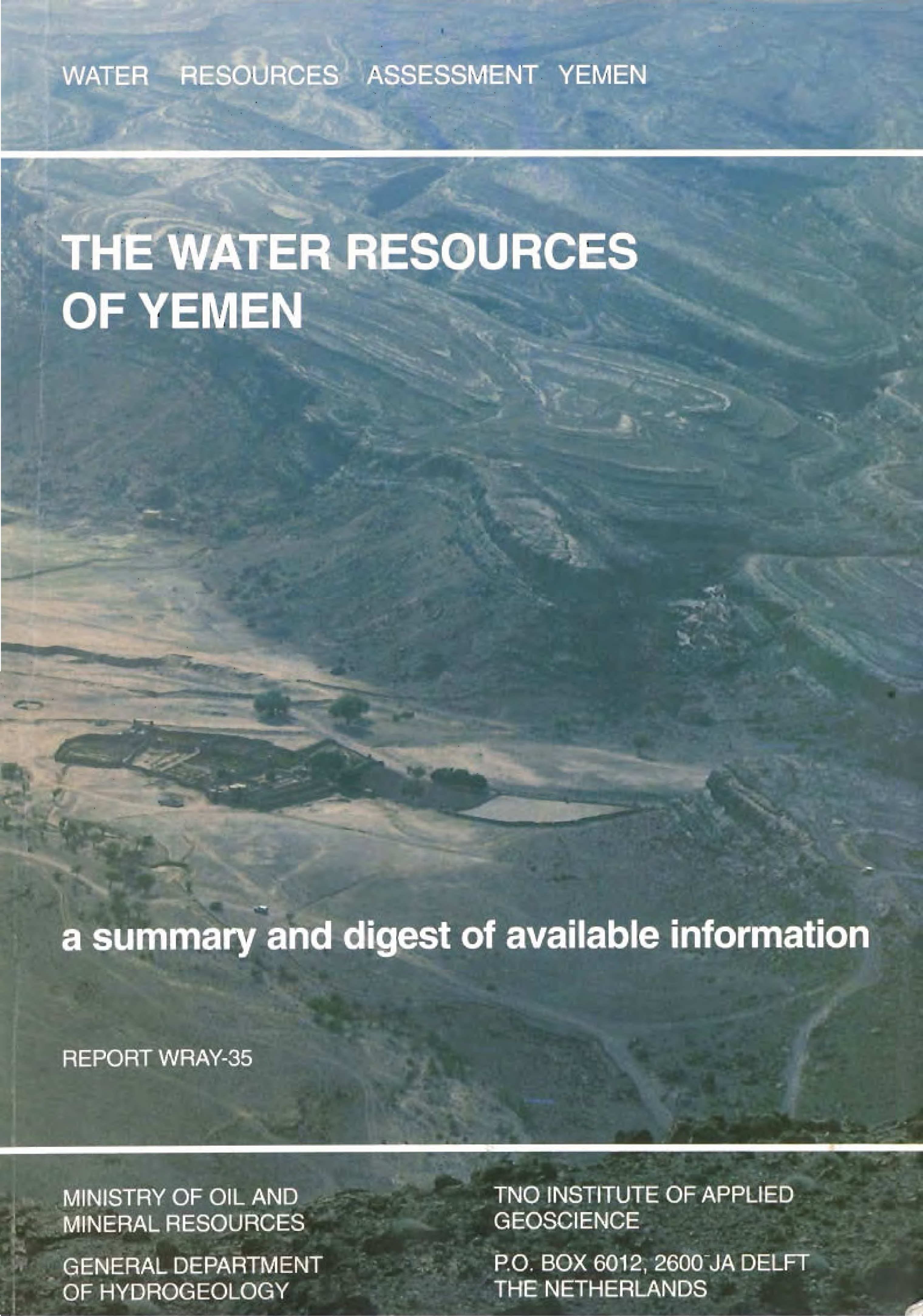

WATER RESOURCES ASSESSMENT YEMEN

THE WATER RESOURCES OF YEMEN

a summary and digest of available information

REPORT WRAY-35

MINISTRY OF OIL AND MINERAL RESOURCES

GENERAL DEPARTMENT OF HYDROGEOLOGY

TNO INSTITUTE OF APPLIED GEOSCIENCE

P.O. BOX 6012, 2600 JA DELFT
THE NETHERLANDS

Hydrog 9 Roel Mulder

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Report WRAY-35

Ministry of Oil and Mineral Resources
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Sana'a, Republic of Yemen

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WATER RESOURCES ASSESSMENT YEMEN

The Republic of Yemen
Ministry of Oil
and Mineral Resources
Mineral Exploration Board

Kingdom of The Netherlands
Ministry of Foreign Affairs
Directorate General of
International Cooperation

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compiled by

Jac A.M. van der Gun and Abdul Aziz Ahmed

in collaboration with

Abdallah Saleh Saif, dr Abdul Majid Mohamed, Salim Ba-Shueib and Ton Negenman

Report WRAY-35

March 1995

Ministry of Oil and Mineral Resources
General Department of Hydrogeology
Sana'a, Republic of Yemen

TNO Institute of Applied Geoscience
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The Netherlands

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ABBREVIATIONS

CSO	Central Statistical Organisation
DOH	Department of Hydrology (presently: GDH)
DHV	DHV Consultants, The Netherlands
EPC	Environmental Protection Council
ERADA	Eastern Region Agricultural Development Authority
FAO	Food and Agricultural Organization (of the United Nations)
GDH	General Department of Hydrogeology (belongs to MOMR)
GDP	Gross Domestic Product
GDWRS	General Department of Water Resources Studies (presently: GDH)
h	hour
HWC	High Water Council
ILACO	International Land Consultants, The Netherlands
ITCZ	Inter-Tropical Convergence Zone
l	litre
MAAR	Ministry of Agriculture and Water Resources
MAWR	Ministry of Agriculture and Agrarian Reform
mg	milligram
m^3	cubic metre
Mm^3	millions of cubic metres
MOMR	Ministry of Oil and Mineral Resources
NORADEP	Northern Region Agricultural Development Project
PDRY	People's Democratic Republic of Yemen
RIRDP	Rada Integrated Rural Development Project
RoY	Republic of Yemen
RSCZ	Red Sea Convergence Zone
s	second
SAWAS	Sources for Sana'a Water Supply Project
SSHARDA	Sana'a-Sadah-Hajjah Regional Development Authority
SURDUP	Southern Uplands Regional Development Project
SYP	Soviet-Yemeni Project
TBWRS	Tihama Basin Water Resources Study
TDA	Tihama development Authority
TNO	Netherlands Organization for Applied Scientific Research
TS-HWC	Technical Secretariat of the High Water Council
UNDP	United Nations Development Programme
WMO	World Meteorological Organization
WRAY	Water Resources Assessment Yemen Project
YAR	Yemen Arab Republic

ABSTRACT

Information on Yemen's diverse water resources is scattered over many reports, publications, maps, archives and data bases. people looking for complete and up-to-date information on the water resources of a specific area in the country often find it difficult and time-consuming to identify, locate and interpret this information. And those who are interested in a general overview of the most important surface water and groundwater systems in Yemen face the risk of easily getting lost in a labyrinth of only partly consistent data and reports, while at the same time not finding essential information on several regions of interest. These were the reasons for the WRAY project to prepare this report, which is intended to provide a clear summary of the present-day water resources conditions of Yemen, with uniform and consistent maps, tables, figures and an extensive list of references for those who are looking for more detail. This report, entitled "The Water Resources of Yemen", is the last technical report to be produced by the WRAY project (report WRAY-35).

The report was prepared by a joint Yemeni-Dutch project team consisting of six persons. After an introduction, the report starts with a brief outline of the geographical setting of the country. This includes physical aspects such as topographic features and geology, and a few socio-economic indicators (demography and economic aspects of water) as well. The subdivision into administrative and geographical regions is presented to facilitate the regional description.

Chapter 3 discusses to the sources of information used to compile this report. Approximately 600 technical reports and publications related to Yemen's water resources were identified and the most relevant ones among them were studied and summarized. Time series of rainfall and other meteorological variables, of runoff and of groundwater levels were collected, screened, processed, analysed and summarized. Altogether, this entailed millions of basic data. Maps and other additional information was studied, and methods were developed to recognize and describe the main hydrological and hydrogeological features in a unified approach. The complete list of references and selected tables with administrative data and summary statistics of the hydrological networks in the country are presented in the appendices.

The climatic conditions of Yemen are reviewed in Chapter 4. The emphasis is on rainfall and on evapotranspiration, because these variables are most significant in relation to the water resources. Variations both in space and in time are taken into consideration. A new national isohyet map has been produced to depict the variations of average annual rainfall over the country. The observed variations are explained as a function of global processes and local factors. Potential evapotranspiration is much less variable in space and in time than rainfall. It is shown that most of the national territory has an arid to hyper-arid climate; limited zones in the mountainous western part of the country, however, have wetter climates ranging from semi-arid to sub-humid.

Chapter 5 deals with surface water. Rain storms in Yemen typically cause flash flows in the numerous wadis, whereas baseflows are low or non-existent. The wadis in Yemen are grouped into four main regional systems, and within these a distinction is made between 'runoff producing zones' and 'runoff absorbing zones'. The report assesses the runoff volumes

generated within these regional systems, as well as in the catchments of the main wadis. The variations of flow in time and in space are linked to meteorological and physiographic factors, thus providing a basis for understanding them and making reasonable estimates for ungauged catchments.

A synopsis of the groundwater conditions then follows in Chapter 6. It starts with a hydrogeological characterization of the different geological formations, which culminates in the presentation of a new hydrogeological overview map. This map attempts to harmonize valuable elements of previously prepared hydrogeological maps (such as Robertson's map of the Republic of Yemen and the Russian map of the southern governorates) with information contained in the numerous reports consulted. It is a small-scale overview map, intending to highlight the main aquifers and their relative importance. The main aquifers are briefly described. Attention is also paid to the dynamic aspects of the groundwater systems and to groundwater quality.

The report concludes with a brief description of water resources development in Yemen, both in the past and at present. Highly successful endeavours alternate with problematic developments and trends. In the context of this report it is easy to understand that physical constraints cannot be ignored if sustainable development of the water resources is aimed for. This and other factors underline the need for effective and integrated water resources management in Yemen.

Additional information which is believed to be of particular interest to the readers of this report is presented in a number of appendices. They include an extensive bibliography related to the water resources of Yemen, administrative data on the hydrometeorological monitoring networks and key-statistics of monitored variables.

1 INTRODUCTION

Water is a natural resource of vital importance: no life is possible without it. In a dry country like Yemen we see this trivial fact clearly reflected in the geographic patterns of human settlement. The centres of population and economic activity could develop only where significant quantities of water are within reach. In modern times, increasing population densities and strong aspirations for a higher level of welfare have stimulated studies to collect and analyse information on the occurrence, quantity and quality of the water resources all over the country. Such water resources assessment studies are an essential tool for the proper development and management of these resources and for adequate economic planning. Several hundreds water resources reconnaissance and assessment studies have been carried out in Yemen in the last 30 years. Most of these studies take an engineering point of view: they are intended to provide a basis for the design and implementation of new domestic, industrial or irrigation water supply systems or for the expansion or improvement of existing ones. The idea behind such studies is in the first place to optimize investments in technical infrastructure, given the specific characteristics of the water resources. That the water resources themselves are finite and vulnerable, and thus a matter of serious concern, is something that has received only limited attention until now, although awareness of the importance of these aspects is growing. In recent years it has triggered a modest number of studies that focus on the information required for controlling and protecting the scarce water resources, and on the development of water resources management plans.

The many scattered studies have resulted in a large quantity of data on the water resources of Yemen and its regions. But it is often difficult to trace and collect the relevant basic information, to fill gaps, to solve apparent contradictions and to fit the pieces of information together to obtain a complete and consistent picture that takes into account the latest field data and interpretations. This report was written with the intention to offer help in this respect: it presents an overview of the water resources conditions of Yemen, compiled on the basis of the many studies mentioned above, and it assists in identifying relevant original studies and other information. It is the result of a joint effort of the General Department of Hydrogeology (GDH) of the Yemeni Ministry of Oil and Mineral Resources and TNO Institute of Applied Geoscience, Delft, The Netherlands. These two partners have been co-operating since 1982 in a programme entitled "Water Resources Assessment Yemen" (WRAY) which expires April 1995. An earlier national water resources compilation - limited to the former Yemen Arab Republic - was produced by the same WRAY project in 1984 (Van Enk and Van der Gun, 1984). Since that report was written, many more reports, maps and basic data have become available, and the regional knowledge of the national and expatriate project team-members has expanded significantly. In addition, the national territory was expanded as a result of the unification of the former YAR and PDRY into the Republic of Yemen in May 1990. These reasons made it desirable to prepare a completely new version of the previous report.

"The Water Resources of Yemen" intends in the first place to provide a consistent and easily readable summary of the hydrology and hydrogeology of Yemen, focusing on general features. As such it is hopefully a useful introduction and reference to anyone interested in the water resources of Yemen. Special attention has been paid to the production of a number of maps that show relevant aspects in a nation-wide context, which in the opinion of the authors are often insufficiently presented in existing reports. But the report also has to serve those who look for more detail on certain phenomena or on certain geographic regions, or who wish to trace original data and reports. Not only does this report therefore include extensive references to the literature on water resources in Yemen, but it has also appendices that include more detailed information or provide a key to accessing additional information. These appendices occupy approximately as many pages as the main text. An extensive list of reports and publications on water in Yemen, administrative data of monitoring networks in Yemen and selected statistics of monitored hydrological variables are the components of these appendices.

A compilation report like this inherently has many flaws, for a number of reasons. First (and most important) of all there are the limitations of time available. Among others, they prevented all the available literature from being studied in depth; thus a selection had to be made of reports that were considered most relevant. Many of these reports appeared impossible to get access to, or only incomplete copies could be studied. The restrictions in time had a similar impact on the compilation, screening and processing of monitoring data, on the preparation of maps, on digesting the information, and on writing the report. Tasks were divided over a study team of six persons, whose names appear on the title page of this report. This was necessary to comply with the voluminous task given, but unavoidably produced some problems as well with regard to coordination and transfer of information. Furthermore, there are the difficulties in fully understanding and critically analysing the results of so many studies done and reported by professionals from countries with widely diverging professional cultures and practices. And finally, condensing the vast quantities of information available to a single concise and consistent report requires many compromises and subjective decisions.

The authors and the other members of the study team are indebted to many organizations and persons who made the compilation of this report possible. First of all to the Governments of Yemen and The Netherlands, for funding the activity. Secondly, to the Ministries, Authorities, companies and projects from which reports or data were obtained. Their huge efforts in field work, often under difficult conditions, provided the building stones to this report. Thirdly, to the many Yemeni and foreign colleagues who expressed their views on water-related aspects of Yemen during discussions and at conferences, thus contributing to our regional knowledge. Next, to the draughtsmen of TNO Institute of Applied Science in The Netherlands, who skilfully prepared the maps and some of the other figures. Finally, to our colleagues in the General Department of Hydrogeology, who pleasantly co-operated for many years in the assessment of water resources in Yemen, and -last but not least- to mr Ali Gaber Alawi, Chairman of the Mineral Exploration Board of the Ministry of Oil and Mineral Resources, who showed continuous interest in the WRAY project and gave it always warm and essential support. All these contributions are gratefully acknowledged.

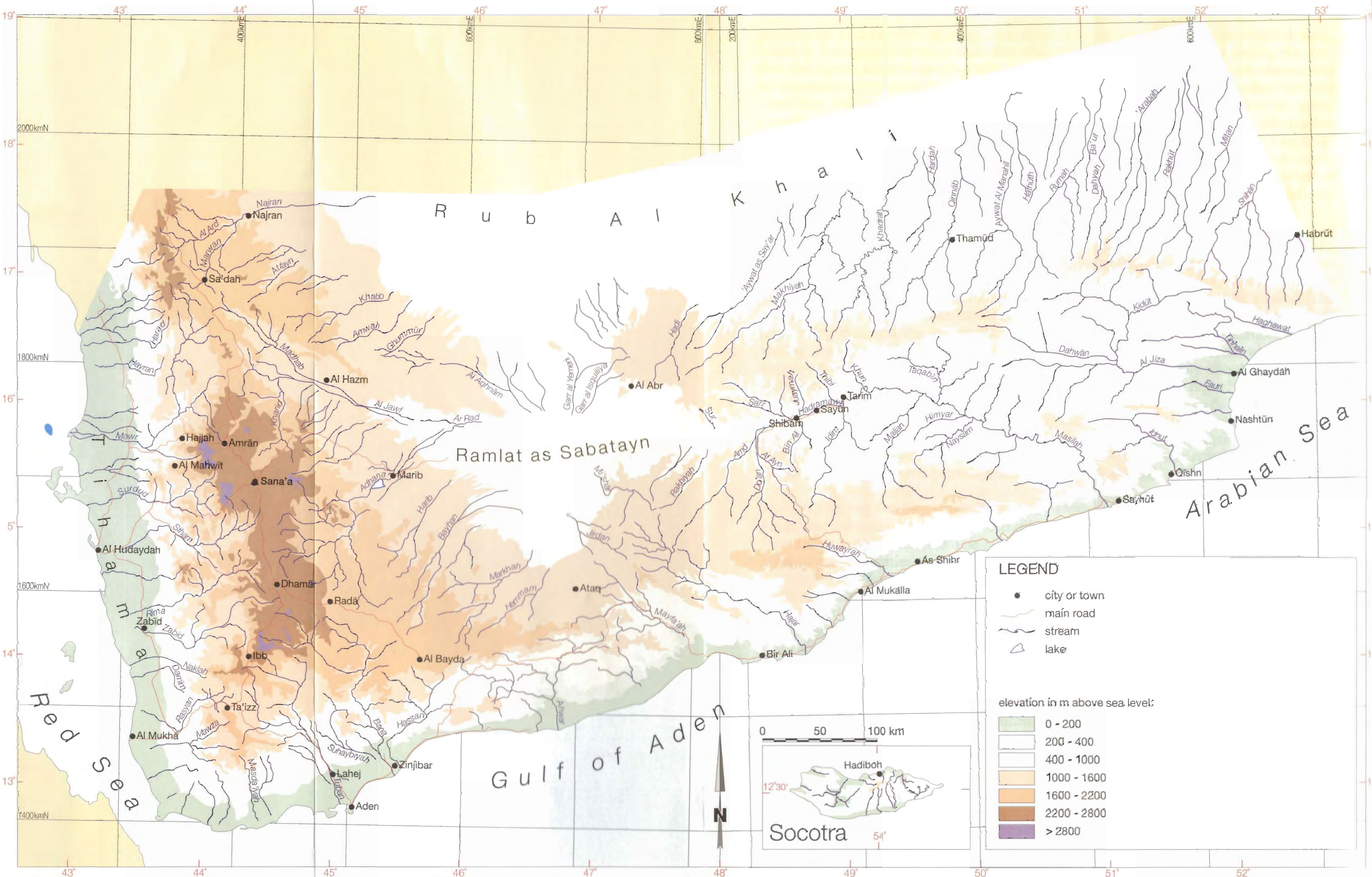


Figure 2.1 Topographic map of Yemen

2 GEOGRAPHICAL SETTING

2.1 Location and general topographic features

The Republic of Yemen is located at the south-southwestern edge of the Arabian Peninsula, between 12° and 19° north of the Equator and between 42° and 55° east of Greenwich. Apart from the mainland it includes many islands; the largest of these are Socotra in the Arabian Sea and Kamaran in the Red Sea. The country is bordered by Saudi Arabia in the North, Oman in the East, the Arabian Sea and the Gulf of Aden in the South, and the Red Sea in the West. The boundary between Yemen and Saudi Arabia has not yet been defined officially. According to the Statistical Year Book 1992 (CSO, 1993) the country has a total area of approximately 550 000 km^2.

A topographic map of Yemen is presented in Figure 2.1. It is in UTM projection and has been based primarily on the topographic maps 1: 1 000 000 and 1: 250 000 produced by Robertson (1991c), with some corrections for the hydrographic network.

The map reveals large contrasts in elevation, especially in the western part of the country. Broad and flat coastal plains border the Red Sea (Tihama) and the Gulf of Aden. They frame the strongly dissected mountain massif of western Yemen, where elevations range from a few hundreds metres to about 3760 metres above sea level. The eastern slopes of this massif are more gentle than the steep western and southern slopes; they merge gradually into the depression of the Ramlat as Sabatayn desert. The topographic expression of the eastern part of the country is somewhat less pronounced, but noteworthy are the topographically elevated belts parallel to Wadi Hadramawt ('Northern and Southern Hadramawt Arcs'), the broad and steep-sided Wadi Hadramawt canyon, and the topographic depression of Al Ghaydah. Only the principal wadis are shown. There is still some confusion on the names of some of the wadis in more remote areas. The main roads and a number of cities and towns are shown for orientation. Most of the urban centres -and certainly the largest ones- are located in the western part of the country.

2.2 Geology

Among the many sources of information on the geology of Yemen, particular reference is made to Beydoun (1964), Geukens (1966), Grolier and Overstreet (1978), El-Anbaawy (1985), the Arab Organisation for Mineral Resources (1986) and Robertson (1991a and 1991c). They are the main sources on which the compilation of the following sections is based.

2.2.1 Structure

The Arabian Peninsula is in a structural sense part of the African-Arabian plate. In Late Cretaceous and Cenozoic times this plate moved both eastward and northward with respect to the Eurasian plate. The subsequent collision of the two plates had a profound impact on the regional geology: in the north and east of the Arabian plate the basement is depressed and thickly covered with relatively young sediments (platform zone), whereas further south and west the Precambrian crystalline basement and its older sedimentary cover are uplifted and partly exposed (Arabian Shield zone).

The overall geological structure of Yemen is dominated by the Precambrian Arabian Shield in the western part of the country and an extensive and thick cover of Phanerozoic subhorizontal sediments further east. The uplifted shield ('Yemeni horst') is steep-sided to the west and south, but slopes gently north-eastwards. It mainly consists of crystalline basement, and is partly covered by sediments and volcanic rocks. Prominent regional tectonic features include the anticlinals known as the southern and northern Hadramawt arches, the rift valleys of the Red Sea and the Gulf of Aden, the Sadah-Al Jawf-Balhaf graben system ('Sabatayn structure'), and the Al Ghaydah Depression (Figure 2.2).

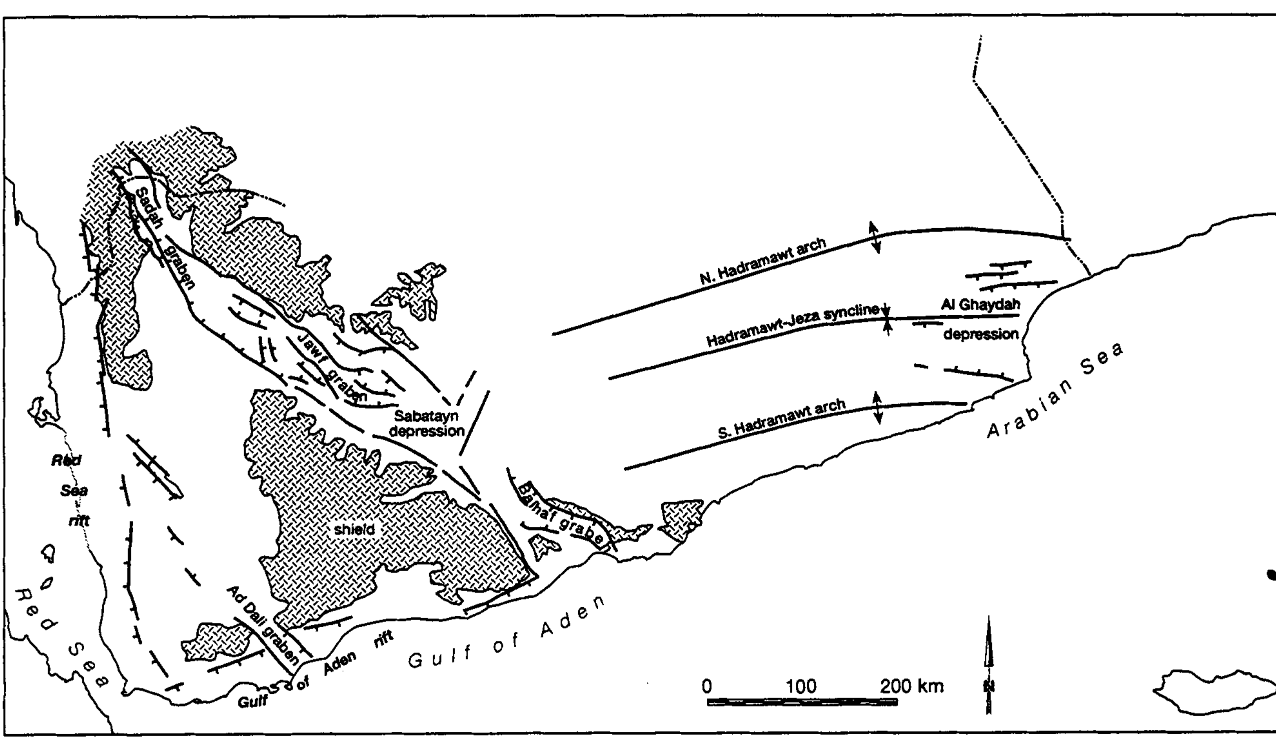


Figure 2.2 Principal tectonic features

2.2.2 Geological history

The Precambrian basement rocks of the area were subjected to intensive folding and to metamorphism. Afterwards, in the Palaeozoic Era, the basement was strongly eroded, levelled to a peneplain and warped. Subsequently it was covered by sediments during the Cambro-Ordovician, Permian, Jurassic and Cretaceous periods. Parts of these sediments are of continental origin, others were deposited in shallow marine or neritic environments.

Rapid subsidence started during the Jurassic period along the line which now defines the Al Jawf graben. It enabled the accumulation of organic-rich shales with petroleum source potential.

At the end of the Cretaceous and continuing during the Tertiary, the present-day western part of the Arabian Peninsula and neighbouring East-Africa was uplifted and started to break into separate blocks. Lava extruded through faults and fissures, and thick extended strata of tuffs and lavas (andesites, basalts, syenites, rhyolites, etc.) covered the Precambrian basement and the overlying -predominantly Mesozoic- sediments.

During the Tertiary the Arabian plate drifted north-eastward and caused the folding of the Zagros mountains in Iran. To the west and south the rift valleys of the present Red Sea and the Gulf of Aden opened between the peninsula and north-eastern Africa. Intensive block-faulting caused the mountains of Yemen and Ethiopia to break into numerous blocks, separated by faults running parallel to the axis of the Red Sea (NNW), the Gulf of Aden (ENE) and the Eritrean rift valley (NNE). The vertical displacement varies from one block to another; in some locations it exceeds 2000 m.
In the eastern part of the country thick blankets of predominantly carboniferous sediments were deposits during the Tertiary period. They dip slightly towards the east-north-east.

Near the end of the Tertiary, local granitic and granodioritic laccoliths, plutons and stocks intruded through the older rocks in several zones of the country.

At the beginning of the Quaternary a new and still continuing phase of volcanic activity started. It produced mainly basaltic eruptions along the major fault systems.

The morphological features of the country, formed largely as a result of the tectonic and volcanic activities during the Tertiary, were modified to some extent during the Quaternary period. The main present-day drainage systems developed; river terraces, alluvial plains and coastal plains were formed; and aeolian deposition took place in the lowlands, on the plateaux and in the vast areas of the Ramlat-as-Sabatayn and Rub-al-Khali.

2.2.3 Stratigraphy

A geological overview map of Yemen, derived and generalized from Robertson's geological map (1991c) is presented as Figure 2.3. It shows the outcrop zones of the most important lithostratigraphic units. For a better understanding, major faults have been indicated as well, as far as their location is detectable at the surface. A few schematic geological cross-sections (Figure 2.4) illustrate the geological setting.

Table 2.1 summarizes the stratigraphy. It shows the names, age and a lithological characteristic of the main stratigraphic units. To a limited extent a differentiation between east and west is made. Names of formations -if available- are mentioned as far as deemed useful for those who deal with water resources. That implies e.g. that formation names of sedimentary units like the Amran and Tawilah Groups are presented in some detail, whereas no differentiation is given for the Precambrian rocks, even though the latter information does exist. For some groups or formations more than one name is in use. In such cases it has been attempted to select the names that are most commonly used and do not give rise to confusion. In the brief descriptions that follow, mention is made of such alternative names.

The stratigraphic characterizations focus on the mainland of Yemen. The geology of Socotra and other islands has been studied in less detail so far. Correlation with rock sequences observed on the mainland is not always clear yet.

The *Precambrian Basement* includes a large variety of rocks, intensely folded, faulted and eroded. It includes from older to younger: the Basement Complex, the Thalab Group and the Ghabar Group. The Basement Complex is composed of metamorphic and intruded igneous rocks. The Thalab rocks are meta-andesites, meta-basalts and meta-rhyolites with tuffs and a basal conglomerate. The Ghabar Group is made up of non-metamorphic sedimentary and volcanic rocks and associated intrusives. Extensive outcrops of basement rocks can be observed in the western part of the country, especially on the eastern, north-western and southern slopes of the NNW-SSE running Yemen Mountains.

The sedimentary *Wajid Group* is present in the north-western part of the country, with continuation in Saudi Arabia. The corresponding sediments are characterized as cross-bedded sandstones and coarse siltstones, unconformably overlying the eroded Precambrian Basement rocks. It is generally believed that the sedimentation took place from south and south-east to north and north-west. Rather diverging opinions have been published on the genetic origin of the sediments; within the Yemen territory, however, the unit is thought to be non-marine, probably deposited under fluviatile conditions (Robertson, 1991a). Some authors (e.g. Roland, 1979) make a distinction between a yellow-brownish ferruginous lower member and a light-coloured upper member. Conglomerate horizons are reported to occur near the boundaries of both members and in the basal part of the Wajid Sandstone. The total thickness of the Wajid Sandstone reaches in the Sadah area a maximum of approximately 600 m (Van Overmeeren, 1985a).

Akbra Shale is observed in a limited area in the north-western part of Yemen, resting unconformably upon Wajid Sandstone or upon basement. The formation consists predominantly of glacial and glacio-lacustrine deposits: varved, laminated mudstones, siltstones and shales, some of which contain dropstones of rounded striated basement rocks (Kruck und Thiele, 1983). Previously, several geologists considered the formation to be the shaly basal part of the Kohlan Sandstone, but the tendency nowadays is to follow Roland (1979) and to consider it as a separate formation.

The Lower-Jurassic *Kohlan Group* is a minor unit, consisting mainly of sandstones with considerable vertical and lateral variation. Its base is always an unconformity with the

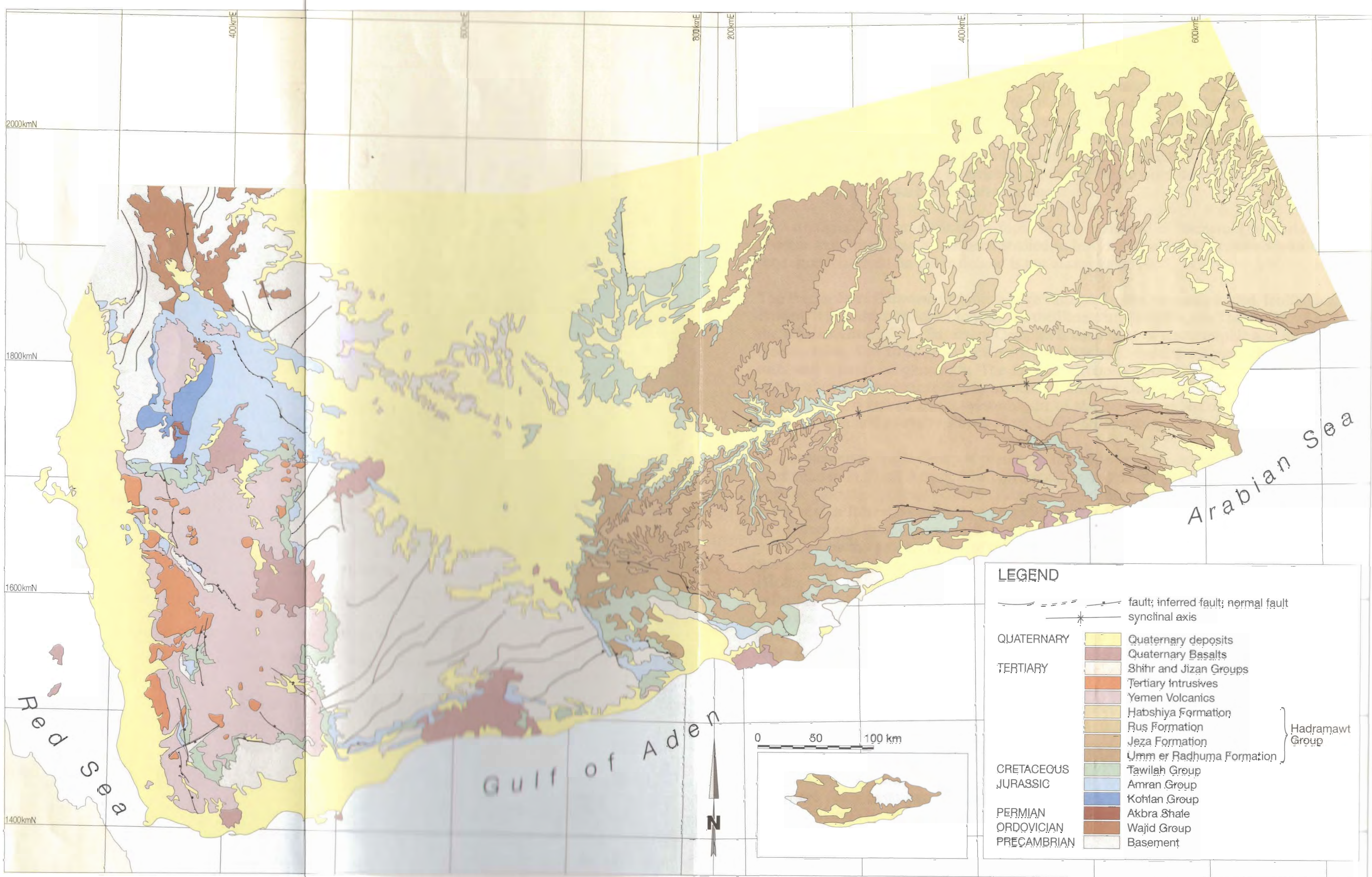


Figure 2.3 Geological map of Yemen

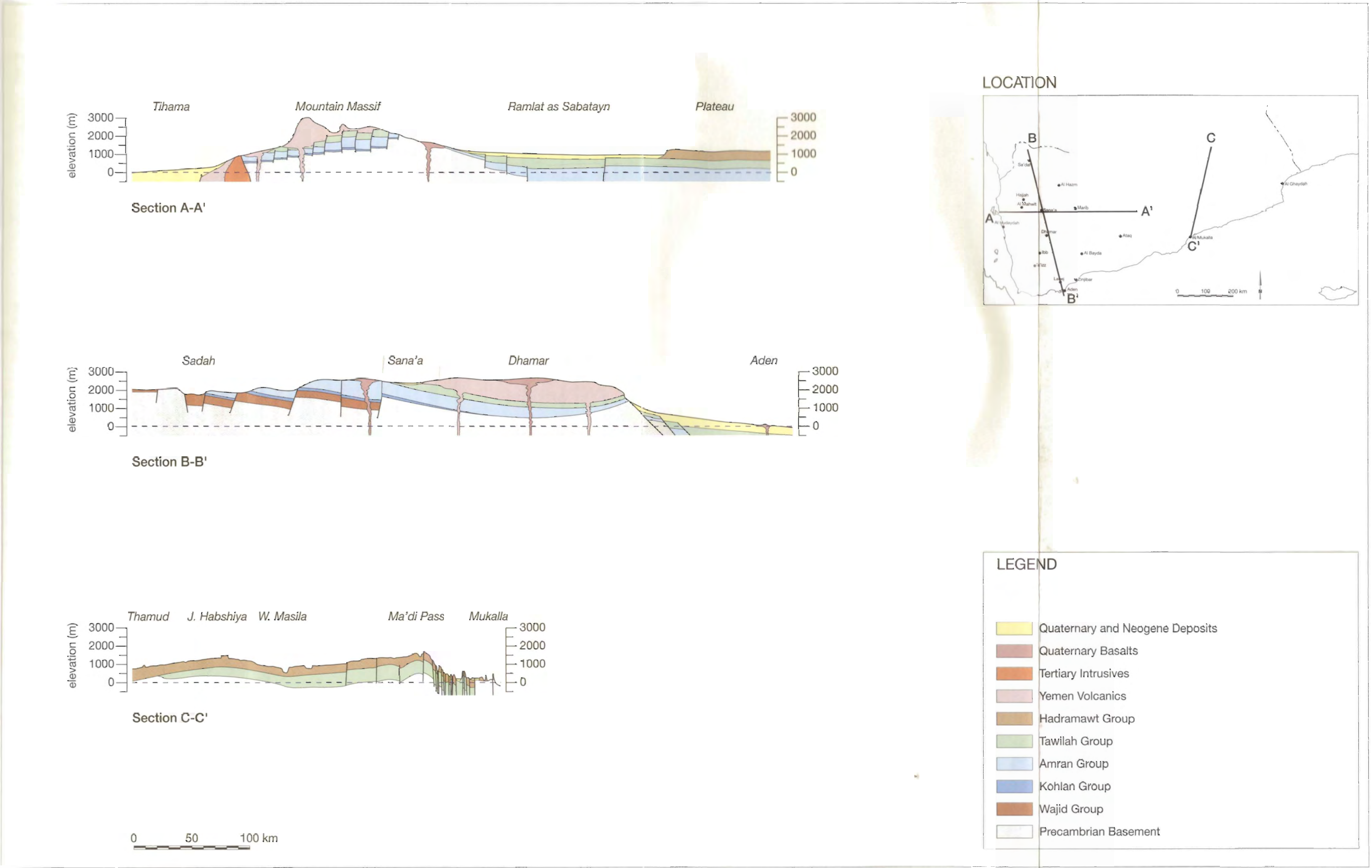


Figure 2.4 *Schematic geological cross-sections*

Table 2.1 Stratigraphic table

AGE			GROUP West	GROUP East	FORMATION West	FORMATION East	LITHOLOGY West	LITHOLOGY East
CENOZOIC	Quaternary	Holocene/ Pleistocene	Quaternary Deposits				sands, gravels, loam, loess, clay, conglomerates, sebkha deposits, marine shell and reef deposits	
			Quaternary Basalts (Aden Volcanics)				basalts, tuffs, agglomerates, trachy-andesites, pumice	
	Tertiary	Oligocene/ Miocene	Jizan Group	Shihr Group	Baid	Irqah	shales, limestones, evaporites	gravelly conglomerates
						Fuwwah		conglom. & fossiliferous limestones
		Miocene/ Eocene	Tertiary Intrusives				granites	
			Yemen Volcanics				basalts, trachy-andesites, rhyolites, pyroclastic rocks	
		Eocene		Hadramawt Group		Habshiya	limestones, marls, shales, gypsum	
						Rus	gypsum, anhydride, dolomitic limestones	
						Jeza	shales, fine-grained limestones	
		Palaeocene				Umm-Er-Radhuma	massive marly and dolomitic limestones	
			Tawilah Group		Medj-Zir		hard argillites, cross-bedded bioclastic sandstones	
MESOZOIC	Cretaceous				Tawilah Sandstone	Sharwayn	yellow sandstones (Kawkaban member), dark red sandstones (Shibam member), and white clayey sandstones (Thula member)	shales, limestones, sandstones
						Mukalla		fine/medium sandstones
						Fartaq		calcarenites
						Harshiyat		sandstones with calcareous horizons
						Qishn		calcarenites, limestones
	Jurassic		Amran Group		Ahjur		bituminous marly and sandy mudstones	
					Nayfa		limestones and dolomites	
					Madbi	Sabatayn	marls and limestones	evaporites and shales
					Shuqra		limestones	
	Lower Jurassic		Kohlan Group		Kohlan Sandstone		sandstones with conglomerate intercalations	
PALEOZ	Permian				Akbra Shale		laminated mudstones, siltstones, shales	
	Cambro-Ordovician		Wajid Group		Wajid Sandstone		cross-bedded sandstones and coarse siltstones	
PC	Pre-cambrian		Precambrian Basement				igneous rocks, metamorphic rocks, metasediments	

underlying older rocks. The thickness of the unit is variable, with an average of some 60 metres. The rocks grade up into the basal limestones of the Amran Group.

The *Amran Group* is a thick series of dominantly calcareous sediments, but locally including significant sequences of shales and evaporites. The carbonates are commonly massive, fissured rocks. Maximum thickness of the Amran Group may exceed 800 m. It is a complex group, with two main depositional environments: a neritic environment which resulted in a limestone and marly facies, and a shallow-water environment resulting in an evaporitic sequence. Several subdivisions have been proposed, but due to gaps in knowledge and difficulties in lateral correlation there is not yet a generally accepted one. Table 2.1 follows the subdivision as originally proposed by Beydoun (1964), but the Ahjur Formation has been added. The latter formation -suggested by El Anbaawy (1985)- was previously known as 'Unnamed Formation' in the Sana'a region.

The rapid subsidence of the extended Al-Jawf graben during Jurassic times has resulted in an extensive sequence of shales and evaporites in the Ramlat Sabatayn region. In oil exploration studies since the beginning of the 1980s the Amran Group in this region tends to be subdivided into (from bottom to top) the Saba, Arwa, Meem and Lam Formations. In this stratigraphic system the Alif and Safer Formations of the Upper-Jurassic Amlah Group follow; the Alif Formation contains hydrocarbon-bearing zones. The Safer Formation, in turn, is overlain by the Azal Formation, which in some reports is considered as part of the Amlah Group, but in others as belonging to the Amran Group. Insufficient information is available to correlate all these formations with those indicated in Table 2.1. It is plausible that the Amlah Group corresponds to the Sabatayn Formation.

The rocks of the *Tawilah Group* have a wide geographical distribution. They are almost continuous east of the basement outcrop of the shield, but in the western part of the country their demonstrated presence is limited to the central and southwestern part of the Yemen mountains, with narrow belts of outcrops bordering the protecting volcanic cover. The unit is mainly composed of non-fossiliferous porous and fissured sandstones, but in the eastern part of the country -in the Al Mahra governorate- the terrestric facies changes into a marine calcarenaceous facies. The total thickness of the formation is in the order of several hundreds of metres.
Table 2.1 shows a distinction between west and east regarding the stratigraphic subdivision. In the western part two formations are distinguished: the Tawilah Sandstone and the Medj-Zir Formation. The latter formation crosses the Cretaceous-Tertiary boundary; it has only recently been considered as part of the Tawilah Group. The subdivision given for the eastern part of the country reflects the lateral variation in facies due to small-scale marine transgressions and regressions in the central part of the area. The hydrogeologically most prominent member of this group in the central and eastern part of the country is the Mukalla Sandstone Formation.

The formations of the Palaeocene/Eocene *Hadramawt Group* form an extensive and almost continuous cover in the eastern half of the country. The group is transgressive from east to west over the Cretaceous Tawilah Group and consists of shallow-water limestones, shales, marls and evaporites. The basal Umm-Er-Radhuma Formation is prominent. It consists dominantly of massive limestones, a few hundreds of metres thick, with outcrops mainly at the western and southern edges of the area where the Hadramawt Group is present. Further east and northward it is covered by younger formations of the group: the Jeza Formation, Rus Formation and Habshiyah Formation. Recently, two new formations were mapped: the Upper Eocene Hamara Formation (sandstones with silts and evaporites) and the Rimah Formation (gypsiferous conglomerates and sandstones). They could in principle be grouped under the Hadramawt Group, which would then extend into the Oligocene (Robertson, 1991a).

The rocks of the *Yemen Volcanics* (also called 'Trap Series') form a large, almost continuous plateau in the western part of the country. The total thickness of the volcanic series may exceed 2000 m. The sequence consists of subhorizontal strata of basic to acidic lavas, ignimbrites and pyroclasts, with intercalated soil horizons. Fuchs (1985) suggests a subdivision into four parts. From bottom to top these are: (a) a melanocratic Basal Series; (b) the well-bedded Haddah Series; (c) the heterogeneous Chaotic Series; and (d) a well-organized Upper Series. The latter two series consist of dominantly leucocratic rocks. Associated with the Yemen Volcanics are alkali-granitic *Tertiary Intrusives*; they are mainly observed in the eastern marginal zone of the Red Sea graben.

The Baid Formation belongs to the *Jizan Group* and is associated with a series of small salt diapirs along the Red Sea coast. The shales, limestones and evaporites of the Baid Formation are observed in a zone along the Red Sea coast, both in outcrops and buried under thick Quaternary covers. The formation is several thousands of metres thick.

The *Shihr Group* includes all sedimentary units whose origins were linked to marginal continental rifting during the Neogene along the north coast of the Gulf of Aden. Outcrops are scattered and of limited extent.

Compared to the Yemen Volcanics, the *Quaternary Basalts* (also named 'Aden Volcanics' or 'Quaternary Volcanics') typically have a much more local occurrence. They include numerous volcanic cones. There is a time gap of approximately 10 million years between the eruptions of the Yemen Volcanics and those of the Quaternary Basalts.

Quaternary Deposits are scattered widely over the country and include alluvial deposits, coastal and littoral deposits, reef deposits and aeolian deposits, with wide variations in lithology. Large continuous covers of Quaternary sediments are encountered in the Rub-al-Khali, the Ramlat-as-Sabatayn, the Red Sea coastal plain (Tihama), the southern and eastern coastal plains and the Wadi Hadramawt valley. They are also present in the numerous wadi beds scattered over the country.

2.3 Administrative and geographical regions

2.3.1 Governorates

The present Republic of Yemen was born in May 1990, as a result of the unification of the former Yemen Arab Republic (YAR) and the People's Democratic Republic of

Yemen (PDRY). These two parts are sometimes still referred to as respectively the northern and the southern part of the country. The country is administratively divided into 17 governorates; six of them are in the territory of the former PDRY ('southern governorates'). Figure 2.5 shows approximate boundaries and the capitals of the governorates. Socotra and the smaller neighbouring islands belong to the Aden governorate.

2.3.2 Geographical regions

The many different landscapes of Yemen can be grouped into five main geographical regions, shown in Figure 2.6 (modified after Robertson, 1991a):

(1)	the Coastal Plains	(a)	Tihama
		(b)	Tuban-Abyan plains
		(c)	Ahwar-Meifa'ah plains
		(d)	Eastern coastal plains
(2)	the Yemen Mountain Massif	(a)	Western Slopes
		(b)	Southern Slopes
		(c)	Eastern Slopes
		(d)	Highland Plains zone
(3)	the Eastern Plateau Region	(a)	Northern Plateau zone
		(b)	Southern plateau zone
		(c)	Wadi Hadramawt
		(d)	Al Ghaydah basin
(4)	the Deserts	(a)	Ramlat as Sabatayn
		(b)	Rub al Khali
(5)	the island Socotra		

Yemen possesses many islands in the Red Sea, Gulf of Aden and Arabian Sea. With the exception of Socotra, they will be neglected in this report, because they are not essential for a general overview.

The Coastal Plains

The Coastal Plains are located within the West Arabian Rift System, which is of Neogene age and separates the Arabian Plate from the African Plate. The Tihama belongs to the western branch of this system: the Red Sea Rift Zone; the coastal plains within it southern branch -the Gulf of Aden Rift- are more restricted in extent.

The Coastal Plains zones have been downfaulted up to a few thousands of metres, which has resulted in the accumulation of thick sequences of Tertiary and Quaternary sediments. The present topography of the coastal plains is flat to slightly sloping and undulating, with maximum elevations of only a few hundred metres above sea level. The surface is typically characterized by alluvial and aeolian deposits.The Coastal Plains have a hot climate, with in general low to very low rainfall. Nevertheless, the plains contain

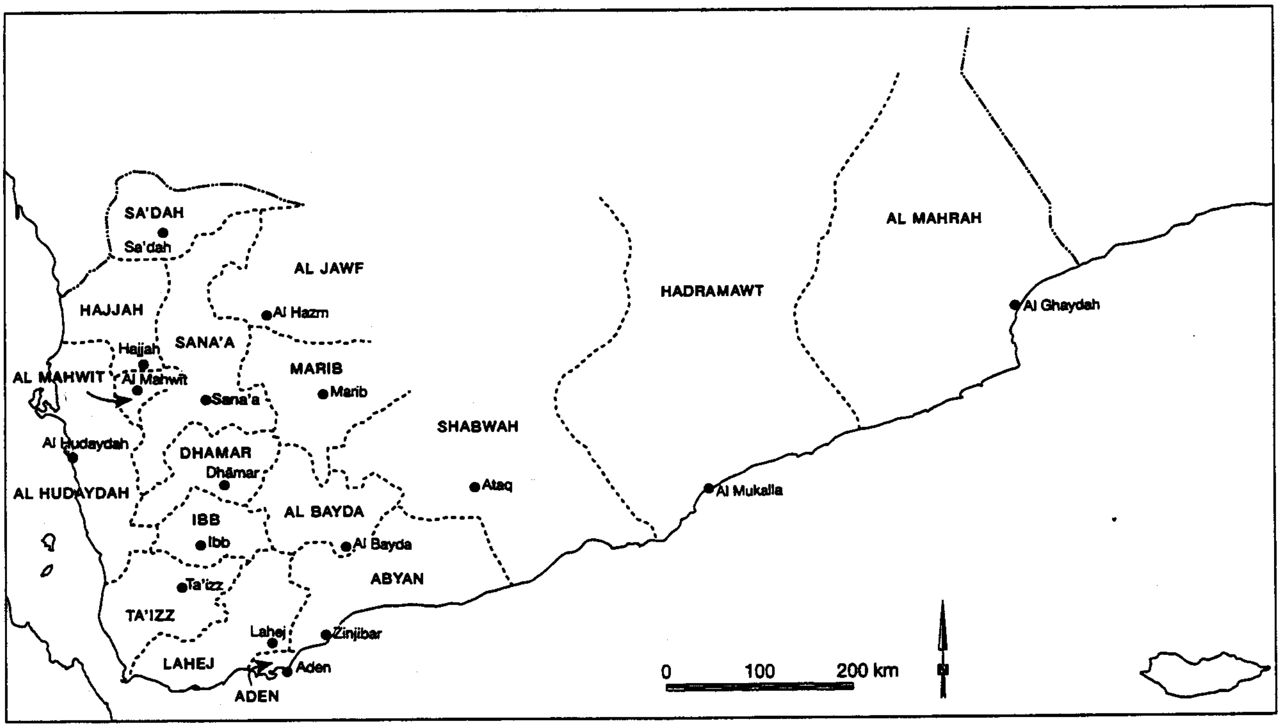


Figure 2.5 Governorates in Yemen

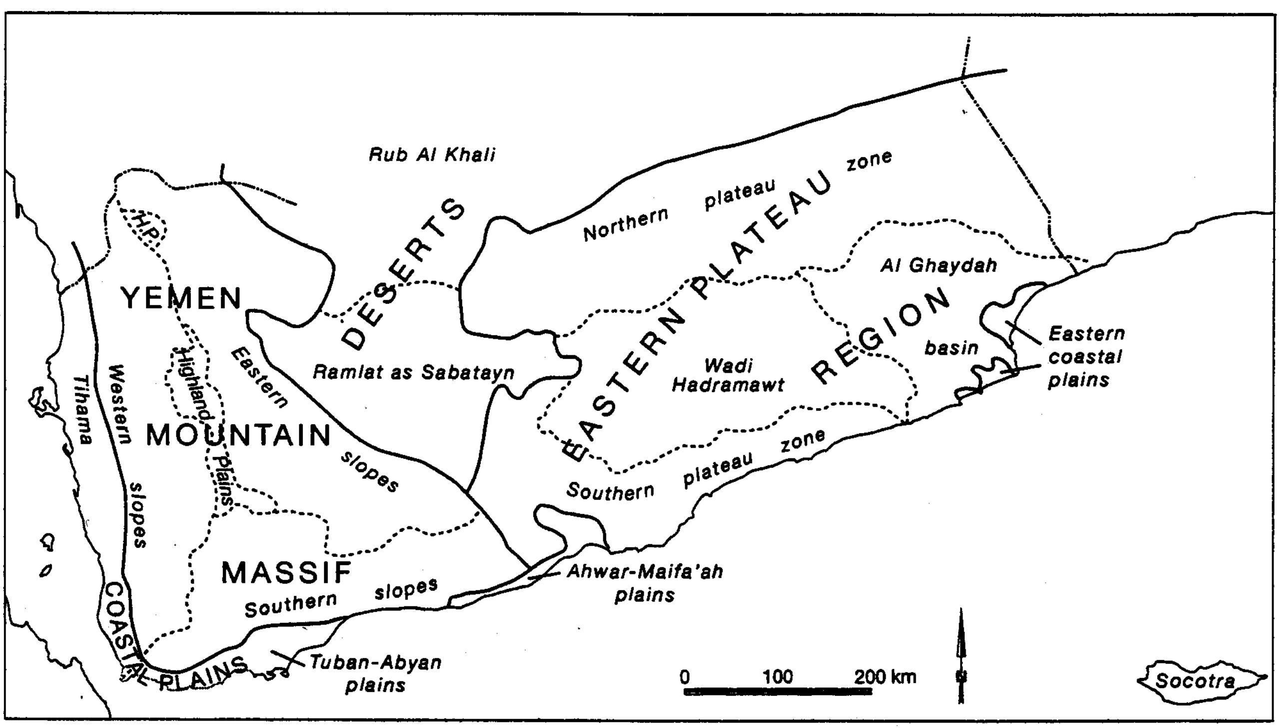


Figure 2.6 Geographical regions

important agricultural zones, due to the numerous wadis that drain the adjoining mountainous and hilly hinterland. The wadis enable spate irrigation to be practised, and they provide recharge to the porous and permeable Quaternary sedimentary aquifers of the plains.

The Yemen Mountain Massif

The Yemen Mountain Massif can be associated with the Arabian Shield. Precambrian rocks outcrop widely in the eastern part of the zone; elsewhere they are covered by Palaeozoic and Mesozoic sediments, which -in turn- in the central west and the southern subzones are topped by thick blankets of Tertiary and Quaternary volcanic rocks.
The Yemen Mountain Massif constitutes an uplifted zone of very irregular and dissected topography, with elevations ranging from a few hundred metres (foothills) to 3760 m above sea level (Jabal Nabi Shuayb near Sana'a). Accordingly, the climate varies from cool at the highest altitudes to hot at lower elevations.

The Western and Southern Slopes are steepest and enjoy moderate to rather high rainfall (on average some 300-500 mm/year, but locally more than 1000 mm/year) because they are favourably oriented in relation to the movement of moist air masses. As a result, rain-fed agriculture is practised widely on numerous terraced mountain slopes, supporting rather high population densities. The Eastern Slopes show a comparatively smoother topography between some 3000 (west) and 1000 m + msl (east). As a result of greater distance from the sources of moisture and unfavourable topographic orientation, average annual rainfall is low and decreases rapidly from west to east. Population is sparse in the area of the Eastern Slopes. Enclosed by the Western, Eastern and Southern Slopes there are a number of important montane plains, the Highland Plains, where physical conditions are favourable for sustaining a relatively large population.

The Eastern Plateau Region

The Eastern Plateau Region is located within the extensive Arabian Platform Zone, which borders the Arabian Shield along its northern, northeastern and eastern margins. The zone is characterized by an extensive and thick sediment cover with a slight and rather uniform dip (around 1°), mainly consisting of Tertiary limestones at the surface. Large subzones are the Northern Plateau zone in the north, Wadi Hadramawt in the centre, the Al Ghaydah Basin in the east, and the Southern Plateau zone south and west of the Wadi Hadramawt area.

Elevations decrease from 1200-1800 m at the main water divides to sea level at the coast and to approximately 900 m at the margins of the Rub Al Khali desert. The plateaux are relatively dissected, in particular by the Wadi Hadramawt and its tributaries. The bed of Wadi Hadramawt is 5 to 20 km wide and lies some 300 m below the level of the plateau, in a gorge controlled by a synclinal alignment. The depression of Al Ghaydah and the course of Wadi Jiza can be associated with the same geological lineament.

The climate in general is hot and dry, with average annual rainfall typically below 100 mm, except in the higher parts along the southern Hadramawt arch. Nevertheless, floods after rare rainfall events may be devastating. Population density is low, except in the Wadi Hadramawt gorge where large areas of agricultural land are irrigated by groundwater pumped from aquifer rocks below the wadi bed.

The nearly horizontal, vast and monotonous limestone plateaux north and south of the Wadi Hadramawt canyon are known as the Northern and Southern Jols.

The Deserts

Between the Yemen Mountain Massif and the Eastern Plateau Region lies the Ramlat as Sabatayn, a sand desert with a maximum W-E extent of some 350 km. Rainfall and vegetation are nearly absent, except along its margins where rivers bring water from adjacent mountain and upland zones.

Northeast of the Yemen Mountains and north of the Hadramawt-Mahra Uplands lies the Rub Al Khali desert (Empty Quarter), which extends far into Saudi Arabia and is approximately half a million km^2 in area. This sand desert is among the most desolate parts of the world.

Socotra

Isolated from the mainland, at considerable distance and of appreciable size, the island of Socotra can be considered as a separate physiographic unit. It has a more exuberant flora and fauna than any other region in Yemen.

2.4 Demographic and economic characteristics of Yemen

2.4.1 Demography

The population density in Yemen - especially in its western part - is relatively high compared to that in other countries of the Arabian Peninsula. Table 2.2 summarizes the census outcomes of 1986 and 1988 for the northern and the southern governorates.

According to The Economic Intelligence Unit (EIU, 1993) the current population growth is extremely high, as a result of a high fertility rate and, in recent years, greatly improved health care; UNDP uses a growth rate of 3.6 % for demographic projections beyond 1990. Assuming this population growth rate, by 1994 the total Yemeni population was some 14.4 million people, including those residing outside the country. Approximately 18 % of the population lives within the 120 urban centres of the country, but this percentage is tending to increase as a consequence of rapid urbanization. The population pyramid shows that slightly more than half of the population belongs to the age group 0-14 years, which creates a large dependency burden for the productive labour force (TS-HWC, 1992a).

Table 2.2 Population statistics

Governorate	Population thousands	Population % of total	Population density[1]
Yemen Arab Republic, 1986 census			
Sana'a	1665	18.6	high
Taiz	1420	15.8	high
Hodeidah	1052	11.7	high
Ibb	1254	14.0	high
Dhamar	699	7.8	high
Hajjah	720	8.0	high
Al Bayda	295	3.3	medium
Sa'dah	297	3.3	medium
Al Mahweet	261	2.9	high
Marib	95	1.1	very low
Al Jawf	43	0.5	very low
Outside the country	1168	13.0	
Total YAR (1986)	*8969*	*100.0*	*high*
People's Democratic Republic Yemen, 1988 census			
Aden	327	15.7	very high
Lahej	485	22.1	medium
Abyan	279	13.4	low
Shabwah	192	9.3	very low
Hadramawt	537	25.9	very low
Al Mahrah	44	2.1	very low
Outside the country	238	11.5	
Total PDRY (1988)	*2076*	*100.0*	*low*

Note:

[1] Population density classes:

very high	:	> 200 inhabitants/km^2
high	:	50 - 200 inhabitants/km^2
medium	:	20 - 50 inhabitants/km^2
low	:	5 - 20 inhabitants/km^2
very low	:	< 5 inhabitants/km^2

Based on information presented in Statistical Yearbooks (CSO) and in TS-HWC (1992a)

Table 2.2 shows two other significant demographic features of Yemen. The first is the large number of Yemenis living abroad. Many Yemenis used to work abroad, especially in Saudi Arabia and other Middle East oil-producing countries. The numbers of Yemenis currently residing outside the country -although not accurately known- are much lower than the ones indicated in Table 2.2, because of the massive repatriation of migrant workers during the 1990/91 Gulf War.

The second notable demographic feature is the non-uniform distribution of the population over the different governorates. This is closely related to the physical environment. By far the largest part of the population lives in the Yemen Mountain area, where rainfall is still significant, although not high in most locations. This explains the the relatively high population densities in the governorates Ibb, Taiz, Al-Mahweet, Sana'a, Dhamar and Hajjah. The hostile physical environment of the desert and eastern upland areas is reflected in very low population densities in governorates such as Al Mahra, Al Jawf, Shabwah, Hadramawt and Marib.

The average population density in Yemen is approximately 26 inhabitants per square kilometre. In the northern governorates the density is several times higher than in the southern part of the country.

2.4.2 Some economic features

Real economic data on the unified Republic of Yemen are still very scarce, but data and estimates from several sources (Central Statistical Organization, TS-HWC, EIU) provide a general picture. Some of these data and estimates are shown in Table 2.3.

Unification in 1990 brought together two economies that were markedly different as regards the role of the government: the YAR with its dynamic market system and the PDRY with its system of central planning and public ownership of production factors. Common features included agriculture as the most important source of employment, a large labour force earning a living abroad, the relatively modest contribution of the mining and manufacturing sectors to the economy, and a substantial informal economy.

In the years before unification, the oil discoveries in the YAR were followed by substantial exploitation of hydrocarbons, but the agricultural sector remained the dominant sector in the YAR's economy, contributing 24 % of the gross domestic product (GDP). It was followed by the manufacturing sector (13 % of GDP) and the government services sector (13 of GDP %). In the PDRY, government services were the largest sector (27% of GDP), followed by agriculture (14 %). The latter includes fishery; the southern governorates have important fishery resources.

The 1990 per capita gross domestic product for Yemen is estimated to be US $ 760. The government services sector was in that year the largest sector in terms of its contribution to the GDP (21.4 %), followed closely by the agricultural sector (TS-HWC, 1992a).

The agricultural sector is still by far the largest sector as far as employment is concerned, but due to subsistence farming and low productivity its contribution to the GDP is

Table 2.3 Selected economic indicators for the Republic of Yemen, 1990

Indicator	Agriculture	Mining	Manu-facturing	Services (private & government sectors)	Total
share of sectors in total labour force (%)	60.2	0.4	4.2	35.2	100.0
share of sectors in GDP (%)	20.6	8.4	12.9	58.1	100.0
share of water in sectoral GDP (%)	33.9	1.9	0.4	8.0	---
share in total volumetric water use (%)	93.1	1.9	0.4	4.6	100.0

Source: TS-HWC, 1992a

disproportionally low. The sector is extremely vulnerable to variations in rainfall and related water resources. Regional inventories suggest that approximately 92 % of the water resources developed in Yemen are used in the agricultural sector.

Upon unification in 1990, the government of the Republic of Yemen embarked on a more liberal economic policy than those that previously existed in the YAR and PDRY, with prominent roles for the market and the private sector. Intensive oil exploration programmes were initiated (some of which have already been successful) and privatization of collectively farmed land was started in the southern provinces. However, the national economy has faced serious problems since then, including the forced return of around one million migrant workers from the Gulf countries, and a high rate of inflation.

3 INFORMATION ON WATER RESOURCES

3.1 Reports and publications

Processed and interpreted information on the water resources of different areas and regions of Yemen and on related subjects such as geology and climatology, is scattered over numerous studies, reports and publications. Approximately 600 references are listed in Appendix 1. Many of these reports and publications are currently available at the libraries of one or more of the following agencies: the General Department of Hydrogeology of the Ministry of Oil and Mineral Resources (Sana'a), the Technical Secretariat of the High Water Council (Sana'a), the Mineral Exploration Board of the Ministry of Oil and Mineral Resources (Sana'a), the Ministry of Agriculture and Water Resources (Sana'a and Aden) and NWSA (Aden). A large number of references, however, could not be accessed in Yemen. Together these reports and publications form an extremely valuable source of information on the water resources of Yemen. Those titles that are considered most relevant for either a general overview or a regional characterization are referred to in the text.

Table 3.1 Availability of reports and publications

Region		Surface water	Ground-water	Water use & demand
Coastal Plains	Tihama	++	++	+
	Tuban-Abyan plain	++	++	0
	Ahwar-Maifa'ah plains	+	+	0
	Eastern plains	-	0	-
Yemen Mountain Massif	Western Slopes	++	+	+
	Eastern Slopes	+	0	-
	Southern Slopes	+	0	0
	Highland Plains	0	++	++
Eastern Plateau Region	Northern Plateau zone	-	0	0
	Southern Plateau zone	0	0	0
	Wadi Hadramawt	++	++	+
	Al Ghaydah basin	-	-	-
Deserts	Rub Al Khali	-	-	-
	Ramlat as Sabatayn	+	+	+
Socotra		0	0	0

Key to classification:
- ++ good regional coverage, fairly detailed information
- \+ incomplete information, fairly detailed for scattered zones only
- 0 mainly qualitative and/or outdated information
- \- information scarce or absent

Not all areas have been studied to the same degree of detail. A relatively large number of reports deal with the western part of the country, in particular the Tihama and the Tuban-Abyan Coastal Plain, the Highland Plains, and the Al Jawf and Marib zones at the north-western edge of the Ramlat as Sabatayn. In the eastern part of the country, only the Wadi Hadramawt canyon has been the subject of a fair number of studies. Other areas have had few or no water resources studies. Table 3.1 gives an overview arranged by region and by subject.

3.2 Monitoring networks

The general aim of hydrological monitoring networks is to observe hydrological variables over time at a number of selected locations. Such variables may include rainfall, evaporation, evapotranspiration, streamflow, surface water levels, groundwater levels, water quality and water use. Well-designed monitoring networks reveal the dynamics of the meteorological or hydrological systems concerned: they characterize the state and natural variations within these systems, and they show how and to what extent these are modified by external change, especially by human activities. Monitoring data are indispensable for proper planning of water resources development and management.

Appendix 2 presents an overview of all Yemeni meteorological, rainfall and streamflow stations known at the General Department of Hydrogeology of MOMR. The tables specify the name, location and elevation of the stations, mention the operating agency, operational status and class of equipment installed, and indicate the period of record. Note that many of the stations mentioned are no longer operational.

The locations of the different types of stations are shown in Figure 3.1. A salient feature is their non-uniform areal distribution. Most of the stations are located in the Yemen Mountain Massif region, on the Western and Southern Coastal Plains and in the surroundings of Wadi Hadramawt. Socotra and the sparsely populated mainland of Al Mahra governorate have only one meteorological station each, and there are no monitoring stations in the vast desert areas.

There is a strong correlation between population density and station density. The density of rainfall stations is also influenced by the expected rainfall amounts. This is why there are only few rainfall stations in low-rainfall zones such as the coastal plains. Unlike the rainfall stations, site selection for stream gauging stations is not based on spatial sampling; the importance of the stream and the specific characteristics of the stream networks are more decisive for their locations. Many of the stream gauging stations are located along the borders of the Yemen Mountain Massif to monitor the yield of individual major mountain catchments. The many stream gauging stations in Wadi Hadramawt indicate an interest in the contribution of the main tributaries to the total volume of Wadi Hadramawt floods and to their infiltration into the alluvial aquifer of Wadi Hadramawt's wadi bed.

Clusters of stations in certain zones reflect the fact that most of the stations were designed as part of project networks in project areas of limited size, rather than as stations of a national monitoring network. Also the type of equipment used is related to

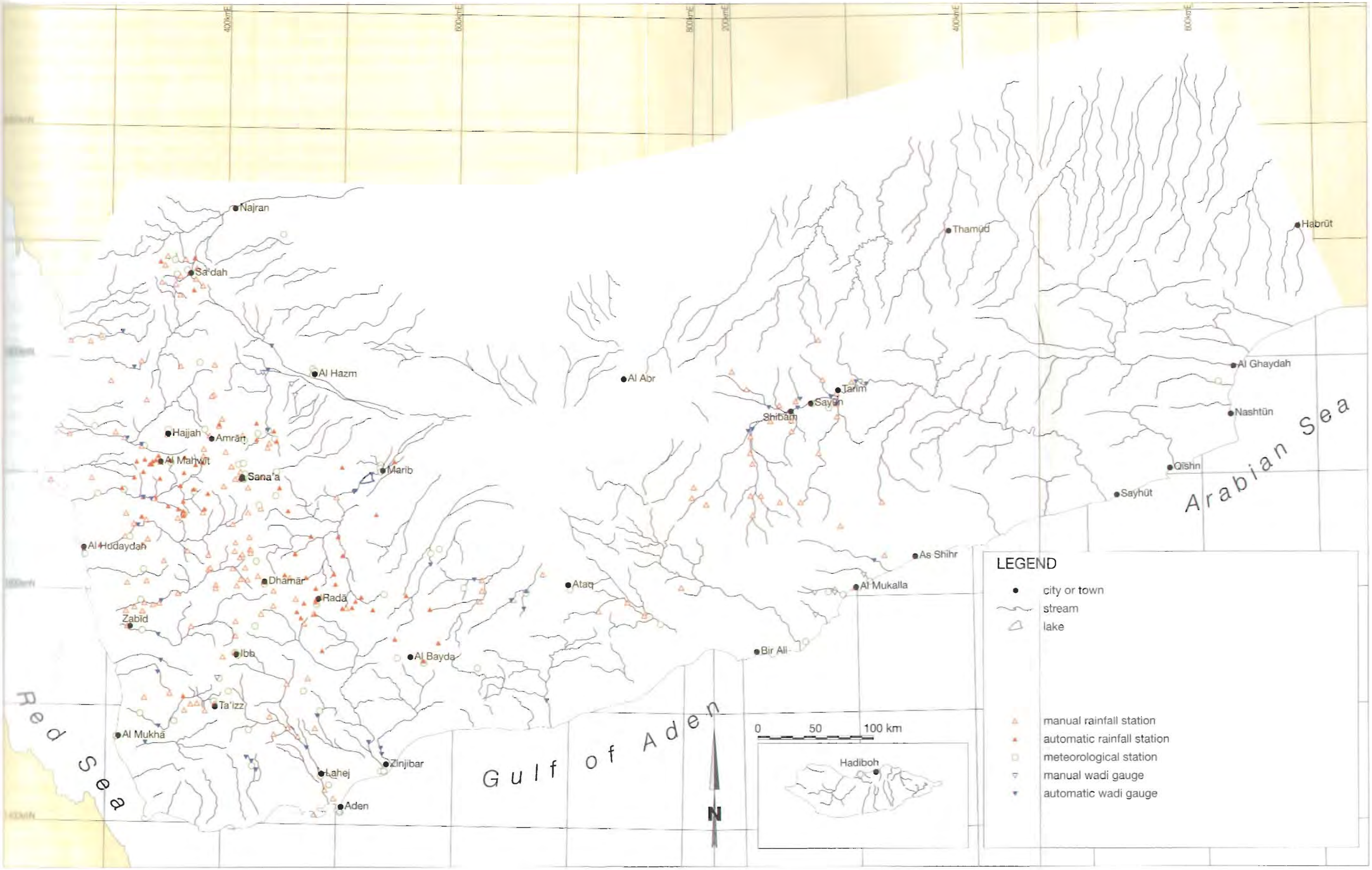


Figure 3.1 Hydrometeorological monitoring stations in Yemen

these project networks: for example, rainfall recording stations are concentrated mainly in the project areas of the WRAY, RIRDP and Mahweet projects. Most of the stream gauging stations are nowadays equipped with water level recorders; some of those in the Hadramawt governorate, however, still rely on staff gauges.

