17°10' North, extending over approximately 1147 km^2. It includes roughly the alluvial Sadah Plain and the bordering hilly and mountainous zones draining towards it. The boundary of the project area coincides with surface water divides.

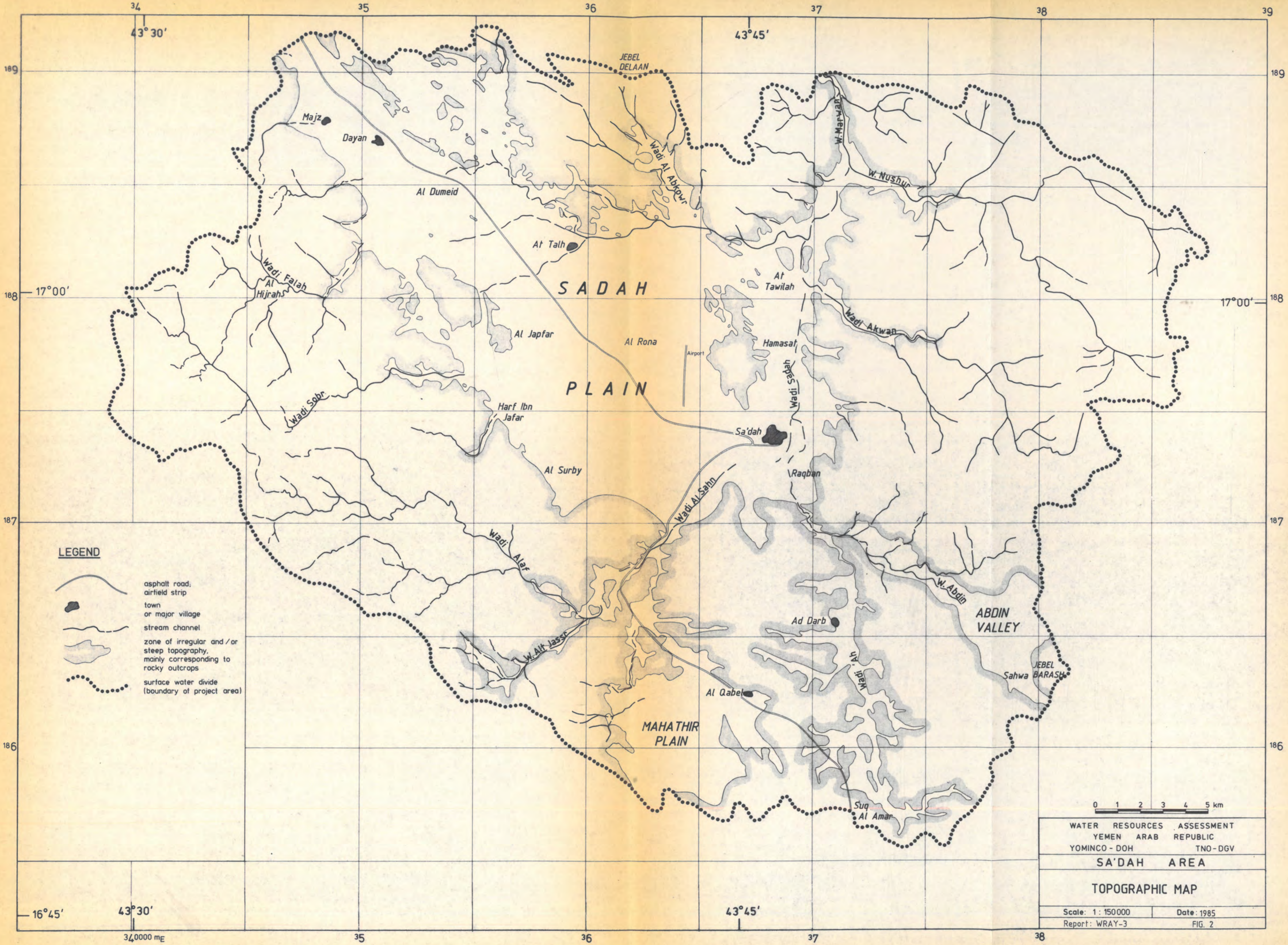
The slightly undulating Sadah Plain slopes gently (0.5-1%) from the NW edge to the centre of the project area and from there it slopes away into the valley of Wadi Marwan that runs north.
The western part of the area is a rugged, dissected mountainous area, descending with a steep escarpment to the plain. It reaches elevations up to 2770 m, which is 950 m above the average level of the Sadah Plain. North, east and south, the bordering zones are hilly and sometimes plateau-like, with maximum elevations of only 150-500 m above the level of the adjoining plain. In the southern part of the area is a second plain: the Mahathir Plain.

The hilly and mountainous zones are dissected by streams (wadis). Their alluvial deposits form narrow, relatively flat strips, suitable for settlements and agriculture.

3.2 Geology

The geological observations made by early pioneers (e.g. Geukens, 1966) on the Sadah area have been followed by more detailed studies carried out by the German Geological Advisory Group, in collaboration with YOMINCO, formerly YMPA (Schulze & Thiele, 1978, Roland, 1979; Meinhold and Trurnit, 1981). In particular, a 1:250 000 geological map has been produced (Roland, 1979), part of which is presented (after some simplification) in figure 3.

A dominant structural-geological feature of the Sadah area is the downthrown structure or graben that traverses the area from NW to



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SA'DAH AREA

TOPOGRAPHIC MAP

Scale: 1:150000 Date: 1985
Report: WRAY-3 FIG. 2

SE. It is considered to be a continuation of the Al Jawf graben, at the intersection with the N-S oriented Aden-Sana'a-Sadah zone of subsidence. Consequently, the most important faults and alignments in the area are NW-SE and N-S. They are accompanied by NE-SW faults of minor importance.
The Sadah Plain (fig. 2) lies inside the Sadah graben. The rocks underneath the alluvial cover are probably dissected by numerous faults of different orientation, resulting in separate blocks of differing vertical displacement.

Table 1 summarizes the principal stratigraphic units and their lithological and hydrogeological characteristics. A brief litho-stratigraphic description follows below.

The oldest observed rocks belong to the Basement Complex and are of Precambrian to Paleozoic age. In the northern and eastern part of the area, the Basement Complex is mainly composed of schists; west of the Sadah Plain, gneissic granites dominate.
Basement rocks are unconformably overlain by either Wajid Sandstones or Akbra Shales, both of Paleozoic age. The Wajid Sandstones were mainly deposited by rivers in a deltaic environment and frequently feature cross-bedding. North of Sadah the grains become finer and are probably of aeolian origin. The Permian Akbra Shales are laminated and have a glacio-marine origin. Although younger than the Wajid sandstones, to date they have only been seen overlying basement rocks.

Triassic - Jurassic Kohlan Sandstones are outcropping on the slopes of escarpments that are topped by Jurassic Amran Limestones. The extent of these fine-grained, friable sandstones and that of the soft Akbra Shales seem closely related to the extent of the overlying Amran Limestones that protect them against erosion.
The Amran Limestones were formed during a major marine transgression during the Jurassic period. They consist of dense calcareous rocks alternating with marls and shales.Starting near the end of the Cretaceous and continuing during the Tertiary, intensive tectonic faulting was accompanied by volcanic activity. Lavas and tuffs - belonging to the Yemen Volcanics (Trap Series) - covered the older rocks and can be observed near the western border of the project area or in the central part of the Jebel Barash.

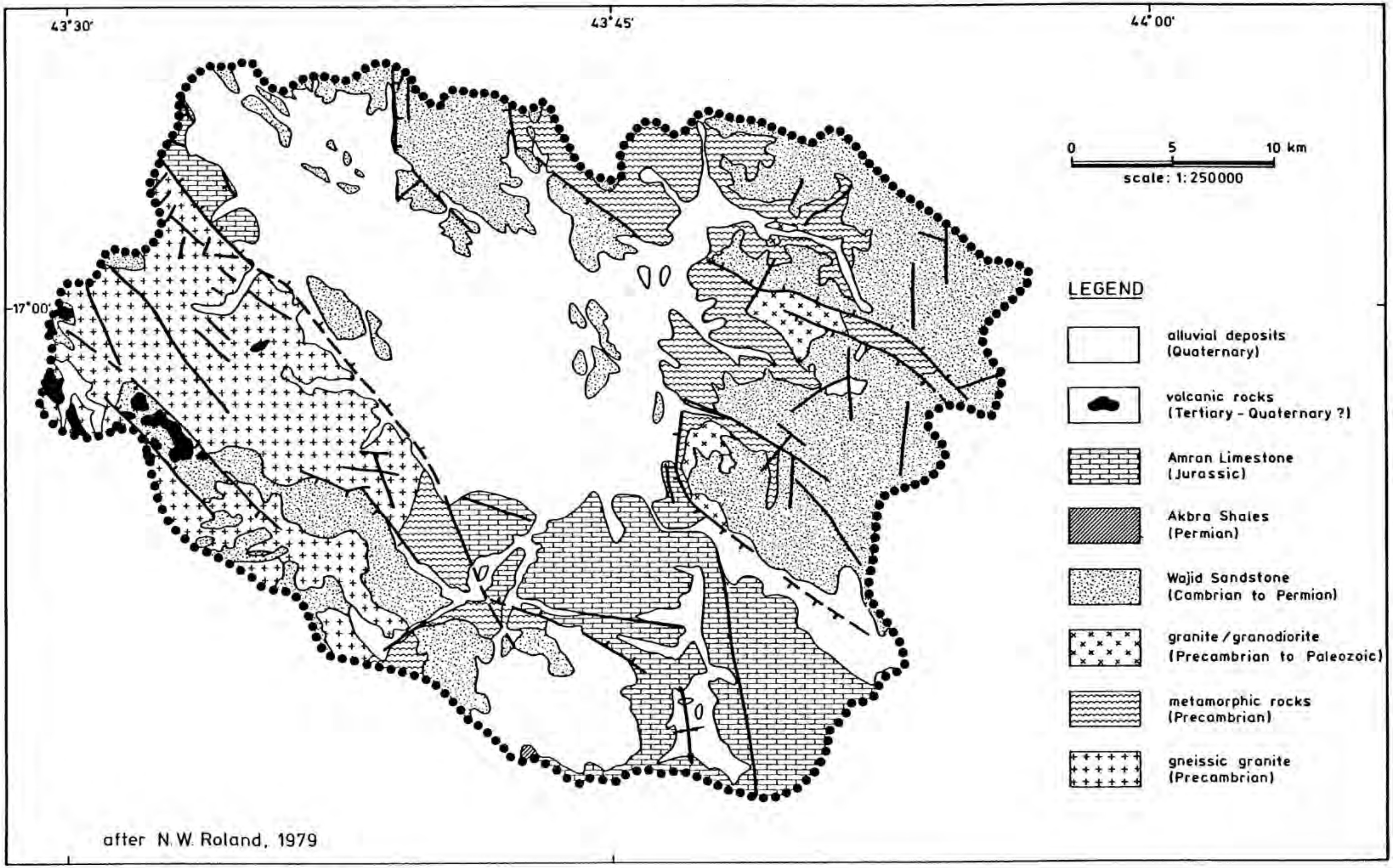


FIG. 3 SIMPLIFIED GEOLOGICAL MAP

	GEOCHRONOLOGY	LITHOSTRATIGRAPHY	LITHOLOGY	HYDROGEOLOGY
Cainozoic	Quaternary	Recent unconsolidated deposits	gravels, sands, silts, clays	medium to high permeability; shallow aquifer pockets in/along wadi beds; mostly unsaturated on the Sadah Plain
	Tertiary	Yemen Volcanics (Trap Series)	basalts, andesites, rhyolites, tuffs	variable, but generally low permeability; hydrogeologically insignificant in the Sada area
Mesozoic	(unconformity)			
	Jurassic	Amran Limestone	partly dolomitic or ferruginous limestone; alternating with shales and marls	poor aquifer, permeable zones limited to fracture zones
	Triassic	Kohlan Sandstone	fine-grained quartz sands	potential aquifer
Paleozoic	Permian	Akbra Shales	glacio-marine laminated shales, containing boulders of basement rocks	low permeability (aquitard/aquiclude)
	Carboniferous	(Upper) Wajid Sandstone	crossbedded medium- to coarse-grained quartz sands with intercalations of clays and silts	poor to moderate aquifer
	(unconformity)			
	Ordovician	(Lower) Wajid Sandstone	crossbedded medium- to coarse-grained quartz sands; quartzitic ironstones; thin basal conglomerates	
	Cambrian			
Precamb		Basement Complex	granites,gneisses, schists, quartzites	impermeable bedrock; locally some water may be present in cracks, fissures and weathered zones near the surface

Table 1. Principal stratigraphic units and their lithological and hydrogeological characteristics.

