

# INTRODUCTION

## Location and General Topography

Yemen is located on the south of the Arabian Peninsula, between latitude 12 and 20 north and longitude 41 and 54 east, with a total area estimated at 555000 km<sup>2</sup> excluding the Empty Quarter. Apart from the mainland it includes more than 112 islands, the largest of which are Soqatra in the Arabian Sea to the Far East of the country with total area of 3650 km<sup>2</sup> 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 Arabian sea and the Gulf of Aden in the south and the red sea in the west. the country has a total area of approximately 550000 km<sup>2</sup>. A topographic map of Yemen is presented in Figure 1. 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 elevation range from a few hundreds meters to about 3760 meters above sea level. The eastern slopes of this massif are gentler than the steep western and southern slopes; they merge gradually into the depression of the Ramalat 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 Wasdi Hadhramout, the broad and steep-sided Wadi Hadhramout canyon, and the topographic depression of Al Ghaydah. Only the principle 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 centers and certainly the largest ones are located in the western part of the country.

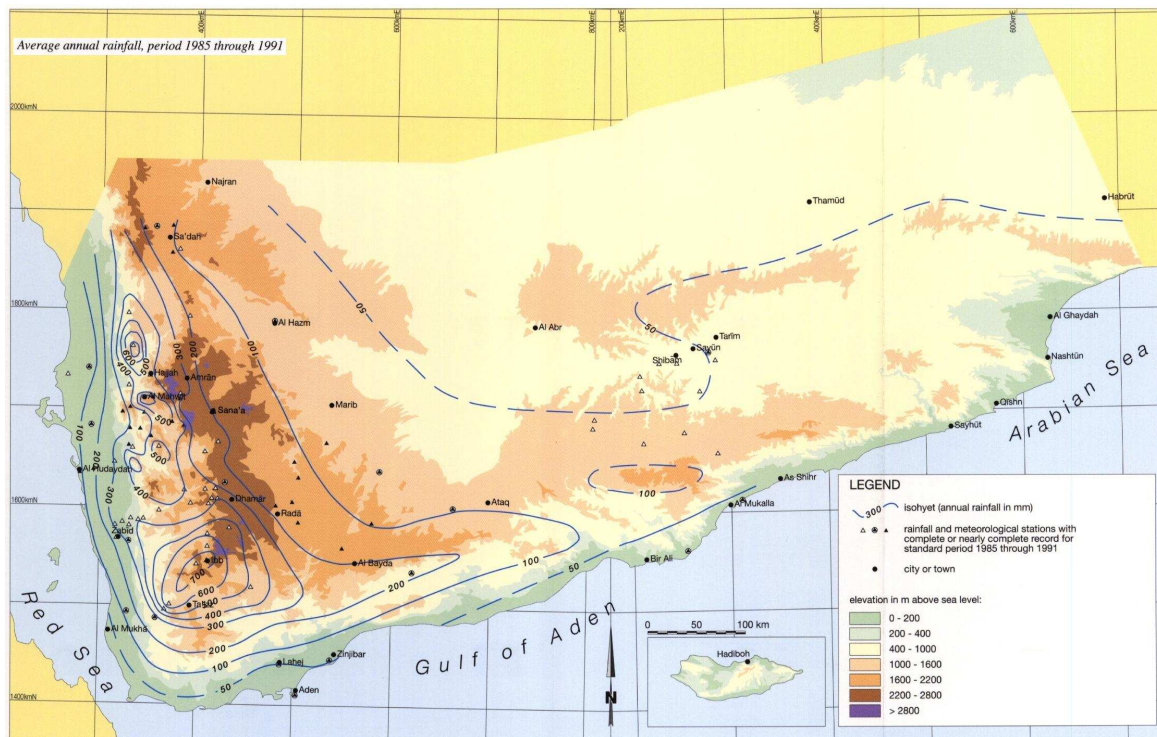


Fig. 1 topographic map of Yemen

The many different landscapes of Yemen can be grouped into five main geographical regions:

### **The Coastal Plains:**

The Plains are located in the west and south-west and are flat to slightly sloping with maximum elevations of only a few hundred meters above sea level. They have a hot climate with generally low to very low rainfall (< 50 mm/year). Nevertheless, the Plains contain important agricultural zones, due to the numerous wadis that drain the adjoining mountainous and hilly hinterland.

### **The Yemen Mountain Massif:**

This massif constitutes a high zone of very irregular and dissected topography, with elevations ranging from a few hundred meters to 3 760 m above sea level. Accordingly, the climate varies from hot at lower elevations to cool at the highest altitudes. The western and southern slopes are the steepest and enjoy moderate to rather high rainfall, on average 300-500 mm/year, but in some places even more than 1000 mm/year. The eastern slopes show a comparatively smoother topography and average rainfall decreases rapidly from west to east.

### **The Eastern Plateau Region:**

This region covers the eastern half of the country. Elevations decrease from 1 200 - 1 800 m at the major watershed lines to 900 m on the northern desert border and to sea level on the coast. The climate in general is hot and dry, with average annual rainfall below 100 mm, except in the higher parts. Nevertheless, floods following rare rainfall may be devastating.

### **The Desert:**

Between the Yemen Mountain Massif and the Eastern Plateau lies the Ramlat As Sabatayn, a sand desert. Rainfall and vegetation are nearly absent, except along its margins where rivers bring water from adjacent mountain and upland zones. In the north lies the Rub Al Khali desert, which extends far into Saudi Arabia and is approximately 500 000 km<sup>2</sup> in area. This sand desert is one of the most desolate parts of the world.

### **The Islands:**

The most important of all the islands is Soqatra, where more exuberant flora and fauna can be found than in any other region in Yemen.

## **Socio-economic features**

### ***Population***

The total population is around 22.1 million (MPD, 2004), of which 74.4 % is rural. The average population density is about 31 inhabitants/km<sup>2</sup>, but in the western part of the

country the density can reach up to 300 inhabitants/km<sup>2</sup> (Ibb province) while in the three eastern provinces of the country the density is less than 5 inhabitants/km<sup>2</sup>. This is closely related to the physical environment. By far the largest part of the population lives in the Yemen Mountain area in the western part of the country, where rainfall is still significant, although not high in many locations. The hostile environment of the desert and eastern upland areas is reflected by low population density. The average demographic growth rate is estimated at 3.5%, which is very high.

### ***Agriculture and economy***

Agriculture contributes 21% to the Gross Domestic Product (GDP) in Yemen, employs 60% of the population, and provides livelihood for rural residents who constitute about 76% of the total population. Agriculture is characterised by low and uncertain crop yields due to drought, insufficient and erratic rainfall, declining soil productivity due to soil erosion and poor crop management practices, and crop losses due to damage by insects and diseases, and malnutrition resulting from inadequate supply of feed (Figure 2).

The main agricultural products are fruit (mango, grape, citrus, banana, papaya and date.), vegetables (tomatoes, potatoes, watermelon, sweet melon, onion and cucumber.), Qat, and Cereals (maize, wheat, sorghum and barley) (Figure 3).

The Yemeni economy has primarily depended on agriculture. Agriculture contributed 25% of the GDP in 1990. Oil has been a main activity in the Yemeni economic. In 1999, Yemeni's oil production reached 143 million barrels at a total value of 412 billion Yemeni Riyals (around 68% of total state revenues).

Cultivated land has expanded from 1.21 thousand hectares in 1990 to 1.28 thousand hectares in 1999, an increase of 14% of land for cereals crops, vegetables, fruit, cash crops and animal food.

Cultivated area for vegetable has also increased from 52,000 hectares to 62,000 hectares during the period. Production increased from 696,000 to 766,000 tons in 1999. Fruit cultivated area has doubled and production has increased to 588,000 tons in 1999. Farmers have turned to cotton plantation as a cash crop following its price liberalization. Therefore, cotton cultivated area increased from 57,000 hectares to 91,000 hectares.

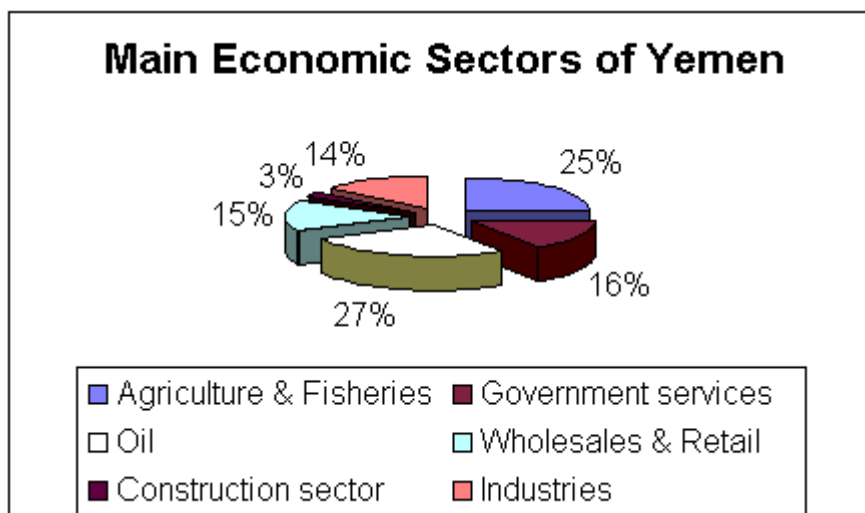


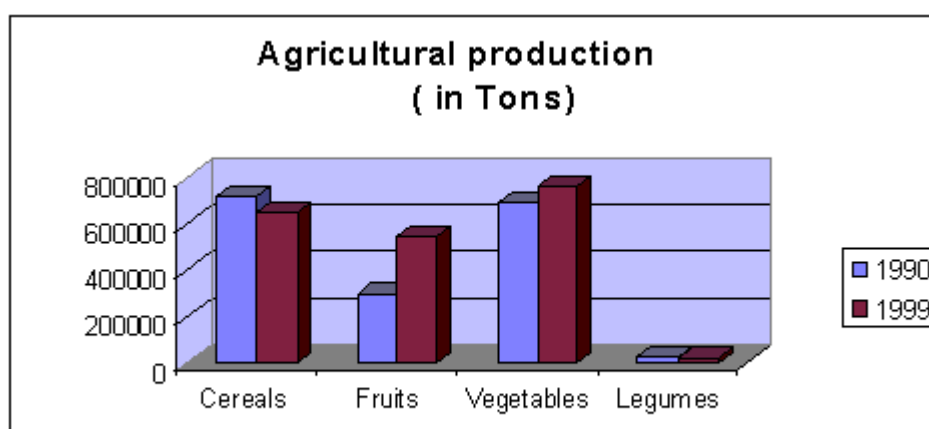
Fig. 2. Main Economic Sectors in Yemen

### ***Agriculture and food security***

There is a close linkage between the poverty incidence among the population and the fluctuation in productivity from year to year.

The contribution of the agriculture sector in realizing food security in Yemen is clarified in the following percentage of production vis-à-vis population needs:

- 100% from thin sorghum consumption.
- 7% from wheat consumption.
- 100% from millet consumption.
- 42 from barley consumption.
- 100% from vegetable consumption.
- 89% from fruit consumption.
- 99% from white meat consumption.
- 68% from red meat consumption.



Source: MPD, 2001

Fig.3. Agriculture production in Yemen

## Land resources

Yemen is among the oldest countries in the world where land and water resources practices have been developed. Terraces erection, rainwater harvesting and dam irrigation techniques were developed since many countries were trackless waste.

The cultivable land is estimated at about 1.67 million ha, which is 3% of the total area (Table 1). In 1998, the total cultivated area was 1.28 million ha, or 68% of the cultivable area, of which 0.87 million ha consisted of annual crops and 0.41 million ha consisted of permanent crops. About 32 million ha is estimated as desert and rock outcrops, while range land are estimated to occupy 16 million ha including those areas which are covered by shrubs, perennial vegetation and grass. Only 1.5 million ha of the total area is considered as a forest and woodlands. (MAI, 2000)

### Physical areas:

Area of the country	1998	55500000 has
Cultivable area	1998	1668858 ha
Cultivated area	1998	872251 ha
annual crops	1998	1 279704 ha
permanent crops	1998	407453 ha

Table 1. Physical areas in Yemen.

## Soils

Since early seventies numerous soil surveys have been carried out in scattered areas of Yemen.

These surveys, carried by various foreign bodies, often through bilateral aid, were undertaken at different levels of intensity and according to different classification systems. As they were in variably carried out within the framework of agricultural and rural development, the main purpose of these soil surveys was to provide the necessary information required for assessing the land potential for crop production. Consequently more effort went into the characterisation and mapping of soils for land capability evaluation, and relatively little attention was paid to the classification and correlation of soils, which in some instances was totally neglected. This is might have been due to the following factors:

- Most soil classification systems depend on some chemical, physical and pedagogical data, which were not always collected or determined.
- International soil classification systems may not always have been appropriate for separating soils at the scale of mapping used, and more simple parameters may have been used to separate the soil types observed.
- Absence of national soil classification standard to guide the soil surveys undertaken in Yemen.

Within the soil surveys carried out so far, hundreds of profiles have been described. These profiles have either been classified according to one or both of the two most common soil classification systems (i. e. USDA Soil Taxonomy (ST) or FAO-Unesco Soil Map of the Word Legend), or were classification according to local criteria.

For the western governorate soil map 1:500 000 (Figure 3), which covers approximately 0.36% of the total land have attained in 1983. The map identifies the predominant soils and presents them at the sub-group level according to the USDA Soil Taxonomy. With the result that 60% of the mapped area is dominated by soil of the *Entisol* order with sub-order of *Orthents*, *Fluvents*, and *Psamments*. The incidence of the sub-order *Orthents*, can be associated with steep slopes; *fluvents*, with plains and wadis; and *psamments*, with sandstone mountain or sand dune plains. Greater groups of these sub-orders are classified as ustic or torric type. Other orders include *Aridisols* (8.7%), *Mollisols* (2.6%), *Inceptisols* (4.3%) and for a limited extent, *Vertisols* and *Alfisols*. *Aridisols* are either calsic or gypsic groups of the orthid sub-order. *Mollisols* are present in the most cool and moist areas of the country. Most of the *Mollisols* are buried in the mountain plains, whereas on the mountain slopes, they have shallow-lithic contact (Bamatraf A., 1987).

The country's soils are generally sandy to silty and loamy in the coastal plains, silty to loamy and clay loamy in the mountainous area, and low in nitrogen, phosphorus, and organic matter, In many areas, shallow soils limit the amount of water available for rainfed crops. Soil erosion caused by runoff and/or winds is often serious. Sand and dust storms, which generally blast across the lowlands and highlands, promote soil erosion (ISNAR, 1993).

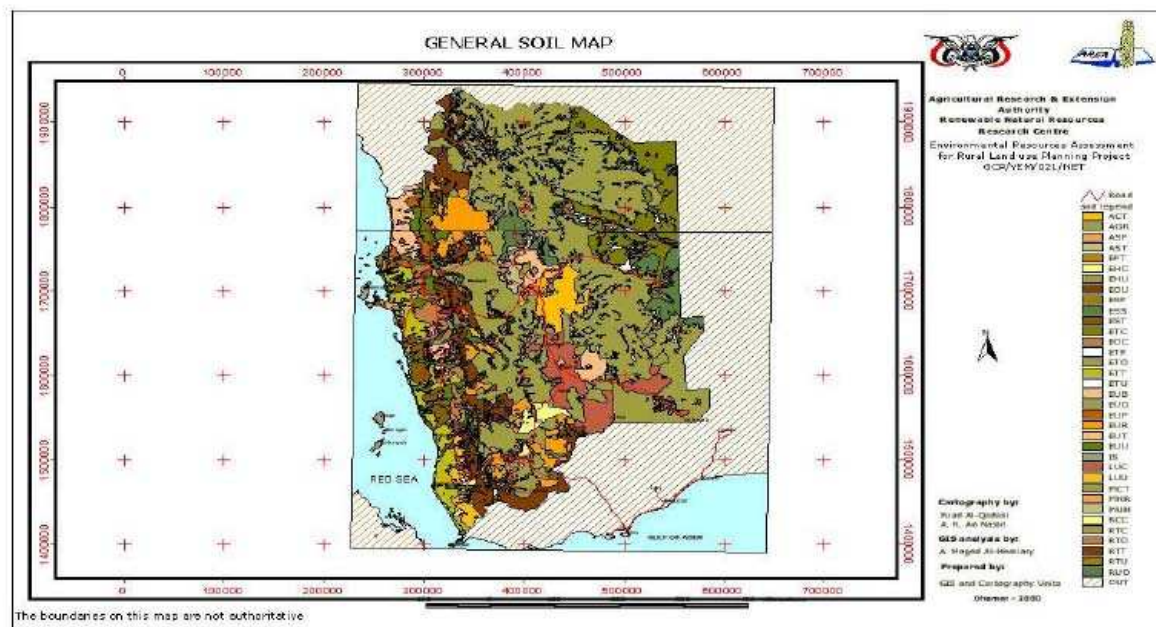


Fig.4. General Soil Map of the Northern Governorates

## **Agroecological systems**

Yemen is characterized by varieties of environmental zones. Since early 80s there were many attempts to classify the agroecological zones, occasionally by using the physiographic features and time to time by using landforms and climatological characteristics. The predominant distinction has given by Bamatraf A. M., 1994 as follows:

Recent demarcation of Agroecological zones in Yemen is not comprehensive, but the country could be divided into three major zones (Figure 5) derived from the five Physical division these are:

### The Coastal Region:

This region includes the low coastal plains facing the Red Sea, the Gulf Aden and the Arabian Sea. Its is makes a coastal strip extending to the Omani border in the east towards the southwest to Bab al Mandab, and north wards to the Saudi border. It starches over an area 2000km long and 20-60km wide, with an altitude ranges 0-500m a. m. l. Many seasonally flowing wadis dissect the region. An arid sub-tropical climate dominates the region with average annual rainfall in the range of 50-300 mm. The climate becomes semi-arid subtropical in areas adjacent to the foothills of the western escarpment.

### The Mountainous Region:

This region includes the most complicated landscapes of the country. It is very irregular and dissected topography, with elevation varies from 500m at the foothills of its western and southern escarpments up to 3700m in the western peaks, then down to 1200m at its north-eastern escarpment. Due to this extreme physiographic diversity, differences in slope and location relative to the Red Sea, Gulf of Aden and Al Rub al-Khali, rainfall varies considerably within the region, with annual averages ranging from less than 300 mm to more than 1000mm. This region is divided into three main catchments, the western slopping towards the Red Sea, the southern towards the Gulf of Aden and the north-eastern towards the empty quarter ( Al Rub al-Khali). The climate is characteristic of the semi-arid tropics, with limited areas of dry temperate intermountain plains at altitudes above 2000m.