Monitoring networks do not yet have a long tradition in Yemen. Even rainfall, which in many countries has been systematically observed for more than a century, was recorded in only seven stations (most of them in the former PDRY) prior to 1960. Most of the rainfall stations currently known were installed during the late 1970s or during the 1980s. Several have been abandoned already and many of the records have major gaps in the period of observation. Including the rain gauges at meteorological stations, 325 rainfall stations have been identified (see Appendix 2), approximately two-thirds of which are currently operational. Around a quarter of the 80 meteorological stations are reported to be defunct. Appendix 2 lists 53 stream gauging stations; it excludes a few stations that never produced a significant record.

Only a few groundwater level monitoring networks are known and these are of limited areal extent. They include the networks of WRAY/GDH in the Sadah basin (31 wells), the lower Surdud (42 wells) and in the Marib zone (62 wells), of RIRDP in the Rada basin (36 wells), of TDA in the Tihama (194 wells) and NWSA in the well fields of Sana'a (47 wells). The approximate numbers of wells indicated above include all manually and automatically monitored sites in the areas concerned; in most cases the networks were reduced after a few years of monitoring, and therefore there are fewer stations today.

In the area of the intermontane plains of western Yemen a network of some 45 monitoring wells was operated by ODA/LRC during 1975-1976; it was then abandoned.

In the framework of this study it proved impossible to obtain accurate information on groundwater level monitoring in the southern governorates. There is evidence that groundwater level monitoring has been practised in the Tuban and Abyan deltas, and also in Wadi Hadramawt (85 wells) and in the Mukalla area (UNDP/DESD, 1992). The actual status of these networks is not known.

There are no known water quality monitoring networks in Yemen, except for regular EC measurements in some of the groundwater level monitoring networks and repeated water quality sampling at the wellfields or headworks of NWSA's water supply.

No other groundwater abstraction monitoring is known in Yemen, other than that at NWSA's main urban water supply systems. 'Snapshots' of groundwater abstraction, however, were made for many areas during well inventories, for some areas repeatedly. No formal networks to monitor surface water diversions are known either.

The hydrological and meteorological networks in Yemen are not operated centrally, but local or regional networks are run by a large number of organizations. Most of the stations started as project stations and after a couple of years were transfered to the government agency under which the project resorted. As a result there is not yet any national standardization of equipment and monitoring practices. Difficult physical conditions, large distances, shortage of operational personnel or operating funds, safety problems, etc. impose heavy constraints to network operation, and often have resulted in fragmentary records, sometimes of poor quality. Automation -especially the introduction of Eprom recorders- has improved the operational conditions and consequently the records as well.

Stream gauging over the different flow ranges is extremely difficult in the capricious wadis in Yemen, thus the rating curves and resulting stream flow records are never very accurate. It should be realized that the older stream flow records -and some of the current ones as well- are based on staff gauge readings (one or two a day) and thus are not suitable for reconstructing instantaneous flows.

Selected statistics on the measured variables are presented in Appendix 3. Original data can be obtained from the operating agencies (which is often difficult). Most of the rainfall and meteorological data, and some of the streamflow data, are already available in the form of digital files at the General Department of Hydrogeology (GDH) at Sana'a.

3.3 Databases

Time series data, well inventory data and other basic numerical information on the climate, hydrology and hydrogeology of Yemen is stored in the database of MOMR's General Department of Hydrogeology, and was extensively consulted for the preparation of this report. This database was established in the framework of the WRAY project as part of the Water Resources Information System of the General Department of Hydrogeology. It was intended as a centralized publicly accessible national water resources database. In spite of shortcomings, it has already fulfilled this task for a number of years.

Given the fact that many organizations and projects are running monitoring networks and are conducting field studies in Yemen, the database of GDH can only operate as a national database in cooperation with these organizations and their databases. The most important partners in this respect are the Civil Aviation and Meteorology Authority, Tihama Development Authority, ERADA, SHARDA and SURDUP, the RIRDP and Mahweet Projects and the Irrigation Department of the Ministry of Agriculture, and the National Water and Sewerage Authority. Data exchange with the database of the Technical Secretariat of the High Water Council has been useful as well.

3.4 Other sources of information

Other sources of information used for this compilation include the topographic, geological and hydrogeological maps available for the entire country or parts of it; aerial photographs and satellite images; field trips; and -last but not least- the knowledge and opinions of many colleagues working on water-related aspects in Yemen. The latter knowledge and opinions were aired and transferred during personal discussions or during symposia or related professional meetings.

4 CLIMATE

4.1 General features

Climate is experienced and commonly described in terms of easily observed variables such as temperature, precipitation, wind and air humidity. These elements do not vary at random, but are largely controlled by deterministic factors. The most fundamental control of climate is the unequal heating of the atmosphere in different parts of the earth. It causes differences in temperature and associated differences in air pressure, which, in turn, give rise to movement of air masses (wind). Solar energy leads to the evaporation and evapotranspiration of water, which supplies moisture to the moving air masses. Cooling air masses tend to lose their moisture in the form of rain, snow, hail or other types of precipitation.

The intensity of incoming solar radiation depends primarily on latitude; as a result, warm climates prevail at low latitudes and cold climates near the poles. The zone of maximum insolation oscillates in a seasonal rhythm inside the tropical belt, which basically defines the seasons and causes a perodically shifting trough of low atmospheric pressure known as the Inter-Tropical Convergence Zone (ITCZ). South-eastern and north-western surface winds (*trade winds*) tend to converge there and replace the local heated air which rises and after reaching greater heights flows towards higher latitudes. The latter air masses cool during this circulation and thus may produce precipitation.

Land masses heat and cool more rapidly than sea masses, and thus the distribution of land and sea masses has a direct impact on the temperature regimes. Indirectly this is also reflected in the pressure and wind systems and the precipitation regimes. The monsoons of Southern Asia are a clear example: persistent dry winds blowing from the cold continent towards the Indian Ocean during winter, alternating with moist winds in the opposite direction during summer.

Ocean and sea currents form another globally or regionally important climatic control; they modify the temperature patterns by transporting large masses of warm or cold water. Other important climatic controls are topographic features such as altitude, exposure and slope of the land, and the nature of the soils or rock outcrops at the land surface. (Trewartha and Horn, 1980)

Yemen has a predominantly semi-arid to arid climate, with rainy seasons during spring and summer, and with high temperatures prevailing throughout the year in low-altitude zones. This is primarily a consequence of the country's location between 12° and 19° North. It causes solar radiation to be of high intensity and during spring and summer it brings the area under the influence of the afore-mentioned ITCZ.

Three large bodies of water affect Yemen's climate: the Indian Ocean (including the Gulf of Aden and the Arabian Sea), the Red Sea and the Mediterranean Sea. They are sources of moisture for the passing air masses and they have an impact on the general atmospheric circulation. With regard to the latter aspect, the Indian Ocean very significantly influences the position of the ITCZ in Western Asia and Eastern Africa, and

Table 4.1 Climatological averages

STATION	ELEVATION (m + m.s.l.)	ANNUAL TOTALS OR AVERAGES P	T	RH	WS	SSD	ET_p
Mocha	5	21.4	29.2	74.1	4.7	8.3	2662
Hudaydah	10	101.5	29.4	76.9	4.7		
Al Kod	13	62.5	25.5	75.0	1.6	8.9	1917
Giar	60	34.6	28.0	64.7	1.8	8.8	2213
Fiyush	65	45.4	28.4	66.0	0.6	8.2	1880
Dahi	70	138.0	30.1	53.4	1.0	7.4	2082
Zuhrah	70	133.0	30.3	61.2	1.7	6.2	2123
Kudeidah	120	144.8	31.0	65.0	2.8	7.7	2523
Lahej	129	55.6	28.3	68.1	1.1	8.1	1975
Khalifah	139	550.8	26.8		1.0	7.2	-
Jaroubah	150	367.4	30.3	59.1	3.1		-
Zabid	240	347.8	29.6	63.0	1.5	7.4	2147
Barh	500	330.1	28.4	68.5	1.8	7.1	2016
Seyun	700	65.2	26.0	42.2	1.0	9.0	2338
Marib	1000	79.2	26.1	22.6	3.4	9.4	3211
Nuqub	1040	70.6	24.9	34.0	1.5		2377*
Jawf	1100	67.0	26.5	22.3	3.4		3427*
Dhala	1150	361.8	22.0	41.0	0.8		-
Hajjah	1300	467.3	23.6	54.8	1.3		-
Ossefra	1350	693.4	24.6	55.2	1.6	8.1	2003
Magash	1885	98.2	20.3	35.1	2.8		-
Dumeid	1950	124.3	19.2	29.4	1.4	7.9	1970
Khabar	2140	225.3	17.8	50.2	1.7	9.0	1898
Irra	2200	183.4	17.4	35.5	4.5		-
Sana'a (CAMA)	2216	183.1	19.2 ?	44.0	3.5	8.5	2475
Sana'a (GDH)	2275	174.4	19.4	30.6	1.1		-
Risabah	2318	299.0	16.1	41.2	2.1	8.6	1997
Dhamar	2360	338.0	16.0	59.7	1.2	8.3	1579
Ketab	2500	360.0	12.9	42.1	2.1		-

P = total precipitation (mm) T = average temperature (°C) RH = average relative humidity (%)
WS = average wind speed (m/s) SSD = average sunshine duration (hrs/day)
ET_p = total potential evapotranspiration (calculated according to Penman, modified by Doorenbos & Pruitt, 1984)
* = calculated using sunshine duration data for Marib

it causes the monsoonal wind system. The presence of the Red Sea produces the so-called Red Sea Convergence Zone effect (RSCZ) which contributes to the spring rainy season (March-May). Light rains sometimes observed during the winter months of December and January are attributed to a similar convergence effect around the Mediterranean Sea. Monsoonal winds reinforce the ITCZ effect during summer, causing the main rainy season (July-September).

The pronounced differences in topographic elevation observed in Yemen strongly influence climatic conditions. Average temperatures decrease more or less linearly with altitude, and the orographic rise of air masses provides an effective cooling mechanism which triggers rainfall. This explains why seaward exposed escarpments such as the Western and Southern Slopes receive more rainfall than the zones facing the interior. Local topographic features cause similar leeside effects, at correspondingly smaller scales. Diurnally alternating wind systems such as sea and land breezes, and uphill- and down-valley winds are also related to local topography.

Table 4.1 presents a summary of meteorological statistics for selected meteorological stations. It merely gives an impression of spatial variability; more detail is provided in Appendices 3.1 through 3.3. The data should be interpreted with caution, because the quality and consistency of the data have not been systematically assessed, but there are ample indications that parts of the records are of poor quality. The degree of standardization in observational equipment and practices is generally low, station supervision is often hampered by difficult access and lack of funds, and detailed station histories are almost absent. Comparison of series and analysis of patterns in space and in time may help distinguish between records of acceptable quality and those that are probably unreliable.

The different meteorological variables will be discussed in the next sections, with the emphasis on precipitation and evapotranspiration.

4.2 Precipitation

4.2.1 Forms of precipitation and principal rainfall mechanisms

Atmospheric precipitation in Yemen comes mainly in the form of rains, but hail is not uncommon in the mountain areas. Snow is exceptionally observed on the highest peaks, such as Jabal Nabi Shuayb, but even there it does not lie for more than a few hours. Unless indicated otherwise, the term 'rain' is used below as a synonym for atmospheric precipitation.

Rain storms are dominantly convective in Yemen. As a result, their areal extent tends to be limited, in spite of the fact that the general circulation that sets the general conditions for the occurrence of rainfall is of a supra-regional scale. During summer periods of intensive convergence of trade winds, complex rain storms may develop, bringing rainfall to extensive areas. But even under such circumstances, there tend to be great differences in amounts of rainfall over short distances. This is consistent with the general observation that most individual storms cover only a limited area, no more than several tens of square kilometres. Orographic effects are strongly controlling the spatial patterns of rainfall.

4.2.2 *Annual rainfall totals: long-term variations*

Annual rainfall totals vary from year to year and from location to location. Most rainfall stations in Yemen have too short a record to enable long-term variations of annual rainfall totals to be studied. For Aden, Sana'a, Tai'zz and Ryan, however, there are relatively long series of observations (see Appendices 2 and 3).

The Aden observations started in 1870 at Steamer Point, where they continued until 1936, with seven missing years in the period between 1871-1886. There is a continuous record from 1940 through 1989 for the nearby Aden Khormaksar station. A Wilcoxon rank-sum test (see for instance Maidment, 1992) shows that both series can be considered as samples of one and the same population, even if a high significance level is chosen. This means that the series can be combined to one homogeneous series. This series has an average of 50.8 mm and a coefficient of variation of 0.97; the latter implies that the interannual variability is considerable. The total series can be reasonably fitted to a log-normal distribution, as is shown in Figure 4.1.

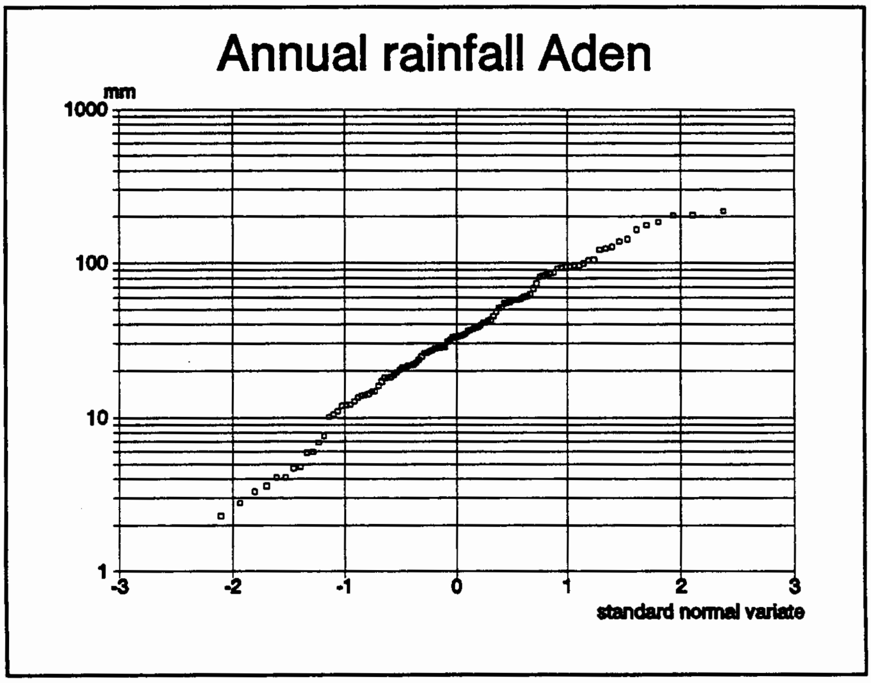


Figure 4.1 Log-normal plot of Aden annual rainfall data

In spite of some missing data (10 years) the series is suitable for the analysis of rainfall variations at Aden over more than a century. Figure 4.2 shows the variation about the mean ('departures from the mean'). A number of conclusions can be drawn. The most important is that there is no significant long-term trend, and no well-defined cycles of dry and wet years. Instead, there is an alternation of short periods of above-average rainfall (1 - 3 years) with irregular, but usually longer periods of below-average rainfall. Note that the positive 'departures' reach higher absolute values than the negative ones, which is consistent with the fact that the series follows a log-normal distribution.

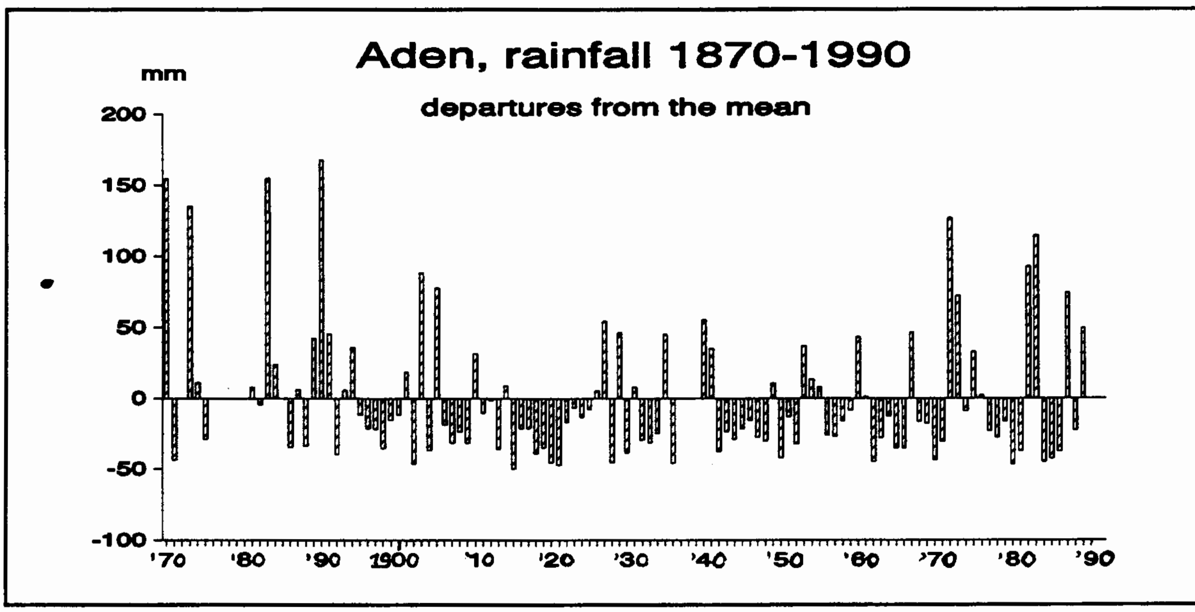


Figure 4.2 Aden annual rainfall: departures from the mean

The next question is whether the pattern of dry and wet years is uniform over the country or larger parts of it. Inspection of the rainfall records of Aden Khormaksar, Ryan, Sana'a Shoub and Ta'izz Town (Figure 4.3) reveals that the series are moderately to poorly correlated, depending on the distance between the stations. Even stations near to each other such as Sana'a Shoub and Sana'a Airport, or Ta'izz Old Airport and Ta'izz Town, have annual correlation coefficients not better than about 0.70. For larger distances between the stations this coefficient quickly drops to insignificant levels. This confirms the general experience that a certain year may be relatively wet in one area of Yemen, but rather dry in other areas, even if the distance is only modest.

The coefficient of variation of the annual rainfall series tends to decrease with increasing average rainfall, as Figure 4.4 shows. This means that variations from year to year are most pronounced at the most arid sites, at least in relative terms, i.e. compared to the average rainfall. This variability is less at the wettest locations, but even there it is still considerable.

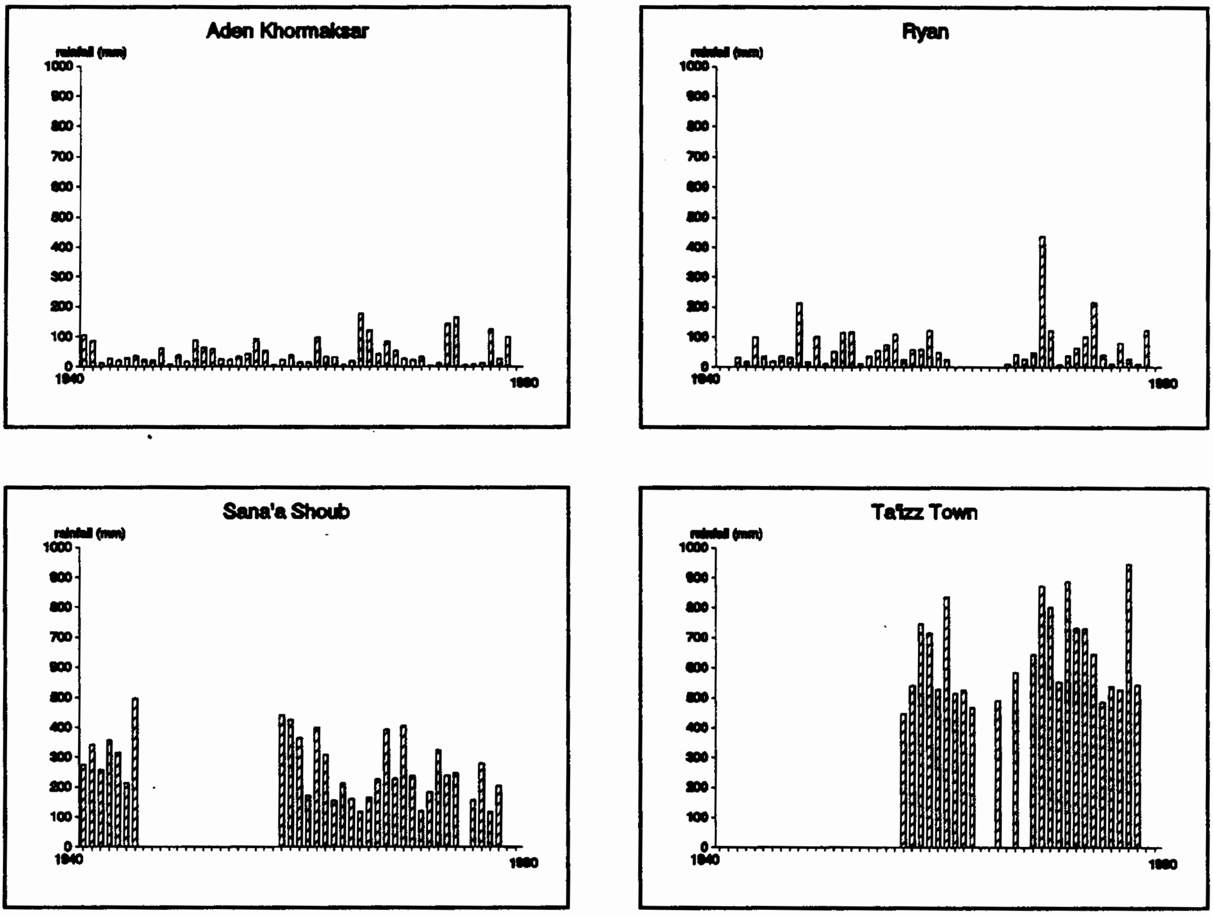


Figure 4.3 Rainfall observed at four stations during the period 1940-1990

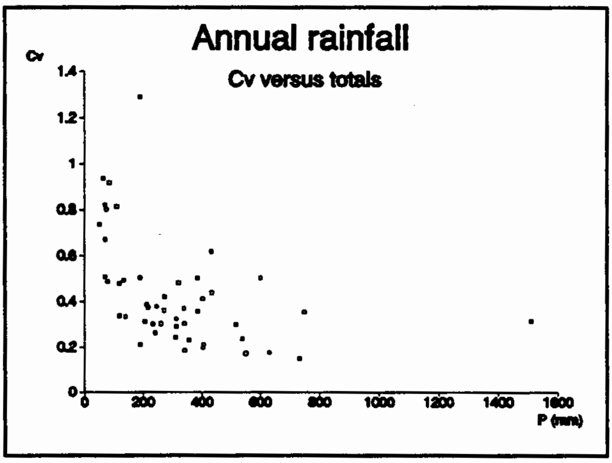


Figure 4.4 Coefficient of variation of the annual rainfall series

4.2.3 Annual rainfall totals: spatial pattern

The spatial pattern of annual rainfall varies from year to year. The controlling topographic factors, however, are strong enough to produce pronounced patterns that are fairly stable for long-term averages of annual rainfall. Yemen has only very few rainfall stations with long records, and most of the relatively long records have several interruptions (see Appendices 2 and 3). Consequently, it is not yet possible to produce a reliable map of long-term annual precipitation for the territory of Yemen.

Figure 4.5 shows the spatial pattern of average annual rainfall over the period 1985 through 1991. This standard period was chosen as the period for which as many rainfall stations as possible have a complete or nearly complete record. The missing data were estimated by using the 'normal ratio method' (see e.g. Linsley et al.,1958; Gray, 1970; WMO, 1970; Maidment, 1992). Using a standard period it becomes meaningful to compare the averages for different stations and to interpolate between them. This does not mean, however, that the accuracy is high. On the contrary, there is no national standardization in gauging equipment, installation and operation; which results in a certain but unknown inconsistency error. Furthermore, most of the rain gauges in Yemen have their rims at 1.2 to 1.5 m above ground surface, or are installed on top of flat roofs (for security reasons), thus a general undercatch due to wind effects may be assumed.

Comparison of the 1985 through 1991 rainfall averages with longer-term averages, for stations with longer records, suggests that this period may have been 10 - 20 % drier than average, although this may be variable for different regions in the country.

In spite of all these restrictions, the isohyet map gives a clear and consistent picture of the spatial pattern of annual rainfall. For the easternmost part of the country additional information on rainfall in Oman was used; the pattern depicted there is somewhat speculative. Average annual rainfall figures higher than some 250 mm are only observed in the western and southern parts of the Yemen Mountain Massive, with a maximum near Ibb (1510 mm). Anywhere else the average annual rainfall is low, especially in Al Mahrah governorate, in the northern part of Hadramawt and in the Ramlat Sabatayn.

Zones of maximum rainfall are evidently controlled by orography, which is particularly striking in the western part of the country. Moist air masses coming from the Red Sea and the Gulf of Aden pass over the coastal plains without producing much rain at these low elevations. But the steep western and southern slopes force the air upwards, which results in cooling and consequently in rainfall. Note that on the western slopes the zone of maximum rainfall is systematically shifted with respect to the zone of maximum elevation; the air masses lose most of their moisture at the first major mountain ridge they meet, and have generally become much drier when they move more eastward. The air flowing from the highlands towards the lower zones of the interior is mostly poor in moisture and generally is moving downslope, which explains why rainfall there is sparse. A similar mechanism acts on the air masses that move in from the Gulf of Aden, but the pattern is less pronounced because the relief is lower. The Ibb - Tai'zz 'high rainfall zone' enjoys rains both from southerly and westerly provenances.

Although it is known that rainfall in the Al Mahrah governorate is generally low, no data are available to reveal a pattern. An aspect of interest might be the occurrence and importance of dew. The adjoining Dhofar region in Oman has green grazing areas during the monsoon months, which are attributed to the occurrence of dew during these particular months. It would be interesting to know whether this phenomenon is important on the Yemeni side of the border too.

A rainfall pattern for Socotra Island cannot yet be established either. Available rainfall data suggest an average rainfall near Hadiboh of 100 - 150 mm per year. Sources of moisture are abundant and topography expression is strong; hence, it is probable that rather high rainfall is enjoyed in the higher parts of the island.

4.2.4 Seasonal patterns

Seasonal rainfall patterns differ from zone to zone and from year to year, but a general characteristic can be given. Most zones in Yemen have a well-defined seasonal rainfall regime, with a first rainy season in spring (March-May) and a second one in late summer (July-September). Long periods of dry weather with few or no clouds are common from October to March, although occasional storms do occur, especially on the western and southern slopes. Around the beginning of spring, however, the heated land surface triggers inland winds, which during a few subsequent months leads to occasional convective rain storms, especially along the mountain slopes. Rainfall decreases significantly in June, which marks a short dry period. The second rainy season usually starts in July. By that time the ITCZ lies over Yemen and warm dry air from the north converges with very moist air originating from the Indian Ocean region. Rains become sporadic around the beginning of autumn; then a new prolonged dry season starts. This general seasonal pattern can be most easily recognized in the zones of relatively high rainfall. Erratic rains may occur during any month of the year. In low precipitation zones they may obscure the seasonal pattern described.

Figure 4.6 shows average monthly rainfall patterns for selected rainfall stations. They all show the two rainy seasons, separated by a markedly drier month of June. This is the case almost anywhere in Yemen; a notable exception is Ibb, where abundant rainfall (around 1500 mm per year) causes the first and second rainy season to merge. Figure 4.7 enables January-June rainfall to be compared with July-December rainfall. It shows a wide spread of ratios for locations where the mean annual rainfall is low; for wetter locations it appears that the first and second six months of the calendar year have approximately the same share in the total annual rainfall. However, rainfall during the second half of the year tends to be more concentrated in a few months: the wettest months on record are usually August or September. In the western part of the country there are slight zonal differences in the ratio of spring rainfall to summer rainfall: in the northern part and in Tihama the spring rainy season is relatively more developed than further south. This is in accordance with the existing ideas on the factors that trigger each of the two rainy seasons.

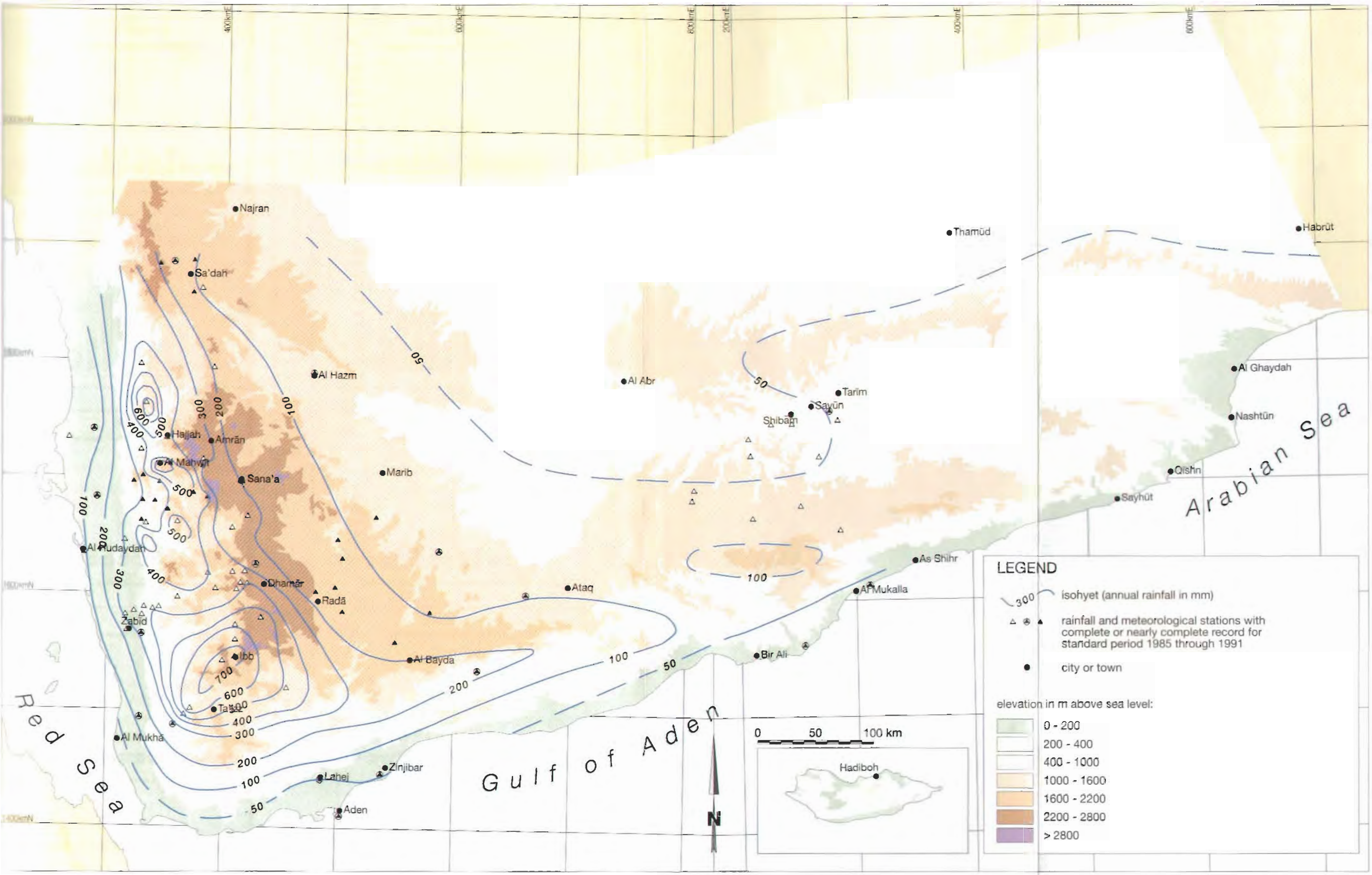


Figure 4.5 Average annual rainfall, period 1985 through 1991

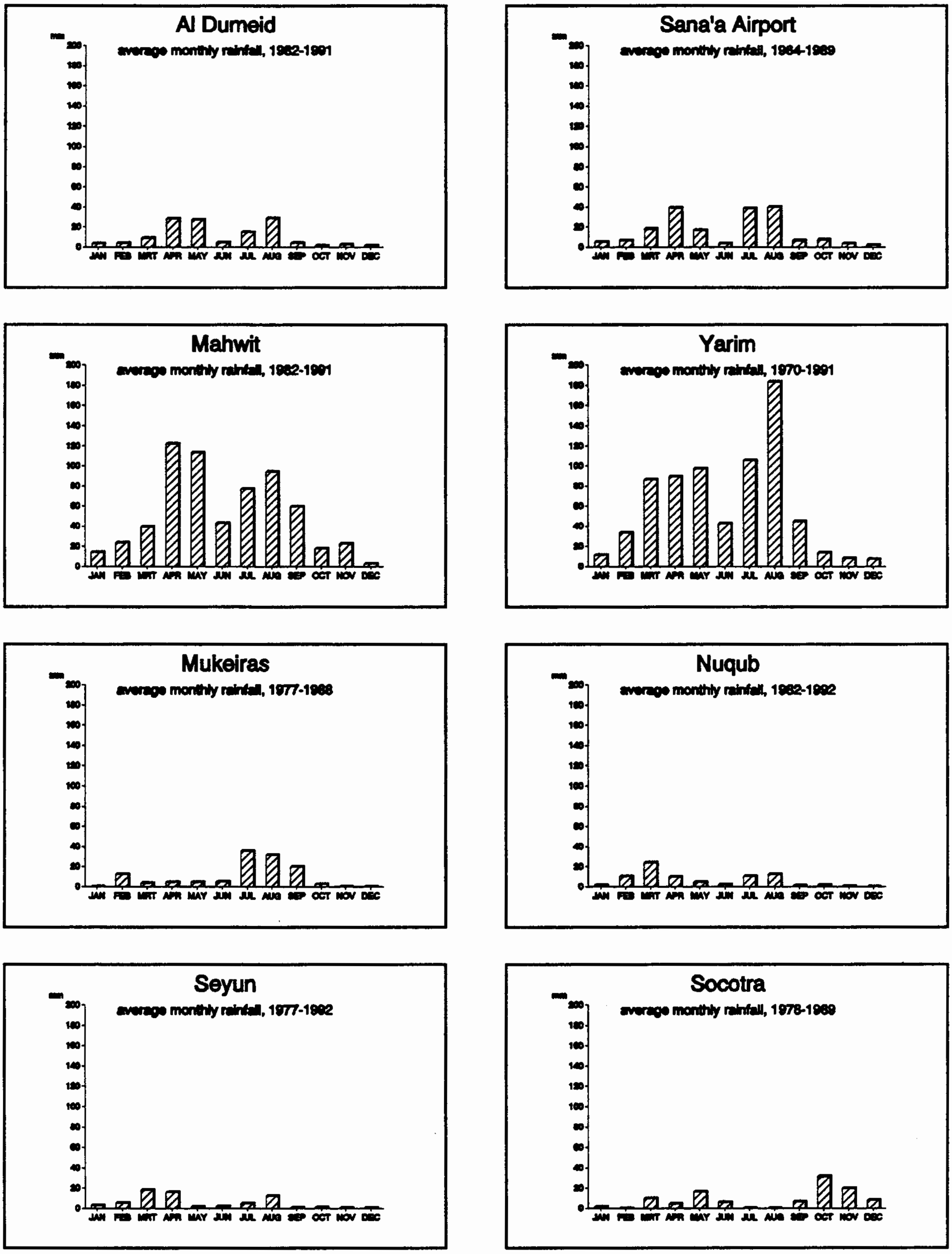


Figure 4.6 Average monthly rainfall at selected rainfall stations

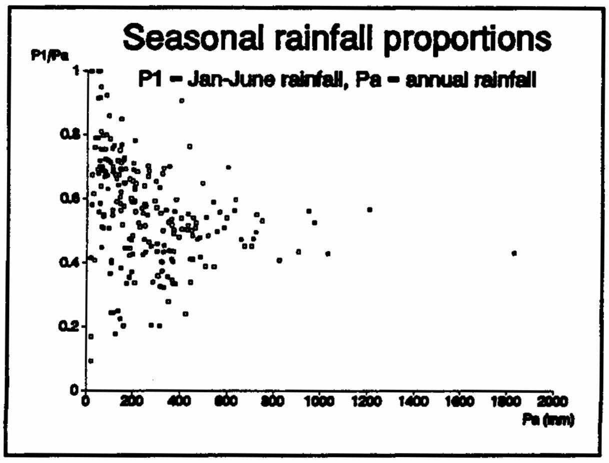


Figure 4.7 January-June rainfall as a proportion of total annual rainfall

4.2.5 Daily rainfall amounts and rainfall intensities

Daily rainfall amounts in Yemen are in most cases the result of only one rain storm. The duration of such a storm is usually rather short, and only exceptionally exceeds a few hours. Differences between zones or locations in the total annual or seasonal rainfall are mainly related to the frequency of rain storms occurring, and only to a minor extent to differences in intensity or duration. TS-HWC (1992c) formulates the hypothesis that, for practical purposes, daily rainfall throughout the former YAR can be considered as samples from a single statistical population of rain storms.

Based on the records of 10 stations with lengths varying from 6 to 15 years, TS-HWC (1992c) shows that the number of days with at least 5 mm of rain ('rainy day') is strongly correlated with the average annual rainfall. This is demonstrated in Figure 4.8, which suggests the following regression equation :

expected number of rainy days (per year) = 0.0552 * mean annual rainfall (in mm)

For these stations the maximum daily rainfall on record ranges from 40.5 to 97.0 mm.

The samples of daily rainfall higher than 5mm for these stations have almost identical statistical properties; they follow (with a coefficient of determination of 0.98) a log-normal distribution with a constant of 2.58 and a slope of 0.61, or in other words : the distribution of daily rainfall (DR) on 'rainy days' (rainfall > 5 mmm) is related to the frequency factor F_n (*normal variate*) of the normal distribution as follows:

$$DR=e^{2.58+0.61*F_n}$$

This supports the hypothesis mentioned above, which -as long as data and analysis for eastern stations are lacking- could be extended to the entire mainland of Yemen. Figure 4.9 shows the defined distribution graphically.

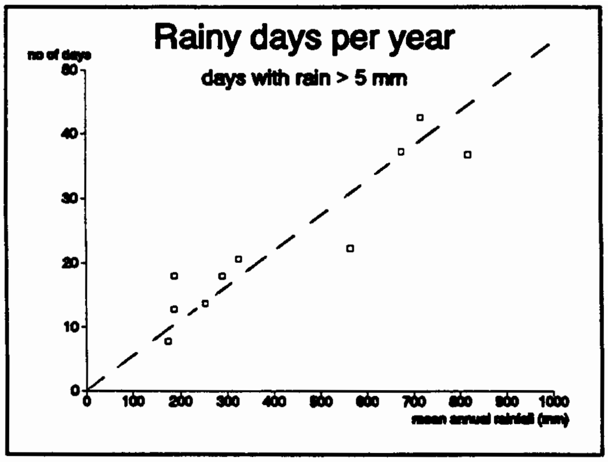


Figure 4.8 *Number of days with rain > 5mm in relation to mean annual rainfall (based on data of 10 stations in Western Yemen; after TS-HWC, 1992c)*

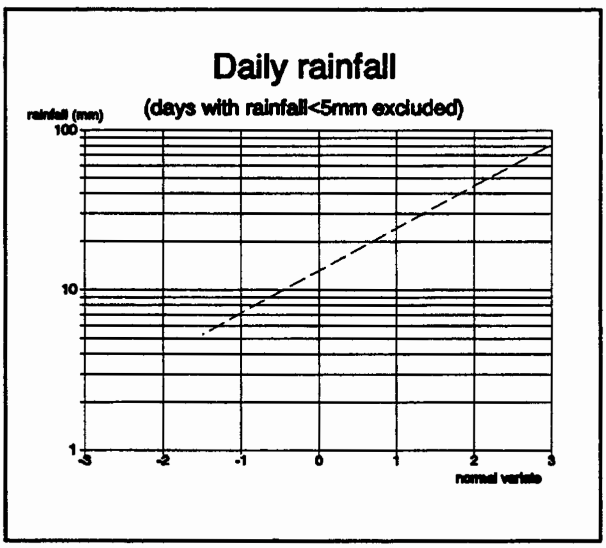


Figure 4.9 *Log-normal distribution of rainfall for days with more than 5 mm of rainfall (after TC-HWC ,1992c; assumed to be valid throughout Yemen)*

Both relations presented above, combined with average annual rainfall data, may yield reasonable estimates of the daily rainfall probabilities at monitored locations; this is shown in more detail by DHV (1993e).

Assuming that only a negligible part of rain storms contribute to two successive 'administrative' rainfall days (running from early morning until early morning next day), then the resulting statistical distributions of daily rainfall will not be significantly different from 24-hour rainfall distributions. This assumption seems plausible, because most rains in Yemen occur during afternoons or early evenings.

No studies have been encountered that have processed large numbers of long records to analyse rainfall in Yemen for periods of less than one day. Hence, no good picture can yet be given of rainfall intensities. Given that most rain storms are rather short and that two or more storms a day at a single location are rare, it is not unlikely that the distributions of rainfalls for any time-interval smaller than 24 hours and larger than 4 hours are only slightly different from those of daily rainfalls.

4.3 Other directly observed meteorological parameters

Important meteorological variables other than precipitation, observed at most of the meteorological stations in Yemen, are: *daily sunshine duration, temperature, relative humidity of the air* and *wind velocity*. They will be commented on briefly below. Average monthly data for Yemeni stations can be found in Appendix 3; Table 4.1 gives a summary of annual means. Average monthly values are depicted in Figure 4.10 for a few selected stations. These are: a station at the coast (Mocha), two stations on the Yemen Mountain Massif (one relatively dry (Al Dumeid near Sadah) and one relatively humid (Dhamar)); and a station in the hyper-arid interior zone (Seyun).

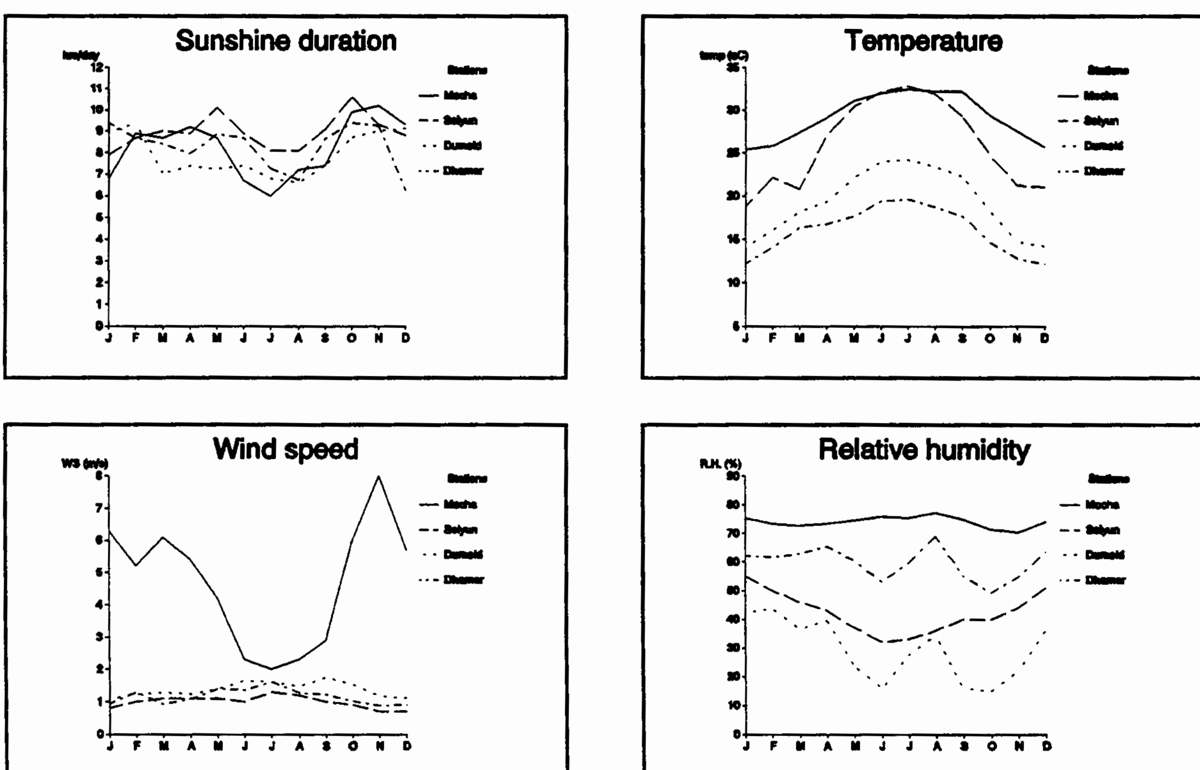


Figure 4.10 Monthly averaged climatological variables at selected stations

Comparisons between records and impressions from field visits suggest that the accuracy and reliability of these meteorological data may be questionable for part of the records. Careful quality assessments are certainly needed, but they are beyond the scope of this report. Relative humidity data are perhaps the most suspect data in this respect, because calibration and processing is more difficult for these than for the other data types. Wind velocity is supposed to be monitored at 2.0 m above ground surface, but it has not been verified whether this is standard practice at all stations. When interpreting the data, it should be borne in mind that the data recorded at a meteorological station are not necessarily representative for its wide surroundings, because spatial variation may be considerable, even over short distances.

Clear skies are predominant in Yemen during most of the year. This is reflected in the records of sunshine duration. Recorded annual average values are between 6 and 9 hours per day, which corresponds to 50 to 75 % of the theoretical maximum. Absence of sunshine during daytime is not only caused by clouds; mountains near the site of observation may also shorten sunshine duration because of the shadows they produce after sunrise and before sunset. Appendix 3 and Figure 4.10 show that from month to month there is only little variation of the number daily sunshine hours; the number reaches a minimum during the summer rainy season. Differences from one station to another are probably more due to local effects (and measurement/processing errors) than to regional variation.

Because solar radiation varies only slightly over the territory of Yemen, the pronounced differences in temperature regime must be associated with other factors. Average temperatures are dominantly controlled by elevation, as is shown in Figure 4.11. It shows an approximately linear relation, with an average temperature gradient of 0.6 °C per 100 metres difference in elevation. The annual range of the temperature (i.e. the difference between the average temperatures of the warmest and the coolest month of the year) is not constant. It is only 6-9 °C in the coastal zones (e.g. Mocha) and on the Western and Eastern Slopes, but increases to 13-16 °C in the arid interior (e.g. Seyun). Proximity to the sea and moisture content of the air are controlling factors. This is also true for the

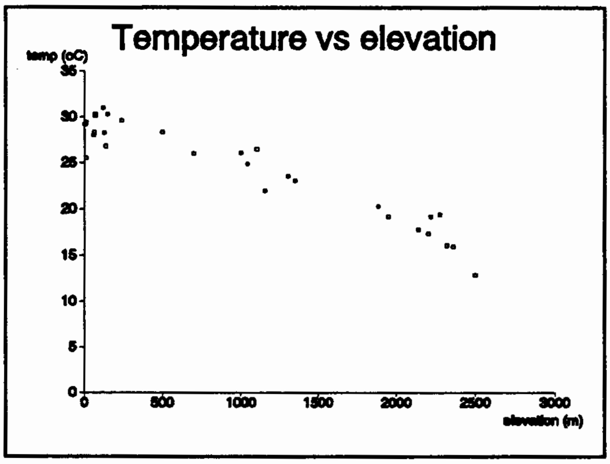


Figure 4.11 The influence of elevation on average temperature

average daily temperature range, which is modest near the coast (less than 10 ^{0}C), but may exceed 20 ^{0}C at higher elevations and in the arid interior.

Relative air humidity shows strong spatial variation. Looking at annual average values (Table 4.1), it can be observed that values between 70 and 80 % are typical for coastal, locations and values of 50 - 70 % for those parts of the coastal plains and deltas that are more than some 20 km from the sea. The average annual relative humidity is usually between 30 and 60 % in the mountain zone of Western Yemen, and it reaches lowest values (20 - 45 %) in the hyper-arid interior. Figure 4.10 reveals an expected negative correlation with temperature and local maxima during the rainy seasons (Dumeid and Dhamar).

Average wind speed in most is of Yemen low to moderate, except on the coast and at well-exposed locations in the mountain zones. It is believed that a significant part of the differences has to be attributed to local effects.

Pan evaporation is measured at several meteorological stations, but the data will not be presented here because the pans are generally not operated under prescribed standard conditions. No attention is given to measured radiation either, because the available records are not well documented, and it must first be ascertained whether the data sets represent total incoming radiation (short- and long-wave), or total short-wave incoming radiation, or net radiation received at the surface (incoming radiation minus back radiation).

4.4 Evaporation and evapotranspiration

The climatological data presented above enable potential evaporation and evapotranspiration to be calculated. The Penman method, Doorenbos and Pruitt (1984) version was used to calculate potential evapotranspiration. Table 4.1 presents the results in terms of average annual totals.

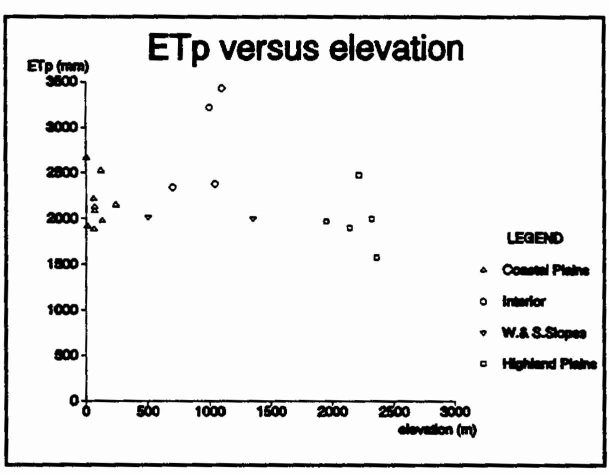


Figure 4.12 Calculated annual Penman evapotranspiration versus elevation

The annual totals range from 1579 mm (Dhamar) and 3427 mm (Al Jawf) for the meteorological stations considered. They depend in a complex way on the climatological variables described in section 4.3. Figure 4.12 shows the calculated potential evapotranspiration in relation to elevation: although there is a tendency for the potential evapotranspiration to decrease at increasing elevations, the relation is certainly not as well-defined as the relation between temperature and elevation (Figure 4.11). Thus factors other than average temperature must have a notable influence on the potential evapotranspiration variations. Analysis shows that quite a large part of the variation is explained by differences in wind speed, which possibly reflects local rather than regional effects. The two prominent 'outliers' in the graph are the data for Marib and Nuqub; low relative humidity is the main cause of their anomalous position.

In spite of all restrictions and inaccuracies, the data allow the following ranges for the annual Penman evapotranspiration in different zones of the country to be indicated tentatively:

coastal zones and foothills:	1800 - 2700 mm
mountain zones of Western Yemen	1500 - 2500 mm
arid zones of the interior	2000 - 3500 mm

The variation in potential evapotranspiration (ET_p) during the year is illustrated in Figure 4.13. Precipitation (P) is shown in the same graphs, in order to highlight the degree of aridity of the sites.

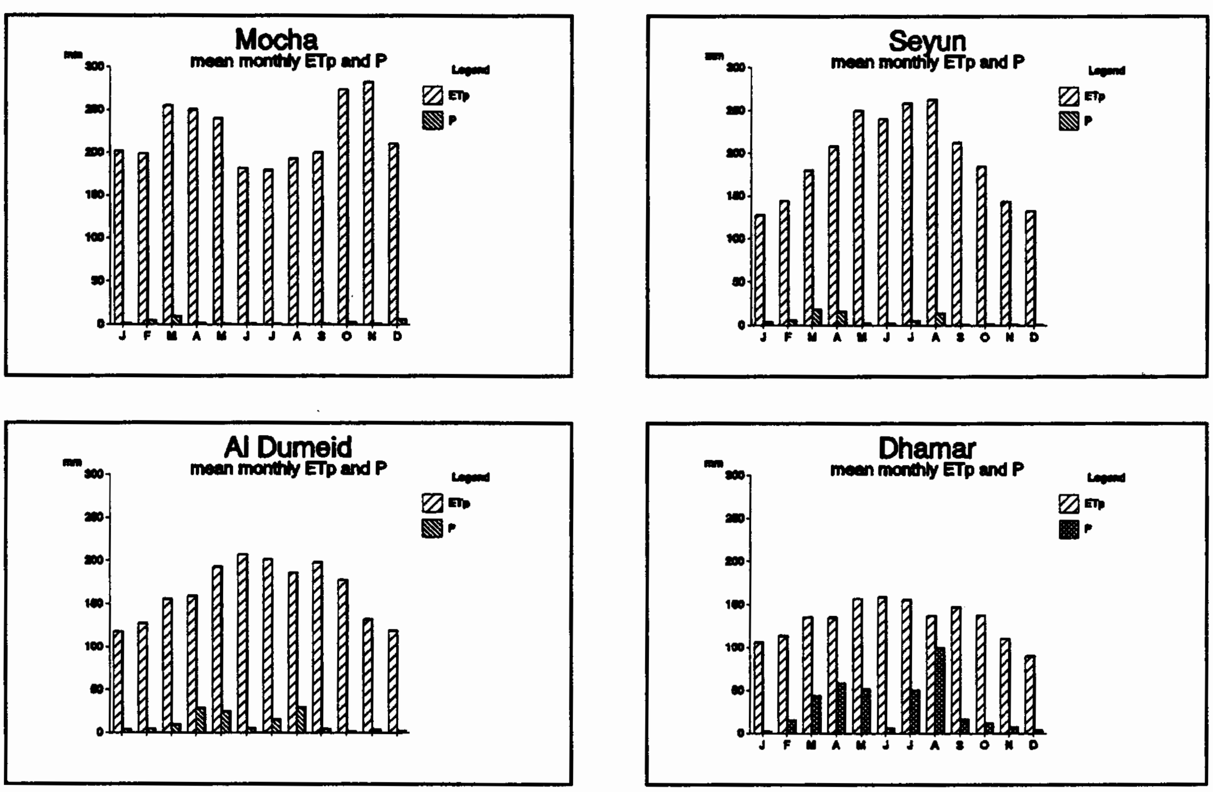


Figure 4.13 Monthly mean Penman evapotranspiration in relation to precipitation

The variation of potential evapotranspiration during the year closely follows the cyclic variation of temperature, with maxima during summer. Only at Mocha is there a temporary depression during summer, related to the special seasonal wind pattern; this is an anomaly which is not reproduced at other coastal meteorological stations.

Figure 4.13 shows clearly that at Mocha, Seyun and Al Dumeid the rainfall is insignificant compared to potential evapotranspiration. This implies that irrigation there is a prerequisite for crop growth. At Dhamar, at the other hand, rainfall during spring and summer months may cover a substantial part of the crop water requirements. For zones with higher annual rainfall the P/ET_p-ratio is even more favourable.

Evaporation from an open water surface (E_o) -which is also called *reference evaporation*- can be estimated from climate data in a similar way, but using an albedo of 0.95 instead of 0.75, and modifying the wind function for a smoother evaporating surface (see Doorenbos and Pruitt, 1984). This results in an annual E_o of 3429 mm for Marib and 1903 mm for Dhamar. For Yemeni conditions, the E_o calculated in this way is 5 - 20 % higher than the corresponding ET_p value, depending on the specific conditions.

On an annual basis, actual evapotranspiration over larger zones in Yemen is only a minor fraction of potential evapotranspiration, because soil water is usually severely lacking. Potential evapotranspiration rates -or values close to it- may be reached only in adequately irrigated zones during periods of full crop development. On the other hand, actual evaporation from small water surfaces will often exceed E_o as a result of advection of energy from the surroundings.

4.5 Climate zones in Yemen

Dry climates predominate in Yemen. According to Köppen's climate classification system, which is based on temperature and rainfall, almost the total territory of Yemen belongs to the climate class BWh (tropical/subtropical desert). Some zones of limited extent in Western Yemen with relatively high rainfall have a steppe climate (BSh) or -in a minor zone around Ibb- even a subhumid warm-temperate climate with a distinct dry period during the winter months (Cw).

Köppen's classification results in a low degree of climatic differentiation within the territory of Yemen. For instance, the Highland plains and surrounding mountains, with average annual rainfall commonly in the range 150-300 mm, are grouped within the same class (BWh) as the Ramlat-as-Sabatayn and Rub-al-Khali deserts, where rains are extremely rare.

To show more detail with respect to aridity, a classification proposed by UNESCO (1979) can be used. It is based on the ratio between average annual precipitation (P) and annual reference evaporation (E_o), and in principle distinguishes five different classes:

hyper-arid	$P/E_o < 0.03$
arid	$0.03 < P/E_o < 0.25$
semi-arid	$0.25 < P/E_o < 0.50$

subhumid $0.50 < P/E_o < 0.75$
humid $P/E_o > 0.75$

Figure 4.14 shows the results of this classification. In terms of aridity, the climate in Yemen is shown to vary from hyper-arid (deserts, most of the plateaux, parts of the coastal plains) to subhumid (scattered wetter zones on the Western and Southern Slopes), with perhaps even humid sites on a very small scale (Ibb).

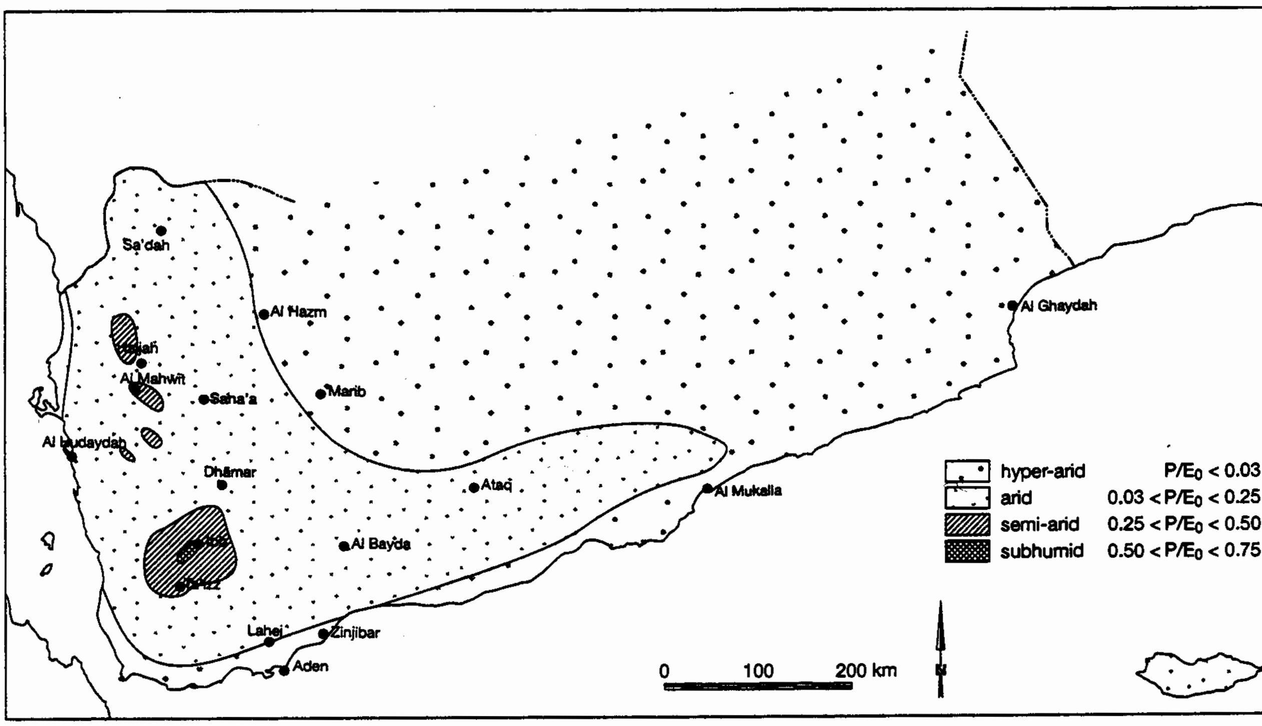


Figure 4.14 Climate zones in Yemen

5 SURFACE WATER

5.1 General features of the runoff processes

When drops of rain reach the surface of the earth during rain storms, they may fall directly into streams or other bodies of surface water (*channel precipitation*), be intercepted by vegetation, infiltrate into the soils, be stored on the land surface (*depression storage*) or run off downslope as *overland flow* to the nearest branch of the drainage network. Under the conditions prevailing in Yemen, a very large part of this water returns directly to the atmosphere within only a few days, by evaporation and transpiration. A smaller portion of the rainfall is converted to *streamflow* (or *runoff*). It is often convenient to divide total runoff into two main components: *quickflow* (or *direct flow*) and *baseflow*. Quickflow is observed in the streams during and/or immediately after the rain storm and is characterized by flood peaks. It is usually associated with channel precipitation, overland flow and *throughflow* (or *interflow*). The latter represents water that infiltrates but reappears after a short stay underground to contribute to streamflow. Baseflow is the nearly constant component of streamflow which may last for long periods without rains. In most cases it is associated mainly with the contribution of groundwater discharging into the rivers.

The runoff process is controlled by a large number of factors; taking into account the conditions encountered in Yemen, the main ones are:

(a) size and shape of the catchment;
(b) rainfall characteristics (total depth and distribution in space and time);
(c) rates of potential evaporation and evapotranspiration;
(d) terrain characteristics of the catchment area (slopes; occurrence and properties of soils, rock outcrops and vegetation);
(e) presence and properties of regional groundwater systems;
(f) land use and other human interference.

Clearly, all other factors remaining constant, larger catchment areas and higher rainfall amounts will result in more runoff. And catchments with a compact shape will produce more violent floods than elongated catchment areas. Also, some of the runoff produced in the upper part of a catchment may be lost again through the river bed (*transmission losses*) on its way downstream; statistically, these losses will increase with distance. Furthermore, a certain depth of rain tends to produce comparatively more runoff if the preceding days or weeks have been rainy. It is common for the first rains after a prolonged dry period to produce little or no runoff in the river beds downstream. It goes without saying that higher rates of potential evapotranspiration will generally lead to higher evapotranspiration losses.

What percentage of the rainfall is finally converted into runoff and the speed of the response to rainfall, largely depends on the nature of the land surface and of the geological formations near the surface. Steep slopes and bare impervious rocks at the surface favour a quick response. Shallow slopes, local topographic depressions, dense vegetation and high permeability of soils and outcropping geological formations, on the other hand, create conditions where rain water may infiltrate or evaporate more easily, thus reducing the volume and frequency of streamflow and increasing the time lag between rainfall and streamflow. The *infiltration capacity* of the surface horizons -in relation to the rainfall intensity- plays a crucial role in the reallocation of rain into the different components of streamflow and the losses mentioned above. Hence, light rains falling onto a permeable surface often fail to produce any runoff at all.

Under certain conditions, groundwater systems present in the catchment area may significantly influence streamflow. By their storage capacity they enable water to remain underground for a long time, thus reducing quickflow; in most cases this water reappears in downstream zones and feeds the baseflows.

Land use may significantly modify the runoff processes. The numerous man-made terraces on the slopes of the Yemen Mountain Massif offer a convincing example. They protect the soils from being washed away; the rains easily infiltrate into the ploughed soils and largely evapotranspire from the cultivated fields; the protecting walls form a barrier to overland flow. Small and large dams, spate irrigation systems and built-up areas are other examples of human controls on the runoff processes.

Rivers in arid and semi-arid zones have a number of typical features. In the first place, rivers that are permanent over the entire length of their stream beds are uncommon in arid zones. On the contrary, most of the rivers are *ephemeral*; only a few have minor baseflows that may be seasonal or even permanent, but only in a limited part of their channel network. Typically, the beds of arid zone rivers are dry for most of the time, and infrequent runoff peaks quickly come and go. The intermittent nature of such rivers (often indicated as *wadis*) can be associated with the long-term precipitation deficits inherent to arid climates. They cause evaporation and evapotranspiration there to play a much more dominant role in the hydrological cycle than in humid climates, thereby reducing the role of streams. Flood peaks, however, are often quick and violent, because the sparse vegetation and limited extent of permeable soils in the catchment areas are incapable of providing effective buffers. It is not uncommon for wadis in low precipitation zones to remain completely dry for several years between flood events.

Another salient feature of arid zones is that saturated contact between streams and regional groundwater reservoirs is relatively rare. Nevertheless, water from wadis usually constitutes the most important source of groundwater recharge. As a rule, recharge is produced after the infiltrated water has moved downward through the unsaturated zone.

Whereas the average discharge of rivers in humid regions normally increases monotonously in downstream direction, this is often not the case for arid zone rivers. Wadis in Yemen demonstrate this very clearly. Distinct parts of the channel networks tend to act as collectors of surface water, whereas others lose some or all of the flow. From upstream to downstream there may be several alternations of 'gaining' and 'losing' wadi segments, but the overall result is that only minor amounts of surface water are discharged into the sea. The phenomenon is obviously related to controlling terrain features, as described above. These observations inspired Van Enk and Van der Gun (1984) to make a distinction between *runoff producing zones* and *runoff absorbing zones*.

The former are thought to be the zones where runoff originates ('source areas'), whereas in the latter zones runoff tends to be lost rather than produced ('sink areas'). A characteristic feature of the runoff absorbing zones is a very low drainage density. Rivers descending from an adjoining runoff producing zone tend to degenerate after flowing a a certain distance (usually a few tens of kilometres) in a runoff absorbing zone.

Figure 5.1 gives an impression of the distribution of runoff producing and runoff absorbing zones over the territory of Yemen. The runoff producing zones are subdivided into zones with a permeable surface and those where outcropping rocks are more or less impermeable. This may be of interest for better understanding differences in runoff regimes; the aggregation level of the map did not allow other relevant terrain features to be incorporated, such as terrain slope and presence of vegetation and terraced agriculture.

Large-scale examples of runoff absorbing zones are the Tihama, the Tuban-Abyan coastal plains, and the Ramlat-as-Sabatayn and Rub-al-Khali deserts. The alluvial Wadi Hadramawt valley and the Highland Plains in the centre of the Yemen Mountain Massif are distinct runoff absorbing zones as well, but at a smaller scale. At increasingly smaller scales, smaller absorbing zones can be distinguished, e.g. local alluvial fills and patches, and cultivated plots. They are too small and too numerous to be shown in Figure 5.1, but they play an important role in the runoff process. Note that the Yemen Mountains in the west and the Plateaux in the east are almost entirely mapped as runoff producing zones.

The intricate pattern of runoff absorbing and runoff producing zones explains to a significant extent the variations in occurrence and magnitude of flows and floods in different parts of the wadi channel networks.

The volumes of stream flow per km^2 of catchment area are largest on the Western and Southern Slopes, because rainfall there is much higher than anywhere else in the country. But there as well as in other parts of Yemen only a minor fraction of rainfall is converted into runoff. For catchment areas of a few thousand km^2 and larger, annual runoff volumes are less than 10 % of the annual rainfall volumes, as will be shown in Section 5.3. Higher *runoff coefficients* (i.e. ratio of runoff to rainfall volumes) are to be expected for smaller catchments, because these offer statistically fewer opportunities for losses. Runoff coefficients for individual intensive rain storms during wet periods can be much higher than the annual average coefficients, because the physical processes that produce losses -such as evaporation and evapotranspiration- are limited in their rates.

5.2 Catchment areas and principal drainage basins

5.2.1 General configuration

The main wadis in Yemen are depicted in Figure 5.1. They have been selected from Robertson's topographic map; simplifications were made to match the scale of the map, and topology or names were adjusted if it seemed plausible that they were incorrect. Names are shown as far as deemed useful for this summary (78 named wadis); unnamed

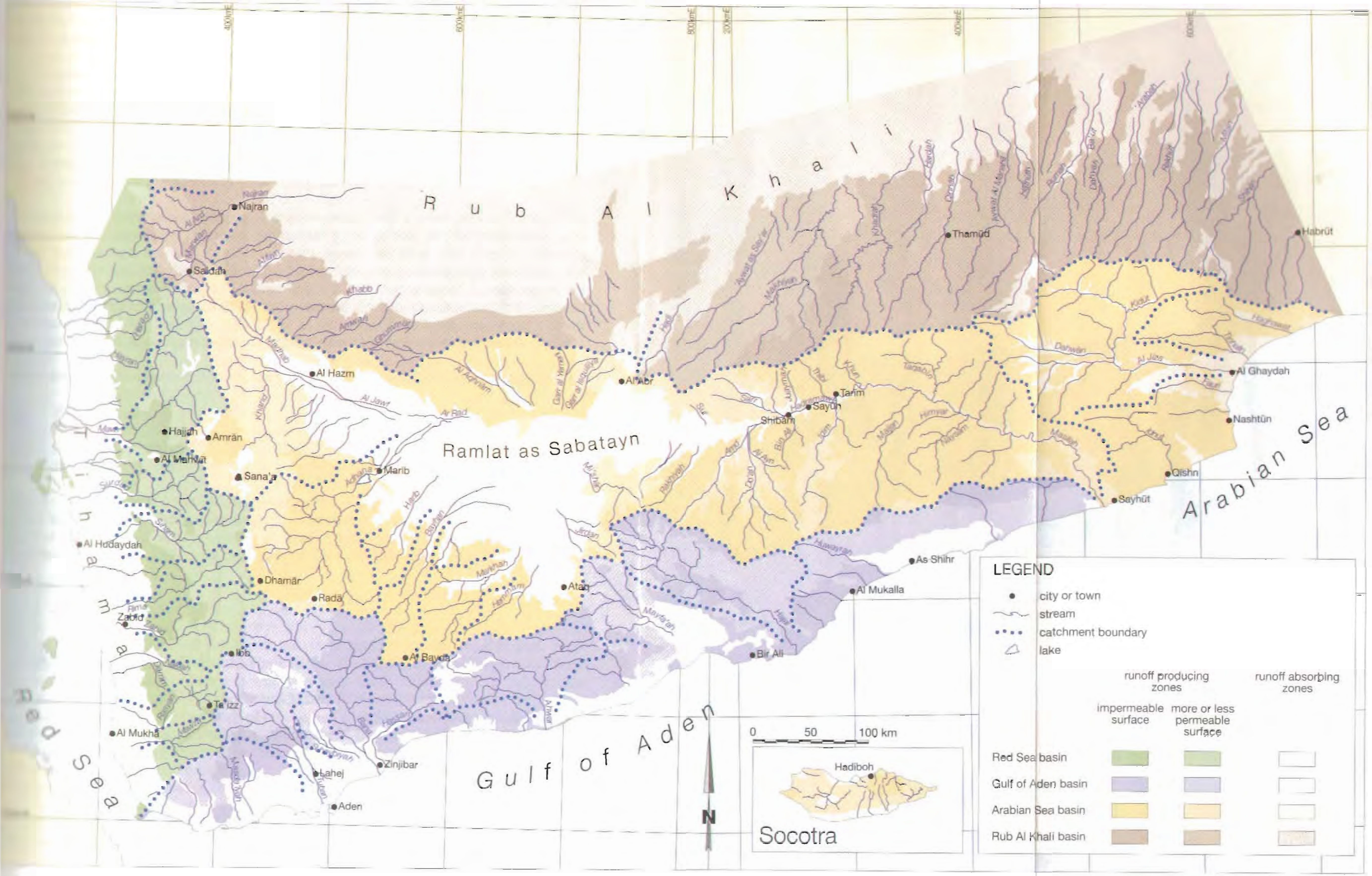


Figure 5.1 Main surface water systems in Yemen

wadis and tributaries are mainly added to provide a better picture of drainage patterns and catchment areas.