Quaternary unconsolidated sediments are present in narrow strips along and underneath the lower reaches of the mountain streams and more extensively on the Sadah and Mahathir Plains. They comprise mainly alluvial sands, silts and clays; on the plains some aeolian deposits may occur.

3.3 Climate

Records from the project's meteorological station at Al Dumeid (fig. 2) give an impression of the climatic conditions on the Sadah Plain (Danikh and Van der Gun, 1985). Figure 4 shows monthly totals and averages of the principal meteorological observations made during 1983. The figures for 1984 were similar, except for the rainfall.

The diagram indicates that a warm-temperate, semi-arid climate prevails, with characteristics typical of high-altitude zones in the tropics.

Average temperature (19.3°C) is moderate by the altitude, but monthly averages show a large annual range for this latitude (13°C). Rainfall has two peaks; one in spring and one in summer. However, the general seasonal pattern may be disturbed in some years: no significant summer rainy season developed during 1984. Total rainfall was 272 mm in 1983 and 59 mm in 1984, which illustrates the large rainfall variability in arid climates.

Average relative humidity is low (43%) and saturation has never yet been reached in the project's Stevenson screen. The seasonal variation in relative humidity seems to be related to the rainfall regime.

Low wind speeds (< 2 m/s) and a consistently high number of daily sunshine hours (around 8 hrs/day) complete the picture.

The annual potential evapotranspiration calculated from these data according to the Penman method is 1360 mm.

The areal distribution of rainfall is shown in figure 5 for the years 1983 and 1984. It is clear that not only elevation, but other factors also determine the variation between locations.

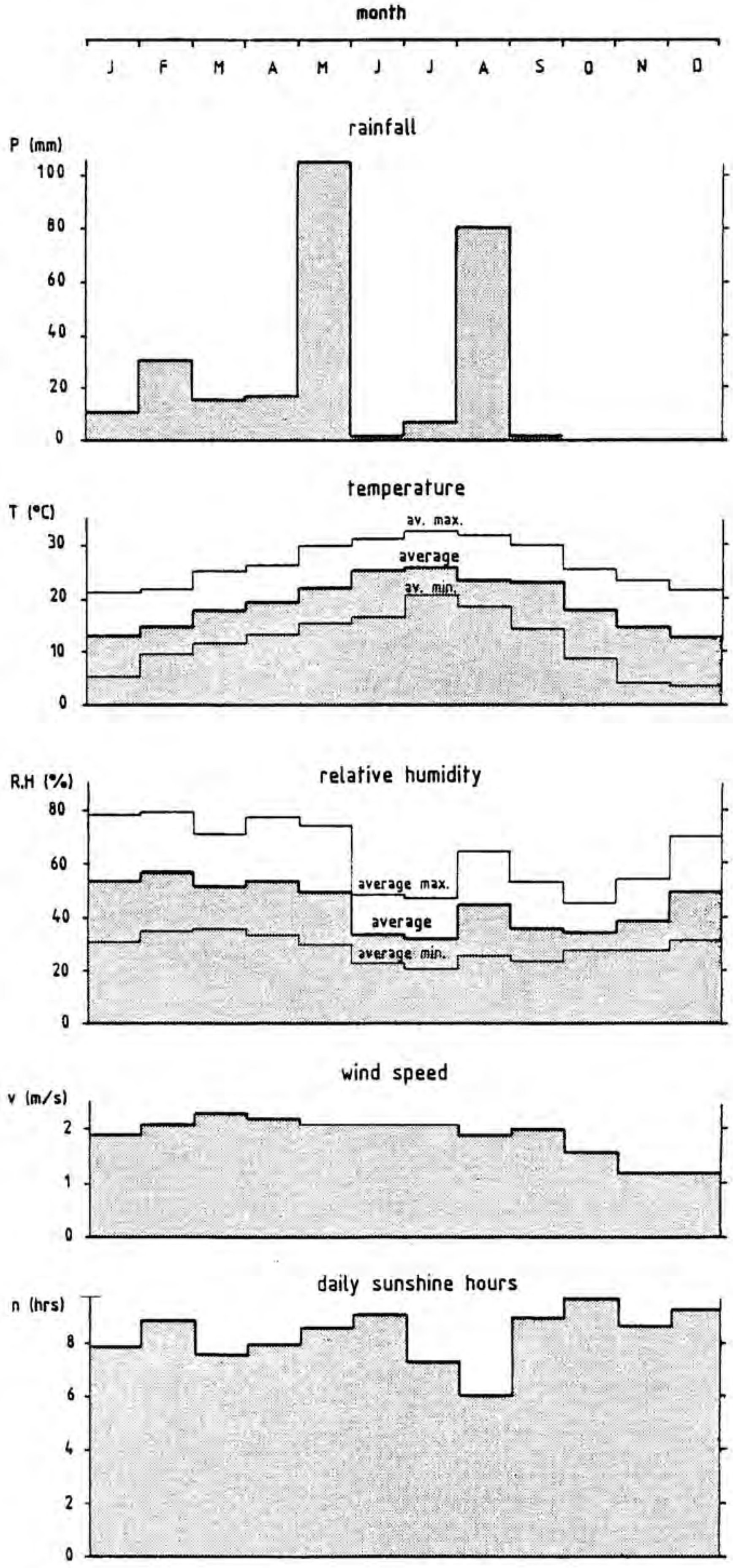


FIG. 4 METEOROLOGICAL STATISTICS AL DUMEID, 1983

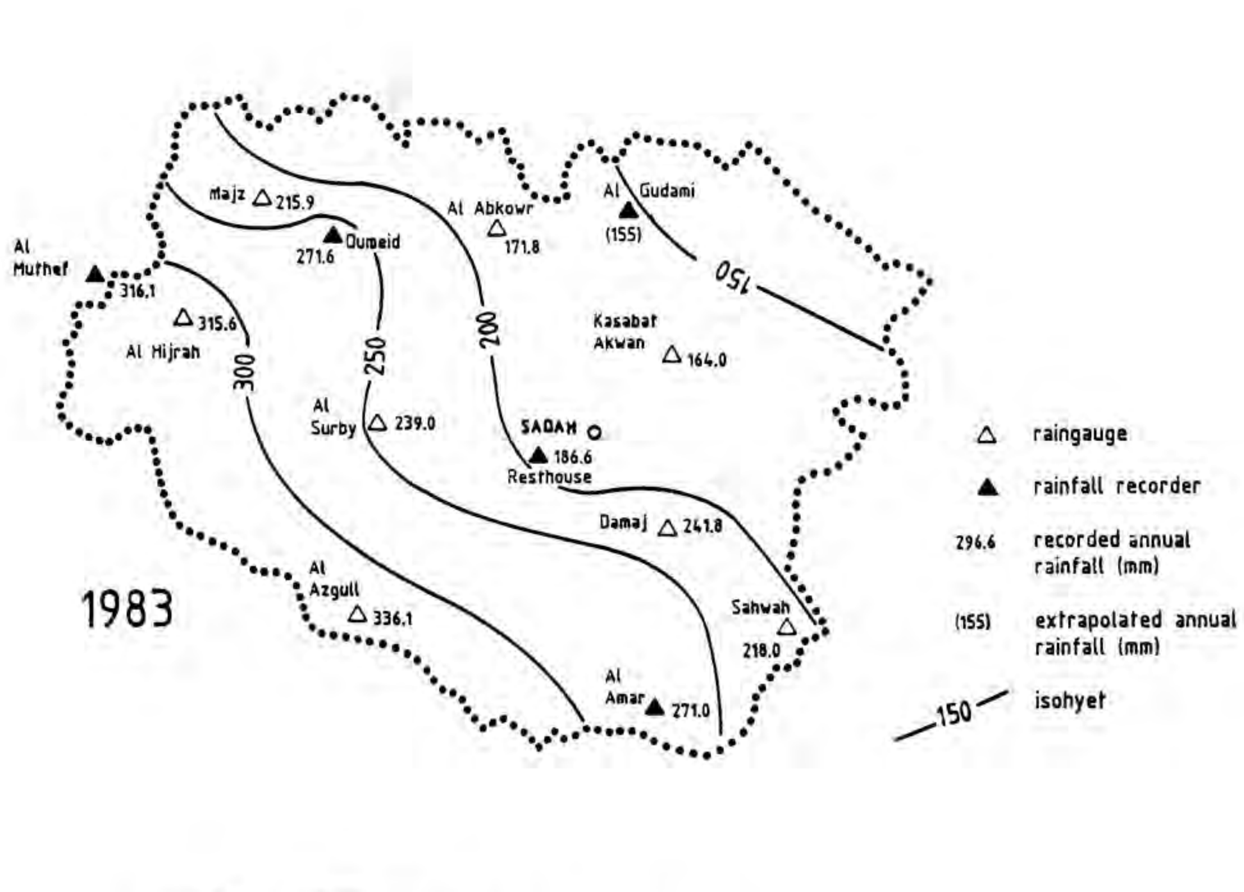


FIG. 5. ANNUAL RAINFALL SADAH AREA, 1983 AND 1984

For the other climatic factors, the areal variation is reasonably predictable on the basis of differences in altitude. The conditions on the plains will be similar to those at Al Dumeid. At higher elevations, average temperatures will be lower; they decrease at a rate of approximately 0-6°C per 100 m of altitude (Van Enk and Van der Gun, 1984). In contrast, relative humidity increases with elevation, but probably also tends to decrease SW-NE.

3.4 Drainage pattern

The project area is situated at Yemen's so-called Eastern Escarpment (see fig. 1), which means that it drains towards the great Arabian Desert, the Empty Quarter.

The area corresponds to the catchment area of Wadi Marwan. All streams (wadis) in the area are tributaries of this stream and collect excess rainfall from the project area. Nevertheless, a small offshoot of Wadi Magsal crosses the NW border and brings some additional run-off to the Sadah Plain. The catchment area of Wadi Magsal (84 km^2) is situated outside the project area and most of its run-off continues flowing through the main wadi to the Wadi Ard system; only a minor part diverts to the Sadah Plain.

Wadi Marwan joins Wadi Ard approximately 40 km north-east of the project area, near the border with Saudi Arabia. Below this confluence, the stream is called Wadi Najran.

As can be assumed from figure 2 and more clearly from figure 3, the alignment of many wadi branches is structurally controlled, especially in the mountainous zones. In the plains, the sub-horizontal topography and the high permeability of the alluvial sediments cause surface run-off to spread and infiltrate. As a result, stream channels are less clearly defined there, and significant run-off is observed only rarely.

3.5 Population and agriculture

From a population distribution map based upon the 1975 census (Swiss Technical Co-operation Service, 1978), the population of the project area can be estimated as being approximately 45 000 in 1975; this figure may have increased to around 55 000 in 1985.

According to the same census (Swiss Technical Co-operation Service, 1978) only two of the villages and towns in the area had more than 1000 inhabitants in 1975; Sadah (4380) and Majz (1245). The corresponding figures for today are probably 5350 and 1520, respectively.

Asphalted roads connect Sadah town to Sana'a and to Saudi Arabia. The town has shops, workshops, hotels and the administrative infrastructure of a provincial centre. Weekly markets are held at At Talh (large market), Sadah, Majz and Suq al Amar. Most of the area's population, however, is involved in agriculture.

The cultivated lands are found on the alluvial deposits near the wadis and in the plains, mostly as isolated clusters and belts. Even on the Sadah Plain the cultivated lands are almost exclusively associated with linear depressions, where run-off tends to concentrate. The total extent of these agricultural zones is 83 km^2, which is 7% of the total area. The principal crops are grapes and other fruits, vegetables, alfalfa, and qat. Only some of the land is irrigated; the remainder is inundated periodically by surface water or is left fallow until the next growing season.
Outside the agricultural zones the land surface is usually bare, except for scattered groups of thorntrees.