### Eastern plateau:

This region is bordered by the mountains zone to the west, the southern coastal plains to the south and the empty quarter to the north. It covers vast expanses of sand desert and dissected plateau with elevation ranging from 500m on its northern and southern sides, to about 2400m on its western side. The average rainfall in this region is generally below 200mm, an arid sub-tropical climate dominates its major agricultural lands.

Map 2.3.1: Agroecological zones

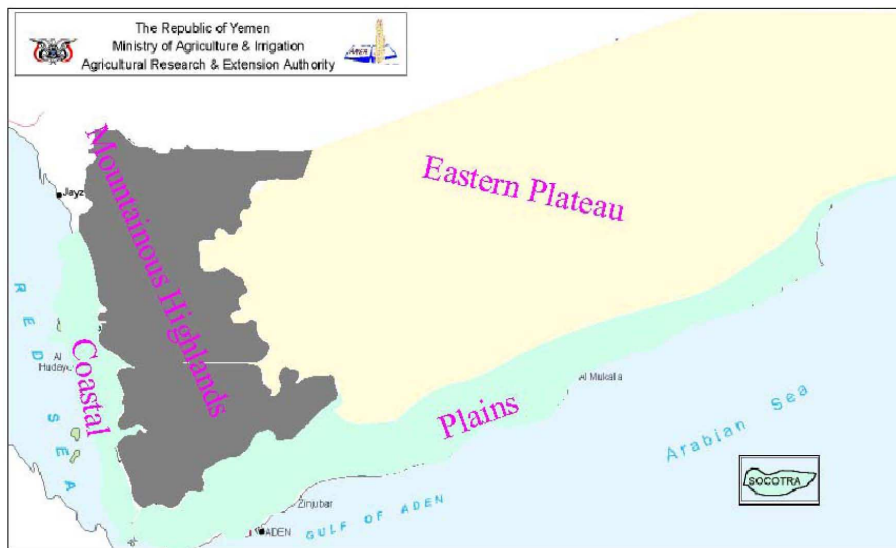


Fig. 5 Agroecological zones in Yemen

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 precipitations (P) and annual reference evaporation (E), and in principle marks five different classes:

- hyper-arid  $P/E < 0.03$
- arid  $0.03 < P/E < 0.25$
- semi-arid  $0.25 < P/E < 0.5$
- subhumid  $0.5 < P/E < 0.75$
- semi humid  $P/E > 0.75$

Figure 6 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 in Ibb. Table 2 shows the Physiographic Regions of Yemen



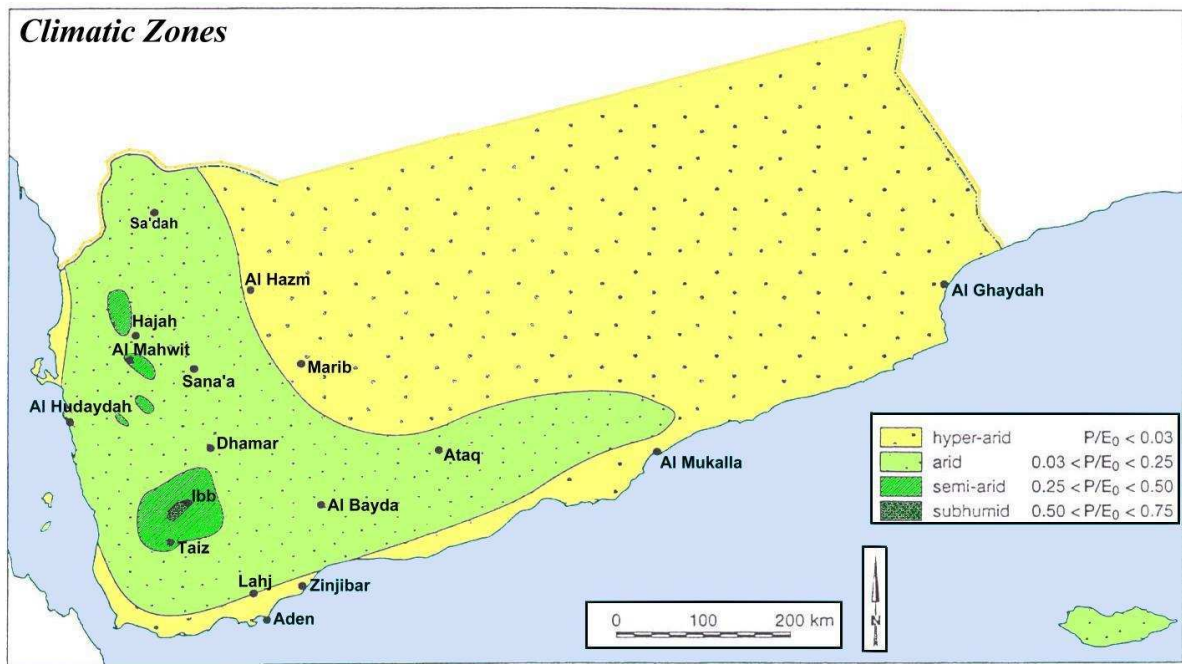


Fig. 6 climatic zones in Yemen

Physiographic unit	Approx. area (km <sup>2</sup> )	% of Total of Land	Major Geological Formation	Predominant Great soil Types	Ecological Zones/Vegetation
Coastal Plain (Tihama)	20,300	3.9	Quaternary alluvial deposits.	<i>Torrifluvents, Torripsamments; Ustifluvents, ustipsamments, Ustipsamments, salortheds.</i>	Arid tropical desert; sand dune vegetation of the Red Sea; Acacia spp.
Southern Uplands	12,000	2.3	Tertiary and quaternary volcanics.	<i>Ustifluvents; ustiorthents; torriorthents;</i> rock outcrop.	Semi-arid subtropical mountains; Acacia spp., Juniperus spp., Euphorbia scrub.
Highlands slopes	45,500	8.6	Tertiary and quaternary volcanics; sedimentary rocks; quaternary alluvial deposits.	Rock outcrop; <i>ustiorthents.</i>	Arid to semi arid temperate mountains, Acaciaspp., juniperus spp., .
Midland slopes	39,200	7.4	Tertiary and quaternary volcanics; Precambrian shield; sedimentary rock.	Rock outcrop; <i>ustiorthents; torripsamments;</i> calcareous loamy and sand plains.	Arid subtropical mountains; Acacia spp., weed rich vegetation.
Eastern and Northeastern Desert plateau.	250,200	47.4	Quaternary alluvial deposits; sand sheets and dunes; calcareous sedimental rocky; sand plains.	<i>Torriorthents, torrifluvents; torripsamments,</i> calcareous loamy and sandy plains.	Arid subtropical desert; sand dune vegetation; absent vegetation except for grasses after rainfall.
Coastal and foothills	55,000	10.4	Hills, sand dunes and sheets; grace and sandy to loamy plains	Deep to shallow calcareous sandy to loamy; saline in coastal area; light yellowish in eastern part.	Arid tropical; desert and semi desert vegetation absent by sea-saline grasses; vegetation on hills; water cockles in wadi.
Middle Montane highland.	84,500	16.0	Volcanic rock basement in the western part, and calcareous rocky plains in the eastern part; sandy to loamy sedimental complex in wadi.	Sandy to loamy in the western part, and calcareous to loamy in the eastern part.	Arid subtropical; vegetation nearly absent, except some in wadi and on soil and rocky plains.
High Montane.	21,000	4.0	Hills, volcanic rocky plains in the west and calcareous rock in the east; sandy loam in wadi.	Sandy to loamy in the west, and calcareous sandy to loamy in the east.	Arid subtropical; vegetation nearly absent; some trees; grasses after rainfall.

Table 2 the Physiographic Regions of Yemen

## Land use

There is inventory of national land cover or land use, except for western northern governorate and of limited scattered areas. There is no clear boundary between land use and land cover in Yemen.

Agricultural land consisting of arable land and land under permanent crops forms about 3% (of which about 450,000 ha of mountain terraces is rainfed, 650,000 ha of relatively flatland in the inter-mountain region). Irrigated lands occupy some 489,000 ha distributed as 98,000 ha spate irrigation, 28,000 ha spring irrigation and 363,000 ha well irrigation.

The land use in upland areas of Yemen, particularly in the north, is based on the unique practice of terracing which permits reliance on rainfed agriculture. This is impeding the immediate runoff and erosion which the topography would otherwise allow, and ensuring the recharge of soil moisture and local groundwater. This terracing is extremely ancient and highly labour-intensive, with entire hillsides covered with stone bunds and earth banks interspersed with terrace areas, which may be as narrow as one meter in steep catchments. It is noteworthy that runoff is delayed during intense storms, with the terraces flooded as though with surface irrigation, and this allows the cultivation of cereal and vegetables on areas of steep slopes and sporadic storms.

The land use in upland areas of Yemen, particularly in the north, is based on the unique practice of terracing which permits reliance on rainfed agriculture. This is impeding the immediate runoff and erosion which the topography would otherwise allow, and ensuring the recharge of soil moisture and local groundwater. This terracing is extremely ancient and highly labour-intensive, with entire hillsides covered with stone bunds and earth banks interspersed with terrace areas, which may be as narrow as one meter in steep catchments. It is noteworthy that runoff is delayed during intense storms, with the terraces flooded as though with surface irrigation, and this allows the cultivation of cereal and vegetables on areas of steep slopes and sporadic storms. Land cover map is shown in Figure 7.

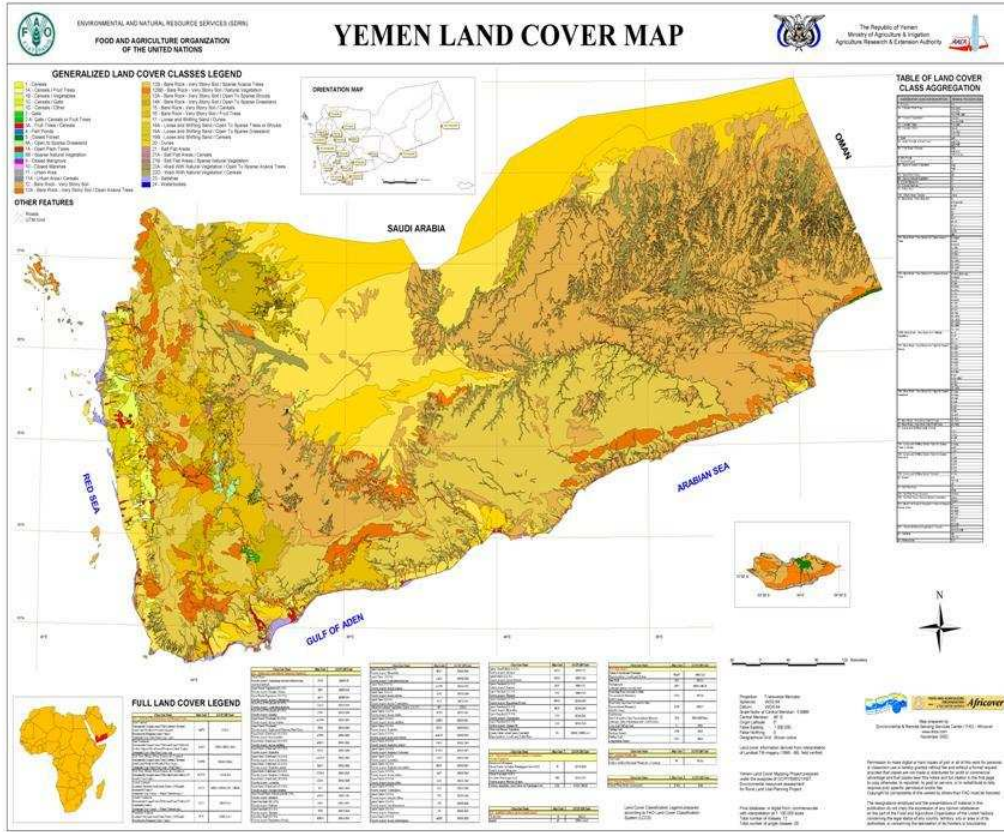


Fig. 7. Yemen land cover map

## GEOLOGY

Among the many source of information on the geology of Yemen, in particular Geukens (1966), Grolier and Overstreet (1978), Al Anbaawy (1985), the Arab Organization for Mineral Resources (1986) and Robertson (1991) were used to compile the following sections. Figure 8 shows the geological map of Yemen.

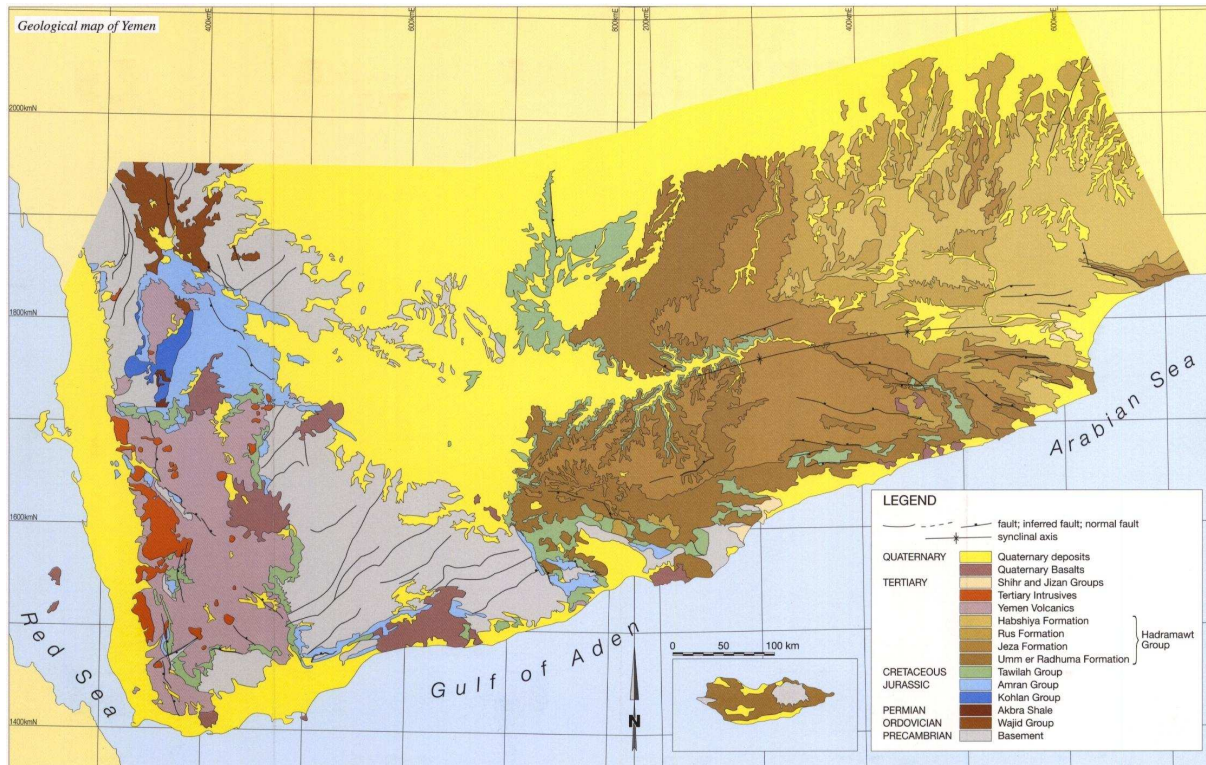


Fig. 8 Geological map of Yemen.

### Structures

The Arabian Peninsula is in a structural sense part of the African-Arabian plate. This plate moved in Late Cretaceous and Cenozoic times both eastward and northwards with respect to the Eurasian plate. The collision in the north had a profound impact on the regional geology: in the north the basement is depressed the thickly covered with relatively young sediments (platform zones), where further south 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 sub horizontal sediments further east. The uplifted shield (Yemeni horst) is steep-sided to the west and south, but slopes gently in north-east direction. It mainly consists of crystalline basement, and is partly covered by sediments and volcanic rocks. Prominent regional tectonic features include the anticlines 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 and the Al Ghaydah Depression.

## **Geological history**

The Precambrian basement rock of the area- part of which of the area-part of which are believed to have originated as a series of volcanic island arcs- were subjected to intensive folding and to metamorphism. Afterward, in the Paleozoic Era, the basement was strongly eroded, leveled to a peneplain and warped. Subsequently it was covered by sediments during the Cambro-Ordovician, Permian, Jurassic and Cretaceous periods.

Rapid subsidence started during the Jurassic period along the line which defines at present 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 neighboring East-Africa was uplifted and started to break into separate blocks.

Lava extruded through faults and fissures, and thick extended strata of ruffs and lavas (andisites, basalts, syenites, rhyolites, etc.) covered the Precambrian basement and the overlying-predominantly Mesozoic-sediment).

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 location it exceeds 2000m.

In the eastern part of the country thick blankets of predominantly carboniferous sediments were deposited during the Tertiary period.

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

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

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 Ramalat Sabatayn and Rub al Khali.

## Stratigraphy

A geological overview map of Yemen derived and generalized from Roberson's geological map (1991) is presented as Figure 8. 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.

Table 3 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. Name of formation-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, in spite of the fact that the latter information does exist. For some groups or formations more than one name is in use. In such cases it was attempted to select those 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 are focusing on the mainland of Yemen. The geology of Socotra and other Islands has been studied in less detail till present. 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, is composed of metamorphic and intruded igneous rocks
- The Thalib Group, is 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 at 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, discordantly 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 fluvial conditions (Robertson, 1991). Some authors (e.g. Roland, 1997) make a distinction between a yellow-brownish ferruginous lower member and a light-coloured upper member and in the basal part of the Wajid Sandstone. The total thickness of the Wajid Sandstone exceeds 600 m.

Akbara 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 continue dropstones of rounded striated basement rocks. Previously, several geologists considered the formation to be the shaly basal part of the Kholan Sandstone, but the tendency nowadays is to follow Roland (1979) and to consider it as a separate formation.

The lower-Jurassic Kholan Group is a minor unit, considering mainly of sandstones with considerable vertical and lateral variation. Its base is always an unconformity with the underlying older rocks. The thickness of the unit is variable with an average of some 60 m. the rocks grade up into the basal limestone of the Amran Group.

The Amran Group is a thick series of dominantly calcareous sediments, but locally including significant sequences of shales and evaporates. The carbonates are commonly massive, fissured rocks. Maximum thickness of the Amran Group may exceed 800 m. it is a complex group, with the two main depositional environments; a neritic environment which resulted in the 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 3 follows the subdivision as originally proposed by Beydoun (1966), but the Ahjur formation is added. The latter formation suggested by El-Anbaawy (1985) was in previously in the Sana'a region know under the name of "Unnamed Formation".