The *catchment area* of a stream at a given site is the area which in principle drains to that particular stream upstream of that site. Each elementary upper branch of a stream network has its own catchment area, which can be defined on the basis of topography. After such a stream branch joins with another one, the corresponding catchment areas combined become the catchment of the downstream branch. This can be repeated all the way down to the stream's mouth at the sea. The fractal-like hierarchy of a wadi-system implies a corresponding hierarchy of nested catchment areas.

Numerous river systems and related catchment areas cover the territory of Yemen. For conceptual and descriptive purposes it is useful to group them into larger zones in such a way that the river systems within each zone have their final base level in common. Such zones are indicated here as *drainage basins*. Assuming natural flow conditions, the base level of a drainage basin is either the sea or a topographic depression where massive evaporation takes place as the main natural discharge mechanism. It is common practice to name the drainage basin after its particular base level, just as -at a lower aggregation level- a catchment area is named after the river towards which it drains.

Accordingly, the territory of Yemen can be subdivided over four main drainage basins:

(1) Red Sea basin
(2) Gulf of Aden basin
(3) Arabian Sea basin
(4) Rub Al Khali basin

Figure 5.1 shows their location and areal extent. The boundary between the Gulf of Aden basin and the Arabian Sea basin is somewhat arbitrary, because the limit of the Gulf of Aden has not been accurately defined. It has been opted to optimally highlight hydrological contrasts. A brief description of the main drainage basins follows.

5.2.2 Red Sea Basin

The main wadis of the Red Sea Basin are, from north to south: Wadi Harad, Wadi Mawr, Wadi Surdud, Wadi Siham, Wadi Rima, Wadi Zabid, Wadi Rasyan and Wadi Mawza. They all have catchment areas greater than 1000 km^2; the largest one (approximately 8000 km^2) is that of Wadi Mawr. These wadis and a number of smaller ones drain the steep western slopes of the Yemen Mountains and lose virtually all their water when traversing the permeable sediments of the coastal plain (Tihama). Direct outflow of surface water into the Red Sea may occur on rare occasions, but the volumes involved are negligible. The wide and well-defined stream beds of the main wadis degenerate quickly westwards and are often hard to trace near the coast.

Given the contrasting terrain properties, maximum flows in each wadi occur at the boundary between the Western Slopes and Tihama. These catchments are endowed with comparatively high rainfall (see Chapter 4) and terrain slopes are steeper than anywhere else in Yemen; both elements favour high flood peaks. On the other hand, factors that tend to smoothe the runoff regimes are present as well. Firstly, in response to dependable rainfall, there are numerous mountain terraces where rainfed agriculture is practised, especially at higher elevations. Secondly, the rains maintain a more flourishing natural vegetation than in many other zones of Yemen. Furthermore, large parts of the upper catchments are covered with rocks of moderate permeability, enabling some of the water to be trapped or delayed before it reaches a wadi channel.

The water from the wadis that is not lost by evapotranspiration in the spate irrigation zones feeds the groundwater system of Tihama and continues moving towards the sea only underground. Under natural conditions, in the past, this water used finally to be discharged mainly into the Red Sea (by groundwater outflow) or into the atmosphere (by evaporation in the sebkhas along the Red Sea coast); both mechanisms with an approximately equal share. Irrigation practices have created a third important discharge component: the evapotranspiration of irrigated crops.

5.2.3 Gulf of Aden Basin

The main wadis (with catchment areas greater than 1000 km^2) of the Gulf of Aden Basin are, from west to east: Wadi Tuban, Wadi Bana, Wadi Hassan, Wadi Ahwar, Wadi Maifa'h, Wadi Hajar and Wadi Huwayrah. There is a great deal of similarity with the Red Sea Basin, but an important difference is that surface water outflow into the Gulf of Aden occurs more frequently, probably at the expense of sebkha discharge. The main reason is that the coastal plains along the Gulf of Aden are less developed and often steeper than those along the Red Sea.

Rainfall in the mountainous catchments is higher than near the coast. Apart from this, the catchments in the western part of the basin enjoy much higher rainfall than those in the central and eastern parts.

5.2.4 Arabian Sea Basin

The Arabian Sea Basin is very complex. Apart from the catchments of the wadis of the Al Ghayda depression (Wadis Haghawat, Tinhalin, Al Jiza, Fauri and Idunut and a few minor ones) and on Socotra and other islands, it contains the 'greater Wadi Hadhramawt system'. The latter can be considered theoretically as one single catchment area, because in principle the topography allows a drop of water to travel by gravity from the headwaters on the Eastern Slopes of the Yemen Mountains all the way down to Wadi Masila's outlet into the Arabian Sea. In practice, however, it is unlikely that surface water migrates over this entire distance, because rainfall rates are low and surface water easily infiltrates in the intercalated 'runoff absorbing zones'. Trapped as groundwater it then takes very large travel times for water to cover the distance from the Eastern Slopes to the Arabian Sea.

Because of its remarkable physiographic features the catchment of the 'greater Wadi Hadhramawt system' can be subdivided from upstream to downstream into a number of zones alternating between runoff producing and runoff absorbing. Neglecting the smaller-scale systems, these are: the Highland mountains draining towards the Highland Plains (runoff producing), the Highland Plains (runoff absorbing), Eastern Slopes and other zones draining towards the Ramlat Sabatayn and Wadi Hadramawt (runoff producing), Ramlat Sabatayn and the wide Wadi Hadramawt bed (runoff absorbing), and the lower Wadi Hadhramawt/Wadi Masila catchments downstream of Tarim (runoff producing). This basin is much drier than the Red Sea Basin and the Gulf of Aden basin, and bare rocks are predominant in its runoff producing catchment zones.

5.2.5 Rub Al Khali Basin

The northward sloping northern zones of the Yemen Mountain Massif and Eastern Plateau Region are dissected by numerous nearly parallel wadis. The most important ones descending from the Yemen Mountain Massive are from west to east: Wadi Najran, Wadi Atfayn, Wadi Khabb, Wadi Amwah and Wadi Ghummur. And those draining the Eastern Plateau: Wadi Hadi, Wadi Aywat As Sayar, Wadi Makhyah, Wadi Khadra, Wadi Hardah, Wadi Qinab, Wadi Aywat, Wadi Harthuth, Wadi Rumah (or Arma), Wadi Dahyah Ba'ut, Wadi 'Arabah, Wadi Rakhut, Wadi Mitan and Wadi Shihan. These and a large number of smaller wadis quickly evacuate the excess water from rare rain storms to the sands of the Rub Al Khali Basin, where it infiltrates and thus recharges groundwater. The exact fate of this groundwater -whether it finally evaporates or discharges into the Arabian Gulf- has not yet been sufficiently studied. There is some evidence that a large part is finally discharged by evaporation in the extensive topographic depression of Al Kidan and Al Ashruq Al Mutardiah in the zone where the territories of Saudi Arabia, Oman and the Emirates meet. The Rub Al Khali Basin is the driest one of the four drainage basins, but green oases are locally present, e.g. in Wadi Najran and Wadi Khabb.

5.3 The shape of the hydrographs

5.3.1 Instantaneous flood hydrographs

The floods of the wadis in Yemen are generally characterized by abruptly rising peaks that rapidly recede; in between the irregular floods the wadis are either dry or carry only minor base flows.

Wadi Surdud will be used as an example to illustrate the hydrograph characteristics of Yemeni wadis. GDH has been operating a gauging station in Wadi Surdud since the beginning of 1984, at a site known as Faj Al Hussein, located just upstream of where the wadi enters the Tihama. The catchment area there measures approximately 2370 km^2. Like almost all other gauging stations in Yemen, the gauging site at Faj Al Hussein is in a natural wadi bed exposed to frequent erosion and redeposition of bed material by floods. Given an uninterrupted water level record, reliable and accurate flows can only be derived if current is metered frequently and accurately. Many hundreds of current meter measurements have been carried out at Faj Al Hussein by GDH, especially

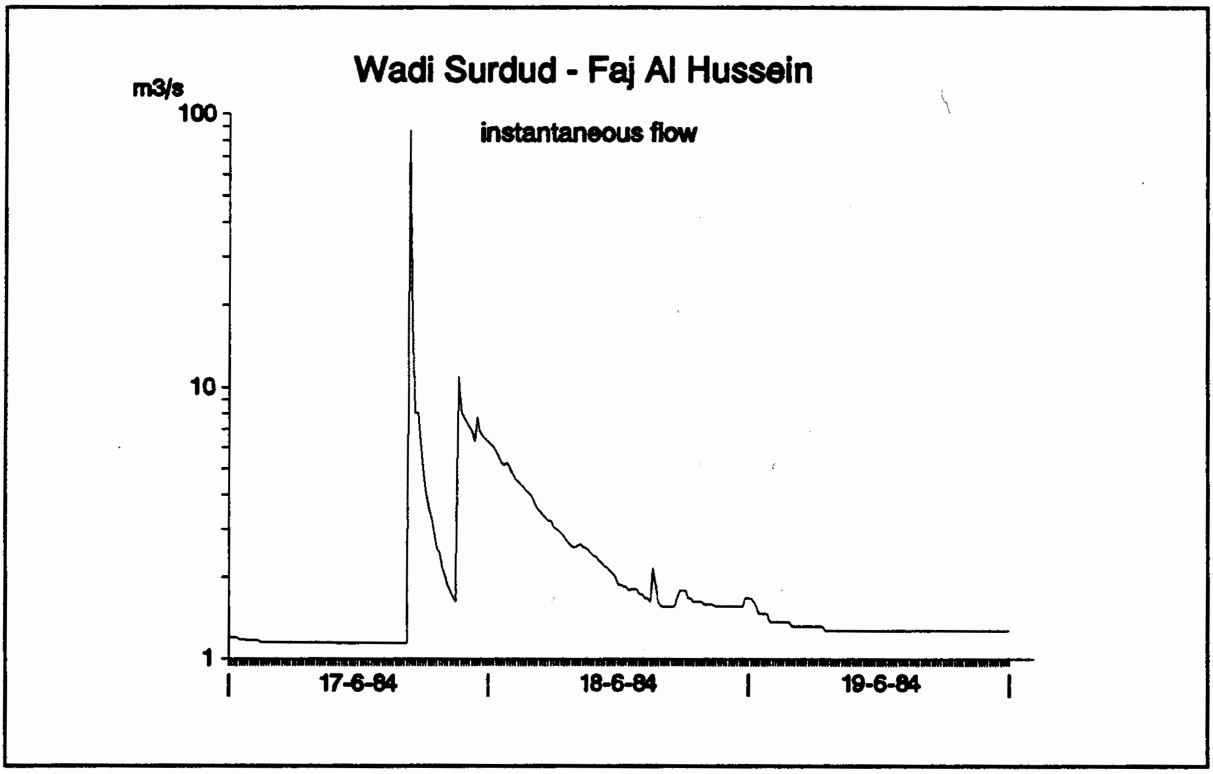


Figure 5.2 Flow record of Wadi Surdud at Faj Al Hussein, 17-19 June 1984

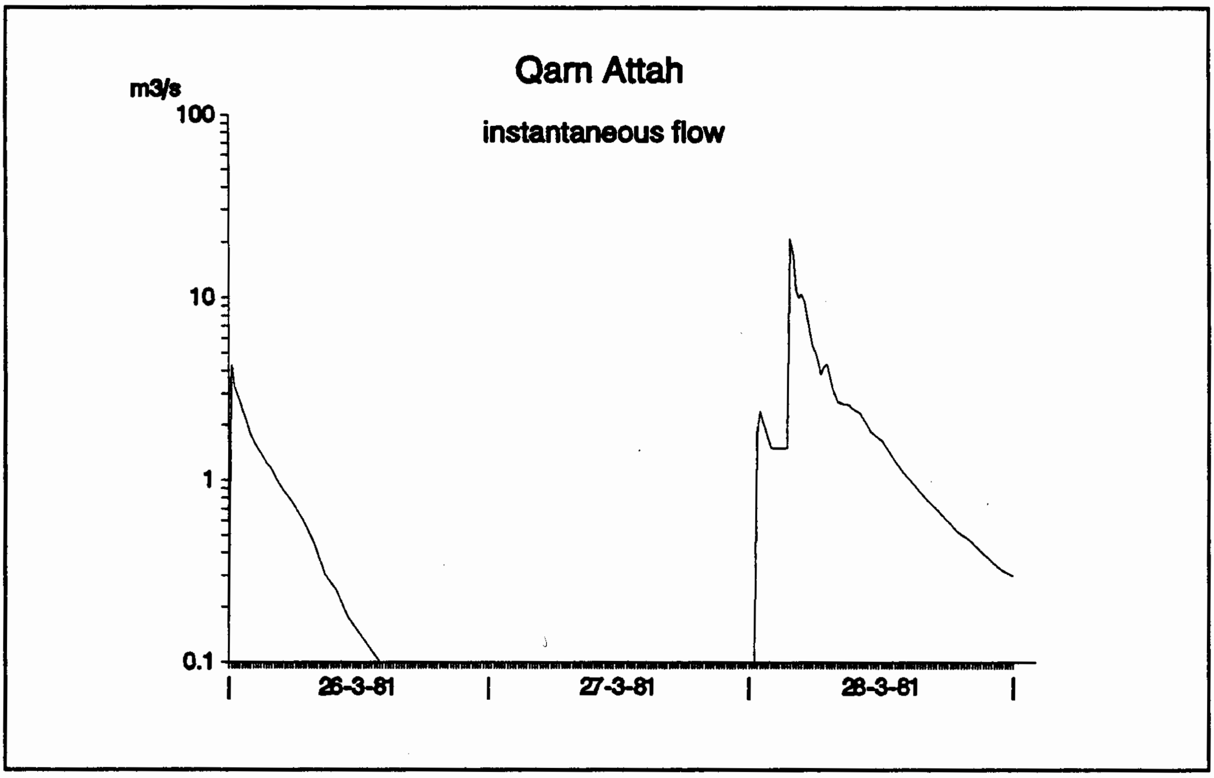


Figure 5.3 Flow record at Qarn Attah, 26-28 March 1981 (data source: RIRDP)

during the years 1984 through 1987, accompanied by detailed topographic surveys of the wadi section after each major flood. Hence these Wadi Surdud flows are considered to be among the most reliable ones available in Yemen.

Figure 5.2 shows an instantaneous record of Wadi Surdud's flow for the period 17 through 19 June 1984, at the end of the first wet season which started rather late, around the middle of May. Note that the vertical scale is logarithmic. At the beginning of the period there is a base flow of approximately 1.1 m^3/s, still relatively high because of the preceding rainy period, but late in the afternoon of the 17th a very steep flood peak was produced, followed around 21.00 h the same night by a second one with lower peak but with a somewhat slower recession. Within one and a half days after the first peak, the wadi had returned completely to base flow.

The very short rising limb of the floods, approximately 15 minutes, is a remarkable feature of the hydrographs. Within that lapse of time the wadi with a flow of 0.5 - 1 m^3/s may turn into a wild stream, with high flow velocities and a discharge often between 100 and 1000 m^3/s. The recession is quick too, but two distinct hydrograph shapes are shown in Figure 5.2. The first flood reaches 87 m^3/s and recedes very quickly. It is thought to represent runoff from the immediate surroundings of the gauging site, hardly buffered by travel in the wide main wadi bed. The second one reaches a maximum of only 11 m^3/s, but due to a slower recession it brings almost twice the volume of water discharged by the first peak. Most flood peaks in the Wadi Surdud record have the characteristics of the second event, which can be associated with rainfall further upstream in the catchment, further away from the gauging station.

A double-peaked flood event such as shown in Figure 5.2 is not uncommon on Wadi Surdud's record. The clouds that bring rain tend to move from west to east, most frequently during the afternoons. Obviously on 17 June they first produced some rain near Faj Al Hussein and later also at several sites further upstream in the Wadi Surdud catchment. The shape of the hydrographs of Wadi Surdud after different short rain storms is nearly constant, if plotted in a semi-logarithmic graph. This means that the time and recession characteristics observed in Figure 5.2 are catchment characteristics virtually independent of rainfall quantity or intensity.

The *time lag* between rainfall and the peaks of the corresponding floods are mostly in the order of 2 to 8 hours for Wadi Surdud, depending on where the rains occurred. The duration of the rains is almost always much shorter.

Other catchments have different characteristics, but most of the main wadis monitored or studied have flood regimes remarkably similar to Wadi Surdud. The time of rise of the flood hydrographs is consistently reported as small, always less than half an hour. And recessions are quick anywhere, although in larger catchments, e.g. in those of Wadi Mawr and Wadi Bana, they may be somewhat slower and in smaller catchments even quicker than in Wadi Surdud.

A short record of floods observed at Qarn Attah in a small wadi west of Rada is presented for comparison (Figure 5.3). The wadi is situated in the headwaters of the Wadi Adhana system and its catchment area is of the order of 100 km^2, thus considerably smaller than that of Wadi Surdud at Faj Al Husein. The floods shown obviously result from short rain storms. The shape of the hydrograph peaks fits in between the two types of peaks commented on for Wadi Surdud. The time of rise is again in the order of 15 minutes, and the recession rate of the floods at Qarn Attah appears to be in between those of the two typical types of recession in Wadi Surdud. The wadi at Qarn Attah is intermittent, hence permanent base flow such as at Faj Al Hussein is lacking.

The fact that little or no attenuation of the flood hydrographs is observed when floods are travelling down the main stream bed may be surprising at first sight, because it is evident that part of the flood volume is stored temporarily. Verwey (1995) provides an explanation based on the diffusive wave approach.

5.3.2 *Baseflows*

Baseflows can usually be modelled adequately on the basis of a *linear reservoir* model. Such models describe the recession of baseflows by the following equation:

$$Q_t = Q_0 \cdot e^{-t/\tau}$$

The characteristic time τ expresses the degree of attenuation of the flow hydrograph (output) if compared to the excess rainfall hyetogram (input). It indicates how much time it takes for the flow rate at any moment during the recession to be reduced to the fraction 1/e (= approximately 37%) of that rate.

A linear reservoir model with τ = 100 days fits Wadi Surdud's baseflow nicely. This value of τ is within the common range of values reported for catchments of comparable size elsewhere in the world (De Zeeuw, 1966; Pilgrim and Cordery in: Maidment, 1992). Although a linear reservoir model is only moderately to poorly suited for direct runoff, applying it to Wadi Surdud's instantaneous hydrographs (see Figure 5.2) shows that the characteristic time of the process of direct runoff is in the order of half a day. Thus, in the catchment of Wadi Surdud the direct flow has a response to rainfall around 200 times quicker than the baseflow.

The baseflow regimes of different wadis in Yemen show much more variation than the direct flow regimes do. Wadi Surdud has a permanent baseflow, which represents a significant part of the total flow, as can be observed in Figure 5.4. This is also true for the other major wadis of the Red Sea Basin; it is postulated that these baseflows are at least partly related to the specific geological condions. But in most wadis anywhere else in the country baseflows are absent or only persisting during wet periods. The most common situation is that the wadi beds are completely dry in between floods.

5.3.3 *Average daily and average monthly flows*

Averaging the flows over periods of one day, one month or longer may be useful to focus on the volumes involved (catchment yield), but it gives a highly distorted picture of the flow rates. This is clearly demonstrated by comparing figures 5.2 and 5.4: maximum

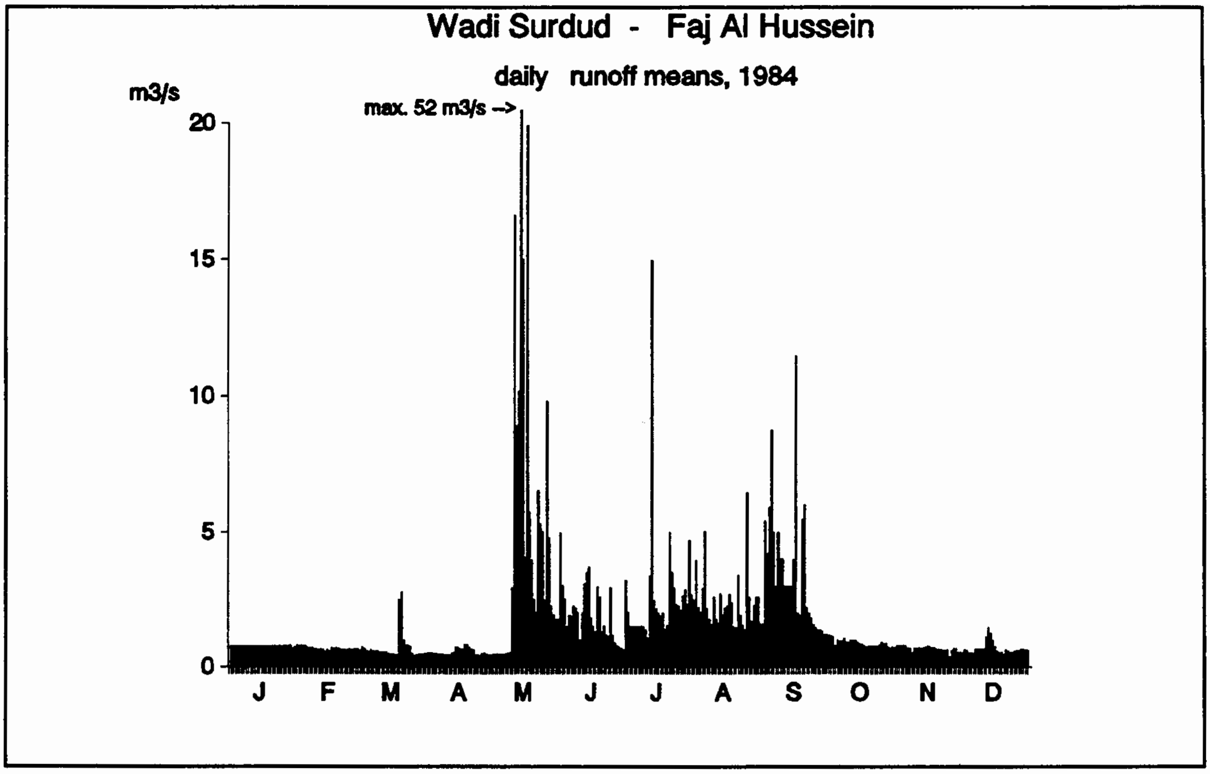


Figure 5.4 Mean daily flows of Wadi Surdud at Faj Al Hussein, 1984

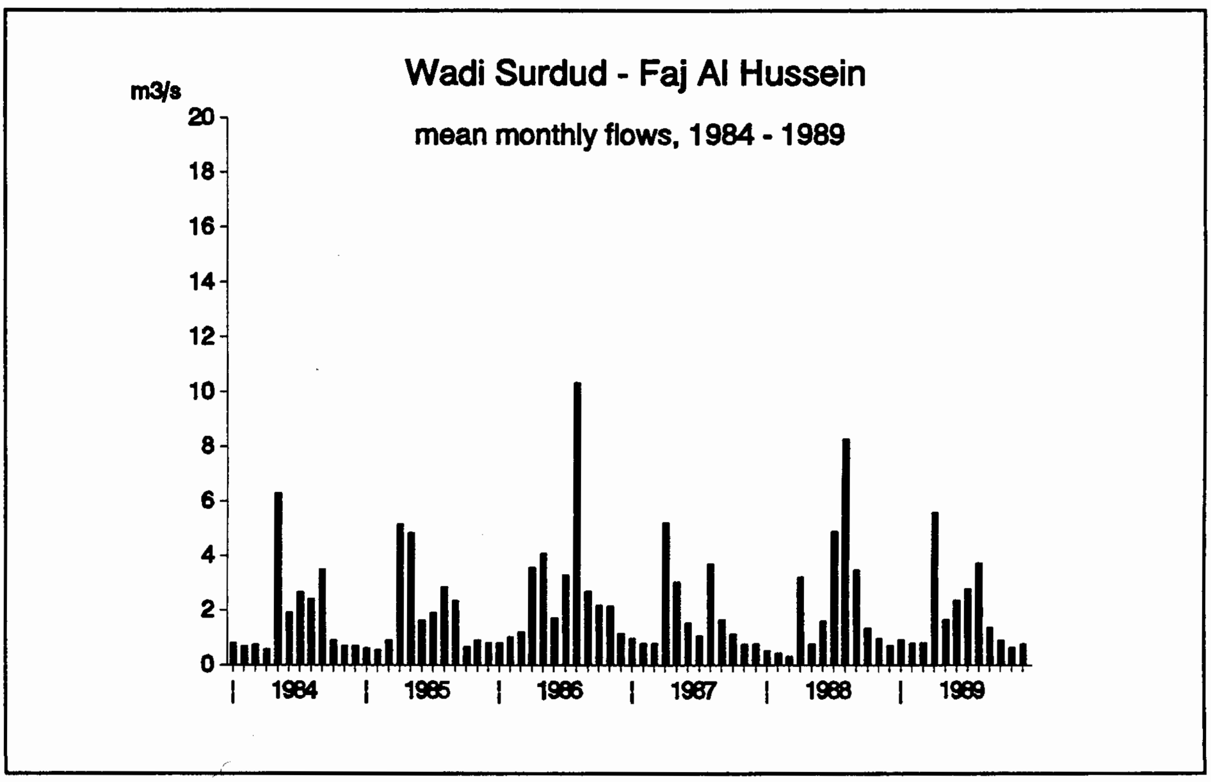


Figure 5.5 Mean monthly flows of Wadi Surdud at Faj Al Hussein, period 1984-1989

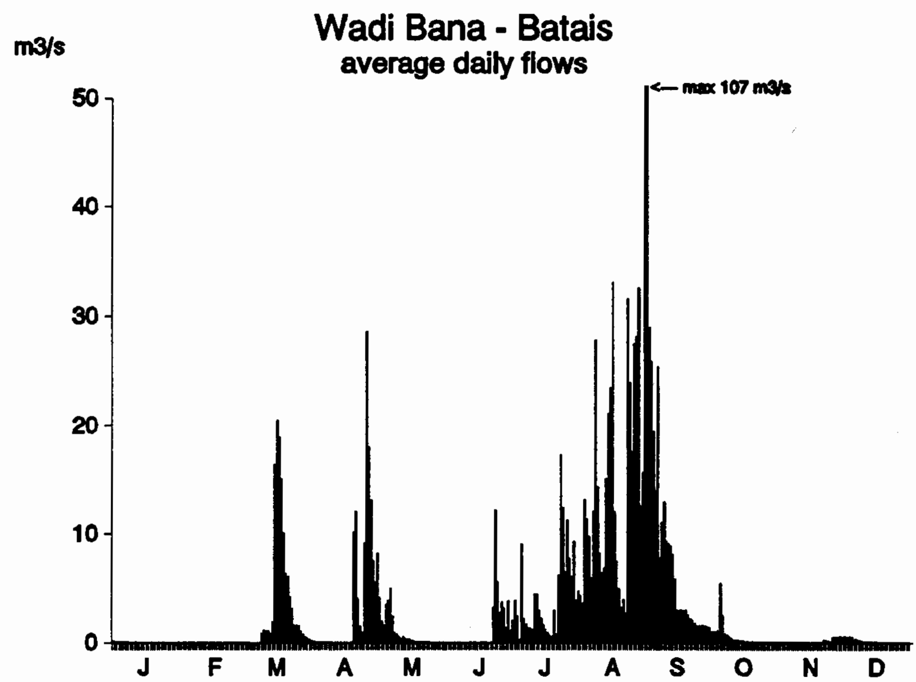


Figure 5.6 Mean daily flows of Wadi Bana at Batais, 1952

instantaneous flows on 17, 18 and 19 June 1984 are 87, 6.3 and 1.68 m^3/s, respectively; whereas the corresponding average flow rates are: 3.35, 2.60 and 1.31 m^3/s. Furthermore, maximum instantaneous flow in 1984 was approximately 600 m^3/s (14 May), compared with a maximum daily average of 52 m^3/s. Averaging the daily values to monthly values (see Figure 5.5), and monthly values to mean monthly values leads to further smoothing.

As discussed above, the quickflows (i.e. floods) of Wadi Surdud have only a low persistence; single flood events come and are depleted completely within two days. In other words: the catchment's 'memory' is small as far as quickflows are concerned.

Figure 5.6 shows daily average flows of Wadi Bana at Batais; the quickflow component does not look significantly more persistent than that of Wadi Surdud, in spite of the fact that Wadi Bana's catchment area is considerably larger. The short duration of the floods in Yemeni wadis -with a time basis of single floods in large wadis usually shorter than two days- implies that the persistence of the quickflows is only slightly greater than that of the daily rainfall.

Comparison between Figure 5.4 and Figure 5.6 emphasizes the differences in baseflow regime. Whereas baseflow constitutes approximately one-third of the total annual flow of Wadi Surdud, it is almost negligible in Wadi Bana.

5.4 Flow volumes

The volume of surface water produced by a catchment during a year, a season or any other lapse of time (*catchment yield*) is extremely important from the point of view of potential water resources utilization. Most of the stream gauging activities carried out in Yemen are (or were) primarily intended to determine flow volumes.

Measured monthly flow volumes are listed in Appendix 3. Below, some statistics derived from these data will be discussed and analysed: annual runoff volumes (averages and coefficient of variation) and the average distribution of the flow volumes over the year (flow regime).

It must be pointed out that the data are of variable reliability and accuracy. The wadis offer extremely difficult conditions for stream gauging. The wide natural wadi beds generally lead to insensitive rating curves that suffer from frequently shifting controls. Current metering is rarely done at intermediate flow rates and never at high rates, because it is difficult to be present at the time floods occur, the floods tend to occur during darkness, and there are usually no provisions -such as a bridge or cableway- for carrying out the measurements at high water levels. Only for a few gauging stations is there some information on how the ratings have been made. Furthermore, the floods are often destructive or may disturb the operation of the installed equipment.

Most of the older data probably are based on staff gauge readings, which implies too large sampling intervals to obtain a record of instantaneous flow and may result in a bias in interpreted daily and monthly averages. Recorded stages frequently suffer from destruction or malfunction of the recording equipment and, as a result, there are frequent gaps in the records. Missing data have been filled in with estimates to some extent for some of the records, but the estimation methods used are normally not documented. Other records have remained full of gaps. Finally, most of the runoff series are only short and calculated averages are referring to different periods. All these factors call for caution in using and comparing the derived statistics.

5.4.1 Observed flow volumes

Table 5.1 lists mean values and coefficients of variation of annual runoff volumes for gauged catchments in Yemen, together with the estimated average annual rainfall and the size of the catchment upstream of the gauging site. Only gauging stations with at least four complete years of record are included. Figure 5.7 shows the location of the catchments concerned. The data give an impression of the average availability of surface water resources at the gauged sites. It will be attempted to link differences in catchment yield to the controlling factors mentioned in section 5.1. This will facilitate making provisional estimates of average annual catchment yield for ungauged catchments.

The table does not include small catchments: the size of the catchments ranges from 460 km^2 (Wadi Rabwa) to ca 22 500 km^2 (Wadi Masila at Qassam, just downstream of Tarim). This means that in all cases there are wadi beds that are filled with alluvial deposits and are sufficiently wide and long to enable significant *transmission losses*. Such

Table 5.1 Summary of mean catchment yield for gauged catchments

Wadi	Catchment area (km^2)	Total annual runoff statistics				Mean P (mm)	Mean RC
		no of years	mean (Mm^3)	mean (mm)	C_v		
Mawr	7912	13	162.3	20.5	0.50	475	0.043
Surdud	2370	5	69.3	29.2	0.22	440	0.066
Rima	2250	8	98.9	44.0	0.64	400	0.110
Zabid	4632	23	125.0	27.0	0.40	550	0.049
Rasyan	1990	7	11.9	6.0	0.76	550	0.011
Tuban	5060	8	109.4	21.6	0.54	465	0.046
Rabwa	460	17	5.8	12.5	0.72	320	0.039
Bana	6200	16	169.9	27.4	0.39	370	0.074
Ahwar	6410	18	70.9	11.0	1.37	190	0.058
Adhana	8300	8	87.5	10.5	0.71	180	0.059
Amd/Doan	6553	4	20.3	3.1	1.24	80	0.039
Al Ayn	1500	4	9.7	6.4	1.17	75	0.086
Sarr	2540	4	3.0	1.2	1.13	45	0.026
Bin Ali	720	4	4.15	5.8	1.30	65	0.089
Juaymah	760	4	0.75	1.0	1.28	35	0.028
Idim	5485	4	41.3	7.5	0.79	70	0.108
Thibi	718	4	1.9	2.6	1.49	40	0.066
Masila (Qassam)	22500*	4	51.0	2.3	0.80	68	0.033

Notes:

(a) Abbreviations:
C_v = coefficient of variation of annual flow volumes
P = annual precipitation (mm)
RC = runoff coefficient (as a fraction)

(b) The catchment area of Wadi Masila presented excludes the Ramlat as Sabatayn and the catchments draining into it.

(c) Source of information for the 'Hadramawt catchments': MacDonald, 1988
For the other catchments, see Appendix 3.5.

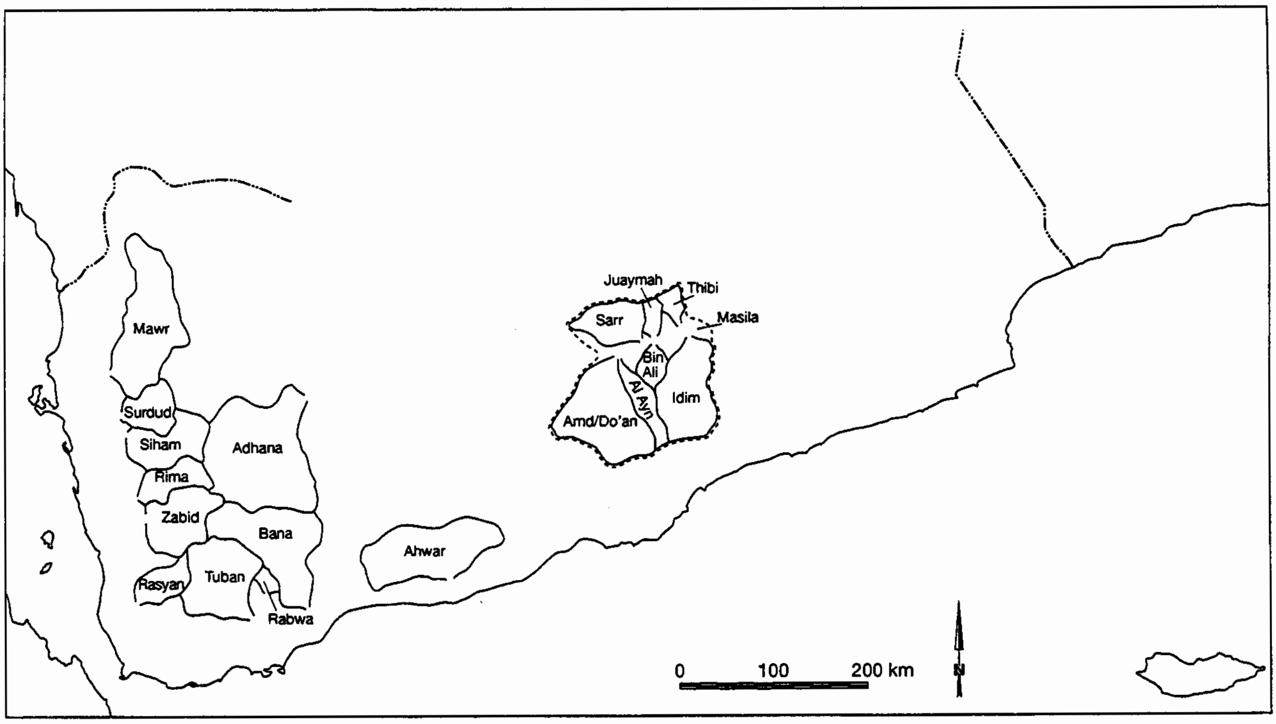


Figure 5.7 Gauged catchments in Yemen with at least four complete years of record

losses are caused by periodically wetting the alluvial material and subsequent evaporation or percolation to deeper groundwater; by runoff disappearing to form an underflow through the bed material; by evaporation from flooded banks and river terraces; or by diversion of the flow for irrigation or other categories of water use. The larger the catchment area, the longer it takes for the 'average droplet' of water to reach the outlet, and the greater the probability that it will be lost on its way downstream. Very small catchments, where such transmission losses are negligible, may give a rather different runoff picture.

Before commenting on the runoff data it is reiterated that the consistency of the statistics may be poor because of different gauging conditions, histories and practices in different wadis. In particular there is some doubt about the data of Wadi Rasyan (quickflow component systematically underestimated ?) and those of Wadi Rima (discharges systematically overestimated ?). The chosen minimum period of four years of record is very short to calculate meaningful averages and standard deviations; increasing it, however, would lead to all information on the dry eastern part of the country being excluded.

The gauged wadis with the highest average yield (more than 100 million cubic metres per year) are -in order of decreasing yield- Wadi Bana, Wadi Mawr, Wadi Zabid and Wadi Tuban. The wadis Rima, Adhana, Ahwar, Surdud, and Masila are within the yield range 50 - 100 Mm^3 per year. All other gauged wadis have lower average annual yields; most of them not primarily due to a small catchment area, but rather to rainfall and/or runoff coefficient being below average.

The mean annual runoff volumes can be expressed as a uniform depth of water over the entire catchment area varying from 1.0 mm (Wadi Juaymah) to 44.0 mm (Wadi Rima). Estimates of the average annual rainfall range from 35 mm (Wadi Juaymah) to 550 mm (Wadi Zabid and Wadi Rasyan). These estimates are slightly higher than would be inferred from the isohyet map for 1985-1991 shown as Figure 4.5.

Scaling down the runoff volumes to uniform catchment size and rainfall rate (m^3 of runoff per m^2 of area and per m of rainfall) results in *runoff coefficients*. Although in a certain catchment the runoff coefficient may vary from event to event, and be higher in wet years than in dry years, it is still convenient to make use of runoff coefficients. They enable catchments to be compared with respect to their runoff generating capabilities.

It is generally believed that runoff coefficients of very small catchments (a few hectares in size) tend to be significantly greater than those of the larger catchments (over 100 km^2) they belong to. As indicated above, this is attributed to transmission losses, which tend to be smaller in small catchments than in large ones. DHV (1993e) reports on a detailed study by Eger (1987) on rainwater harvesting in and around the Amran Plain. Measurements were made of runoff from areas with size ranging from 100 to 300 m^2. The water from the runoff areas was caught on 'run-on areas' which were cultivated; the runoff areas were 1 to 15 times larger than the run-on areas. Eger's results are summarized as follows by DHV :

(a) Threshold value (rainfall not causing runoff) was between 5 and 7.5 mm.
(b) Runoff coefficients on an annual basis varied between 25% and 50%. The lowest values occurred at the Amran Valley bottom and the highest (40% to 50%) were found on the undulating limestones and gently sloping basalts; the runoff coefficient of the steeply sloping basalts was 30%.
(c) Individual storms with a total rainfall above 20 mm and intensities higher than 10 mm/h had runoff coefficients of the order of 70% on basalt and limestone, and of 50% in loamy sand areas. Storms of 10 mm and more with intensities above 5 mm/h could still have runoff coefficients of about 25%.

As Table 5.1 shows, the annual mean runoff coefficients for catchments of a few hundred km^2 in size are smaller by approximately one order of magnitude. They are shown graphically in Figure 5.8.

A few conclusions can be drawn. First of all, in spite of the preceding information on the impact of catchment size, no significant relation is observed between runoff coefficient and catchment size. Obviously the mean annual runoff coefficient is rather large for very small catchment areas, and then tends to decrease for increasing catchment areas, but

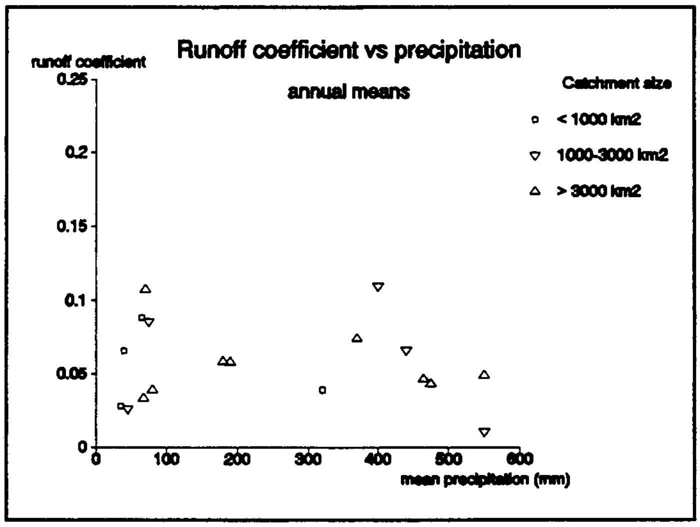


Figure 5.8 Mean annual runoff coefficients in relation to rainfall and catchment size

is rather stable before the catchment area becomes of the order of hundreds of km^2. A second conclusion is that there is no clear relation between annual rainfall and runoff coefficient. At first sight, the 'threshold concept' would suggest a lower runoff coefficient for areas of lower rainfall. Nevertheless, the effect is apparently balanced by the fact that more natural vegetation and agricultural crops are present in areas of higher rainfall. Consequently, the variation of the calculated coefficients around their mean of 5.5% mainly results from factors other than annual rainfall and catchment size.

Differences in land and water use in the catchments may explain part of the variation observed. Man-made mountain terraces and widespread runoff harvesting practices deserve special attention in this respect; they have yet not been inventoried and uniformly mapped for the catchments concerned.

The limited data available do not allow the impacts of terrain features and different geological units to be unravelled; however, the explicit role of the runoff absorbing zones can be convincingly demonstrated. For example, taking into account the 'real' (=entire) catchment area of Wadi Masila - thus including Ramlat Sabatayn and the catchments draining towards it -instead of only the area downstream of it, would result in a runoff coefficient in the order of 0.5%. Even without this unproductive part of the catchment, Wadi Masila at the Qassam gauging station and Wadi Hadramawt near Shibam and Ghuraf (where some measurements were made) have lower runoff coefficients than the main tributaries to the Wadi Hadramawt/Masila; this is because streamflow is quickly lost in the very wide and permeable bed of the Wadi Hadramawt.

It cannot be excluded that the observed variation in runoff coefficients largely reflects monitoring deficiencies rather than differences in catchment characteristics. The location of the gauging stations concerned is a very important factor in this respect. Except for the Qassam station in Wadi Masila, all stations are at the boundary of a runoff producing zone (the catchment) and a runoff absorbing zone located downstream. It is there that changes of wadi runoff in the downstream direction are most prominent: in most of the wadis it is observed that a substantial part or sometimes even all of the surface water discharge disappears there, over a distance of only several to a few tens of kilometres downstream. Usually there are not many degrees of freedom in selecting a site for a gauging station, nor, without monitoring, is it easily observable whether or not a considerable part of the wadi discharge is already infiltrating into the wadi bed upstream. Consequently, whereas for one wadi the gauging station may measure virtually all runoff produced, it may be that in another wadi a significant part of the catchment's discharge may bypass the gauging station in the form of underflow. Interpretation of Table 5.1 and Figure 5.8 should also consider the fact that the records are generally short to very short and that they are not simultaneous. Finally, large systematic errors may be present, resulting in particular from inaccurate and/or outdated rating curves.

In accordance with the observation that the calculated runoff coefficients are not significantly dependent on rainfall, a plot of mean annual runoff versus mean annual rainfall -shown in Figure 5.9- can be fitted with straight line according to:

$$\text{Runoff (mm)} = 0.055 * \text{Precipitation (mm)}$$

The large degree of scatter of the individual points make it impossible to detect a possible threshold and/or non-linearities in the rainfall-runoff relation from the data set.

The coefficient of variation of the annual runoff volumes has almost the same range as the annual rainfall's coefficient of variation (see Figure 4.4) and furthermore, it increases in low precipitation areas. The latter phenomenon is to be expected, because both the rains and runoff events in such areas are more erratic than elsewhere.

In the analysis described above it is tacitly assumed that trends in time are absent. This is not necessarily true; on the contrary, in some regions there are indications that present

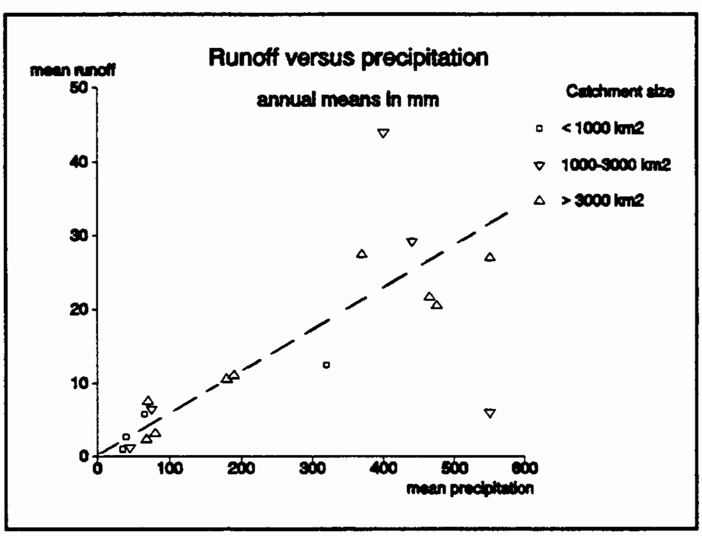


Figure 5.9 Mean annual runoff versus mean annual rainfall (large catchment areas)

catchment yields are systematically lower than in the past. It is difficult to statistically prove or reject the hypothesis of trends being present, because of the unavailablity of long uninterrupted flow records of good quality, and -above all- of the confounding effect of major changes in observational practices and equipment over time.

Comments on decreasing catchment yields refer in particular to the flow that wadis of the Western Slopes bring to the Tihama zone. As an example, Van der Gun (1985) points to lower baseflows in the Wadi Surdud in the early 1980s as compared to the mid-1960s, although he admits that the differences may be largely due to differences in observational accuracies. Nevertheless, there is no doubt that water use upstream of the gauging site has expanded; e.g. water-consuming banana plantations have become much more extensive in the foothill area. The very low frequency of spates in the downstream part of Wadi Surdud's spate irrigation system in recent years (Scheele, 1990) supports the contention that flow volumes may be lower now than previously. According to DHV (1988a and 1988b) the average wadi flow volumes entering Tihama during the period 1983-87 were even not more than 70% of the assumed long-term annual average. DHV concludes tentatively that the reduced wadi flows result from below-average rainfall in the middle and upper catchments, augmented by increased use of water in the upstream areas. The impression exists that the influence of increasing upstream water use is certainly relevant and that in other areas also the runoff volumes reaching the lower areas might be decreasing systematically as a result of more intensive diversions of water or more widespread water harvesting.

5.4.2 Extrapolation to ungauged catchments

The analysis presented in section 5.4.1 allows provisional estimates to be made of the mean annual volumes of runoff produced in ungauged runoff producing zones. It will be clear from the above that the reliability and accuracy of such figures are poor, because the variability of the observed flows has not yet been adequately explained as a function of the controlling factors, and the time series analysed may even be non-stationary, in a statistical sense.

The main reason for presenting the figures is that they give an impression of the volumes of surface water passing from the main complexes of runoff producing areas to the largest runoff absorbing areas. These volumes of water enable spate irrigation to be practised and provide the bulk of groundwater recharge to the important regional aquifers in these runoff absorbing areas. It is believed that part of the unexplained variation in the runoff coefficients may disappear by aggregating individual wadis to larger complexes. A second reason for presenting runoff estimates for ungauged catchments is that -in spite of their inaccuracy- they will indicate the relative importance of the different wadis in terms of catchment yield.
It must be stressed that the figures do not estimate the total runoff produced in the catchments, but the runoff volumes produced at their outlets to the sea or to a regional runoff absorbing area.

Table 5.2 presents the estimates. They suggest that 36 % of the estimated 2.0 billion cubic metres of surface water produced annually comes from the Western Slopes. The

Table 5.2 Estimates of mean annual runoff for runoff producing catchments in Yemen

	Area (km2)	Mean annual P (mm/yr)	Mean annual runoff (Mm^3/yr) gauged	formula	adopted
RED SEA BASIN					
Wadi Harad	1700	375		35	35
Wadi Mawr	7910	475	162	207	162
Wadi Surdud	2700	440	69	65	69
Wadi Siham	4050	400		89	89
Wadi Rima	2750	550	99	83	90
Wadi Zabid	4450	550	125	135	125
Wadi Rasyan	1990	465	12	51	45
Wadi Mawza	1600	325		29	29
Minor wadis	5850	300		97	97
Total	*33000*	*3880*		*790*	*741*
GULF OF ADEN BASIN					
Wadi Tuban	5060	465	109	129	109
Wadi Suhaybiya	1400	200		19	19
Wadi Bana	6200	370	170	126	170
Wadi Hassan	3000	250		41	41
Wadi Ahwar	6410	200	71	71	71
Wadi Mayfa'ah	4300	100		24	24
Wadi Hajar	9900	100		54	54
Minor wadis west	2900	100		16	16
Minor wadis east	7500	75		31	31
Total	*46680*			*511*	*535*
ARABIAN SEA BASIN					
(a) Draining towards Ramlat Sabatayn					
Wadi Al Jawf	12000	175		116	116
Wadi Adhana	8300	180	87	82	87
Wadi Harib	2500	100		14	14
Wadi Bayhan	3000	125		21	21
Wadi Markah	4000	110		24	24

Table 5.2 Estimates of mean annual runoff .... (continued)

	Area (km2)	Mean annual P (mm/yr)	Mean annual runoff (Mm^3/yr) gauged	formula	adopted
(a) Draining towards Ramlat Sabatayn (cont.'d)					
Minor wadis west	3000	100		17	17
Minor wadis north	7500	45		19	19
Minor wadis east	5000	60		17	17
Subtotal	*45300*			*308*	*315*
(b) Wadi Hadramawt/Masila tributaries					
Wadi Amd/Doan	6550	80	20	29	25
Wadi Al Ayn	1500	75	10	6	8
Wadi Sarr	2540	45	3	6	4
Wadi Bin Ali	720	65	4	3	3
Wadi Juaymah	760	35	1	1	1
Wadi Idim	5485	70	41	21	30
Wadi Thibi	720	40	2	2	2
Minor Hadr.tributaries	3800	45		9	9
Masila tributaries	24000	60		79	79
Subtotal	*46075*			*157*	*161*
(c) Al Ghaydah basin					
Wadi Al Jiza	15000	60		50	50
other wadis	9000	55		27	27
Subtotal	*24000*			*77*	*77*
Total Ar.Sea Basin	*115375*			*542*	*553*
RUB-AL-KHALI BASIN					
Wadi Najran	4400	125		30	30
Other wadis west	16500	40		36	36
Wadis East	70000	35		135	135
Total	*90900*			*171*	*171*

Note: The catchment areas for some of the wadis mentioned in this table may be slightly larger than those mentioned in Table 5.1, because the latter exclude runoff producing areas downstream of the gauging station.

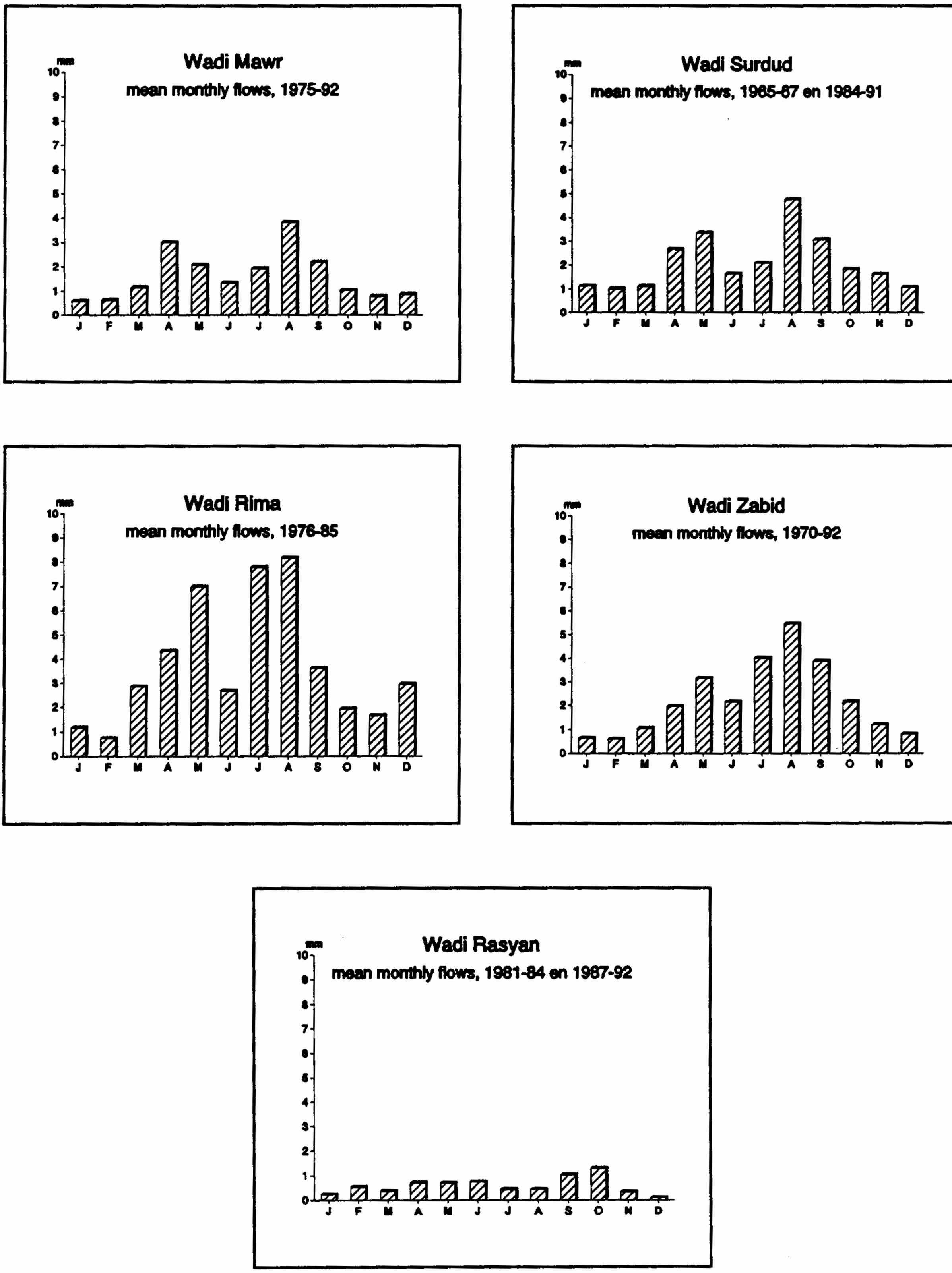


Figure 5.10 Average monthly flows of gauged wadis, Western Slopes

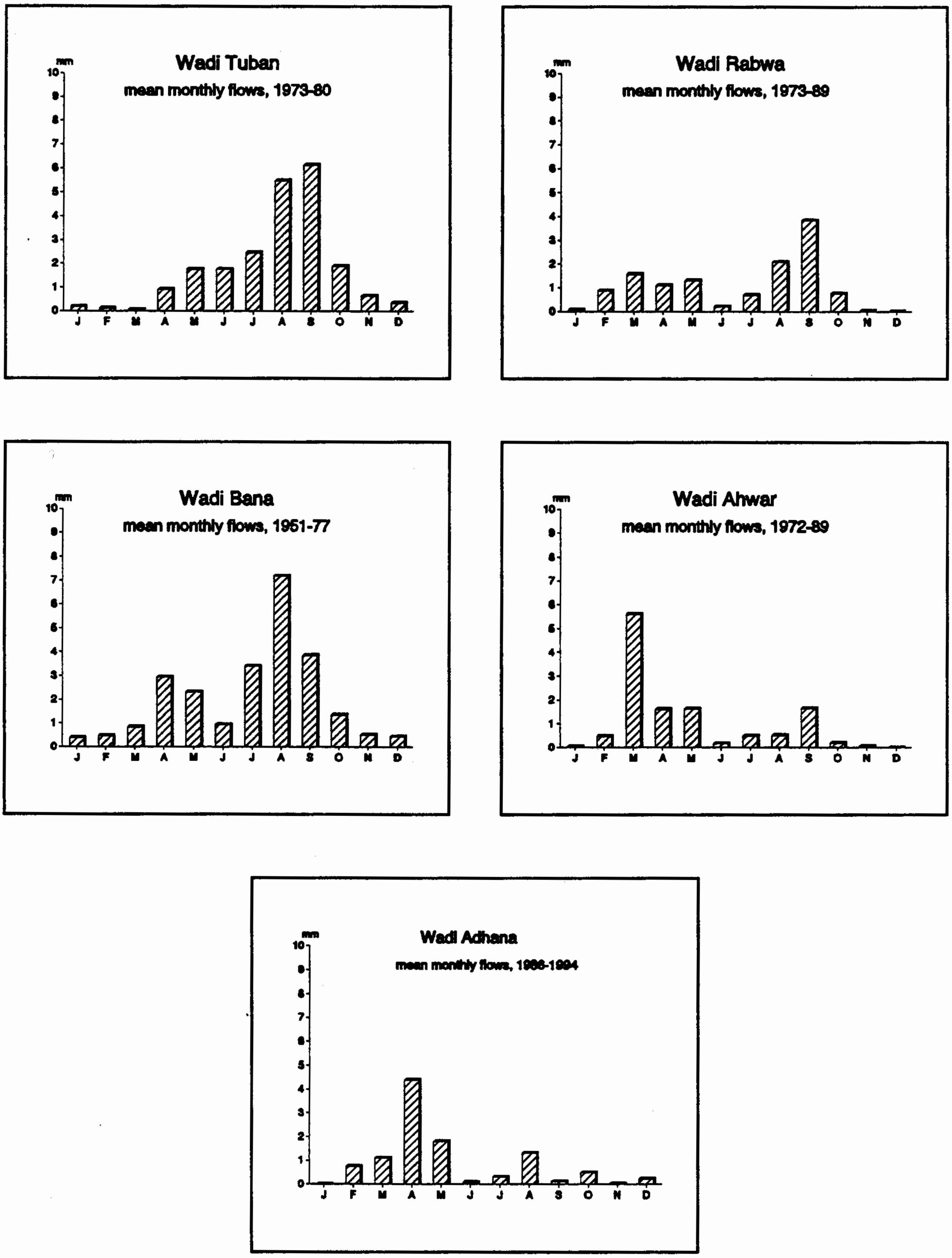


Figure 5.11 Average monthly flows of gauged wadis, Southern and Eastern Slopes

contributions of the Gulf of Aden catchments, the Arabian Sea catchments and the Rub Al Khali catchments are respectively 27 %, 28 % and 9 %. According to the adopted estimates, there are only five wadis with average annual runoff higher than 100 Mm^3/year; in order of decreasing yield: Wadi Bana, Wadi Mawr, Wadi Zabid, Wadi Tuban and Wadi Al Jawf. And nine wadis are likely to score between 50 and 100 Mm^3/year on average: Wadi Masila, Wadi Rima, Wadi Siham, Wadi Adhana, Wadi Surdud, Wadi Hajar, Wadi Hassan, Wadi Hajar and Wadi Al Jiza. Wadi Masila may even belong to the group that produces more than 100 Mm^3/year; a major uncertainty is to what extent the flow volumes of the tributaries downstream of Tarim are lost in the bed of Wadi Masila.

5.4.3 Monthly flow volumes

The monthly distribution of flows defines the regime of a stream. Figures 5.10 and 5.11 give an impression of the regimes of the gauged wadis. Runoff is expressed in mm to facilitate comparison between the catchments. The graphs show *average* monthly flows in order to display values representative of the average seasonal variations; a disadvantage of averaging is that the regimes look smoother than they would have done if the monthly figures for any year on record had been shown.

A general feature of the regimes is the occurrence of two flood seasons, corresponding with the rainy seasons mentioned in Chapter 4. The records of Wadi Harad, Wadi Mawr, Wadi Surdud and Wadi Rima show that in the northern and central part of the Western Slopes the summer season brings slightly more water than the spring season. The second season is dominant in the southern part of the Western Slopes and the western part of the Southern slopes (Wadi Zabid, Tuban, Bana). Elsewhere, on the Eastern Slopes and more eastward, the general pattern is that most water arrives during the spring season.

The wadis descending from the Yemen Mountain Massif have relatively large runoff volumes per unit area, as shown above. In the areas where rainfall is substantially less, the regimes becomes more erratic. All the major wadis draining the Western Slopes are permanent in the foothill zone and have baseflows that represent a significant part of the total annual runoff volumes. According to some sources (DHV, 1988; HWC, 1992) these baseflows contribute around 60 % of the annual flow volume, but modelling the Wadi Surdud daily average flows (Van der Gun and Wesseling, 1990) and inspection of data for other major wadis suggest that 40 % is probably a better average figure.

Most of the wadis elsewhere in the country are intermittent or have very small seasonal baseflows. Notable exceptions are Wadi Kharid (tributary of Wadi Jawf) and Wadi Hajar (west of Mukalla). Both have large springs in their headwaters.

5.5 Peak flows

Records of instantaneous peak flow rates are rare in Yemen. Table 5.3 presents the maximum floods observed for individual wadis, as far as found in reports or other data sources. They are shown graphically in Figure 5.12 as a function of catchment size.

It is believed that only the value given for Wadi Bana is a rather extreme event; Atkins (1984) associates it with a recurrence interval of 50 to 70 years. Extreme floods of the same probability of occurrence in the other major wadis will probably be in the order of a few thousands of cubic metres per second, too. This contention is supported by the *Creager envelopes* shown in Figure 5.12. Creager's envelopes of world floods estimate Probable Maximum Floods (PMF) as a function of catchment size A (in km^2), using the following equation (UN-ECAFE/WMO, 1967):

$$Q=1.3C\cdot(0.385\cdot A)^{0.935\cdot A^{-0.048}}$$

The factor C is assumed to be constant for a certain geographical region. The observed Wadi Bana flood suggests that C should have a value of at least 25 for Yemeni conditions. The magnitude of flood peaks is approximately proportional to the root of the catchment area. It is believed that modal values of annual maximum floods range between 300 and 1000 m^3/s for the major wadis in Yemen.

Table 5.3 Observed maximum flood peaks in Yemen, as reported in the literature

Wadi	Catchment area (km2)	Maximum observed Q (m3/s)	Date of occurrence	Source of information
Surdud	2370	600	5/1984	Van der Gun, 1985
Bana	6200	3810	3/1982	Atkins, 84
Adhana	8300	600	4/1987	Uil and Dufour, 1990
Amd/Doan	6553	985	3/1981	Selkhozpromexport, 1982
Al Ayn	1500	500	10/1977	Sogreah, 1978
Sarr	2540	2160	3/1989	WHADP
Bin Ali	720	200	4/1977	Sogreah, 1978
Juaymah	760	559	3/1989	WHADP
Idim	5485	1314	3/1981	Soviet-Yemeni study
Thibi	718	350	7/1978	Sogreah, 1978
Masila (Qassam)	22500	975	10/1977	Sogreah, 1978
Hadramawt (Shibam)	12800	974	4/1987	MacDonald & Partners, 1988

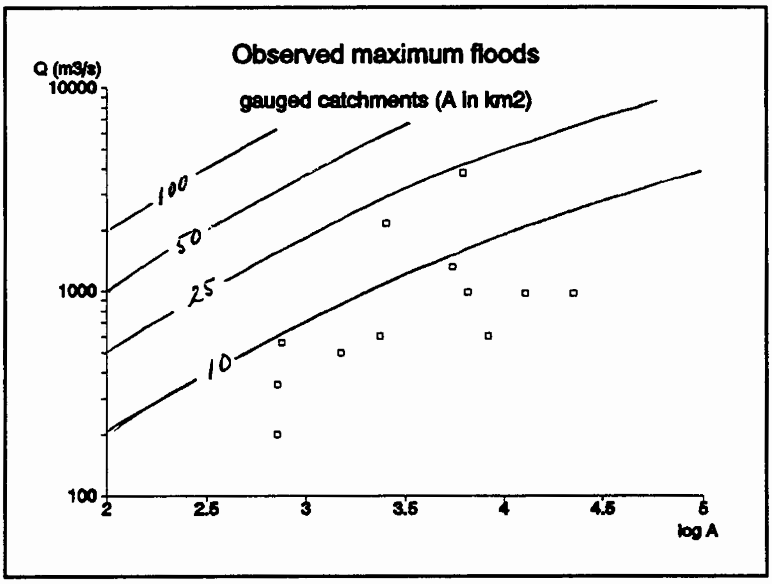


Figure 5.12 Observed flood peak rates in Yemeni wadis (Creager curves for different values of C added)

5.6 Surface water quality

There are no networks monitoring surface water quality in Yemen, as far as known. Various projects have measured surface water salinity, but ony at a few sites; in most cases measurements of electrical conductivity, obtained during current metering. Water use and groundwater quality -which have usually been studied in more detail- give additional clues about the mineralization of the water.

Surface water is fresh in general, but the concentration of dissolved solids tends to vary inversely with the discharge rate. Al Eryani (1979) mentions reported total dissolved solids (TDS) contents of 290 mg/l in Wadi Rima to 500 mg/l in Wadi Zabid, however, without specifying whether these are typical values for quickflows, base flows or average flows. The mentioned values correspond with electrical conductivites at 25 °C (EC_{25}) of 455 and 740 micromho/cm, respectively. TDS values can be estimated from EC_{25} measurements by multiplying the EC value (in micromho/cm) by a factor of approximately 2/3.
The WRAY project has monitored electrical conductivity at its stream gauging stations in the wadis Surdud and Adhana, and in the Abyan delta. The resulting data show that the EC_{25} of the water of Wadi Surdud at Faj Al Hussein is relatively low: it typically varies between 500 and 600 micromho/cm during baseflows, and drops to 300 micromho/cm or slightly more during floods. The corresponding figures for Wadi Bana are 1500 -1800 micromho/cm for periods of low flows, and 400-500 micromho/cm for floods.

As yet there have been no regional inventories or mapping of typical surface water qualities in Yemen.

5.7 Sediment transport

The sediment transport by the wadis is considerable. All floods observed in the wadis are yellowish-brown in colour due to the load of suspended sediment. The water becomes opaque towards the exhaustion of the quickflow component, and water becomes crystal clear again when the wadi resumes its baseflow regime. Bed load is also very significant, especially in wadis with a steep gradient such as those descending from the Western and Southern Slopes. These wadis quickly will fill the space behind any dam constructed accross their beds.

The regimes of the wadis make it very difficult to monitor sediment transport by sampling techniques. No record of such sediment transport monitoring has been found. In WRAY's water resources assessment study of the Wadi Adhana area another approach was followed (Nio, 1989). It involved measuring the sediment accumulation in the Marib lake from April 1986 to March 1989. The echo-sounding equipment used was capable of showing the upper and lower boundaries of the sediments that accumulated in the lake after the new Marib dam was constructed. The sediments that were previously at the surface are more consolidated. It was estimated that 4.5 million m^3 of sediments were trapped in the lake during the three years preceding the survey; the average of 1.5 million m^3 per year corresponds to a layer of 0.2 mm averaged over the entire catchment. This value is probably significantly below the long-term average, because no really high flows were observed during the period 1986-89. On the basis of surveys in the catchment area and an analysis of the wadi bed material, two main types of sediments were distinguished. The first type consists of coarse material (very coarse sands to boulders), mainly originating from the wadi's valley walls. The bulk of the sediments are sandy, mainly originating from the Tawilah Sandstone outcrops in the western part of the catchment area. The large basement outcrop areas within the catchment yield comparatively low amounts of sediments.

6 GROUNDWATER

Groundwater is commonly defined as the subsurface water of the *saturated zone*, i.e. the zone in which the pores and fissures of the soil and rocks are, in principle, completely filled with water. This water flows underground, mainly under gravitational forces, and can be abstracted by means of wells or drains. Between the ground surface and the groundwater domain there is usually a zone where the pores and fissures contain both water and air; movement of water in this *unsaturated zone* is governed not only by gravitational forces but also by matrix forces.

The occurrence of groundwater, the amounts of groundwater stored, the flow rates underground, the groundwater levels and their fluctuations, groundwater quality, and the type and location of groundwater discharge phenomena are controlled by a large number of factors. The most important ones are: the types of rock present below the surface, the geometry of the different rock units (geological formations), the topography of the land surface, the climatic and hydrological regimes in the area, vegetation and human activities.

Unlike surface water, groundwater is an invisible resource. The domain it occupies is usually very extensive, both laterally and with depth, and access for making observations is relatively difficult and expensive. Consequently, available field data are seldom sufficient for deriving a satisfactory picture of the groundwater system merely by interpolation. This implies that interpretation depends strongly on general geological and hydrological knowledge and experience, and thus may be rather subjective or even speculative.

Typically, the volumes of water stored in groundwater systems are usually much larger and the fluxes much smaller than those of the surface water systems present in the same region. Hence, the processes in groundwater systems tend to be many orders of magnitude slower than those in surface water systems. This has important implications for the exploitation and management of the resource. When studying the present state or processes in groundwater it should be borne in mind that they may still reflect factors that were acting long ago (sometimes in past geological periods) and are no longer present.

The main groundwater systems known in Yemen will be described below. The focus will first be on the more or less time-independent characteristics of the systems: the rock units with their hydraulic properties and lateral and vertical extents. Afterwards, attention will be paid to the more dynamic aspects: recharge, discharge and flow of groundwater, and groundwater quality.

6.1 Hydrogeological characteristics of the different geological formations

Conventional descriptions of groundwater systems are based on the classification of rock units according to their porosity and permeability, often integrated over the thickness of the rock unit. Observed or assumed contrasts with regard to these hydraulic properties enable rock units to be classified into *aquifers, aquitards, aquicludes* and *aquifuges*. The differences between these classes are relative rather than absolute, and depend on the role the unit plays in the regional storage and movement of groundwater. Saturated geological units that can transmit substantial quantities of groundwater under ordinary hydraulic gradients are called aquifers. If the permeability of a saturated unit is too low to permit the flow of significant quantities of groundwater then it is called an aquiclude. Aquitards occupy an intermediate position: they are less permeable than aquifers, but they may be permeable enough to transmit quantities of water that are significant in terms of regional groundwater flow. An aquifuge, finally, is an impermeable formation neither containing nor transmitting water. Only aquifers permit large-scale groundwater abstraction by wells.