4. SURFACE WATER

4.1 General characteristics

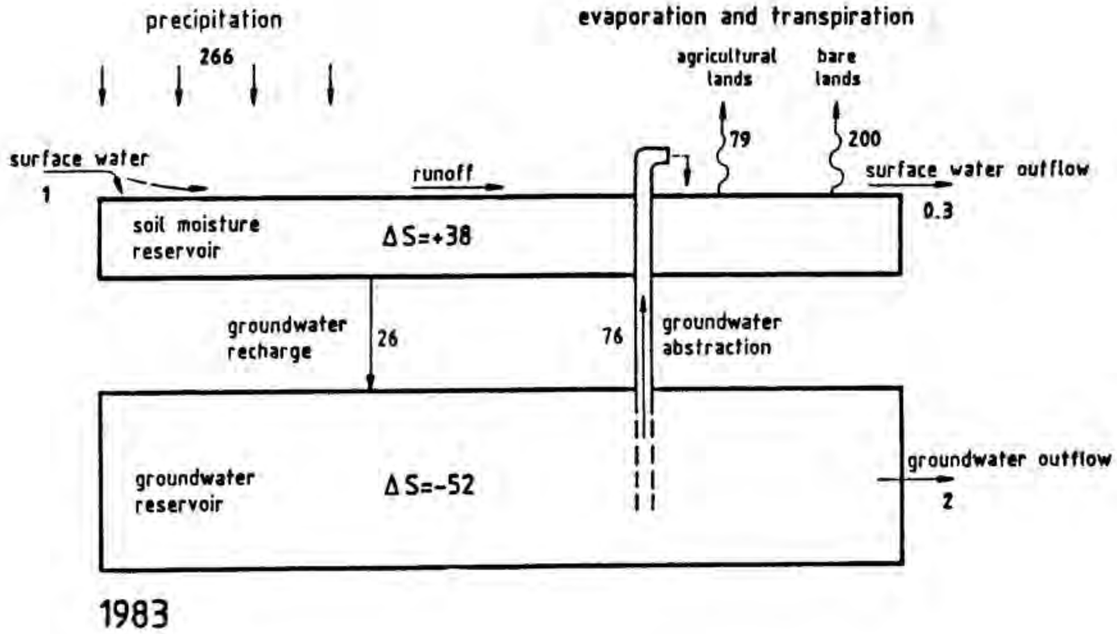
When rain falls in such quantities or intensities that the soil is unable to absorb all of it, part of it runs off. This is observed most frequently in the hardrock outcrop zones, where topography is relatively steep and water absorption capacity of the surface rocks low. In these zones, run-off quickly concentrates in the wadi channel systems where part of it disappears again by infiltration into the alluvial fills of the major wadis.

Where the wadis enter the Sadah Plain, their stream channels tend to split into several branches and within a short distance run-off usually infiltrates completely into the permeable alluvial deposits. Stream channels in the central and lower parts of the Sadah Plain only exceptionally carry run-off, after very heavy rain storms. When this happens, some parts of the plain and Marwan valley can flood and surface water leaves the project area through Wadi Marwan's stream channel. This was observed only twice during 1983 and once during 1984, although the mountain streams that bring water to the plain carried water much more frequently.
Neither permanent or seasonal streams nor surface water storage systems of any importance are present in the area.

4.2 Surface water and the area's water budget

The main components of the area's annual water budgets for 1983 and 1984 are presented schematically in figure 6, which shows net inflows and outflows and the resulting changes in stored water. All figures were estimated on the basis of actual observations, except for the changes in soil moisture storage (unsaturated zone) that were calculated by difference from the other water balance terms (Danikh and Van der Gun, 1985).

In spite of low accuracy of the presented figures, there is no doubt that surface water inflow and outflow are insignificant components of the area's annual water budget. Nevertheless, surface water run-off is more important in the Sadah area than these figures



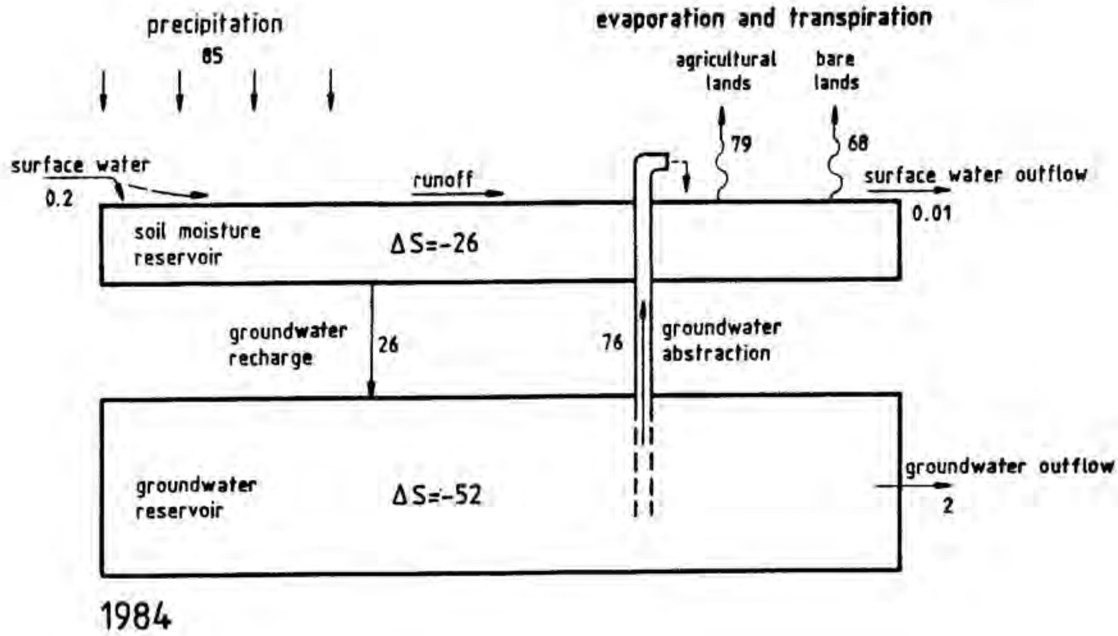


FIG. 6 ANNUAL WATER BUDGETS SADAH AREA
(all figures in millions of m^3; ΔS=change in storage)

suggest. A large percentage of rainfall inside the area runs off in some way and tends to concentrate the amounts of water in certain zones. In some of these zones agriculture is flourishing (as a result of water availability), in others infiltration becomes sufficiently intensive to replenish the groundwater significantly. In particular the alluvium-covered Sadah Plain appears very efficient in intercepting run-off and may be characterized as a 'run-off absorbing zone'.

The rainfall pattern in 1983 differed greatly from that in 1984:the year 1984 was exceptionally dry, whereas 1983 probably represents average or slightly wetter than average conditions. It can be observed that run-off is most sensitive for variations in rainfall. The budgets show that soil moisture storage and evaporation or evapotranspiration in 'bare lands' zones also fluctuate greatly in response to rainfall variations.

4.3 Surface water use

Given the very intermittent regime of wadi flows, the possibilities for constructing simple or more sophisticated works to bring surface water to where it can be used are restricted. However, close observation shows that the population of the Sadah area in fact make intelligent use of available surface water resources. Traditionally they have located their agricultural lands on sites that are occasionally inundated or moistened by surface water. Typical sites are along wadi courses and locations where sheet flow tends to concentrate before it reaches a stream channel. The agricultural lands are often surrounded by walls left open on the upstream side, which protect the lands against the destructive impact of floods and prevent the water from leaving the plots again. There are very few dams and ditches to divert the water to the cultivated lands, because efficient use is being made of the local topographic characteristics.

Typically, in this way the lands are moistened or flooded only a few times a year, but the amounts of water involved are stored in the soil and contribute substantially to crop growth. It is estimated that in the project area these surface water resources provide almost 25% of the water required for evapotranspiration on the agricultural lands (under current conditions).

It is noteworthy that the distribution of population and agricultural zones is linked to the availability of surface water, as described above. Only recently, when pumping of groundwater was introduced, did it become feasible to have agricultural lands on higher parts of the Sadah Plain.

5. GROUNDWATER

5.1 General aspects

Groundwater is present in pores, fissures and cracks in rock units. Such a rock unit constitutes an exploitable groundwater reservoir (aquifer) if groundwater is able to move through it and accumulates in sufficient quantity.

Consequently, this chapter begins by distinguishing between aquifers and non-aquifer units. Relevant information concerning properties of the rock matrix and the groundwater inside will be presented for the main aquifer (Sadah sandstone aquifer) and in less detail for other aquifer units. Finally, attention is paid to groundwater abstraction, in relation to storage, discharge and renewal (recharge) of groundwater.

5.2 Principal aquifer systems

The principal aquifers in the area are shown in figure 8. Some of the lateral boundaries are still tentative or subjective.

Briefly, three types of aquifer units are of importance:

- sandstone aquifer units (Wajid Sandstones and perhaps also Kohlan Sandstones);
- limestone aquifer units (Amran Limestone);
- local 'wadi' aquifer zones (saturated Quaternary unconsolidated deposits and weathered/fractured hardrock, recharged through unconsolidated deposits).

Their geochronological position and a brief lithological characteristic can be found in table 1.

Some of the area's unconsolidated deposits and sandstones have not been classified as aquifers because they are situated largely or entirely above the regional water table.
Aquifer units of regional extent are situated within the Sadah graben system only. Outside this area, favourable zones for groundwater development are generally associated with the narrow valleys of wadis.