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 Al-Sabatayn region. In oil exploration studies since the beginning of the 1980s the Amran Group in this region tends to be subdivided in (from bottom to top) the Saba, Arwa, Meem Lm Formations. In this stratigraphic system follow the Alif and Safer Formations of the Upper-Jurassic Amlah Group; the Alif Formation contains Hydrocarbon-bearing zones. The Safer Formation in turn, is overlain by the Azal Formation, which is in some reports considered as part of the Amlah Group, but in others as belonging to the Amran Group. Insufficient information is available yet to correlate all these formations to those indicated in Table 3 It is plausible that the Amlah Group corresponds to the Sabatayen Formation.

The rocks of the Tawillah Group have a wide geographical distribution. They are almost continues east of the basement outgroup of the shield, but in the western part of the country their demonstrated presence is limited to the central and southwestern part of Yemen mountains, with narrow belts of outgroups bordering the protecting volcanic cover. The unit is mainly composed of non fossiliferous fissured sandstones, but in the eastern part of the country in the Al-Mahra governorate the terrestrial facies changes into a marine calcarenaceous facies. The total thickness of the formation is in order of several hundreded of meters.

Table 3 shows a distinction between west and east regarding the stratigraphic subdivision. In the western part two formations are distinguished: the Tawilah Sandstone and Madjzir Formation. The latter formation crosses the Cretaceous-Tertiary boundary; only recently it is being 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 formation of the Palaeocene/Eocene Hadramawt Group from 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 evaporates. Prominent is the basal Umm Er-Radumma Formation of dominantly massive limestone, several hundreds of meters thick, with outcrops mainly at the western and southern edges of the area where the Hadramout Group is present. More east and northward it is covered by younger formations of the group. Recently, two new formations were mapped: the Upper Eocene Hamara Formation (Sandstones with silts and evaporates) and the Rimah Formation (gypsiferous conglomerates and sandstones). They could in principle be grouped under the Hadramout Group, which then would extend into the Oligocene (Roberston, 1991).

The rock of the Yemen Volcanics from a large, almost continuous plateau in the western part of the country. The total thickness of the volcanic series may exceed 200m. The sequence consisted of sub horizontal strata of basic to acidic lavas, ignimbrites and pyroclasts, with intercalated soil horizons. Fuchs (1985) suggests a subdivision in four parts. From bottom to top these are:

- a- melanocratic Basal Series;
- b- the well bedded Haddah Series,
- c- the chaotic Series,
- d- Well-organized Upper Series.

The latter two series consists of dominantly leucocratic rocks. Associated with the Yemen Volcanic are alkali-granitic Tertiary Intrusives; they are mainly observed in the eastern marginal zone of the red sea.

The Baid Formation belongs to the Jizan Group and is associated with a series of small salt diabys along the red sea coast. The shales, limestone 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 meters 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 the Yemen Volcanic, the Quaternary Basalt have typically a much more local occurrence. They include numerous volcanic cones. There is a gap in time of the approximately 10 million years between the eruptions of the Yemen volcanic 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 Alsabateen, the red sea coastal plain

(Tihama), the southern and eastern coastal plains and the Wadi Hadramout valley. They are also present in the numerous wadi beds scattered over the country.

## **Natural hazards**

### ***Land degradation***

Due to the physiographic characteristics of the country, most of the arable lands are located within watershed entities. The accelerating degradation of watershed basins of Yemen has serious economic, ecological, environmental and social implications

Insufficient information, however, is currently available on the magnitude of resources degradation, on the extent of soil erosion and sand encroachment. Most arable and watershed areas are subject to extensive soil erosion and desertification. Sand encroachment on agricultural land areas in the south (around Aden), west (specially Wadi Mawr and southern Tihama) and east (specially around Marib and wadi Al Jawf) probably represents the most immediate and serious environmental threat in Yemen at present.

Erosion from the steep basins has resulted in talus fans with coarse gravel and silt along the foothills and gently sloping areas of fine silt along the alluvial plains below the outfalls of wadis in the coastal and interior plains.

### ***Flooding***

Flooding occurs during monsoon season leading to loss of productive agricultural lands along the wadis, increasing sedimentation and significant widening of downstream wadi bed.

### ***Firewood***

The natural vegetation of acacia scrub in the foothills has been degraded by the search for firewood. Natural forests have almost disappeared due to overcutting for construction, fuelwood, and fodder.

Currently, there is no inventory of national forest resources. In addition, there is no detailed data on desertification (e.g. location and extension of sand dunes, movement, and patterns) trends in the degradation of terraces (e.g. ownership, size, impact and magnitude of soil erosion).

AGE			GROUP		FORMATION		LITHOLOGY		
			West	East	West	East	West	East	
C E N O Z O I C	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		
						Umm-Er-Radhuma	massive marly and dolomitic limestones		
Palaeocene					Medj-Zir	hard argillites, cross-bedded bioclastic sandstones			
					Tawilah Group	Tawilah Sandstone	Sharwayn	yellow sandstones (Kawkaban member), dark red sandstones (Shibam member), and white clayey sandstones (Thula member)	shales, limestones, sandstones
M E S O Z O I C	Cretaceous				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			Kohlant Group	Kohlant Sandstone	sandstones with conglomerate intercalations			
Permian				Akbra Shale	laminated mudstones, siltstones, shales				
				Wajid Group	Wajid Sandstone	cross-bedded sandstones and coarse siltstones			
Pre-cambrian			Precambrian Base. ment		igneous rocks, metamorphic rocks, metasediments				

Table 3. stratigraphic table

## CLIMATE

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 in the first place a consequence of the country's location between 12 and 19 grad Northern Latitude. It causes solar radiation to be of high intensity and it brings the area during spring and summer under the influence of the afore-mentioned ITCZ.

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 for poor quality of part of the records. 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 pattern in space and in time may help distinguish between records of acceptable quality and those that are probably unreliable.

### ***Rainfall***

Rainy seasons occur during the spring and summer (Table 4). The climate of Yemen is strongly influenced by the mountainous nature of the country (Bruggeman, 1997). Rainfall rises from less than 50mm along the Red Sea and Gulf of Aden coasts to a maximum of 500-800mm in the western highlands and decreases steadily to below 50mm inland (Figure 9)

The rainfall depends on two main mechanisms, the Red Sea Convergence and the Monsoonal Inter tropical Convergence Zone. The former influence is most noticeable in the west of the country, this is active from March to May and to some extent in autumn, while the latter reaches the country in July-September, moving north and then south again so that its influence lasts longer in the south. Seaward exposed escarpments such as the western and southern slopes receive more rainfall than the zones facing the interior. The average temperature decreases more or less linearly with the latitude.

STATION	ZONE	ELEVATION (m)	ANNUAL TOTALS OR AVERAGES					
			P	T	RH	WS	SSD	ET <sub>p</sub>
Mocha	1a	5	21.4	29.2	74.1	4.7	8.3	2662
Hudaydah	1a	10	101.5	29.4	76.9	4.7		
Al Kod	1b	13	64.5	25.5	75.0	1.6	8.9	1917
Giar	1b	60	34.6	28.0	64.7	1.8	8.8	2213
Fiyush	1a	65	45.4	28.4	66.0	0.6	8.2	1880
Dahi	1a	70	138.0	30.1	53.4	1.0	7.4	2082
Zuhrah	1a	70	133.0	30.3	61.2	1.7	6.2	2123
Kudeidah	1a	120	141.6	31.0	65.0	2.8	7.7	2523
Lahej	1b	129	55.6	28.3	68.1	1.1	8.1	1975
Khalifah	1a	139	550.8	26.8		1.0	7.2	-
Jaroubah	1a	150	367.4	30.3	59.1	3.1		-
Zabid	1a	240	347.8	29.6	63.0	1.5	7.5	2147
Barh	2a	500	330.1	28.4	68.5	1.8	7.1	2016
Seyun	3c	700	64.6	26.0	42.2	1.0	9.0	2338
Marib	4a	1000	79.2	26.1	22.6	3.4	9.4	3211
Nuqub	4a	1040	70.6	24.9	34.0	1.5		2377*
Jawf	4a	1100	67.0	26.5	22.3	3.4		3427*
Dhala	2b	1150	354.9	22.0	41.0			-
Hajjah	2a	1300	259.0	23.6	54.8	1.3		-
Ossefra	2a	1350	458.4	23.1	56.5	1.8	8.1	2003
Magash	2d	1885	98.2	20.3	35.1	2.8		-
Dumeid	2d	1950	126.2	19.2	29.4	1.4	7.9	1970
Khabar	2d	2140	188.4	17.8	50.2	1.7	9.0	1898
Irra	2d	2200	183.4	17.4	35.5	4.5		-
Sana'a (CAMA)	2d	2216	<u>150.0</u>	19.2 ?	44.1	3.5	8.5	2475
Sana'a (GDH)	2d	2275	174.4	19.4	30.6	1.1		-
Risabah	2d	2318	295.2	16.1	41.2	2.1	8.6	1997
Dhamar	2d	2360	360.0	16.0	59.7	1.2	8.3	1579
Ketab	2d	2500	360.0	12.9	42.1	2.1		-

P = precipitation (mm), T = average temperature (°C), RH = relative humidity (%),  
WS = wind speed (m/s), SSD = sunshine duration (hrs/day)  
ET<sub>p</sub> = potential evapotranspiration (calculated according to Penman, modified by Doorenbos & Pruitt, 1977)  
\* = calculated using sunshine duration data for Marib

Table 4 presents a summary of metrological statistics for selected metrological stations.

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 greatly. This is consistent with the general observation that most individual storms cover only a limited area, not more than some tens of square kilometers in extent. Orographic effects are strongly controlling the spatial patterns of rainfall.

Annual rainfall totals vary from year to year and from location to location. Most rainfall stations in Yemen have too short record to study long-term variations of annual rainfall totals. For Aden, Sana'a, Taiz and Rayan, however, there are relatively long series of observations. Topographic factors controlling the spatial patterns are strong enough to produce pronounced patterns that are rather 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. Consequently, it is not yet possible to produce a reliable map of long-term annual precipitation for the territory of Yemen. The spatial pattern of average annual rainfall over the period 1985 through 1991, shown in Figure 9 may serve as a first estimate of long-term average isohyets map.

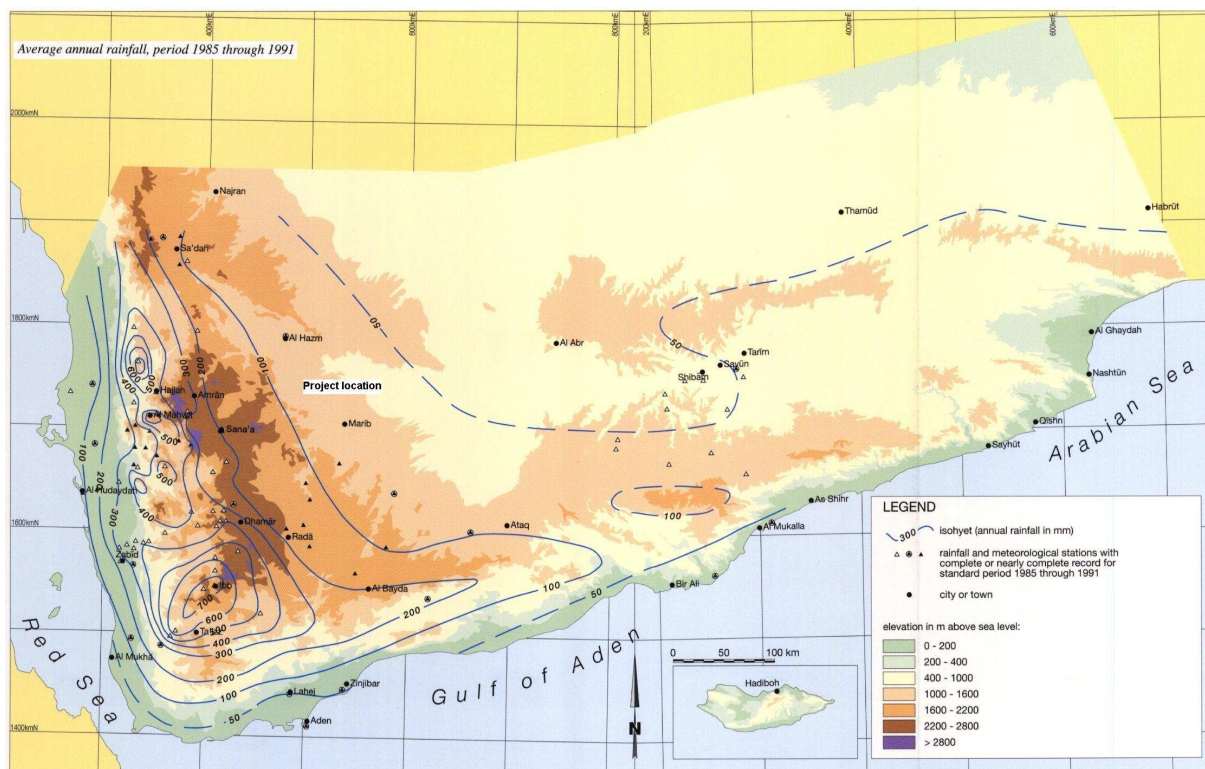


Fig. 9 Average monthly rainfall patterns for selected rainfall stations.

The coefficient of variation of the annual rainfall series tends to decrease with increasing average rainfall, as Figure 10 shows. This means that variations from year to year are most pronounced at the most arid sites, at least in relative term, i.e. compared to the average rainfall. This variability is less at the wettest locations, but even there it is still considerable.

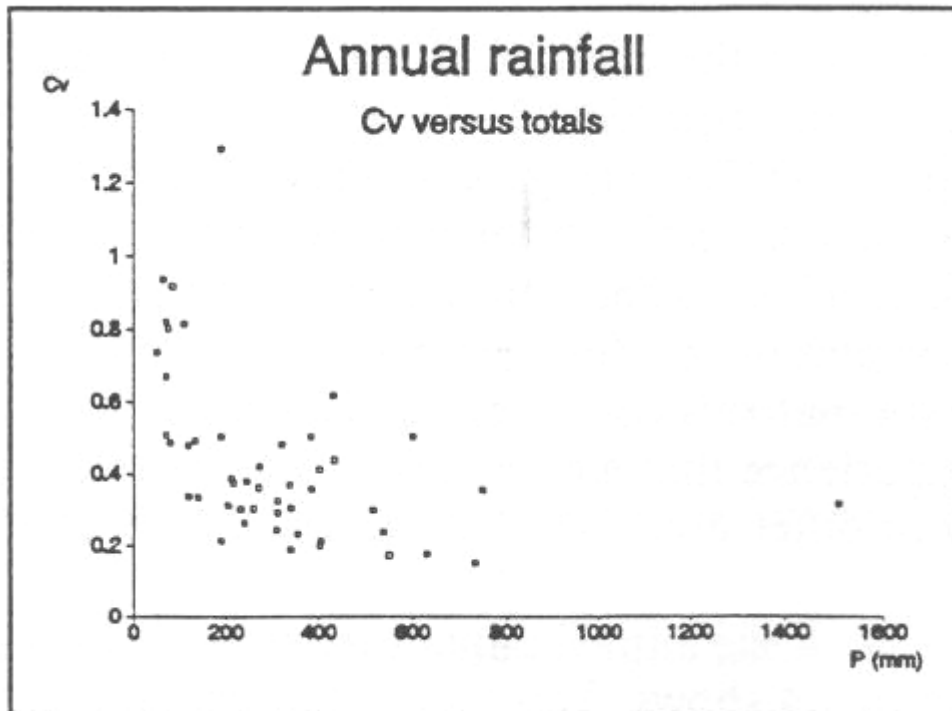


Fig. 10 Coefficient of variation of the annual rainfall series.

In spite of all restrictions gives the isohyets map 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 depicted pattern there is slightly speculative. Average annual rainfall figures higher than 250 mm are only observed in the western and southern parts of the Yemen Mountain Massive, with the 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 Ramalat Al-Sabatayen.

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 the coastal plain without producing much rain at these low elevations. But the steep western and southern slopes force the air in an upward direction, which results in cooling and consequently in rainfall. Note that on the western slopes the zone of the maximum rainfall is systematically shifted with respect to the zone of maximum elevation; the air masses loose of their moisture at the first major mountain ridge they meet, and have generally become much drier when they move more eastward. The air that is passing from the highlands towards the lower zones of the interior is mostly poor in moisture and moves generally downslopes, which explain that rainfall there is sparse. A similar mechanism acts on the air masses that move in from Gulf of Aden, but the pattern is less pronounced because the relief is lower. The high rainfall zone Ibb and Taiz enjoys rains both from southerly and westerly provenance.

Although it is known that rainfall in the Al-Mahrah governorate is generally low, there are no data available to depict a pattern. An aspect of interest might be the

occurrence and importance of dew. The adjoining Dhofar region in Oman has green grazing area during the monsoon months., which is attributed to the occurrence of dew during these particular months. It is of interest to know whether this phenomenon is important for Yemeni side of the border as well.

A rainfall pattern for Socotra Island can not yet be established either. Available rainfall data suggest an average rainfall near Hadibo of 100-150 mm per year. Source 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.

Seasonal rainfall patterns differ from 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 leads during a few subsequent months 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 starts usually in July. By the time the ITCZ lies over Yemen and warm dry air from the north converges with very moist air originating from Indian Ocean region. Rain becomes 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 be obscure the described seasonal pattern.

The relationship between the mean annual rainfall and topography is shown in Fig. 11, where a west-east section is considered. The section shows the increase in annual rainfall with elevation up to the mid length of the section, beyond which the rainfall drops sharply in the mountain plains and further to the east in the eastern mountain areas.

Daily rainfall amount in Yemen are in most cases the result of only one rain storm. The duration of such storm is usually rather short, and only exceptionally exceeds a few hours. Difference between zones or locations in the total annual or seasonal rainfall is 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 as single statistical population of rain storms.

Based on the record 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 0 is strongly correlated with the average annual rainfall. This is demonstrated in Figure 11, which suggests the following regression equation:

**Expected number of rainy days (per year) = 0.0552\*mean annual rainfall (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 proprieties; 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 the daily rainfall (DR) on rainy days (rainfall > 5mm) is related to the frequency factor  $F_N$  (normal variate) of the normal distribution as follows:

$$DR=e^{2.58+0.61 \cdot F_n}$$

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 12 shows the defined distribution graphically.