Many groundwater studies make use of a related but slightly different classification. Focusing on groundwater as a source for water supply they tend to differentiate between exploitable aquifers and rock units that have no appreciable water resources (*non-aquifer rock units*). The latter include roughly all aquicludes and aquifuges, and perhaps part of the aquitards. The former range from highly productive aquifers to poorly productive and/or discontinuous aquifers; the latter category corresponds on a regional scale to aquitards.

The occurrence and lithology of the geological units observed in Yemen have been described in section 2.4. Table 6.1 presents a general hydrogeological characteristic for each of these formations; it may facilitate hydrogeological schematization and mapping. Note the relatively favourable properties of the Quaternary deposits and the sandstones of the Tawilah and Wajid Groups; they constitute the most important aquifers of the country. The Yemen Volcanics and the limestones of the Amran Group and the Umm Er Radhuma Formation are generally less permeable, but they owe their significance to their considerable thickness and large areal extent.

6.2 Spatial distribution of regional aquifers in Yemen

The numerous studies on groundwater in different areas in Yemen are far from uniform with respect to the concepts used for hydrogeological schematization and classification. If the relevant phenomena and variations have to be analysed and compared on a national scale, then it is necessary to re-interpret the available information within the framework of a single consistent methodology for schematization and classification.

Two recent mapping projects - the Satellite Mapping Project carried out under the Yemeni Joint Project for Natural Resources (Robertson, 1991a, 1991d) and the Russian-assisted Hydrogeological Mapping Project of the former PDRY (Zarubezhgeologia, 1992) faced this problem, and developed rather different approaches. They will be briefly outlined below, to be followed by the approach adopted for this report.

Robertson's hydrogeological map

Robertson (1991a/1991d) prepared 1: 250 000 and 1: 1 000 000 hydrogeological maps for the total territory of present-day Yemen, as part of an integrated map series

Table 6.1 Hydrogeological characterization of stratigraphic units

GROUP or FORMATION West	GROUP or FORMATION East	LITHOLOGY West	LITHOLOGY East	GENERALIZED HYDROGEOLOGY West	GENERALIZED HYDROGEOLOGY East
Quaternary Deposits		sands, gravels, loam, loess, clay, conglomerates, sebkha deposits, marine shell and reef deposits		local and regional porous aquifers, ranging from poorly productive to highly productive; in some zones,however, completely dry beds	
Quaternary Basalts (Aden Volcanics)		basalts, tuffs, agglomerates, trachy-andesites, pumice		in general, aquitards or poor aquifers; favourable exceptions in some zones	
Baid	Irqah	shales, limestones, evaporites	gravelly conglomerates	aquitards and other non-aquifer rocks	potential aquifer rocks
	Fuwwah		conglom. & fossiliferous limestones		aquitards
Tertiary Intrusives		granites		non-aquifer rocks	
Yemen Volcanics		basalts, trachy-andesites, rhyolites, pyroclastic rocks		extensive but poorly productive fissure aquifers and aquitards	
	Habshiya	limestones, marls, shales, gypsum		aquitards and poorly productive aquifer rocks	
	Rus	gypsum, anhydride, dolomitic limestones		aquitards and poorly productive aquifer rocks	
	Jiza	shales, fine-grained limestones		non-aquifer rocks	
	Umm-Er-Radhuma	massive marly and dolomitic limestones		poorly to moderately productive aquifers	
Medj-Zir		hard argillites, cross-bedded bioclastic sandstones		aquitards or poorly productive aquifers	
Tawilah Sandstone	Sharwayn	yellow sandstones (Kawkaban member), dark red sandstones (Shibam member) and white clayey sandstones (Thula member)	shales, limestones, sandstones	moderately to highly productive mixed pore/fissure aquifers	aquitards to poor aquifers
	Mukalla		fine/medium sandstones		extensive and very productive mixed pore/fissure aquifers
	Fartaq		calcarenites		aquitards to poor aquifers
	Harshiyat		sandstones with calcareous horizons		poor aquifer rocks
	Qishn		calcarenites, limestones		aquitards
Ahjur		bituminous marly and sandy mudstones		aquitards, aquicludes	
Nayfa		limestones and dolomites		poorly to moderately productive fissure aquifers	
Madbi	Sabatayn	marls and limestones	evaporites and shales		non-aquifer rocks
Shuqra		limestones			
Kohlan Sandstone		sandstones with conglomerate intercalations		poorly productive aquifer rocks	
Akbra Shale		laminated mudstones, siltstones, shales		aquitards/aquicludes	
Wajid Sandstone		cross-bedded sandstones and coarse siltstones		poorly to moderately productive porous aquifers (only productive where hundreds of metres thick)	
Precambrian Basement		igneous rocks, metamorphic rocks, metasediments		generally non-aquifer rocks, but water-bearing in thin weathered zones and in fractured zones	

consisting of topographic, geological, hydrogeological and volcanic/earthquake hazard maps. The maps were based in the first place on interpretation of satellite images, but other information such as existing hydrogeological and geological reports and maps was used too. Field checks were made on a very limited scale. The printed maps are accompanied by an 81-page chapter "Hydrogeological Maps" in the Final Report of the Satellite Mapping Project (Robertson, 1991a)

Robertson (1991a, 1991d) made use of the UNESCO legend for Hydrogeological Maps (1970, 1983) and the methodology for hydrogeological classification and mapping is transparent and straightforward. Three steps summarize the procedure:

(1) Generalized properties of the lithostratigraphic units as regards flow and storage of groundwater were established.

(2) Geological outcrop zones were interpreted according to a six-fold UNESCO classification of hydrogeological units:
- 1a highly productive pore aquifers
- 1b moderately or poorly productive pore aquifers
- 2a highly productive fissure aquifers
- 2b moderately or poorly productive fissure aquifers
- 3a strata with local and limited groundwater resources
- 3b units with essentially no groundwater.

Within each of the eight hydrogeological provinces distinguished, all outcrops of a certain geological formation were assigned (without further differentiation) to one of these classes only.

(3) The zones were coloured in six colours according to these classes, with ornaments to indicate the geological formation, and details such as piezometry and occurrence of saline groundwater were added in line symbols.

The maps are very clear and easy to read. They are strongly linked to the set of geological maps produced under the same contract, in the sense that the geological units shown on the geological map (outcrops) -and not any deeper rock units- are assumed to be the most relevant hydrogeological rock units. This is main weakness of the maps. They are too rooted in the surface geological maps and not enough in field data and in the numerous reports available. The maps show several misinterpretations, especially in zones where Quaternary sediment covers are unsaturated or hydrogeologically insignificant and deeper rock units constitute the main aquifer (e.g. in the Sa'da and Sana'a basins). And they do not show the very extensive and permeable Mukalla Sandstone aquifer which is present in the Ramlat as Sabatayn area and further east, in the area of the Northern and Southern Jawls. In spite of these flaws it must be pointed out that the maps constitute an important document on the hydrogeology of Yemen, valuable if used with a critical attitude.

Russian hydrogeological map

Zarubezhgeologia (1992) prepared a hydrogeological map at scale 1: 500 000 for the territory of the southern provinces, consisting of eight hand-painted sheets and accompanied by an Explanatory Note of 260 pages. In addition, data of some 700 wells and springs are presented in a separate Catalogue of Water Points.

The hydrogeological classification of rock units used on these maps first considers a subdivision of the territory in tectonic zones: the Nubian-Arabian Shield, the Arabian Platform and the Aden Rift, and these are subdivided, in turn, into subzones. The valleys and plains of larger wadis with their Pliocene-Quaternary infills, however, are considered as 'independent hydrogeological structures'. The rocks within each of these zones and subzones are subsequently differentiated according to geological formation (designated by colour), type of void (shown by a symbol) and the estimated quantity of water available (*potential 'exploitational' groundwater resources (PEGWR)*, indicated by the intensity of the colour). The mapping technique used allows two superimposed hydrogeological units to be depicted. This brings the third spatial dimension in view, although the maps fail to show the continuation of important aquifers where they underlie two other units, even though these might be less important. The legend to the hydrogeological map allows for adding additional features (water quality, depth to groundwater, type of voids, local features, etc.).

The work seems to be based on profound geological knowledge and on many local hydrogeological data. Resulting maps are as detailed and complete as the 1: 500 000 scale allows, and are likely to be reliable. The hydrogeological classification can be criticized as being a little confusing and in some details unlogical, and is not always followed consistently in the explanatory note. The maps are difficult to read. The classification and legend tend to stress geological structure and stratigraphy at the expense of the more relevant information on the continuity and boundaries of the aquifers and on the type of aquifer voids. Furthermore, criteria for the assessment of the resources are not well-defined, e.g. the allowable storage depletion is rather arbitrary, which reduces the value of PEGWR as an indicator of the groundwater resources potential. Nevertheless, the maps and the explanatory note constitute the most important summarizing document on the hydrogeology of the former PDRY. Due to the limited number of copies available (hand-painted maps) it is believed that only few hydrogeologists in Yemen have ever studied or used the map.

A new schematic hydrogeological map

Based on the information contained in the maps discussed above, on study of numerous reports and on observations in the field during many years, a small-scale schematic hydrogeological map was prepared for this report (Figure 6.1). It cannot compete with the former maps in terms of detail, because of its much smaller scale (which is approximately 1: 3 100 000), but it may serve for a quick and clear overview of the main features, with corrections for some of the deficiencies observed on the larger-scale maps.

The UNESCO classification of aquifer units is followed, but in between porous aquifers and fissure aquifers a category of *mixed pore/fissure aquifers* has been added. This type of aquifer is characterized by the storage of groundwater and the permeability of the rock being linked to both primary voids (pores) and secondary ones (fissures). The following hydrogeological classes then result:

- 1a highly productive pore aquifers
- 1b moderately or poorly productive pore aquifers
- 2a highly productive fissure aquifers

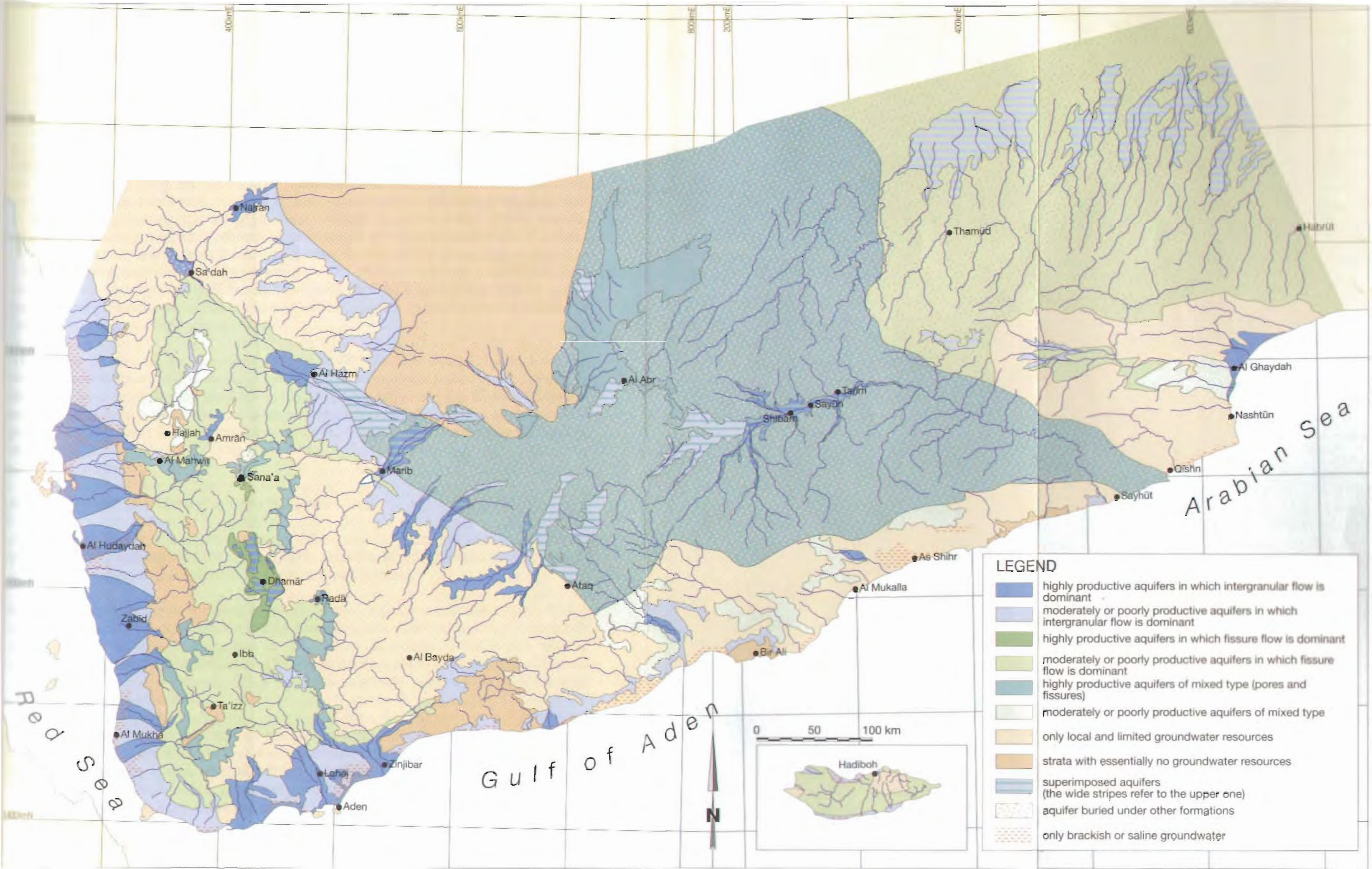


Figure 6.1 Schematic hydrogeological map of Yemen

2b	moderately or poorly productive fissure aquifers
3a	highly productive mixed pore/fissure aquifers
3b	moderately or poorly productive mixed pore/fissure aquifers
4a	strata with local and limited groundwater resources
4b	units with essentially no groundwater.

Unlike Robertson's map, this overview map attempts to depict the most relevant aquifer units within depths that are most relevant for groundwater abstraction (down to some 400 to 600 m below ground surface), and not necessarily the hydrogeological characteristics of the outcropping formation. The differentiation into productive aquifers and moderately/poorly productive aquifers is based primarily on hydraulic properties such as transmissivity and on the assumed stored volume of groundwater. Other aspects, playing a secondary role, are: intensity of recharge, the lateral continuity of the aquifer beds and hydraulic contrasts with other rock units. Superposition of aquifers is shown to a limited extent -only the most important zones- in order to preserve a relatively clear map. Symbols identify the aquifer units in terms of geological formations. Finally, major zones where groundwater in the mapped aquifers is known to be brackish or saline are indicated on the overview map as well.

The ideas developed by Zarubezhgeologia (1992) on the overall hydrogeological structure are reflected in Figure 6.1. They largely determine the boundaries adopted for the extensive aquifers in the platform area (Mukalla aquifer and the Um-Er-Radhuma aquifer). And they have been used as an additional key to interpret the significance of pre-Quaternary rocks in the rifted zones of the Al Ghaydah basin and along the Gulf of Aden.

6.3 Principal groundwater systems in Yemen

As shown in Figure 6.1, there are large differences between the aquifer complexes present in different parts of the country. This, plus the large variations in hydrological conditions leads to a great diversity of groundwater systems.

On the uplifted shield in the west only the Yemen Volcanics and the Amran Group constitute aquifers of considerable lateral extension, but their productivity is generally moderate to low. The best aquifers in the Yemen Mountain Massif region are the sediments in the basins of the Highland Plains (tectonic features have contributed to the development of these basins). They combine relatively high transmissivities with favourable recharge conditions.

Much larger aquifer systems exist in the platform region east of the shield. Mention should be made in the first place of the Mukalla sandstone aquifer, the largest aquifer complex in Yemen. It dips eastward under calcareous rocks of the Um-Er-Radhuma Formation which constitutes a moderately productive but very extensive aquifer in the east, continuing over large distances in Saudi Arabia and Oman.

Aquifer conditions are generally less favourable in the rifted zones, except in the Red Sea Rift and in the western part of the Gulf of Aden Rift. Thick blankets of Quaternary sediments have accumulated in these latter zones; they constitute excellent aquifers with high transmissivities and good exposure to recharge. Similar but less thick and less productive Quaternary aquifer systems are found along the eastern boundary of the basement outcrops of the shield, at the margins of the desert. Numerous small alluvial aquifer systems are scattered all over the country, but considerations of scale prevented them from being depicted in Figure 6.1.

A brief description of the main groundwater systems in Yemen follows.

6.3.1 Alluvial wadi fills (strip aquifers)

Alluvial deposits in wadi valley bottoms constitute aquifers of limited dimensions that are widespread all over Yemen. They are the most convenient places to look for shallow subsurface water and not so many years ago groundwater abstraction in Yemen was largely confined to this type of aquifer. Because their width (a few metres to a few hundred metres) is small compared to their length, they are known under the name *strip aquifers*. The deposits are usually unsorted but coarse and uncemented, and thus highly permeable. Their thickness tends to increase in downstream direction and normally does not exceed a few tens of metres.

Wadi fill aquifers have extremely favourable recharge conditions: their permeable deposits cause part of eventual wadi floods to be intercepted by infiltration, and they may also collect water from springs and seepage zones along the wadi. But due to their small aquifer volumes and relatively high permeabilities they are liable to become depleted during prolonged dry periods, especially in the higher parts of the wadi channel network.

Impervious basement prevents downward percolation of water from the wadi beds. In some areas (e.g. in the Sirwah area, between Sana'a and Marib) this leads to pools in the wadi bed where stagnant surface water remains for several months after the last rains, even in the upper branches of the wadi channel network. The associated Quaternary wadi bed sediments are then likely to contain some water permanently.

6.3.2 Quaternary aquifers of plains, alluvial fans and deltas

Quaternary aquifers of plains, alluvial fans and deltas are usually situated at the mouth of one or more large wadis. They are actively recharged by these wadis, partly by subsurface flows (*underflows*) via the interconnected wadi fill aquifers. The most important representatives of this category of aquifers are the Quaternary aquifer complexes of Tihama and the southern coastal plains, those at the western and southern edges of the Ramlat Sabatayn, and the Pliocene-Quaternary deposits of Wadi Hadramawt. They also occur in isolated small tectonic basins, scattered over the country, e.g. in the Highland Plains zone.

The Quaternary aquifer system in the Tihama

The Red Sea graben, formed mainly during the Tertiary, is filled to a total thickness of several thousand metres with fluvial, marine and coastal sediments. The arid Tihama zone in the Republic of Yemen is in the eastern part of this graben system. Most of its Cenozoic graben fill consists of Tertiary sediments, generally poorly permeable and containing saline formation water. However, these are overlain by Quaternary deposits containing predominantly fresh groundwater. They constitute the most productive aquifer system of the Republic of Yemen, extending over more than 400 km along the coast over a width of 30 to 60 km between the escarpment of the Yemen Mountain Massif and the Red Sea. This aquifer system is recharged by the streams descending from the mountains; part of this recharge is produced by infiltration through the wadi beds, another part infiltrates after the floods have been routed through a spate irrigation system.

The Tihama Quaternary aquifer system is not a single, laterally homogeneous aquifer: observed patterns of hydraulic conductivity, piezometric level and groundwater mineralization suggest that it is composed of a number of semi-independent 'groundwater flow domains' (Ritsema, 1986; Van der Gun, 1986a; Van der Gun et al, 1992). These domains are more or less fan-shaped and are considered to act as preferential zones for groundwater flow. In the hydrogeological overview map (Figure 6.1) they are shown as the darker coloured zones bordered by lighter coloured ones.

A groundwater flow domain includes a recharge zone, one or more corresponding discharge zones, and the aquifer part connecting them. Recharge zones are associated with streams and can be found in the eastern part of the Tihama, while natural discharge of groundwater occurs at the western side, by evaporation on the coastal salt flats (sebkhas) or by submarine groundwater outflow. Outside the groundwater flow domains, groundwater is almost stagnant. Such 'stagnation zones' produce a certain hydraulic isolation between the groundwater flow domains.

This interpretation of lateral zoning within the Tihama aquifer system is consistent with current views on Quaternary sedimentation and on groundwater flow between natural recharge and discharge zones. The predominant role of the major streams (wadis) and their topographic position in relation to the aquifer system and to the natural drainage base (Red Sea) explain the observed patterns. These factors account for the observed distribution of coarser and finer sediments, the diverging groundwater flow pattern from recharge zones of limited areal extent to a virtually continuous discharge zone at the Red Sea coast, and the presence of certain zones where groundwater is relatively stagnant.

Recent studies on the Tihama Quaternary aquifer system include those of WRAY (Van der Gun, 1986a), TBWRS (DHV, 1988) and NORADEP (DHV, 1993). They subdivide the Tihama aquifer into separate *groundwater provinces* which correspond to the groundwater domains described above. The main groundwater provinces are those of Wadi Harad/Wadi Hayran, Wadi Mawr, Wadi Surdud, Wadi Siham, Wadi Rima/Wadi Zabid, Wadi Rasyan and Wadi Mawza.

A cross-section through the Wadi Surdud province (Figure 6.2) illustrates the position of the Quaternary deposits. A special feature in this particular case is the salt tectonics which have resulted in a salt diapir outcropping in the western part of the area. The thickness of the Quaternary deposits is commonly between 50 and 250 m in these

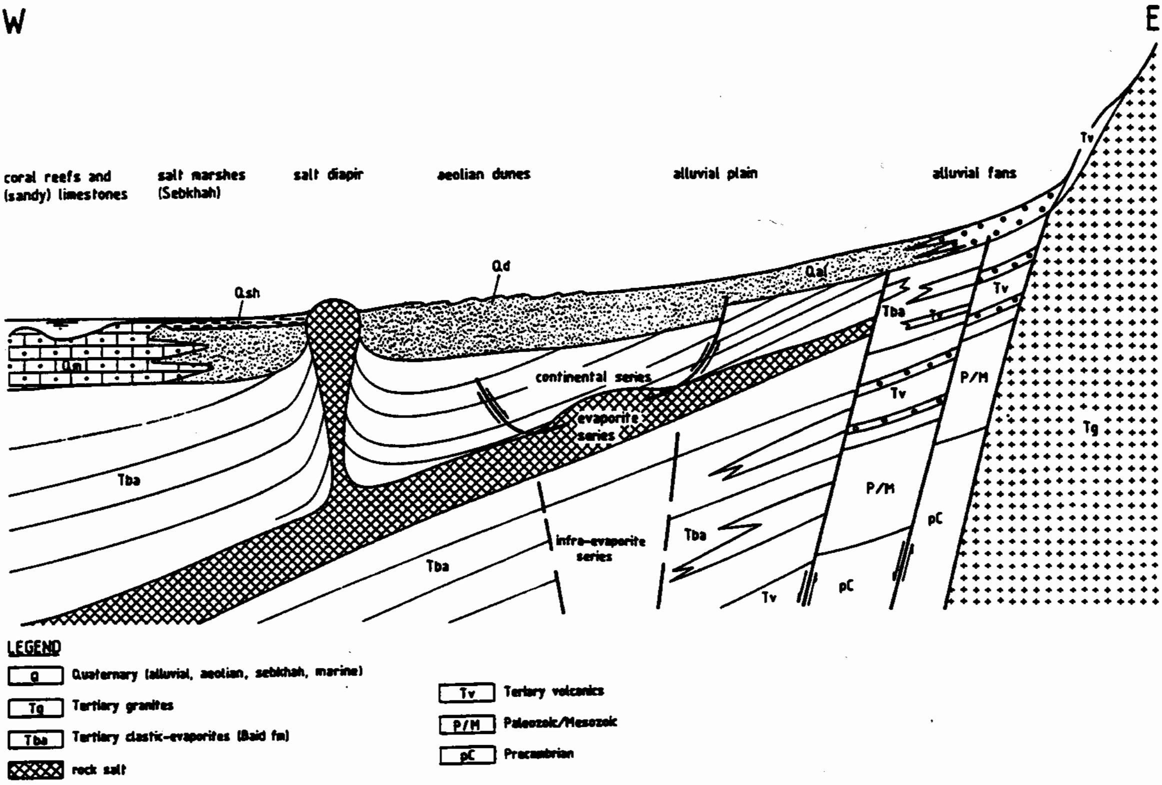


Figure 6.2 Schematic geological cross-section through Tihama's Surdud province

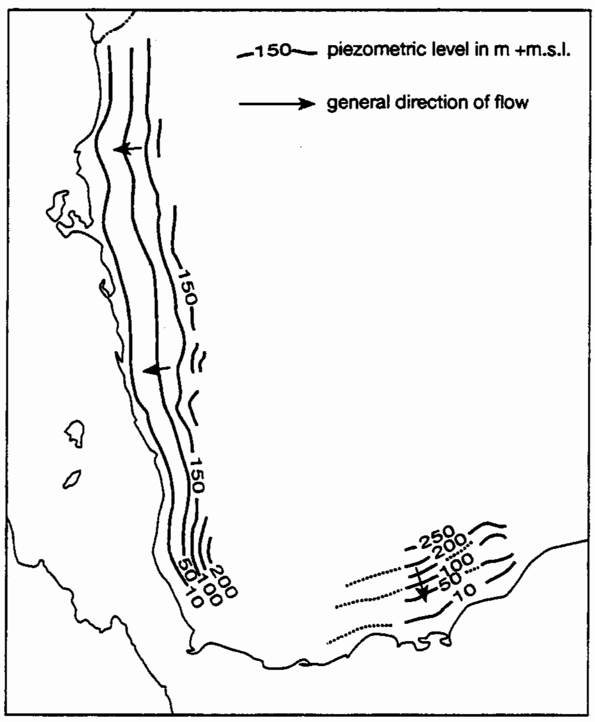


Figure 6.3 Piezometric levels in the Tihama and south-western coastal plains

Tihama groundwater provinces. Transmissivities tend to range from 500 to 3000 m^2/day, with highest values in the westernmost half of the area. The general direction of groundwater flow is from east to west, with piezometric levels between 150 and 250 m + msl at the eastern boundary of the aquifer system (see Figure 6.3). Depth to groundwater is usually between 10 and 50 m.

There is also an east-west increase in the mineral content of the groundwater. Brackish groundwater close to the land surface is common along the coast, but coastal zones of shallow brackish groundwater alternate with zones where groundwater at the coast is still fresh over a depth of 100-200 m. These differences are attributable to different discharge mechanisms: groundwater discharge respectively by evaporation (sebkhas) and by concentrated submarine groundwater outflows. Anomalous groundwater salinity patterns occur in the Wadi Mawr and Wadi Siham provinces; they still need to be studied.

The deltas of the southern coastal plains

The southern coastal plains are located in the Gulf of Aden Rift and show a certain similarity to the Tihama, in the sense that they are also situated in sediment accumulation zones between the mountains and the sea, and are actively recharged by mountain rivers. A difference is that the graben system is less developed than that of the Red Sea, especially in its eastern part. As a result, the thickness of the Quaternary deposits is less than in Tihama, but it is still sufficient to host important aquifer systems. The basal parts of the aquifer systems are probably of Pliocene age (Zarubezhgeologia, 1992). A number of more or less independent flow domains, that are even more pronounced than those in Tihama, can be distinguished. The most important ones are from west to east: Tuban Delta, Abyan Delta, Ahwar Delta and Maifa'ah Plain.

The aquifer system of *Tuban Delta* is highly heterogeneous in the zone of the Upper Delta, north of Lahej. The thickness may increase from 30 m to some 120-170 m, but no highly transmissive zones are observed at depths below 90 m. Aquifer depths increase in the Lower Delta, at least to 200 m, which is the largest known drilling depth in the area. Slightly cemented Quaternary sediments have been observed in the Lower Delta, and phreatic conditions are said to change to semi-confined conditions near the coast (Zarubezhgeologia, 1992). Groundwater is known to be brackish in the coastal fringes.

Two major wadis dissect and recharge *Abyan Delta*: Wadi Bana and Wadi Hassan. Between the small northern zone and the large southern zone of the delta there is a small uplifted central zone with scattered basement outcrops and a relatively shallow basement elsewhere. Sandstone underlies the Quaternary sediments in the northern zone and the southern zone, and locally in the central zone as well; the sandstone in the northern zone is Mukulla sandstone, whereas the stratigraphy of the sandstone (arkose) in the southern zone has not yet been defined. The maximum thickness of the Quaternary deposits is 100 m and more in the northern zone, some 50-60 m in the central zone and approximately 100 m in the southern zone. Basement near the coast, however, is at great depth (probably 800 m or more). In most of the southern zone of the delta a clay layer separating permeable Quaternary sediments from the thick sandstone unit underneath seems to be present. Transmissivities of the Quaternary series are thought to vary from 300 to 10 000 m^2/day; the sandstone transmissivities are estimated to be several orders of magnitude lower (Negenman, 1995a). Groundwater mineralization is remarkably high in Abyan Delta compared to other deltas and coastal zones in Yemen.

The *delta of Wadi Ahwar* is smaller than the Tuban and Abyan deltas. It is made up of Quaternary alluvial and marine deposits (maximum thickness 50 m ?) underlain widely by Pliocene conglomerates (up to 50 m thick). Depth to the water table is reported to vary from 2 m near the sea to some 20 m further inland. Mineralization of the groundwater is rather diverse and according to Zarubezhgeologia (1992) it may reach values close to 10 000 mg/l.

Wadi Maifa'ah opens to a vast plain which slopes gently down towards the sea from an absolute height of 700 m. The eastern part of that plain is occupied by sand dunes. The Quaternary series, composed of gravel-pebble material, unsorted sands and loams, constitutes an aquifer usually some tens of metres thick. It is underlain by Pliocene-Quaternary pebblestones and conglomerates cemented with a carbonate-clayey material (Zarubezhgeologia, 1992).

River plains at the western and southern margins of the Ramlat as Sabatayn

The largest wadi systems running from the Yemen Mountain Massif towards the Ramlat as Sabatayn are Wadi Jawf, Wadi Adhana, Wadi Beihan and Wadi Markhah. Their associated Quaternary wadi fills and river plain deposits constitute relatively important aquifers. Recharge is concentrated in limited zones around the main wadi beds and produces large 'pockets' of relatively fresh water that laterally become increasingly brackish.

The Quaternary alluvial and eolian deposits of *Wadi Jawf*'s river plain constitute an aquifer of rather limited thickness. Agrar- und Hydrotechnik (1982) reports thickness values of 50-70 m in the western part, but only 10-20 m in the Al Hazm area. The depth to groundwater was 5-15 m in 1980 (more recent data are not available). Relatively poor water quality, with EC_{25} exceeding 2000 micromho/cm is found east of the Wadi Madhab/Kharid confluence and between the wadi channels. The Quaternary aquifer is underlain in the western zone by moderately productive limestones of the Amran Group. Many wells tap from these limestones. East of Al Hazm are the westernmost edges of the vast Mukalla Sandstone basin (Yemen Hunt Oil Company, 1993); the Quaternary deposits are probably hydraulically connected with these productive sandstones.

Wadi Adhana recharges a similar but more compact alluvial river plain. Investigations of this *Marib Plain* by the WRAY project (Uil and Dufour, 1990) show that the thickness of the Quaternary series is generally 50-70 m. In the westernmost fringes it is underlain by sediments of the Amran Group, but from about 5 km east of Old Marib further east it forms one aquifer complex with underlying Mukalla sandstone which quickly thickens towards the centre of Ramlat as Sabatayn. The transmissivity of the Quaternary aquifer beds is high in the zone studied, which enables productive wells to be drilled. The main direction of groundwater flow coincides with that of the wadi, which is north-east. Water quality is generally good; a large central zone where EC_{25} is lower than 750 micromho/cm testifies to the influence of recharge by the wadi. The recharge process has been altered by the construction of a dam in the Wadi Adhana in 1986. Uncontrolled floods and spate irrigation have been replaced by controlled releases from the Marib reservoir for regulated irrigation in the area. It is not yet known how this affects average annual recharge.

The Quaternary aquifer systems associated with *Wadi Markhah, Wadi Beihan* and the other wadi systems in the region (Brunner, 1991) show similarities, but the groundwater systems are less productive where the catchments are smaller and their climate drier. The latter is especially the case at the southern edges of the Ramlat Sabatayn.

Quaternary aquifer of Wadi Hadramawt

Wadi Hadramawt is located in a canyon cut into the carbonate rocks of the Hadramawt Group. Figure 6.4 shows a schematic cross-section through Wadi Hadramawt's canyon. The vertical sides of the canyon rise -on average- to some 300 m above the top of the Quaternary deposits which form the wadi beds inside the canyon. These Quaternary deposits constitute an aquifer approximately 90 km long, from 20 km (west) to 1.5 km (Wadi Masila near Qassam) wide, and locally more than 100 m thick. Not only does this aquifer have rather high transmissivities, it is also very favourably located with respect to sources of recharge. Various large tributaries quickly bring floods from around 22 500 km^2 of the bare limestone-covered Jawl plateaus to the Wadi Hadramawt canyon, where they largely infiltrate into the Quaternary aquifer (see Chapter 5).

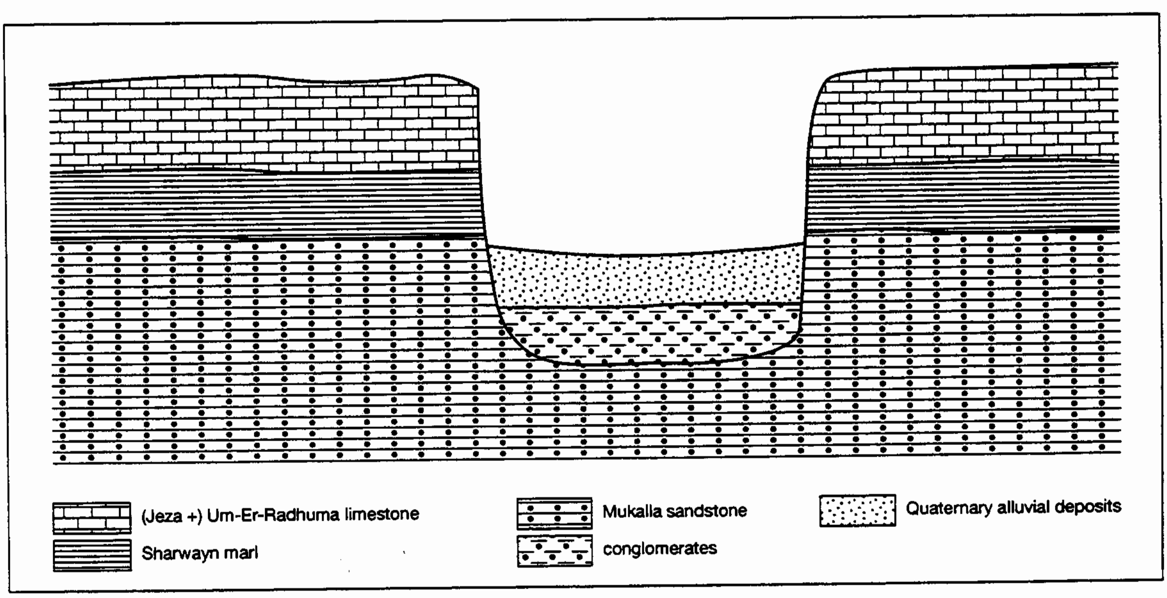


Figure 6.4 Schematic geological cross-section through Wadi Hadramawt

Groundwater levels in the Quaternary deposits are relatively shallow, generally 20-30 m below surface. But according to McDonald (1988) they declined some 20 to 25 m on average during the period 1952-1984. These previously very shallow water tables are consistent with observations made by Van der Meulen and Von Wissmann (1932) who observed baseflows, small pools of stagnant water and white salt crusts on the soil surface, especially in the eastern part of Wadi Hadramawt.

As can be seen in Figure 6.4, the wadi has completely eroded the limestone rocks of the Um-Er Radhuma Formation and part of the underlying Mukalla sandstones. Between the Quaternary deposits and the Mukalla sandstones there is a bed of conglomerates of Quaternary to Pliocene age. Quaternary deposits, Pliocene conglomerates and Cretaceous Mukalla sandstones are hydraulically interconnected. The latter unit contains water of much better water quality than that of the Quaternary aquifer and therefore has become the most important aquifer unit in the region. The conglomerates seem to act partly as an aquitard through which leakage occurs between the sandstone aquifer and the Quaternary aquifer.

The water in the Quaternary aquifer has rather high mineralization, with salt contents rising to more than 10 000 mg/l along the longitudinal axis of the wadi. Relatively fresh groundwater (salt content less than 2000 mg/l) is only encountered immediately along the flanks of the steep-sided canyon and in the mouths of the tributaries.

6.3.3 Groundwater basins of the Highland Plains

Highland Plains are scattered over the Yemen Mountain Massif. Most of them are located relatively near the main water divide that separates the Red Sea Basin from the other three drainage basins of the mainland. Many of these plains constitute small, but relatively favourable areas for groundwater development. This is because of a number of factors (Van der Gun, 1986b):

(a) groundwater levels are (or used to be) within a few tens of metres below the ground surface;
(b) the hydraulic conductivity of their rocks is higher than that of the surrounding rock units;
(c) subhorizontal topography and the presence of alluvial deposits favour groundwater replenishment;
(d) surface water leaves the plains only on rare occasions and in insignificant amounts; natural discharge from these areas is mainly by evaporation and subsurface outflow.

The most important highland groundwater basins are - from north to south : the Sadah Basin, the Amran Basin, the Sana'a Basin, the Ma'bar-Dhamar Plains and Rada Basin. They will be briefly described below.

The *Sadah basin* is defined by the Sadah graben, a strongly downfaulted block where Wajid Sandstones occur under a 30-60 m thick cover of unconsolidated Quaternary deposits. These unconsolidated cover deposits are largely unsaturated, but they are effective in trapping surface water flows from the surrounding mountains and thus contributing to the recharge of the Wajid Sandstones. These Wajid Sandstones are poorly cemented sandstones with low porosity, in which flow is dominantly intergranular. They generally have low hydraulic conductivities, but their thickness under the Sadah Plain is mostly between 300 and 600 m (Van Overmeeren, 1985a). The resulting moderate transmissivities coupled with uniformity and large permissible drawdowns make the sandstone aquifer easily exploitable. The abstraction rates exceed the average recharge by one order of magnitude. In 1984 the WRAY project made a prognosis of groundwater level declines to be expected under uncontrolled pumping (Elderhorst and Van der Gun, 1985); these were later confirmed by continued monitoring by the GDH (see e.g. Al-Barakani and Kamphuis, 1992a through 1993b) and by NORADEP's well inventory (DHV, 1993m). Regional groundwater levels fell by some 40 metres on average in the period 1983-1992.

The *Amran basin* is filled with Quaternary alluvial deposits, with intercalations of Quaternary basalts (Tibbits and Aubel, 1980). The former ones constitute an aquifer with the latter functioning as aquitards. Measured transmissivities of the aquifer range from 75 to 860 m^2/day; transmissivity is thought to increase towards the centre of the valley. Groundwater quality is generally good, except in some zones west of Amran town. Groundwater pumping in the Amran basin is intensive and has caused general water level declines of 70 to 140 m during the period 1977-1991 (DHV, 1993s). Present-day groundwater flow is mainly towards the centres of concentrated abstraction.

The *Sana'a basin* is characterized by a complex groundwater system which -in spite of several major studies carried out during the last 20 years (including Italconsult, 1972; Mosgiprovodkhoz, 1986; Bloemendaal et al., 1994a; TS-HWC, 1992i)- is only imperfectly known. Figure 6.5 gives an impression of the geology. Hydrogeologically important units are the Quaternary alluvial deposits, the Tertiary Yemen Volcanics, the Cretaceous Tawilah Sandstones and -perhaps- the Kohlan Sandstones. Alluvial deposits used to be an important source of groundwater in the past, but serious declines of the groundwater levels have reduced their role. The Tawilah Sandstones have become the most important exploited aquifer unit since they were explored in the early 1970s. Flow in this aquifer is believed to be through fissures and pores (mixed aquifer type). These sandstones are absent in the northern part of the Sana'a Basin, probably partly due to erosion; perhaps the unexplored Kohlan sandstone may provide water there. South of Sana'a the Tawilah Sandstones dip under a complex of Tertiary volcanic rocks and intercalated alluvial sediments. Productive wells have been sunk in the Tawilah Sandstone in the southern zones of the urban area, but further south the volcanic/alluvial complex is the only significant aquifer known. High rates of abstraction have severely affected the piezometric levels in the Tawilah Sandstones (see Figure 6.6). Studies are being undertaken by the SAWAS project to determine the remaining life-time of the Tawilah sandstone aquifer as a source of water for Sana'a's urban water supply. Groundwater quality is generally good in the Sana'a basin, but polluted zones have been observed in the urban area and north of Sana'a city, where untreated sewage water is infiltrating. A review of hydrogeological studies and data related to the Sana'a basin is given by Nash (1991).

The *Central Highland Plains* or *Ma'abar-Dhamar-Kitab Plains* consist of a number of larger and smaller plains. Some of them -such as Qa Jahran- are filled to great depths (> 100 m) with alluvial deposits, which constitute the main aquifer system. On other plains -where there is hardly any alluvial material- groundwater is mainly found in the volcanic rocks; these constitute a fissure-type aquifer which is locally highly permeable because of tectonic features. It seems that under these Central Highland Plains the volcanic rock complex is more productive than in most other zones where the Yemen Volcanics are present. In Figure 6.1 it is therefore classified under the category of highly productive aquifers. Chilton (1980) gives a clear and rather detailed description of the groundwater conditions of the area; the report, however, is outdated as far as the groundwater abstractions and groundwater levels are concerned.

A more diverse geology is found in the area of the *Rada Basin* (see Figure 6.7). The main aquifer consists of fractured Tawilah Sandstones. On the Rada Plain these are overlain by Quaternary alluvial deposits which locally form a shallow aquifer. Volcanic rocks occur as well, but are locally less important groundwater systems. All these groundwater systems are interconnected. In general, water quality is good to moderate, but groundwater becomes brackish at the downflow end of the Rada Plain. Groundwater is intensely abstracted in the Rada area, which has led to locally significant declines of the groundwater levels (ILACO, 1984 and 1990a).

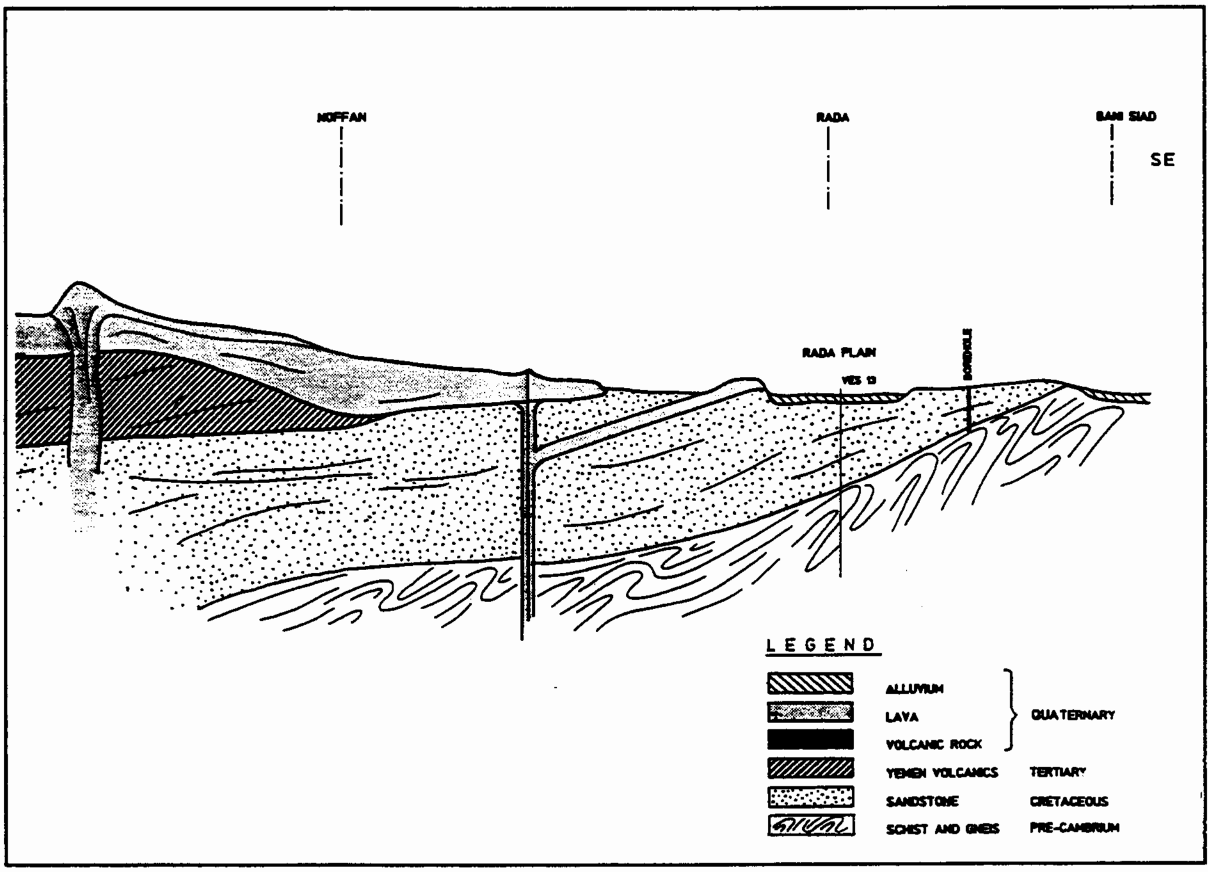


Figure 6.7 NW-SE cross-section through the Rada area (ILACO, 1990a)

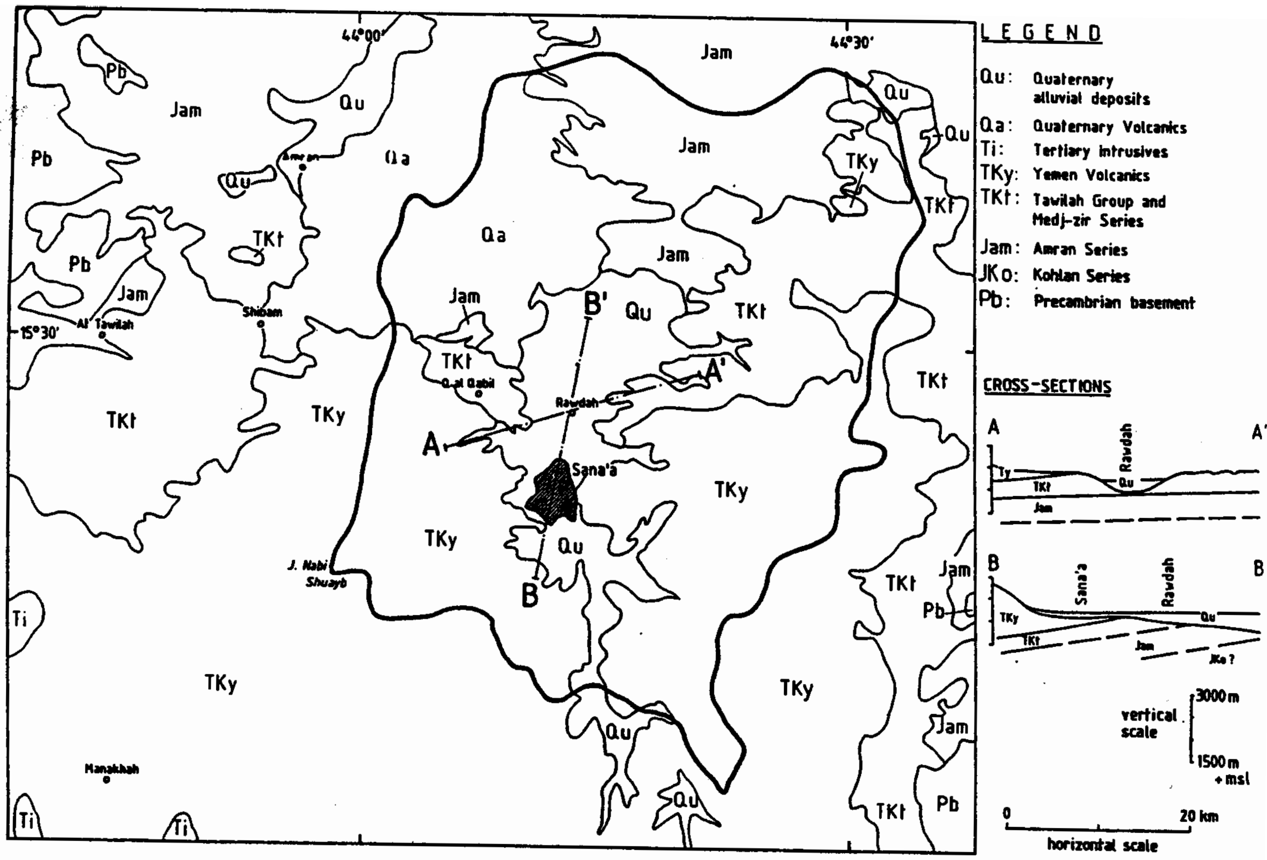


Figure 6.5 Geological setting of the Sana'a basin

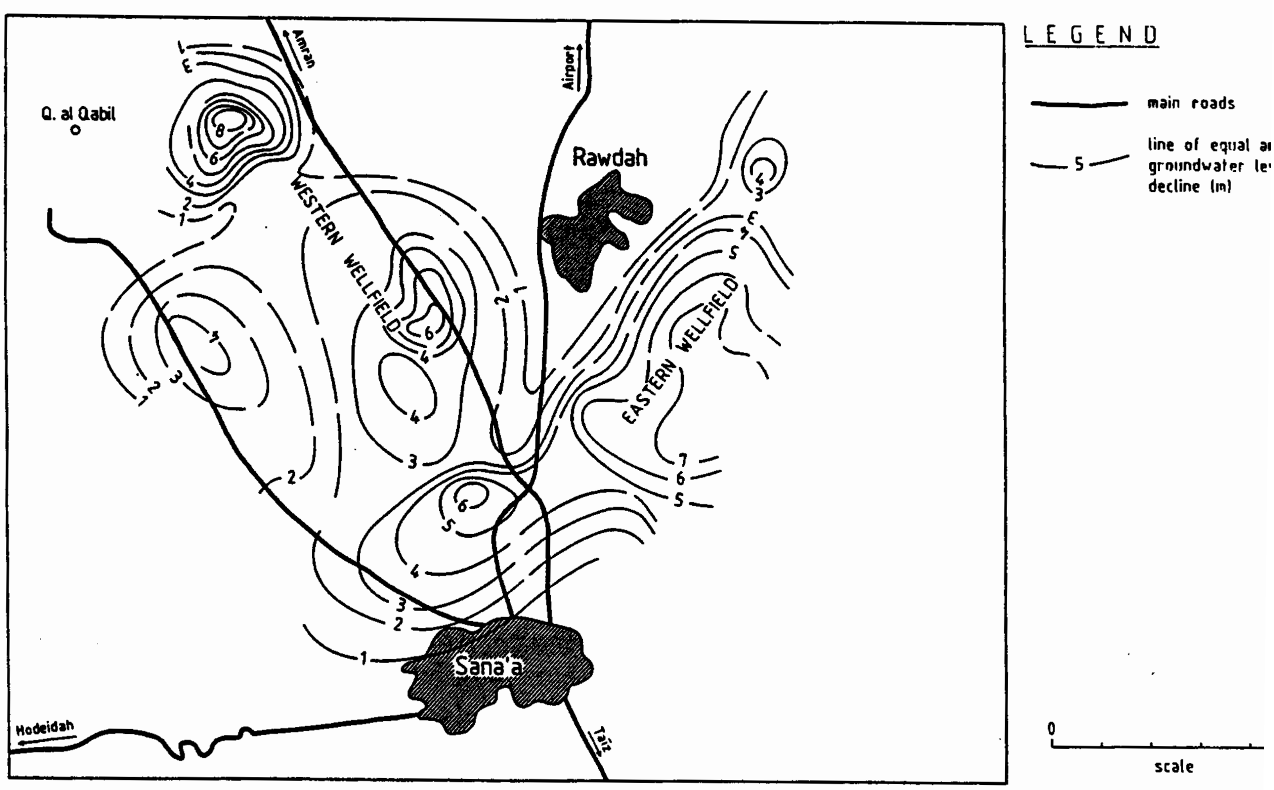


Figure 6.6 Mean annual fall in groundwater level in the Tawilah Sandstones near Sana'a, period 1980-1985 (after Mosgiprovodkhoz, 1986)

6.3.4 *The regional Mukalla Sandstone Aquifer*

East of the shield and north of the Al Ghaydah basin and of the rifted zone along the Gulf of Aden is an extensive basin where thick strata of Mesozoic and Tertiary sediments have been deposited. This basin -which Zarubezhgeologia (1992) indicated as the Tawilah Artesian basin- extends far northwards over the platform zone of the Arabian peninsula.
Mukalla Sandstone averaging 300-400 m in thickness is widely present in this basin (see Figure 2.4) and forms a continuous regional aquifer of large lateral extent. In the western part (Ramlat as Sabatayn zone) it rests upon Jurassic sediments, a thick series containing saline water, and with oil-bearing zones. Further east, it probably directly overlies the Precambrian basement. In the Ramlat as Sabatayn it is overlain by Quaternary continental deposits, a few metres to more than 150 metres thick and probably largely unsaturated. In the Plateau Region it is capped by a thick sequence (around 300 m) of carbonate rocks of the Hadramawt Group.

The Mukalla Sandstones are reported to have a maximum thickness of approximately 1000 m in the Shabwah area; the underlying Jurassic deposits there are even thicker (around 3000 m). The sandstone strata dip in easterly to north-easterly directions; they are no longer of practical interest in the eastern part of the Plateau Zone, because of their great depth and a gradual transition to a less permeable marine facies. The related eastern boundary and also the southern boundary of the basin indicated in Figure 6.1 were copied from Zarubezhgeologia (1992). The western boundary could be defined with reasonable accuracy on the basis of available geological maps and data presented by Yemen Hunt Oil Company (1993) and Uil and Dufour (1990). Only its northern tip is uncertain: it was taken as the envelope of the Mukalla Sandstone outcrops visible on the geological maps.

Although the sandstones have not yet been sufficiently explored, it can already be stated that they constitute the largest groundwater system in Yemen, storing huge quantities of groundwater. The depth to the aquifer is modest under Quaternary deposits of the Ramlat as Sabatayn, but the aquifer horizons are generally at considerable depth in the Plateau area, especially in the southern and eastern part where they are generally at 300-400 m below ground surface. In deeply eroded wadi valleys they are locally exposed or at rather shallow depths below the wadi beds. This is e.g. the case in Wadi Hadramawt (see Figure 6.4), the only zone where massive abstraction from this extensive aquifer unit is currently taking place. Mukalla Sandstones outcrop over a large area in the western part of the Northern Plateau Zone (see Figure 2.3), but groundwater levels there are between 100 and 200 m deep.

The Mukalla sandstones generally have high porosities (up to 25 % ?) and it is assumed that both pores and fissures contribute to groundwater flow. The transmissivity of the sandstone aquifer is rated as high; in the Wadi Hadramawt area it has been shown to be variable, but values in the range of 3000 to 3500 m^2/day are not uncommon (Kazgiprovodkhoz, 1983).

Figure 6.8 shows (in a fragmentary way) the piezometry in the aquifer unit. It shows the effect of groundwater recharge from wadis in the western and central part of the aquifer,

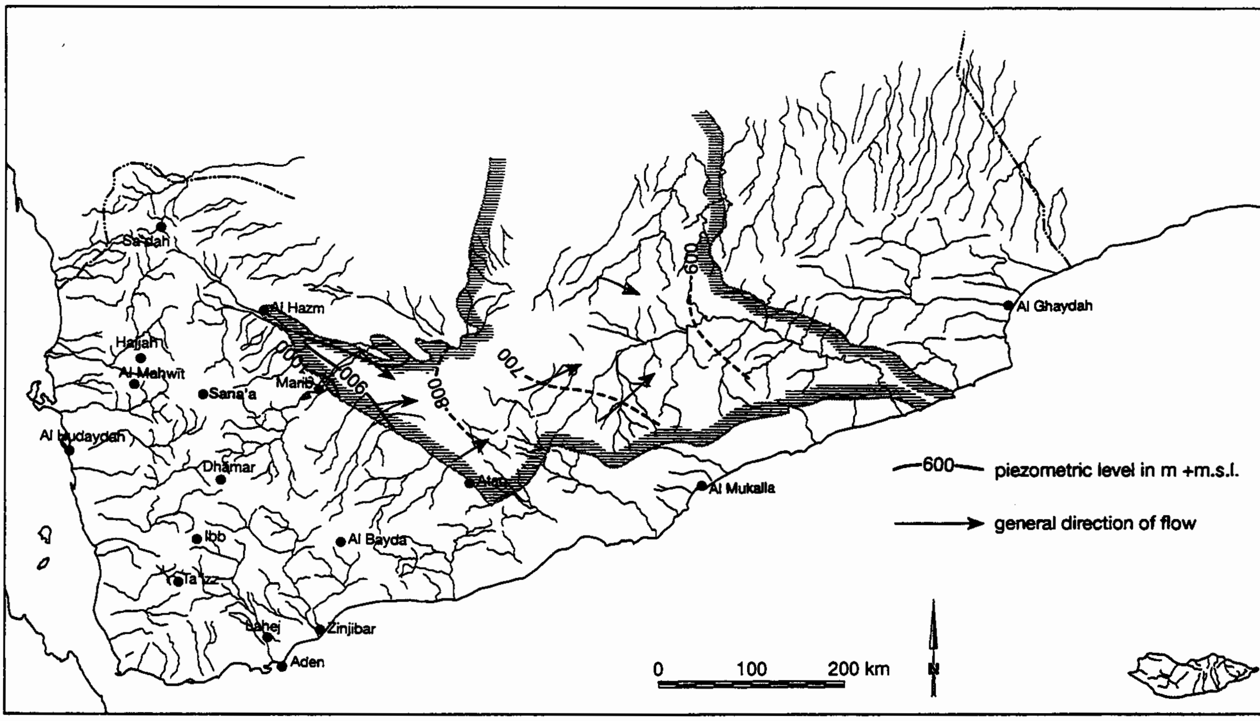


Figure 6.8 Piezometric levels in the Regional Mukalla Sandstone Aquifer

but it does not yet clearly reveal the natural discharge mechanisms. The groundwater quality in this regional Mukalla sandstone aquifer is reported to be good. The maps of Zarubezhgeologia (1992) indicate that the mineral content of the water in this aquifer is generally below 1000 mg/l and that the overlying sediments in most of the zones - insofar as they are saturated- generally have groundwater of markedly higher mineralization. Chemical analysis shows somewhat higher values (around 1500 mg/l) for groundwater occurring in Mukalla Sandstone of the 'Masila block', between Mukalla and Wadi Hadramawt (Komex, 1993).

It can be observed that the Mukalla Sandstone unit is in some zones in direct hydraulic contact with overlying Quaternary deposits. This occurs in and along the Ramlat as Sabatayn and in the deeply eroded valleys of the Wadi Hadramawt and its tributaries. Together, these Cretaceous and Quaternary sediments can be considered as one aquifer complex: the "*extended Mukalla Complex* "

6.3.5 Other regionally extensive aquifers

Other regionally extensive aquifers are the Amran Limestones and the Yemen Volcanics in the western part of the country, and the Um-Er-Radhuma in the eastern part.

The *Amran Limestones* form an extensive and thick outcrop over the mountain massif between Sana'a and Sadah (see figures 2.3 and 2.4). Groundwater in the rocks of this Amran Group flows predominantly through fissures. The hydraulic properties of the massive limestones, shales and marls belonging to this stratigraphic unit are generally not very favourable for groundwater development, but productive wells are observed locally, especially near wadis. Alternations of more permeable and less permeable beds create multi-layer conditions with perched water bodies and with springs along the outcrops of less permeable horizons (Agrar-und Hydrotechnik, 1989).

The presence of *Kohlan* and *Wajid Sandstones* under these rocks of the Amran Group has been demonstrated by seismic surveys. Although they are likely to have better hydraulic properties, they are at great depth (probably 400-500 m near Sadah and more than 1000 m north of Sana'a), their lateral continuity has not yet been defined, and the quality of their groundwater is still unknown. Investigations such as those by the ongoing SAWAS project have to determine their significance as aquifer rocks.

The *Yemen Volcanics* are predominant and almost continuous in the Yemen Mountains south of Sana'a (see figures 2.3 and 2.4); a second large area of occurrence is on the Shahara massif between Hajjah and Sadah (Figure 2.3). The thick and stratified Yemen volcanics constitute a generally poor, fissured regional aquifer system. Depth to groundwater is highly variable, and many drilling attempts have resulted in dry or poorly productive wells. Nevertheless, there are also rather favourable groundwater zones in this regional aquifer system. An example is the Central Highland Plains area, where tectonic activity has probably enhanced the hydraulic properties of the rocks (see also section 6.3.3).

The *Um-Er-Radhuma Limestones* are extensive in the Plateau Region. They form outcrops in the western part of that region and are prominent in the cliffs of Wadi Hadramawt and those that frame the Ramlat Sabatayn at its eastern side. Eastwards they dip under younger formations of the Hadramawt Group (Figure 2.3). They are known as fissured, karstic rock units. Their waterbearing properties are poor in the western part of their zone of occurrence, but further east -in the north-eastern part of Hadramawt and the northern part of Al Mahrah- they are considered as moderately productive aquifers. In that zone they are buried under a 100-300 m thick cover of younger sediments of the Hadramawt Group. The water there in the Um-Er-Radhuma aquifer has generally a mineral content lower than 1000 mg/l (Zarubezhgeologia, 1992). This and the occurrence of artesian wells suggest that in the east an upward flow of groundwater takes place from the Cretaceous sediments into the rock units of the overlying Hadramawt Group.

6.3.6 Other groundwater systems

Pre-Quaternary aquifers of relatively small dimensions are present in different parts of the country. Wajid Sandstones and Tawilah Sandstones are the most important formations in this respect, in the western part of the country (see Figure 2.3 and Figure 6.1). They have already been discussed in section 6.3.3, but they occur also outside the Highland Plain basins. Mukalla Sandstone blocks are probably the best target for groundwater development in the Aden rift zone east of Wadi Ahwar. The significance of the Shihr formation as an aquifer rock complex is not yet clear. Zarubezhgeologia (1992) classifies the same formation and also the Habshiyah Formation as probably the best aquifer rocks in the Al Ghayda basin.

Weathered and fractured basement may locally be very important for groundwater development. However, it does not have the development potential of productive and regional aquifers.

6.4 Groundwater recharge, storage and discharge

6.4.1 Groundwater recharge

Groundwater systems are in a dynamic state as a result of the replenishment of the groundwater resources (*groundwater recharge*) on the one hand, and discharge processes on the other hand. Groundwater level records may reveal how, for different time scales, these in- and outflows are balanced by changes of the stored volumes of groundwater. They also show the general direction of flow between recharge and discharge zones.

Groundwater recharge is produced either by direct infiltration of rainfall in excess of the water-holding capacity of the soils (*direct recharge*), or by the infiltration of water that has passed through one or more other phases of the hydrological cycle after it reached the surface in the form of precipitation (*indirect recharge*). The latter category includes the replenishment of groundwater by infiltrating surface water and by percolating 'irrigation water losses' and waste water. A special form of indirect recharge is *artificial recharge*, which is produced by human interference with the deliberate purpose of replenishing the groundwater system in question. Some recharge processes are mainly controlled by natural factors. They are often combined under the name *natural recharge*, as opposed to *induced recharge* which is related to human activities (irrigation, production of waste water, artificial recharge, etc.).

Direct recharge of groundwater is generally very low in Yemen. This is a logical consequence of the prevailing rainfall regimes. It causes the soils to be rather dry during most of the time. Any rainfall that does not run off immediately in the form of overland flow tends to be easily accommodated in the upper soil zone, from where it is lost almost entirely by evaporation and evapotranspiration during subsequent days. Only if large quantities of rainfall are produced within a few days, will it be possible for the soil moisture reservoirs to become saturated and produce significant percolation to the groundwater reservoirs below. It is clear that -given a certain rainfall regime- the direct recharge in runoff absorbing zones is likely to be greater than in the runoff producing zones.

The main form of natural groundwater recharge in Yemen is by infiltration of surface water from wadis. In Chapter 5 it was already described how the wadis tend to collect excess water in the steep and relatively impermeable catchments (runoff producing zones) and lose part or all of their flows as soon as they traverse flat and permeable terrains (runoff absorbing zones). The mapped pattern of runoff absorbing and runoff producing zones (Figure 5.1) allows the main groundwater recharge zones on a macro-scale to be localized.

In between this indirect recharge by wadis and the direct recharge by rainfall there are also recharge processes active during the overland flow phase. Water moving as overland flow towards the nearest branches of the wadi channel network passes over different types of land surface. On its way down it may flow into fissures and cracks of solid rocks, it may accumulate in ponds or be trapped in more permeable soils, and from there replenish groundwater. This form of recharge (for convenience, classified under 'direct recharge' here) may play a role in the recharge of the extensive aquifer rocks of the rugged mountain massifs and plateaux.

The infiltration losses produced in irrigated zones are quantitatively the most important form of induced groundwater recharge in Yemen. In intensely irrigated zones such as the Highland Plains they may exceed the natural recharge of the groundwater reservoirs. Induced recharge by discharge of domestic or industrial waste waters are comparatively unimportant in Yemen, at least from the point of view of water quantity. Artificial recharge is not practised at all.

The overall effect of irrigation on groundwater recharge depends mainly on the source of irrigation water, thus on whether it is surface water or groundwater. Compared to a 'natural' situation without irrigation, applying groundwater for irrigation tends to increase groundwater recharge; it produces an 'intensification' of the hydrological cycle. Diverting surface water for irrigation or 'harvesting' overland flow (which is widely practised in Yemen), on the other hand, usually has the net effect of reducing groundwater recharge. In these activities water is intentionally converted into evapotranspiration, and -under Yemeni conditions- infiltration losses then tend to be less than the volume of water that would infiltrate under natural conditions.

6.4.2 Groundwater discharge

Like recharge, groundwater discharge can also be divided into 'natural' and 'induced' or 'man-made' components. In Yemen the latter category entails groundwater abstraction only; the former one includes discharge by springs, by outflow into streams (baseflow), by evaporation and evapotranspiration, and by submarine outflow.

Springs occur in many zones of Yemen, in particular in the mountain and plateaux areas. Many of them are in the Amran Limestones, in the rocks of the Hadramawt Group or in the Volcanic areas. But they are also found as in sandstone rocks, e.g. in the upper part of Wadi Surdud catchment (Wadi Ahjar zone), where hundreds of small springs are located along the contact between Tawilah Sandstones and the rocks of the underlying Amran Group (Dufour, 1989). The Mukalla sandstone outcrops in the rifted zone east of Wadi Ahwar are also scattered with springs (Robertson, 1991d; TS-HWC, 1992d). They give a steady baseflow to Wadi Hajar, the only permanent stream in southern Yemen. Some of the springs in the catchment of Wadi Hajar are obviously thermal springs (Van der Meulen and Von Wissmann, 1932)

Most of the springs known have only small flows, in the order of a few litres per second. The larger springs include those in the centre of Wadi Surdud catchment (Neumann-Redlin, 1991) and the Wadi Kharid springs, about 25 km north of Sana'a. Most springs have fresh water of ordinary temperature, but thermal and thermo-mineral springs are present as well. Dowgiallo (1986) presents an overview of identified thermal springs in the former YAR. He distinguishes one group connected with faults of the eastern margin of the Red Sea graben and/or with Tertiary granitic intrusions. Another group is associated with vulcanism.

Discharge of groundwater by *outflow into streams*, where it constitutes baseflow, often occurs in association with springs. It is typical for the upper and intermediate parts of the wadis in the wetter zones, e.g. in the area of the Western Slopes. The lower parts of the streams, however, near the sea and at the edge of the desert do not collect base flows.

Evaporation and evapotranspiration is an important mechanism of natural groundwater discharge, as in many other arid zones. Typical features are sebkhas along the coast and white-crusted evaporation zones in wadi beds, especially at narrow outlets of groundwater basins, such as at the Sadah Plain, Radah Plain and in the eastern part of Wadi Hadramawt.

Submarine outflow is a common discharge mechanism of coastal aquifers. It is estimated that it accounts for about half of the natural discharge of the Tihama and the Tuban-Abyan aquifers.

Groundwater abstraction has gained enormously in importance over the last 25-30 years. Less than one generation ago it was a minor component of the total discharge of the groundwater systems, nowadays it is the dominant form of groundwater discharge of most of Yemen's groundwater systems. The explosive increase in groundwater abstraction was triggered by the introduction of modern technology such as drilling rigs and powerful pumps (since the 1960s) and the growing water demands of a developing society.

6.4.3 Estimates of groundwater recharge, storage and abstraction

The evident scarcity of water in Yemen has led to many estimates of groundwater recharge and groundwater abstraction. These variables -mostly presented as annual totals- are covered in many reports on groundwater investigations in areas of major interest. Groundwater storage (i.e. the volume of water stored in the groundwater systems), on the other hand, has been addressed in a few cases only (e.g. Van der Gun, 1985a and 1986a; TS-HWC, 1992d). Knowledge of the variables recharge, storage and abstraction is indispensable for appropriate groundwater quantity management.

Estimates of groundwater abstraction result mainly from well inventories. These inventories commonly encompass large numbers of wells, and a compromise has to be found between the time spent and the accuracy of the data inventoried. This mostly results in abstraction data that cannot yield very accurate areal abstraction figures. Nevertheless, the methodologies used are straightforward, probably unbiased and rather uniform. It is estimated that areal abstraction figures generally have errors within some

Table 6.2 Estimates of groundwater abstraction rates

AREA	LATEST WELL INVENTORY/ASSESMENT				1994 ESTIMATES	
	Reference	No.of pumped wells	Total abstraction (Mm^3/yr)	Year	Total abstraction (Mm^3/yr)	
Highland Plains :						*500*
Baqim Plain	DHV,1993n	107	6.1	1991	6	
Sadah Plain	DHV,1993m	2330	80.4	1992	80	
Al Harf, Hamra and Al Ashash Plains	DHV,1993	346	11.9	1991	12	
Attaf Plain	DHV,1993r	112	14.8	1991	15	
Amran Valley	DHV,1993s	800	77.2	1991	77	
Sana'a Basin	TS-HWC,'92i		180.6	1990	185	
Dhamar Plains	Chilton,1980	395	11	1976	40 (?)	
Rada Plain	Ilaco, 1984	556	9.0	1983	25 (?)	
Tihama zones:						*810*
Northern zone	DHV, 1988	676	114	1984	120	
Wadi Mawr	DHV, 1988	1200	156	1984	165	
Wadi Surdud	DHV, 1988	900	117	1984	125	
Wadi Siham	DHV, 1988	960	125	1984	135	
Jahabah	DHV, 1988	1088	141	1984	150	
Wadi Rima/Zabid	DHV, 1988	1983	261	1984	280	
Wadi Rasyan	DHV, 1988	431	30	1984	33	
Wadi Mawza	DHV, 1988	442	30	1984	33	
Other zones	DHV, 1988	516	53	1984	54	
Southern coastal plains:						*250*
Tuban delta	McDonald,'86a		87.2	1984	90	
Wadi Rabwa	Selkhozp.,'90a		5.8	1988	7	
Abyan delta	WRAY, 1995		86.4	1993	87	
Wadi Ahwar	Selkhozp., '90b		5.8	1988	7	
Fuwah-Buweish-Huweira-Arf-Khird	Sogreah, 1980a		9.8	1980	15	
Ramlat as Sabatayn fringe zone:						*375*
Al Jawf Plain	AHT, 1982	800	30	1982	40	
Marib Plain	WRAY, 1992	1869	174	1991	180	
Beihan zone	WBAP	842	75	1986	80	
Wadi Markhah zone	Strojexport, 1984		12.8	1982	20	
Wadi Hadramawt	McDonald,1988		158.9	1985	180	*200*

Note: abstraction in regions other than the five listed above entails comparatively minor volumes of water.