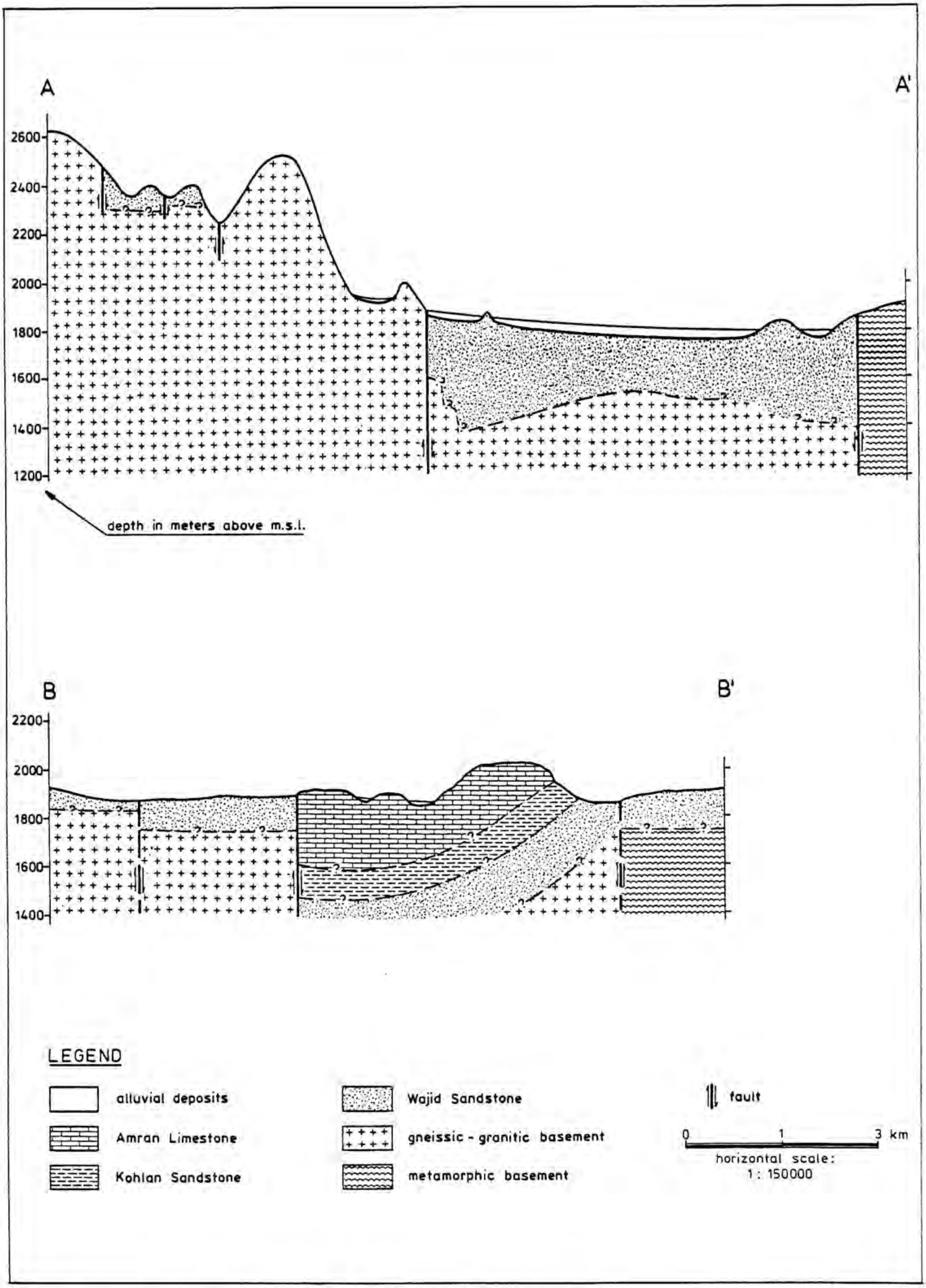
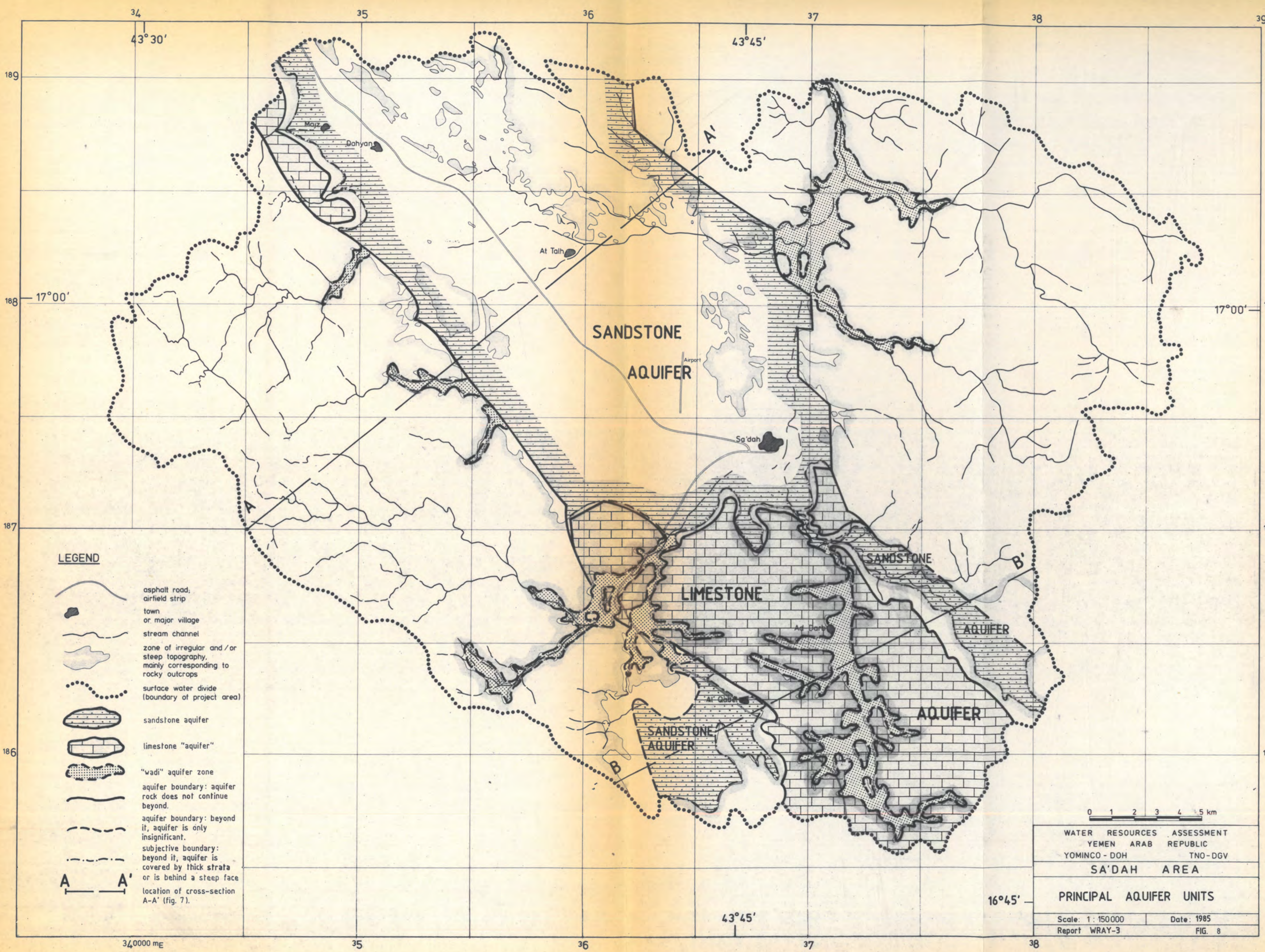


FIG. 7 CROSS SECTIONS THROUGH THE AQUIFER SYSTEMS



43°30'
43°45'
17°00'
16°45'
SANDSTONE AQUIFER
LIMESTONE AQUIFER
SANDSTONE AQUIFER
SANDSTONE AQUIFER
Maiz
Dahyan
At Talh
Airport
Sa'dah
Ad Darb
Al Qabil
A
A'
B
B'
LEGEND
asphalt road, airfield strip
town or major village
stream channel
zone of irregular and/or steep topography, mainly corresponding to rocky outcrops
surface water divide (boundary of project area)
sandstone aquifer
limestone "aquifer"
"wadi" aquifer zone
aquifer boundary: aquifer rock does not continue beyond.
aquifer boundary: beyond it, aquifer is only insignificant.
subjective boundary: beyond it, aquifer is covered by thick strata or is behind a steep face
A A'
location of cross-section A-A' (fig. 7).
0 1 2 3 4 5 km
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SA'DAH AREA
PRINCIPAL AQUIFER UNITS
Scale: 1 : 150000
Date: 1985
Report WRAY-3
FIG. 8
340000 mE

Two schematic cross-sections are presented in figure 7 in order to make the position of the aquifers more clear. Depths and lateral extensions are partly speculative, because data are lacking.

5.2.1 The sandstone aquifer units

The area's most important aquifer unit is undoubtedly the sandstone aquifer of the Sadah Plain and its extension southeastwards. On the plain and in the western part of the Abdin Valley it is covered by relatively permeable unconsolidated sediments, usually between 10 m and 40 m thick. These sediments are unsaturated, but nevertheless constitute a hydrogeologically important unit: water infiltrates easily into these deposits and subsequently may recharge the underlying sandstone aquifer.
In the southeastern part of the area the sandstones are thought to continue under thick strata of the outcropping Amran Limestone series. The Sadah sandstone aquifer is bounded laterally by the major faults of the Sadah graben system (Gamal et al., 1985a).

The Sadah sandstone aquifer is thought to consist of Wajid Sandstones and - if present - overlying Kohlan Sandstones. The Kohlan Series is expected to be present still under the Amran Limestone strata and probably in those parts of the Sadah Plain where the basement is relatively deep (Van Overmeeren, 1985a).
The depth to the underlying impermeable basement rocks is considerable and seems to be greatly influenced by tectonic block-faulting (fig. 9). On the Sadah Plain the depth to basement has been assessed by geophysical methods and by exploratory drilling: it ranges from 100-150 m locally in the northern part up to 600-650 m on some blocks in the central and eastern zones (Van Overmeeren, 1985a and 1985b; Elewaut, 1985).

A second sandstone aquifer, of minor importance, includes the Wajid Sandstones on the Mahathir Plain, as far as situated between the two main fault systems (western and north-eastern boundaries). To the north the aquifer wedges out on top of basement rocks, but its

thickness apparently increases quickly in opposite direction (200 m (?) in the centre of the plain) and the aquifer probably dips under the thick confining strata of Abra Shales observed in the eastern and southern parts of Mahathir Plain.
Hydraulic continuity between the Sadah sandstone aquifer and the Mahathir sandstone aquifer is presumed to be absent, because along the fault acting as their common boundary the Sadah sandstone has been downthrown and now abuts against basement rocks (fig. 8).

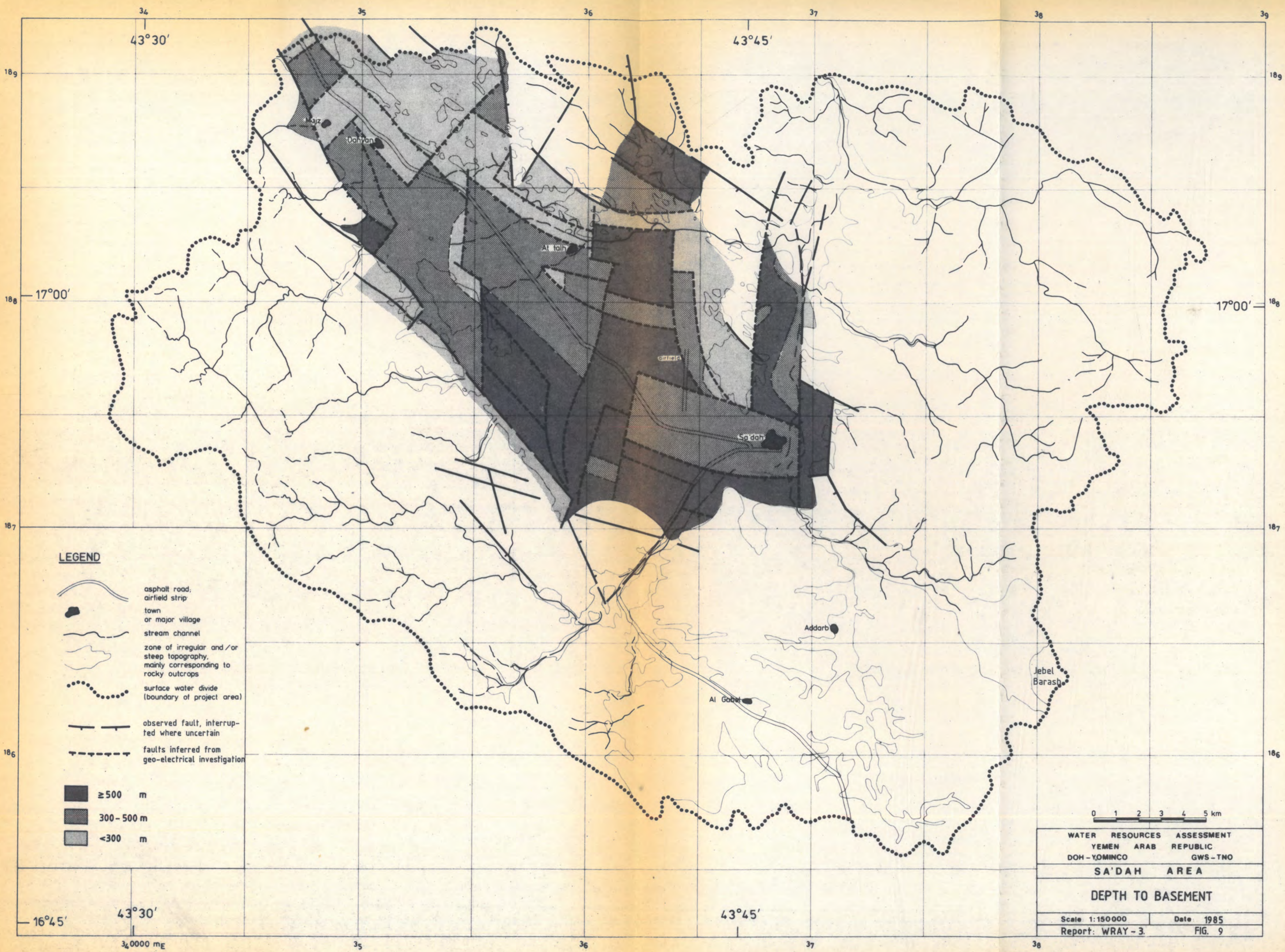
The sandstones' average porosity is in the range of 5-15% (Gamal et al., 1985b; Elewaut, 1985) and the average specific yield has been estimated as 7.5%. Hydraulic conductivities derived from aquifer tests (Gamal et al., 1985b) are usually low (0.1-0.3 m/day). It is assumed that a dual hydraulic conductivity is present: groundwater flow takes place both through the sandstone pores and through fissures, cracks and other secondary open spaces. Most probably, such a complex conductive system becomes more efficient when larger dimensions in space and time are involved; for that reason, effective hydraulic conductivity values for regional flow might be higher than the ones governing flow to a well during periods of seven hours (Elderhorst and Van der Gun, 1985).