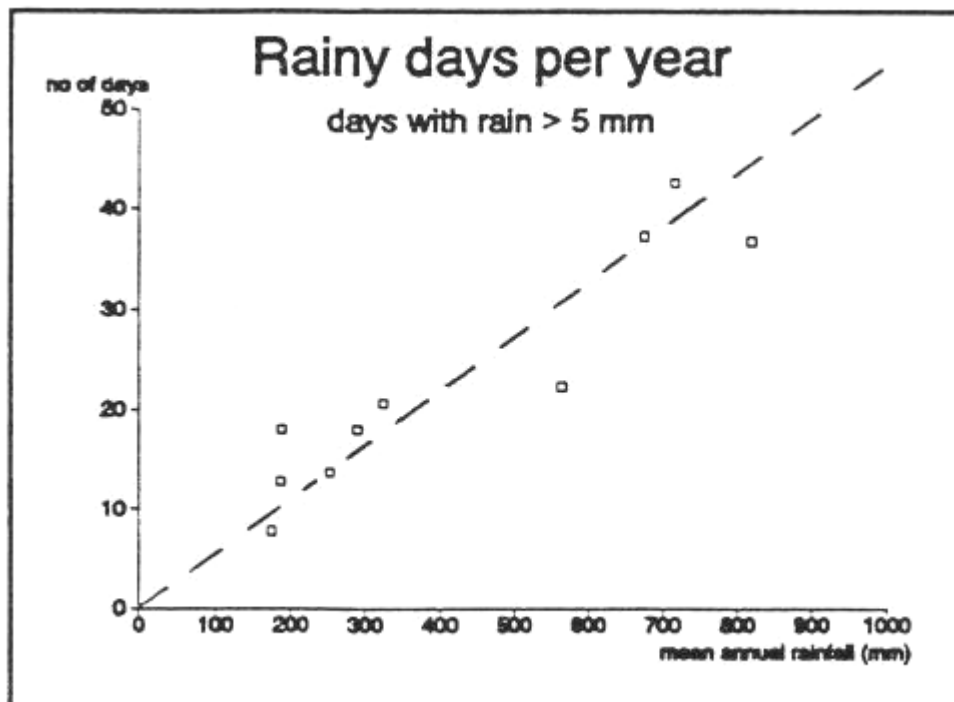


Figure 11 Number of days with rain > 5mm in relation to mean annual rainfall (----)  
page 31

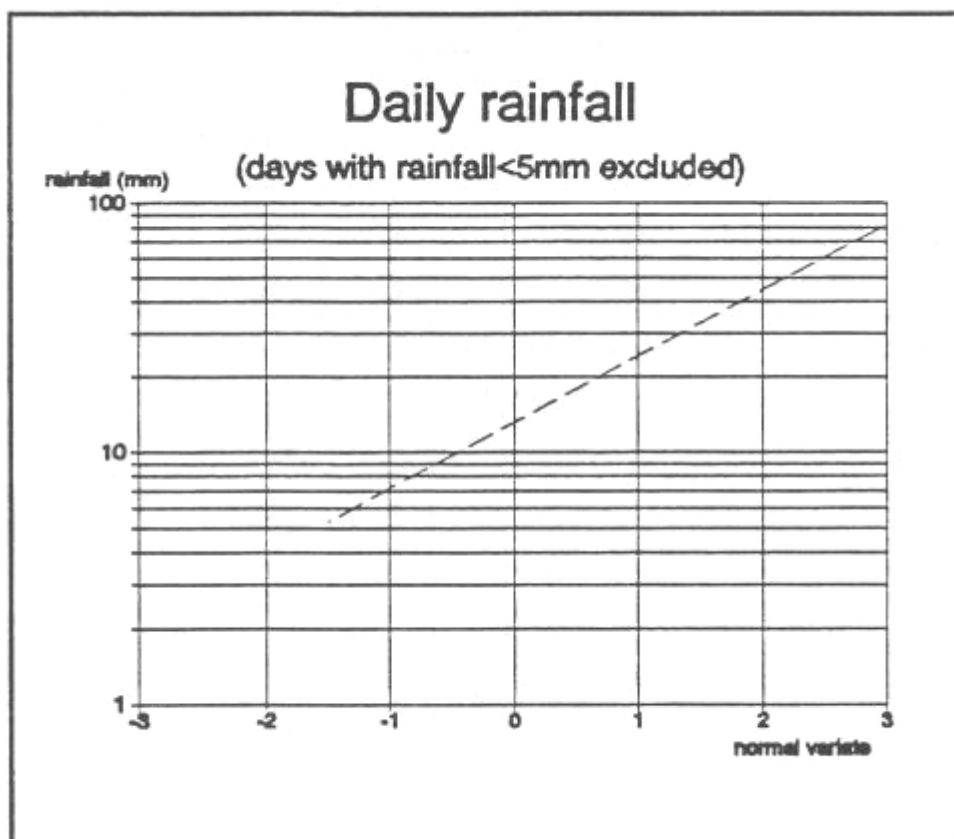


Figure 12 log-normal distribution of rainfall for days with more than 5mm of rainfall

From a statistical analysis of the rainfall data at stations in the Mawr, Zabid and Rima'a catchments the frequency distribution of the annual maximum daily point rainfall at the western escarpment has been established. The assumptions underlying the said analysis is that rainfall events are statistically independent and that the area homogenous with respect to rainfall. These conditions are not completely satisfied. As such the frequency distribution should be used with caution.

### ***Temperature***

Average temperatures are dominantly controlled by elevation. There is an approximately linear relation, this relation is disturbed by the proximity of the sea in the coastal areas. Mean annual temperature range from less than 12.5°C in the central highland to 30°C in the coastal plains. However, the winter temperatures may decrease to freezing the highlands. Figure 13 shows the temperature versus elevation in Yemen. The figures show that, there is a tendency for the temperatures to decrease at increasing elevations.

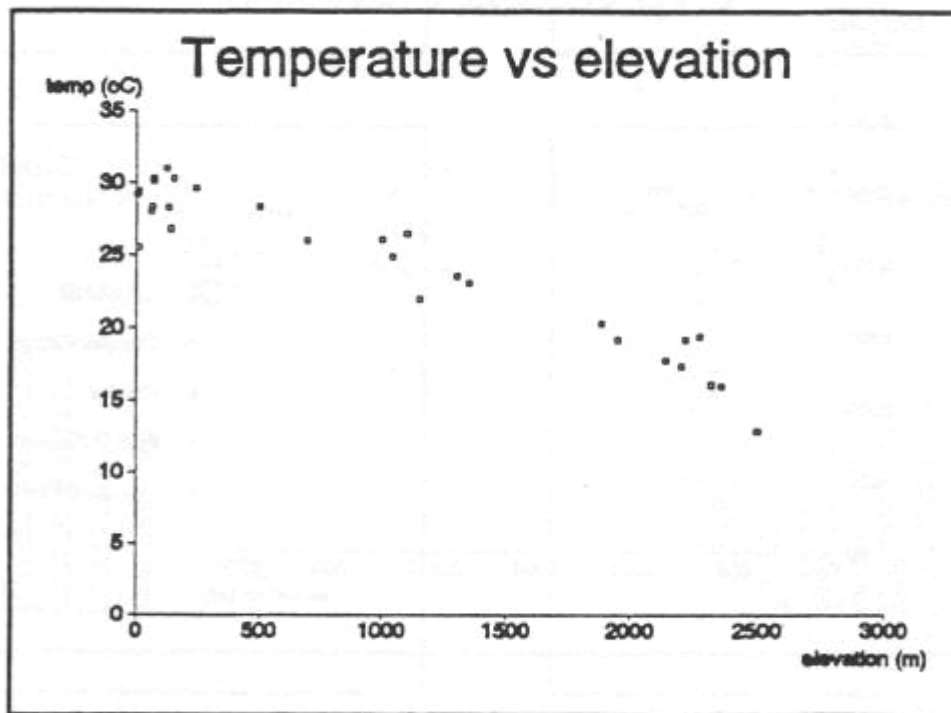


Figure 13 the influence of elevation on average temperature

### ***Evaporation and evapotranspiration***

the penman method, Doorenbos and Pruitt (1984) version was used to calculate potential evapotranspiration. Table 4 presents the results in term of average annual totals. The annual totals range from 1579mm (Dhamar) and 3427mm (Al Jawf) for the meteorological stations considered. 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.

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

- Costal 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 (PET) during the growing period is illustrated in Figure 14.

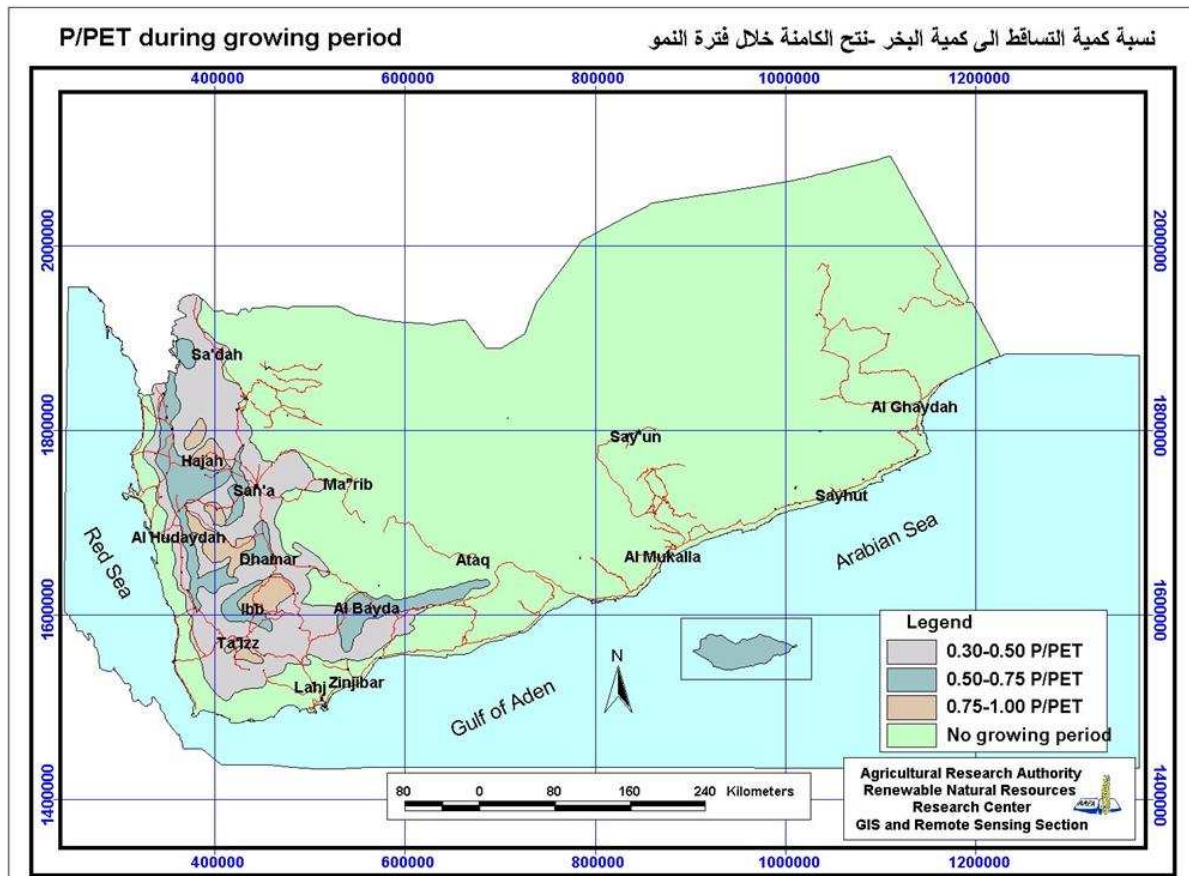


Figure 14 Rainfall/potential evapotranspiration during the growing period

Figure 14 shows clearly that in the eastern part of the country the rainfall is insignificant compared to potential evapotranspiration. This implies that irrigation there is a prerequisite for crop growth. In the western part, at the other hand, rainfall during the growing period may cover a substantial part of the crop water requirements. For zones with higher annual rainfall the P/PET –ratio is even more favorable.

Evaporation from an open water surfaces ( $E_0$ ) is controlled by meteorological conditions. Evaporation from bare soils and evapotranspiration from vegetated surface, however, are controlled by soil moisture. They attain their potential level if there is no soil moisture deficit; in such a case the rate is dependent only upon meteorological factors.

When considering potential evapotranspiration, it is tacitly assumed that fully developed, green vegetation covers the total surface.

Evaporation exceeds rainfall over most of the territory of Yemen this implies that except in some limited areas, soil moisture deficit prevails most of the year; evapotranspiration rates are usually far below their potential level, which may only be reached during and shortly after rainy spells. For such areas, reduction factors must be used when actual evapotranspiration is estimated from potential evapotranspiration may be close to the potential value.

Class A pan evaporation rates usually exceed true evaporation from large water bodies. As such, reduction factors of .065 to 0.80 are often applied to pan evaporation in arid and semi arid zones.

The Penman approach to the assessment of evaporation and evapotranspiration has been applied to a number of latitudes. The meteorological data and Penman evaporation at the selected latitudes are included in table 5.

<b>Elevation meters +m.s.l</b>	<b>n/N*</b>	<b>Temperature C</b>	<b>Relative humidity %</b>	<b>Wind speed m/s</b>	<b>Evaporation mm/yr</b>
0	0.7	30.0	75	3.0	2534
50	0.7	30.0	70	2.6	2491
100	0.7	30.0	68	2.2	2435
200	0.7	30.0	63	1.7	2381
500	0.7	28.1	62	1.7	2266
1000	0.7	25.0	59	1.7	2116
1500	0.7	21.9	56	1.7	1925
2000	0.7	18.8	54	1.7	1784
2500	0.7	15.6	52	1.7	1645

Table 5 Penman evaporation for different elevation in Yemen.

\* n/N: Ratio between actual and possible duration of sunshine

Potential evapotranspiration is closely related to open water evaporation (as a first approximation it can be estimated at 70% to 80% of the evaporation rate). However, the actual evapotranspiration is substantially lower in Yemen, except in well-irrigated areas.

## 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, stream flow, surface water levels, groundwater levels, water quality and water use. Well-designed monitoring networks reveal the dynamics of the meteorological or hydrological 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.

The locations of the different types of stations are shown in Figure 15. 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 plain and in the surroundings of Wadi Hadramout. Socotra and the sparsely populated mainland of Al-Mahra governorate have a few meteorological stations each, and there are no monitoring stations in the vast desert area. The existing and proposed monitoring stations in Yemen are shown in the Figures 15 and 16.

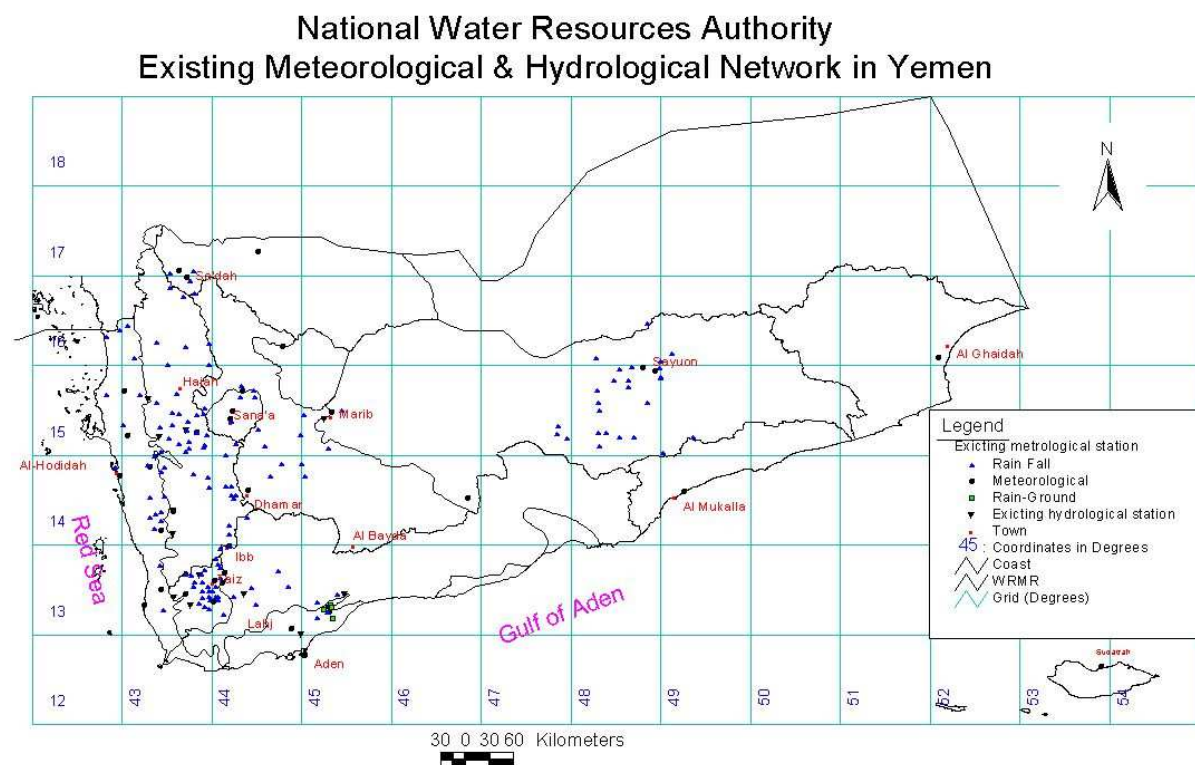


Fig. 15 Existing hydrometeorological monitoring stations in Yemen

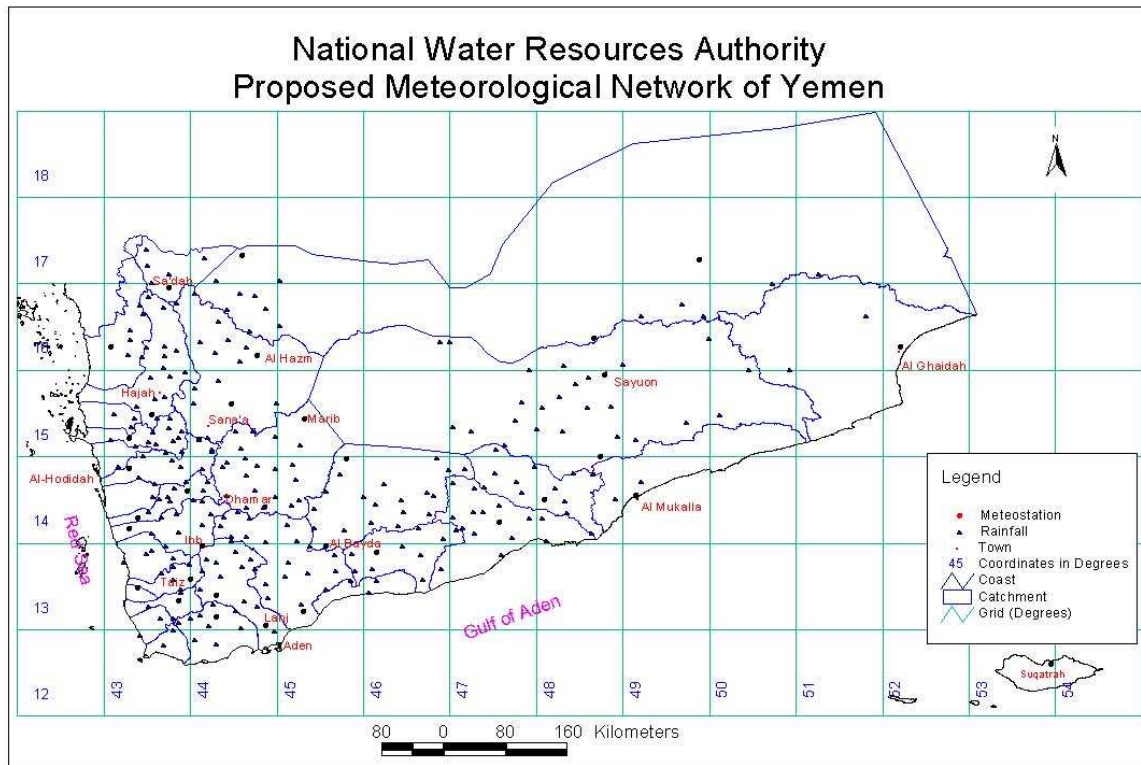


Fig. 16 Proposed hydrometeorological monitoring stations in Yemen

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 streams gauging stations are located along the border of the Yemen Mountain Massif to monitor the yield of individual major mountain cathments. The many stream gauging stations in Wadi Hadhramout indicate an interest in the contribution of the main tributaries to the total volume of Wadi Hadhramout floods and to their infiltration into the alluvial aquifer of the Wadi Hathramout's wadi beds.