15-20% for the moment in time they were made. Updating old estimates by mere extrapolation is likely to produce larger errors.

Estimates of annual groundwater abstraction are listed in table 6.2. This table mentions the abstraction figures as determined in the latest well inventories for the areas concerned, and it extrapolates these figures to estimates for current conditions. The extrapolation takes into account the number of years that have passed, the trends observed in the past, and the present conditions in the area. The total estimated for the five major groundwater abstraction regions takes into account zones additional to the ones mentioned in the table.

The assessment of groundwater recharge is much more difficult. It has to be estimated by indirect methods, and lack of reliable data is usually a severe constraint. Methods used for studies in Yemen include water balance methods, throughflow estimation, tracer techniques, modelling techniques and empirical relations with rainfall. The resulting estimates are of variable reliability and generally not very accurate. Furthermore, methodological differences and unavoidable subjectivities make the different estimates difficult to compare. This can be demonstrated by means of the many estimates of the average annual groundwater recharge in the Sana'a basin that have appeared in different reports. Reported values include: 59 Mm^3 (Italconsult, 1973), 45 Mm^3 (Howard Humphreys, 1977), 28 Mm^3 (Charalambous, 1982), 59 Mm^3 (Howard Humphreys, 1983) and 42 Mm^3 (TS-HWC, 1992i).

An important criterion for judging and adopting estimates of recharge is the degree of consistency with the figures and ideas on surface water volumes presented in Chapter 5. Assuming that surface water runoff is the predominant source of 'natural' recharge (see Section 6.4.1) a reasonable estimate of this 'natural recharge' can be made by identifying the catchments that drain towards the aquifer unit considered, estimating their mean annual yield, and allocating this yield in defined proportions to groundwater recharge, 'net' water consumption in surface irrigation areas and surface water outflow. The 'proportions' depend on local conditions. If wadis disappear completely, without being diverted for surface water irrigation, then it may be assumed that some 95 % of the flow will be converted to recharge. If they are actively used for spate irrigation, then in general some 20 - 30 % will be effectively lost to evapotranspiration. Surface water outflow (e.g. into the sea) is significant in only a few areas.

Estimates of stored volumes of groundwater are inherently inaccurate. The areal extent of the aquifers is often fairly well known, but their depth and/or their average porosity are usually more speculative. It is nevertheless possible -and useful- to define the order of magnitude of the storage of the main aquifer systems.

Aggregating estimates of groundwater abstraction, groundwater recharge and stored volume of groundwater for the major aquifer complexes leads to the provisional picture presented in Table 6.3. The category 'fresh water' in storage as mentioned in this table does include slighly brackish water as well.

It can be inferred that at national scale groundwater abstraction is exceeding already the rate of groundwater recharge. For individual developed areas the situation is much worse than the national or regional averages reveal. The most endangered aquifer systems in this respect are those of the Highland Plains, where the groundwater abstractions are several times the average recharge rates. Note that the Extended Mukalla Complex (see 6.3.4) has a huge volume of water in storage but a comparatively low rate of recharge.

The volumes of water stored in the groundwater systems act as buffers that may temporarily bridge the gap between abstraction rates and recharge rates. For small wadi systems the stored volume is of the same order of magnitude as the average annual recharge, thus the buffer function is very limited. At the other end of the scale there is the Mukalla Complex: the total storage exceeds the recharge by more than four orders of magnitude, and the potential buffer function thus is very large. It must be added, however, that other factors such as technical, economic or water quality considerations may become critical long before the aquifer system is physically exhausted. An appropriate storage management strategy has not yet been adopted for the Extended Mukalla Complex, nor for any other regional aquifer system in Yemen.

Table 6.3 Current abstraction rates, recharge rates and groundwater storage for the main aquifer complexes in Yemen

Aquifer complex	Approximate abstraction (Mm^3/year)	Approximate average recharge (Mm^3/year)	Fresh groundwater stored (Mm^3)	Remarks
Tihama Quaternary aquifer	810	550	250 000	Quaternary aquifer
Southern Coastal Plains (west of Mukalla)	225	375	70 000	several Quaternary aquifer units
Extended Mukalla Complex	575	500	10 000 000	Cretaceous Sandstone with interconnected Quaternary deposits
Highland Plains	500	100	50 000	various isolated units with variable lithology

Notes: (1) Recharge in this table is 'natural recharge' as defined in Section 6.4.1, thus it does not include return flow from abstracted groundwater
(2) Recharge and storage figures are only tentative
(3) Fore definition of the Extended Mukalla Complex, see section 6.3.4.

6.4.4 The response of the groundwater systems to increasing abstractions

The strongly increased groundwater abstractions in Yemen have drastically changed the regimes and conditions of the main groundwater systems. The most easily observable effect is that groundwater levels have declined and are likely to continue declining in the future. The rates of decline are alarmingly high in many zones, especially in the Yemen Highlands, where declining trends between 2 and 6 m/year are commonly observed. Figure 6.9 demonstrates this very clearly for the Sana'a basin. But this is certainly not the

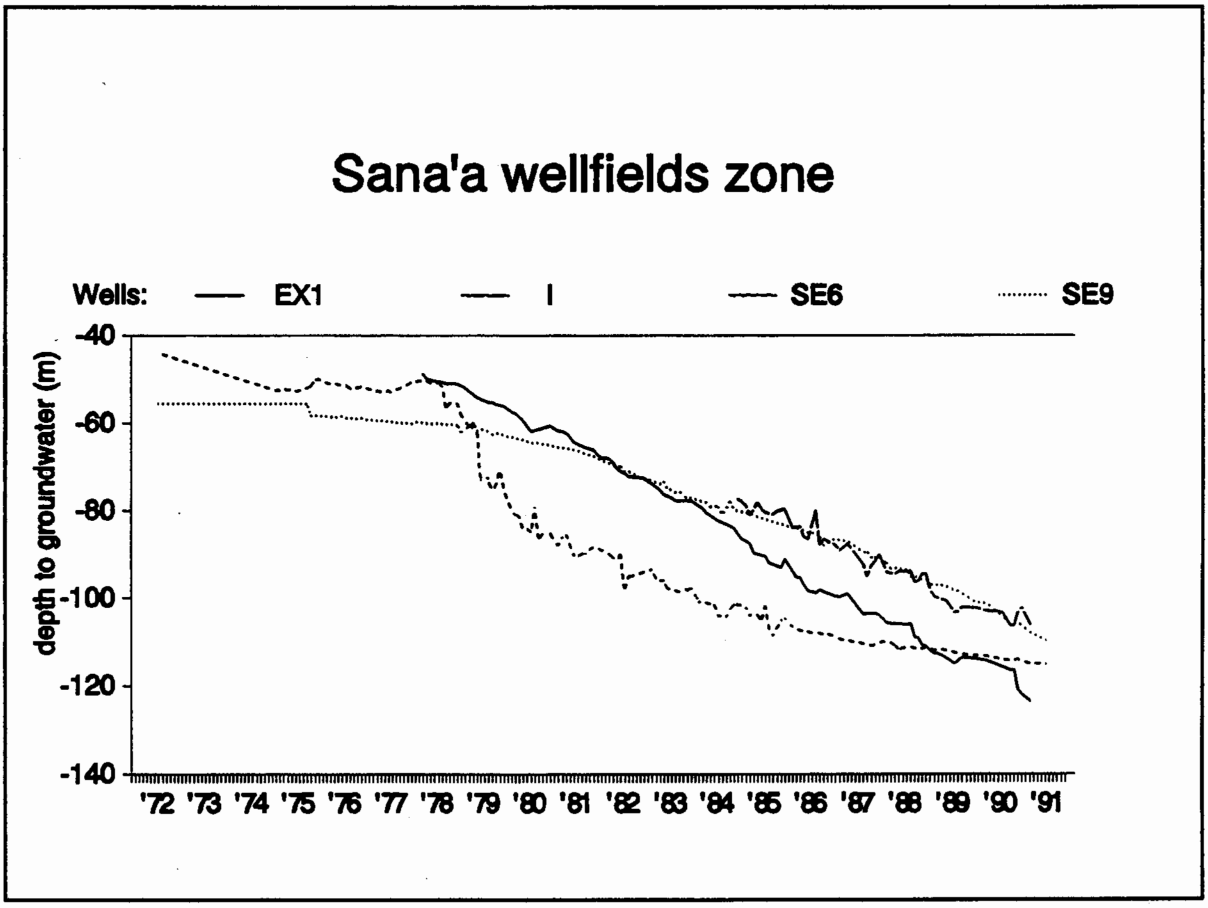


Figure 6.9 Changing groundwater levels in the Sana'a basin

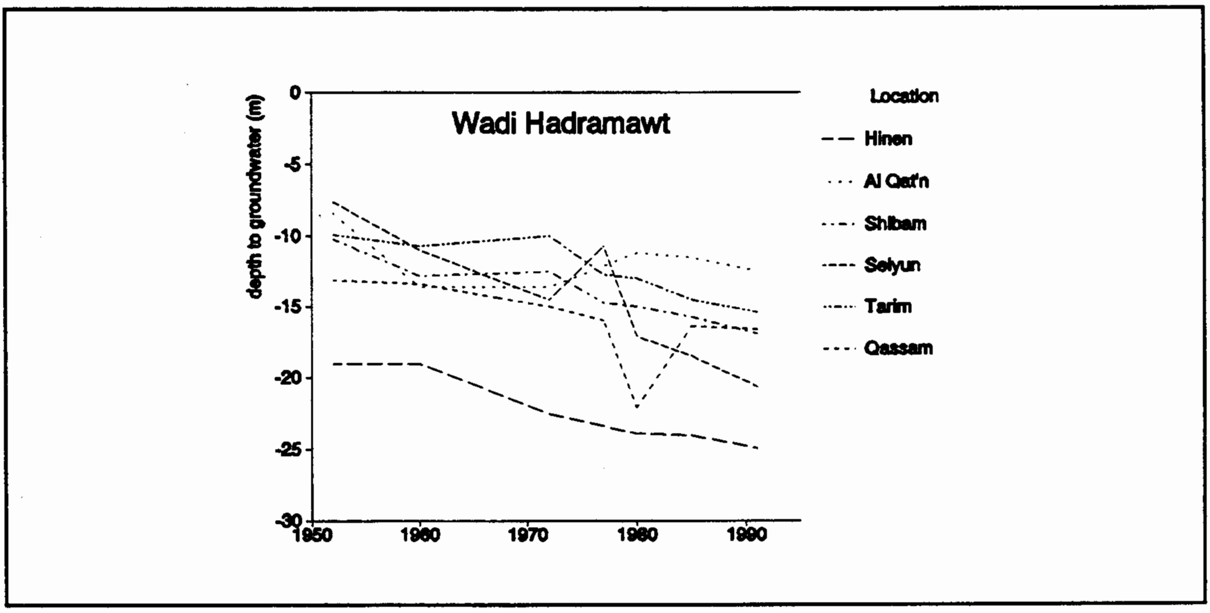


Figure 6.10 Groundwater level trends in Wadi Hadramawt

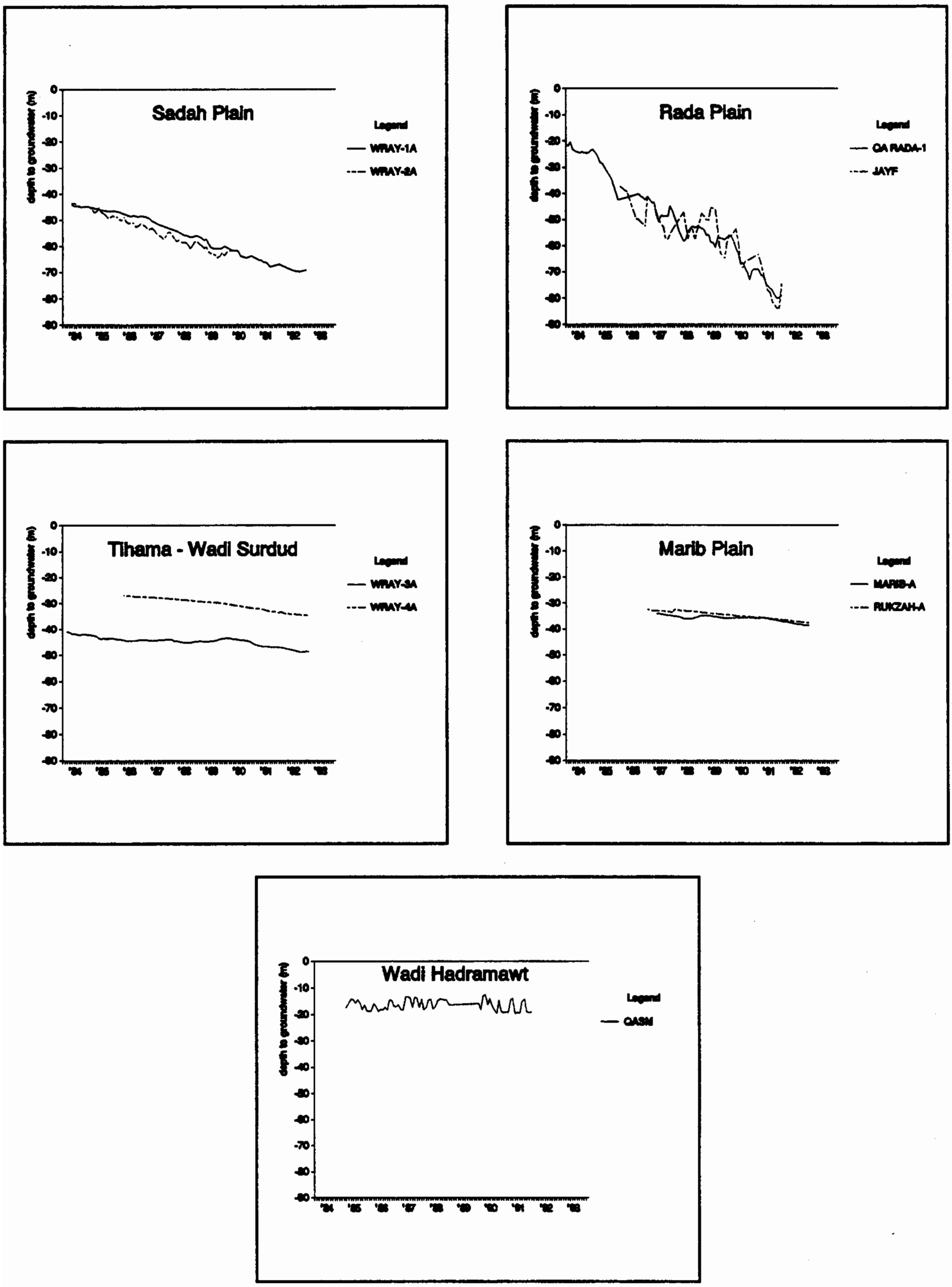


Figure 6.11 Selected groundwater level hydrographs

only area where groundwater levels are falling rapidly. The phenomenon is generally observed in all monitored areas, as Figure 6.10 and Figure 6.11 show.

Declining groundwater levels may initially have favourable side-effects, such as reducing unused natural groundwater discharge of groundwater and terminating salination processes in zones where groundwater used to be very shallow. One of the more immediate negative effects is that springs and traditional water works such as the ghayls in the Sana'a area will dry up. Over time, the negative side-effects gradually become increasingly dominant and harmful. They range from higher groundwater abstraction cost to physical exhaustion of the aquifers. This is already being felt very severely in many areas in Yemen. In special cases the changing groundwater regimes will have groundwater quality implications as well. This is particularly the case in coastal aquifers, where connate saline water may upcone under the wells, and where high abstraction rates may trigger sea water intrusion. In closed basins where groundwater outflow has ceased because of declining groundwater levels (e.g. the Sadah basin) there may also be salinity problems on the long term, because the dynamic salt balance of the groundwater system has changed.

6.5 Groundwater quality

Groundwater quality has not been studied in great detail in Yemen. In most studies the quality of groundwater has been assessed in terms of its suitability for intended use as irrigation water or drinking water. This means that the main interest is usually in the degree of mineralization of the water encountered. Many electrical conductivity measurements have been done for this purpose in almost all parts of the country. As a result there is a reasonable picture of the occurrence of fresh and brackish/saline groundwater in the country. Figure 6.1 shows some of the main features. An indication of regional characteristics was already given in section 6.3.

Standard hydrochemical analyses are known for only a limited number of sites in the country. They confirm general expectations on the hydrochemical evolution of the groundwater based on the Chebotarev sequence or related concepts (see e.g. Freeze and Cherry, 1979). Groundwater in recharge zones is almost always a $Ca(HCO_3)_2$-type water of low mineralization. Downflow there is a gradual increase of dissolved solids, and sulphates and chlorides become more prominent and eventually dominant in groundwater evaporation zones. In coastal areas there is an additional influence of connate or intruded sea water, which involves mixing and ion exchange processes. The changing groundwater regimes under heavy abstraction may be a factor of great importance for coastal water quality, as has been pointed out in section 6.4.4. A graphical illustration of groundwater types found in different areas is presented in Figure 6.12.

Thermal waters usually have an anomalous chemical composition. Some data are provided by Dowgiallo (1986). The 'Hammam Ali' sample shown in Figure 6.12 (Dhamar Montane Plains) is an example of a thermal water.

Groundwater pollution has not yet received much attention in Yemen. This does not mean that it is not relevant. On the contrary, it may be assumed that intensive return

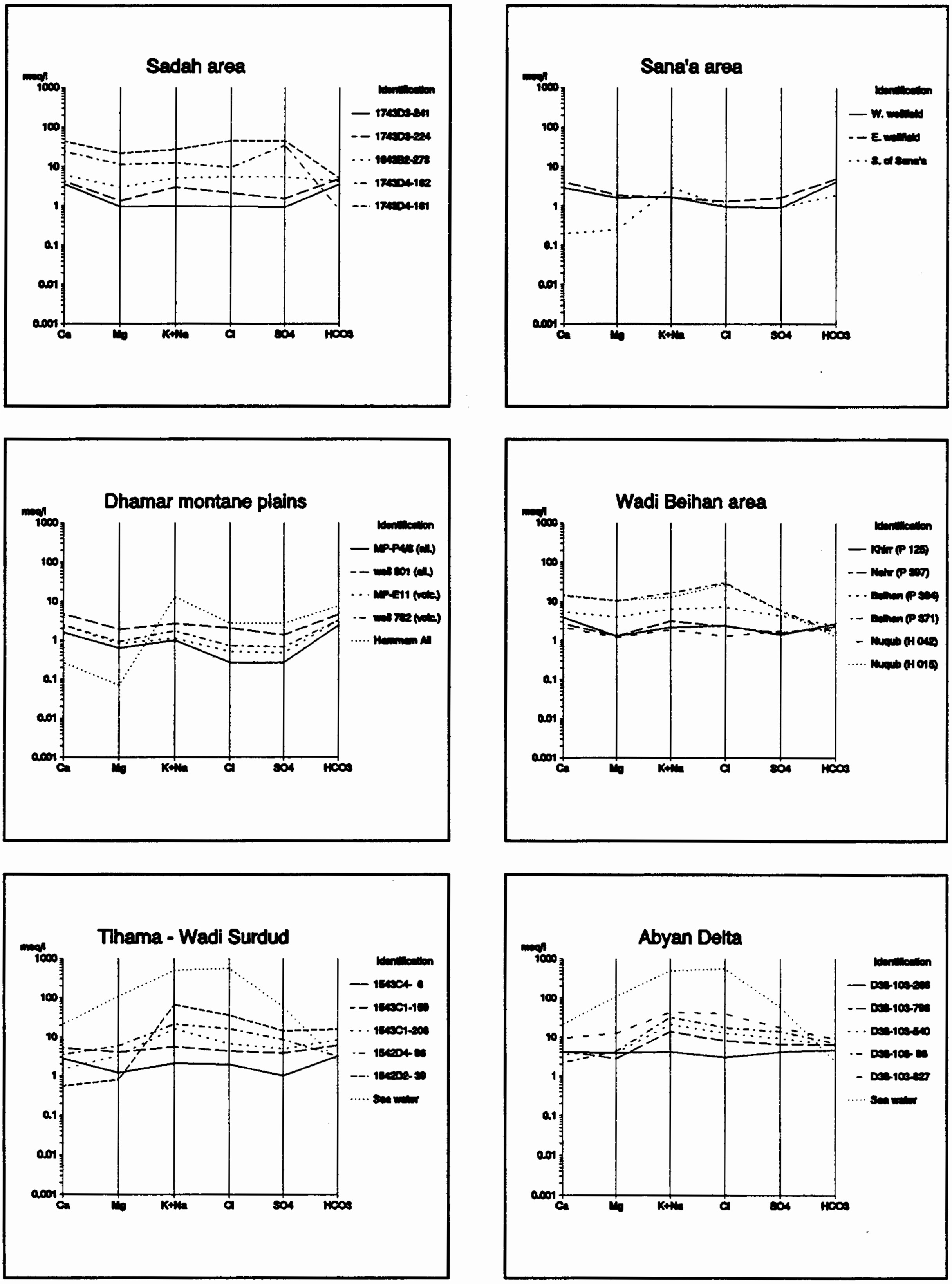


Figure 6.12 Groundwater chemistry of selected groundwater samples

flows of groundwater used in irrigation will profoundly change the quality of shallow groundwaters. And groundwater pollution in urban zones is already perceptible in Yemen too, as several reports testify. For instance, Al Eryany and Ba-Issa (1989) mention increased nitrate levels and bacterial contamination in NWSA's wells along the Marib road near Sana'a, and they refer also to other cases of groundwater contamination in the Sana'a area. Sewage water from Sana'a evacuated to the waste water stabilisation ponds near Rawda is already contaminating the groundwaters downflow. Nevertheless, this sewage water constitutes only a minor part of the domestic waste water. Approximately 90 % of the urban population of Sana'a still depends on cess-pits for the disposal of domestic waste water, which is also a severe threat for the groundwater quality. Al Hamdi (1994) studied in this context groundwater pollution in Sana'a city, on the basis of water samples taken from 100-300 m deep boreholes; his focus is on deeper groundwater because of its relevance for domestic water supply. He concludes that the nitrate levels almost anywhere in Sana'a city are above the normal 'background' concentrations, but with extremes (105-160 mg/l) in the central part of the city. The high nitrate concentrations are associated with high chloride levels and high EC values.

7 WATER RESOURCES DEVELOPMENT AND MANAGEMENT

7.1 Ancient and traditional water resources development systems

Impressive remains of ancient water resources engineering structures can still be admired in Yemen, and several traditional methods of water resources development and use have not only survived for many centuries, but also continue to play an important role today.

The best known hydraulic structure of ancient Yemen is undoubtedly the *Great Dam near Marib*. Interesting accounts on this Sabean dam and the related irrigation system are presented by Brunner and Haefner (1986) and by Schmidt (1987). They mention that the thickness of the irrigation sediments in the Marib Plain suggests that irrigation took place there as early as the second or even late third millennium BC. The construction of the Great Dam in the sixth century BC was apparently preceded by a long period of steady development and perfection of irrigation engineering; remnants of older engineering works are silent witnesses. The Great Dam near Marib was constructed at the narrowest part of the bed of Wadi Adhana, where this wadi leaves the gap cut in the limestones of Jabal Balaq and enters the wide Marib Plain. It had a length of 680 m and was 16-18 m high in the centre of the wadi.

The dam was designed as a flood control dam: it was intended not to store water, but to control the floods and divert them immediately to the irrigation canal networks on the northern and southern banks. The diversion took place at the northern and southern intake structures of the complex at the dam site (see Figure 7.1), which have survived till the present day. The water of the floods there was routed through a stilling basin and entered from there the main canals leading to the irrigated 'Northern' and 'Southern Oasis'. The structures and main canals were designed in such a way that operation by people was only needed at the field level. The system itself could largely handle the floods of Wadi Adhana, down to the tertiary level. This was made possible by a number of structures, such as spillways at the main intakes of the northern and southern sluices, structures to distribute the water over different secondary canals, and drop structures to bring excess water from the canals back into the wadi. The irrigation method involved ponding the fields with at least half a metre of water. The water carried fertile silts to the fields and the excess water percolating through the soil prevented soil salinization.

The extent of irrigation silts present in the area - still visible ten years ago - indicates the area cultivated under the Sabeans, some 9600 ha. This is more than the extent of simultaneously irrigated lands; it is estimated that the system served a maximum area of approximately 5600 ha.

The system was in use until the beginning of the seventh century AD, thus for approximately 1200 years. Its apparent success could not have been achieved without a well-organized society with firm political leadership and an advanced technical level. The dam was washed away and rebuilt several times, which required huge efforts. The final collapse -which is mentioned in the Holy Koran, Surah XXXIV (Sura Saba)- marks an abrupt socio-economic decline of the area, accompanied with massive migration of the farmers. It must have been preceded by a decline in political strength. Until recently,

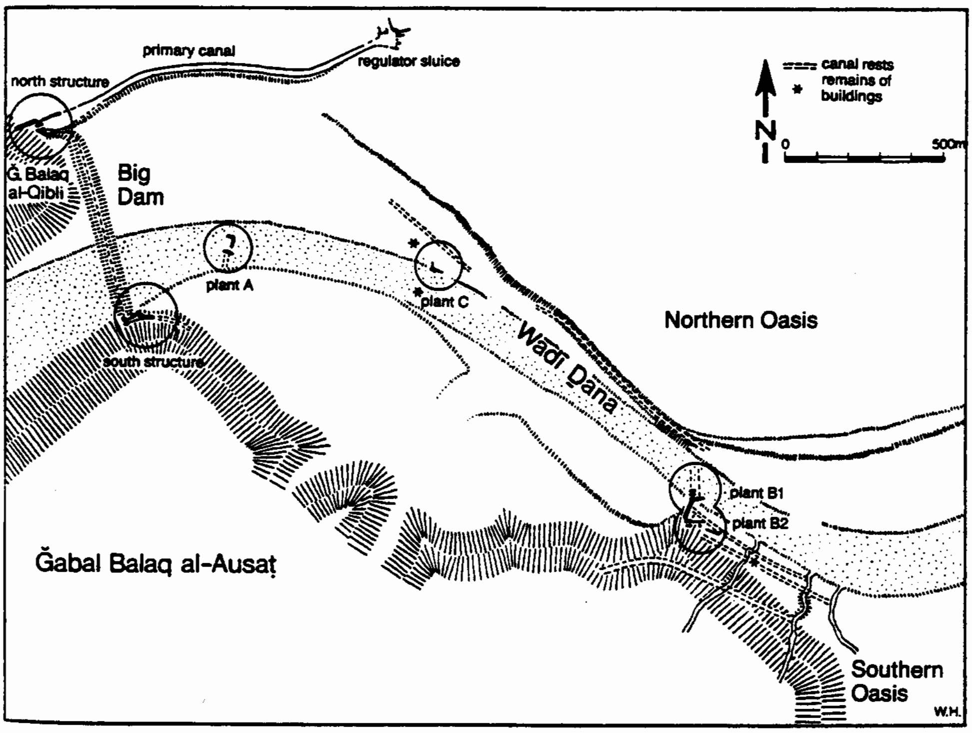


Figure 7.1 The ancient Marib dam (Schmidt, 1987)

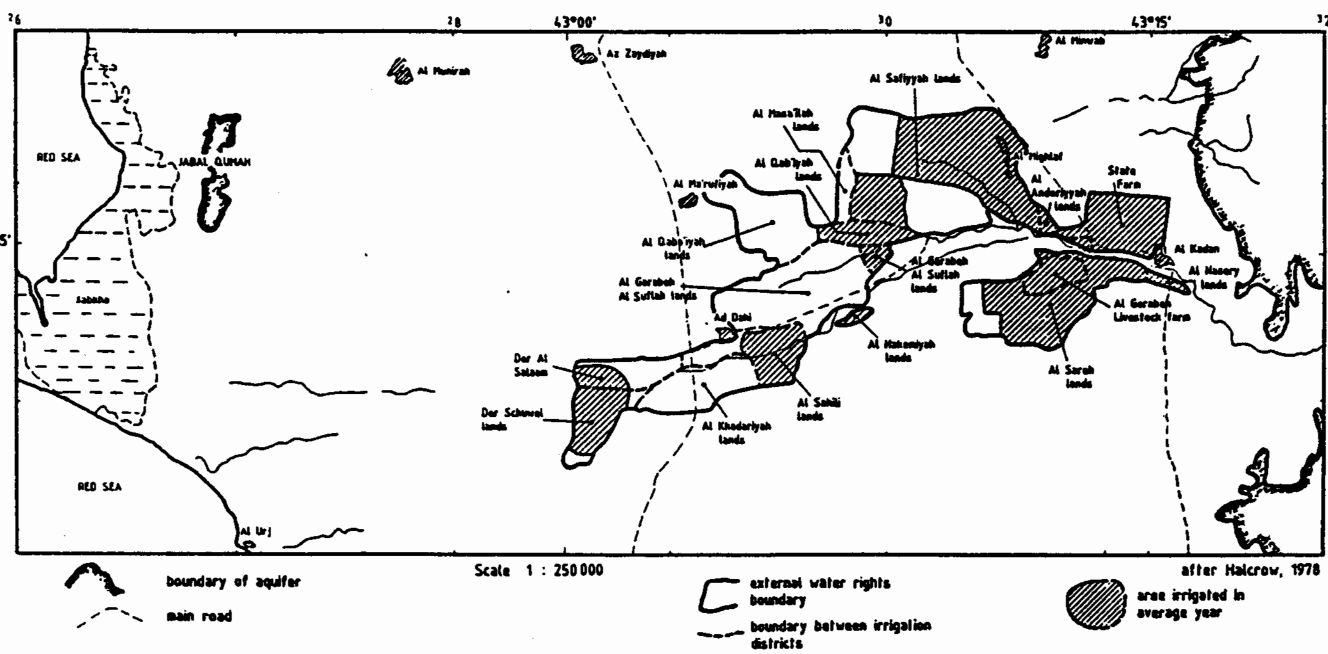


Figure 7.2 Spate irrigation command area of Wadi Surdud (Van der Gun, 1986a)

the floods of Wadi Adhana had ceased to be controlled, and cultivation of crops was mainly based on traditional spate irrigation, encompassing some 3900 ha by 1980.

Traditional spate irrigation is practised widely in the plains in which major wadis debouch. The wadis there have no baseflows as a rule. Spate irrigation is based on the diversion of the occasional floods (*spates* or *sayls*) that reach the plain. These floods are uncontrolled, unpredictable and sometimes devastating. A number of non-permanent earthen deflectors and cross-dams several metres high have been erected in the wadi bed to divert the flood water to the agricultural lands on either side of the wadi. These diversion works are washed away during high floods, which to a certain extent prevents too much water from entering the main intake canals. The deflectors or cross-dams are sometimes deliberately breached to allocate more water to the downstream parts of the command area, after the corresponding upstream irrigable lands have received a reasonable share of the water.

Allocation generally follows the traditional principle prevailing in Islamic countries: upstream areas take water before the immediate area downstream and higher land receives water before lower-lying land. The magnitude of the floods is usually such that they cannot be handled by one diversion at a time, and thus in most wadis there are arrangements for a proportional allocation among the units of irrigated lands located in the upstream part of the command area. The lands within these zones commonly receive water at least once a season, but the moment they get it is difficult to predict. In contrast, the lands at the tail end of the command area receive water only once in several years. This results from the variability of the flood regime of the wadi, the posteriority with respect to allocation, and the huge infiltration losses the floods experience on their way down the permeable wadi bed.

Canal systems are usually poorly developed in traditional irrigation systems, probably because of the partially uncontrolled intake of water, and field-to-field application is usually applied. The water is applied directly to the fields adjacent to the main canals, where it is ponded inside 0.5 to 1.0 m high bunds; after having saturated the soil there sufficiently, a bund is breached to allow the water to enter the next field.

Traditional spate irrigation is characterized by low technical and economic efficiencies, and allocation is often a cause of conflicts between the farmers from different zones within the command area. The farmers in a traditional spate irrigation system face great uncertainty as to whether and when they will receive water, and after planting they are sometimes obliged to have the flood water passing over their land again in order to satisfy the water demands of lower fields on one field-to-field run. They tend to cultivate sorghum mainly, which is relatively resistant to drought and to excessive flooding. Traditional spate irrigation systems are at least one thousand years old in several wadis of Yemen. The systems lack a centralized management; operation is by the collectivity of farmers, with officials assigned for conflict resolution. Interesting descriptions are given, among others, by Halcrow (1978) and by Maktari (1971); they describe the spate irrigation systems of respectively Wadi Surdud and Wadi Tuban. It seems that the systems and their operation remained without significant technical innovations over many centuries, until wadi improvement projects were undertaken during recent years (see section 7.2).

Spate irrigation command areas are usually several times larger than the area actually irrigated in an average year (see Figure 7.2). Assuming that the total extent in hectares is adapted to the wadi's runoff regime, the total command area gives an impression of the volumes of water available during an exceptionally wet year. The factor limiting agricultural development in spate irrigated zones is water, not soils. The spates carry always substantial quantities of sediments in suspension. For that reason they are not used to supply domestic water, but only for irrigation.

The *Aden Tanks*, located north of Crater, are an example of another approach to make use of the available surface water. They consist of 17 cisterns dating from the Himyaritic or Sabean period, partly cut into the lava rocks, partly built from stone. They catch runoff from the small catchment of Wadi Tawila on the slopes of Jabal Shamsan. The cisterns have a total capacity of approximately 45 000 m^3. They were rehabilitated in 1856 by the British, and used to supply drinking water to Aden city. At present they no longer have this function; the water caught is used for watering city lawns and gardens (Wald, 1980; Piepenburg, 1987).

The use of *cisterns* to catch runoff from relatively small catchments is widespread over Yemen. In olden days these cisterns used to be important for drinking water supply in remote areas where groundwater or baseflows are not readily available. Some cisterns were built to store water from springs, e.g. the large cistern at Hadda. Traditional cisterns in Yemen are usually rectangular in shape, with a storage capacity of up to a few hundreds of cubic metres. They are commonly lined with stones and cement, and the larger ones have flights of steps for easy access.

Wherever *baseflows* occur in wadis they are used for irrigation and domestic water supply. Base flows are much easier to handle and use than the spates produced by the wadis. They contain no suspended sediment and their flows are very predictable. On the other hand, the mineralization of the baseflow water is systematically higher than that during spates. On a national scale, the volume of baseflow is much smaller than that of the spates. Only a few wadis -mainly the major wadis in the Red Sea basin- have baseflows that are almost equal in volume to the direct flows.

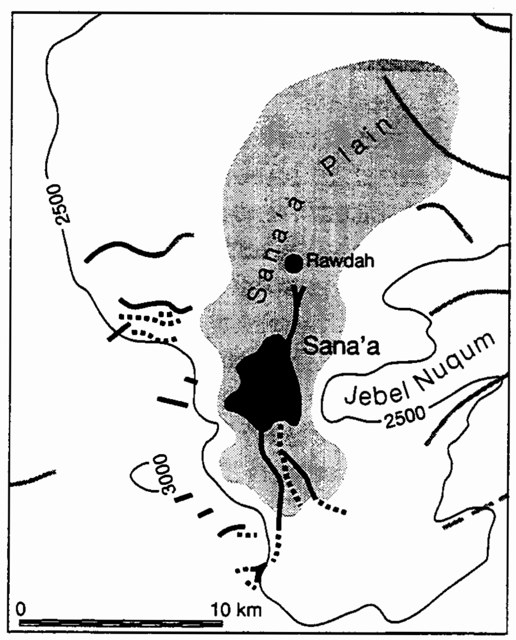
Given that baseflows are usually present only in rather narrow wadi valleys, it is commonly observed that the scarce irrigable lands (on the river terraces) rather than the flow rates limit the extent of baseflow irrigation. The number of baseflow-irrigated hectares in Yemen is estimated to be less than one-tenth of the area under spate irrigation.

Springs occur in many zones of the country and it is mostly very simple to use their water. Their yields are normally small and constitute a minor source of the regional water resources used; except for a zone like Wadi Ahjar (in the upper part of the Wadi Surdud catchment) where they are abundant and constitute the major source of water developed.

The *ghayls of Sana'a* constitute another remarkable type of water resources development works in Yemen. A *ghayl* or gallery is comparable to the Iranian *khanat* and the Omani *falaj*; it taps groundwater and conveys it by gravity over distances of several kilometres. The ghayls consist partly of tunnels a few metres below ground surface, partly of open canals running two or three metres below the general surface level. Descriptions of the ghayls of Sana'a are presented by Serjeant et al. (1983) and by Jungfer (1987). The ghayls of Sana'a are very old: the first known account of their existence is from 799 AD, but they are probably older. Figure 7.3 shows the location of known ghayls in the Sana'a area. A few long southern ones (Alaf, Al-Barmaki, Al-Aswad) bring water to Sana'a; a few others (Al-Mahdi, Al-Mansur and Abu Talib) convey water from Sana'a to Rawdah. The latter ones prove that groundwater levels in the centre of Sana'a used to be shallow in ancient times. Most of the water was used for irrigation, but in Sana'a city it was also used for religious ablutions at the mosques and for domestic purposes.

Conveying water from a certain populated zone to somewhere else, where it is used by other people, requires a powerful ruler. It is known that some of the ghayls were destroyed several times. The major efforts related to the excavation and maintenance of the ghayls suggest that benefits of the water were rated highly. The total flow of the ghayls that run into and from Sana'a city must have been several hundreds of litres per second; nowadays they are completely dry and abandoned, as a result of lowered groundwater levels.

Ghayls are also known to exist or have existed in other parts of the country, e.g. at Al Janad near Tai'zz and in the catchment of Ghayl ba Wasir in the coastal area of Hadramawt. Their role in the past and at present has not yet been assessed.



7.3 Ancient ghayls in the Sana'a area (after Jungfer, 1987)

Dug wells are the most common traditional way of developing groundwater. There are many thousands of dug wells in Yemen. These wells have diameters between 0.6 m and 1.5 m and extend to a few metres below the local static groundwater level. Dug wells as deep as 60 metres are known in Yemen, but most are much shallower. The dug wells are commonly excavated in alluvial material. Depending on local conditions they are unlined or have a simple lining made of large stones, or -more recently- concrete rings. Until about 25 years ago there were no power-driven pumps available and water was abstracted by hand or by animal traction, using the bucket-and-rope method. Donkeys or camels were used to lift the buckets or goat-skins filled with water to irrigate small fields in the surroundings. The paths along which these animals had to move are still visible near many of the wells, and they give an indication of the depth to groundwater in those days.

Water harvesting is a traditional and often skilfully applied method of water resources exploitation in many zones of Yemen. It is based on collecting and retaining overland flow in zones where soils permit agriculture. The receiving zone ('run-on zone') is always smaller than the zone where overland flow is produced ('runoff zone'), thus a multiplier effect is produced which enables agricultural production in low precipitation zones. The numerous *man-made mountain terraces* that cover considerable parts of the Western and Southern Slopes collect and retain rains and overland flow in a similar way. They are surrounded by walls of stones, not only to retain water but also to prevent the soils being washed away. As a result there are large extents of green agricultural lands on the mountain slopes during wet periods, the 'Hanging gardens of Yemen' (Milroy, 1990).

7.2 Modern water resources development

7.2.1 A revolution in groundwater resources development

Political change and general economic development during recent decades have introduced many technological innovations. Three of them contributed to an unprecedented change in groundwater abstraction and use: the introduction of power-driven pumps, the arrival of drilling rigs, and systematic field studies for groundwater exploration.

The introduction of powerful pumps had an enormous effect on the volumes of water abstracted from a single well. The use of drilling rigs enabled much deeper wells to be made, normally in much less time than the dug wells and at a competitive cost. It also allowed wells to be constructed in hard-rock formations where digging is difficult or impossible. Modern groundwater exploration techniques revealed the existence of several thus far unknown aquifers in consolidated rocks. Examples are the Tawilah Sandstone aquifer in the Sana'a Plain and the extensive Mukalla Sandstone aquifer.

The combined effect has produced a revolution in groundwater abstraction. Farmers have been especially active in this development. The number of irrigation wells has rapidly increased during recent decades, and the volumes of groundwater used for irrigation have increased even more. Figure 7.4 shows the increase in the number of wells in Tihama during the period 1973-1987; a similar rapid growth of the number of wells can be observed in many other zones of Yemen.

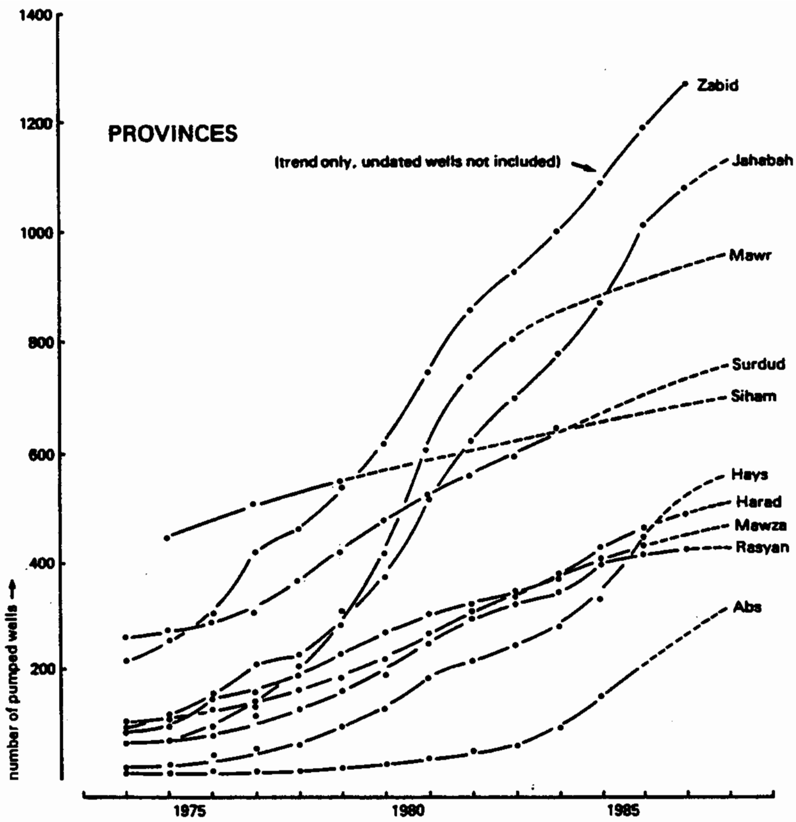


Figure 7.4 *Increase in the number of wells in the Tihama, period 1973-1987 (Source: DHV, 1988d)*

A very significant increase of groundwater abstraction has taken place in virtually all densely populated areas of Yemen. Groundwater abstracted by means of pumped wells there has become by far the most important source of water for irrigation. It is a profitable source of water, and -above all- on the short term a reliable one due to the large volumes of groundwater in storage.

7.2.2 Modern projects for developing surface water resources

Surface water development has also been modernized since the 1970s in several zones of the country. The modernization focuses mainly on the construction of hydraulic works, many of them to replace those of traditional spate irrigation systems.

Spate irrigation improvement projects have been carried out in the zones of Wadi Tuban, Abyan Delta, Wadi Zabid, Wadi Rima and Wadi Mawr. General characteristics of these projects are the construction of spate breakers, permanent diversion weirs, lined canals and auxiliary structures. They are intended to improve the control of the spates, to reduce the almost continuous and huge needs for reconstruction and repairs of diversion works and canals inherent to the traditional spate irrigation systems, and to improve the efficiency of the systems by reducing losses of surface water. The new systems meet these objectives to a certain extent, but they have paid relatively little attention to aspects other than structures and canals. An important change with respect to the traditional spate irrigation systems is the mode of operation and water allocation. Whereas this used to be directly in the hands of the groups of farmers benefiting from the spates, it is now the responsibility of a governmental organization in the new ('improved') spate irrigation systems.

The *Marib Dam and Irrigation Project* brought about a radical change in surface water development and use in the Marib area. Under this project a new dam was constructed during 1984-87 on the Wadi Adhana, a few kilometres upstream of the site of the ancient dam. The concept of this new dam is quite different from that of its famous predecessor. Whereas the ancient dam was a flood control dam constructed to divert the spates of Wadi Adhana directly to the agricultural lands, the new one is a storage dam intended to create a reservoir from which to supply irrigation water in a completely regulated way. The capacity of the reservoir is 400 Mm^3, or twice the average annual catchment yield as estimated by the designer. The objective of the Irrigation Project was to irrigate an overall area of about 6800 ha by means of integrated development of surface water and groundwater (World Bank, 1988), with shares of respectively 57 % and 43 % of the total volume of water supplied. Primary canals have been completed according to design and also part of the secondary canals. Numerous problems have delayed and frustrated the completion and successful operation of the new system. A major problem is that the average annual catchment yield appears to be much lower than was assumed by the design. The hydrological record obtained thus far shows that it is probably even less than half of the assumed 200 Mm^3/year (see Chapter 5).

Small dams are an element in several water and land development projects carried out in recent years. Opinions differ as to their potential significance and merits. It seems that sofar they are only of local importance.

7.2.3 Public water supply

The city of Aden was the first *urban centre* of Yemen to have a *piped water supply system*. It became operational in the late 1930s. The system was fed by a well-field at Sheikh Othman and served a limited part of the Aden population. Only since the beginning of the seventies have there been significant efforts to organize adequate municipal water supply systems in all urban centres. In the former PDRY the Public Water Corporation (PWC) became responsible for urban water supply and sanitation (around 1970), whereas a few years later a similar task was given to the National Water and Sewerage Authority (NWSA) in the former YAR. After the Unification of 1990 both organisations were merged to form a new NWSA.

Public water supply in the urban centres has expanded considerably in recent years. Table 7.1 presents the quantities supplied in 1990 or 1991 in the main urban centres. The

Table 7.1 Public water supply in the main urban centres (1990 or 1991 data)

City or town	no. of connections	connected population	% of population connected	production (Mm^3/year)	average consumption (l/cap/day)
Northern cities/towns (1990 data)					
Sana'a	49 000	392 000	62	8.50	59.4
Tai'zz	26 980	215 800	89	3.18	40.0
Hodeidah	23 540	188 300	94	4.09	59.5
Ibb	4 400	35 200	67	0.59	45.7
Dhamar	7 000	56 000	81	0.95	46.4
Hajjah	2 820	22 560	47	0.40	49.0
Subtotal	*113 740*	*909 860*	*73*	*17.71*	*53.3*
Southern cities/towns (1991 data)					
Greater Aden	55 329	443 000	94	30.48	185
Al Hotta (Lahej)	9 894	80 000		2.12	73
Tor Al Baha	2 977	24 000		0.35	40
Al Dhali	3 670	29 000		0.40	37
Mukalla	15 676	125 000	90	5.23	115
Al Ghayl	4 995	40 000		0.71	48
Al Shaher	4 606	36 800		0.62	46
Seyun	9 977	80 000		2.14	73
Subtotal	*107 124*	*858 200*		*42.05*	*134*

After TS-HWC (1992f) on the basis of data supplied by NWSA and PWC.

number of people served is estimated on the basis of eight persons per connection. Note that the annual volumes of water supplied to the southern urban centres is more than twice the supply to the northern centres, in spite of a smaller urban population. The level of service in the southern centres is higher than in the northern towns and cities, with a greater percentage of people connected and a higher per capita consumption. Several urban centres in the north -such as Sana'a and Tai'zz- have serious water supply problems. Many people there have to rely partly or completely on private supply systems.

All the urban water supply projects use groundwater. Depletion of the groundwater resources is creating problems in several urban centres. Groundwater salinity problems are affecting the wellfield of Hodeidah and some of the wellfields of Aden. Groundwater pollution is another threat to the groundwater resources used for urban water supply.

Rural water supply projects are widespread over the country. They rely almost entirely on groundwater from wells.

7.3 Current water use and future water demands

Table 7.2 summarizes the estimated volumes of water used or consumed in 1990, and presents prognoses of water requirements in the year 2010. The current (1995) overall water use is probably some 8-10 % higher than the 1990 estimates.

Table 7.2 Total water use (1990) and future water requirements (2010), in Mm^3/year

	Northern governorates		Southern governorates		Total country	
	1990	2010	1990	2010	1990	2010
Agriculture	1577	1991	1123	1337	2700	3328
Manufacturing & mining	14	44	17	46	31	90
Municipal	119	426	49	126	168	552
Total	1710	2461	1189	1509	2899	3970

After TS-HWC (1992e)

The estimates of future water demands in the year 2010 are based on assumed growth scenarios described in TS-HWC (1992e), and thus are extrapolations of current trends. There is much uncertainty involved, thus the data are only indicative of the order of magnitude.

7.4 Towards water resources management

7.4.1 Water resources management issues

Many changes have occurred during recent years in Yemen with respect to water resources development and use. It is beyond any doubt that the increased water use in agriculture and in industry has raised the economic output significantly (by reducing risks and by allowing larger production scales). And it is also unquestionable that the newly established public water supply systems are a major contribution to the general well-being of the population. The benefits obtained thus far are motivating forces behind the further expansion of water resources development.

But after the initial enthusiasm fed by the short-term benefits of the new water development activities it has gradually become clear that successful and sustainable exploitation of the water resources is threatened by many problems. Recognizing these problems in time, making a correct diagnosis, and choosing and implementing appropriate solutions are indispensable steps that must be taken to ensure sustainability of the country's precious water resources. Key factors underlying most of the problems are the limited availability of water (because Yemen is and will remain an arid country) and the rather high population density in Yemen: together, they result in scarcety of water.

The most serious and obvious problem is the *rapid depletion of groundwater resources*. Many studies and inventories carried out in recent years have revealed that almost all important groundwater systems in Yemen are being overexploited at alarming rates. Continuing groundwater monitoring confirms predictions made during many assessment studies (see Chapter 6). Among the most critical areas are the Sana'a basin, the Rada basin and the Sadah basin. During the mid-1980s groundwater depletion in the Sana'a basin triggered an emergency situation with regard to the public water supply of Sana'a city and made it clear that other sources of water have to be found to ensure adequate urban water supply in the near future. Worst-case predictions made in 1985 on possible depletion of the Wajid sandstone aquifer of the Sadah Plain (Elderhorst and Van der Gun, 1985; Van der Gun, 1985a) have unfortunately come true and groundwater levels have declined on average some 40 metres in only nine years, with far-reaching consequences for well yields and the profitability of groundwater-based irrigation (DHV, 1993m). Similar trends can be observed elsewhere, especially on the Yemen Highland Plains, where groundwater abstraction rates are commonly several times the average rates of natural groundwater recharge (see Chapter 6).
The socio-economic consequences of groundwater resources depletion are dramatic: groundwater will become too expensive for use in agriculture (in certain zones it may even run out); as a result, regional agricultural economies based on groundwater irrigation are doomed to collapse, if the water resources are not adequately controlled. There is an increasing awareness in Yemen regarding the problem of groundwater deletion.

The stocks of usable groundwater may be further reduced by *groundwater salination* and *groundwater pollution*. The former hazard is particularly present in coastal aquifers, the latter one in urban areas (see section 6.5) and in areas of intensive agriculture. Proper water resources management measures may reduce these risks and protect the groundwater resources.

Environmental impacts of water resources development have to be taken into account as well. An eloquent example is the environmental degradation of the village of Hadda south of Sana'a after the springs there dried up a number of years ago. Although not intended, this drying-up is the result of groundwater development in the region.

The general scarcity of water triggers an *ever-increasing competition for water*. This kind of competition does not produce efficiency or optimal conditions. On the contrary, uncontrolled competition for water will probably lead to socio-economic problems (inequitable distribution of the profits from water, economic collapse in the long run).

7.4.2 New roles for the government

New or technically modernized water resources systems - such as the new Marib Dam and Irrigation System, improved spate irrigation systems, small dam schemes, and public water supply systems - create new conditions for the communities of people concerned. In many cases they imply a greater role for the government than before. Successful interplay between government officials and the beneficiaries of the system requires great efforts from both sides. Monitoring is necessary to ensure that optimal results are obtained and that conflicts are properly solved.

Although inaccurate, the figures on water resources availability and water demands mentioned in this report show that there is an increasing incompatibility between the demand for water and the rate of renewal of the water resources. This is already clear at a national (averaged) level, but the lack of balance is even more acute if one considers selected areas of high population density and strong economic activity. The Government of Yemen, however, has committed itself to a sustainable use of the water resources, which was reiterated in an official statement issued on the UN Conference on Environment and Development held in 1992 in Rio de Janeiro. This task is not easy. The finiteness of the water resources and the high water demands dictate that *demand management* will become unavoidable. Hence, difficult allocation problems will have to be solved, including the reduction of water allocated for purposes that yield low economic returns and sacrificing present gains to preserve benefits for future generations; groundwater pumping will have to be controlled effectively; efficiencies of water use will need to be enhanced, and very substantial efforts will be required to protect the resources from salination and pollution.

There is growing awareness that issues like the ones mentioned in section 7.4.1 call for centralized control. This is a logical consequence of the fact that water is a *common property resource* which to a large extent is used privately; under such conditions private preferences tend to diverge from societal preferences. The government of Yemen is currently considering the creation of a *water resources management authority.* Such an authority should develop and establish sensible and valid principles for the allocation of the scarce water resources, prepare integrated regional water resources management plans, carry out environmental impact studies, implement the measures indicated in the plans, and monitor the changing state of the water resources systems. It should be supported by a legal framework and related regulations (see TS-HWS, 1991b and 1992b; and Task Force, 1992).

The need for water resources management also triggered a number of water resources management studies during recent years. Examples are those carried out by the WRAY project (Van der Gun and Wesseling, 1991; Saif et al., 1993), the TS-HWC (1992i and 1992j) and DHV (1994). They have contributed to the development of planning approaches and to the growth of public awareness of water resources management problems in Yemen.

Measures to be implemented at field level may include the introduction of water-saving techniques (e.g. improving irrigation efficiencies and imposing a water tariff), groundwater licensing, and the enforcement of pollution control regulations.

7.4.3 The role of water resources information

An indispensable input to the process of water resources management is *information* on the nature and state of the water resources of the different regions of the country. This information is not only the basis for the identification of options for water resources development and management. It also allows the intentional and unintentional impacts of measures or projects considered to be predicted at local and regional scales. And it enables the uncertainty of such predictions to be assessed, thus providing sound guidelines for efficient collection of additional data.

If this report contributes to satisfying this information demand, by helping the water resources conditions of Yemen to be understood and relevant data to be located, then it will have achieved its main goal.

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APPENDICES

APPENDIX 1

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APPENDIX 2

Administratative data on hydrological monitoring networks

APPENDIX 2.1

LIST OF RAINFALL AND METEOROLOGICAL STATIONS

(a) Sana'a, Taiz, Hodeidah, Ibb, Dhamar, Hajjah, Al Bayda, Sadah, Al Mahweet, Marib and Al Jawf Governorates

STATION NAME	ORG.	GDH FILE	RAINFALL or METEO	LOCATION			ELEV
				MAPSHEET	UTM N (m)	UTM E (m)	(m)
Abkowr	GDH	ABKOWR	R	1743 D3	1885.350	363.850	1880
Adiat	SAWAS	ADIAT	R	1543 D1	1700.000	364.000	1840
Ahmar, Bayt Al	CAMA	ALAHMAR	R	1544 C4	1672.100	431.940	
Amar	GDH	ALAMAR-A	R	1643 B2	1858.200	371.550	1963
Amir	TDA	AL-AMIR	R	1543 D3	1662.444	360.246	2200
Araqah	MOS	ARAQAH	M	1544 C2	1703.900	444.600	2880
Arqub	MAHWI	ARQUB-A	R	1543 C2	1710.100	338.300	1320
Asal	GDH	ASAL-A	R	1544 D3	1669.620	455.460	2110
Ash'a, Al	MOA		M	1544 C1	1797.000	377.000	1200
Asir Mil.base	GDH	ASR	R	1544 C1	1696.250	409.300	2400
Attius	GDH	ATTIUS-A	R	1445 A1	1631.250	503.250	1625
Azgull	GDH	AZGULL	R	1643 B1	1863.700	355.800	2015
Bab Al-Maljeb	SAWAS	MALJEB	R	1543 D3	1675.000	365.000	1200
Bab Dayan	SAWAS	DAYAN	R	1543 D1	1688.500	361.600	880
Bajil	CAMA	BAJIL	R	1543 C4	1665.900	315.600	185
Bani Sabir	SAWAS		M	1544 A4	1736.950	428.450	2260
Barh	TDA	AL-BARH	M	1343 D1	1487.288	359.268	500
Basat	TDA	BASAT	R	1443 C2	1585.000	324.000	150
Bawn	MAWR	AlBawn	M	1543 B4	1739.766	382.144	2150
Bawn	MOA	ALBAWN1	R	1544 A1	1742.700	394.600	2200
Bayda	MOA	AL-BAYDA	M	1345 A2	1544.500	551.000	2000
Beit Astan	SAWAS	ASTAN	R	1544 A2	1743.500	427.250	2350
Bir Basl	SAWAS	BIRBASL	R	1544 A4	1729.350	443.750	2090
Buqa, Al	CAMA	AL-BUQA	M	1744 D1	1908.438	448.060	1200
Dabaat	CAMA	ADDAB'AT	R	1544 C2	1698.700	432.250	2460
Dabab,Wadi Ad	TDA	ADDABAB	R	1343 B4	1496.300	386.300	1200
Dabira	TDA	ALDABIRA	R	1443 B2	1634.736	369.055	1000

STATION NAME	ORG.	GDH FILE	RAINFALL or METEO	LOCATION			ELEV
				MAPSHEET	UTM N (m)	UTM E (m)	(m)
Dahi	GDH	ADDAHI-A	M	1543 C3	1682.330	290.820	70
Damaj	GDH	DAMAJ	R	1643 B2	1868.400	372.900	1895
Dar Salem	MOS	DARSALM	R	1544 C2	1689.600	420.400	2310
Darb	DAFRD	ADDARB	R	1444 A4	1613.500	430.100	2435
DarNajd	RIRDP	DAR-NAJD	R	1444 D2	1597.000	485.800	2110
Darwan	GDH	DARWAN	R	1544 A3	1719.800	401.000	2440
Dawran	CHRDP	DARWAN1	R	1443 A3	1629.500	414.400	2400
DelilSumara	TDA	ADDALIL	R	1444 C3	1560.801	411.846	1680
Dhamar	RLIP	DHAMAR	M	1444 A4	1606.815	435.354	2360
Dhamar	DAFRD	DHAF	R	1444 A2	1646.800	422.300	2400
Dhamar	DAFRD	DHAMAR-1	R	1444 A4	1607.700	435.500	2420
Dimnah	TDA	ADDIMNAH	R	1443 C2	1588.858	332.858	270
Dumeid	GDH	DUMEID-A	M	1743 D3	1884.600	354.620	1950
Dutrat	MOA	DUTRAT	M	1544 A4	1732.700	442.600	2060
Faqih, Bayt Al	TDA	AL-FAQIH	R	1443 A4	1606.700	317.900	120
Fawwarah	TDA	ALFOWARA	R	1444 A1	1658.000	408.000	1500
Fulayh	TDA	FULAYH	R	1443 D4	1568.550	373.250	800
Gawadir	TDA	GAWADIR	R	1443 D1	1586.967	340.037	350
Ghamr	GDH	GHAMR-A	R	1543 D1	1695.350	344.620	924
GhUjla	GDH	GHUJLA-A	R	1545 C2	1713.480	547.175	1051
Giblah	RDPM	Giblah	R	1543 B3	1714.700	343.000	1140
Gudami	GDH	GUDAMI-A	R	1743 D4	1885.350	371.750	1810
Gumeisha (FAO)	FAO	GUMISCHA	R	1443 A1	1637.700	293.400	45
Habaka/Girnah	TDA	HABAKA	R	1443 D1	1597.900	361.670	900
Habashi	TDA	HABASHI	R	1343 B4	1496.460	368.336	950
Hagag	RDPM	HAGAG-A	R	1543 C2	1695.900	322.500	1400
Haima	TDA	AL-HAIMA	R	1543 D4	1667.858	381.777	1600
Hajar (RIRDP)	RIRDP	AL-HAJAR	R	1444 D1	1582.800	464.600	2600
Hajdah	TDA	HAJDAH	R	1343 B4	1501.965	373.774	1150
Hajjah (MOA)	MOA	HAJJA	M	1543 B3	1738.700	350.400	1300
Hajjah (TDA)	TDA	HAJJAH	R	1543 B3	1734.425	349.959	1650

STATION NAME	ORG.	GDH FILE	RAINFALL or METEO	LOCATION			ELEV
				MAPSHEET	UTM N (m)	UTM E (m)	(m)
Hamal (TDA)	TDA	AL-HAMAL	R	1443 B4	1630.958	386.977	2000
Hamam Ali	TDA	HAMAMALI	R	1444 A3	1619.806	408.465	2000
Harad	MOA	HARAD	M	1643 C1	1816.850	292.650	110
Har,Wadi	TDA	WADI-HAR	R	1444 A3	1605.044	412.002	2000
Haymah,Wadi	NWSA	HAYMAH	M	1344 A1	1524.000	397.500	1650
Hazm, Al	MOA	HAZM	M	1644 D4	1788.000	474.800	1080
Hazm, Al	CAMA	AL-HAZM	M	1644 D4	1792.800	475.200	1080
Hidad	TDA	AL-HIDAD	R	1444 A3	1610.562	415.613	2500
Hijrah	DAFRD	ALHIJRAH	R	1444 A2	1633.200	423.200	2340
Hijrah	GDH	HIJRAH	R	1743 D3	1880.150	346.550	2080
Hijrat Makinah	MOS		R	1544 A4	1724.000	437.200	2240
Hijrat Ma'bar	CHRDP		R	1444 A2	1636.200	423.000	2335
Hisn Shamat	SAWAS	SHAMAT	R	1543 D2	1700.800	374.350	2600
Hudaydah	CAMA	Hudaydah	M	1442 B2	1630.600	280.500	10
Hudaydah	TDA	HUDAYDA1	R	1442 B2	1634.000	280.000	10
Huth	TDA	HUTH	R	1643 D4	1795.046	389.900	1900
Ibb	CAMA	IBB-2	M	1344 A1	1546.000	411.700	1800
Ibb	MOA	IBB-1	M	1344 A1	1544.203	413.589	1760
Ibb	TDA	IBB	R	1344 A1	1546.053	411.795	1800
Irra	MOA	IRRA	M	1544 C1	1709.400	411.750	2200
Jabal Taraf	RDPM	TARAF	R	1543 D1	1707.300	337.100	1000
Jabin	TDA	JABIN	R	1443 B3	1626.000	349.000	2300
Jabri, Bayt Al	RIRDP	AL-JABRI	R	1445 C1	1587.000	507.000	1970
Jannat	GDH	ALJANNAT	R	1543 B4	1734.250	386.700	2250
Jarubah	MOA	JAROUBA	M	1443 C2	1591.150	329.220	150
Jawf	MOA	JAWF	M	1644 D4	1791.300	476.500	1100
Jihanah	CAMA	JIHANAH	M	1544 C4	1683.400	444.500	2240
Jiraf, Al	CAMA		R	1544 C1	1703.000	414.000	2230
Jubah	GDH	ALJUBA-A	R	1545 C4	1666.750	532.000	1300
Juban	RIRDP	JUBAN	M	1444 D4	1548.500	487.000	2060
Jubayr	RIRDP	JUBAYR	R	1444 D1	1577.300	468.300	2290

STATION NAME	ORG.	GDH FILE	RAINFALL or METEO	LOCATION			ELEV
				MAPSHEET	UTM N (m)	UTM E (m)	(m)
Kadan	GDH	ALKADAN	R	1543 C4	1686.650	312.200	170
Kadan	MOA		M	1543 C4	1686.000	313.000	250
Kadima,HaradAl	TDA	ALKADIMA	R	1643 C1	1818.000	292.000	90
Kahal	MOA	KAHEL	R	1543 D4	1664.000	365.000	2400
Kamer	CAMA	KAMER	R	1543 B2	1768.000	388.000	
Kasabat Akwan	GDH	AKWAN	R	1643 B2	1877.650	373.600	1860
Ketab	MOA	KETAB	M	1444 C4	1570.100	428.000	2500
Khabar	RIRDP	KHABAR	M	1444 D2	1590.950	481.060	2140
Khadrah	RIRDP	ALKHADRA	R	1444 D1	1590.400	470.800	2280
Khadrah	TDA	KHADRAH	R	1642 D2	1813.000	283.000	50
Khalifah, Al	TDA	KHALIBAH	M	1443 A2	1646.000	319.000	139
Khamir	TDA	KHAMIR	R	1643 B4	1769.232	389.432	2356
Khamis	GDH	KHAMIS-A	R	1543 D3	1679.280	340.240	520
Khamis	TDA	KHAMIS	R	1543 D3	1679.000	339.000	450
Khamlu	GDH	KHAMLU-A	R	1543 C4	1679.490	330.320	364
Khasha'a	RIRDP	KHASHA'A	R	1445 C1	1586.000	504.000	1960
Khulagah	MOS	KHULAGAH	R	1544 A4	1727.800	438.400	2080
Kudeihah	TDA	KUDAYHAH	M	1343 C2	1492.989	330.429	120
Kudmah Maraiya	TDA	KUDMAH	R	1543 A3	1736.000	306.000	180
Lahimah,Wadi	RDPM	LAHIMAH	R	1543 C2	1707.300	335.400	1000
Lahj	DAFRD	LAHJ	R	1444 A1	1631.900	416.100	2180
Lariud	RIRDP	LARIUD	R	1444 D2	1590.900	481.100	2000
Ma'adi	MOS	MA'ADI	M	1544 A4	1739.900	437.100	1900
Ma'adi, Al	SAWAS	MA'ADI	R	1544 A4	1737.750	442.250	2020
Mabar	DAFRD	MABAR	R	1444 A2	1635.800	423.700	2340
Madaf	RIRDP	MADAF	R	1444 D2	1580.900	480.700	2120
Mafhaq	GDH	MAFHAQ-A	R	1543 D4	1670.260	382.810	1620
Magash	MOA	ALMAGASH	M	1743 D3	1884.300	354.800	1885
Maghreba	TDA	MAGHREBA	R	1443 A2	1644.164	335.030	1200
Mahabisha	TDA	MAHABISH	R	1543 A2	1764.000	332.000	1600
Mahatt	TDA	ALMAHATT	R	1443 C2	1581.596	316.625	95

STATION NAME	ORG.	GDH FILE	RAINFALL or METEO	LOCATION			ELEV
				MAPSHEET	UTM N (m)	UTM E (m)	(m)
Mahwit	TDA	MAHWIT	R	1543 D1	1710.488	344.437	2100
Mahwit	RDPM	MAHWIT1	R	1543 D1	1711.000	344.300	2120
Mahwit	MOA	MAHWIT-2	M	1543 D1	1709.500	353.200	1970
Mai'na	RDPM	MAINA	R	1543 D1	1711.000	340.900	1600
Majhiz	MOA	MAJHIZ	M	1544 C1	1703.150	400.850	2480
Majz	GDH	MAJZ	R	1743 D3	1887.800	348.700	1995
Makarib	MOA	MAKARIB	M	1544 A3	1730.350	416.500	2220
Manakha	MOA	MANACHAH	M	1543 D3	1666.600	364.800	2230
Manakha	GDH	MANAKHAH	R	1543 D3	1666.800	364.700	2280
Manakha	SAWAS	MANAKHAH	R	1543 D3	1666.650	364.770	2280
Manasah	RIRDP	MANASIH	R	1444 B3	1612.300	472.300	2340
Manjidah	GDH	MANJIDAH	R	1544 A1	1743.250	394.700	2200
Mansur,Wadi	RIRDP	MANSUR	R	1445 C1	1592.000	515.000	1880
Maqbanah	TDA	MAQBANAH	R	1343 B4	1510.600	356.000	980
Maqwalah	MOA	MAQWALAH	M	1544 C4	1674.900	430.100	2510
Maram	DAFRD	MARAM	R	1444 B3	1612.800	457.800	2560
Marib	MOA	MARIB	M	1545 C2	1705.000	535.000	1000
Marib	CAMA	MARIB1	M	1545 C2	1710.600	534.900	1100
Marib	MOA	MARIB2	M	1545 C2	1708.000	534.400	1100
Markha	RIRDP	MARKHA	M	1446 A3	1605.500	608.000	1560
Marran, Bayt	MOS		R	1544 A3	1735.000	415.000	2460
Masnaah	TDA	MASNA'AH	R	1444 A3	1620.500	418.700	2000
Maswarah	RIRDP	MASWARAH	R	1445 D1	1586.000	579.000	1900
Mawsanah	MOA	MAWSANAH	R	1543 D3	1669.550	361.000	1360
Mayan	GDH	MAYAN-A	R	1543 D2	1709.460	380.900	2280
Midi	TDA	MIDI	R	1642 D2	1813.500	266.000	10
Mikras	TDA	MIKRAS	R	1543 A4	1730.900	313.800	200
Milh	TDA	AL-MILH	R	1542 B4	1733.752	266.200	20
Mind	CAMA	MIND	R	1544 C1	1690.250	399.650	2700
Mirwah	RDPM	MIRWAH	R	1543 C2	1711.100	331.500	1200
Mishrafah	TDA	MISHRAFA	R	1443 D1	1588.777	345.441	450