5.2.2 The limestone aquifer units

These units constitute poor aquifers and from the point of view of regional groundwater flow could even be termed 'aquitards'. Groundwater storage and flow seem to be predominantly related to fissures and cracks, and, consequently, hydraulic characteristics may vary considerably from one location to another. The aquifer units are composed of dense limestones alternating with shales and marls, all belonging to the Amran Series. They occur in the Sadah graben and their lateral extent is well known (fig. 3). Probably none of the wells drilled in these units has penetrated the total sequence, which means that total thickness of the major limestone aquifer unit may exceed 300 m in its central part.

5.2.3 The local 'wadi' aquifer zones

These aquifer zones are linked to the valleys of the major wadis (including the alluvium-filled Wadi 'Ah depression that collects surface run-off from the major limestone unit).


43°30'
43°45'
17°00'
16°45'
Majz
Dahyan
At talh
Airfield
Sa'dah
Addarb
Al Gabel
Jebel Barash
LEGEND
asphalt road; airfield strip
town or major village
stream channel
zone of irregular and / or steep topography, mainly corresponding to rocky outcrops
surface water divide (boundary of project area)
observed fault, interrupted where uncertain
faults inferred from geo-electrical investigation
≥500 m
300 - 500 m
<300 m
0 1 2 3 4 5 km
WATER RESOURCES ASSESSMENT
YEMEN ARAB REPUBLIC
DOH - YOMINCO
GWS - TNO
SA'DAH AREA
DEPTH TO BASEMENT
Scale 1:150000
Date 1985
Report: WRAY - 3.
FIG. 9
340000 mE

Their hydraulic characteristics are considered to be more favourable than those of the surrounding zones, for a number of reasons:

- the alignments of the zones are tectonically controlled, which suggests that locally rocks are more intensively fractured and/or weathered than elsewhere;
- the overlying alluvial sediments favour the local rate of re-charge (as on the Sadah Plain);
- the alluvial sediments (although largely unsaturated) probably maintain hydraulic continuity throughout the zones, notably via the wadi channel beds.

Both the lateral extent and the effective depth of these local aquifer zones are much smaller than those of the sandstone and limestone aquifer units. However, they constitute the most favourable groundwater zones outside the graben structure.

5.3 Other rock units

A minor part of the alluvial deposits in the area is included in the local 'wadi' aquifer zones described above. Most of the alluvial deposits, however, lie above the phreatic level and thus belong to the unsaturated zone. Their hydrogeological significance has been commented on above (section 5.2.1).

Igneous and metamorphic basement rocks outcrop in a considerable part of the project area (fig. 3). Outside the so-called 'wadi aquifer zones' their water producing capacities are considered to be very low and their contribution to regional groundwater flow insignificant. Small amounts of water are stored in cracks and fissures, at shallow depths.

Wajid Sandstone strata encountered outside the Sadah graben system may offer possibilities for groundwater development locally. They have not been classified as aquifers because they are of limited thickness (low transmissivity) and recharge is probably very low (because of irregular topography and absence of alluvial cover). Seepage points are sometimes present where contacts with the underlying basement rocks are exposed, e.g. along wadi Nushur.
Permian Akbra shales are observed locally (southern and eastern edges of Mahathir Plain); they constitute important aquitards.

5.4 Groundwater levels and groundwater flow

Figure 10 shows the depth to groundwater as observed during the period 1982/1983. Depths of 20-40 m are common on the Sadah Plain, but in the eastern part of Abdin Valley phreatic levels are deeper than 100 m. Relatively shallow water tables are encountered in the 'wadi aquifer zones' and on the Mahathir Plain.

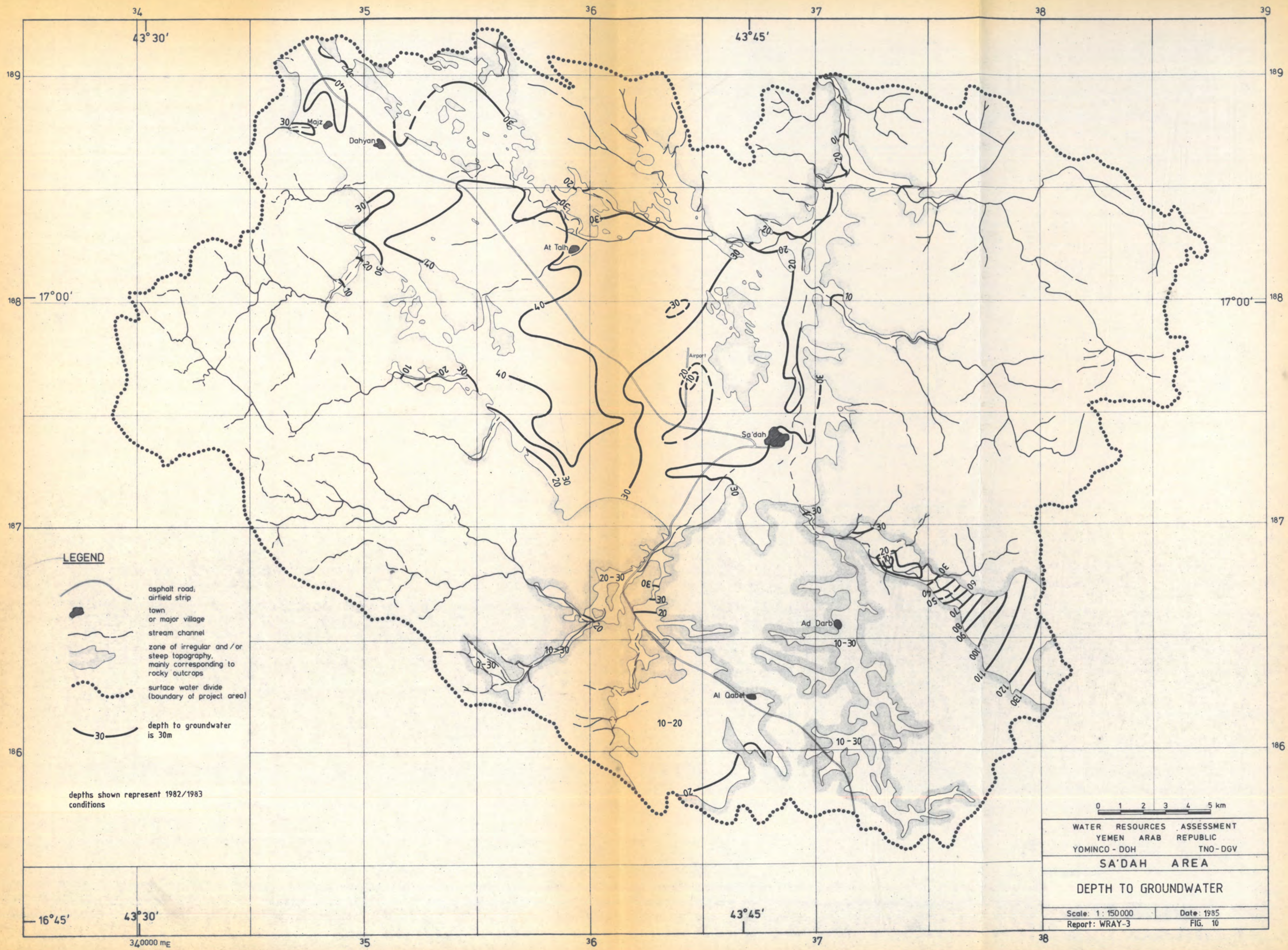
Considerable short-duration oscillations in water level can be observed on the Sadah Plain because of pumping in nearby wells. Their amplitude may be still 1-2 m a few hundred metres from a pumped well (Danikh and Van der Gun, 1985). Low transmissivities and 'delayed gravity response' contribute to this phenomenon (Gamal et al., 1985b).

Seasonal variations in groundwater level resulting from recharge are evident in the wadi aquifer zones, but are not clearly visible in the sandstone wells' hydrographs. In the latter case recharge is probably smoothed out in time because infiltrated water has to pass through a thick alluvial cover.

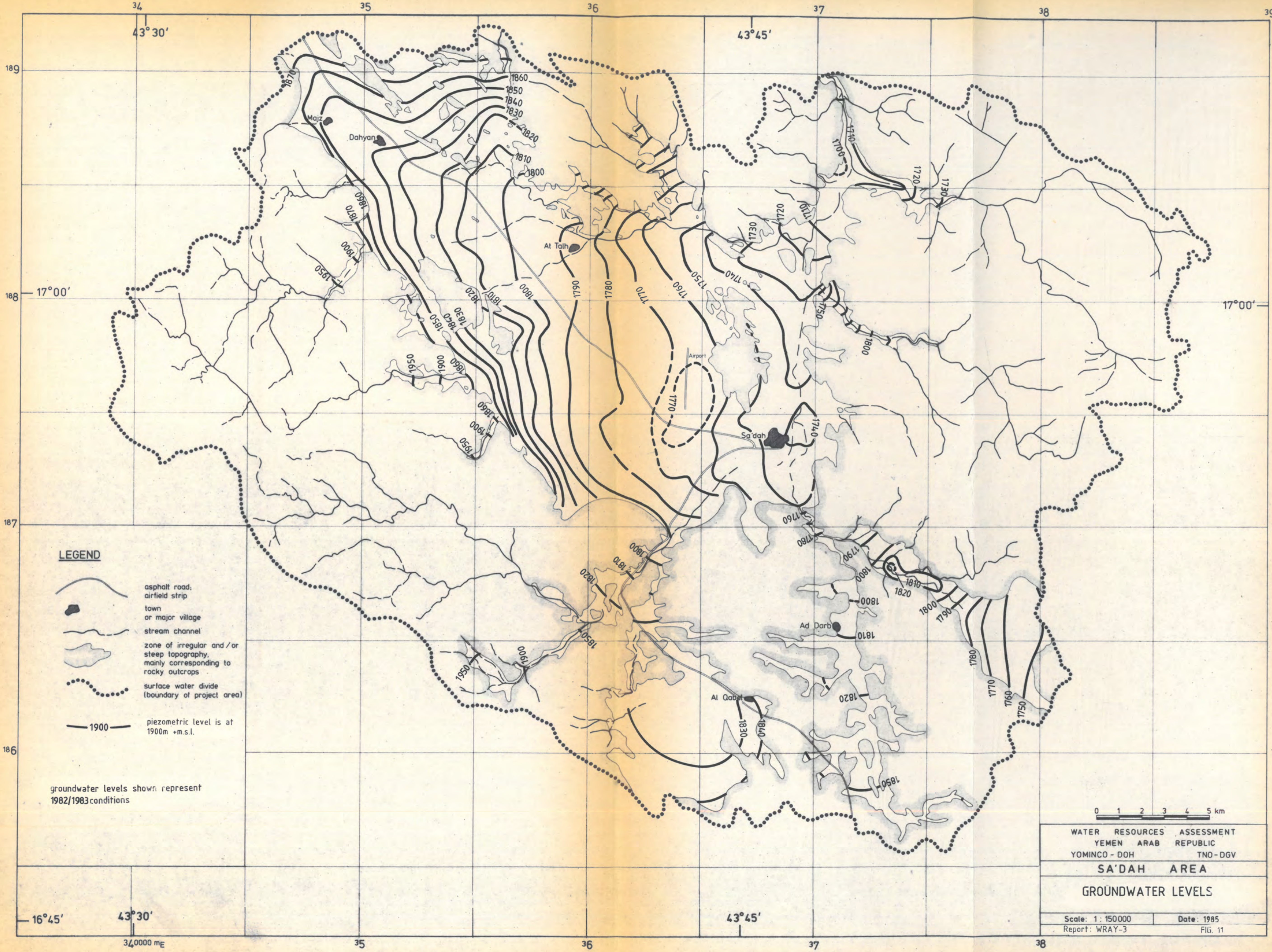
In spite of the short period of observation (2 years) there is strong evidence for a regional trend of groundwater level decline in the Sadah Plain. This trend is around 2-3 m/year in the eastern part, and averaged approximately 1.5 m/year over the Sadah Plain (Danikh and Van der Gun, 1985).
The piezometric map presented in figure 11 suggests a pronounced convergence of groundwater flow towards the Sadah Plain. The wadi aquifer zones and the limestone aquifer units contribute to the recharge of the Sadah sandstone aquifer. Significant outflow of groundwater across the project area's boundaries only occurs through the valley of Wadi Marwan (near the surface water outlet) and around and south of Jebel Barash.