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 these project networks. Most of the stream gauging stations are nowadays equipped with water level recorders; some of those in the Hadramout 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 prior to 1960. most of the rainfall stations currently known were installed during the late 1970s or during the 1980s. Several have been abounded already and many of the record have major gabs in the period of observation.

Only a few groundwater level monitoring networks are known and these are of limited areal extent. They include a networks of NWRA, NWASA, TDA in the major wadis in the country, in the Sana's and Sadah basin and in the Marib zones. The approximate numbers of well 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.

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 od headworks of NWSA's water supply.

No other groundwater abstraction monitoring is known in Yemen, other than 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 diversion are known either.

The hydrological and meteorological networks in Yemen are not operated centrally, but local or regional networks are run by different organizations. Most of the stations started as project stations and after a couple of Years were transferred to the government agency under which the project stored. As a result there is not yet any national standardization of equipment and monitoring practices. Difficult physical conditions, large distance, 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 records- has improved the operational conditions and consequently the records as well.

Stream gauging station 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- air based on staff gauge readings (one or two a day) and thus are not suitable for reconstructing instantaneous flows.

## **Database**

Tome series data, well inventory data and other basic numerical information on the climate, hydrology and hydrogeology of Yemen is stored in database of NWRA (National Water Resources Authority. it was intended as a centralized publicly accessible national water resources database.

Given the fact that many organizations and projects are running monitoring networks and are conducting field studies in Yemen, the database of NWRA 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 (CAMA), Tihama Development Authority (TDA), ERADA, NORADEP, SSHARDA, SURDUP, GDI of the MOI, and NWSA.



## WATER RESOURCES

### *Water availability*

Rainfall is the major source of all water in country. During the last decades, Yemen has been facing the pressing problem of providing water demands for a population growing rapidly. The agriculture sector is by far the major consumer of water and will continue will to be so in the future. The pressing need to increase agricultural products, people's domestic needs and industrial uses has lead to the available water resources depletion.

Water shortage is a serious problem in Yemen where the current estimated water use are by far exceeding (almost 30%) the renewable water resources (Figure 17)

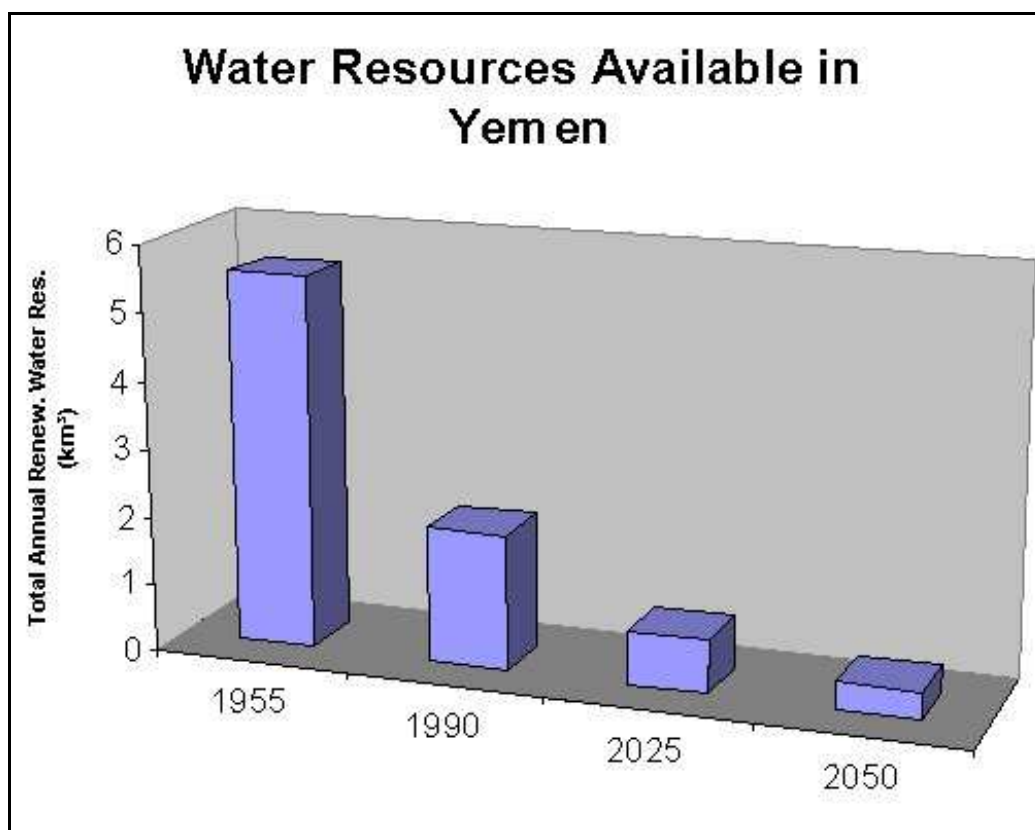


Fig. 17 Available water resources in Yemen

### *Surface water*

#### *General features of the runoff processes*

Rainfall is the main source for surface water in the country. Most all the wadis are ephemeral, only a few have minor bas flows that may seasonal or permanent, but only in a limited part of their channels. The wadi beds are dry most of the time, and infrequent runoff peaks quickly occur and disappear. Flood peaks are often quick and

infrequent because of sparse vegetation and mostly impermeable nature of the soil in the catchment areas.

Baseflow is nearly constant components 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: the main ones are taking into account the conditions encountered in Yemen:

- Size and shape of the catchment;
- Rainfall characteristics (total depth and distribution in space and time);
- Rates of potential evaporation and evapotranspiration;
- Terrain characteristics of the catchment areas (slopes; occurrence and properties of soils, rock outcrops and vegetation);
- Land use and other human interferences.

It is evident that –all other factors remaining constant- larger catchment areas and higher rainfall quantities will result in more runoff. And that catchments with the compact shape will produce more violent floods than elongated catchment areas. Next, runoff produced in the upper part of a catchment may get partially lost again on its way downstream through the river bed (transmission losses); statistically these losses will increase with distance. Furthermore, a certain depth of rain tends to produce comparatively more runoff when the preceding days or weeks were rainy already. It is commonly experienced in Yemen that the first rain after a prolonged dry period produces little or no runoff in the river beds downstream. It goes without saying that higher rates of potential evapotranspiration generally will lead to higher evapotranspiration losses.

Which percentage of the rainfall finally is converted into runoff and how quick the response is to rainfall, is strongly controlled by the nature of the land surface and of the geologic formations near the surface. Steep slopes and bare impervious rocks at the surface favour a quick response. Weak terrain 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 causing streamflow to be less voluminous and less frequent, and more retarded with respect to rainfall.

Especially the infiltration capacity of the surface horizons-in relation to the rainfall intensity plays a crucial role in the repartition of rain into the different components of streamflow and the losses mentioned above. Light rains falling onto a permeable surface, hence, often fail to produce any runoff at all.

Groundwater systems present in the catchment area may under certain conditions 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 base flow.

Land use may modify significantly the runoff processes. The numerous man made terraces on the slopes of the Yemen Mountain Massive offer a convincing example. They protect the soils from being washed away; the rains are easily infiltrating into the ploughed soils and are largely used for evapotranspiration of the cultivated fields; and the protecting walls from a barrier to overland flow. Small and large dams, spate irrigation systems and build-up areas 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 rivers have minor baseflows that may be seasonal or even permanent, but only in a limited part of their channel network. The beds of arid zone rivers typically are dry during 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 vegetations and limited extent of permeable soils in the catchment areas are incapable to provide effective buffers. It is not uncommon for wadis in low precipitation zones to remain completely dry for several years in between flood events.

Another salient feature of arid zones is that saturated contact between streams and regional groundwater reservoirs are 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 zones.

Whereas the average discharge of rivers in humid regions normally increases monotonously in downstream direction, this is often not the case of arid zone rivers. Wadis in Yemen demonstrate this very clearly. Distinct parts of the channel networks tend to act as collectors of surface water, others rather loose part of the flow or even all of it. From upstream to downstream there may be several alternations of 'gaining' or 'losing' wadi segments, but the overall result is that only minor quantities of surface water are discharged into the sea. The phenomenon is obviously related to controlling terrain features, as described above.

Table 6 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.

These may be of interest for better understanding difference in runoff regimes; the aggregation level of the map did not allow incorporating other relevant terrain features such as terrain slopes and presence of vegetation and terraced agricultures.

Table 6 Annual runoff, estimated annual rainfall and the size of the catchments

Continental Watersheds	Catchment Name	Area in Km <sup>2</sup>	No. of Years	Mean annual rainfall (mm)	Annual Runoff Mm <sup>3</sup>
<b>Red Sea (Tihama) Catchment</b>	Northern Tihama catchments, (Wadi Hayran, Abs, Harad...etc.)	8800	(20)	480	15
	Wadi Mawr	8100	(20)	650	129/237
	Wadi Surdud	2700	(20)	500	82/121
	Wadi Siham	4900	(20)	570	73/130
	Wadi Rima	2700	(20)	560	50/103
	Wadi Zabid	4700	(20)	400	86/164
	Wadi Nakhlah, Dumim...etc.	1500	(20)	500	5
	Wadi Resyan	2000	(20)	400	45/61
	Wadi Mawza	1500	(est)	350	20/38
	<b>Total Area</b>	<b>36900</b>			
<b>Al Rub' Al Khali Catchment</b>	Wadi Najran Al-Rub Alkhali catchment (W. Amlah, Khubb, Qu'aff, Northeast wadis....etc)	4400 84100	(est) (est)	140 150	70 ----
	<b>Total Area</b>	<b>88500</b>			
<b>Arabian Sea Catchment</b>	Ramlat Al-Sabatayn catchments (W. Harib, W. Al Aqman...etc.)	9100	(est)	150	48.4/15
	Wadi al-Jawf	14000	(9)	200	150/35
	Wadi Adhanah	12600	(est)	150	100/33
	Wadi Bayhan.	3600	(est)	17	2
	Wadi Markhah	3900	(est)	120/70	5
	Wadi Hammam	1850	(est)	90/55	1.6
	Wadi Nissab	1800	(est)	64	2.3
	Eastern catchments (W. Al Jiza, W. Fauri, W. Indent, W. Haghwat, W. Tinalin...etc.)	55000	-----	-----	--
	Wadi Hadramawt	21000	(est)	73	2
	<b>Total Area</b>	<b>211350</b>			
<b>Gulf of Aden Catchment</b>	South-western Catchments	7800	(est)	300	15/45
	Wadi Tuban	6500	(7)	150/250	80/120
	Wadi Bana	8000	(15)	75/650	169
	Wadi Hassan	3500	(est)	70/200	30
	Wadi Rabwa (Suhaybiyah)	1900	(15)	34	5.8
	Wadi Ahwar	6400	(15)	261	70.9
	Wadi Maifa'ah	8600	(est)	239	80
	Wadi Hajar	9300	(est)	225	20.3
	Mukalla catchment	5000	(est)	69	1.7
<b>Total Area</b>	<b>57000</b>				
<b>Grand Total</b>	<b>393750</b>				

Table 6 Annual runoff, estimated annual rainfall and the size of the catchments

Large-scale examples of runoff absorbing zone are the Tihama, the Tuban-Abyan coastal plains, and the Ramlat Al-sabatayen and Arub'a Alkhali deserts. The alluvial Wadi Hadramawt valley and the highland plains in the center of the Yemen Mountain massive are distinct runoff absorbing zones as well, but at a smaller scale. At increasingly smaller scales, smaller-sized absorbing zone can be distinguished, e.g. local alluvial fills and patches, and plots of cultivated lands. They are too small and too numerous to be shown in Figure 2.9 (page 24), but they play an important role in the runoff process. Note that the Yemen Mountains in the west and in 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<sup>2</sup> of catchment area largest on the western and southern slopes, because of 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 thousands km<sup>2</sup> and larger, annual runoff volumes are less than 10% of the annual rainfall volumes. Higher runoff coefficient ( i.e. ratio of runoff over rainfall volumes) are to expected for smaller catchment, because these offer statistically fewer opportunities for losses. Runoff coefficient for individual intensive rain storms during wet periods can be much higher than the annual average coefficient, because the physical processes that produce losses- such as evaporation and evapotranspiration- are limited in their rate.

### ***Catchmen areas and principal drainage basins***

The main wadis in Yemen are depicted in Figure 18, they have been selected from Robertson's topographic map; simplification were made to match the scale of the map, and topology or names were adjusted if reports made plausible that they were incorrect.

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.

Numerous wadis systems and related catchment areas cover the domain of Yemen. For simplicity, the country has divided into four major drainage basins, regrouping numerous smaller wadis (Figure 18):

- The Red Sea basin.
- The Gulf of Aden basin.
- The Arabian Sea basin.
- The Rub Al Khali interior basin.

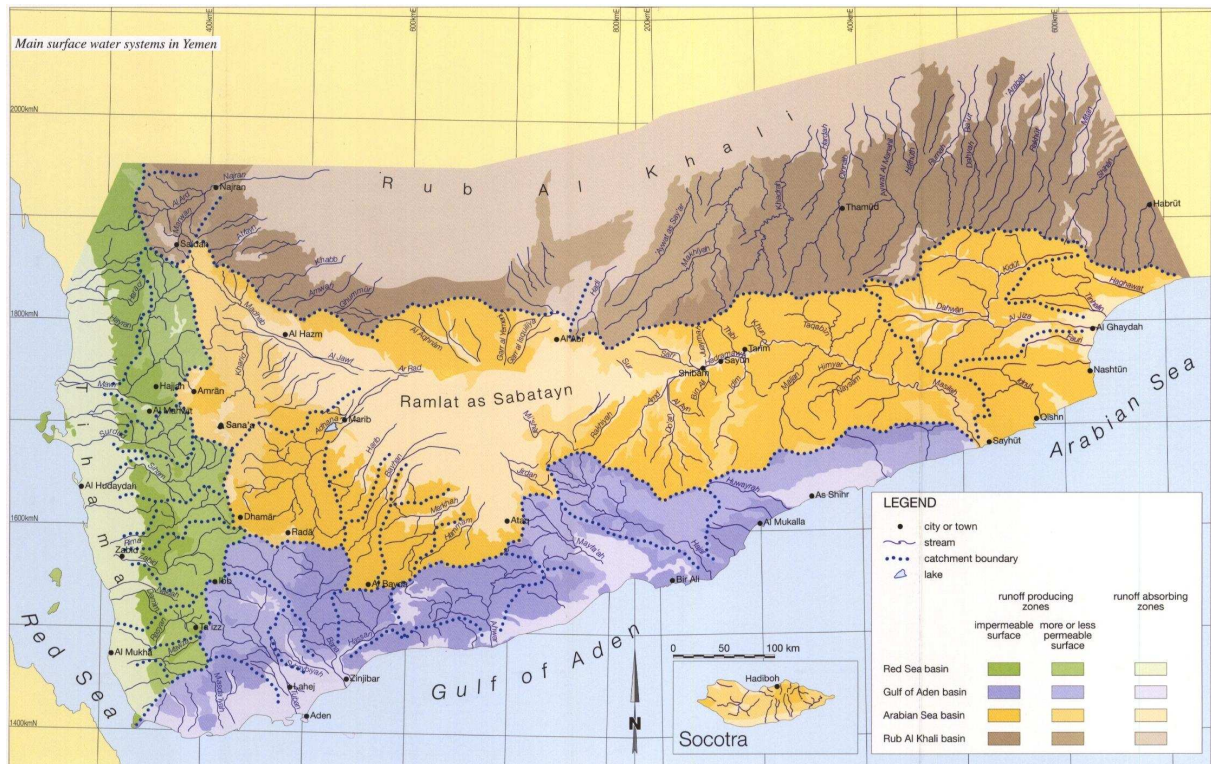


Fig. 18 Watershed map (Van der Gun, et al., 1995).

Surface water resources have been estimated at 2.1 billion m<sup>3</sup>/year, but this quantity corresponds to the runoff from major wadis and does not include the runoff produced within the smaller catchments. Water use was estimated at about 2.8 billion m<sup>3</sup>/year. The country thus overdrew its resources by 0.7 billion m<sup>3</sup>/year. In general, all surface water sources in Yemen are harnessed and exploited.

Most surface water flows are intermittent; they usually carry water at and after short heavy rains. A number of floods on a periodicity of rains and it vary from 50 in wadis of the western slope to 3 - 4 in wadis with upstream in the southern slopes. Table 6 lists annual runoff volumes, estimated annual rainfall and the size of the catchments.

These estimates show that approximately 40 % of the runoff were comes from the western slopes. Whereas, The Gulf of Aden, Arabian Sea and Al Rub Alkhali contribute of 30 %, 25 % and 5 % respectively. Annual precipitation is approximately 65 billion m<sup>3</sup>. The surface runoff to the sea measured in some major wadis is estimated at 1430 million m<sup>3</sup>/year. (Al Hemiary, 1999).

### ***The shape of the Hydrographs***

#### **Instantaneous flood hydrographs**

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

Inspection of some of the recorded water level hydrographs shows that time to peak for floods resulting from rain storms of short duration ranges from approximately 15 to 60 minutes.

Figure 19 shows an instantaneous record of Wdi Surdud's flow with 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<sup>3</sup>/s, still relatively high because of the preceding rainy period, but late in the afternoon of the 17<sup>th</sup> 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 the base flow.