STATION NAME	ORG.	GDH FILE	RAINFALL or METEO	LOCATION			ELEV
				MAPSHEET	UTM N (m)	UTM E (m)	(m)
Mokha	CAMA	MUKHA	M	1343 C2	1473.015	309.850	5
Mosalla	RIRDP	MOSALLA	R	1444 D2	1593.600	481.300	2200
Muthef	GDH	MUTHEF-A	R	1743 D3	1882.350	342.800	2500
Na'ta	RIRDP	NA'TA	R	1445 D1	1597.400	558.700	1750
Nagil Sam	GDH	NGLSAM-A	R	1444 B2	1647.590	475.840	1630
Nozaih,Al	TDA	NOZAIH	R	1343 B4	1507.900	367.200	750
Nuqabah	RIRDP	NUQABAH	R	1444 B4	1615.400	496.000	1880
Ossefra	MOA	OSSEFRA	M	1344 A3	1503.600	393.500	1350
Qa'mah	CAMA	AL QAMAH	M	1443 C2	1618.000	331.500	2340
Qadam	MOA	AL-QADAM	R	1543 D3	1671.860	351.970	980
Qadam	GDH	QADAM-A	R	1543 D3	1671.860	351.980	920
Qahmah	TDA	ALQAHMAH	R	1443 C2	1581.494	331.011	180
Qarry	RIRDP	AL-QARI	R	1444 B4	1606.500	497.900	1970
Qarwah	GDH	QARWAH-A	R	1544 D1	1689.375	447.785	2350
Rabu,suq al	TDA	AL-RABU	R	1643 C2	1780.000	301.000	180
Rada'a	RIRDP	RADA'	R	1444 D2	1593.570	483.030	2140
Rahaba	GDH	RAHABA-A	R	1444 B2	1647.310	499.120	1470
Rahban	RIRDP	RAHBAN	R	1445 C2	1584.900	529.900	1980
Raydah	GDH	RAYDAH	R	1544 A1	1748.600	397.100	2190
Rihab	TDA	RIHAB	R	1444 C3	1573.500	411.800	1500
Risabah	DAFRD	DAFRD	M	1444 A4	1626.300	428.000	2318
Rizwa	DAFRD	RIZWA	R	1444 A1	1634.700	409.800	2200
Robei	TDA	AL-ROBEI	R	1343 B4	1501.940	379.185	1250
Ruba	DAFRD	ARRUBA	R	1444 C1	1602.560	393.970	2020
Ruba	TDA	AL-RUBA	R	1643 C3	1780.000	301.000	180
Rubat	RIRDP	RUBAT	R	1445 C4	1560.000	549.000	1980
Rubu Utmah	CHRDP		R	1444 A3	1605.400	394.300	2040
Rujum	GDH	RUJUM-A	R	1543 D1	1709.590	353.320	1970
Rujum	RDPM	RUJUM	R	1543 D1	1709.300	353.100	1940
Sadah	MOA	SADAH	M	1643 B1	1872.400	356.500	1790
Sadah Salam	GDH	SALAM-A	R	1643 B2	1872.650	367.000	1880

STATION NAME	ORG.	GDH FILE	RAINFALL or METEO	LOCATION			ELEV
				MAPSHEET	UTM N (m)	UTM E (m)	(m)
Sadah	CAMA	SADAH1	M	1643 B1	1876.000	365.000	1800
Safaqayn	RDPM	SAFAQAYN	R	1543 C2	1701.000	330.100	2120
Safiah	RIRDP	SAFIAH	R	1445 C1	1595.700	519.500	1890
Sahwah	GDH	SAHWAH	R	1643 B2	1862.600	379.050	1970
Said, Bait AL	TDA	BAITSAID	R	1443 A4	1608.200	334.200	210
Saidiyah	TDA	SAIDIYAH	R	1343 A4	1507.000	334.000	220
Salf	GDH	ASSALF-A	R	1543 D4	1683.400	385.800	2920
Salif	GDH	ASSALIF	R	1542 D1	1694.000	249.900	5
Sama Al Ulya	DAFRD	SAMAH	R	1444 C2	1601.100	444.200	2520
Sama'ah, Al	RIRDP	SAMA'AH	R	1445 D4	1557.000	586.500	2030
Sana'a Airport	CAMA	SANA'A	M	1544 C1	1710.000	416.000	2190
Sana'a Town	VAR	SANA'A1	M	1544 C1	1697.100	416.000	2240
Sana'a	GDH	MINIST-A	M	1544 C1	1696.500	412.400	2275
Sana'a	CAMA	CAMA	R	1544 C1	1697.100	415.100	2216
Sanaban	DAFRD	SANABAN	R	1444 D1	1594.500	463.600	2350
Sanam	TDA	AS-SANAM	R	1444 A4	1610.544	421.000	2400
Saqayn	TDA	SAQAYN	R	1643 B1	1865.409	343.753	2230
Shaharah	TDA	SHAHARAH	R	1643 D3	1793.364	361.046	2200
Shamir, Mahal	TDA	SHAMIRI	R	1443 A2	1657.163	322.570	200
Shaqab	DAFRD	ASHSHAQB	R	1444 C2	1588.000	444.000	2500
Sharaf	RIRDP		R	1445 C1	1586.900	512.000	1870
Sharq	DAFRD	AL-SHARK	R	1443 B4	1618.700	387.320	1300
Sharq	TDA	ASHSHIRQ	R	1443 B4	1619.888	388.721	1500
Sherwab	GDH	SHERWB-A	R	1544 D4	1683.090	497.800	1270
Shibam	TDA	SHIBAM	R	1543 B4	1715.787	381.700	2600
Shoub Farm	MOA	SHU'UB	M	1544 C1	1701.000	417.500	2250
Sirwah	GDH	SIRWAH-A	R	1545 C1	1707.875	502.050	1480
Suar	RIRDP	SUAR	R	1444 D2	1582.000	480.000	2180
Azaydiyah	TDA	ZAYDIYAH	R	1543 C1	1696.000	286.000	60
Sukhnah	TDA	SUKHNAH	R	1443 A2	1638.658	331.404	350
Surby	GDH	SURABI	R	1643 B1	1871.050	359.650	1930

STATION NAME	ORG.	GDH FILE	RAINFALL or METEO	LOCATION			ELEV
				MAPSHEET	UTM N (m)	UTM E (m)	(m)
Taiz Town	VAR.	TAIZTOWN	R	1344 A3	1502.000	393.900	1400
Taiz Yard	NWSA	TAIZYARD	R	1344 A3	1502.260	394.400	1290
Taiz new airp	CAMA	TAIZ1	M	1344 A3	1513.000	406.000	1475
Talab	RIRDP	TALAB	R	1444 D3	1573.000	471.000	2500
Tawilah	RDPM	TAWILA-A	R	1543 D1	1713.800	365.500	2700
Thawban	GDH	THAWBAN-A	R	1444 B1	1632.000	462.550	2130
Therhaan	HARAZ	THERHAAN	R	1543 D3	1666.000	364.800	2230
Thula	GDH	THILA	R	1543 B4	1722.000	382.250	2800
Tur	MOA		M	1543 A4	1724.000	330.000	380
Tur	TDA	AT-TUR	R	1543 A4	1723.511	328.437	200
Udein	TDA	AL-UDEIN	R	1344 A1	1542.405	400.979	1700
Uwair, Bani	TDA	UWAIR	R	1643 B1	1854.231	359.661	2100
Wa,alah	RIRDP	WA'ALAH	R	1445 D1	1597.400	558.700	1750
Wahbiah	RIRDP	WAHBIAH	M	1445 C2	1599.000	539.000	1995
Wallan	TDA	WALLAN	R	1544 C4	1668.200	421.100	2500
Waqir	TDA	WAQIR	R	1443 A2	1646.152	315.314	230
Warazan	MOA	WARAZAN	M	1344 C2	1480.500	423.800	1200
Waset	RDPM	WASET-A	R	1543 C2	1709.600	324.000	1000
Wash'hah	TDA	WASH'HA	R	1643 C2	1797.294	327.221	230
Yarim	TDA	YARIM	R	1444 C1	1580.700	433.550	2400
Yusuf, Bani	GDH	YUSUF-A	R	1543 D4	1685.400	373.350	1480
Yusuf, Bani	SAWAS	YUSUF1	M	1543 D4	1685.400	373.350	1480
Zabid Town	TDA	ZABID	R	1443 C4	1568.674	318.330	105
Zabid(Gerbah)	TDA	ALJIRBAH	M	1443 C4	1564.899	330.899	240
Zakhim	RIRDP	ZAKHIM	R	1444 B3	1614.500	453.500	2640
Zhar,Wadi	GDH	WADIZHAR	R	1544 C1	1707.350	406.150	2240
Zinkah, Deir	TDA	ZINQAH	R	1543 C4	1660.773	333.352	450
Zuhaif	GDH	ZUHAIF-A	R	1543 C2	1662.340	329.440	1280
Zuhrah	TDA	ZUHRAH	M	1543 A3	1740.600	287.500	70
Zuwab	RIRDP	ZUWAB	R	1444 B4	1603.200	480.800	2190

(b) Aden, Lahej, Abyan, Shabwah, Hadramawt and Al Mahra Governorates

STATION NAME	ORG.	GDH FILE	RAINFALL or METEO	LOCATION			ELEV.
				MAPSHEET	UTM N (m)	UTM E (m)	(m)
Aden		ADEN	R	38D-115	1413.93	503.618	27
AlGharib	WHADP	GHARIB	R	39D-27	1661.145	286.748	1400
Albayth	DI		R	1447 B4	1608.516	796.389	510
AlGeidah	CAMA	ALGEIDAH	M	39E-141	1778.479	615.870	
AlHagrain	WHADP	HAGRAIN	R	1542 A4	1715.452	212.100	
AlHaleh	WHADP	ALHALEH	R	38D-36	1695.383	806.062	
AlHujayr	NWSA		R	1446 A3	1612.574	623.882	
AlJawadeh	WHADP	JAWADEH	R	1542 B1	1764.989	235.941	
Alkhoribeh	WHADP	KHARIBEH	R	38D-25	1671.166	211.553	
Alkod	DI	ALKOD	M	38D-103	1446.597	539.750	13
AlMashhad	WHADP	ALMASHED	R	1542 A4	1724.701	210.427	
ALMinsaf	WHADP	ALMINSAF	R	38E-133	1780.109	207.751	
AlQatan	WHADP	ALQATAN	R	1542 B1	1752.159	228.644	
AlRudood	WHADP	ALRUDOOD	R	39D-3	1755.230	285.829	
AlSufal	DI	AL-SUFAL	M	38D-62	1561.829	255.279	5
Alugubeih	WHADP	ALUGUBIH	R	1542 D3	1681.768	252.897	
Amaqin	DI	AMAGIN	R	1447 C2	1595.085	749.791	
Amd	WHADP	AMD	R	1547 D4	1680.762	817.010	1335
Ataq	CAMA		M	38D-58	1605.694	699.367	
Azzan	DI	AZZAN	R	1447 C2	1584.164	764.293	500
Bahran	WHADP	BAHRAN	R	1542 A4	1739.487	208.802	
Beihan	DA	BEIHAN	M	1445 B1	1634.510	578.923	1150
Bodhan	WHADP	BODHAN	R	38D-25	1687.796	209.965	
Dhala	DI	DHALA	M	1344 B3	1514.581	471.161	1150
Dhira Vill	NWSA		R	1444 A1	1641.922	410.342	220
Dura	DI	DURA	R	1446 C2	1596.130	650.919	
Fiyush	DI	FIYUSH	M	38D-114	1435.090	494.577	65
Fuwah(mukalla)	DA		M	1443 C1	1602.110	288.024	25
Gaidun	WHADP	GAIDUN	R	38D-25	1671.166	211.553	

STATION NAME	ORG.	GDH FILE	RAINFALL or METEO	LOCATION			ELEV.
				MAPSHEET	UTM N (m)	UTM E (m)	(m)
Ghail Bawazir	NWSA		R	39D-39	1635.020	324.201	
Ghail Bin Yumin	WHA	BIN YUMIN	R	39D-27	1681.136	322.750	
Giar	DI	GIAR	M	38D-103	1446.394	537.943	
Gol madram	DI	MADRAAM	R	38D-90	1475.878	467.512	450
Habban	DI	HABBAN	R	1447 C2	1587.467	724.689	
Habilin	DI	HABILIN	M	38D-90	1497.980	485.573	
Hainan	WHADP	HAINAN	R	39D-1	1754.150	885.410	1040
Hajar	NWSA		R	1446 C1	1594.128	622.178	
Harad	DI	HARAD	R	1344 B1	1520.131	456.755	1100
Hisn Hasan	NWSA		R	38D-58	1618.424	675.919	
Jawala	DI		R	38D-114	1429.782	490.961	52
Jueimah	WHADP	JUEIMAH	R	1542 B1	1768.514	250.263	
Karish	DI	KARISH	R	1344 C2	1477.560	445.857	750
Katbah	WHADP	KATBAH	R	39E-134	1775.000	285.000	950
Khalla	DI	KHALLA	R	1344 B2	1525.638	474.779	1350
Khawrah	NWSA		R	1446 A3	1603.355	623.929	
Khirba Vill	DI		R	1442 B4	1605.862	280.869	120
Khormaksar	CAMA	KORMAKSR	M	38D-115	1410.872	503.617	4
Lahej	DI	LAHIJ	M	38D-102	1442.689	487.351	129
Little Aden	DI		R	38D-114	1409.011	481.908	12
Meifaah	DA	MEIFAAH	M	38D-72	1576.941	778.766	450
Milah	DI	MILAH	R	38D-90	1483.238	481.956	600
Moudia	DI	MOUDIA	M	38D-81	1536.967	620.653	820
Mukalla(PWC)	NWSA		R	39D-51	1607.553	298.852	30
Mukiras	D1	MUKIRAS	M	1345 B1	1540.477	573.819	2150
Mukiras1	RIRDP	MUKIRAS1	R	1345 B1	1540.477	573.819	2150
Musaimer	DI	MUSIMER	R	38D-90	1483.264	458.499	600
Nissab	DI	NISSAB	M	38D-58	1603.574	661.652	1100
Nissab-1	RIRDP	NISSAB-1	R	38D-58	1603.574	661.652	1100
Nuqub	DA	NUQUB	M	1445 B2	1638.222	586.085	1040

STATION NAME	ORG.	GDH FILE	RAINFALL or METEO	LOCATION			ELEV.
				MAPSHEET	UTM N (m)	UTM E (m)	(m)
Orisma	D1	ORISMA	R	1344 A4	1492.510	442.280	900
Perim	DI	PERIM	R	38D-123	1398.957	329.848	29
Q.Bamasood	WHADP	BAMASOOD	R	1543 D4	1686.133	804.391	
Qasm	WHADP	QASM	R	39E-135	1784.626	298.594	
Riyan	CAMA	RIAN	M	39D-51	1612.986	311.469	24
Sabiha(turbaha)	DI		M	1344 C4	1450.150	427.735	580
Sah	WHADP	SAH	R	1542 B4	1724.030	269.441	
Seiyun	ARC	SEIYUN	M	1542 B2	1762.679	278.761	700
Seiyun1	CAMA	SEIYUN	M	1542 B2	1766.513	264.520	620
Sharj Asharif	WHADP	ASHARIF	R	1542 D3	1681.963	234.981	850
Sheik Othman	DI	OTHMAN	R	38D-114	1422.408	498.192	14
Shibam	WHADP	SHIBAM	R	1542 B1	1751.950	246.506	
Sidara	DI	SIDARAH	M	1442 B4	1604.066	275.462	460
Slasil	WHADP	SLASIL	R	1642 D2	1821.800	270.454	
Sobeikh	WHADP	SOBEIKH	R	38D-25	1687.686	218.922	
Socotra	CAMA	SOCOTRA	M	39D-132	1398.350	815.071	
Thibi	NWSA		R	1642 D4	1786.713	273.651	800
W.Bani Ali	WHADP	BIN ALI	R	1542 B1	1742.725	246.402	750
W.Buwaysh (pwc)	DI		R	39D-51	1618.560	306.125	25
W.Huwayrah	DI		R	39D-39	1657.473	284.922	1440
W.Sarr	NWSA		R	38E-133	1795.042	195.286	1100
Yabhoodh	WHADP	YABHOODH	R	1542 B4	1766.319	284.151	

LIST OF STREAM GAUGING STATIONS

WADI	STATION	ORG.	LOCATION			ELEV.
			MAP SHEET	UTM-N (m)	UTM-E (m)	(m)
Red sea basin						
Wadi Harad		TDA	1643 C1	1822.5	310.5	220
Wadi Hayran		TDA	1643 C4	1792.0	320.6	280
Wadi Mawr	Shat al Erg	TDA	1543 A4	1727.4	316.6	230
Wadi La'ah		TDA	1543 A4	1725.0	328.5	360
Wadi Surdud	Faj-Al-Hussein-A	GDH	1543 C4	1680.1	330.4	340
Wadi Surdud	Faj-Al-Hussein-A	GDH	1543 C4	1680.1	330.2	340
Wadi Surdud	Shat Ad Darba	TDA	1343 C4	1679.0	337.0	430
Wadi Surdud	Dayan confluence	NWSA	1543 D1	1688.5	361.5	925
Wadi Siham	Mahal Saleem	TDA	1443 A4	1656.0	326.0	390
Wadi Rima	Misrafah	TDA	1443 D1	1590.0	346.0	390
Wadi Zabid	Kolah	TDA	1443 D3	1561.0	345.0	320
Wadi Nakhlah		TDA	1343 B1	1539.0	347.6	330
Wadi Damim	Qabna	TDA	1343 B1	1532.0	349.4	320
Wadi Rasyan	Gorge	TDA	1343 D1	1483.0	346.0	270
Wadi Haymah		NWSA	1344 A2	1524.0	397.0	1650
Wadi Mawza	Assufariyah	TDA	1343 D1	1470.6	335.0	360
Gulf of Aden Basin						
Wadi Ma'adin	Tor Al Bahr	DA	1344 C4	1457.5	422.4	
Wadi Ma'adin	Upper	NWSA	1344 C4	1454.5	427.0	575
Wadi Ma'adin	Lower	NWSA	1344 C4	1447.0	431.0	460
Wadi Tuban	Dukeim	DI	38D-102	1466.7	474.7	
Wadi Warazan		NWSA	1344 C1	1483.4	418.8	1100
Wadi Rabwa	Saba weir	DA	38D-90	1494.3	483.8	
Wadi Bana	Batais	SYP	38D-91	1474.0	523.5	
Wadi Hassan	Al Haig	SYP	38D-103	1463.0	532.5	
Wadi Hassan	Al Miyuh	DI	38D-103	1466.7	536.1	
Wadi Ahwar	Fuad Weir	DA	38D-106	1510.0	684.0	

WADI	STATION	ORG.	LOCATION			ELEV.
			MAP SHEET	UTM-N (m)	UTM-E (m)	(m)
Wadi Amaqn	Haban	DA	1442 C2	1584.2	264.3	
Wadi Khirba	Khirba Ford	DA	1442 B4	1604.0	280.9	
Wadi Khirba	Jarashah	DA	1446 A3	1603.4	263.9	
Wadi Buwaysh	PWC	DA	39D-51	1618.6	306.1	
Wadi Huwayrah	Seiyun ford	DA	39D-39	1631.4	315.2	
Arabian Sea basin (Ramlat-as-Sabatayn)						
Wadi Kharid	Dam Site 2a	NWSA	1544 A4	1740.5	436.6	1925
Wadi Kharid	Gurdud	AHT	1644 C4	1791.2	436.0	1190
Wadi Kharid	Sec.gauge	AHT	1644 C4	1789.0	434.0	1200
Wadi Habash		AHT	1644 C4	1789.0	434.0	1200
Wadi Assaghi		AHT	1644 D3	1780.0	456.4	1200
Wadi Madhab		AHT	1644 C2	1811.5	439.7	1220
Wadi Adhana	Dam	ERADA	1545 C1	1718.0	526.0	1140
Wadi Adhana	Dhana-1	GDH	1545 C1	1687.9	512.2	1180
Wadi Adhana	Dhana-2	GDH	1545 C1	1688.3	512.9	1180
Wadi Beyhan	Nuqub	DA	1445 B3	1625.3	579.0	1040
Wadi Markhah	Hagar Markhah	DA	1446 A3	1607.0	616.7	
Wadi Hammam	Mukail (Dura)	DA	1446 C2	1596.1	649.1	
Wadi Hammam (?)	Husn Al War	DA	1446 C2	1588.8	660.0	
Arabian Sea Basin (Wadi Hadramawt)						
Wadi Hadramawt	Shibam	WHADP	1542 B1	1763.0	252.0	
Wadi Doan	Gaudah	WHADP	38D-1	1743.2	205.3	
Wadi Al Ayn	Ajliniyah	WHADP	38D-1	1745.0	210.7	
Wadi Sarr		WHADP	1542 B1	1763.2	227.0	
Wadi Bin Ali	Road	WHADP	1542 B1	1759.3	246.6	
Wadi Juaymah		WHADP	38E-134	1770.3	253.9	
Wadi Thibi		WHADP	1642 D4	1771.9	280.6	
Wadi Idim	Ghuraf	WHADP	1542 B2	1766.3	284.2	
Wadi Masila	Qassam	WHADP	39E-135	1784.6	302.2	
Wadi Masila		WHADP	39E-135	1782.7	311.1	

LIST OF GROUNDWATER LEVEL MONITORING NETWORKS

Agency	Area	Total Number of wells		Period of record
		Manual	Automatic	
GDH	Marib	54	8	1987-93
GDH	Surdud	38	4	1984-93
GDH	Sadah	29	2	1984-92
TDA	Mawr	36	-	1978-92
TDA	Siham	22	-	1986-92
TDA	Rima	61	-	1975-77 1981-92
TDA	Zabid	45	-	1970-92
TDA	Rasyan	30	-	1980-92
RIRDP	Rada	20	16	1977-92
NWSA	Sana'a	44	3	1990-93
ODA/LRC	Dhamar Montane Plains	45		1975-76
?	Tuban Delta	?		
?	Abyan Delta	?		
?	Wadi Bayhan	?		
WHAP	Wadi Hadramawt	85		

PERIODS OF RECORD - RAINFALL AND METEOROLOGICAL STATIONS

(a) Sana'a, Taiz, Hodeidah, Ibb, Dhamar, Hajjah, Al Bayda, Sadah, Al Mahweet, Marib and Al Jawf Governorates

STATION NAME	AVAILABLE YEARS				REMARKS	
	1960	1970	1980	1990	STATUS	TYPE
Abkowr			+*5***		-	m
Ahmar, Bayt Al			+5*		o	m
Amar			+***6789	012	o	e
Amir		+	0*23456789	01	o	m
Araqah			+4*		-	m
Arqub				12	o	e
Asal			+789	012	o	e
Ash'a, Al			+		o	e
Asir Mil. base		+678			-	m
Attius			+789	01*	o	e
Azgull			+****		-	m
Bajil	+*	**2*45**89	0*		-	m
Barh			+*23456789	01	o	m/c
Basat		+89	0123*56789	01	o	m
Bawn		+***9	01234567*	**	o	m/c
Bawn			+7 9		o	m
Bayda			+8*		o	e
Buqa, Al			+		o	c
Dabaat		+3456*8*			-	m
Dabab,Wadi Ad			+89	*1	o	m
Dabira		++	0123456789	01	o	m
Dahi			+56789	012	o	m/c/e
Damaj			*		-	m
Dar Salem			+4*		-	m
Darb		+ +789	012 4		-	m

STATION NAME	AVAILABLE YEARS				REMARKS	
	1960	1970	1980	1990	STATUS	TYPE
Dar Najd		+			-	m
Darwan		+3456 8	*		-	m
Dawran		+			-	m
Delil Sumara	+	0123456**9	0123456789	01	o	m
Dhamar			+345678		-	m/c
Dhamar		+* 89	012345678		o	m
Dhamar		+6789	0*2345678		o	m
Dimnah		+ +9	012*456789	01	o	m
Dumeid			+34*6789	012	o	c/e
Dutrat			+4*6		o	m/c
Faqih, Bayt Al			+789	01	o	m
Fawwarah		+ +	0123456789	01	o	m
Fulayh		+123*			-	m
Gawadir		+89	0123456789	01	o	m
Ghamr			+56*89	012	o	c/e
Ghujla			+89	0*2	o	e
Giblah			+ 89		-	c
Gudami			+34**789	012	o	e
Gumeisha		234567			-	c
Habaka/Girnah		+ +9	01+ **6789	01	o	m
Habashi			+34*6789	*1	o	m
Hagag				12	o	e
Haima		+	*123456789	01	o	m
Hajar		+	01*34**78	0	o	c
Hajdah			+*23456*89	01	o	m
Hajjah			+789		o	e
Hajjah		+567**	*** *56789	01	o	m
Hamal		+*	**23456789	01	o	m
Hamam Ali		+* 89	01**456789	01	o	m
Harad			+*8*		-	e
Har,Wadi		0123***789	0123456789	*1	o	m

STATION NAME	AVAILABLE YEARS				REMARKS	
	1960	1970	1980	1990	STATUS	TYPE
Haymah,Wadi			+		o	m
Hazm, Al			+		o	m/c
Hazm, Al			+67		o	m/c
Hidad		+ *9	0123456789	01	o	m
Hijrah			*1**45*78		o	m
Hijrah			+234567		-	m
Hijrat Makinah			+		o	m
Hijrat Ma'bar			+		-	m
Hudaydah	+4**	***678*	0 3456789		o	c
Hudaydah			+6789	01	o	e
Huth		+**7*	123*56789	01	o	m
Ibb			+		o	c
Ibb			+*345*789		o	c
Ibb	+	0123456789	0123456789	01	o	m
Irra			+ +789		o	e
Jabal Taraf			*7**		-	c
Jabin			+		-	m
Jabri, Bayt Al		*	*234		-	c
Jannat		+67 9	01		-	m
Jarubah		+	+6789		-	m/c
Jawf			+789	0*	o	m/c
Jihanah			+		o	m/c
Jiraf, Al		+			-	m
Jubah			+789	012	o	e
Juban			+ +	01	o	e
Jubayr			+*7		o	e
Kadan		+3**			-	c
Kadan		+			o	e
Kadima,Harad Al			+789	01	o	m
Kahal			+5*		-	c
Kamer			** *56		-	m

STATION NAME	AVAILABLE YEARS				REMARKS	
	1960	1970	1980	1990	STATUS	TYPE
Kasabat Akwan			+**		-	m
Ketab			+89	01	o	e
Khabar		+7+9	0123456789	012	o	m/c/e
Khadrah		+	+23456789	012	o	c
Khadrah			+789	01	o	m
Khalifah, Al			+89	01	o	m/c
Khamir		+34*6*	*** *6789	01	o	m
Khamis			*56789	01	o	c/e
Khamis		+*			-	m
Khamlu			+56*89	01	o	m/e
Khasha'a			+34*6789	**	o	c
Khulagah			+		-	m
Kudeihah			+*23456789	0*2	o	c/e
Kudmah Maraiya			+789	01	o	m
Lahimah,Wadi			*789		-	c
Lahj		5*7**	012 +6		-	m
Lariud			+ *	01	o	e
Ma'adi			+		o	m
Mabar		567	012*456		o	m
Madaf		+	+34567**	*1	o	c
Mafhaq			+56*89	01	o	c/e
Magash			+89	0*	o	c
Maghreba		+*	0123*56789	01	o	m
Mahabish		+56* *	0123*56789	01	o	m
Mahatt		+ 89	01234*6789	01	o	m
Mahwit		+****	* *3456789	01	o	m
Mahwit			+78*	+2	o	c
Mahwit			+8*	0	o	e
Mai'na			+789		-	c
Majhiz			+4**		o	m/c
Majz			+*4**		-	m

STATION NAME	AVAILABLE YEARS				REMARKS	
	1960	1970	1980	1990	STATUS	TYPE
Makarib			+4**		-	m
Manakha			+3		-	m/c
Manakha		+9	*		-	c
Manasih			+45**89	0*	o	c
Manjidah		+6789			-	c
Mansur,Wadi			+		-	e
Maqbanah			+89	*1	o	m
Maqwalah			+4**		-	m
Maram		+6789	0123456789		o	m
Marib			+789		o	m/c
Marib		8*	*2+4*6*		o	m/c
Marib			+		o	e
Markha				+	o	e
Marran, Bayt			+		o	m
Masnaah		+**+9	0123456789	01	o	m
Maswarah			+89	0	o	e
Mawsanah			+5*		-	c
Mayan			+56*89	012	o	c/e
Midi			+789	01	o	m
Mikras		+*			-	m
Milh		+ **89	0123456789	01	o	m
Mind		+3456*89	0		-	m
Mirwah			+ **	*	-	c
Mishrafah		+ +9	*1***56789	01	o	m
Mokha		+* 89	+45678		o	m/c
Mosalla				+	o	e
Muthef			+34*6789	012	o	c/e
Na'ta			+		-	e
Nagil Sam			+789	01	o	e
Nozaih,Al			+89	01	o	c
Nuqabah			+34567**		o	c

STATION NAME	AVAILABLE YEARS				REMARKS	
	1960	1970	1980	1990	STATUS	TYPE
Ossefra		+	0123*5*789	012	o	m/c
Qa,mah			+		o	m/c
Qadam			+56		-	c
Qadam			+ 6*89	012	o	m/e
Qahmah		+ *9	01*3456789	01	o	m
Qarry			+45678*	0*	o	c
Qarwah			+78*	01	o	e
Rabu,suq Al			+789	01	o	m
Rada'a		+ +89	*12345*789	012	o	m/e
Rahaba			+789	01	o	e
Rahban			+	1	o	e
Raydah		+67 9	0*2		-	m
Rihab	+	0123456789	0123456789	01	o	m
Risabah		+9	0123456789	*	o	m/c
Rizwa		+678*	01*34567		-	m
Robei			+ **789	01	o	m
Ruba			+678		o	m
Ruba			+7		-	m
Rubat			+**	1	o	e
Rubu Utmah			+		o	m
Rujum			+5**89	012	o	m/e
Rujum			** *		-	c
Sadah			+		o	e
Sadah Salam			+345*789	012	o	c/e
Sadah			678		o	m/c
Safaqayn			+ *9		-	c
Safiah			+**		o	e
Sahwah			+456		-	m
Said, Bait Al			+*89	01	o	m
Saidiyah			+789	01	o	m
Salf		+*	** +56789	012	o	c/e

STATION NAME	AVAILABLE YEARS				REMARKS	
	1960	1970	1980	1990	STATUS	TYPE
Salif			+ ****	*	-	m
Sama Al Ulya		+6789	012 456*8		o	m
Sama'ah, As			+8	1	o	e
Sana'a Airport	+*	*******789	01 3456789	0	o	m/c
Sana'a Town	3456789	0123456789	0123		o	m/c
Sana'a			+	0*2	o	e
Sana'a		789	*		o	m
Sanaban		+6789	012345678		o	m
Sanam		+ 8*	01*3456789	*1	o	m
Saqayn		+56**	*123*56789	01	o	m
Shaharah		+5	*56***	01	o	m
Shamir, Mahal		+*	0123456789	01	o	m
Shaqab		+67*9	0123 *		-	m
Sharaf			+		o	e
Sharq			+567		-	m
Sharq		+ 89	01*3456789	01	o	m
Sherwab			+*89	01	o	e
Shibam		+567**	0123456789	**	o	m
Shoub Farm	456 89	0123456789	01 3		o	m/c
Sirwah			+8*	*12	o	e
Suar		9	***3		-	m
Azaydiyah			+789	01	o	m
Sukhnah		+*	0123*56789	01	o	m
Surby			+*567		-	m
Taiz Town	0123456789	23456789	01		o	m
Taiz Yard		+*6*	0123456789	0	o	m
Taiz new airp			3456789		o	m/c
Talab			+1 +		-	m
Tawilah			+* 9	12	o	c/e
Thawban			+***	*12	o	e
Therhaan			012+***		x	x

STATION NAME	AVAILABLE YEARS				REMARKS	
	1960	1970	1980	1990	STATUS	TYPE
Thula		+6789	0123		-	m
Tur			8		-	e
Tur		*56789	0123456789	01	o	m
Udein		01*345*789	0123456789	01	o	m
Uwair, Bani		+5* *	0123456789	01	o	m
Wa,alah				+2	o	e
Wahbiah				+	o	e
Wallan		+*	0*23456789	01	o	m
Waqir		++	0123456789	0*	o	m
Warazan			+*9	*1	o	e
Waset				12	o	e
Wash'hah		+*7*9	**2345*789	01	o	m
Yarim	+	0123456789	0123456789	01	o	m
Yusuf, Bani			+56789	0*2	o	m/e
Yusuf, Bani				+123	o	e
Zabid Town	+	01234* **9	*123456789	01	o	m
Zabid(Gerbah)	+	0123456789	123456789	01	o	c/e
Zakhim				+2	o	e
Zhar,Wadi		+78	01*		-	m
Zinkah, Deir		+*	*1*3456789	01	o	m
Zuhaif			+56789	012	o	m/e
Zuhrah		*3* +	*123*56789	01	o	m
Zuwab		+	0+2345*789	0*2	o	c

-	not operated	+	date of instalation
o	operated	*	incomplete data
m	manual	x	unknown
e	electronic	R	rainfall station
c	chart	m	meteo station

(b) Aden, Lahej, Abyan, Shabwah, Hadramawt and Al Mahra Governorates

STATION NAME	AVAILABLE YEARS						REMARKS	
	1940	1950	1960	1970	1980	1990	STATUS	TYPE
A. Gharib					56789	0	o	m
Albayth					+		o	m
AlGeidah					67		o	m/c
AlHagrain					89	01	o	m
AlHaleh					56789	01	o	m
AlHujayr					23		-	m
AlJawadeh					89	01	o	m
Alkhoribeh					56789	01	o	m
Alkod		89	0123456789	0123456789	0123456789	01	o	m/c
AlMashhad					56789	01	o	m
AlMinsaf					89	01	o	m
AlQatan					56789	01	o	m
AlRudood					56789	01	o	m
AlSufal					34*678	01	o	m/c
Alugubeih					56789	01	o	m
Amaqin				+			-	m
Amd					89	01	o	m
Ataq							o	m/c
Azzan				+			-	m
Bahran					56789	01	o	m
Beihan					2345678		-	m/c
Bodhan						1	o	m
Dhala				3456789	01234567		-	m/c
Dhira Vill					+		o	m
Dura					012		-	m
Fiyush				3456789	012345678		o	m/c
Fuwah(mukalla)					+		o	m/c
Gaidun					*6789	01	o	m
Ghail Bawazir					+		o	m
Ghail Bin yumin					89	01	o	m

STATION NAME	AVAILABLE YEARS						REMARKS	
	1940	1950	1960	1970	1980	1990	STATUS	TYPE
Giar					56789	0	o	m/c
Gol madram				3456789	012345		-	m
Habban				+			-	m
Habilin					89	012	o	m/c
Hainan					9	01	o	m
Hajar					23		-	m
Harad				+			-	m
Hisn Hasan					23		-	m
Jawala				+			-	m
Jueimah					89	01	o	m
Karish				456789	012345		-	m
Katbah					89	01	o	m
Khalla				56789	23		-	m
Khawrah					23		-	m
Khirba Vill					+		o	m
Kormaksar	89	0123456789	0123456789	0123456789	0+234 67 9	0	o	m/c
Lahej				3456789	0123456789	01	o	m/c
Little Aden		+					-	m
Meifaah				5			-	m/c
Milah				5678			-	m
Moudia					23456789	0	o	m/c
Mukalla(PWC)					+		o	m
Mukiras				789	01 78	+	-	m/c
Mukiras						+	o	e
Musaimer				3456789	0123456		-	m
Nissab					0123		-	m/c
Nissab						+	o	e
Nuqub			56		23456789	012	o	m/c
Orisma				3456789	012345		-	m
Perim	12345678						-	m
Q.Bamasood					56789	01	o	m

STATION NAME	AVAILABLE YEARS						REMARKS	
	1940	1950	1960	1970	1980	1990	STATUS	TYPE
Qasm					56789	01	o	m
Riyan				3456789	0123456789	0	o	m/c
Sabiha(turbaha)							o	m
Sah					56789	01	o	m
Seiyun				789	0123456789	012	o	m/c
Seiyun					0123456		o	m/c
Sharj Asharif					56789	01	o	m
Sheik Othman	6789						-	m
Shibam					56789	01	o	m
Sidarah					456789	01	o	m/c
Slasil					89	01	o	m
Sobeikh					89	01	o	m
Socotra				89	012 6789		o	m/c
Thibi					+		-	m
W.Bani Ali					+	01	o	m
W.Buwaysh (pwc)					+		o	m
W.Huwayrah					+		o	m
W.Sarr					+		-	m
Yabhoodh						01	o	m

-	not operated	+	date of instalation
o	operated	*	incomplete data
m	manual	x	unknown
e	electronic	R	rainfall station
c	chart	m	meteo station

PERIODS OF RECORD - STREAM FLOW STATIONS

WADI	STATION	AVAILABLE YEARS					REMARKS	
		1950	1960	1970	1980	'90	STATUS	TYPE
Red sea basin								
Wadi Harad					***9	12	o	c
Wadi Hayran					****9	12	o	c
Wadi Mawr	Shat al Erg			5678*	0**3456789	12	o	f
Wadi La'ah				567			o	c
Wadi Surdud	F.a.Hussein-A				456789	12	o	e
Wadi Surdud	F.a.Hussein-B					+	o	e
Wadi Surdud	Sh.A dDarba				***89	12	o	f
Wadi Surdud	Dayan confl.					+	o	e
Wadi Siham	Mahal Saleem				+67*9	12	o	c
Wadi Rima	Misrafah			67*9	0*2345		o	f
Wadi Zabid	Kolah			012345678*	123456789	12	o	m
Wadi Nakhlah					***8*	12	o	c
Wadi Damim	Qabna				789	12	o	c
Wadi Rasyan	Gorge				**34**789	0*2	o	f
Wadi Haymah					+		o	m
Wadi Mawza	Assufariyah				+ 8*	12	o	c
Gulf of Aden Basin								
Wadi Ma'adin	Tor Al Bahr				-6789	012	o	c
Wadi Ma'adin	Upper			+			o	c
Wadi Ma'adin	Lower			+			o	c
Wadi Tuban	Dukeim			-23456789	123456789	012	o	f
Wadi Warazan					+		o	m
Wadi Rabwa	Saba weir			3456789	123456789		o	c
Wadi Bana	Batais	23456789	12345		+		o	c
Wadi Hassan	Al Haig				+89		-	f
Wadi Hassan	Al Miyuh				+678		-	c
Wadi Ahwar	Fuad Weir	+		23456789	123456789		o	c
Wadi Amaqn	Haban			+			-	c
Wadi Khirba	Khirba Ford				-456789	012	o	c
Wadi Khirba	Jarashah				-3456789	012	o	c
Wadi Buwaysh	PWC				-456789	012	o	c

WADI	STATION	AVAILABLE YEARS					REMARKS	
		1950	1960	1970	1980	'90	STATUS	TYPE
W. Huwayrah	Seiyun ford				-456789	012	o	c
Arabian Sea basin (Ramlat-as-Sabatayn)								
Wadi Kharid	Dam Site 2a					+	-	e
Wadi Kharid	Gurdud				+		-	m/c
Wadi Kharid	Sec.gauge				+		-	m
Wadi Habash					+		-	m
Wadi Assaghi					+		-	m
Wadi Madhab					+		-	m/c
Wadi Adhana	Dam				6789	12	o	e
Wadi Adhana	Dhana-1				89	12	o	e
Wadi Adhana	Dhana-2				89	12	o	e
Wadi Beyhan	Nuqub				+789		o	c
W. Markhah	Hagar				-3456789	012	o	c
W. Hammam	Mukail				+12		o	c
W. Hammam (?)	Husn Al War				+12		o	c
Arabian Sea Basin (Wadi Hadramawt)								
Wadi Hadra-mawt	Shibam			-89	0123456		-	c
Wadi Doan	Gaudah			-89	123456789	01	-	c
Wadi Al Ayn	Ajliniyah			-89	123456789	01	-	c
Wadi Sarr				-789	123456789	0	-	c
Wadi Bin Ali	Road			-89	123456789		-	c
Wadi Juaymah				+	123456789	0	-	c
Wadi Thibi				-89	123456789	01	-	c
Wadi Idim	Ghuraf			-89	123456789	01	-	c
Wadi Masila	Qassam			+	01234567		-	c
Wadi Masila				-89	123456789		-	c

-	not operated	+	date of instalation
o	operated	*	incomplete data
m	manual	x	unknown
e	electronic		
c	chart		

APPENDIX 3

Selected statistics of processed monitoring data

3.1 Annual rainfall, period 1985-1991
3.2 Average monthly rainfall
3.3 Average monthly values of meteorological variables
3.4 Average monthly and annual runoff
3.5 Monthly and annual flow volumes

ANNUAL RAINFALL, PERIOD 1985 - 1991
(in mm)

STATION	ORG.	1985	1986	1987	1988	1989	1990	1991	MEAN	Correlated to :
Amar	GDH	96.0	140.2	4.5	163.0	46.5	63.0	15.0	75.5	
Amir	TDA	554.6	670.8	599.6	691.6	424.7	392.8	278.8	516.1	
Barh	TDA	278.9	360.0	342.0	245.2	97.2	179.8	206.2	244.2	
Basat	TDA	444.7	371.0	375.8	763.0	335.9	240.0	153.9	383.5	
Dabira	TDA	153.2	255.2	146.2	158.4	304.9	255.0	168.2	205.9	
Dahi	GDH	204.8	125.2	144.1	223.9	75.0	35.5	132.5	134.4	
Dalil Sumara	TDA	812.5	578.7	679.6	671.8	594.0	633.9	451.6	631.7	
Dimnah	TDA	194.0	204.5	418.5	548.1	259.0	156.5	467.0	321.1	
Dumeid	GDH	134.0	189.2	63.5	133.0	111.5	177.0	30.0	119.7	
Fawwarah	TDA	243.2	347.5	163.7	232.8	264.9	161.1	102.7	216.6	
Gawadir	TDA	430.1	295.3	649.0	471.4	530.9	174.2	263.9	402.1	
Ghamr	TDA	598.1	375.4	*251.0	336.0	383.0	241.0	222.5	*344.0	Mahwit
Gudami	GDH	210.8	*109.0	72.0	121.5	55.0	116.0	10.5	*99.0	Muthef, Bani Awer
Habaka	TDA	*188.0	284.5	202.5	398.0	450.8	349.1	246.5	*303.0	Mishrafah, Sharq
Habashi	TDA	395.7	424.3	680.9	440.0	574.7	*352.0	350.6	*460.0	Barh
Haima	TDA	467.0	371.1	284.8	170.1	191.5	270.9	153.5	272.7	

STATION	ORG.	1985	1986	1987	1988	1989	1990	1991	MEAN	Correlated to :
Hajdah	TDA	305.0	*906.0	795.0	733.0	986.0	863.0	238.5	*657.0	Barh
Hajjah	TDA	126.4	156.3	587.2	840.3	572.0	509.0	231.0	431.7	
Hamal	TDA	343.3	424.6	362.9	409.3	454.8	*429.0	337.4	*394.0	Sharq, Hamam Ali
Hamam Ali	TDA	263.4	167.1	400.1	330.2	437.6	274.0	309.0	311.6	
Wadi Har	TDA	240.9	383.7	370.4	388.1	372.0	*318.0	175.9	*321.0	Hadid, Ham.Ali, Masnh
Hidad	TDA	366.9	369.0	350.0	405.3	368.6	409.0	110.0	339.8	
Hudaydah	TDA	13.9	43.2	51.3	108.1	251.0	71.5	58.9	85.4	
Huth	TDA	33.5	58.6	720.3	270.9	128.5	61.9	64.7	191.2	
Ibb	TDA	2052.9	819.5	1597.6	1572.2	1920.2	1703.7	903.7	1510.0	
Khamis	GDH	295.9	326.6	312.8	434.0	496.5	359.5	264.5	355.7	
Khamlu	GDH	262.1	382.1	*325.0	326.5	383.0	237.0	199.5	*302.0	Khamis, Dar Zankhah
Kudeihah	TDA	102.0	164.6	97.9	103.3	272.6	29.1	0.0	110.0	
Mafhaq	GDH	303.0	351.7	310.9	299.5	188.0	241.5	128.5	260.4	
Maghreba	TDA	570.1	699.0	513.0	505.5	686.5	449.5	339.5	537.6	
Mahabisha	TDA	776.5	1083.0	1003.2	669.4	872.3	392.7	441.5	748.4	
Mahatt	TDA	379.0	310.2	293.0	212.8	435.0	257.0	281.1	309.7	
Mahwit	TDA	1130.1	944.1	483.6	1068.2	571.0	406.9	239.6	*692.0	
Masnaah	TDA	379.0	310.2	293.0	212.0	435.0	257.0	281.1	309.6	
Mayan	GDH	258.4	324.5	177.5	196.0	320.0	154.5	188.5	231.0	
Milh	TDA	78.5	50.9	48.7	161.0	57.7	91.5	72.0	80.0	

STATION	ORG.	1985	1986	1987	1988	1989	1990	1991	MEAN	Correlated to :
Mishrafah	TDA	163.7	552.9	550.5	326.9	419.8	344.0	338.0	385.1	
Muthef	GDH	188.3	220.6	260.0	199.0	148.0	161.0	154.0	190.4	
Qadam	GDH	*550.0	809.8	*435.0	227.0	336.0	295.5	307.0	*422.0	Amir, Hamah
Qahmah	TDA	271.4	333.1	232.3	407.3	346.0	154.3	151.8	270.9	
Rihab	TDA	427.9	648.5	512.0	439.8	520.0	1259.0	396.6	600.5	
Risabah	DAFRD	310.0	277.2	277.1	304.0	357.2	*252.0	*215.0	*285.0	Masna'ah
Rujum	GDH	711.7	*793.0	428.0	972.0	510.5	581.0	286.0	*581.5	Mahwit
Sadah Salam	GDH	170.4	*99.5	47.0	80.5	58.0	91.5	105.5	*93.0	Bani Awer
Salf	GDH	533.3	569.1	409.0	681.0	471.0	212.5	157.0	433.3	
Sanam	TDA	353.0	430.2	511.5	545.7	454.2	*378.0	188.4	*409.0	Masna'ah, Hadid
Saqayn	TDA	228.5	317.8	269.5	274.9	157.7	150.0	89.0	212.5	
Shamir	TDA	459.2	603.5	299.5	304.3	638.2	354.5	*331.0	*427.0	Zankhah, Maghrabeh
Sharq	DAFRD	301.7	377.8	324.0	353.2	486.2	480.0	509.5	404.6	
Shibam	TDA	349.9	493.7	230.0	320.8	508.2	270.0	188.8	337.3	
Sukhnah	TDA	372.0	471.6	539.3	318.6	579.6	*359.0	251.7	*413.0	Maghrabeh
Tur	TDA	354.4	511.5	502.0	429.5	375.5	325.5	321.0	402.8	
Udein	TDA	618.3	676.3	773.0	669.5	897.0	859.0	640.0	733.3	
Uwair,Bani	TDA	116.9	151.0	156.0	213.0	169.0	101.0	73.0	140.0	
Wallan	TDA	230.0	343.0	164.0	289.8	253.0	230.0	171.7	240.2	
Waqir	TDA	319.8	349.9	306.8	458.2	326.8	302.7	118.7	311.8	

STATION	ORG.	1985	1986	1987	1988	1989	1990	1991	MEAN	Correlated to :
Wash'hah	TAD	442.4	*588.0	547.3	389.4	352.7	501.4	203.8	*432.0	Mahabish
Yarim	TDA	533.3	607.0	546.2	688.6	596.6	396.2	481.0	549.8	
Bani Yusuf	GDH	465.8	698.3	485.9	665.0	433.0	321.0	*288.5	*480.0	Himah
Zabid Town	TDA	238.5	145.8	121.0	358.2	250.5	144.7	78.3	191.0	
Zabid Gerbah	TDA	*337.0	491.7	350.1	556.8	289.2	287.6	159.0	*353.0	Zabid, Mahat, Qhmah
Zinkah,Deir	TDA	259.2	408.1	402.6	287.7	401.7	332.0	289.3	340.1	
Zuhaif	GDH	573.9	651.2	*447.0	530.5	559.5	241.5	275.5	*468.0	Zinkhah, Shamir
Zuhrah	TDA	149.4	160.2	*59.0	121.1	26.2	112.7	14.2	*92.0	Milh
Zuwab	RIRDP	99.9	112.5	178.6	146.4	139.7	100.0	54.4	119.0	
Al Haleh	WHADP	18.9	78.8	82.5	78.2	94.6	92.1	4.8	71.8	Seiyun
Al-Khoribeh	WHADP	*15.0	23.1	135.4	80.8	139.1	67.1	24.9	*69.0	Seiyun
Al-Kod	DI	118.3	6.0	88.0	40.4	161.4	0.0	35.7	64.3	
Al-Mashhad	WHADP	*6.0	37.2	50.0	16.0	14.0	43.0	14.8	*26.0	Seiyun
Al-Qatan	WHADP	*9.0	19.5	85.3	0.0	106.1	49.3	14.3	*41.0	Seiyun
Al-Rudood	WHADP	*12.0	44.6	65.7	42.3	111.3	21.1	80.0	*54.0	Seiyun
Bahran	WAHDP	*7.0	3.5	52.4	2.6	101.1	27.9	21.3	*31.0	Seiyun
Gaidun	WAHDP	*12.0	80.9	66.9	78.5	129.8	3.3	0.0	*53.0	Seiyun
Lahej	DI	24.2	11.0	70.4	70.0	106.9	28.7	1.8	51.9	
Nuqub	DA	20.4	66.4	99.5	35.8	107.9	145.4	23.9	71.3	
Q.Bamasood	WHADP	*11.0	45.1	52.5	53.0	55.3	88.6	64.3	*53.0	Seiyun

STATION	ORG.	1985	1986	1987	1988	1989	1990	1991	MEAN	Correlated to :
Ryan	CAMA	10.5	80.3	26.0	9.5	120.1	14.0	*27.0	*41.0	Seiyun
Sah	WAHDP	*9.0	65.7	71.8	12.6	91.5	26.0	25.0	*43.0	Seiyun
Seiyun	ARC	13.5	68.0	110.3	8.4	174.9	77.0	44.0	70.9	
Shibam	WAHDP	*9.0	89.1	98.6	19.7	10.8	42.8	33.5	*43.0	Seiyun

* Corrected sum or average partly based on corrected figures

AVERAGE MONTHLY RAINFALL
(in mm)

STATION	JAN	FEB	MRT	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR	PERIOD
Abkowr	4.4	6.5	14.4	28.5	36.6	23.4	7.7	18.9	1.1	0.0	2.8	3.9	148.2	83-86
Ahmar,Bayt Al	6.4	11.7	22.1	46.5	72.1	2.5	3.5	33.1	0.7	0.0	8.0	0.0	206.6	84-86
Amar	9.7	6.5	7.4	23.5	5.3	3.4	11.1	19.5	0.3	0.5	0.6	0.7	88.5	86-92
Amir	10.2	14.8	70.4	131.7	68.2	22.4	51.9	96.3	30.3	19.7	13.7	9.3	538.9	79-91
Araqah	7.5	0.0	4.6	48.9	51.8	0.0	9.2	28.9	0.0	0.0	0.0	6.0	156.9	83-85
Asal	0.0	7.1	21.3	60.4	2.1	0.5	21.7	22.3	6.5	13.8	0.3	2.5	158.5	87-92
Asir Mil.base	0.0	5.3	54.7	106.7	12.3	39.7	34.3	125.7	9.4	49.1	12.8	0.1	450.1	75-78
Attius	0.4	10.6	27.5	47.3	0.0	1.7	24.2	20.1	4.0	0.0	0.0	0.3	136.1	87-91
Azgull	19.4	26.3	18.7	45.4	33.6	3.5	44.5	23.4	0.2	0.0	0.0	0.0	215.0	83-86
Bajil	6.6	1.4	11.7	27.5	43.9	35.9	15.6	57.8	89.2	32.4	32.5	12.1	366.6	72-82
Barh	13.2	3.3	19.2	36.4	52.8	25.0	28.0	26.6	83.0	33.3	5.9	3.4	330.1	81-91
Basat	0.1	15.4	12.7	10.3	39.9	24.0	24.3	53.0	78.1	45.6	3.9	6.3	313.6	78-91
Bawn (MAWR)	7.0	13.0	39.0	31.0	36.0	2.0	38.0	55.0	6.0	10.0	5.0	8.0	250.0	83-87
Dabaat	0.0	4.2	20.9	41.5	23.9	0.6	28.7	61.1	2.3	4.3	1.2	4.5	193.2	72-79
Dabira	10.5	10.0	25.6	50.6	29.4	16.7	27.9	30.4	33.1	11.4	6.3	8.3	260.2	78-91

STATION	JAN	FEB	MRT	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR	PERIOD
Dahi	0.8	5.0	1.7	12.6	13.8	0.7	7.1	36.4	37.3	17.1	1.3	4.2	138.0	84-92
Dar salem	2.8	0.0	6.3	48.1	58.7	0.0	1.5	30.2	0.0	0.0	0.0	11.9	159.5	83-85
Darb	6.9	10.7	93.3	50.3	33.2	28.5	58.2	84.4	20.0	6.5	28.4	11.1	431.5	76-82
Dar Najd	0.0	0.0	1.6	0.2	0.2	0.0	4.5	7.2	3.8	0.0	0.0	4.4	21.9	79-80
Dawran (GDH)	3.6	0.9	8.6	22.1	39.9	4.8	19.0	35.6	4.3	11.8	1.1	2.3	154.0	72-80
DelilSumara	3.5	15.4	56.4	93.1	87.9	61.1	116.4	156.6	70.3	20.9	17.7	2.3	701.6	70-91
Dhamar(RLIP)	0.5	25.2	36.1	71.4	54.1	3.4	37.2	84.9	15.5	4.0	0.0	5.6	338.0	83-88
Dhamar(DAFRD)	1.8	16.9	44.9	65.7	52.9	6.0	58.0	110.0	14.8	10.6	6.8	3.4	391.8	75-88
Dhamar	2.5	7.2	59.5	83.9	39.9	1.9	29.1	60.3	6.7	7.0	4.6	4.9	307.5	75-88
Dimnah(TDA)	4.0	4.1	19.4	27.1	55.9	16.2	40.5	54.9	77.2	47.3	15.2	16.6	378.4	78-91
Dumeid	3.6	4.3	8.2	27.6	30.2	2.3	12.4	25.9	3.4	1.5	3.2	1.7	124.3	83-92
Dutrat	0.4	25.2	16.4	35.8	37.9	3.0	16.3	49.6	5.9	0.0	0.0	11.0	201.5	83-86
Faqih,BaytAl	0.0	14.4	4.1	9.9	29.0	0.0	43.0	53.8	82.1	41.6	0.0	1.5	279.4	87-91
Fawwarah	14.5	14.9	60.9	47.3	21.6	16.7	28.8	30.8	12.3	6.2	6.7	2.2	262.9	79-91
Fulayh	0.9	0.0	24.7	34.9	38.3	24.4	23.7	51.6	46.7	22.8	4.4	0.3	272.7	70-74
Gawadir	17.2	28.4	20.8	43.5	62.5	24.1	54.2	54.9	86.3	55.6	30.8	29.2	507.5	78-91
Ghamr	3.3	8.8	29.7	73.0	68.6	26.1	35.2	70.1	28.2	12.5	11.2	7.3	374.0	84-92
Ghujla	0.5	8.9	4.5	22.8	0.5	0.9	2.5	4.4	1.3	6.9	0.0	1.3	54.5	88-92
Giblah	27.5	53.5	32.4	131.5	42.5	155.0	142.5	270.0	160.0	0.0	0.0	15.0	1029.9	88-90
Gudami	4.0	3.5	13.0	39.8	13.8	3.6	5.3	10.1	2.2	1.5	1.1	0.9	98.8	82-92

STATION	JAN	FEB	MRT	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR	PERIOD
Gumeisha(FAO)	2.5	2.8	11.3	4.7	1.1	0.0	3.1	45.1	33.6	15.5	6.0	0.1	125.8	72-77
Habaka/Girnah	2.9	8.4	15.4	35.8	23.7	34.0	77.9	84.0	33.3	3.0	2.9	0.3	321.6	78-91
Habashi	7.4	11.6	22.7	54.5	85.8	68.4	58.3	46.2	113.7	29.4	10.6	7.9	516.5	82-91
Haima	2.5	28.8	43.0	62.5	37.7	19.5	35.6	49.5	8.0	2.5	3.1	3.5	296.2	79-91
Hajer(RIRDP)	2.5	4.3	36.4	45.3	22.8	5.7	19.3	42.7	13.2	4.2	1.5	11.1	209.0	79-90
Hajdah	24.0	59.7	34.4	76.5	126.7	76.7	95.4	71.8	113.0	24.1	24.6	21.4	748.3	81-91
Hajjah(MOA)	10.5	16.3	62.3	88.8	61.9	27.3	73.1	82.7	34.3	1.8	5.5	11.8	476.3	86-91
Hajjah(TDA)	11.6	21.2	35.8	110.3	38.9	26.4	44.5	101.4	38.0	0.0	10.5	29.0	467.6	85-91
Hamal(TDA)	0.0	16.1	56.3	75.9	62.9	13.2	66.1	91.6	39.5	14.3	7.3	3.8	447	81-91
Hamamali	0.9	15.5	41.0	94.8	66.7	25.9	37.8	88.7	38.1	9.7	17.12	16.7	453	78-91
Harad	4.3	5.0	3.2	58.6	10.0	48.2	33.1	55.6	46.1	9.1	4.0	42.9	320.1	86-89
Har,Wadi	8.3	10.1	45.8	50.6	44.5	15.9	49.2	48.6	20.4	2.5	15.8	3.7	315.4	70-91
Hidad(TDA)	0.1	10.9	34.7	62.2	25.6	29.6	48.6	74.9	28.0	0.0	3.1	8.5	326.2	78-91
Hijrah(DAFRD)	1.6	11.4	46.1	63.5	26.2	8.9	28.1	27.9	9.5	13.1	5.4	5.0	246.7	80-88
Hijrah(GDH)	7.7	20.0	23.4	36.4	18.6	8.7	6.9	40.6	0.0	0.3	0.6	2.6	165.8	80-87
Hudaydah(TDA)	18.4	15.7	12.3	32.8	2.6	0.0	5.34	11.9	3.8	3.0	0.0	2.4	108.3	87-91
Huth	8.6	4.1	48.5	51.7	19.5	6.0	30.4	17.8	3.8	4.6	2.7	2.7	200.4	74-91
Ibb(MOA)	8.2	21.1	45.3	78.6	107.1	134.6	183.3	170.7	119.5	17.3	14.9	4.0	904.6	81-89
Ibb(TDA)	15.7	31.6	98.7	147.9	243.4	252.2	322.4	333.0	244.5	85.12	42.3	16.8	1833.6	70-91
Irra	0.5	1.3	12.5	51.8	10.3	1.3	36.8	51.3	7.0	0.0	1.3	9.3	183.4	886-89

STATION	JAN	FEB	MRT	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR	PERIOD
Jabri,Bayt Al	9.9	2.0	34.8	14.3	17.1	0.6	3.3	6.2	5.0	6.0	15.2	0.0	114.4	79-84
Jannat	4.0	1.4	26.4	34.0	24.8	11.8	17.7	78.9	16.5	20.4	4.8	0.0	240.7	75-80
Jarubah	7.0	12.5	23.0	19.5	49.8	11.6	22.0	61.6	100.0	56.6	0.4	3.4	367.4	85-89
Jawf	3.0	9.2	12.4	16.0	3.6	1.8	7.7	2.8	2.7	1.2	0.8	5.6	66.8	86-91
Jubah	0.4	8.3	13.1	33.9	1.1	0.2	8.3	8.2	1.1	0.0	0.0	4.1	78.7	87-92
Jubayr	0.0	4.9	28.4	52.0	17.4	2.5	1.9	5.2	22.2	13.8	3.0	10.6	162.5	85-87
Kadan (GDH)	0.0	17.9	8.0	1.1	52.4	22.4	28.6	83.1	98.9	70.5	37.2	3.8	423.9	72-75
Kadima,Harad Al	0.4	5.7	0.3	15.6	5.3	5.4	10.3	33.2	51.2	12.2	2.2	18.9	160.7	86-91
Kahal	0.0	17.6	46.4	178.5	55.2	21.7	70.7	83.6	18.7	0.0	0.0	0.0	492.4	85-86
Kamer	2.2	0.5	31.6	65.5	23.9	12.2	36.7	29.5	1.9	0.0	1.3	4.4	209.7	80-86
Kasabat Akwan	12.8	8.1	8.1	17.8	12.1	23.0	13.3	43.5	0.0	0.0	0.0	6.6	145.3	83-86
Ketab	2.3	39.2	21.9	36.7	37.8	12.0	44.0	79.0	40.7	10.2	16.3	19.4	360.0	87-91
Khabar	11.4	8.9	46.5	43.1	19.8	3.4	25.5	48.1	7.3	6.4	2.9	2.0	225.3	76-92
Khadrah(RIRDP)	3.5	12.6	49.4	41.7	20.7	2.4	21.7	35.4	8.7	2.3	4.3	3.0	205.7	81-92
Khadrah	0.4	5.7	0.3	15.6	5.3	5.4	10.3	33.2	51.2	12.2	2.0	18.9	160.5	86-91
Khamir(TDA)	0.0	7.7	24.7	77.8	9.8	9.5	21.5	41.3	3.0	0.0	0.0	10.7	206	86-91
Khamis(GDH)	1.6	7.9	5.7	49.9	53.6	35.4	55.9	81.8	47.0	6.9	0.5	6.1	352.3	84-91
Khamlu	0.0	9.3	8.9	52.0	47.7	20.3	26.7	83.8	39.1	4.9	2.2	6.2	301.1	84-91
Khasha'a	1.4	7.4	13.5	32.5	5.2	2.8	14.8	25.2	2.7	0.0	1.5	4.3	111.3	85-92
Kudeihah	7.8	18.3	5.8	22.2	27.2	3.8	2.3	7.8	25.0	14.4	8.4	1.8	144.8	82-92

STATION	JAN	FEB	MRT	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR	PERIOD
Kudmah Maraiya	0.0	0.8	7.6	17.0	27.0	11.6	31.7	76.3	88.0	41.4	1.6	11.2	314.2	87-91
Lahinah,wadi	25.0	12.7	22.8	150.0	31.9	157.1	91.4	147.9	57.7	17.2	0.0	2.5	716.1	86-89
Lahj	9.1	39.4	202.5	155.1	82.8	45.1	102.9	170.3	29.3	37.6	59.7	15.3	949.1	75-86
Mabar	2.3	9.2	60.2	62.8	32.4	5.6	27.6	36.7	8.1	36.8	6.8	2.5	291.0	75-86
Madaf	3.6	9.1	30.7	31.2	20.7	4.4	8.3	28.9	2.9	0.0	2.1	2.9	144.7	82-91
Mafhaq(GDH)	0.1	8.3	24.5	72.4	30.1	9.3	33.5	45.3	16.8	1.8	3.3	5.2	250.6	84-92
Magash	5.5	2.7	9.3	25.7	12.9	8.1	12.4	10.6	8.7	0.7	0.1	1.5	98.2	87-91
Maghreba	24.0	40.1	68.2	99.0	55.5	29.4	51.7	101.5	41.0	15.3	24.0	16.9	566.6	80-91
Mahabish(TDA)	28.2	24.6	48.8	199.3	62.0	16.1	25.7	99.4	35.0	17.3	20.4	22.8	599.6	75-91
Mahatt	3.9	12.4	9.9	7.9	23.6	7.8	22.4	38.5	34.8	15.5	3.8	3.4	184.0	78-91
Mahwit(TDA)	14.3	23.7	39.2	122.2	113.2	42.6	77.0	94.2	59.6	17.7	22.7	2.8	629.2	82-91
Mahwit(RDPM)	13.8	9.5	17.5	115.3	82.5	66.1	101.0	173.7	67.8	5.0	12.7	8.5	673.4	86-89
Mahwit(MOA)	1.4	12.6	4.9	99.6	16.3	46.6	69.5	103.0	56.1	22.0	0.4	8.4	440.8	87-90
Mai'na	20.5	8.3	18.5	146.7	82.3	60.1	136.7	210.4	92.3	30.8	15.9	0.6	823.1	86-89
Majhiz	1.5	4.9	32.7	66.8	139.2	1.6	20.4	82.1	0.0	0.0	0.0	3.3	352.5	83-86
Majz	9.2	10.6	10.7	31.5	28.3	14.8	11.4	28.1	0.7	0.0	0.3	1.9	147.5	83-87
Makarib	2.5	3.5	18.7	23.8	29.4	0.0	2.0	20.6	0.0	0.0	0.0	13.5	114.0	83-86
Manakha(GDH)	0.3	0.0	4.0	18.3	64.1	9.9	69.3	77.7	32.9	0.5	5.0	1.8	283.8	78-80
Manakha(MOA)	0.0	0.3	23.2	66.3	105.8	32.6	49.2	35.3	15.8	0.0	0.0	0.0	328.5	83-85
Manasih	3.0	4.8	20.0	45.6	10.9	0.3	15.1	18.9	5.2	0.0	0.0	4.0	127.8	83-91

STATION	JAN	FEB	MRT	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR	PERIOD
Manjidah	6.5	0.0	19.3	35.3	54.2	1.4	32.2	72.9	1.1	17.5	2.0	4.1	246.5	75-79
Magwalah	2.5	3.8	12.1	61.2	62.8	0.0	6.0	36.3	0.0	0.0	0.5	15.6	200.8	83-86
Maram	4.5	10.9	42.7	43.4	30.6	2.4	27.9	60.6	3.8	7.2	6.2	2.0	242.1	75-89
Marib(CAMA)	0.0	7.4	14.9	40.5	1.3	0.8	1.7	1.9	1.5	0.0	0.0	0.3	70.3	74-89
Masnaah	7.3	32.2	41.7	67.2	28.3	15.9	44.6	64.4	18.7	7.1	14.6	17.9	360.0	75-91
Maswarah	0.9	16.1	7.1	21.4	0.2	1.9	23.8	6.6	13.4	0.0	0.0	2.2	93.6	88-90
Mawsanah(MOA)	0.0	22.3	29.9	117.1	44.8	21.0	99.3	57.6	40.1	29.8	0.0	0.0	461.9	85-86
Mayan	2.0	12.7	24.3	67.0	32.7	5.6	30.6	51.9	3.2	4.6	3.3	9.7	247.6	84-92
Midi	4.3	17.0	0.1	22.7	0.2	0.1	0.4	3.3	10.9	11.6	1.4	36.8	108.8	86-91
Milh(TDA)	11.5	4.5	0.4	13.0	6.6	0.0	3.2	7.0	4.4	4.4	8.5	7.1	70.7	78-91
Mind	6.4	1.9	16.1	38.0	47.4	6.5	33.7	57.2	10.0	8.5	1.7	0.1	227.5	72-80
Mishrafah	16.7	23.2	35.6	29.0	63.8	18.3	43.9	64.9	41.9	17.1	5.3	10.7	370.4	78-91
Mokha	0.0	4.1	9.2	1.1	0.0	0.0	0.0	0.0	0.0	1.7	0.0	5.3	21.4	75-88
Muthef	8.6	8.8	22.6	49.3	25.7	6.0	17.3	29.7	3.7	2.5	1.3	7.5	183.0	82-92
NagilSam	0.0	16.3	15.6	64.8	1.8	0.8	23.4	15.5	2.3	0.0	0.0	2.7	143.2	87-91
Nuqabah	0.0	12.9	20.5	38.8	8.9	1.6	8.3	24.0	1.4	1.7	1.4	3.1	122.7	82-89
Ossefra	5.8	9.0	37.3	55.6	59.7	54.4	43.4	57.2	81.7	63.5	166.8	5.0	639.4	79-92
Qadam(MOA)	0.0	0.0	27.0	190.0	84.8	31.6	66.6	17.0	17.0	2.7	0.0	0.0	437.3	85-86
Qadam(GDH)	0.3	7.7	43.2	95.9	22.1	19.2	54.7	66.3	26.6	15.7	5.5	6.4	363.6	86-92
Qahmah(TDA)	2.7	15.7	27.3	11.3	56.9	15.9	41.0	50.5	67.6	27.3	2.4	4.5	323.1	78-91

STATION	JAN	FEB	MRT	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR	PERIOD
Qarry	0.4	13.1	26.7	35.0	14.9	5.5	6.3	14.5	12.7	0.0	2.7	1.1	133.0	83-91
Qarwah	0.4	13.1	24.2	32.9	33.7	2.2	12.8	34.7	4.3	2.9	0.0	10.5	171.7	86-91
Rada'a(RIRDP)	7.9	12.4	47.5	37.6	22.4	1.9	23.7	29.9	7.5	3.0	3.2	1.1	198.0	76-91
Rahaba	0.1	16.5	16.6	53.3	1.1	1.2	15.4	7.4	3.2	0.0	0.0	1.2	116.0	87-91
Raydah	3.5	1.5	21.5	35.3	43.2	4.0	39.1	87.7	13.2	0.0	2.2	0.4	251.6	75-82
Rihab	13.3	13.5	34.0	74.9	95.4	45.9	73.6	102.8	59.6	25.9	14.1	2.3	555.3	70-91
Risabah(DAFRD)	7.6	13.8	50.7	61.7	30.6	6.4	35.9	64.1	10.0	10.4	2.9	4.7	298.8	79-90
Rizwa	2.0	5.1	63.1	86.5	53.1	7.8	24.0	43.2	9.6	8.1	13.7	5.1	321.4	75-87
Robei	2.6	26.5	5.6	23.8	33.8	38.9	37.3	46.2	72.4	12.5	0.6	1.1	301.3	85-91
Rubat	0.0	16.8	18.5	32.4	11.8	4.8	18.5	31.3	8.4	1.8	0.0	0.0	144.3	87-91
Rujum(GDH)	1.3	8.5	23.4	65.5	58.6	39.8	77.9	157.9	60.0	6.0	1.6	6.3	506.3	84-92
SadahSalam (GDH)	2.7	3.8	9.0	19.8	18.0	6.6	14.9	26.7	1.8	4.5	0.3	1.2	109.4	83-92
Sahwah	21.8	14.7	17.0	33.5	29.9	8.2	4.4	17.9	0.0	0.0	0.0	0.0	147.4	83-86
Saidiyah	3.3	9.7	0.0	5.8	21.9	2.2	14.3	20.8	17.9	11.5	0.0	0.0	107.4	87-91
Salf	4.5	11.9	27.0	121.5	43.5	7.2	57.0	107.6	12.9	7.9	10.4	17.3	428.7	84-92
Salif	9.5	11.0	11.7	136.8	6.0	7.0	67.3	75.0	7.3	0.0	0.0	38.5	370.1	84-90
Sama Al Ulya	2.6	5.6	33.9	47.8	32.3	0.6	40.0	68.1	17.9	10.9	3.0	1.5	264.2	75-88
Sanaban	2.6	12.1	39.9	32.3	23.1	3.2	21.6	33.3	6.9	13.8	3.0	0.0	191.9	76-88
Sanam	6.7	29.5	60.4	88.8	28.2	13.6	38.8	73.7	22.8	7.5	1.4	9.4	380.8	78-91
Sana'a Airport	5.9	12.5	18.7	39.6	17.8	5.7	25.4	36.9	5.3	8.5	3.5	3.3	183.1	68-89