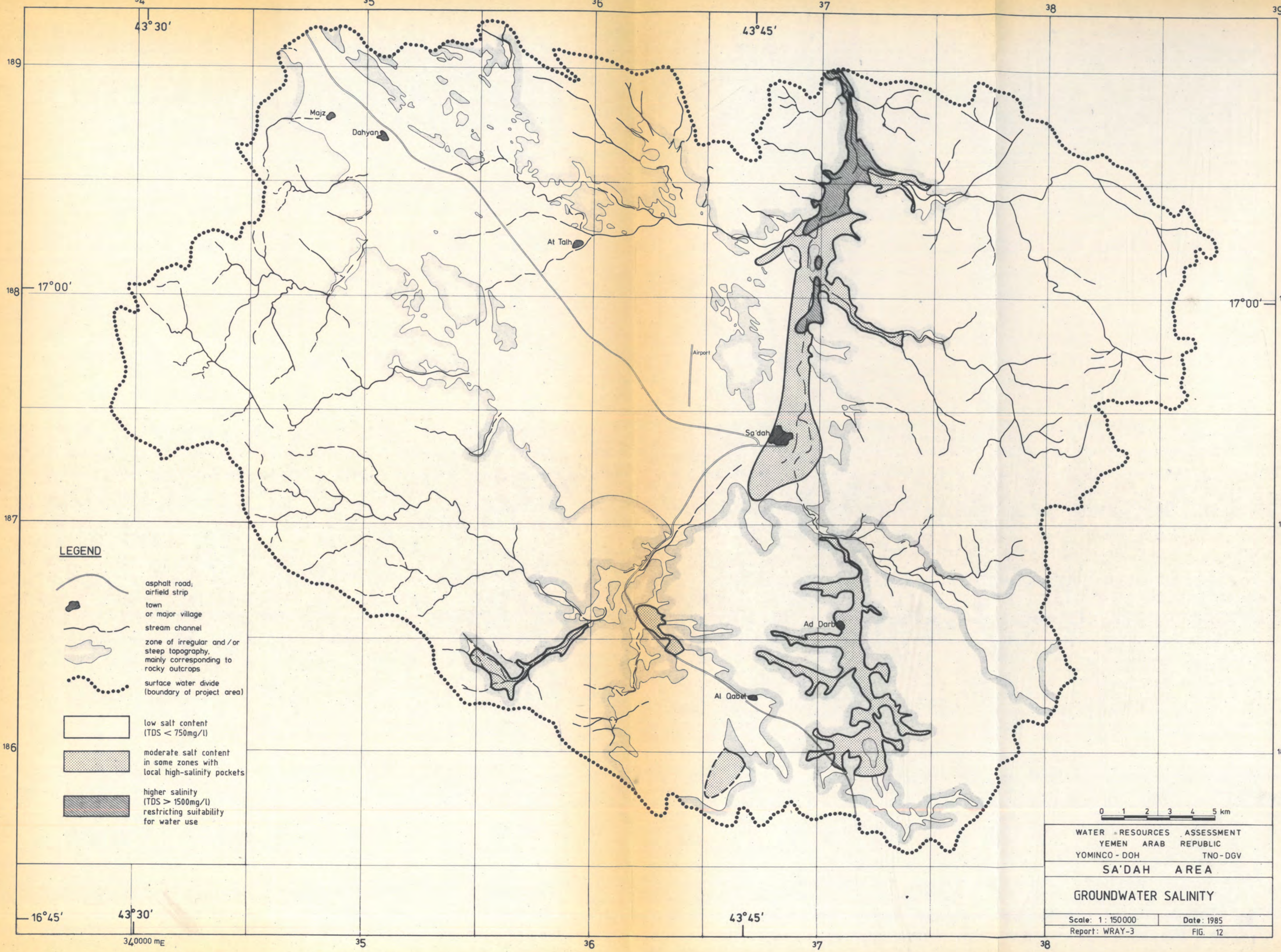
5.5 Groundwater quality

Groundwater is fresh and chemically of good quality almost everywhere within the sandstone aquifer, the deeper parts included (Gamal



LEGEND
asphalt road; airfield strip
town or major village
stream channel
zone of irregular and / or steep topography, mainly corresponding to rocky outcrops
surface water divide (boundary of project area)
depth to groundwater is 30m
depths shown represent 1982/1983 conditions
Majz
Dahyan
At Talh
Airport
Sa'dah
Ad Darb
Al Qabel
43°30'
43°45'
17°00'
16°45'
340000 mE
0 1 2 3 4 5 km
WATER RESOURCES ASSESSMENT
YEMEN ARAB REPUBLIC
YOMINCO - DOH
TNO - DGV
SA'DAH AREA
DEPTH TO GROUNDWATER
Scale: 1 : 150000
Date: 1985
Report: WRAY-3
FIG. 10


43°30'
43°45'
17°00'
16°45'
340000 mE
Majz
Dahyan
At Talh
Airport
Sa'dah
Ad Darb
Al Qabel
LEGEND
asphalt road; airfield strip
town or major village
stream channel
zone of irregular and / or steep topography, mainly corresponding to rocky outcrops
surface water divide (boundary of project area)
1900
piezometric level is at 1900m +m.s.l.
groundwater levels shown represent 1982/1983 conditions
0 1 2 3 4 5 km
WATER RESOURCES ASSESSMENT
YEMEN ARAB REPUBLIC
YOMINCO - DOH
TNO-DGV
SA'DAH AREA
GROUNDWATER LEVELS
Scale: 1: 150000
Date: 1985
Report: WRAY-3
FIG. 11



34
35
36
37
38
39
43°30'
43°45'
189
188
187
186
17°00'
16°45'
340000 mE
Majz
Dahyan
At Talh
Airport
Sa'dah
Ad Darb
Al Qabel
LEGEND
asphalt road; airfield strip
town or major village
stream channel
zone of irregular and/or steep topography, mainly corresponding to rocky outcrops
surface water divide (boundary of project area)
low salt content (TDS < 750mg/l)
moderate salt content in some zones with local high-salinity pockets
higher salinity (TDS > 1500mg/l) restricting suitability for water use
0 1 2 3 4 5 km
WATER RESOURCES ASSESSMENT
YEMEN ARAB REPUBLIC
YOMINCO - DOH
TNO - DGV
SA'DAH AREA
GROUNDWATER SALINITY
Scale: 1 : 150000
Date: 1985
Report: WRAY-3
FIG. 12

et al., 1985a; Van Overmeeren, 1985a; Elewaut, 1985). The water is of the calcium-bicarbonate type and electrical conductivities of 1000 micromho/cm are only exceeded in a belt along Wadi Sadah, near the outlet of the Sadah Plain (evaporation) and in the southern part of the Mahathir Plain (Akbra shales).

Salinity prohibits or severely restricts the practical utilization of groundwater in large parts of the lower Marwan, Nushur and Akwan valleys. Here, the electrical conductivities of groundwater are commonly 2000-6000 micromho/cm, although pockets of fresher water are present. Fig. 12 is a groundwater salinity map.

The temperature of groundwater pumped from the sandstone aquifer (22-26°C) is markedly higher than that of the wadi aquifers' water (18-24°C); this is because the sandstone units are thicker.

The bacteriological quality of the groundwater may not everywhere meet accepted standards for public water supply, because many dug wells are visibly contaminated.

5.6 Groundwater wells and abstractions

It may be assumed that well digging has a long tradition in the Sadah area. Nevertheless, important changes have occurred during recent years (Gamal et al., 1985). They are shown in figures 13 and 14.

As figure 13 shows, the area had almost 800 wells at the beginning of 1970 and since then 10-15 additional wells were dug each year until 1976. However, the introduction of drilling rigs in that year marked the beginning of a new era: from 1978 onwards the number of wells increased drastically and the majority of the 2000 wells present in 1983 are drilled wells. Well-digging is still continuing in the area, but has become rare on the Sadah Plain.

Before the advent of well drilling, water was abstracted manually from dug wells. Donkeys or camels were used to lift the buckets of

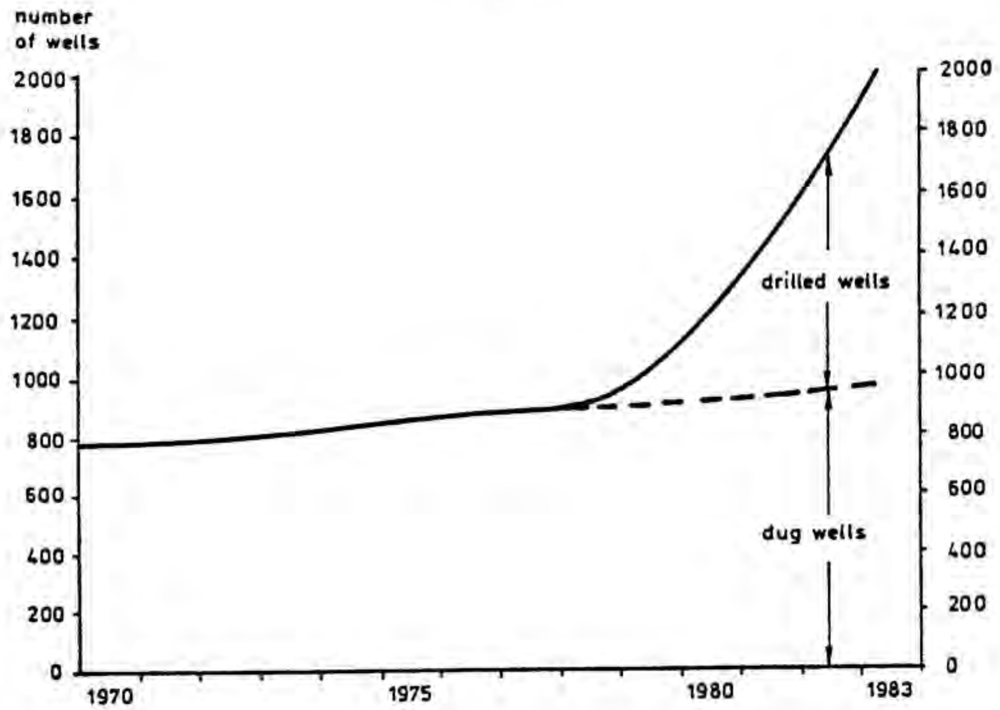


FIG. 13 INCREASE IN THE NUMBER OF WELLS

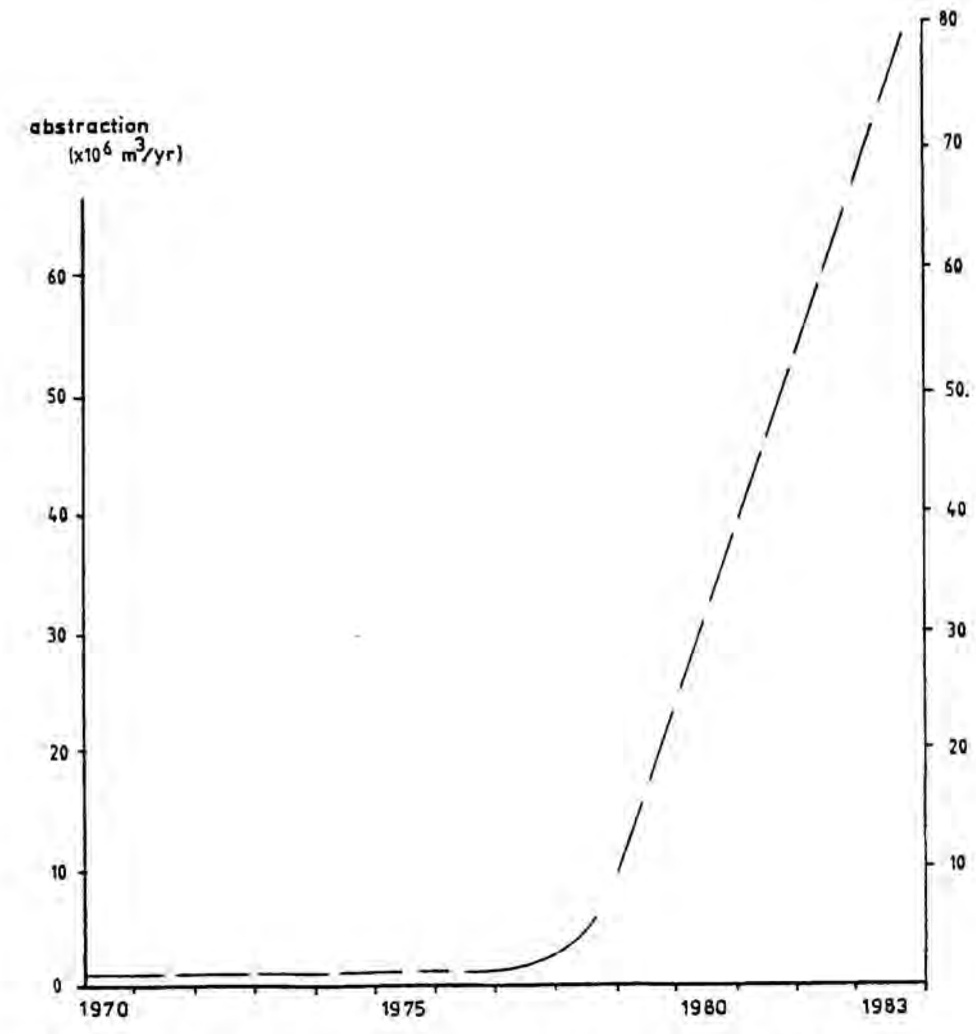


FIG.14 ESTIMATED INCREASE IN GROUNDWATER ABSTRACTION

water for irrigating small fields; the paths along which these animals had to move are still visible near many wells. In only a few locations (in zones of shallow water tables) have small-capacity suction pumps that might date back from before 1976 been observed. It is clear that the groundwater abstraction at that time was very low and probably added up to less than $1x10^6$ m^3/year for the total area.