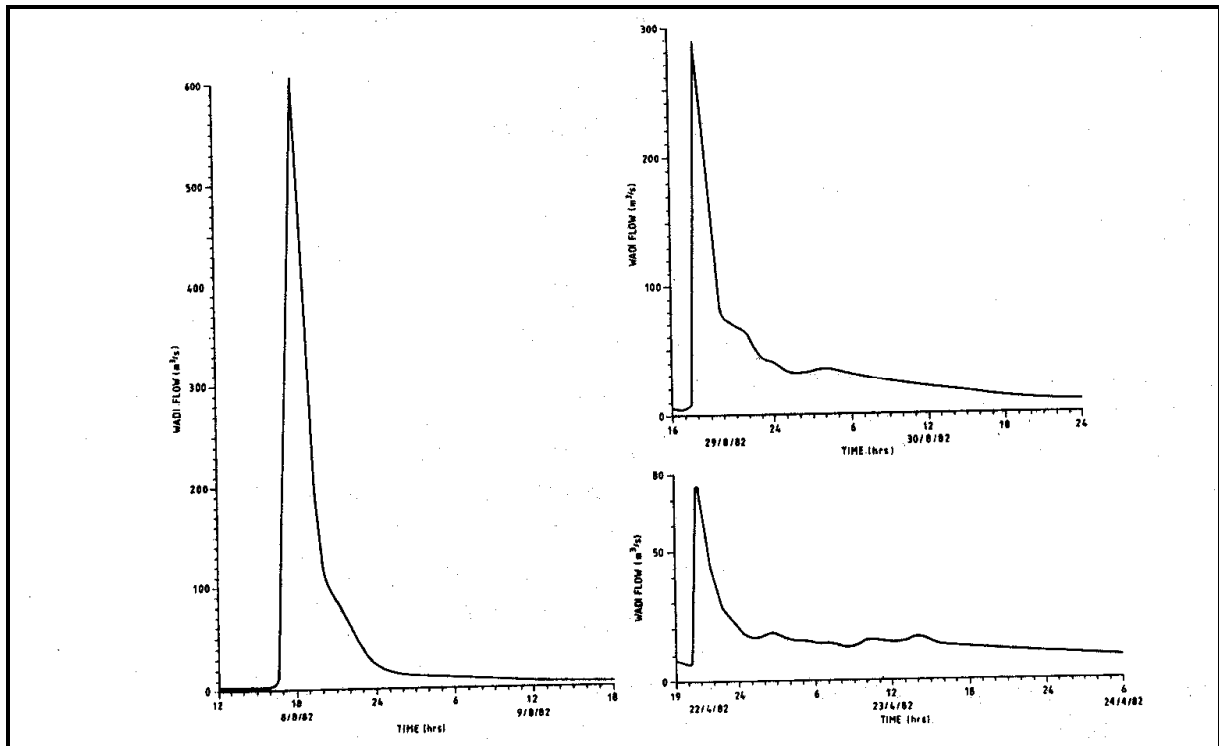


Fig. 19 An instantaneous flow record of Wdi Surdud's at Faj Al-Husain, 17-19 June 1984.

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<sup>3</sup>/s may turn into a wild stream, with high flow velocities and a discharge often between 100 and 1000 m<sup>3</sup>/s. the recession is quick too, but two distinct hydrograph shapes are shown in Figure 19. The first flood reaches 87 m<sup>3</sup>/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<sup>3</sup>/s, but due to a slower recession it brings almost twice the volume of water discharged by the first peak. For Wadi Rima'a for example, records (1978-1990) it has been found that 70-90% of the annual runoff volumes resulted from the lower segment of the hydrograph (0-15 m<sup>3</sup>/s); the contribution of the flows exceeding 100 m<sup>3</sup>/s was only 3-7%.

Most floods 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.

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 a recession are quick anywhere, although in larger cathments, 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.

Several factors are responsible for the immediate response of the catchments to rainfall. Among these factors are the steep topographic slope of the stream channels, the sparse vegetation and the low permeability of most outcropping rocks.

### **Base flow**

The base flows regimes of different wadis in Yemen shows much more variation than the direct flow regimes do. Major wadis in Yemen especially in the western part of the country have a permanent baseflow, which represents a significant part of the total flow; it is postulated that these baseflows are at least partly related to the specific geological conditions. 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.

### **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, but it gives a highly distorted picture of the flow rates. This is clearly demonstrated by comparing figures 5.2 and 5.4: maximum instantaneous flow on 17,18 and 19 June 1984 are 87,6.3 and 1.68 m<sup>3</sup>/s. furthermore, maximum instantaneous flow in 1984 was approximately 600 m<sup>3</sup>/s, compared with a maximum daily average of 52 m<sup>3</sup>/s. averaging the daily values to monthly values and monthly values to mean monthly values leads to further smoothing.

### **Flow volume**

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

Measured monthly flow volumes for some wadis in Yemen are listed in Table 6. below, some statistics derived from these data will be discussed and analysis:



annual runoff volumes (averages and coefficient of variation) and the average distribution of the flow volumes over the year.

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 curve 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 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 rating curves 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 distribution 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.

Table 6 does not include small catchments: the size of the catchments ranges from 460 km<sup>2</sup> (Wadi Rabwa) to ca 22500 km<sup>2</sup>. 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 losses are caused by periodically wetting the alluvial material and subsequent evaporation or percolation to deeper groundwater; by runoff disappearing to from 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 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.

It is generally believed that runoff coefficients of very small catchments tend to be significantly greater than those of the larger catchments they belong to. as indicated above, this is attributed to transmission losses, which tend to be smaller in small catchments than in larger ones. DHV (1993) 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<sup>2</sup>. the water from the runoff areas was caught on “run-on areas” which were cultivated; the runoff area were 1 to 15 times larger than the run-on areas. Eger’s results are summarized as follows by DHV:

- Threshold value (rainfall not causing runoff) was between 5 and 7.5 mm.
- Runoff coefficient on an annual basis varied between 25% and 50%. The lowest values occurred at the Amran Vally bottom and the

highest (40% to 50%) were found on the undulating limestone and gently sloping basalt; the runoff coefficient on the steeply sloping basalt was 30%.

- Individual storms with a total rainfall above 20 mm and intensities higher than 10 mm/hr had runoff coefficient of the order of 70% on basalt and Limestone, and of 50% in loamy sand areas. Storm of 10 mm and more with intensities above 5 mm/hr could still have runoff coefficient of about 25%.

The annual mean runoff coefficient for catchments of a few hundred km<sup>2</sup> in size is smaller by approximately one order of magnitude. They are shown graphically in Figure 20.

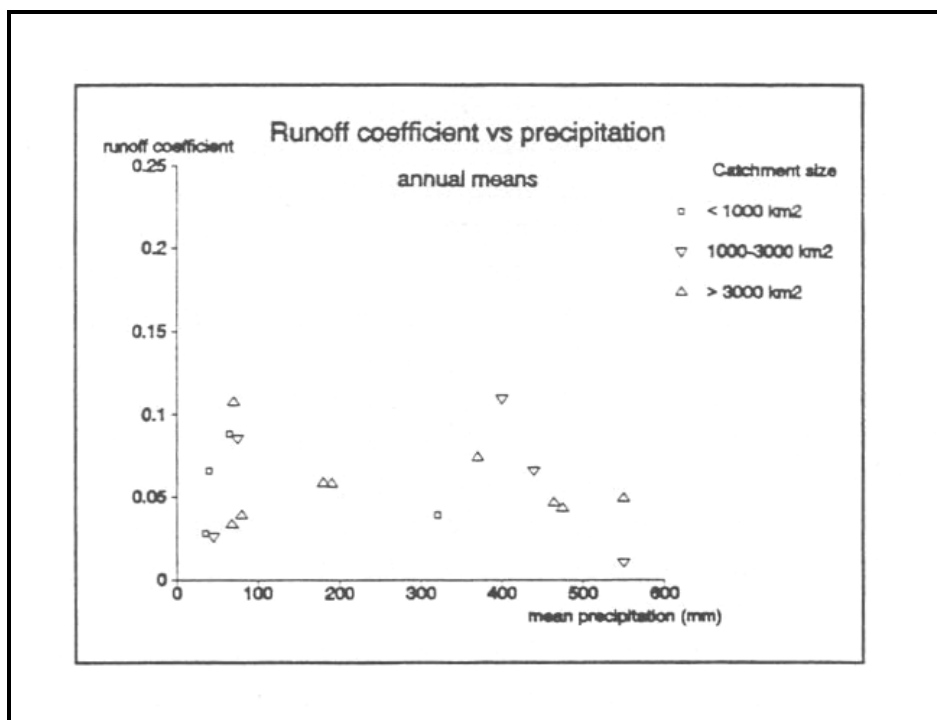


Figure 20 Mean annual runoff coefficients in relation to rainfall and catchment size (Van der Gun, et al., 1995).

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 is rather stable before the catchment area becomes of the order of hundreds of km<sup>2</sup>. 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 coefficient around their mean of 5.5% mainly results from factors other than annual catchment size.

Difference in land and water use in the catchment 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 no been inventoried and uniformly mapped for the catchment concerned.

In accordance with the observation that the calculated runoff coefficient 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 makes 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 Fig. 21) 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.

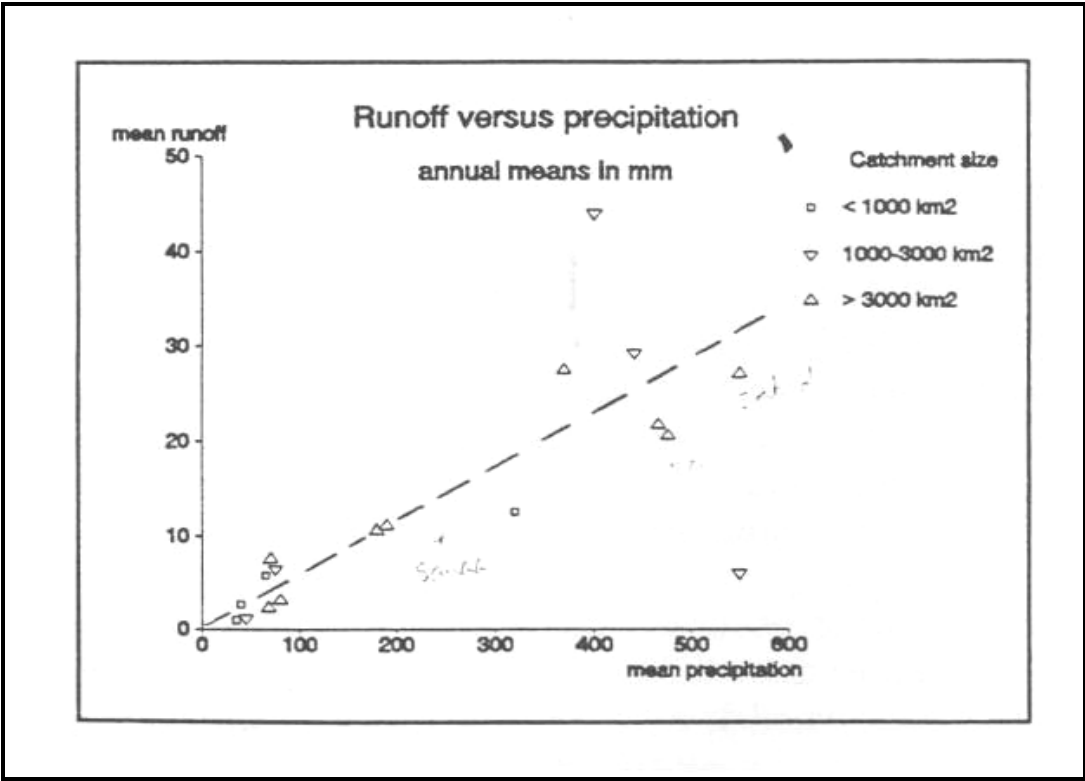


Figure 21 Mean annual runoff versus mean annual rainfall (large catchment areas) (Van der Gun, et al.,1995).

In the analysis described above it is tacitly assumed that trends in time are absent. This is not necessarily true; on the country, in some region there are indication that present 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 unavailability 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 cathment yields refer in particular to the flow that wadis of the western slopes bring to Tihama zone.

Estimates of probable maximum flood (pmf) made by different authorities are shown in Fig. 22. pmf's here are meant to be the highest floods recurring on the average once in 10.000 years. In Fig.9 the so -called Creager envelopes with C-values of 10, 25, 50 and 100 are drawn. These envelopes are represented by the equation:

$$Q = 1.3C (2.59 A)^{(0.854 A^{-0.048})}$$

Where Q denotes the maximum instantaneous discharge in m<sup>3</sup>/s, and A is catchment area in km<sup>2</sup>

The envelope with C=25 exceeds all historical data. This line may be regarded as corresponding to a recurrence interval of 50 years. On the other hand the envelope with C=80 narrowly exceeds all the pmf estimates. As such this envelope can be used for estimating the probably maximum floods.

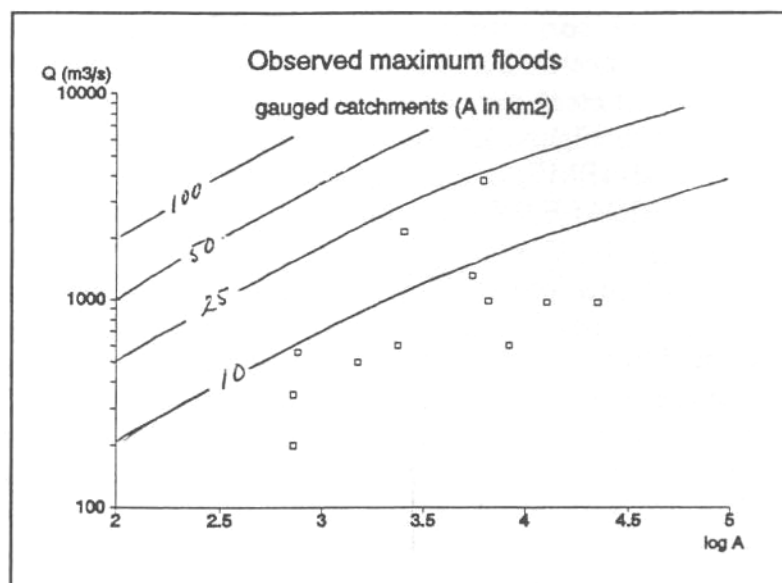


Fig. 22 Observed flood peak rates in Yemeni wadis (Creager curves for different values of C added) (Van der Gun, et al., 1995).

## **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 only 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. Total Dissolved solids values (TDS) can be estimated from ( $EC_{25}$ ) measurements by multiplying the EC values (in micromho/cm) by a factor of approximately 2/3.

The WRY project has monitored electrical conductivity at its stream gauging stations in the Wadi Surdud and Adhanah, and in the Abyan Delta. The resulting data show that the  $EC_{25}$  of the Water of Wadi Surdud at Faj Al-Husseini is relatively low: it typically varies between 500 and 600 micromho/cm during base flow, 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.

## **SEDIMENT TRANSPORT**

the sediment transport by the wadi is considerable. All floods observed in the wadi are yellowish-brown in color 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 base flow 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 across their beds.

The regimes of the wadis make very difficult to monitor sediment transport by sampling techniques. No record of such sediment transport monitoring has been found. In WRAY's water resources assessments study of the Wadi Adhanah area 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<sup>3</sup> of sediments were trapped in the lake during the three years preceding the survey; the average of 1.5 million m<sup>3</sup> per year corresponds to a layer of 0.2 mm averaged over the entire catchment. The value is probably significantly below the long term average, because no really high flows were observed during the period 1986-89. Noman (2001) mentioned in his study that, the average sediment concentration in Wadi surdud during the flood was 10-15 kg/m<sup>3</sup>. On the basis of surveys in the catchment area and an analysis of the Wadi bed material, two main types of sediment were distinguished. The first type consist of coarse material (coarse sands to boulders), mainly originating from the Wadi's valley walls. The bulk of the sediments are sandy, mainly originating from Tawilah sandstone outcrops. The

basement and volcanic outcrop areas within the catchment yield comparatively low amounts of the sediments.

## **GROUNDWATER**

During the last 20 years, groundwater resources in Yemen have been subject to severe exploitation to meet a continuously increasing water demand for irrigation and domestic use. Thousands of new bore holes were drilled and many existing dug wells were deepened, when they became dry because of over abstraction. This rapid and uncontrolled ground water development did not run parallel with a proper ground water management. Therefore, ground water resources have not been adequately quantified (Bamatraf, 1994).

Renewable groundwater resources have been estimated at 1 525 million m<sup>3</sup>/year (FAO, 1997), a large part probably coming from infiltration in the wadi beds. A major groundwater aquifer was recently discovered in the eastern part of the country with an estimated storage of 360 billion m<sup>3</sup>. This aquifer is still under study and it is not known whether the groundwater is rechargeable or whether it is all fossil water.

### ***Hydrological 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 units. Observed or assumed contrasts with regard to these hydraulic properties lead to classification of rock units into aquifers, aquitards, aquicludes and aquifuges. The differences between these classes are relative rather than absolute and depend on the role the units 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 is called an aquaclude. 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 view of regional groundwater flow. An aquifer, 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 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 aquifers, 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 unit observed in Yemen have been described in section 2.2. Table 3 presents a general hydrogeological characteristics of each of these formations; it may facilitate hydrogeological schematization and mapping. Note the relatively favorable 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 Volcanic and the limestone of the Amran Group and the Umm Er Radhumma Formation are generally less permeable, but they owe their significance to their considerable thickness and large areal extent.

## **Spatial distribution of regional aquifers in Yemen**

A small scale schematic hydrological map is presented in Figure 23; it is based on the information contained in available map, on study of numerous reports and on observations in the field during many years. It may serve for a quick and clear overview of the main groundwater conditions in Yemen.

The UNESCO classification of aquifer units is followed, but in between porous aquifers and fissure aquifers a category of mixed pore/fissure aquifers is defined. This type of aquifers 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 pure aquifers
- 1b. moderately or poorly productive pore aquifers
- 2a. highly productive fissure aquifers
- 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.

This overview map attempt 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 in productive aquifers and moderately/poorly productive aquifers is based primarily on hydraulic properties such as transmissivity and on the assumed stored volume of groundwater. Some other aspects play a role as well, although a secondary one: 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 the 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.