STATION	JAN	FEB	MRT	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR	PERIOD
Sana'a Town	5.0	7.0	26.0	50.0	31.0	5.0	50.0	77.0	6.0	6.0	8.0	4.0	275.0	32-83
Sana'a(GDH)	0.8	2.8	35.2	16.7	26.5	1.0	11.7	62.5	9.0	6.5	1.2	0.5	174.4	90-92
Sana'a	15.2	5.3	35.6	27.0	14.2	24.9	7.6	38.2	34.4	0.2	0.3	3.3	206.2	77-79
Saqayn	10.7	19.6	54.9	69.6	14.8	12.9	30.0	40.8	1.2	2.8	0.9	7.3	266.1	81-91
Shaharah	4.6	5.7	33.8	66.9	44.6	28.5	47.8	74.5	36.4	0.0	0.0	2.1	344.9	85-91
Shamir,Mahal	8.1	10.3	7.2	28.0	75.2	22.2	32.6	75.3	99.3	59.0	21.5	6.2	445.0	79-91
Shaqab	0.7	3.0	23.6	22.6	23.5	11.0	29.8	46.9	16.0	13.6	3.5	3.1	197.3	75-83
Sharq (DAFRD)	0.8	16.0	48.6	169.3	154.5	30.5	43.2	78.3	43.0	8.2	4.7	4.6	601.7	84-87
Sharq (TDA)	9.4	14.7	29.0	79.4	51.3	34.1	46.8	68.6	29.6	21.5	10.9	8.9	404.2	78-91
Sherwab	0.1	15.0	14.5	42.3	2.0	0.9	13.1	11.5	6.1	0.0	0.1	3.8	109.4	86-91
Shibam	3.7	9.5	36.8	82.5	46.2	25.9	70.7	101.0	11.2	7.5	5.0	5.0	405.0	75-91
Shu'ub	4.0	8.3	21.6	29.0	26.4	6.8	18.6	47.2	10.4	21.0	2.0	1.2	197.8	77-83
Sirwah	0.5	2.6	8.2	22.7	3.9	6.3	6.8	1.9	2.6	0.3	0.	2.9	58.7	87-91
Azaydiyah	0.7	1.9	0.5	16.5	6.2	0.8	7.6	23.1	26.9	18.3	1.1	4.7	108.4	86-91
Suknah	12.1	14.0	13.8	39.3	66.1	41.0	39.7	72.2	73.9	51.9	18.3	11.3	453.6	80-91
Surby	9.0	15.2	118.8	159.7	46.3	15.0	5.8	30.9	0.0	0.0	0.7	0.0	401.4	83-87
TaizYard	8.6	11.7	40.9	77.8	95.7	76.5	58.0	88.8	104.3	80.3	10.8	5.5	658.0	74-90
Tawilah	9.0	11.3	15.8	50.3	14.8	40.3	48.8	131.5	4.0	1.0	0.0	0.0	326.8	91-92
Thawban	0.2	5.2	21.3	40.5	4.7	6.3	18.0	14.3	1.2	0.0	0.0	0.6	112.3	87-92
Therhaan	3.3	0.2	3.9	18.3	28.9	3.1	20.8	4.2	2.6	0.4	0.1	0.0	85.8	80-86

STATION	JAN	FEB	MRT	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR	PERIOD
Thula	1.4	25.4	105.9	78.6	45.2	42.8	54.9	170.0	30.4	13.9	13.9	3.9	586.3	75-83
Tur(TDA)	2.4	5.2	13.7	69.6	74.7	45.1	62.0	119.1	96.2	39.0	12.3	4.2	543.5	75-91
Udein(TDA)	4.1	19.1	39.2	66.9	116.9	92.0	118.2	127.7	66.7	38.0	18.0	4.6	711.4	70-91
Uwair,Bani	6.5	14.1	20.3	42.9	15.9	4.5	15.6	34.1	1.9	1.6	0.0	3.0	160.4	75-91
Wagir	4.2	14.4	7.7	27.6	29.6	23.2	29.7	53.7	88.7	49.1	1.95	1.2	331.1	80-91
Wallan	3.1	13.5	58.0	89.7	18.6	0.4	17.9	30.6	6.1	11.3	2.3	9.5	261.1	80-91
Warazan	0.7	16.0	1.6	2.8	14.3	74.0	35.4	87.8	55.7	16.3	0.1	0.0	304.7	87-91
Wash'hah/Ahim	18.0	14.3	27.8	94.3	64.7	18.7	39.7	47.9	23.6	25.0	35.6	21.0	430.6	75-91
Yarim	11.1	33.3	86.1	89.4	97.2	42.3	105.3	183.3	44.5	13.7	8.4	7.1	721.7	70-91
Yusuf,Bani	1.6	2.4	20.7	81.5	56.6	39.5	105.4	125.1	37.3	5.5	3.7	5.5	484.8	85-92
Zabid Town	3.8	8.3	5.5	10.7	15.6	5.4	24.9	28.6	51.4	20.9	3.7	0.8	179.6	69-91
Zabid(Gerbah)	4.3	14.4	11.5	18.3	43.9	5.0	39.3	64.8	95.6	44.9	3.9	1.9	347.8	69-91
Zhar,Wadi	4.8	6.0	10.4	19.6	28.6	2.6	34.5	66.5	4.3	0.0	6.3	2.1	185.7	76-83
Zinkah,Deir	1.5	7.7	10.2	44.7	46.3	38.2	56.9	92.04	40.5	12.2	12.6	4.3	367.8	82-91
Zuhaif	10.2	13.2	18.5	70.3	84.6	35.0	53.6	105.6	45.9	19.0	13.6	13.7	483.0	84-92
Zuhrah	5.3	2.2	2.0	21.5	19.5	1.0	3.1	13.6	29.9	19.2	1.3	14.6	133.0	79-91
Zuwab	1.6	11.4	34.1	34.1	10.1	0.8	12.3	23.4	4.0	0.5	3.2	1.4	136.8	80-92

STATION	JAN	FEB	MRT	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR	PERIOD
A.Gharib	0.0	12.0	31.2	9.9	0.0	2.1	0.0	2.9	0.0	0.0	0.0	0.0	58.1	85-90
Al-Hagrain	0.0	5.7	6.9	12.1	0.0	0.6	2.2	2.6	1.2	0.0	2.0	0.0	33.3	88-91
Al-Haleh	0.5	8.3	9.3	21.0	0.0	1.0	11.0	14.8	7.0	0.0	0.0	0.0	72.9	85-91
Al-Jawadeh	0.0	5.9	32.5	24.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	63.0	88-91
Al-Khoribeh	0.0	9.4	18.5	18.9	6.1	0.7	14.4	9.0	1.3	0.0	0.0	0.0	78.3	85-91
Al-Khod	5.0	7.7	8.1	3.0	4.4	1.6	1.8	6.8	15.2	7.6	1.3	2.7	65.2	58-91
Al-Mashhad	0.0	8.6	5.1	3.4	0.0	0.0	3.7	5.1	1.9	0.0	0.0	0.0	27.8	85-91
Al-Minsaf	0.0	8.7	26.0	17.8	0.0	0.0	3.5	0.0	0.0	1.4	0.0	0.0	57.4	88-91
Al-Qatan	0.0	7.6	17.8	15.7	0.0	0.5	0.5	3.0	0.4	0.0	0.0	0.0	45.5	85-91
Al-Rudood	0.4	7.5	22.9	14.8	0.0	2.1	1.9	7.3	0.5	1.5	0.0	0.0	58.9	85-91
Al-Sufal	1.2	0.9	3.4	0.0	0.3	2.3	6.7	0.0	0.0	0.0	2.7	2.0	19.5	83-91
Alugubeih	0.0	6.8	8.7	37.5	0.0	0.0	3.3	4.7	3.6	0.0	1.9	0.0	66.5	85-91
Amd	1.5	2.9	7.5	15.8	6.1	2.3	1.8	6.9	0.9	0.0	0.0	0.0	45.7	88-91
Bahran	0.0	1.1	8.2	17.1	0.0	0.6	4.5	2.7	0.0	0.0	0.0	0.0	34.2	85-91
Beihan	0.0	2.6	8.4	36.0	18.5	1.3	4.9	9.7	1.3	0.0	0.9	0.0	83.6	82-88
Dhala	4.2	7.8	36.9	30.9	46.7	22.1	63.2	97.8	35.0	8.6	1.9	6.7	361.8	73-87
Fiyush	2.1	7.9	8.1	2.8	8.8	1.5	0.4	2.8	8.2	0.6	1.1	0.9	45.2	73-88
Gaidun	1.5	0.0	13.1	22.3	0.0	1.2	17.8	1.2	2.5	0.0	0.0	0.0	59.6	85-91
Ghail Bin Yumin	0.0	0.0	12.2	0.0	0.0	0.0	3.3	4.4	0.0	0.0	1.1	0.0	21.0	88-91
Giar	2.7	0.8	6.3	4.3	0.0	0.0	9.0	2.1	8.5	0.0	0.0	0.8	34.6	85-90

STATION	JAN	FEB	MRT	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR	PERIOD
Gol madram	1.7	5.9	24.7	7.9	14.3	18.8	21.3	16.6	34.8	8.3	2.2	7.8	164.3	73-85
Habilin	0.6	1.6	31.6	3.4	13.8	7.0	14.0	30.4	60.0	5.7	3.5	0.0	172.7	88-92
Jueimah	0.0	18.3	31.4	19.7	0.0	8.0	3.8	0.0	0.0	2.6	0.0	0.0	83.8	88-91
Karish	0.0	33.2	14.9	7.2	20.9	6.6	22.8	27.8	51.0	1.5	0.0	0.0	186.0	74-85
Katbah	0.0	14.5	2.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	16.8	88-91
Khalla	1.5	5.0	2.8	16.9	16.7	27.3	31.3	72.2	23.4	10.2	0.7	0.0	207.2	75-83
Khormaksar	5.8	6.9	5.1	5.1	5.0	0.3	2.0	3.4	5.6	2.9	2.3	6.0	50.4	48-90
Lahej	2.0	6.9	10.0	4.9	7.7	1.0	3.2	5.9	12.8	0.5	0.5	0.2	55.6	73-91
Milah	0.0	17.3	0.8	14.8	47.3	36.7	28.5	43.2	24.0	4.0	4.7	6.2	227.5	75.78
Moudia	1.0	22.9	39.8	20.6	35.8	13.9	11.3	14.8	69.9	4.8	0.0	0.0	234.8	82-90
Mukiras (DI)	0.0	12.0	3.2	4.5	4.5	5.0	35.4	31.6	19.4	2.5	0.0	0.0	118.1	77-88
Musaimer	7.6	31.2	17.3	15.6	64.5	12.9	52.0	48.0	74.9	30.2	5.1	2.7	362.0	73-84
Nissab (DI)	2.2	9.3	43.3	9.9	6.7	0.1	6.8	19.6	2.0	0.2	0.0	0.0	100.1	80-83
Nuqub	1.1	10.2	23.8	9.7	4.2	1.8	10.4	12.4	1.0	1.4	0.1	0.0	76.1	82-92
Orisma	3.3	5.2	20.2	15.8	51.9	27.0	40.1	89.6	75.2	15.1	1.8	0.9	346.1	73-85
Q.Bamasood	0.0	6.4	14.1	19.1	0.0	1.2	4.7	8.4	4.7	0.0	0.0	0.0	58.6	85-91
Qasm	0.0	9.0	43.0	23.7	0.1	6.3	5.1	6.7	1.1	0.0	0.0	0.0	95.4	85-91
Riyan	2.4	17.1	10.9	25.4	1.5	0.7	1.2	1.4	1.7	4.6	6.4	3.6	76.9	73-90
Sah	0.0	0.9	10.1	15.4	0.4	5.4	0.0	12.3	1.8	1.2	0.0	0.0	47.5	85-91
Seiyun	2.9	5.2	18.0	15.5	1.7	1.7	4.7	13.4	0.5	0.9	0.5	0.2	65.2	77-92

STATION	JAN	FEB	MRT	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR	PERIOD
Seiyun	5.9	4.7	6.5	13.5	1.3	5.9	1.1	13.4	0.1	0.0	0.1	0.1	52.6	80-86
Sharj Asharif	0.0	9.7	31.4	20.3	0.0	0.0	9.6	3.4	0.5	0.0	0.0	0.0	74.9	88-91
Shibam	0.0	9.5	14.5	18.8	0.0	6.7	1.9	1.2	0.2	1.2	0.0	0.0	54.0	74-91
Sidarah	21.2	0.6	2.6	11.7	1.9	0.8	0.0	0.5	26.4	4.0	0.1	1.4	71.2	84-91
Slasil	0.0	11.4	30.1	4.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	45.8	88-91
Sobeikh	0.0	7.8	7.7	14.1	3.3	0.0	21.9	7.5	1.8	0.0	0.0	0.0	64.1	88-91
Socotra	1.1	0.0	9.8	4.5	16.3	6.0	0.0	0.0	6.2	31.2	19.6	7.8	102.9	78-89
W.Banni Ali	0.0	0.0	3.4	0.0	0.0	0.0	3.0	8.8	0.0	5.0	0.0	0.0	20.2	90-91
Yabhoodh	0.0	0.0	11.7	4.9	0.0	0.0	0.0	0.0	0.0	1.9	0.0	0.0	18.5	90-91

AVERAGE MONTHLY VALUES OF METEOROLOGICAL VARIABLES

Note : the meteorological data are expressed in the following units:

rain: mm
relative humidity: %
solar radiation: $cal.day^{-1}cm^{-2}$
temperature: °C
wind speed (at 2 m): m/s
sunshine duration: hours/day

STATION	VARIABLE	PERIOD	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR
Barh	rain	81-91	13.2	3.3	19.2	36.4	52.8	25	28	26.6	83	33.3	5.9	3.4	330.1
	temp.	83-91	25.3	25.4	27.6	28.5	28.8	30.1	31.2	31.6	30.1	29.3	27.7	25.8	28.45
	rel. hum.	83-91	72.8	74.3	74.5	69.8	72.2	67.8	66	65.3	67.8	62.5	58.1	71.3	68.5
	wind speed	83-91	1.4	1.6	1.9	2	1.6	1.9	2.2	2.3	1.7	1.6	1.6	1.3	1.7
	solar rad.														
	daily sun	83-91	6.9	5.6	6.1	6.3	8.5	7.7	5.1	6.5	6.7	8.7	9.6	7.9	7.1
Dahi	rain	84-92	0.8	5.0	1.6	12.6	13.8	0.8	7.1	39.2	34.5	17.1	1.3	3.7	138
	temp.	84-91	25.1	25.5	27.7	29.3	32.3	34.1	34	34	33	30.9	28	26.8	30.1
	relat. hum.	84-91	62.6	64.8	60.7	52.9	50.3	45.5	43.2	48.4	52.9	51.1	51.9	58.8	53.4
	wind speed	89-91	0.98	0.91	1.11	1.04	0.87	0.90	1.32	1.16	0.85	0.91	0.99	0.99	1
	solar rad.	87-91	368	381	434	513	530	527	465	470	476	481	449	379	456
	daily sun	84-88	7.26	6.38	7.05	8.01	8.09	7.28	5.26	5.16	6.03	8.40	8.51	7.22	7.35

STATION	VARIABLE	PERIOD	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR
Dumeld	rain	83-92	3.6	4.3	8.2	27.6	30.2	2.3	12.4	25.9	3.4	1.5	3.2	1.7	124.3
	temp.	83-92	14.1	16	18.2	19.3	22.1	24	24.2	23.4	22.3	18.3	14.7	14.2	19
	relat. hum.	83-92	42.4	43.6	36.6	39.5	23.4	16	27.5	34.4	15.9	15	22	36.2	29.4
	wind speed	87-92	1.08	1.23	1.28	1.23	1.39	1.65	1.62	1.47	1.75	1.54	1.17	1.12	1.38
	solar rad.	86-92	410	439	488	488	524	505	460	441	506	497	438	385	465
	daily sun	83-86	8.94	9.37	7.02	7.38	7.24	7.41	6.80	6.60	7.42	8.73	9.02	9.14	7.92
Dhamar	rain	83-88	0.5	25.2	36.1	71.4	54.1	3.4	37.2	84.9	15.5	4.0	0.0	5.6	338
	temp.	82-88	12.2	14	16.3	16.7	17.7	19.4	19.6	18.7	17.7	14.6	12.8	12.1	16
	relat. hum.	82-88	62.1	61.6	62.8	65.5	60.4	53.1	59.7	69.1	55.2	49.2	54.7	63.4	59.7
	wind speed	87-88	.95	1.30	.93	1.08	1.40	1.35	1.62	1.27	1.22	1.03	.89	.91	1.16
	solar rad.														
	daily sun	82-88	9.4	8.7	8.4	7.9	8.9	8.7	7.3	6.7	8.7	9.4	9.2	6.3	8.3
Hajjah	rain	86-91	10.5	16.3	62.3	88.8	61.9	27.3	73.1	82.7	34.3	1.8	5.5	11.8	476.3
	temp.	86-91	20.5	22.1	24	24.2	25	26.2	26.5	26.5	25.5	24.3	18.1	19.9	23.6
	relat. hum.	86-91	60.3	60	57.3	57.7	53.4	48.5	53.6	55.6	51.3	48	54	58.5	54.8
	wind speed	86-91	1.36	1.44	1.42	1.20	1.28	1.22	1.37	1.13	1.17	1.27	1.35	1.16	1.28
	solar rad.	86-91	336	365	439	489	528	497	429	460	495	454	375	318	433
	daily sun														

STATION	VARIABLE	PERIOD	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR
Irra	rain	86-89	0.5	1.3	12.5	51.8	10.3	1.3	36.8	51.3	7.0	0.0	1.3	9.3	183.4
	temp.	86-89	13	15.3	17.7	18.1	19.5	21.1	22.1	21.6	19	15.2	13.1	13.2	17.4
	relat. hum.	86-89	37.7	35.6	32.6	50.2	32.8	27.2	35.1	46.9	32.6	26.8	29.2	39.2	35.5
	wind speed	86-88	3.93	5.75	5.64	4.16	4.50	6.4	4.6	4.03	4.02	3.81	3.47	3.53	4.49
	solar rad.	86-89	220	200	213	211	210	183	207	204	217	207	178	160	201
	daily sun														
Jaroubah	rain	85-89	7.0	12.5	23.0	19.5	49.8	11.6	22.0	61.6	100	56.6	0.4	3.4	367.4
	temp.	85-89	25.7	27	28.6	30.9	32.5	34	34.1	33.4	32.4	30.5	28.2	26.4	30.3
	relat. hum.	85-89	63.1	64.2	63.1	55.2	56.1	52	51.7	55.4	61.9	64.8	57.7	63.7	59.1
	wind speed	85-89	2.68	2.78	2.63	2.75	3.25	3.37	4.55	4.35	2.55	2.54	2.73	2.55	3.06
	solar rad.	85-89	394	407	444	518	532	493	444	456	460	495	452	390	457
	daily sun														
Jawf	rain	86-91	3.0	9.2	12.4	16.0	3.6	1.8	7.7	2.8	2.7	1.2	0.8	5.6	67.0
	temp.	86-91	19.5	22.7	26	26.8	28.9	31.6	32.8	32.5	29.9	25.2	21	19.6	26.5
	relat. hum.	86-91	32.2	30.3	28.5	31.9	16.6	16.5	20.3	21.8	14.8	13.4	16.6	25.4	22.3
	wind speed	86-91	2.35	2.86	2.92	2.72	2.72	2.98	5.55	5.23	3.94	3.57	3.18	0.15	3.43
	solar rad.	86-91	489	528	580	615	608	645	572	563	605	589	543	487	569
	daily sun														

STATION	VARIABLE	PERIOD	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR
Ketab	rain	87-91	2.3	39.2	21.9	36.7	37.8	12	44	79	40.7	10.2	16.3	19.4	360
	temp.	87-91	9.7	10.9	12.2	13.4	15.0	15.9	16.6	16.5	14.9	11.8	8.7	8.9	12.9
	relat. hum.	87-91	42	44.2	41.6	42.7	37.9	42.6	52	53.2	46.6	37.6	32.6	32.8	42.1
	wind speed	87-91	2.05	2.13	2.06	2.02	2.28	2.32	2.41	2.11	2.16	2.19	1.93	1.90	2.13
	solar rad.	87-91	462	487	525	518	565	526	456	344	508	532	493	448	497
	daily sun														
Khabar	rain	76-92	11.4	8.9	46.5	43.1	19.8	3.4	25.5	48.1	7.3	6.4	2.9	2.0	225.3
	temp.	78-91	13.5	15.4	17.6	18.7	19.9	21.3	22.2	22.1	19.6	15.8	13.6	13.6	17.8
	relat. hum.	78-91	51.0	51.8	56.3	57.0	49.5	41.7	47.6	55.2	46.8	44.4	48.5	52.9	50.2
	wind speed	78-91	1.20	1.46	1.56	1.65	1.84	2.20	2.58	2.20	1.90	1.51	1.19	1.19	1.71
	solar rad.														
	daily sun	78-91	9.75	8.79	8.73	8.31	9.49	9.34	7.27	7.25	8.64	10.13	10.27	9.80	8.98
Khalifah	rain	87-91	4.3	45.3	4.9	51	31.2	27.9	18.8	78.9	132.8	76.5	0	8.6	550.8
	temp.	87-91	25.7	26.9	25.2	30.8	32.8	33.6	33.9	32.9	31.6	29.4	27.8	26.4	26.8
	relat. hum.	90	83	86	78	69	83						52	58	62
	wind speed	87-91	1.1	1.1	1.1	.9	.9	1	1.4	1.2	1	.9	.9	2.7	1
	solar rad.														
	daily sun	87-91	6.5	5.6	5.7	7	8.4	7.1	6	7.2	8.4	6.2	8.5	8	7.2

STATION	VARIABLE	PERIOD	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR
Kudeihah	rain	82-92	7.8	18.3	5.8	22.2	27.2	3.8	2.3	7.8	25.0	14.4	8.4	1.8	144.8
	temp.	83-91	27.8	28.1	30.2	31.8	32.9	33.5	33.9	33.8	32.7	31.2	28.7	26.8	30.6
	relat. hum.	83-91	66.5	72.3	68.7	69	66	64.5	64.2	64.3	62	62	61.5	65.8	65.5
	wind speed	83-91	3.1	3.1	3.1	3.1	2.5	2.6	2.8	3.1	1.9	2.3	2.9	3	2.8
	solar rad.														
	daily sun	83-91	7.3	6.7	7.6	8.1	9.1	7.6	4.6	7.3	7.1	9	9.9	8.2	7.7
Magash	rain	87-91	5.5	2.7	9.3	25.7	12.9	8.1	12.4	10.6	8.7	.7	.1	1.5	98.16
	temp.	87-91	15.6	17.4	19.8	20.4	23.3	24.5	25.3	24.8	22.8	19	15.9	14.8	20.3
	relat. hum.	87-91	48.4	46.1	40.2	42.3	25.7	27.2	35.3	41.4	26	23.2	27.1	37.9	35.1
	wind speed	87-91	2.68	3.24	2.97	2.72	3.04	2.88	3.02	2.67	3.30	2.99	2.30	2.30	2.84
	solar rad.	87-91	437	466	540	536	609	590	518	501	559	543	483	421	516
	daily sun														
Marib-MOA	rain	85-89	.8	10.7	8.3	28.7	1.3	9.5	23	4	1.5	4	3.8	4.5	79.2
	temp.	86-89	17.9	22.2	25.6	26.3	27.9	31.7	33.3	33	29.6	25	21.2	19	26.1
	relat. hum.	86-89	34.3	31.2	33.6	40	15.8	14	16.6	17.8	13.4	14.3	19.4	33.2	22.6
	wind speed	86-89	1.45	1.78	1.86	1.87	1.72	3.90	4.3	3.81	4.28	3.01	2.53	2.43	3.36
	solar rad.	86-89	464	508	522	274	604	598	548	540	584	561	510	454	514
	daily sun														

STATION	VARIABLE	PERIOD	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR
Ossefra	rain	79-92	5.8	9.0	37.3	55.6	59.7	54.4	43.4	57.2	81.7	63.5	166.8	5.0	639.4
	temp.	79-92	21.3	22.1	24.1	25.3	26.6	27.2	26.5	26.1	26.5	24.6	23.3	22.0	24.6
	relat. hum.	80-89	61.3	60.9	54.6	51.9	51.8	52.8	56.3	58.5	55.5	49.7	51.2	57.6	55.2
	wind speed	79-88	2.0	1.6	2.0	2.2	1.5	1.2	1.3	1.2	1.2	1.8	1.8	1.9	1.6
	solar rad.														
	daily sun	80-89	8.3	10.0	7.9	7.9	8.5	8.0	7.1	7.0	7.8	8.9	9.1	9.0	8.1
Risabah	rain	79-90	7.6	13.8	50.7	61.7	30.6	6.4	35.9	64.1	10.0	10.4	2.9	4.7	299
	temp.	81-88	12.3	14	16.5	17.3	18.6	19.3	19.6	19.3	17.6	14.3	13	11.8	16.1
	relat. hum.	88	44.65	41.65	30.1	31.95	21.3	22.5	51.2	62	58.05	40.15	43.55	47.3	41.2
	wind speed	81-88	1.86	2.14	2.19	2.07	2.22	2.35	2.51	2.38	2.18	2.03	1.80	1.71	2.12
	solar rad.														
	daily sun	81-88	9.5	9.2	8.3	7.9	8.1	8.4	6.7	6.5	8.7	10.2	10.1	9.5	8.6
Zabid (GERBA)	rain	69-91	4.3	14.4	11.5	18.3	43.9	5.0	39.3	64.8	95.6	44.9	3.9	1.9	347.8
	temp.	70-91	25.2	26.1	29.2	31	31.8	33.7	33	32.6	31.2	29.5	26.9	25.4	29.6
	relat. hum	70-91	69.3	69.3	64.4	61.5	59.2	57.1	56.4	56.6	62.3	63.9	66.6	68.8	63.0
	wind speed	79-91	1.3	1.3	1.6	1.6	1.7	1.6	1.9	2.2	1.5	1.1	1.1	1.1	1.5
	solar rad.														
	daily sun	79-91	7.2	6.9	6.7	7.8	8.2	6.8	5	6.1	7.3	8.9	9.5	8	7.4

STATION	VARIABLE	PERIOD	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR
Zuhrah	rain	79-91	5.3	2.2	2	21.5	19.5	1	3.1	13.6	29.9	19.2	1.3	14.6	133
	temp.	80-91	25.6	28.7	28.5	30.3	32	33.5	33.6	33.3	31.9	30.3	28.1	27.3	30.3
	relat. hum.	86-91	68.8	66.6	85.3	62	64	63.8	61.6	63.2	59	52.5	50.9	56.7	61.2
	wind speed	80-91	2.1	1.7	1.9	1.8	1.7	1.7	2	1.9	2	1.3	1.3	1.5	1.7
	solar rad.														
	daily sun	80-91	5.6	5.5	4.7	7.3	6.7	4.9	5.2	5.2	6.4	7.6	8.7	7.1	6.2
Sana'a (CAMA)	rain	88-89	5.9	12.5	18.7	39.6	17.8	5.7	25.4	36.9	5.3	8.5	3.5	3.3	183.1
	temp.	83-90	?	16.8	19.1	19.6	21.9	23.5	24	23.5	21.4	18.5	15.7	13	19.2 ?
	relat. hum.	83-90	46.3	49.9	49.4	57.8	43.8	41	35.8	47.7	39.4	38.7	39.5	39.4	44
	wind speed	85-87	2.8	2.7	3.2	4.4	3.8	4.8	4.6	4.3	3.2	2.9	2.4	2.8	3.5
	solar rad.	85-89	340	379	411	382	456	424	402	393	444	431	342	334	395
	daily sun	86-89	10.4	4.6	4.2	7.7	10.1	9.6	7.8	7.6	9.5	10.6	10.2	9.6	8.5
Sana'a (GDH)	rain	90-92	0.8	2.8	35.2	16.7	26.5	1	11.7	62.5	9	6.5	1.2	.5	174.4
	temp.	90-92	15.5	17.2	16.6	19.6	21.4	23.1	22.1	26.3	21.2	18.2	14.7	16.3	19.4
	relat. hum.	90-92	35.6	36.6	35.6	33.7	43.6	29.6	34.3	34.2	16.2	14.6	20.5	33.2	30.6
	wind speed	90-92	1.2	1.3	1.2	2.2	.99	1.04	.86	1.1	1.1	.9	.6	.7	1.1
	solar rad.	91-92	400	433	530	553	547	613	454	472	540	545	446	408	495
	daily sun														

STATION	VARIABLE	PERIOD	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR
Hudaydah	rain	63-89	8.8	9.8	9.7	19.7	4.7	0.1	16.5	14.0	6.2	2.1	2.6	7.3	101.5
	temp.	83-90	25.1	26.1	27.3	29.6	31.4	32.7	33	32.6	32	30.3	27.1	25.4	29.4
	relat.hum.	83-90	79.5	79.8	81.3	80.1	78.3	75.6	74.4	73.9	70.8	75	74.4	79.5	76.9
	wind speed	83-90	4.9	5.2	5.2	4.8	5.3	4.0	4.6	4.6	4.1	4.3	4.6	5.0	4.7
	solar rad.	84-88	415	413	454	507	492	466	413	436	426	464	442	402	444
Mukha	rain	75-79	0.0	4.1	9.2	1.1	0.0	0.0	0.0	0.0	0.0	1.7	0.0	5.3	21.4
	temp.	83-90	25.4	25.8	27.4	29.1	31.1	32	32.4	32.2	32.2	29.4	27.5	25.7	29.2
	relat.hum.	84-90	75.4	73.4	72.8	73.5	74.5	75.8	75.4	77.2	75	71.4	70.4	74.1	74.1
	wind speed	83-90	6.3	5.2	6.1	5.4	4.2	2.3	2.0	2.3	2.9	6.0	8.0	5.7	4.7
	daily sun	84-88	6.8	8.9	8.7	9.2	8.7	6.7	6.0	7.2	7.4	9.9	10.2	9.3	8.3

STATION	VARIABLES	PERIOD	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR
Al-Khod	rain	58-91	5	7.7	8.1	3	4.4	1.6	1.8	6.8	15.2	7.6	1.3	2.7	65.2
	temp.	76-91	23.1	23.6	26.3	26.2	29.6	29.1	26.9	26.2	26.1	24.1	23.5	21.4	25.5
	relat. hum.	58-68, 71-91	75	76	77	76	77	74	74	75	77	76	74	74	75
	wind speed	72-91	1.8	1.9	1.9	1.7	1.5	1.6	1.8	1.6	1.4	1.4	1.2	1.6	1.6
	daily sun	58-68, 76-91	8.1	8.5	8.5	8.9	10.2	8.9	7.9	8.4	8.6	10	10.4	8.7	8.9
Giar	rain	85-90	2.7	0.8	6.3	4.3	0.0	0.0	9.1	2.1	8.5	0.0	0.0	0.8	34.6
	temp.	85-90	23.6	25.6	26.1	27.6	29.3	31.5	31.3	31.5	30.5	28	25.6	24.8	28
	relat. hum.	85-90	70.3	66.5	67.8	63.8	61.3	59.2	61.4	60	67.2	67.4	62.8	68.5	64.7
	wind speed	85-90	1.80	2.10	2	2	1.50	2.10	1.60	1.50	1.50	1.90	1.70	1.90	1.8
	solar rad.														
	daily sun	85-90	7.04	7.7	8.02	9.1	8.7	8.7	7.8	8.4	8.8	9.9	13.3	8.4	8.8
Nuqub	rain	65-66, 82-92	0.9	9.41	20.14	12.93	3.52	1.5	8.82	11.35	0.83	1.19	0.08	0.0	70.64
	temp.	65-66, 78-79, 82-92	18.7	20.6	23.3	23.4	27.1	30.6	31.7	29	28.1	26.1	21.5	18.1	24.9
	relat. hum.	65-66, 83-92	39	38	35	40	31	27	28	34	32	34	36	31	34
	wind speed	83-87, 90-91	1	1.5	1.9	2	1.6	1.4	1.7	2	1.6	1.4	1	1.3	1.5
	solar rad.	83-88	396	408	403	434	464	444	367	402	401	426	425	370	411

STATION	VARIABLES	PERIOD	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR
Dhala	rain	73-87	4.2	7.8	36.9	30.9	46.7	22.1	63.2	97.8	35.0	8.6	1.9	6.7	361.8
	temp.	77-87	17.9	19.1	20.8	22.4	24	26.4	25	24.8	23.9	21.4	19.1	18.9	22
	relat. hum.	77-82, 86-87	55	55	57	32	29	38	35	34	33	33	50	39	41
	wind speed	77-87	1.1	1.3	0.8	0.9	0.9	0.8	0.8	0.8	0.7	0.8	0.7	0.8	0.8
	solar rad.														
	daily sun														
Fiyush	rain.	73-88	2.14	7.9	8.2	2.8	8.8	1.5	.4	2.8	8.3	.6	1.1	.9	45.4
	temp.	73-86	24.2	24.4	26.2	28.7	30.8	32.6	32.5	32.2	31	27.8	25.5	24.6	28.4
	relat. hum.	73-85	71	69	68	64	65	62	63	62	69	67	66	40	66
	wind speed	73-88	0.5	0.7	0.7	0.6	0.5	0.5	0.6	0.6	0.6	0.5	0.5	0.6	0.6
	solar rad.	73-79, 83-86	371	424	481	508	512	502	466	466	463	468	461	412	406
	daily sun	80-91	7.6	7.7	7.6	8.5	9.6	8	7.6	7.8	7.8	8.8	8.7	8.3	8.2
Lahej	rain	73-91	2.0	6.9	10.0	4.9	7.7	1.0	3.2	5.9	12.8	0.5	0.5	0.2	55.6
	temp.	73-88	24.6	24.8	26.2	28.3	30.3	32.4	32.2	32.1	30.8	27.7	25.8	24.3	28.3
	relat. hum.	73-88	73	75	74	70	67	62	62	63	69	67	66	70	68.1
	wind speed	73-88	1.13	1.20	1.23	1.11	1.13	.98	1.14	1.15	1.01	1.16	1.04	1	1.11
	solar rad.	74-86	360	366	444	462	465	459	437	456	419	454	430	385	428
	daily sun	73-90	7	7.5	7.8	8.9	9.5	8.6	7.4	7.8	8	8.7	9.1	7.8	8.1

STATION	VARIABLES	PERIOD	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR
Selyun	rain	77-92	2.9	5.2	18.0	15.5	1.7	1.7	4.7	13.4	0.5	0.9	0.5	0.2	65.2
	temp.	77-92	18.8	22.1	20.8	27	30.4	32.1	32.8	31.9	29.3	24.8	21.2	21	26
	relat. hum.	77-92	55	50	46	43	37	32	33	36	40	40	44	51	42
	wind speed	77-92	0.8	1.0	1.1	1.1	1.1	1.0	1.3	1.2	1.0	0.9	0.7	0.7	1.0
	solar rad.	86-89	414	428	462	546	560	500	485	466	493	469	421	376	468
	daily sun	80-91	7.9	8.7	9.0	8.9	10.1	8.9	8.1	8.1	9.1	10.6	9.3	8.8	8.9
Sufal	rain	83-91	1.2	0.91	3.4	0.0	0.3	2.3	6.7	0.0	0.0	0.0	2.7	2.0	19.5
	temp.	88-89	23.5	25.3	26.5	27.8	30.5	32.1	33.7	32.4	32.0	27.0	25.8	23.3	28.3
	relat. hum.	84-89	81	72	71	74	76	69	62	61	68	72	81	70	71
	wind speed	78-88	2.5	2.8	2.9	2.8	2.7	3.2	3.0	3.3	3.2	2.2	2.3	3.0	2.8
	solar rad.	78-88	305	338	380	411	379	422	427	272	332	355	324	322	320
	daily sun	78-86	8.1	8.7	10.4	8.7	10.4	8.3	6.8	6.9	5.5	9.9	9.6	8.8	8.5
Meffiah	rain	75	0.0	0.0	0.0	0.0	15.9	15.9	24.5	27.3	43.4	0.0	0.0	0.0	127
	temp.	78-82	23.3	23.6	25.4	27.0	29.4	32.3	32.5	33.0	30.1	27.4	26.8	24.9	27.9
	relat. hum.	78-82	64	66	63	59	64	55	50	57	64	61	58	64	60
	wind speed	78-82	1.6	1.6	2.2	1.8	1.9	1.9	1.7	1.8	1.9	2.3	1.4	1.6	1.8
	solar rad.	78-80	284	303	321	370	374	427	334	400	363	521	513	450	388
	daily sun	78-79	6.9	0.6	10.1	9.9	10.2	6.1	7.6	7.9	6.7	8.0	6.0	6.8	7.8

STATION	VARIABLES	PERIOD	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR
Mukiras	rain	77-88	0.0	12.0	3.2	4.5	4.5	5.0	35.4	31.6	19.4	2.5	0.0	0.0	119.1
	temp	77-80,'88	13	13.9	16.7	17.7	19.5	22.8	20.9	20.6	19.4	16.4	14.3	13.2	17.4
	relat. hum.	77-80,'88	65	69	49	53	53.5	44.6	62	61	59	57.5	47.5	53	56.2
	wind speed	77-80,'88	0.79	1.81	1.92	1.96	1.37	1.30	1.15	1.14	1.18	1.41	2.14	1.42	1.47
	solar rad.	77-80,'88	215	257	413	316	367	290	243	288	299	398	374	347	317
	daily sun	78-79, 87-88	7.5	10	10.1	8.9	7.6	7.3	8.2	7.7		10.9			8.7
Nissab	rain	80-83	2.2	9.3	43.3	9.9	6.7	0.1	6.8	19.6	2.0	0.2	0.0	0.0	100.1
	temp.	80-84	19.1	21.9	24.8	26.6	28.5	30.8	32.3	31.2	28.7	24.4	21.4	18.9	25.7
	relat. hum.	80-84	49	54	51	47	42	36	42	44	42	42	46	48	75
	wind speed	80-83	1.8	1.9	2.2	1.7	1.6	1.6	2.1	2.0	1.7	1.4	1.3	1.3	1.7
	solar rad.														
	daily sun	80-84	9.7	8.9	9.8	9.5	10.7	10.2	8.4	9.0	9.7	10.4	10.2	9.9	9.7
Beihan	rain	82-88	0.0	2.6	8.4	36.0	18.5	1.3	4.9	9.7	1.3	0.0	0.9	0.0	83.6
	temp.	83-85	18.6	19.7	24.7	28.3	29	29.6	31.6	31.4	28.3	22.4	20	18.2	25.2
	relat. hum.	83-85	41	37	45	40	30	28	42	32	30	36	42	42	37
	wind speed	83-85	0.9	1.1	1.3	1.1	0.8	0.5	0.4	0.4	0.6	0.9	0.6	0.6	0.8
	solar rad.	84-88	413	323	425	421	416	414	366	372	401	438	406	371	397
	daily sun														

STATION	VARIABLES	PERIOD	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR
Socotra	rain	78-89	1.1	0.0	9.8	4.5	16.3	6.0	0.0	0.0	6.2	31.2	19.6	7.8	102.9
	temp.	78-82	26.0	26.2	27.8	29.6	31.1	33.4	32.0	31.7	29.4	27.0	26.7	25.7	28.9
	relat. hum.	78-82	68	66	66	65	66	48	45	45	77	72	68	68	63
	wind speed	78-82	1.6	1.6	1.5	1.1	1.5	3.2	3.7	2.8	1.9	1.2	1.5	1.3	1.9
	daily sun	78-82	6.7	8.2	8.4	8.8	7.8	7.7	9.3	7.2	9.8	9.8	8.9	7.7	8.4

AVERAGE MONTHLY AND ANNUAL RUNOFF
(in Mm^3)

WADI	CATCHM. AREA (km2)	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR	PERIOD
Mawr	7912	4.35	4.99	9.07	23.65	16.34	10.63	15.18	30.16	17.25	8.20	6.12	6.78	162.3	75-92
La'ah	1140	1.06	0.70	1.07	2.35	3.40	2.50	0.90	5.20	6.50	4.60	1.70	1.60	31.6	75-77
Surdud	2370	2.76	2.48	2.73	6.53	8.19	4.00	5.01	11.64	7.51	4.50	4.01	2.65	69.3	65-67, 84-91
Rima	2250	2.62	1.66	6.43	9.78	15.71	6.04	17.53	18.38	8.13	4.33	3.75	2.63	98.9	76-85
Zabid	4632	2.93	2.71	4.67	9.13	14.58	9.86	18.64	25.30	17.97	9.88	5.48	3.73	125.0	70-92
Rasyan	1990	0.48	1.09	0.74	1.41	1.40	1.47	0.88	0.89	2.02	2.56	0.66	0.19	11.9	81-84, 87-92
Tuban	5060	0.89	0.52	0.25	4.58	8.83	8.87	12.37	27.67	31.00	9.53	3.24	1.69	109.4	73-80
Rabwa	460	0.03	0.40	0.72	0.50	0.60	0.09	0.32	0.96	1.77	0.65	0.01	0.00	5.76	73-89
Bana	6200	2.37	2.87	5.15	18.19	14.30	5.83	21.08	44.49	23.89	8.32	3.15	2.71	169.9	51-77
Ahwar	6410	0.23	3.03	35.84	10.26	10.37	1.06	3.11	3.26	10.55	1.22	0.29	0.00	70.9	72-89
Adhanah	8300	0.00	6.24	9.08	36.33	14.93	0.63	2.47	10.82	0.94	4.05	0.21	1.83	87.5	87-94
Amd/Doan	6553													20.3	77,78-81
Al Ayn	1500													9.68	77,78-81
Sarr	2540													3.00	77,78-81

WADI	CATCHM. AREA (km2)	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR	PERIOD
Bin Ali	720													4.15	77,78-81
Juaymah	760													0.75	77,78-81
Idim	5485													41.3	77,78-81
Thibi	718													1.90	77,78-81
Masila	22500													51.0	77,78-81

Note : The mean annual flow volume is calculated as the mean of available complete annual flow volumes. The figure may differ from the sum of the monthly means if data for some of the months are missing.

MONTHLY AND ANNUAL FLOW VOLUMES, WADI MAWR - SHAT AL ERG
(in Mm^3)
Source of data: TDA, 1993

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL
1975	6.90	5.40	6.30	19.66	8.23	24.17	25.02	27.41	17.78	9.81	5.11	6.39	162.2
1976	4.45	4.01	6.38	22.84	18.03	13.33	23.77	33.32	24.02	11.79	10.96	10.45	183.4
1977	11.59	8.95	10.96	38.84	33.83	13.11	12.06	9.62	14.32	27.75	18.26	16.62	215.9
1978	20.71	19.27	17.36	20.14	40.12	20.28	36.11	50.65	42.88	27.50	28.33	21.11	344.5
1979	---	---	*5.80	5.46	18.53	3.41	9.75	---	---	---	---	*6.85	---
1980	3.40	*1.14	*0.19	7.94	*13.34	5.54	7.09	*65.65	19.53	*0.98	3.43	2.11	---
1981	*1.34	---	*5.68	*44.98	*26.24	*12.62	18.65	*14.76	8.08	4.09	3.25	---	---
1982	---	*0.14	6.05	35.40	26.11	8.45	12.10	31.14	*3.87	---	---	---	---
1983	3.43	6.90	5.12	14.95	12.06	14.95	6.44	7.21	7.30	3.55	2.29	1.35	85.6
1984	1.49	1.62	*0.80	*5.40	*20.16	*2.86	7.54	10.13	5.40	2.09	1.63	1.30	---
1985	3.28	1.13	16.17	40.65	16.32	8.39	14.08	18.38	10.68	4.65	2.07	2.37	138.2
1986	1.71	2.00	11.85	45.98	23.50	8.16	18.13	30.40	23.62	7.45	5.94	6.81	185.6
1987	1.99	3.06	11.67	23.82	13.64	4.88	5.21	24.06	6.16	2.09	1.42	1.48	99.5
1988	1.81	2.42	2.55	6.93	2.42	7.33	15.92	19.07	13.31	4.22	2.78	2.30	81.0
1989	1.78	1.57	13.71	40.88	10.00	23.78	8.16	33.06	13.16	3.24	0.98	1.42	151.7
1990	1.18	7.85	11.63	28.27	4.73	10.50	11.80	12.18	5.93	2.10	1.11	0.84	98.1
1991	0.89	5.08	6.78	25.02	12.90	1.00	13.90	15.04	8.02	2.44	1.94	4.00	97.0
1992	0.64	0.64	0.42	1.62	4.72	2.88	27.47	130.74	55.82	10.16	8.41	23.29	266.8
MEAN	4.35	4.99	9.07	23.65	16.34	10.63	15.18	30.16	17.25	8.20	6.12	6.79	162.3

* = data not complete   --- = data missing

MONTHLY AND ANNUAL FLOW VOLUMES, WADI SURDUD - FAJ AL HUSSEIN
(in Mm^3)

Source of data: WRAY/GDH (Mahyoub and Kamphuis, 1993)

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL
1965	5.73	5.52	5.76	7.31	4.90	4.72	8.54	12.05	5.60	6.19	6.66	4.18	77.2
1966	4.15	3.53	3.56	4.51	5.68	4.92	6.21	7.63	5.00	4.90	4.82	2.76	57.7
1967	2.33	1.77	3.03	7.98	6.00	5.18	5.46	28.39	14.46	9.45	6.48	3.32	93.9
1984	2.14	1.73	1.90	1.43	16.82	4.92	7.12	6.32	9.23	2.41	1.81	1.90	57.7
1985	1.61	1.28	2.33	13.30	12.91	4.12	5.01	7.58	6.01	1.69	2.26	2.12	60.2
1986	2.06	2.40	(3.16)	9.23	10.87	(4.28)	(8.79)	19.26	(6.89)	5.73	5.52	3.03	
1987	2.51	1.84	2.05	(13.6)	7.90	3.91	2.76	9.87	(3.11)	(2.01)	(1.68)	(1.47)	
1988	1.55	1.74	1.62	(5.65)	---	---	---	(20.9)	10.65	3.69	3.63	2.91	
1989	(2.33)	(1.08)	---	(15.0)	(1.99)	(0.22)	---	(2.0)	(0.24)	---	(1.61)	---	
1991	---	---	1.55	1.92	0.46	0.22	0.61	2.00	1.63	1.90	0.88	0.98	
MEAN	2.76	2.48	2.73	6.53	8.19	4.00	5.01	11.64	7.51	4.50	4.01	2.65	69.3

( ) = based on incomplete data or estimated values --- = data is missing

MONTHLY AND ANNUAL FLOW VOLUMES, WADI RIMA - MISHRAFA
(in Mm^3)

Source of data: TDA, 1993

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL
1976	1.72	1.11	4.84	26.72	19.34	15.44	10.45	10.65	7.16	3.42	3.67	1.40	105.9
1977	3.12	2.51	1.75	12.21	20.67	9.11	9.57	29.82	7.88	9.07	10.15	7.80	123.7
1978	8.37	---	---	---	---	---	---	---	4.46	3.36	3.00	2.84	---
1979	2.04	1.43	27.44	4.10	33.59	7.84	79.53	55.88	24.50	3.28	1.99	2.03	243.7
1980	1.60	1.53	1.64	2.35	7.20	4.71	7.98	11.97	6.49	2.34	2.19	1.22	51.2
1981	---	---	---	15.90	8.78	4.93	9.31	20.84	6.30	2.88	0.93	0.57	---
1982	2.49	1.53	5.52	5.45	8.57	2.70	7.60	8.92	5.89	11.68	11.03	5.28	76.7
1983	1.97	4.21	3.72	7.77	10.59	4.01	6.49	6.62	5.59	1.69	1.40	1.29	55.4
1984	1.48	0.63	4.95	0.70	21.42	3.64	17.50	9.81	5.79	2.47	1.79	2.23	72.5
1985	0.79	0.36	1.59	12.84	11.23	2.01	9.34	10.94	7.27	3.15	1.34	1.65	62.5
MEAN	**2.62**	**1.66**	**6.43**	**9.78**	**15.71**	**6.04**	**17.53**	**18.38**	**8.13**	**4.33**	**3.75**	**2.63**	**98.9**

--- = data is missing

MONTHLY AND ANNUAL FLOW VOLUMES, WADI ZABID - KOLAH
(in Mm^3)

Source of data: TDA, 1993

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL
1970	2.87	1.31	3.12	6.83	5.85	6.31	24.27	20.52	15.95	18.53	3.62	2.79	110.0
1971	3.25	2.16	5.01	5.11	13.21	8.13	18.49	27.52	25.78	8.78	5.80	2.99	126.2
1972	3.61	2.39	5.69	10.99	12.27	12.58	25.57	21.73	15.56	6.46	4.47	4.05	125.4
1973	3.87	2.03	1.29	2.18	5.59	7.00	12.82	31.23	17.99	6.73	0.03	1.99	94.8
1974	2.12	1.43	6.82	4.97	17.10	9.80	22.90	39.71	30.03	11.54	3.22	2.16	151.8
1975	2.50	2.36	3.23	9.31	5.03	10.26	39.36	83.50	50.27	17.00	7.58	5.71	236.2
1976	2.23	5.09	4.92	11.39	27.84	19.54	20.65	24.37	19.14	9.70	9.06	4.37	161.3
1977	5.29	3.55	3.37	8.25	34.53	15.73	11.58	19.53	29.55	48.09	36.23	21.88	237.5
1978	10.08	11.11	3.33	4.57	5.97	13.45	36.92	48.51	24.17	12.12	11.43	7.07	188.7
1979	6.02	8.07	10.26	18.31	14.06	23.25	55.57	30.46	10.00	4.92	3.83	---	184.8
1980	3.68	2.95	4.21	4.29	20.53	22.01	9.70	12.49	13.04	9.40	2.92	2.50	108.1
1981	1.12	0.92	26.90	15.02	23.65	13.87	25.48	19.58	14.76	6.93	3.39	2.42	154.0
1982	3.92	2.24	4.00	5.59	3.63	3.83	10.87	11.21	21.12	10.30	11.94	4.55	93.2
1983	3.76	4.11	4.04	46.77	12.28	5.24	9.79	8.41	13.62	5.17	2.88	2.28	118.4
1984	3.82	2.94	2.50	0.81	59.93	6.66	9.66	14.54	8.45	4.97	3.20	3.26	120.7
1985	2.06	1.85	1.04	7.87	7.96	7.05	7.88	8.96	8.61	3.54	1.50	1.05	59.4
1986	1.10	1.26	2.75	6.47	9.33	5.98	7.23	13.18	12.70	12.63	2.69	1.20	76.5
1987	1.32	1.13	7.76	9.14	12.91	8.28	13.42	26.64	20.07	7.22	1.32	0.69	109.9
1988	1.20	0.93	0.43	14.34	4.75	5.14	12.53	39.10	12.15	5.56	1.64	1.26	99.9

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL
1989	1.45	2.38	1.08	10.46	5.05	11.45	12.53	22.98	11.81	3.98	1.16	0.83	85.2
1990	1.23	1.45	0.63	3.90	8.42	2.86	20.47	29.22	16.99	3.20	0.49	0.30	45.8
1991	0.47	0.37	4.84	2.10	13.08	2.49	6.29	8.55	5.29	1.54	6.96	8.41	98.1
1992	0.46	0.29	0.17	1.42	12.32	5.96	14.76	20.06	16.30	10.99	0.61	0.34	89.3
MEAN	2.93	2.71	4.67	9.13	14.58	9.86	18.64	25.30	17.97	9.88	5.48	3.73	125.0

--- = data is missing

MONTHLY AND ANNUAL FLOW VOLUMES, WADI RASYAN - GORGE
(in Mm^3)

Source of data: TDA, 1993

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL
1981	0.40	0.02	0.62	3.94	---	---	*	*	---	5.65	1.49	---	---
1982	1.80	1.28	0.97	1.40	4.90	3.14	1.40	1.09	2.90	1.70	1.90	---	---
1983	0.76	3.55	2.13	4.51	3.12	4.12	1.72	0.85	2.43	2.84	1.55	0.72	28.3
1984	0.87	0.87	0.76	0.26	1.85	2.49	2.18	2.55	5.44	3.08	0.62	0.17	21.1
1985	---	---	---	---	---	---	---	---	---	---	---	---	---
1986	---	---	---	---	---	---	---	---	---	---	0.08	0.03	---
1987	0.02	0.11	0.09	0.62	0.09	0.07	0.05	0.04	0.04	2.54	0.12	0.15	3.9
1988	0.09	1.46	1.32	1.02	0.29	1.15	0.79	0.93	1.25	1.76	0.42	0.23	10.7
1989	0.20	2.28	0.37	0.41	0.17	0.41	0.29	0.16	1.02	1.10	0.20	0.12	6.7
1990	0.15	0.15	0.29	0.48	0.61	0.26	0.50	0.17	1.35	1.51	0.13	0.07	5.7
1992	0.07	0.07	0.07	0.07	0.15	0.10	0.13	1.30	1.72	2.90	0.10	0.00	6.7
MEAN	0.48	1.09	0.74	1.41	1.40	1.47	0.88	0.89	2.02	2.56	0.66	0.19	11.9

--- = data is missing

MONTHLY AND ANNUAL FLOW VOLUMES, WADI TUBAN - DUKEIM
(in Mm^3)

Source of data: GDC, 1981b

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL
1973	0.46	0.32	0.21	0.19	0.42	7.90	8.20	26.00	18.00	0.58	0.34	0.20	62.8
1974	0.19	0.08	0.09	0.75	9.50	13.40	13.40	21.10	18.10	2.85	1.18	0.56	81.2
1975	0.33	0.52	0.29	19.70	3.09	3.79	8.80	16.10	52.90	6.97	1.85	1.25	116.0
1976	0.80	0.51	0.35	5.55	5.13	4.58	6.77	7.28	6.79	3.91	2.99	1.16	45.8
1977	0.65	0.15	0.07	1.69	27.60	26.50	33.60	58.90	42.70	19.10	7.76	3.77	222.0
1978	1.91	1.65	0.52	0.55	13.10	3.04	4.67	48.70	57.10	30.70	5.92	2.13	170.0
1979	1.38	0.27	0.12	4.00	4.89	1.58	11.80	19.40	34.80	7.32	3.53	2.75	91.8
1980	1.40	0.65	0.35	4.18	6.93	10.20	11.70	23.90	17.60	4.83	2.31	1.68	85.7
MEAN	0.89	0.52	0.25	4.58	8.83	8.87	12.37	27.67	31.00	9.53	3.24	1.69	109.4

MONTHLY AND ANNUALFLOW VOLUMES WADI RABWA - SABA WEIR
(in Mm^3)

Source of data: Selkhozpromexport, 1990a

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL
1973	0.00	0.00	0.00	0.00	5.00	0.00	0.10	0.65	0.00	0.00	0.00	0.00	5.75
1974	0.00	0.00	0.00	0.00	0.25	0.00	0.25	0.00	5.82	0.00	0.00	0.00	6.32
1975	0.00	0.00	0.00	2.72	0.00	0.13	0.12	2.11	3.20	0.94	0.00	0.00	9.22
1976	0.00	0.00	0.00	0.45	0.25	0.00	0.75	0.50	0.45	0.55	0.00	0.00	2.95
1977	0.00	0.00	0.00	0.00	0.36	0.29	0.73	0.69	0.16	8.16	0.00	0.00	5.40
1978	0.00	0.80	0.00	0.00	0.00	0.00	0.95	1.05	2.15	0.00	0.00	0.00	4.95
1979	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.98	0.13	0.00	0.00	0.00	1.11
1980	0.00	0.00	0.00	0.72	0.00	0.00	0.00	2.48	0.00	0.00	0.00	0.00	3.20
1981	0.00	0.00	0.54	0.74	0.00	0.00	0.16	0.50	0.25	0.00	0.00	0.00	2.19
1982	0.00	3.16	7.30	0.00	0.92	0.00	0.00	0.37	5.63	0.20	0.18	0.00	17.76
1983	0.00	2.26	0.29	3.00	1.47	0.27	2.26	0.28	2.10	0.00	0.00	0.00	11.93
1984	0.00	0.00	0.00	0.00	0.42	0.90	0.00	0.48	0.40	0.00	0.00	0.00	2.20
1985	0.00	0.00	0.00	0.00	1.58	0.00	0.00	0.04	2.90	0.00	0.00	0.00	4.51
1986	0.35	0.20	0.30	0.75	0.00	0.00	0.00	3.20	1.30	0.25	0.00	0.00	6.35
1987	0.00	0.00	1.14	0.11	0.00	0.00	0.11	1.99	3.02	0.89	0.00	0.00	7.25
1988	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.92	2.57	0.00	0.00	0.00	3.48
1989	0.20	0.40	2.67	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.27
MEAN	0.03	0.40	0.72	0.50	0.60	0.09	0.32	0.96	1.77	0.65	0.01	0.00	5.76

MONTHLY AND ANNUALFLOW VOLUMES WADI BANA - BATAIS
(in Mm^3)

Source of data: Sogreah, 1980b

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL
1951	---	---	14.00	10.50	11.00	1.60	13.80	115.50	14.60	3.60	1.50	2.00	188.1
1952	1.50	0.80	1.10	11.20	2.70	3.70	11.70	54.30	32.60	0.50	0.40	0.90	121.4
1953	0.20	0.10	0.20	33.30	2.40	3.30	50.00	38.50	32.40	3.80	3.90	10.80	178.9
1954	1.40	2.40	13.50	10.60	8.80	14.60	66.60	88.10	43.20	16.30	7.30	6.10	278.9
1955	14.60	2.60	6.10	4.50	6.00	8.60	20.20	37.50	54.80	4.30	2.80	4.20	166.2
1956	2.30	1.30	0.60	12.90	1.10	2.00	14.80	51.30	18.50	20.50	1.50	1.20	128.0
1957	1.30	4.80	6.10	56.00	88.00	18.00	18.00	62.40	13.80	5.70	7.30	5.20	286.6
1958	5.70	3.80	2.50	10.30	0.30	2.10	17.30	31.50	6.40	2.20	2.10	1.80	86.0
1959	1.80	1.60	1.00	0.50	8.80	3.00	12.80	52.00	39.80	4.20	2.40	2.90	130.8
1960	1.90	1.70	13.50	21.20	30.30	2.00	10.00	11.70	17.80	14.00	1.10	2.30	127.5
1961	1.10	1.50	1.00	5.40	1.10	4.80	12.10	39.70	18.20	2.10	2.40	1.30	90.7
1962	0.40	0.40	3.10	5.80	2.80	11.60	8.00	67.80	46.70	2.10	1.40	1.20	151.3
1963	2.20	1.00	0.60	77.00	49.30	8.80	37.40	57.00	17.10	6.70	5.60	2.10	264.8
1964	2.00	1.50	0.50	37.30	4.30	4.50	50.60	62.30	33.60	12.50	2.50	3.90	215.5
1965	2.90	0.60	0.20	25.80	0.60	0.10	20.90	46.10	15.50	3.40	7.40	1.40	124.9
1966	2.20	7.60	1.20	4.60	---	3.10	11.70	29.50	32.30	2.70	1.90	0.20	
1967	---	---	3.80	18.20	50.70	---	41.40	20.90	13.60	---	---	---	
1968	0.30	6.10	1.80	24.70	11.00	7.00	48.40	40.70	27.50	4.90	6.00	0.50	178.9
1969	3.10	4.80	12.80	6.70	8.70	---	4.20	57.70	31.60	0.70	1.60	4.50	

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL
1970	3.90	0.90	30.50	15.60	5.30	---	22.30	39.70	12.30	6.70	0.10	0.30	
1971	0.20	---	5.20	5.10	27.60	11.00	9.40	13.50	10.50	---	---	---	
1972	---	---	---	---	---	---	---	---	---	---	---	---	
1973	0.20	---	---	---	0.80	0.70	0.80	8.70	20.00	64.20	0.20	---	
1974	---	2.00	2.60	0.20	5.90	6.20	10.30	---	---	---	---	3.20	
1975	---	---	---	---	---	---	---	---	---	---	---	---	
1976	---	13.00	1.00	19.70	13.30	5.60	8.80	5.40	3.30	2.00	6.80	0.90	
1977	0.60	1.70	0.70	19.40	2.30	6.00	5.60	36.00	17.30	---	---	---	
MEAN	2.37	2.87	5.15	18.19	14.30	5.83	21.06	44.49	23.89	8.32	3.15	2.71	169.9

--- = data is missing

MONTHLY AND ANNUAL FLOW VOLUMES, WADI AHWAR - FUADWEIR
(in Mm^3)
Source of data: Selkhozpromexport, 1990b

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL
1972	0.90	36.00	16.60	13.70	11.30	0.00	0.00	0.00	7.94	0.00	0.00	0.00	86.4
1973	0.00	0.00	0.94	0.00	6.27	0.00	0.00	0.00	9.05	0.00	0.00	0.00	16.3
1974	0.00	0.00	0.00	0.00	1.30	2.40	0.60	2.40	76.00	0.00	0.00	0.00	82.8
1975	0.00	0.00	0.00	11.30	0.00	0.00	0.00	0.00	16.60	0.00	0.00	0.00	27.9
1976	0.00	0.00	22.80	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	22.8
1977	0.00	0.00	0.00	51.00	109.90	0.00	0.00	0.16	0.59	5.20	0.00	0.00	16.5
1978	0.00	5.67	0.16	0.00	5.56	0.00	2.64	0.17	0.41	3.49	0.00	0.00	18.1
1979	0.00	0.00	0.33	0.00	0.00	0.00	0.00	0.38	0.27	0.00	0.05	0.00	1.0
1960	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.40	12.50	2.70	0.00	0.00	17.6
1981	0.00	0.00	129.40	0.00	0.00	0.00	1.48	1.15	1.56	2.00	0.00	0.00	136.0
1982	0.00	0.00	225.00	0.00	16.50	0.00	10.30	22.49	15.40	0.00	0.00	0.00	290.0
1983	0.00	12.90	0.00	0.00	0.00	0.00	0.00	0.00	0.00	5.10	0.00	0.00	20.5
1984	0.00	0.00	0.00	0.00	33.90	0.00	0.00	0.00	0.00	0.00	0.00	0.00	33.9
1985	0.00	0.00	0.00	0.00	0.00	0.00	11.83	0.00	6.87	0.00	0.00	0.00	18.7
1986	0.76	0.00	0.00	0.00	0.48	0.00	0.00	18.00	16.12	0.00	0.00	0.00	34.6
1987	2.53	0.00	6.52	0.00	0.65	2.63	0.53	1.25	0.00	0.00	0.00	0.00	11.6
1988	0.00	0.00	0.00	7.00	0.86	14.01	28.65	10.20	26.57	3.51	5.16	0.00	96.0
1989	0.00	0.00	243.40	101.70	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	345.1
MEAN	**0.23**	**3.03**	**35.84**	**10.26**	**10.37**	**1.06**	**3.11**	**3.26**	**10.55**	**1.22**	**0.29**	**0.00**	**70.9**

MONTHLY AND ANNUAL FLOW VOLUMES, WADI ADHANA - DAM
(in Mm^3)

Source of data: ERADA

YEAR	JAN	FEB	MRT	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR
1987	0.00	0.00	15.80	115.90	0.30	1.15	0.57	1.50	0.00	0.00	1.70	0.84	137.8
1988	0.00	10.36	3.48	32.29	2.07	3.87	19.21	8.35	7.49	0.38	0.00	0.00	87.5
1989	0.00	0.08	13.50	34.70	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	48.3
1990	0.00	22.22	0.00	23.00	4.28	0.00	0.00	0.00	0.00	0.00	0.00	0.00	49.5
1991	0.00	0.00	13.00	11.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	24.0
1992	0.00	1.04	4.84	7.72	5.45	0.00	0.00	65.70	0.00	32.00	0.00	13.80	130.6
1993	0.00	16.18	8.00	64.00	107.34	0.00	0.00	0.00	0.00	0.00	0.00	0.00	195.5
1994	0.00	0.00	14.00	2.00	0.00	0.00	0.00	11.00	0.00	0.00	0.00	0.00	27.0
MEAN	0.00	6.24	9.08	36.33	14.93	0.63	2.47	10.82	0.94	4.05	0.21	1.83	87.5