The widespread introduction of pumps and the rapidly increasing number of wells gave an unprecedent boost to groundwater abstraction in the area (fig. 14). The total abstraction in 1983 was approximately $76x10^6 m^3$.

Table 2 summarizes some relevant data on wells and groundwater abstraction for the different aquifer systems.

aquifer unit	no. of pumped wells	% drilled	average depth (m)	average yield (l/s)	total abstraction ($x10^6 m^3$/yr)
Sadah sandstone	1159	91	116	6.7	58.2
Mahathir sandstone	37	95	138	5.7	2.5
Wadi'Ah (limestone/wadi zone)	131	55	103	5.9	6.7
other 'wadi aquifer zones'	257	32	33	5.9	8.4
Total for area	1584	78	102	6.5	75.8

Table 2: Pumped wells and groundwater abstraction.

None of the aquifers in the area offer excellent conditions for groundwater abstraction: in order to obtain moderate yields (5-10 l/s) drilled wells must be relatively deep and be pumped to considerable drawdowns. In the sandstone aquifers, drawdowns of 10-30 metres are common in drilled wells.

The areal distribution of groundwater abstraction is shown in figure 15. Approximately 99% of all pumped groundwater is used for irrigation.

5.7 Groundwater storage

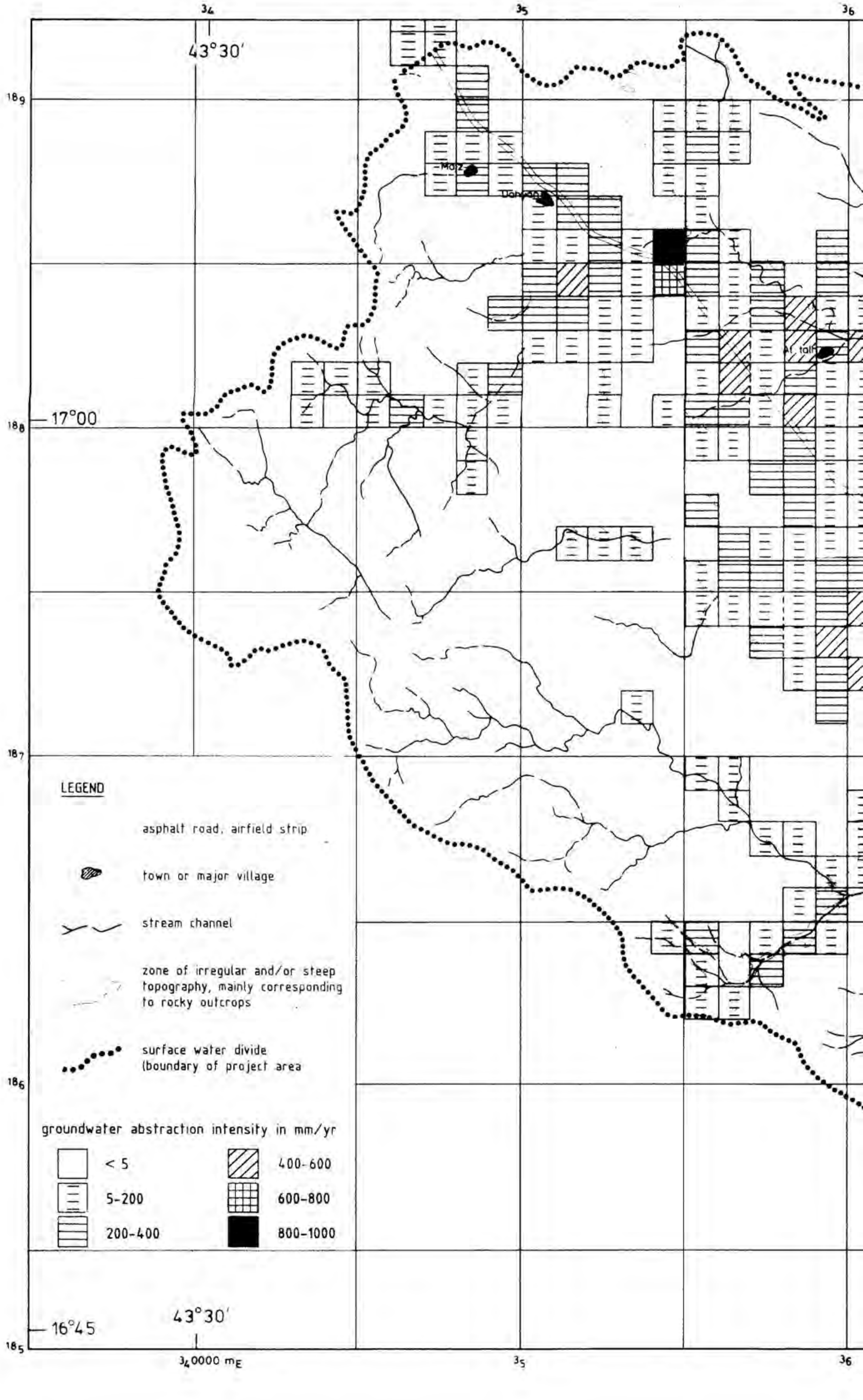
By far the largest groundwater reservoir of the area is the Sadah sandstone aquifer. The amount of groundwater stored inside it is of the order of 10^4 millions of cubic metres.
Less detailed information is available for the other units, but their groundwater storage probably adds up to less than 5% of the figure mentioned above.

5.8 Groundwater discharge and replenishment

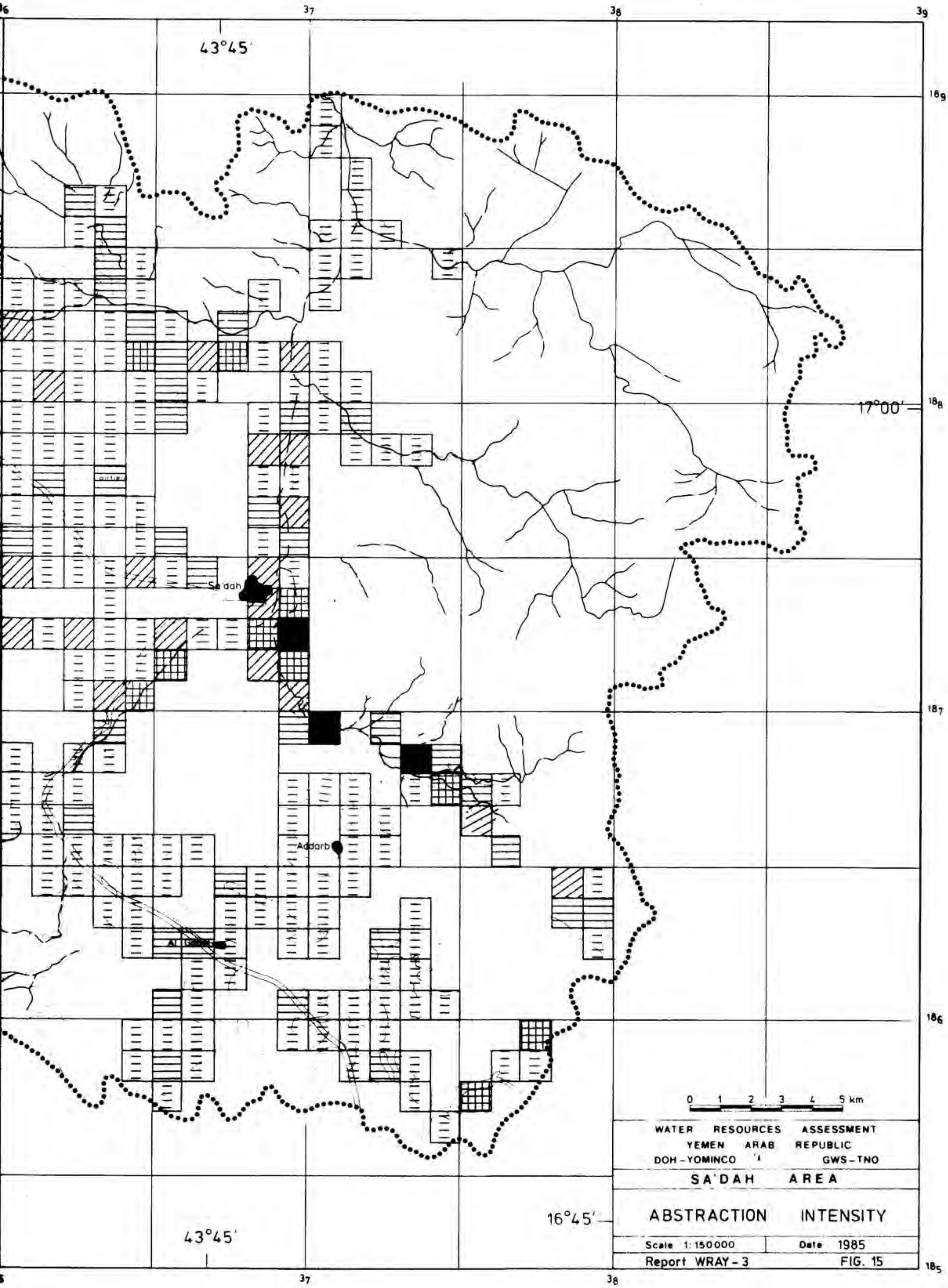
In the past, most of the area's groundwater discharge took place by evaporation and evapotranspiration in zones with shallow water-tables, by springs and by subsurface outflow across the boundaries. The average rate of this 'natural discharge' was in equilibrium with the average rate of replenishment (recharge). Groundwater abstraction (artifical discharge), however, has increased enormously in recent years and is now several times greater than the original natural discharge. As a result, natural discharge has diminished and will decrease more and more.

It is difficult to assess groundwater recharge, because it cannot be measured directly. Analysis of the information collected (Danikh and Van der Gun, 1985; Elderhorst and Van der Gun, 1985) indicates that the average rate of recharge under 1983/1984 conditions is unlikely to exceed 26 million cubic metres a year (fig. 6). It is assumed that $11x10^6$ m^3 of this corresponds to the 'natural recharge' and $15x10^6$ m^3 to additional recharge by return flow of pumped groundwater (20%).

It is clear that the dynamic equilibrium between recharge and discharge of groundwater has been disturbed by the very high groundwater abstraction rate. As a result, groundwater storage is being depleted (fig. 6). Declining water levels can only become stable again if groundwater abstraction is reduced. Groundwater abstraction should not exceed the difference between recharge and natural discharge.