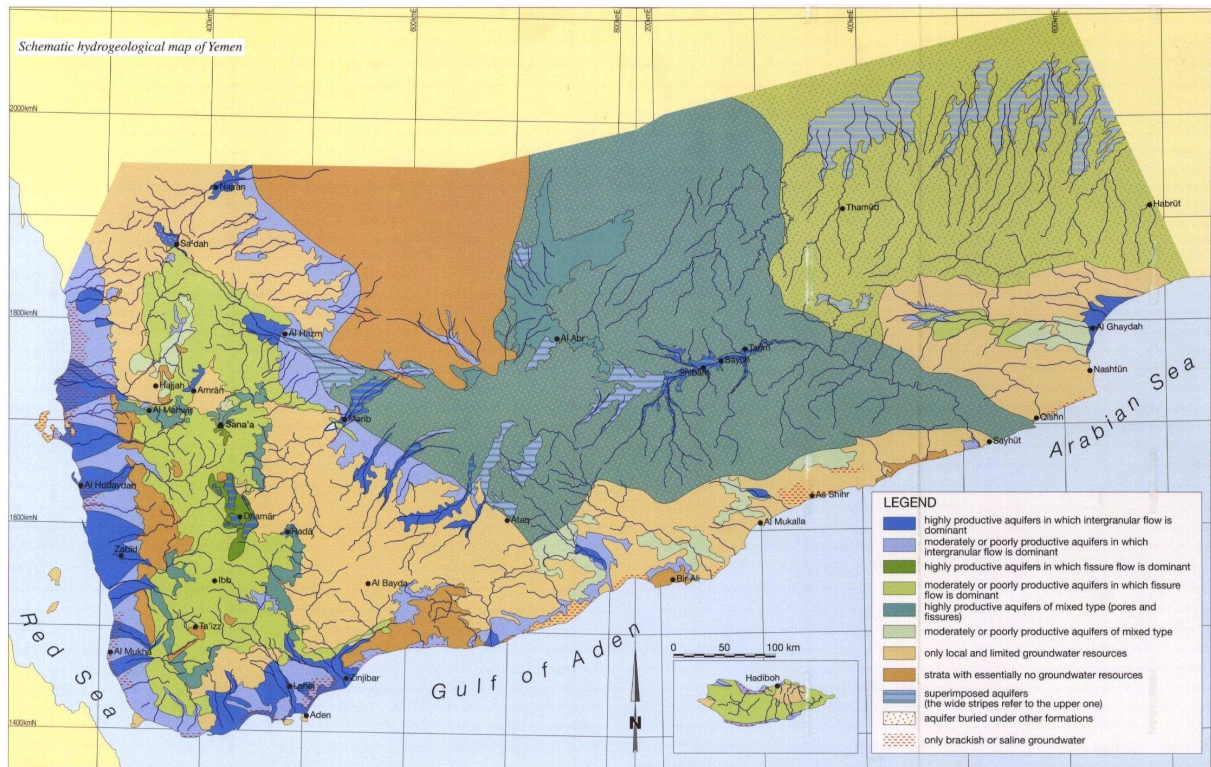


Fig. 23 Hydrogeological map of Yemen

### Principle groundwater systems in Yemen

As shown in Figure 23, there are large differences between the aquifer complexes present in different parts of the country. Adding of these difference also the large variations in hydrological conditions leads to a great diversity of groundwater systems.

On the uplifted shield in the west only the Yemen Volcanic and the Amran Group constitute aquifers of considerable lateral extension, but their productivity is generally moderate to low. The best aquifers in Yemen Mountain Massif region are the sediments in the tectonically influenced basins of the Highland Plains. They combine relatively high transmissivities with favourable recharge conditions.

Much larger aquifer systems exist in the platform region east of the shields. 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-Raduma Formation which constitutes in the east a moderately productive but very extensive aquifer, continuing over large distance 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 scattered boundary of the basement outcrops of the shield, at the margins of the desert.

### **Groundwater recharge, storage and discharge**

Groundwater systems are in a dynamic state as a result of the replenishment of the groundwater resources 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 or rainfall in excess of the water-holding capacity of the soils 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. The latter category includes the replenishment of groundwater by infiltration surface water and by percolating 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 indirect 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 zones, 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 reservoir 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. It was already described how the wadis tend to collect excess water in the steep and relatively impermeable catchments (runoff producing zones) and lost 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 24) allows the main groundwater recharge zones on a macro scale to be localized.

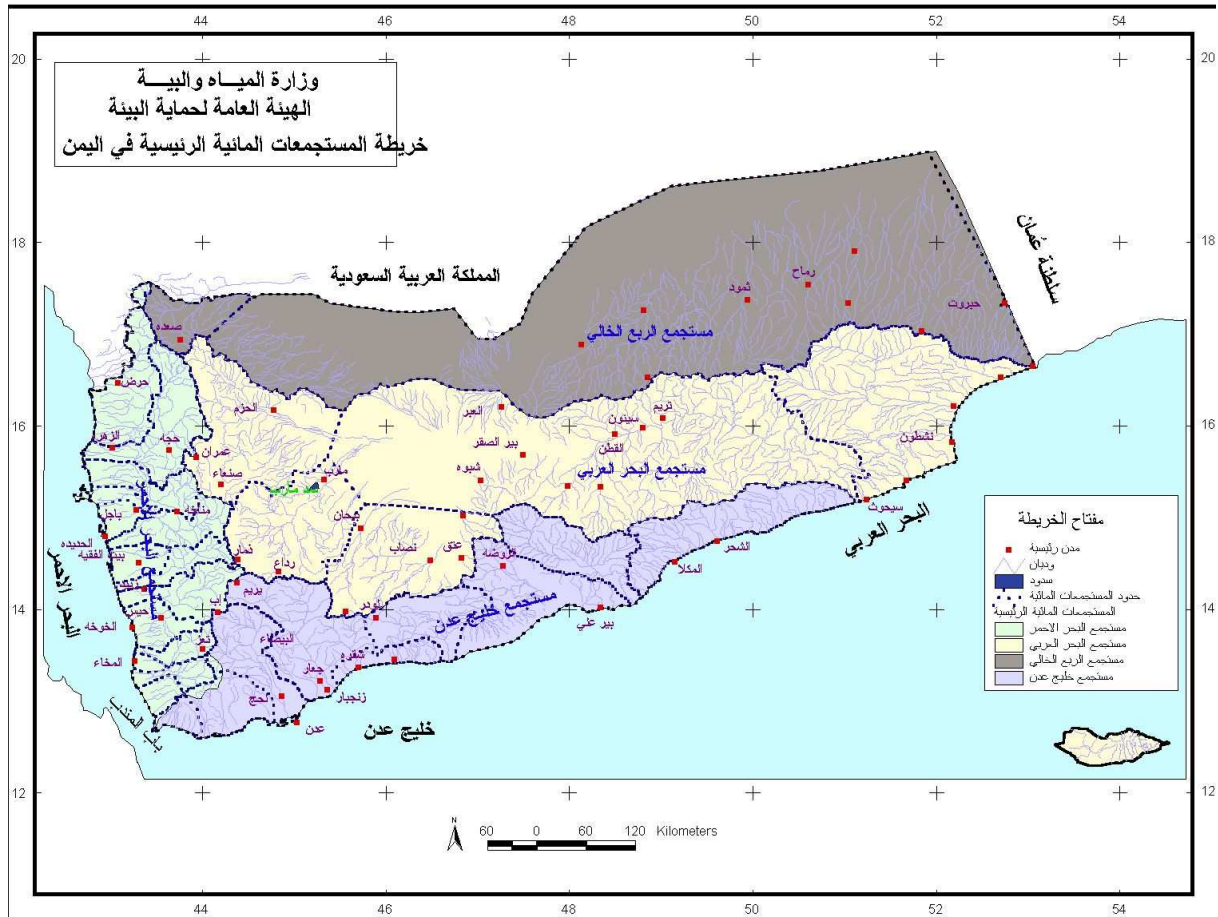


Fig. 24 Main surface water systems in Yemen

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 surfaces. 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 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 a quantitatively 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 recharges by discharge of domestic or industrial waste waters are comparatively unimportant in Yemen, at least from the point of view of water quantity.

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 practiced 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 condition- infiltration losses then tend to be less than the volume of water that would infiltrate under natural conditions.

### **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 spring, by outflow in 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 Limestone, in the rocks of 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 hundred of small springs are located along the contact between Tawilah Sandstone and the rocks of the underlying Amran Group. The Mukalla sandstone outcrops in the rifted zone east of Wadi Ahwar are also scattered with springs. They give a steady baseflow to Wadi Hajar, the only permanent stream in southern Yemen. Most of the springs known have only small flow, in the order a few liters per second. The larger springs include those in the centre of Wadi Surdud catchment 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.

Discharge of groundwater by outflow into stream, where it constitutes baseflow, often occurs in association with springs. It is typical for the upper and intermediate parts of the wadis in wetter zone, 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-crusts evaporation zones in wadi beds, especially at narrow outlets of groundwater basins, such as at the Sadah plain, Rada'a plain and in the eastern part of Wadi Hadramout.

Submarine outflow is a common discharge mechanism of coastal aquifers. It is estimated that it account 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 and the growing water demands of a developing society.

## **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 total are covered in many reports on groundwater investigations in areas of major interest. Groundwater storage has been addressed in a few cases only. 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 accurate areal abstraction figures. Nevertheless, the methodologies used are straightforward, probably unbiased and rather uniform.

Estimates of annual groundwater abstraction are listed in table 7. 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.

AREA	LATEST WELL INVENTORY/ASSESSMENT				1994 ESTIMATES	
	Reference	No. of pumped wells	Total abstraction (Mm <sup>3</sup> /yr)	Year	Total abstraction (Mm <sup>3</sup> /yr)	
<i>Highland Plains :</i>					Revised 500	
Baqim Plain	DHV,1993n	107	6.1	1991	6	
Sadah Plain	DHV,1993m	2330	80.4	1992	80	24.9
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	65.0
Sana'a Basin	TS-HWC,'92i		180.6	1990	185	30.1
Dhamar Plains	Chilton,1980	395	11	1976	40 (?)	17.2
Rada Plain	Ilaco, 1984	556	9.0	1983	25 (?)	9.6
<i>Tihama zones:</i>					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	
<i>Southern coastal plains:</i>					250	
Tuban delta	McDonald,'86a		87.2	1984	90	23
Wadi Rabwa	Selkhozp.,'90a		5.8	1988	7	298
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	
<i>Ramlat as Sabatayn fringe zone:</i>					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	
<i>Wadi Hadramawt</i>	McDonald,1988		158.9	1985	180	200

Table 7 Estimates of groundwater abstraction rates

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,

through flow estimation, tracer techniques, modeling techniques and empirical relations with rainfall. The resulting estimates are of variable reliability and generally not very accurate. Furthermore, methodological difference and unavoidable subjectives 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 includes: 59 Mm<sup>3</sup> (Italconsult, 1973), 45 Mm<sup>3</sup> (Howard Humphrys, 1977), 28 Mm<sup>3</sup> (Charalambous, 1982), 59 Mm<sup>3</sup> (Howard Humphrys, 1983) 42 Mm<sup>3</sup> (TC-HWC, 1992), Al-Aryani et. Al, 1992), SAWAS, 1996, WEC, 2001, 2003 and the GAF, 2005.

Aggregating estimates of groundwater abstraction, groundwater recharge and stored volume of groundwater for the major aquifer complex leads to the provisional picture presented in Table 8. The category fresh water in storage as mentioned in this table does include slightly brackish water as well.

<b>Aquifer complex</b>	<b>Approximate abstraction (Mm<sup>3</sup>/year)</b>	<b>Approximate average recharge (Mm<sup>3</sup>/year)</b>	<b>Fresh groundwater stored (Mm<sup>3</sup>)</b>	<b>Remarks</b>
Tiham Quaternary aquifer	810	550	250000	Quaternary aquifer
Southern Coastal Plains	225	375	70000	Several Quaternary aquifer units
Extended Mukalla Complex	575	500	10000000	Cretaceous sandstone
Highland Plains	500	100	50000	Various isolated units

Table 8 current abstraction rates, recharge and ground water storage for the main aquifer complex in Yemen.

The volume of water stored in the groundwater system act as buffers that may temporarily bridge the gap between abstraction rates and recharge rates. For small wadis 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.

## GROUNDWATER QUALITY

Groundwater quality has not 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.

Standard hydrochemical analysis are known for only a limited number of sites in the country. They confirm general expectation on the hydrochemical evaluation of the groundwater based on the Chebotarev sequence or related concept. Groundwater in recharge zones is almost always a  $\text{Ca}(\text{HCO}_3)_2$  type water of low mineralization. Downflow there is a gradual increase of dissolved solids, 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.

Thermal waters usually have an anomalous chemical composition,. Some data are provided by Dowgiallo (1986). The Hammam Ali in Dhamar Mountain plains) is an example of thermal water.

Groundwater pollution has not yet received much attention in Yemen. This does not mean that is not relevant. On the country, it may be assumed that intensive return flows of groundwater used in irrigation will profoundly change the quality of shallow ground waters. And groundwater pollution in urban zones is already perceptible in Yemen too, as several reports testify. For instance, Al Eryane and Ba-Issa (1989) mention increased nitrate levels and bacterial contamination in NWSA's well 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 stabilization ponds near Rawda is already contaminating the groundwater downflow. Nevertheless, this sewage water constitutes only a minor part of the domestic waste water. Approximately 50% of the urban population of Sana'a city still depend 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 100-300m 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 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.



## **WATER HARVESTING**

The first water harvesting system in history was built in the Arab region. Researchers have found signs of early water harvesting structures constructed over 9000 years ago in the Edom Mountains in southern Jordan. One of the earliest documented complete water harvesting systems is located in the Negev Desert, which could have been built about 4000 years ago (Gary, 1994). Remnants of other installations were also discovered in Iraq and on the Arabian Peninsula, along the routes used at the time by caravans. The water harvesting installations consisted mainly of means to collect rainwater and divert it into natural and/or artificial ponds and reservoirs (Bazza, 1994).

Water harvesting installations dating from 2500 to 1800 BC have been discovered in Palestine. They consisted mainly of cisterns with catchments areas cleared of gravel and smoothed to increase runoff.

In Jordan, there is indication of early runoff farming water harvesting structures believed to have been constructed over 9,000 years ago. Evidence exists that simple runoff farming water harvesting structures were used in Southern Mesopotamia as early as in 4,500 BC (Bruins, Evenari and Nessler.1986).

In Yemen, ruins of dams and reservoirs as well as the unique, spectacular mountain terraces, confirm the long history of water harvesting. The great historical Marib dam and its collapse are mentioned in the Holy Koran. Recent archaeological excavations discovered ruins of irrigation structures around Marib city dating from the middle of the third millennium BC (some 4000 years ago). Farmers in this same area are still irrigating with floodwater, making the region perhaps one of the few places on earth where runoff agriculture has been continuously used since the earliest settlement (Bamatraf, 1994).

Recent studies in Yemen on water harvesting, (Tahir, 2002), indicate that villagers in the mountainous areas are well acquainted with water harvesting systems for hundreds of years. They use the collected water for drinking, animal watering and supplementary irrigation particularly in the drier seasons. They mainly building cisterns to collect run off from clear and well selected catchment areas well away from the villages to prevent pollution. Old local manufactured material such as *Khadad* is used to cement the cisterns which proved to be of high quality and can withstand all environmental changes such as weather, rain, temperature, etc and can last longer periods. However, further research is needed on such material.

### **CONCEPTS AND CLASSIFICATIONS OF WATER HARVESTING TECHNIQUES**

Water harvesting is based on the utilization of surface runoff; therefore it requires runoff producing and runoff receiving areas. In most cases, with the exception of floodwater harvesting from far away catchments, water harvesting utilizes the rainfall from the same location or region. It does not include its conveyance over long distances or its use after enriching the groundwater reservoir. Water harvesting projects are generally local and small-scale projects.

According to Nasr (1999), there are two basic types of water harvesting systems:

- Direct water application system, where the runoff water is stored in the soil of the crop growing area during the precipitation,
- Supplemental water system, where the collected water is stored offsite in some reservoirs and later used to irrigate a certain crop area.

According to (Prinz, 1996), and (FAO, 1997), Figure 1 classifies water-harvesting techniques, with some modification by the authors of this study.

Water harvesting is considered as a management technique for collecting, storing, and distributing rainwater for any productive use. In general, water harvesting can make water available in regions where other sources are too distant or too costly, making water harvesting able for supplying water for small villages, households, livestock, and agriculture.

(Prinz, 1996), Described the water harvesting techniques along with sub-types as given in Table 9. below. The main rainwater harvesting techniques used in the Arab regions are summarized in Table 10.