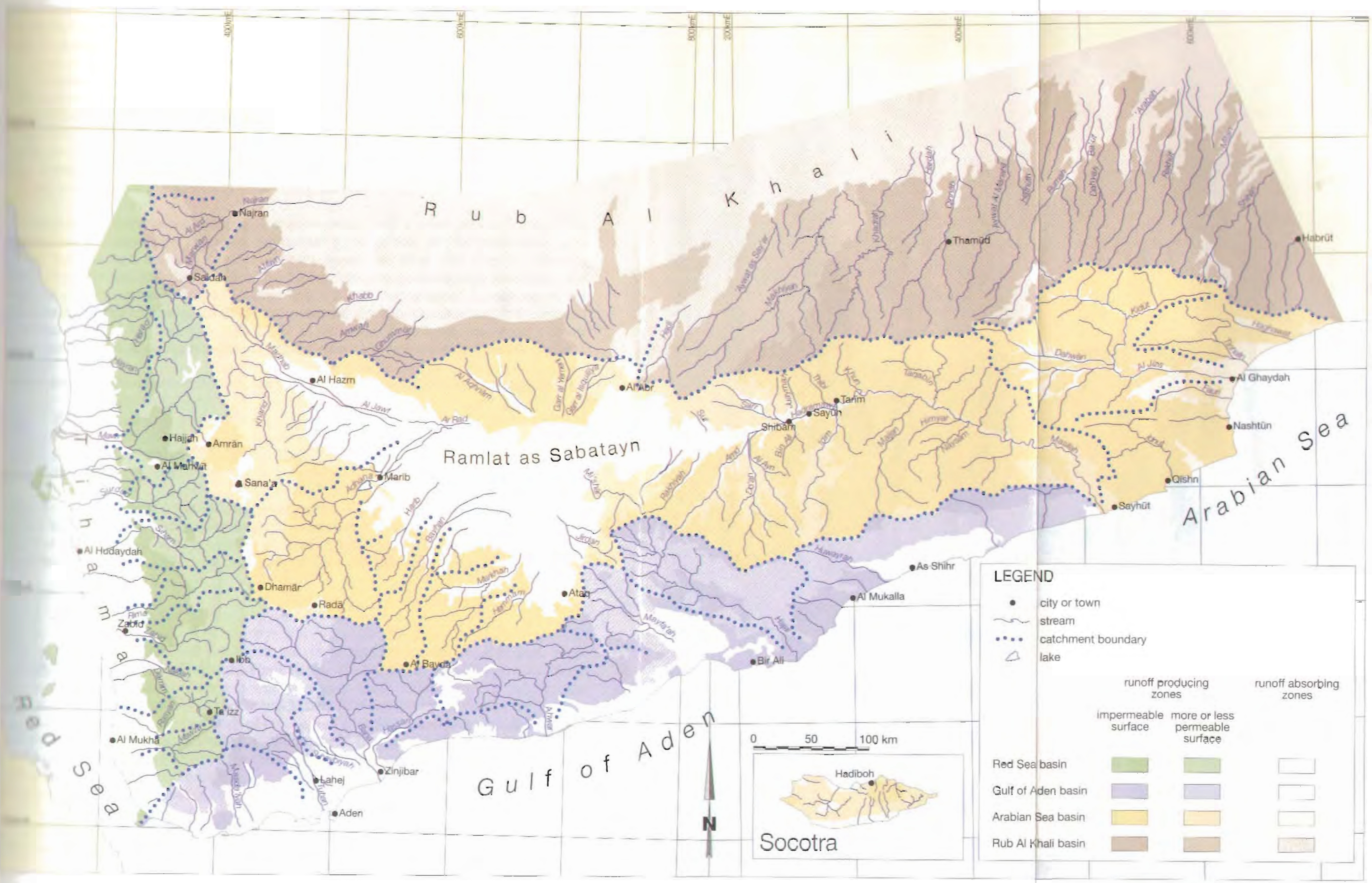


Figure 5.1 Main surface water systems in Yemen

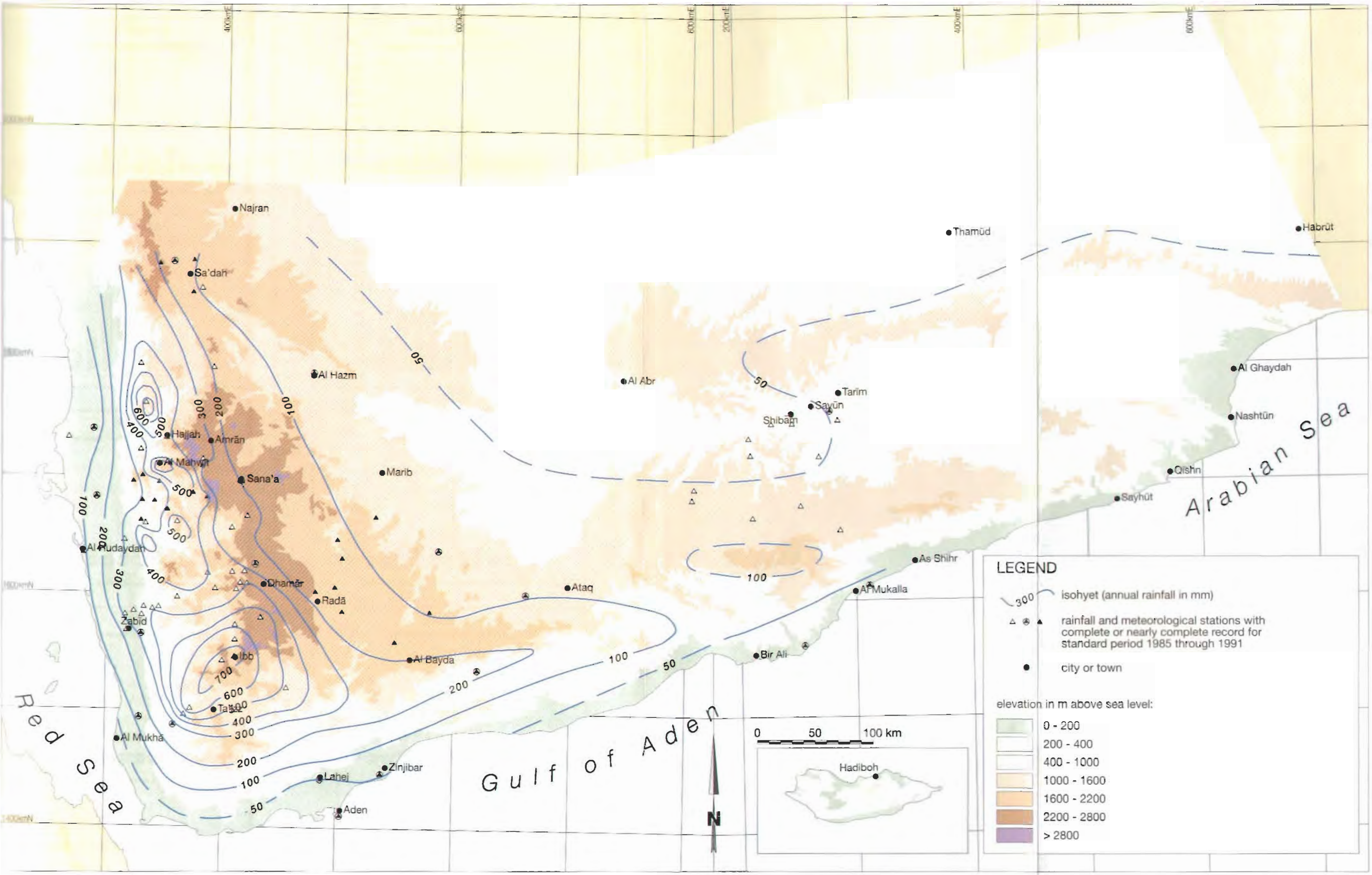


Figure 4.5 Average annual rainfall, period 1985 through 1991

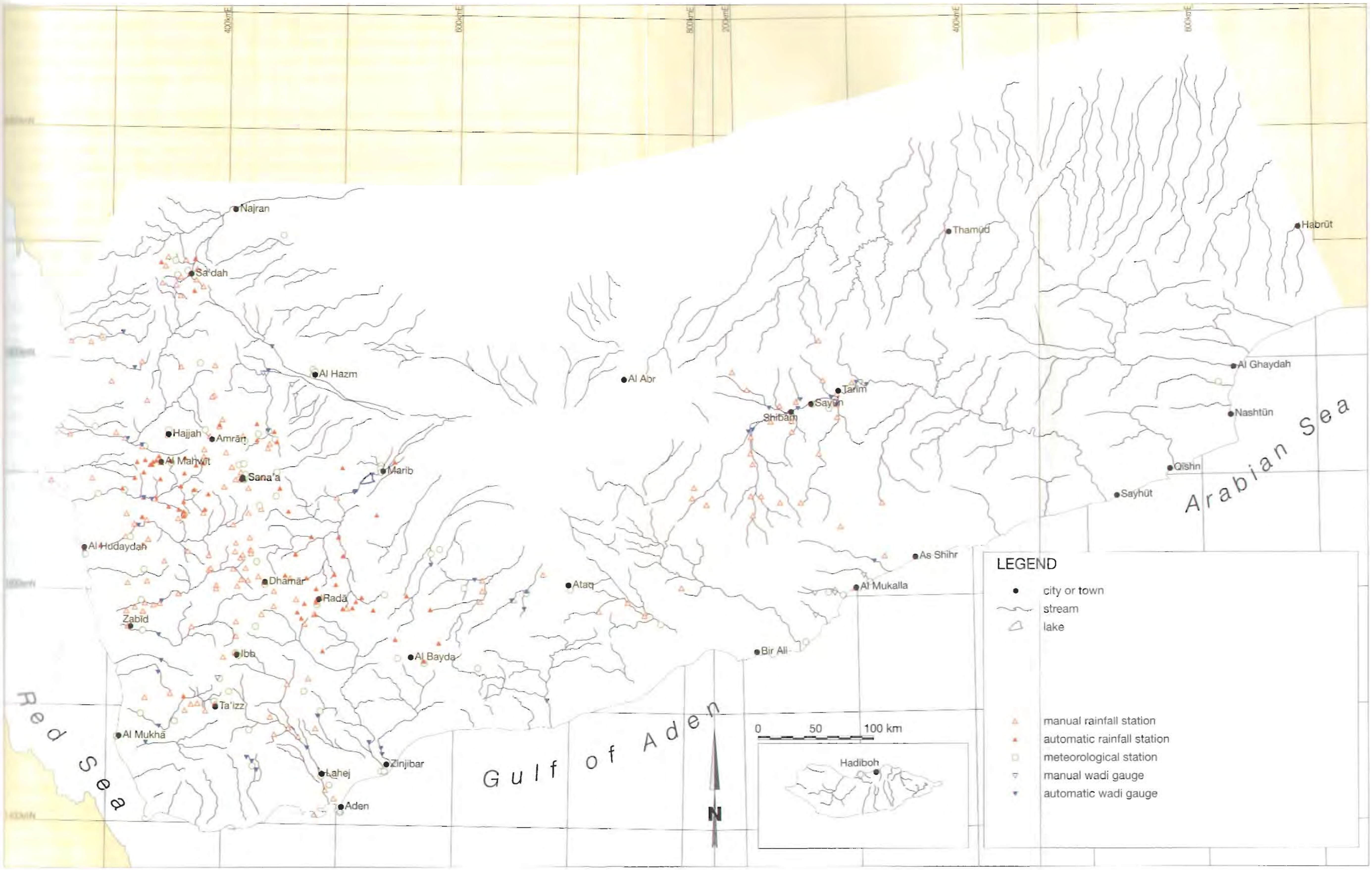


Figure 3.1 *Hydrometeorological monitoring stations in Yemen*

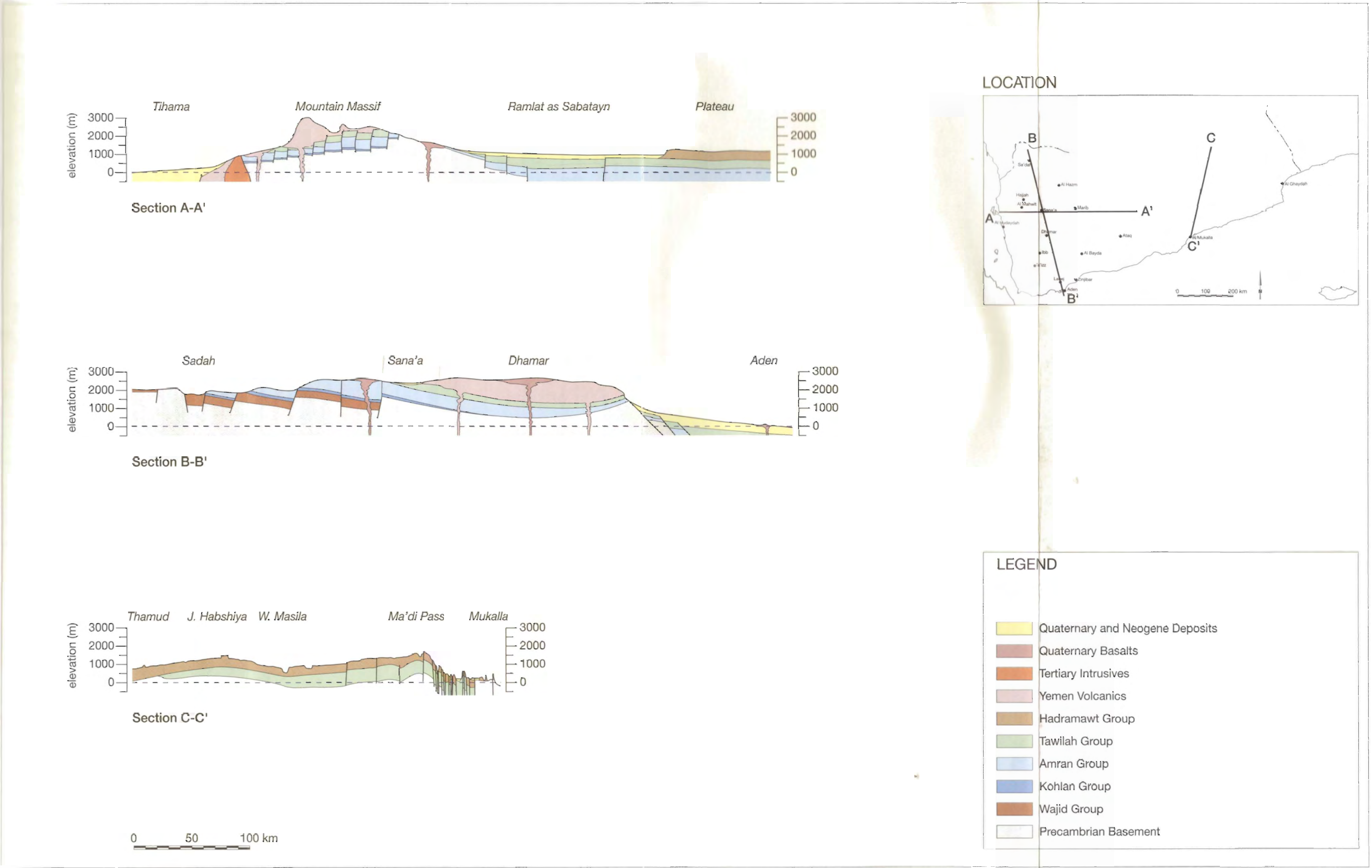


Figure 2.4 *Schematic geological cross-sections*

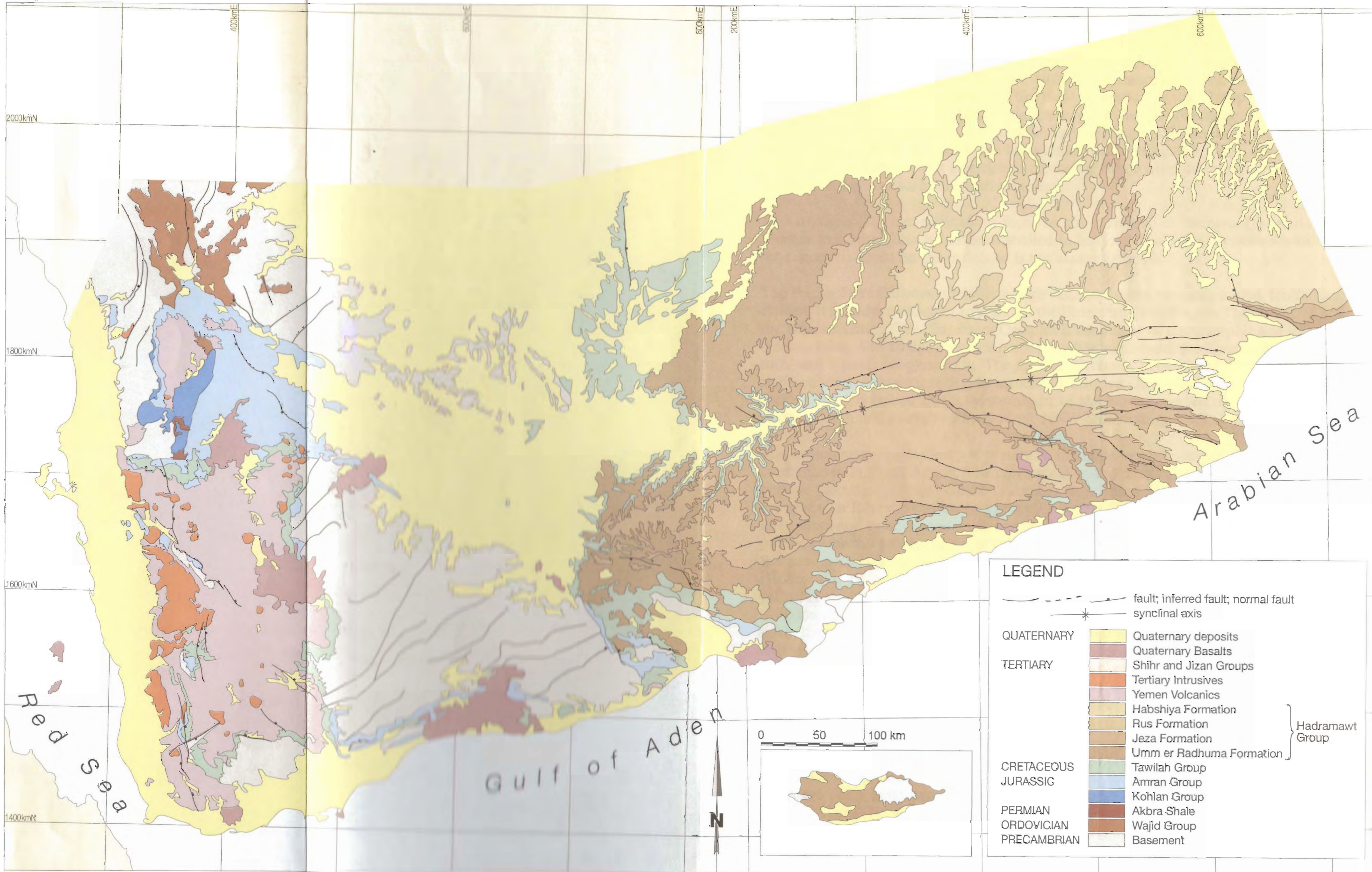


Figure 2.3 Geological map of Yemen

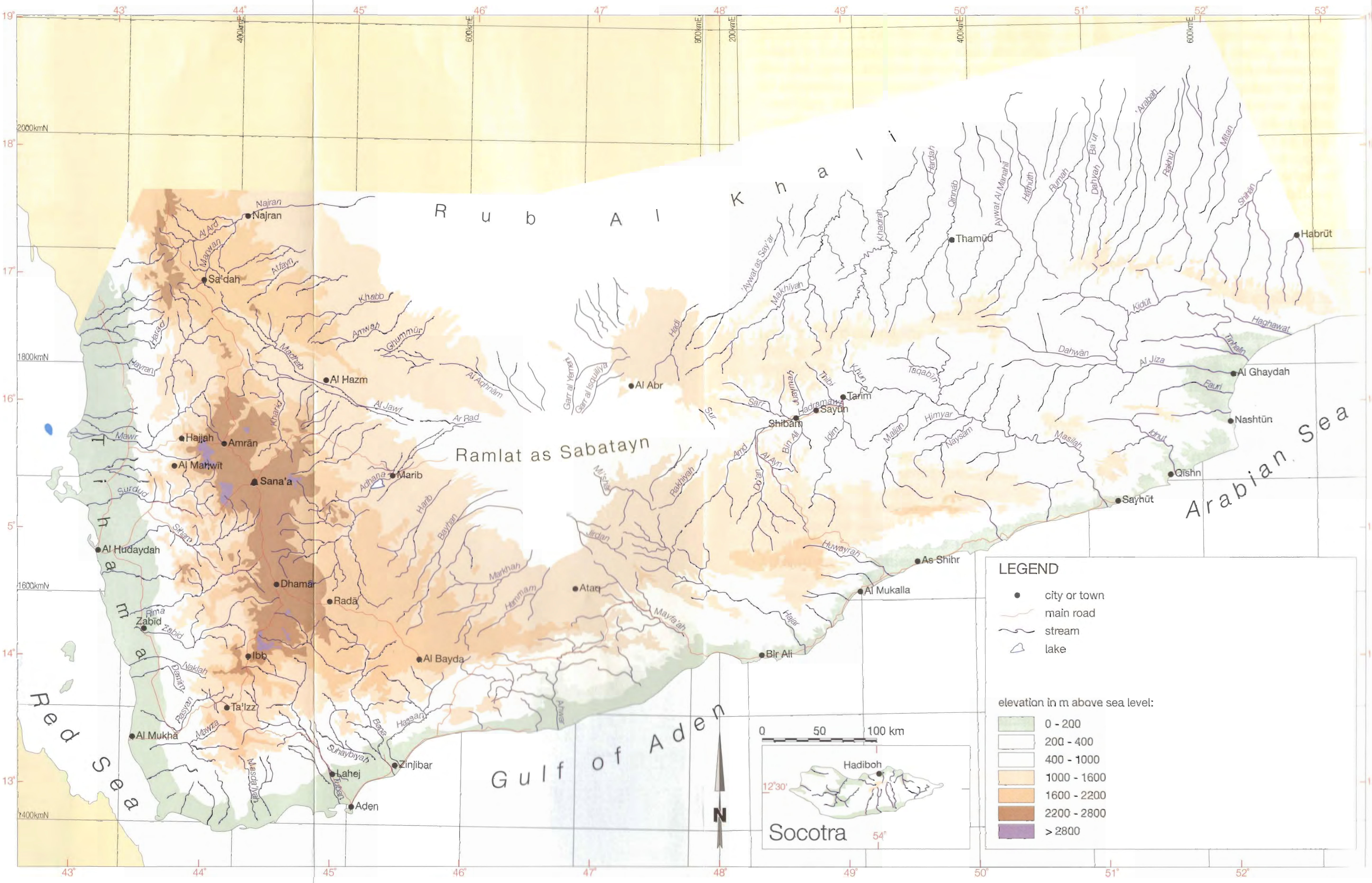


Figure 2.1 Topographic map of Yemen

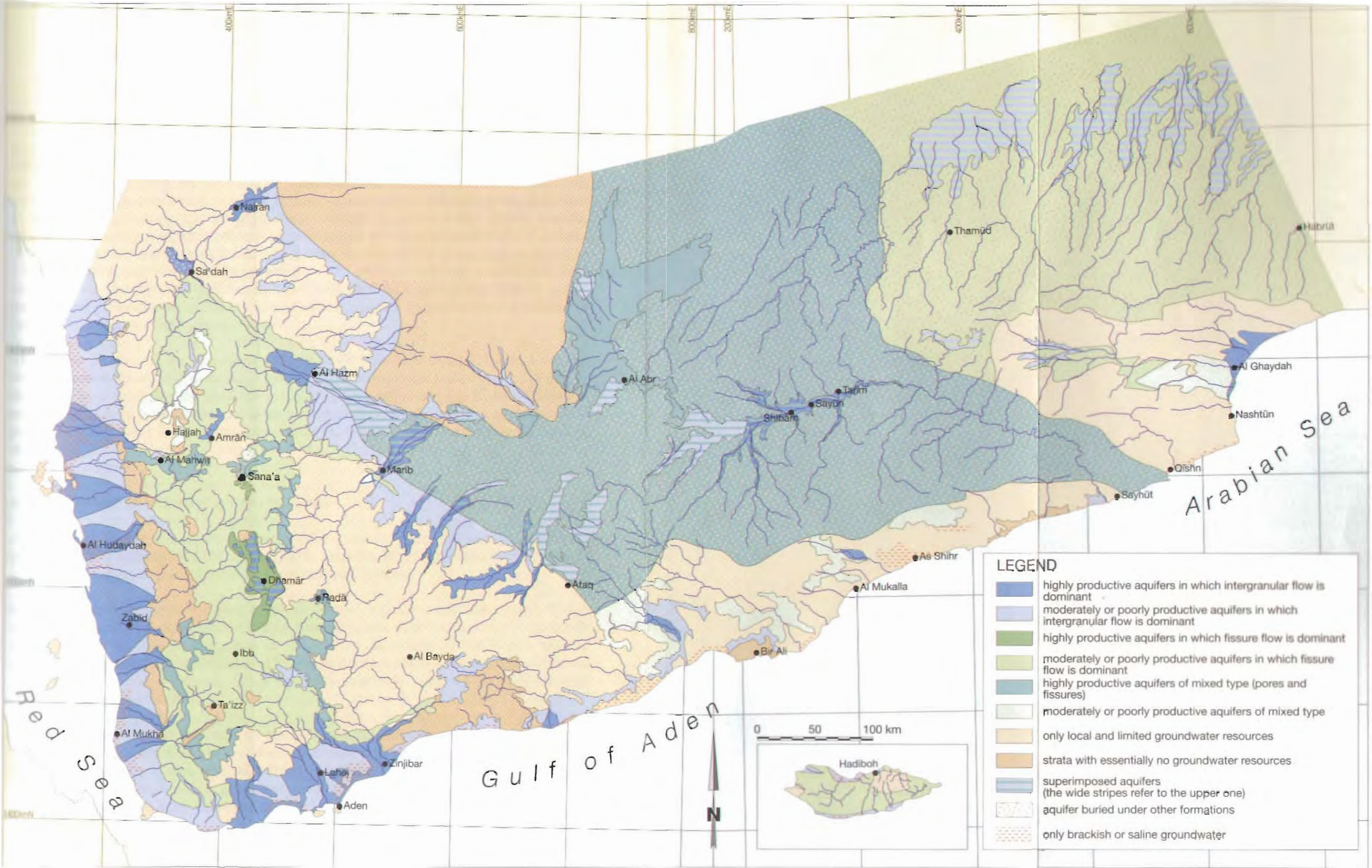


Figure 6.1 Schematic hydrogeological map of Yemen

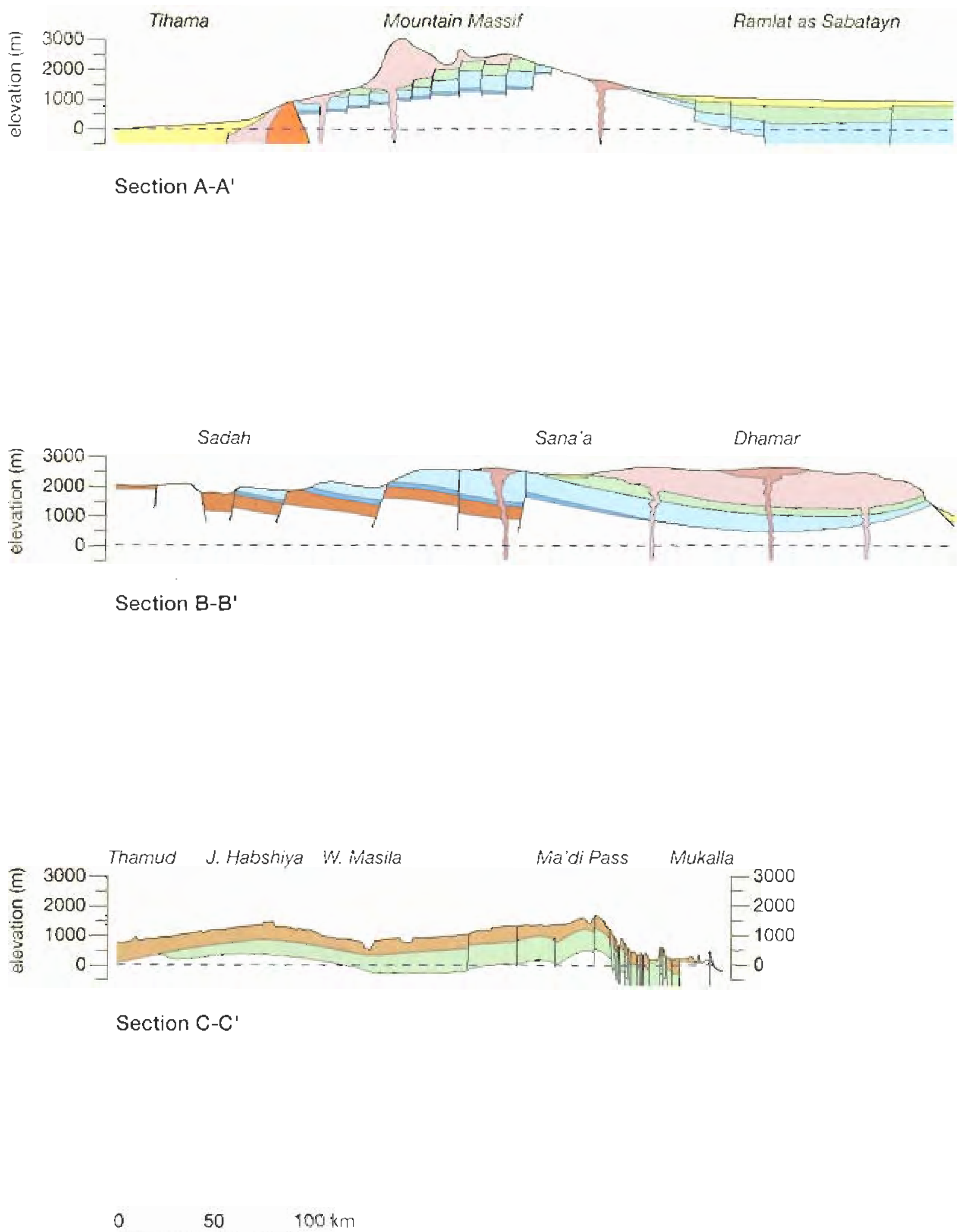
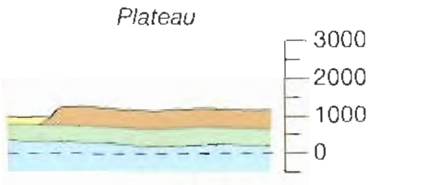
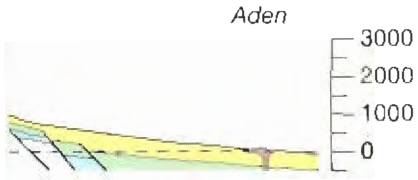
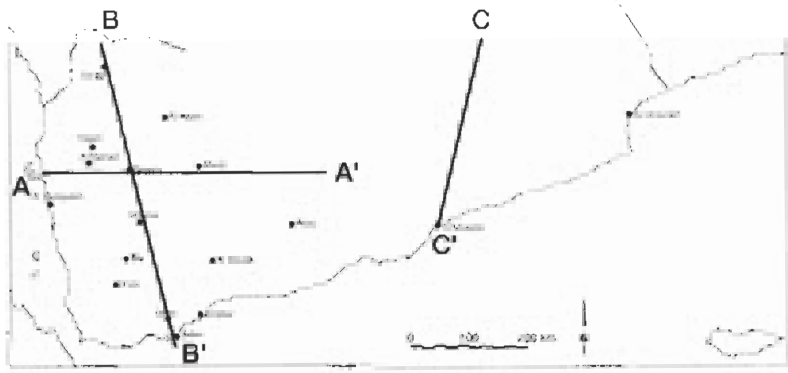


Figure 2.4 Schematic geological cross-sections





LOCATION



LEGEND

- Quaternary and Neogene Deposits
- Quaternary Basalts
- Tertiary Intrusives
- Yemen Volcanics
- Hadramawt Group
- Tawilah Group
- Amran Group
- Kohlan Group
- Wajid Group
- Precambrian Basement

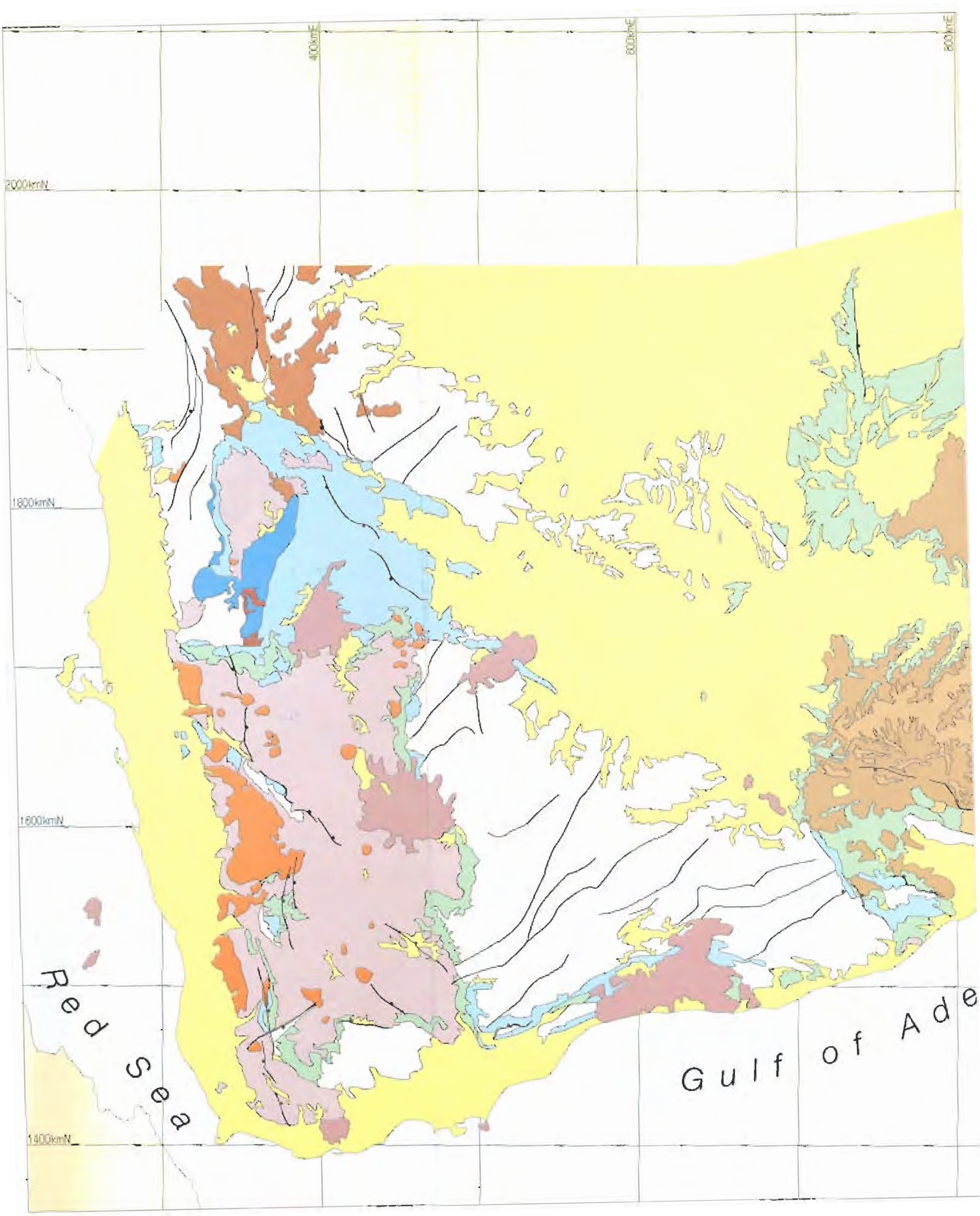
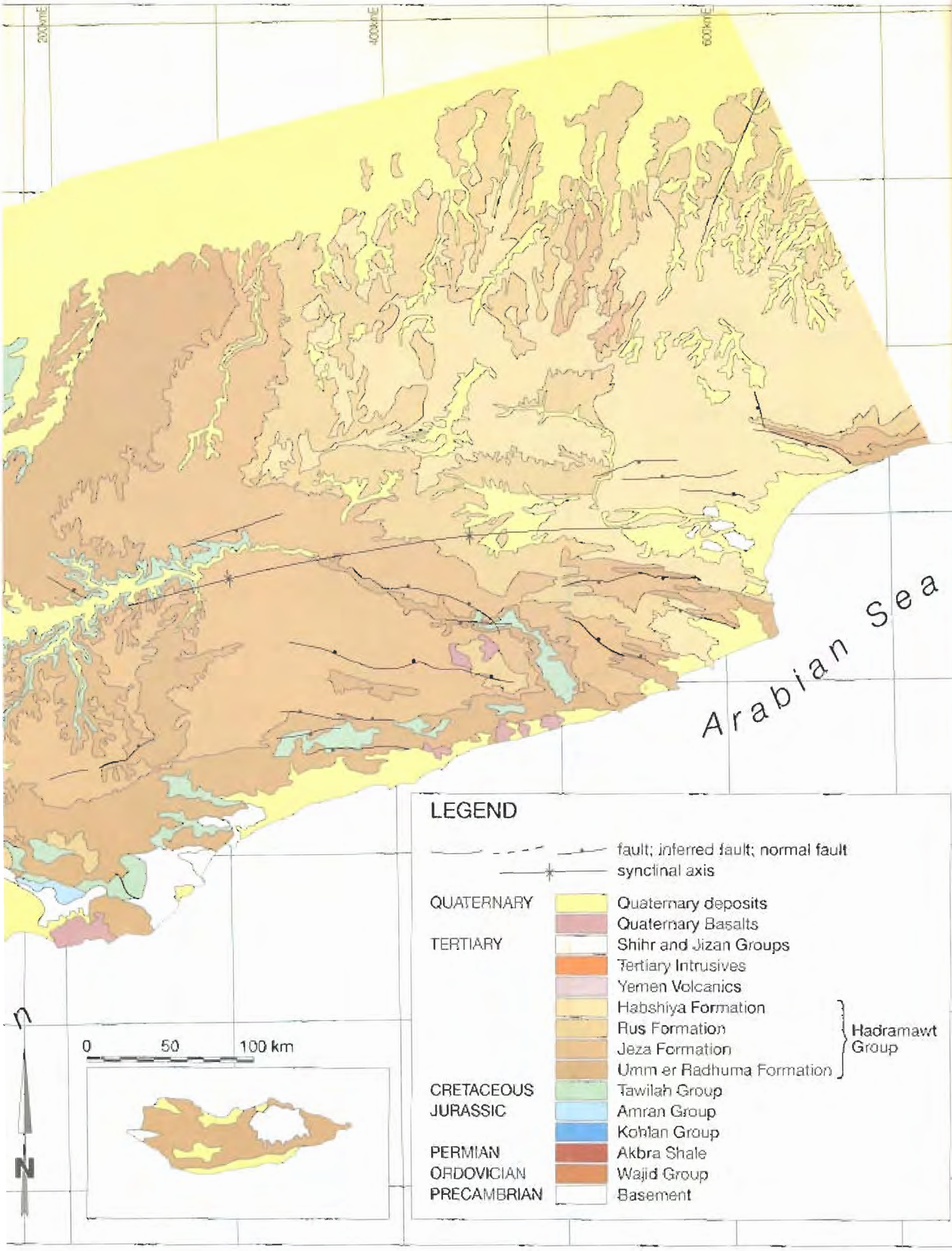


Figure 2.3 Geological map of Yemen


200kmE
400kmE
600kmE
Arabian Sea
LEGEND
fault; inferred fault; normal fault
synclinal axis
QUATERNARY
Quaternary deposits
Quaternary Basalts
TERTIARY
Shihr and Jizan Groups
Tertiary Intrusives
Yemen Volcanics
Habshiya Formation
Rus Formation
Jeza Formation
Umm er Radhuma Formation
Hadramawt Group
CRETACEOUS
Tawilah Group
JURASSIC
Amran Group
Kohlan Group
PERMIAN
Akbra Shale
ORDOVICIAN
Wajid Group
PRECAMBRIAN
Basement
0
50
100 km
N

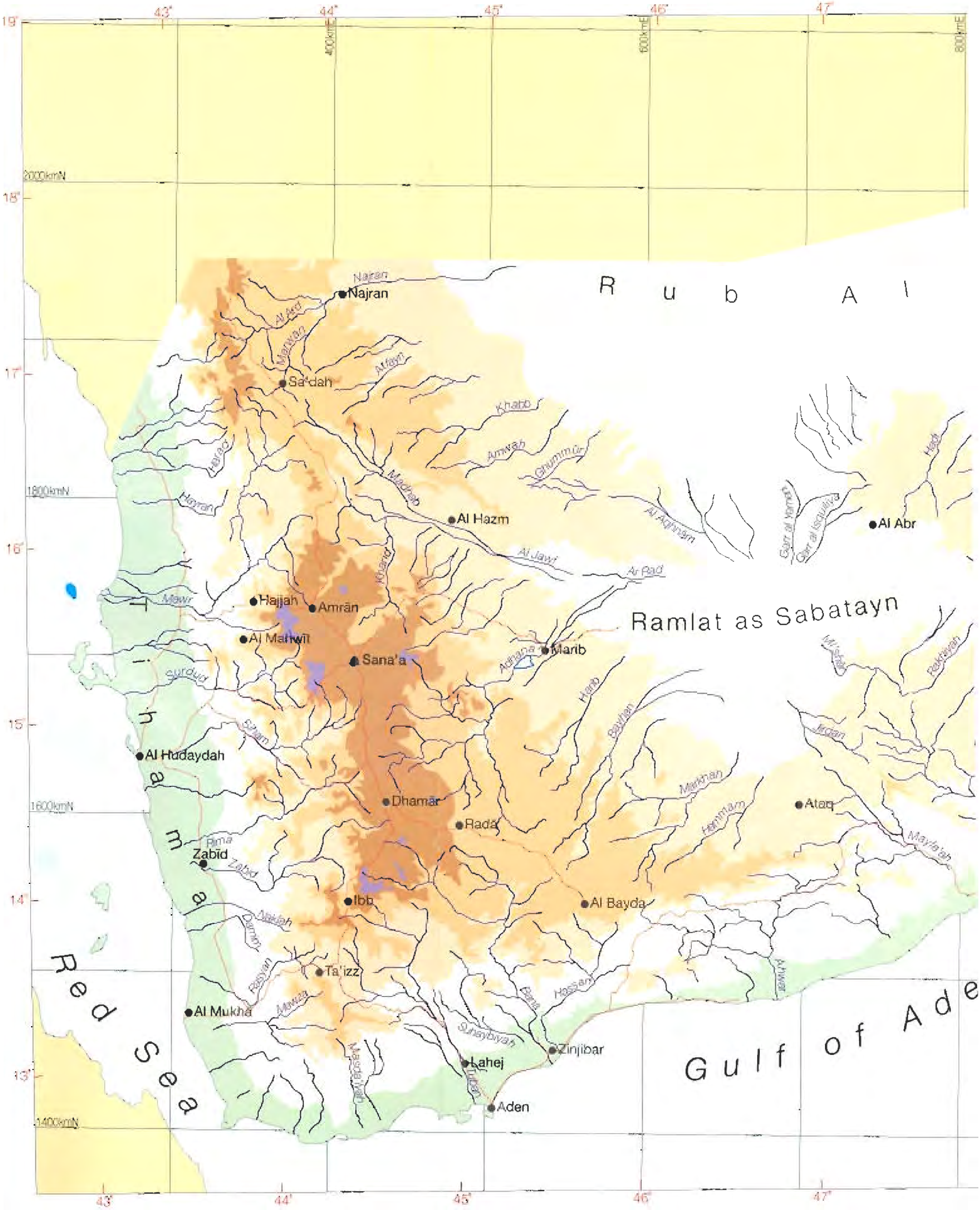
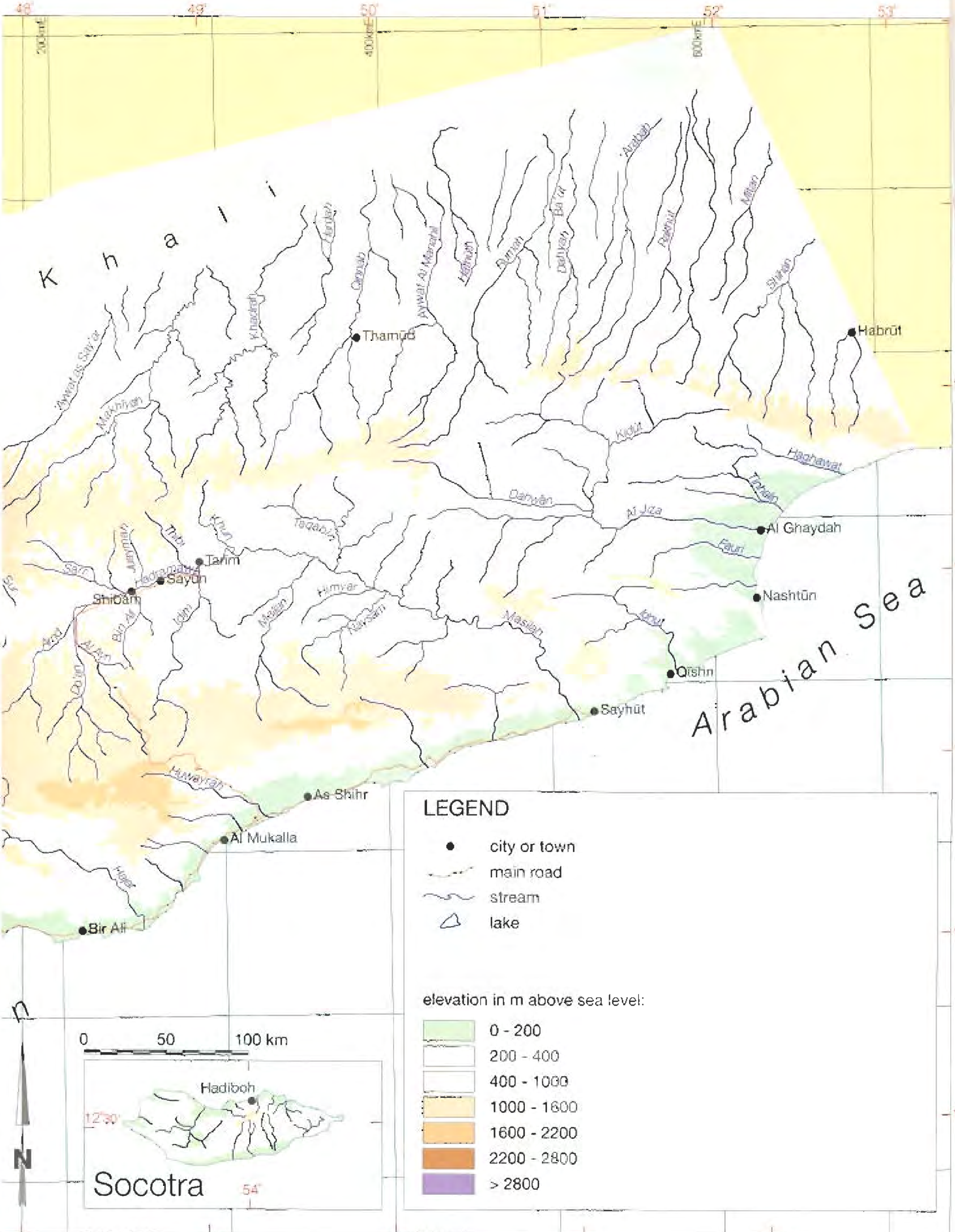


Figure 2.1 Topographic map of Yemen



48°
49°
50°
51°
52°
53°
200kmE
400kmE
600kmE
K h a l i
Arabian Sea
Thamūd
Habrūt
Tarim
Sayūn
Shibām
Al Ghaydah
Nashtūn
Qīshn
Sayhūt
As Shihr
Al Mukalla
Bir Ali
Hadramawt
Dahyān
Al Jiza
Haghawat
Kidūt
Taqabin
Himyar
Masīlah
Huwayrah
Hajar
Idim
Khun
Thibi
Jaymah
Sarr
Rakhiyah
Makhiyah
Dahyah
Ba'ur
Dathūt
Mitan
Arabah
Ramah
Hāfūn
Ghinnah
Aywat as Say'ar
Aywar Al Manahil
Khadrah
Masīlah
Navsam
Jeza
Faurī
Tinhalin
Shihan
LEGEND
city or town
main road
stream
lake
elevation in m above sea level:
0 - 200
200 - 400
400 - 1000
1000 - 1600
1600 - 2200
2200 - 2800
> 2800
0
50
100 km
N
Hadiboh
12°30'
54°
Socotra

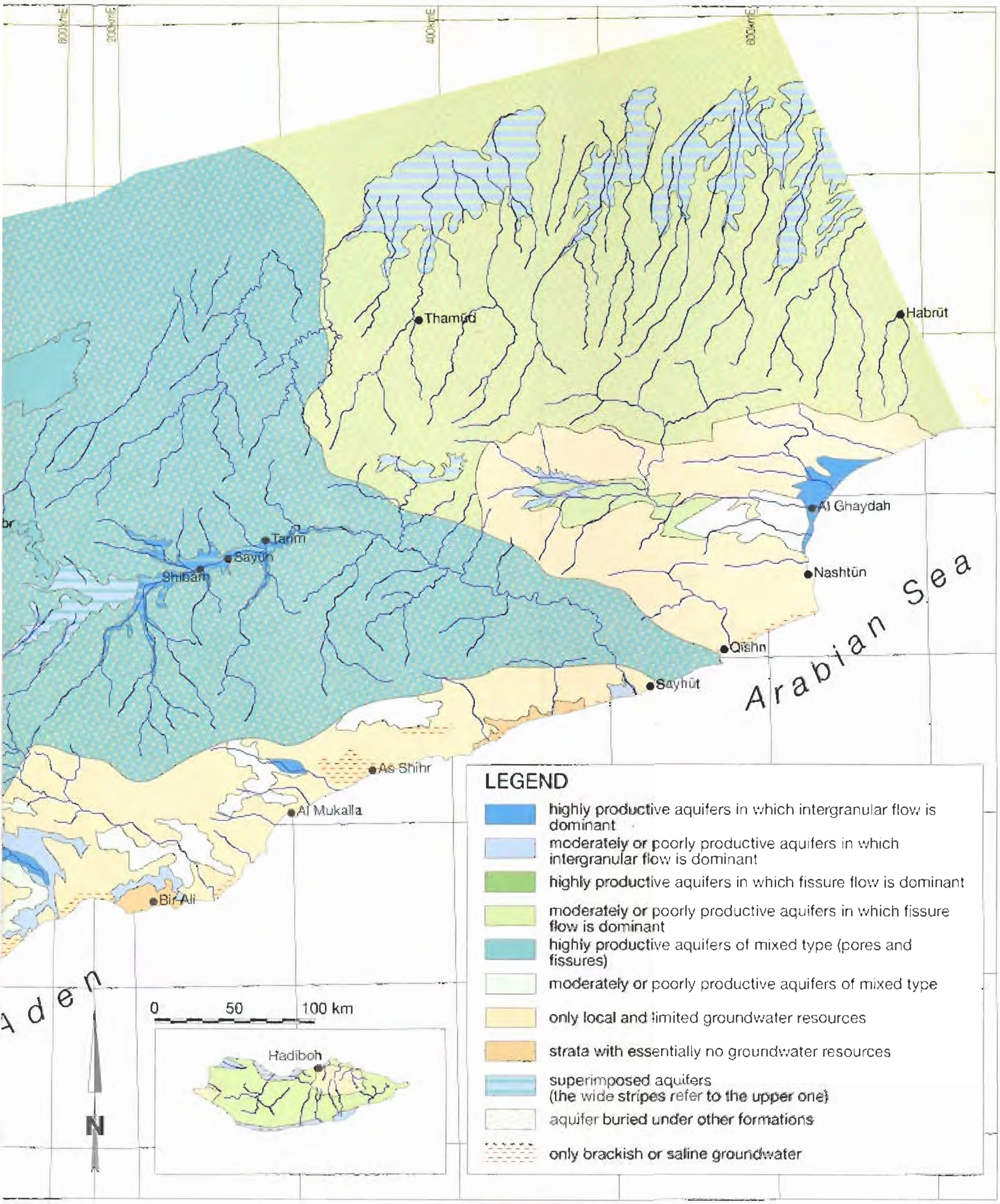
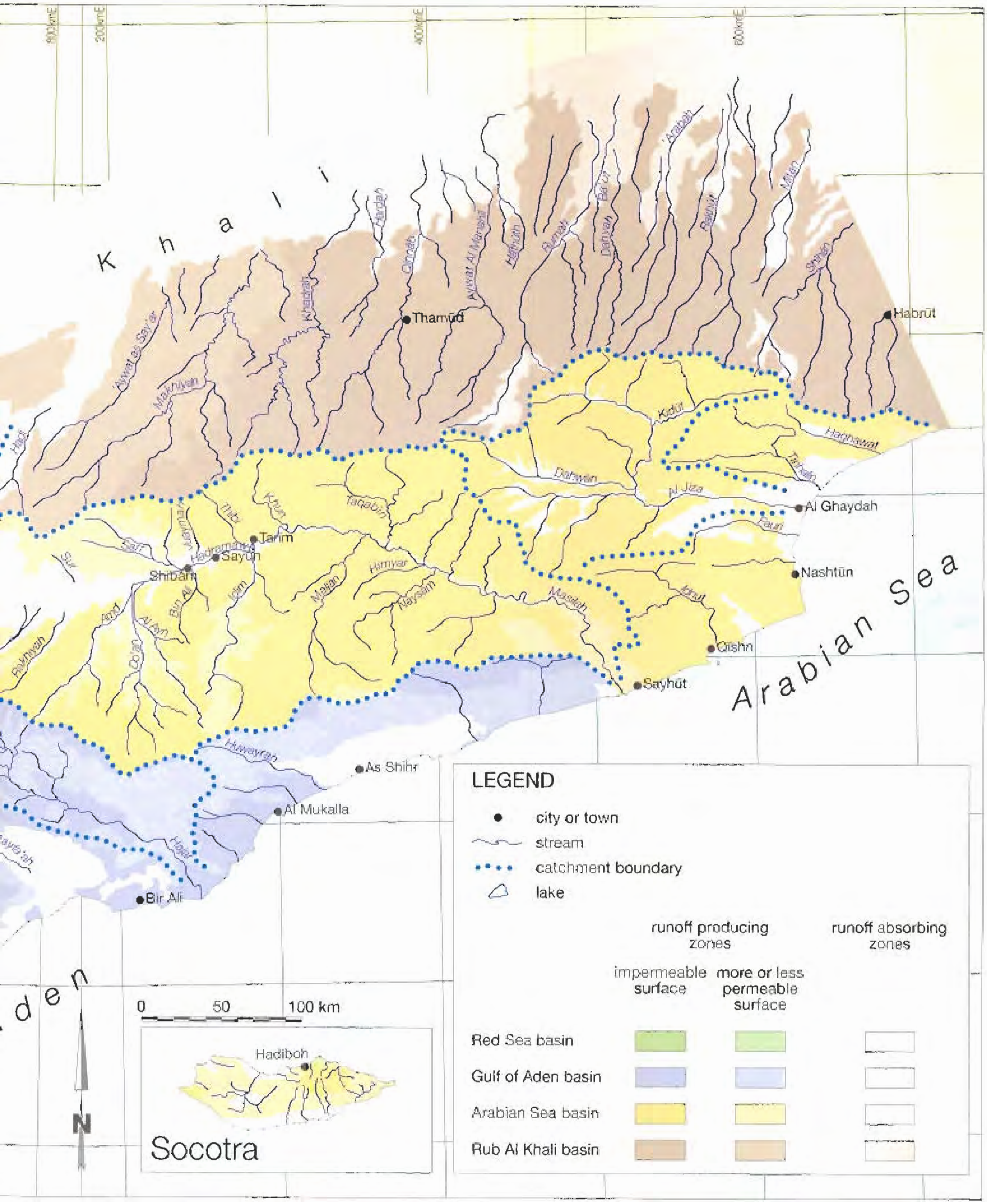

Thamūd
Habrūt
Al Ghaydah
Nashtūn
Qishn
Sayhūt
Tarim
Sayun
Shibam
As Shihr
Al Mukalla
Bir Ali
Arabian Sea
Aden
0 50 100 km
Hadiboh
N
LEGEND
highly productive aquifers in which intergranular flow is dominant
moderately or poorly productive aquifers in which intergranular flow is dominant
highly productive aquifers in which fissure flow is dominant
moderately or poorly productive aquifers in which fissure flow is dominant
highly productive aquifers of mixed type (pores and fissures)
moderately or poorly productive aquifers of mixed type
only local and limited groundwater resources
strata with essentially no groundwater resources
superimposed aquifers
(the wide stripes refer to the upper one)
aquifer buried under other formations
only brackish or saline groundwater

Figure 6.1 Schematic hydrogeological map of Yemen



K h a l i
Thamūd
Habrūt
Al Ghaydah
Nashtūn
Qishn
Sayhūt
Tarim
Sayūn
Shibām
As Shihr
Al Mukalla
Bir Ali
Arabian Sea
d e n
Makhiyah
Khadrah
Hadramawt
Dahwan
Al Jiza
Kidūt
Haghawat
Taqabirn
Himyar
Masilah
Huwayrah
Hajar
Arabah
Rabiil
Miflah
LEGEND
city or town
stream
catchment boundary
lake
runoff producing zones
runoff absorbing zones
impermeable surface
more or less permeable surface
Red Sea basin
Gulf of Aden basin
Arabian Sea basin
Rub Al Khali basin
0
50
100 km
Hadiboh
Socotra
N

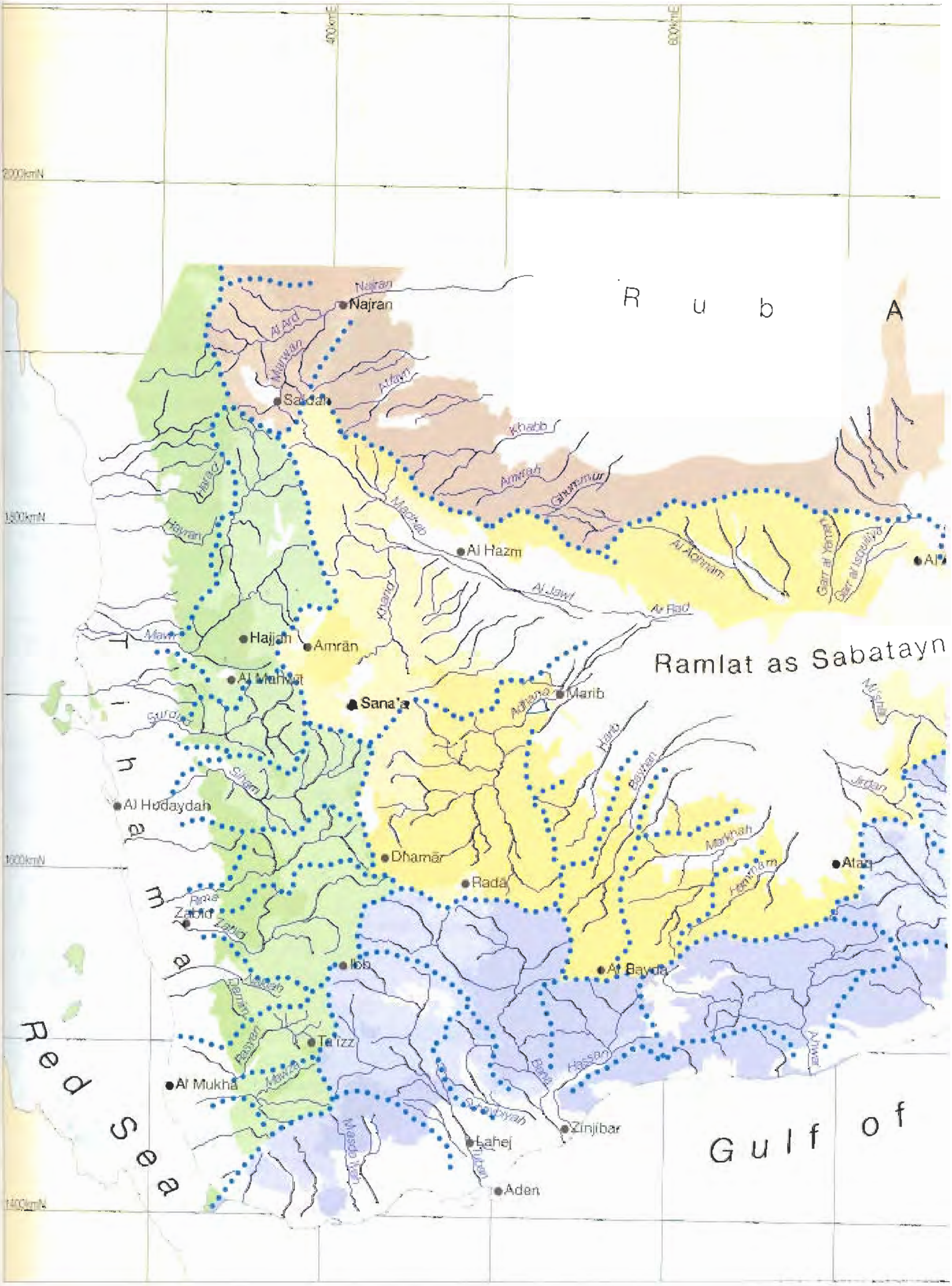
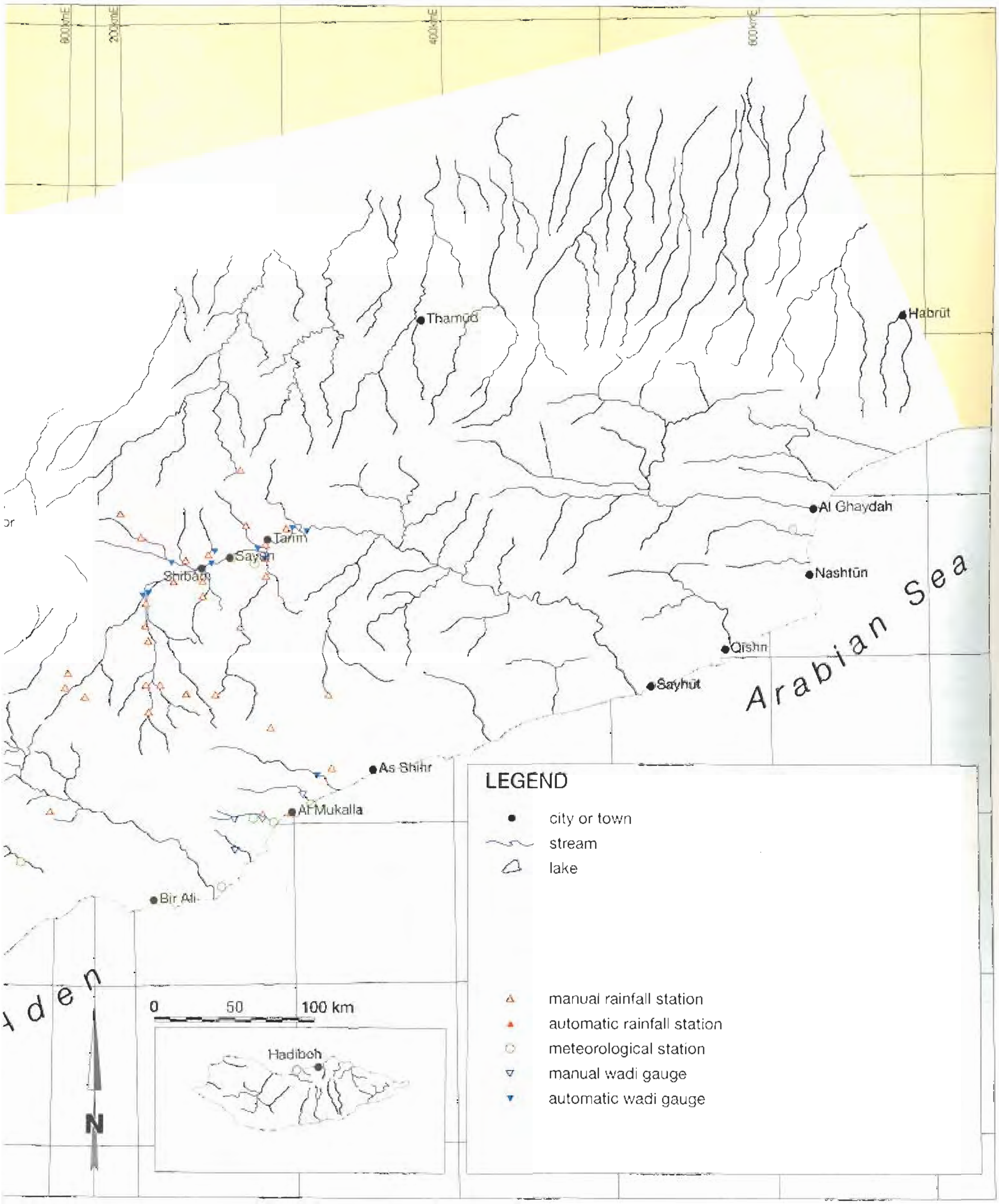


Figure 5.1 Main surface water systems in Yemen



Thamūd
Habrūt
Al Ghaydah
Nashtūn
Qishn
Sayhūt
Tarim
Sayūn
Shibām
As Shihr
Al Mukalla
Bir Ali
Arabian Sea
den
0 50 100 km
N
Hadiboh
LEGEND
city or town
stream
lake
manual rainfall station
automatic rainfall station
meteorological station
manual wadi gauge
automatic wadi gauge

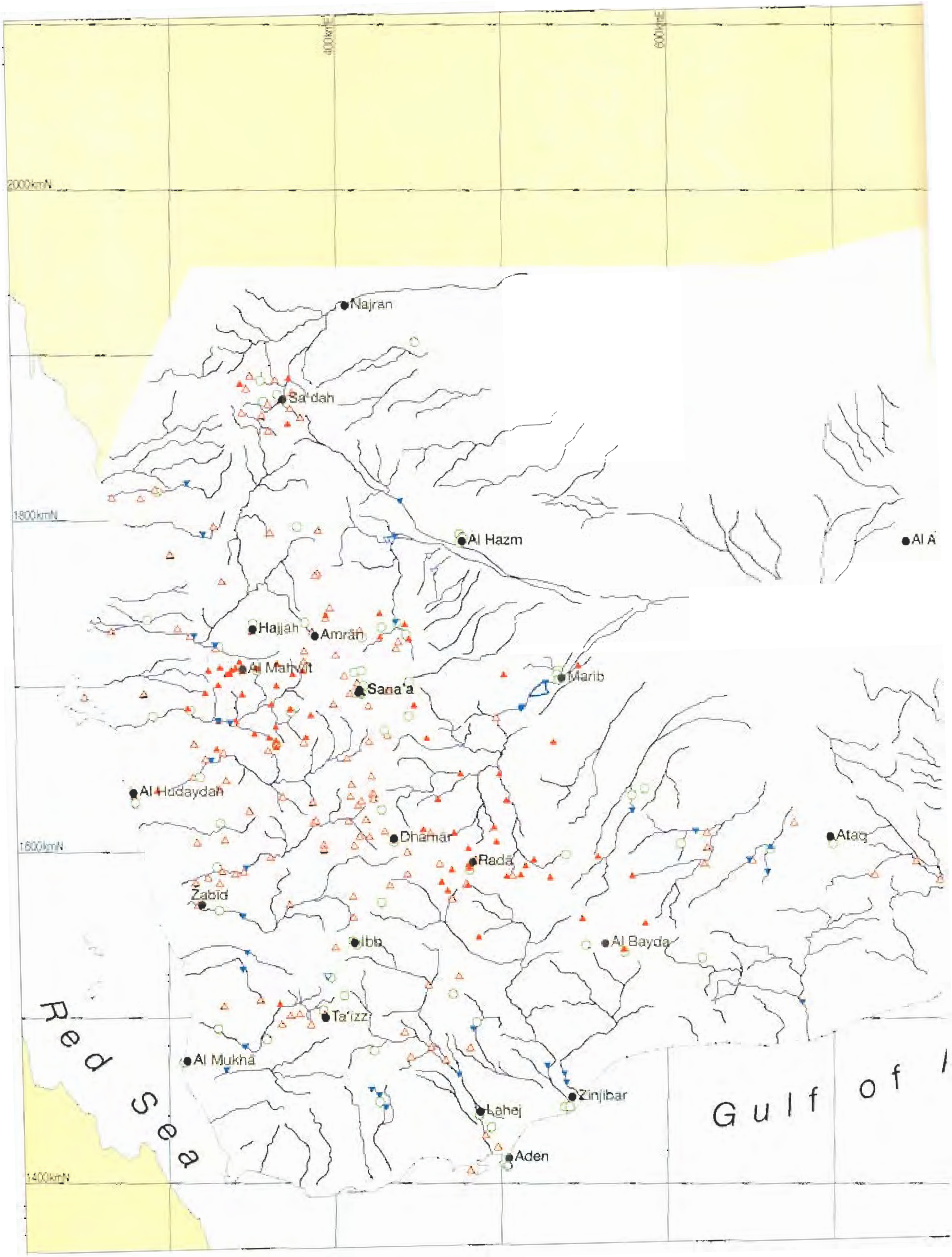
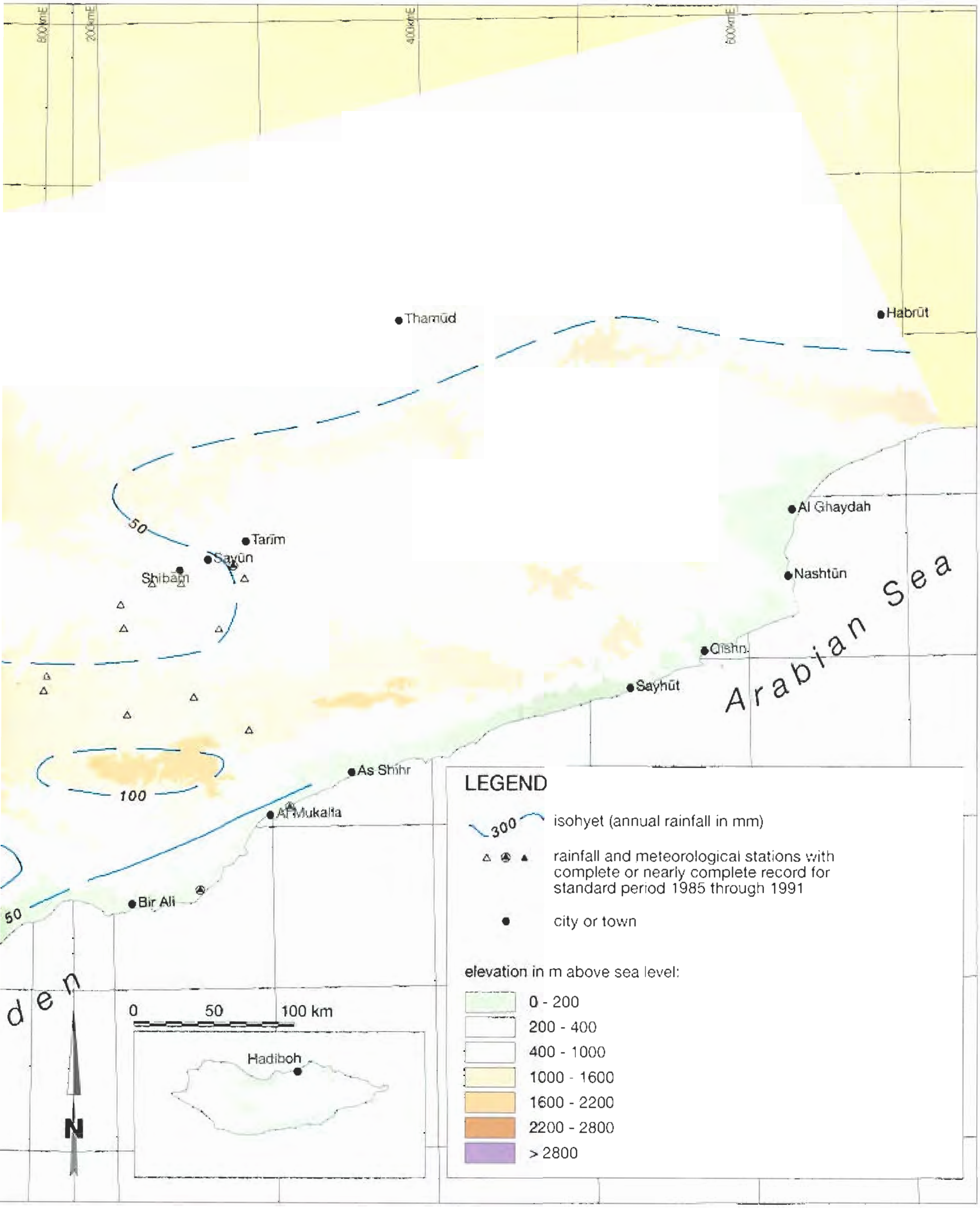


Figure 3.1 Hydrometeorological monitoring stations in Yemen



600kmE
200kmE
400kmE
600kmE
Thamūd
Habrūt
Al Ghaydah
Nashtūn
Tarīm
Sayūn
Shibām
Qishn
Sayhūt
Arabian Sea
As Shihr
Al Mukalla
Bir Ali
50
100
den
0 50 100 km
Hadiboh
N
LEGEND
300
isohyet (annual rainfall in mm)
rainfall and meteorological stations with complete or nearly complete record for standard period 1985 through 1991
city or town
elevation in m above sea level:
0 - 200
200 - 400
400 - 1000
1000 - 1600
1600 - 2200
2200 - 2800
> 2800

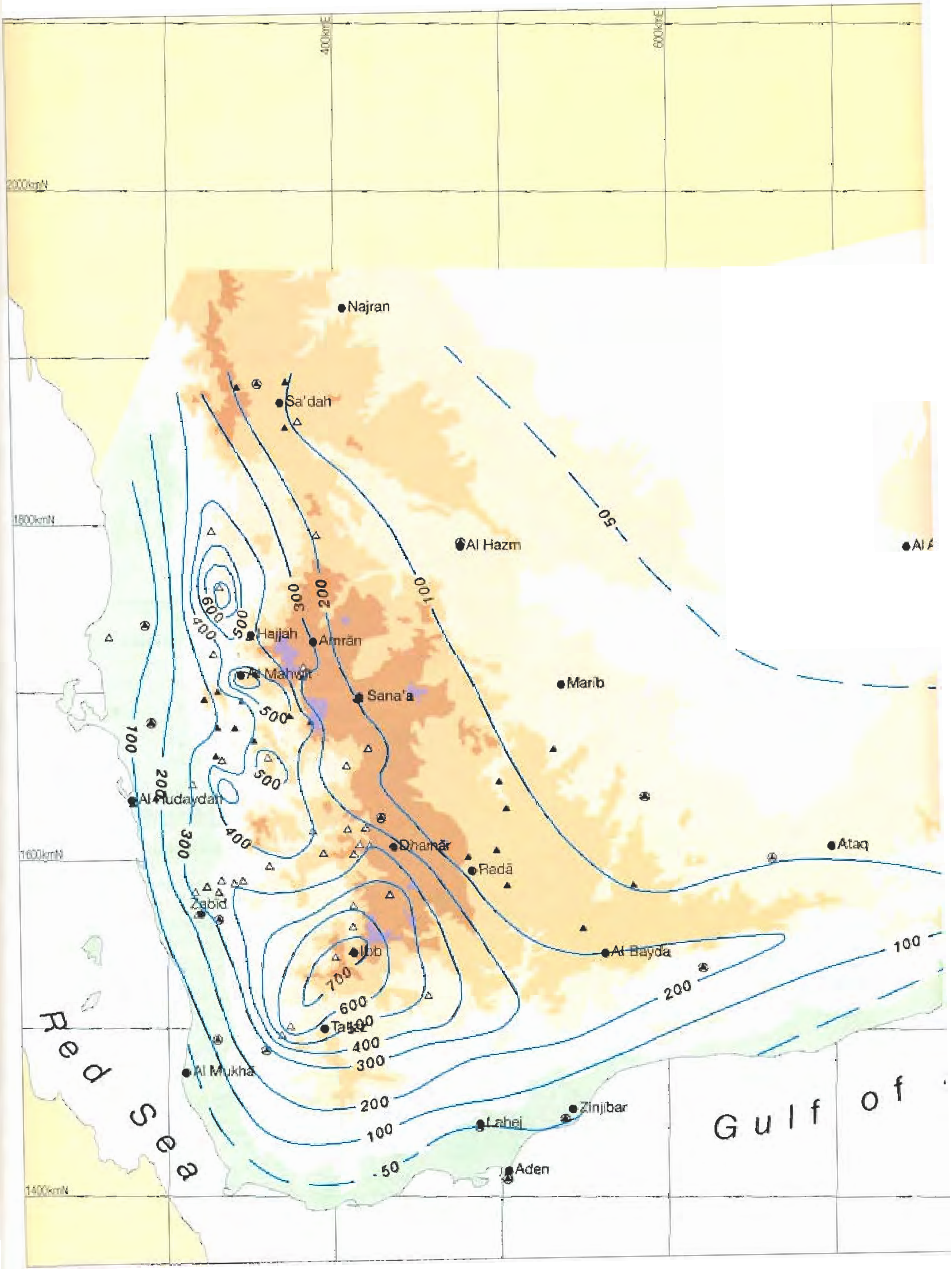


Figure 4.5 Average annual rainfall, period 1985 through 1991