43°30′
17°00′
16°45
LEGEND
asphalt road, airfield strip
town or major village
stream channel
zone of irregular and/or steep topography, mainly corresponding to rocky outcrops
surface water divide (boundary of project area
groundwater abstraction intensity in mm/yr
< 5
5-200
200-400
400-600
600-800
800-1000
3₄0000 mE



WATER RESOURCES ASSESSMENT
YEMEN ARAB REPUBLIC
DOH – YOMINCO GWS – TNO

SA'DAH AREA

ABSTRACTION INTENSITY

Scale 1:150000 | Date 1985

Report WRAY – 3 | FIG. 15

6. FUTURE DEVELOPMENT AND MANAGEMENT OF WATER RESOURCES

6.1 Surface water development

Surface water flows in the area are intermittent, unpredictable, of short duration and sometimes devastating. In order to make efficient use of such a resource when it is convenient, a storage reservoir is required. There are, however, no surface water reservoirs in the area, except for small cistern-type ones. This is partly because of regimes of the wadis and partly because of the lack of suitable sites for such structures. It is said that in previous times there was a dam at the lower end of Wadi Abdin; this seems to be one of the few suitable sites for such a structure.

The lack of surface water storage reservoirs does not imply that all surface water is lost. As been mentioned before (section 4.3), intelligent use is made of soil reservoirs in all parts of the area to intercept, store and utilize surface water. In this way, a substantial part of total run-off benefits agriculture. Another part of run-off infiltrates and recharges the groundwater reservoirs.
Because surface water outflow from the area is minor, the only significant losses of surface water occur by evaporation from bare, uncultivated zones. It is unlikely that these losses can be suppressed easily.

Briefly, there seems to be little scope and little need for surface water diversion or retention dams. Rather, the prevailing 'run-off harvesting systems' should be preserved and - where possible - improved.

6.2 Groundwater resources management

Both groundwater storage and the rate of renewal (recharge) condition the availability of groundwater.
In small, local aquifer systems (e.g. wadi aquifer zones) the controlling influence of recharge is often apparent: wells become dry or less productive during the dry season or in years of little rainfall. As a result, groundwater abstraction there adapts almost automatically to the prevailing rate of recharge.

In larger, regional aquifers (Sadah sandstone aquifer), there is usually no such mechanism for directly adjusting the total abstraction, because groundwater in storage acts as a buffer. This offers more flexibility for the people who are exploiting the resource, but - on the other hand - requires external vigilance and control in order to protect the aquifer. If over-exploitation continues for too long, in the long run its negative effects might outweigh its initial advantages.

The important Sadah sandstone aquifer is in a state of severe over-exploitation, necessarily accompanied by falling groundwater levels (Danikh and Van der Gun, 1985).
These falling water levels may create a number of technical problems (drilling, pumping), cause unit costs of water to increase and, finally, reduce or even stop the availability of groundwater (exhaustion). It is worth examining expected future conditions and the possibilities of improving them by groundwater management.

In order to predict what might happen in the future, a numerical model study was carried out for the main part of the Sadah sandstone aquifer (Elderhorst and Van der Gun, 1985). The Prickett-Lonnquist Aquifer Simulation Model was adopted for this purpose. Groundwater abstraction was considered as being a 'controllable' variable, to be influenced by groundwater management activities. Scenarios were defined and effects predicted for each of the following management strategies:

1. uncontrolled groundwater development, assuming that expansion will stop only when no more irrigable land is available;
2. uncontrolled groundwater development, assuming that total abstraction becomes increasingly subject to negative feedback from decreasing economic benefits and from technical problems;
3. partial control: no more new wells or pumps allowed;
4. complete control: total regional abstraction rate reduced to the average rate of recharge.

Groundwater levels were simulated by the model over a period of 200 years. Such a long period is necessary because groundwater systems

react very slowly and thus also recover extremely slowly from any undesired condition. The results for scenario 4 are sensitive for inaccuracies in the data on the groundwater system; conditions for scenarios 1, 2 and 3 are more favourable in this respect.
Table 3 summarizes the main characteristics of the assumed scenarios and the practical consequences that different management strategies may produce.
All scenarios also include some groundwater mining. The more intensive the mining during a certain period, the more pronounced will be its advantages (more water developed) and its disadvantages (see table 3).

Scenario 1 shows a disastrous development: the available groundwater resources are exhausted in a relatively short time. It is a pure 'mining' scenario, that finally puts an end to groundwater-irrigated agriculture in the area. Such a development should be prevented at all costs.
It is not known whether under absence of water resources management the scenario 1 will result or any other scenario in between the scenarios 1 and 2. This depends on future socio-economic factors that are unknown yet. But even under scenario 2 very large declines in groundwater will still occur: a high percentage of existing wells will fall dry, the real costs of pumped groundwater will increase dramatically and some zones of the aquifer will even become exhausted. The model study showed that these negative effects can be reduced substantially by selecting and implementing proper groundwater management strategies (Elderhorst and Van der Gun, 1985).

In scenarios 2, 3 and 4 the most problematic of the disadvantages of more intensive groundwater 'mining' is probably the effect of higher unit water costs. The high costs of pumped groundwater already constitute a fundamental economic problem in the country's agriculture. It is true that cropping patterns can be adjusted in order to avoid negative economic returns from pumped groundwater, e.g. by excluding cereals and alfalfa and focussing more on tree crops and profitable vegetables. Seen in a wider perspective - national or regional - it is unlikely that such an adaptation will be realistic

Characteristics and effects	Scenario 1	Scenario 2	Scenario 3	Scenario 4
- Controlling factor in groundwater development	irrigable lands	water production costs	no new wells or pumps allowed	strict control of total abstraction
- Expected volume of groundwater developed during period 1983-2183 (in millions of cubic metres)	>9628	7440	5880	2500
- Expected average groundwater level decline (m) after				
50 years	270	84	51	15
200 years	-	133	105	41
- Percentage of area where aquifer will be exhausted after 200 years	100	8	6	3
- Average costs per m^3 of pumped groundwater (YR) in 1983	0.70	0.70	0.70	0.70
after 50 years	~ 4.00	1.66	1.29	0.86
after 200 years	-	2.24	1.91	1.16
- Expected net benefits from groundwater-irrigated agriculture after 50 years for selected crops:				
sorghum	negative	negative	negative	negative
wheat	negative	negative	negative	negative
barley	negative	negative	negative	negative
alfalfa	negative	negative	negative	zero
maize	negative	negative	moderate	moderate
vegetables/fruits	negative	good	good	good
potatoes	moderate	high	high	high
q at	high	very high	very high	very high
- Percentage of existing wells falling dry within 30 years	90	32	22	10

Notes: 1) Under scenario 1 complete exhaustion after 58 years
2) Cost and returns on the basis of present values.

Table 3: Groundwater abstraction scenarios and their predicted effects for the Sadah sandstone aquifer.

on a large scale, because similar problems of groundwater storage depletion threaten many other zones, especially the other Highland Plains. Furthermore, doubling or tripling the real costs of pumped groundwater means an equivalent absolute loss of income to the farmers.

Obviously, there are good reasons for controlling groundwater abstraction in the Sadah area, in particular from the sandstone aquifers. It is recommended to formulate and implement a water management strategy in order to reduce regional groundwater abstraction. Preferably, such a strategy should fit into an overall national water management policy.
For the Sadah area, the option of not permitting any new well to be constructed or deepened, nor any new pump to be installed should be implemented immediately. Only very special, well-defined cases (e.g. wells exclusively for domestic water supply) should be exempted.

6.3 Groundwater development

In cases where drilling of new wells is permitted, intelligent use of the outcomes of the Sadah water resources assessment study may contribute to adequate decisions on well siting and design. As a result, funds will be saved by reducing the number of dry or poorly productive wells.

The selection of suitable sites can be guided by the detailed basic field data and the maps and interpretations based upon them. All this information is available in the database of YOMINCO's Department of Hydrology at Sana'a; the most important aspects are covered by this report and its technical annexes.

The type of well to be chosen for a particular site and the design to be made depend on the type of aquifer found there. These aspects are discussed below for each of the aquifer units distinguished.
In the 'wadi aquifer zones' hydraulic conductivity is generally expected to decrease with depth. The project's findings indicate that in these zones wells deeper than 60-70 m are no more productive than shallower wells and are thus not economically justified. From the hydraulic point of view, wide-diameter wells are preferable.

The sandstone aquifers are in general very thick and are tapped by many drilled wells, most of which are deeper than 100 m. Here, drilled wells (small diameter, but deeper) are preferable to dug wells (wide diameter), because the former are less sensitive to the declining groundwater levels. The rather low hydraulic conductivity of the sandstone requires that at least 60-100 m of the well should extend below the groundwater table in order to permit sufficient flow towards the well (5-10 l/s). The benefits of deeper wells are probably offset by rapidly increasing drilling costs. It is as yet unknown, whether greater well depths might extend the wells' useful life, by reducing groundwater entry velocities at the well face.

The success of drilling in the limestone aquifer units beyond the local 'wadi aquifer zones' is very variable and unpredictable. It depends on whether important fracture and fissure systems are struck. Tectonic features should be identified before a well is drilled in these rocks. Furthermore, there is geological evidence that a more reliable sandstone aquifer underlies the limestone beds. Deepening dry limestone boreholes until they penetrate this sandstone unit might turn them into productive wells. It is not known, however, how deep the sandstone aquifer is situated and, consequently, whether the economics of such deepening would be favourable.

6.4 Improving irrigation efficiencies

The Sadah water resources assessment study did not include observation and analysis of the efficiency of the actual water use. Nevertheless, the efficiency of the use of pumped groundwater can certainly be improved, because modern water-economizing irrigation techniques (e.g. trickle irrigation) are not being used and most pumped groundwater is still conveyed through unlined ditches. These techniques should be studied and appropriate improvements should be implemented. More efficient water use will not only reduce water input costs per unit of agricultural land, but will also help conserve of the area's limited water resources.

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APPENDIX 1: List of persons involved in the Sadah water resources assessment

Supervision

Ali Gaber Alawi	Director General Geological Survey Board, YOMINCO (- 1984)
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Ali Atroos	Hydrogeologist
Noori Gamal	Hydrogeologist
Abdul Latif Hasan	Geophysicist
Mohamed Assabahi	Geophysicist
Mohamed Abdul Hamid	Geophysicist
Khaled Ashahari	Geophysicist
Adel Derhem	Geophysicist
Abdul Rahman Abdullah	Drilling supervisor
Saad Saleh	Hydrological technician
Abdallah Nasher	Hydrological technician
Mohammed Nassiri	Hydrological technician
Fuad Al Kabir	Hydrological technician
Abdul Elah Al-Arasi	Hydrogeological technician
Nabeel Abdul Qadir	Hydrogeological technician
Abdul Azis Hussein	Hydrogeological technician
Ali Shamsan	Hydrogeological technician
Ahmed Abdu Saef	Hydrogeological technician
Mohamed El-Fakeh	Geophysical technician
Kennedy Kasim	Geophysical technician
Aidroos Ahmed Ali	Geophysical technician
Ebrahim Ali Saef	Geophysical technician
Ahmed Addahbaly	Assistant

YOMINCO/DOH team (continued)

Abdul Wahab Al-Ariqi	Accounter
Ahmed Abdulla Ali	Administrator
Tahir Ali Musleh	Mechanic
Abdul Hakim Wahib	Driver
Yahya Al-Akwa'a	Driver
Saleh Al-Koal	Driver
Mohamed Nagi	Driver
Yahya Al Kibsi	Processing technician
Faisal Mohamed	Cook
Hail Abdullah	Cook
Abdu Abbas	Cleaner
Hamida	Draughtswomen
Fatima	Typist

Dutch resident team

Jac van der Gun	Co-manager/hydrologist (TNO-DGV)
Ronald van Overmeeren	Geophysicist (TNO-DGV)
Flip Nota	Database specialist (DGIS)
Dirk van de Leygraaf	Technician (TNO-DGV)

TNO-DGV headquarters (incl. short missions)

Wil Ewalts	Geophysical engineer
Emile Elewaut	Geophysicist
Joop Beekman	Drilling supervisor
Wilbert Elderhorst	Hydrologist
Peter Mulder	Hydrologist
Ruud Nicolaas	Draughtsman
Ad van de Ven	Draughtsman
Piet Tuin	Draughtsman
Grace van Dullemen	Typist
Jet Clarenburg	Typist