Water Harvesting Group	Rainwater Harvesting			Floodwater Harvesting		Groundwater Harvesting		
Water Harvesting Type	Rooftops	Micro-catchment	Macro-catchment	FWH Within the Streambed	Floodwater Diversion	Qanat Systems	Special Wells	Ground-water Dams
Technique	Treated Contours Surfaces Bunds e.g. Sealed Paved, Compacted, Smooth-ended Surfaces	Contour Bunds Interrow-WH Meskat Types WH Contour Bench Terraces	Hillside Conduit Systems Cultivated Reservoirs Tanks  Jessour Macro-Catchment	Jessour Type  Percolation Dams	Wild Flooding  Water Dispersion Water Distribution Spate Irrigation	Short Qanats  Medium Sized Qanats Long Distance Qanat	Sand Storage Dams Sub-surface Dam	Horizontal Wells  Artesian Well
Kind of Storage	Cisterns, Ponds, Tank	Soil Profile (Ponds)	Soil Profile Cisterns, Ponds,	Soil Profile		Ponds	Substrate Profile	
				Reservoirs	Ponds			
Aquifer Recharge	None	Very Limited	Limited	Strong	Very Strong	Limited	Medium	Medium

Table 9. Runoff farming water-harvesting techniques (Prinz 1996)

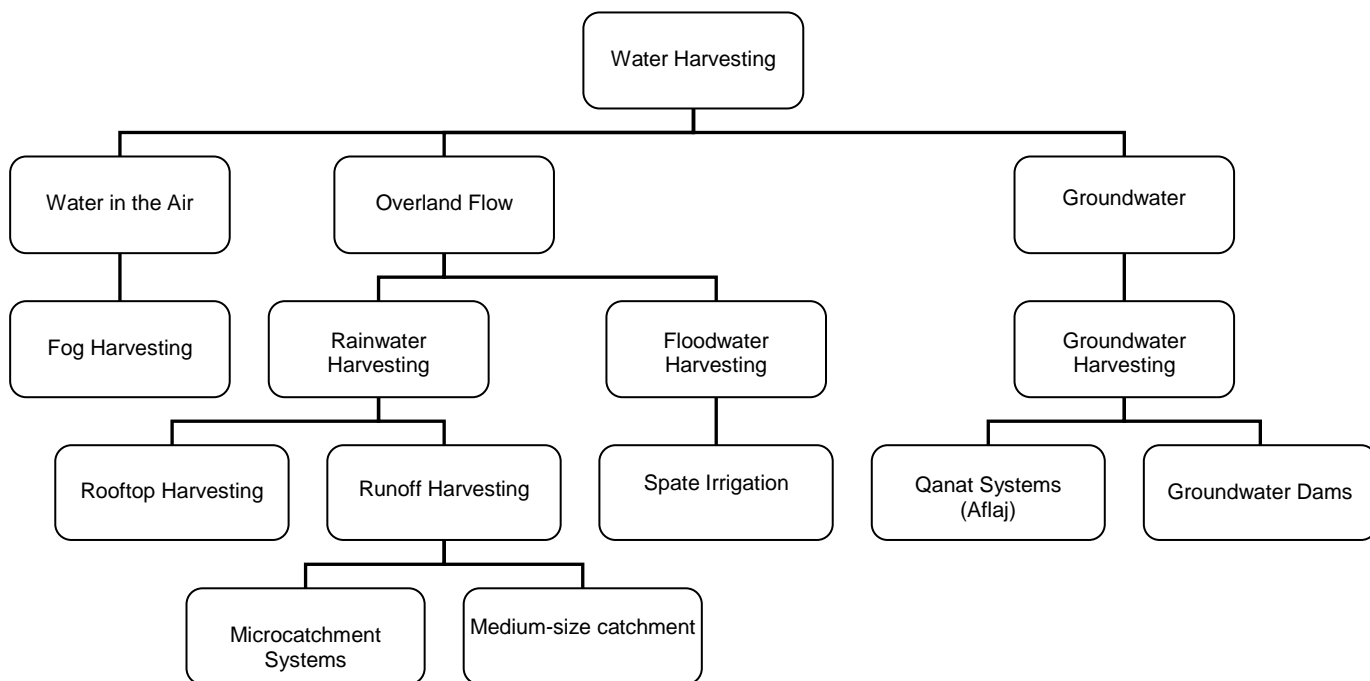


Fig. 25 Classification of water harvesting techniques (Printz, 1996)

Water Sources	Objectives	Water Harvesting Techniques	Country
Rainfall	-To increase rainfall effectiveness -To conserve water (and Soil)	Terraces Contour-ridge terracing Dams	Yemen, Jordan Yemen, Tunisia, Jordan Libya, Syria, Tunisia, Jordan Egypt, Libya, Tunisia, Jordan
Local runoff	- To collect water - To store harvested water	Micro-catchment Cisterns	Yemen; Egypt, Libya, Syria, Jordan, Morocco, Yemen, Egypt, Libya, Morocco
Wadi flow (flood and base flow)	- To protect land against flood	Earth dykes (spate irrigation and small-head pumps& earth canals) Wadi -bank enforcement	Yemen, Egypt, Libya, Tunisia, Jordan Yemen, Libya,
Spring water	-To deliver water to participants within water rights limits - To store limited quantities for short periods	Earth canals, Cisterns	Yemen, Egypt, Libya, Morocco
Ground water	- To abstract water from shallow aquifers - To exploit ground-water stored in the coastal sand Dunes	Shallow dug wells and pits, Galleries	Yemen, Egypt, Libya, Tunisia, Jordan, Morocco Egypt

Table 10 Rainwater harvesting techniques used in the Arab Region (Nasr, 1999)

## ***FOG HARVESTING***

This innovative technology is based on the process of collecting water from fogs under favorable climatic and topographic conditions. Fogs are defined as a mass of water vapor condensed into small water droplets at, or just above, the Earth's surface. The small water droplets present in the fog precipitate when they come in contact with objects.

In Hajjah region west Yemen (FogQuest, Canada), assist in the construction, sitting and installation of 25 small fog collectors (SFCs) and one large fog collectors (see Plate 1) in and near communities in the Hajja province. This part of Yemen receives periodic rain events during parts of the year but is generally extremely arid during the winter, December through March, with frequent fog but no rain. It is this period where fog collection may be able to make a major difference for the water supplies of the people. Initially, the traditional cisterns carved out of the bedrock are used to store the runoff water.

The study period was from 1 January to 31 March 2003. These are the dry winter months when rainfall is virtually non-existent and the need for water is very high. Sufficient fog water was obtained to justify a large project. The study resulted in low fog collection in most parts of the experimented area with a minimum of 0.5 l/d and a maximum of 11.5 /d with an average of 6.0 l/d. The conclusions drawn are that more investigation is needed on the various parameters contributing to the fog collection such as wind direction, relative humidity, temperature, and SFCs technologies. More sites should be studied either in Hajja or elsewhere in Yemen such as in the eastern parts of Al-Mahra region in the eastern part of the country. Studies carried out by (FogQuest, Canada), near Salalah in the Sultanate of Oman in 1989 and 1990 showed extremely high fog collection rates on the coastal mountains during the summer. This is an indication that the east coast of Yemen may have good potential.



Plate 1 Big (3x2) m<sup>2</sup> and small (1x1) m<sup>2</sup> fog collectors in Hajjah area in Yemen (Authors)

## RAINWATER HARVESTING SYSTEMS

### ***Rooftop water harvesting systems***

The roof water harvesting in Yemen has the advantage of being low cost, relatively simple in design (household technology), less laborious and it saves time. It provides adequate water during the rainy season, a period when the rural people are busy with farming activities. They are more appropriate in mountainous areas where there are no ground water sources, and where rainwater is the only feasible means of providing a water supply. In such areas it is difficult to think that communities can be served by a centralized water supply schemes which proved to be very expensive in terms of implementation, operation and maintenance. Other sources require long walk and time for women and children to fetch water. The quality of water is also reported as good compared to other water sources in the rural areas.

In Taiz Region, during the rainy season, roof water is collected in a dug-out structure, known as Seqaya. These structures are excavated into the hard rocks. In addition to roof water surface runoff is also collected into the hard rocks. Surface run-off is also collected into the dug-out structures for multifarious uses. In hilly areas of Al-Hujaria District, roof with provision of border-line lead pipe and outlet is common. The harvested rainwater, in turn, is guided to an underground storage tank through a settling tank for domestic use.

### ***Terracing***

The objective of terracing in these regions is to collect rainfall for farming and slow down the runoff process. Rain water collects in the terraces and soaks into the shallow soil. Walls at the edge of the terraces prevent runoff from flowing down to the next terrace except during intense rainfall events. The walls of the terraces are built of stones, while voids between the stones allow water to move down to successive terraces without eroding the soil. Water can also move from level to level near the sloping bedrock. Subsurface drainage is required in these areas to channel flow from one terrace to the next trap fine sediment. They are designed and constructed in a manner to allow the passage of runoff through sheet flow, which prevents damage to the terraces from runoff concentrating at certain points. This method is effective if terraces are constructed in the upper parts of the wadi.



Plate 2. Terraces on mountain slopes in the Yemen Highlands

### **Ponds**

Farm ponds are small storage structures used for collecting and storing run-off water. As per the method of construction and their suitability for different topographic conditions farm ponds are classified into 3 categories, viz. Excavated farm ponds suited for flat topography, embankment ponds for hilly and rugged terrains with frequent wide and deep water courses; and excavated-cum-embankment type ponds. Selection of the location of the farm pond is dependent on several factors such as potentiality for yielding sizeable quantity of run-off, rainfall, land topography, soil type and structure, permeability/water-holding capacity, land-use pattern etc. Structurally, the excavated farm ponds could be of 3 types: square, rectangular and circular. All farm ponds must have the provision of removal of excess run-off water by providing 'drop inlet spill-way under normal condition' and 'emergency spill-way' to dispose off overflow of water after heavy rains. Such spill-way should ideally discharge into a grass waterway to avoid excessive erosion.

### **Cistern system**

*Karif* or *Majel* is a local name for cistern in the mountainous area of Yemen. It is generally underground tank, constructed from masonry or concretes and usually covered and used for the collection and storage of surface run-off. This system of rainwater harvesting is also common in the rural areas of Botswana, Ghana, Kenya, India, Sri Lanka, Thailand and Indonesia. Water thus collected in is generally used for drinking and other domestic uses.

### **Medium-size catchment water harvesting systems**

Medium-size catchment runoff farming refers to large-scale rainwater harvesting. This may be the diversion of a natural wadi, or a wadi flowing from a natural catchment. The collected flow is immediately diverted by a diversion structure to flood irrigate an adjacent agricultural field. The catchment should be big enough to provide the needed irrigation water. The diversion structure may consist of a stone barrier across the wadi or the intermittent stream. When the rainwater flows into the wadi, it will be slowed down and diverted from its course in the stream channel to flow over the rather broad flat floodplain bordering the wadi. Strategic placement of rock barriers and crops will allow the maximum use to be made of the floodwaters with the minimum damage to land and crops. Careful design and layout are necessary to withstand floods and prevent erosion.

In Morocco's Anti Atlas region, Kutsch, (1982), investigated the traditional and partly still practiced water-harvesting techniques. He found a wealth of experience and a great variety of locally well-adapted systems (Prinz, 1996). In Algeria, the "lacs collinaires", the rainwater storage ponds are traditional means of water harvesting for agriculture.

The open ponds are mainly used for watering animals. In Tunisia, the "Meskat" and the "Jessour" (see Figure 26) systems have a long tradition and are also still practiced. The "Jessour" system is a terraced wadi system with earth dikes ("tabia"), which are often reinforced by dry stone walls ("sirra"). The sediments accumulating behind the dikes are used for cropping. Most Jessours have a lateral or central spillway (Prinz, 1996).

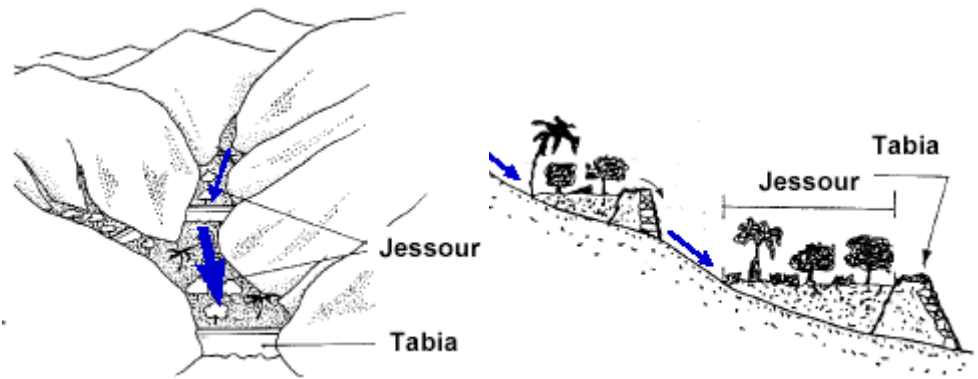


Fig. 26. A row of "Jessour" in the South of Tunisia. (Prinz 1996).

### **Dams**

Except for the reservoir behind the Ma'rib dam with a capacity of 400 million m<sup>3</sup>, which provides water irrigation for an area of 10 000 hectare, there are no large bodies of surface water in the country (Bamatraf, 1994).

Small dams existed in Yemen throughout history, as a means of improving water control, breaking spate or enhancing ground water infiltration. Over the last five years, government has embarked on an ambitious "small dam" program as a response to gravity water storage in the country. The program at present provides for construction or rehabilitation many hydraulic structures.

A total number of these structures is estimated to be about 547, out of which 173 are dams, 145 reservoirs, 195 weirs and 34 unclassified category. The hydraulic structure which have been completed are 132 (51 dams, 34 reservoirs, 41wiers and 6 unclassified) MAI, 2000. The total dam capacity is estimated at 0.18 km<sup>3</sup>.

In general, the dams are built for irrigation and domestic purposes, but at the same time they contribute to groundwater recharge. There are also many flood control dams, which are not intended to store water, but to divert the spate floods immediately to the adjacent irrigation network (spate irrigation).

### **FLOOD WATER HARVESTING (SPATE IRRIGATION)**

Flood water harvesting, known as 'large catchment water harvesting' or 'Spate Irrigation', is the simplest type of water harvesting, where cultivated areas lie within and immediately adjacent to an ephemeral stream or wadi. It is rations the occasional floodwaters form storms in the mountainous catchment areas to the coastal and foothill areas.

Traditionally, agriculture in Yemen has depended on dry farming using either rainfall or spate irrigation. Rained agriculture is practiced on terraces in most of the

highlands, while spate irrigation is practiced along the wadi courses and coastal plains of Tihama and south and eastern parts of Yemen. More than 1.6 million hectares are regularly cultivated. Of the cultivated area, 50% is rain fed, 32% under well irrigation, and 18% under spate irrigation and base flow. Spate irrigation is widely used in Yemen for the production of major crops; A large portion of the cultivated area relies on spate irrigation. Figure 27 shows the irrigated area under floodwater harvesting in Yemen and other countries in North Africa and the Middle East, according to FAO (1997).

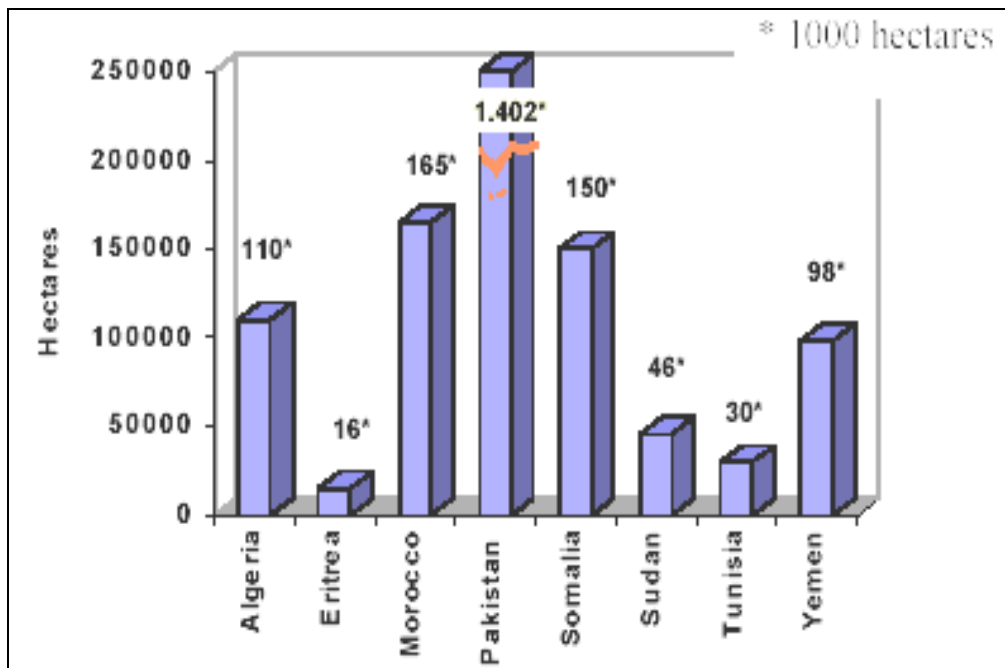


Fig. 27 Area under spate irrigation in selected countries (FAO, 1997)

The country's particular topographic structure affects and modifies the climate on a regional basis, especially rainfall distribution, and influences the availability of water for agriculture. The majority of Yemen consists of rugged terrain of igneous and metamorphic rock. Some areas receive rainfall in excess of 500 mm/yr. Extensive terracing is being practiced in the mountainous areas.

The hydrographic system of Yemen consists of rain fed watercourses (wadis) occasionally flooding but usually dry, draining from the main watershed along the three major escarpments. In the rugged slopes of the Western escarpment seven major wadis run toward the Red Sea, which they sometimes reach during periods of heavy rain. In the southern slopes the wadis of Tuban and Bana run, through a similar but less precipitous course, to the Gulf of Aden. Table 11 presents average of total annual flow at some selected wadi in Yemen.



Wadi Name	Bana	Zabid	Surdud	Mawr	Adhana	Masila	Tuban	Jaza'a
Catchment Area (km <sup>2</sup> )	6200	4632	2370	7912	8300	22500	5060	15000
Average Annual flow (Mm <sup>3</sup> )	169.9	125	69.3	162.3	87.5	51	109.4	60

Table 11 Mean catchment yield for gauged wadis in Yemen (Van der Gu, and Ahmed, 1995)

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. Surface water is considered to be an important source for irrigation in Yemen; it is estimated to be about 1,500 Mm<sup>3</sup>/year. Several dams and dikes were built on many main wadis for the purpose of directing spate waters into man made spate irrigation systems. Cultivation of flood is carried out through the sources of water include either direct rainfall or flood water spate as seen in Plate 3. The flash flood, as it appears along the wadi banks, is diverted using temporary structures to small individual farmlands located along the wadi banks, and the diverted water is spread into the field as to irrigate crops.

### ***Traditional spate irrigation in YEMEN***

The fundamental feature of traditional spate irrigation systems in Yemen is the well-established principle which gives upstream irrigators priority rights to water abstraction over the downstream users. Once the upstream user has satisfied his needs, he has an obligation to release water downstream (Tahir et al, 1996). With traditional systems, modest and often temporary deflectors allow water to pass to lower off-takes, thus creating a perception amongst farmers, of a large degree of fairness in water utilization. During the early part of the season, one or two run-off irrigation improves the establishment of the crop stand and the last season runoff (three or four irrigation) will bring the crop to full maturity.

Spate systems are made in such a way that ideally the largest floods are kept away from the command area. Very large floods would create considerable damage to the command area. They would destroy flood diversion channels and cause streams to shift. This is where the ingenuity of many of the traditional systems comes in. Spurs and bunds are generally made in such a way that the main diversion structures in the river break when floods are too big. Breaking of diversion structures also serves to maintain the floodwater entitlements of downstream landowners. The structures can be classified as follows (Camacho, 1986).



Plate 3. Wadi Surdud in Tihama region west Yemen in spate (authors)

*Deflectors or (Al-Qaid):*

Low earthen bunds, protected with brushwood and stones from the wadi extend into the minor bed of the wadi at a acute angle to the bank (Figure 4); This structure built to divert water from the main wadi to agricultural lands in quantities proportional to the irrigated area and the size of the flood in the wadi.

*High earthen bunds or (Ogma):*

Local farmers build an earthen bank or (Ogma) of wadi bed material across the low flow channel of the wadi, with the object of diverting the entire low stage of the spate flow to their fields. During a large spate, as there is no prevision for a spillway, the (Ogma) is either breached deliberately or it is over-topped and breaches as the flood rises. See (Figure 28).

*Drop structures (Al Masaqit):*

these are built in spate canals when a channel has a steep longitudinal gradient, or the water is transferred from a high channel to lower one. The structure is built on a foundation of dry stone, occasionally mixed with a little concrete. The remaining part of the structure is constructed with stone interlocked properly, the gaps filled with smaller stone.

*Spillways (Al Masakhil):*

the purpose of this structures is to control the quantities of water which enter the main spate canal. Al Masakhil is usually built on the earth embankment of the canals from medium size stone. The frame of the structure on both sides of the embankments goes down deep in to the foundation, so the supporting soil has no direct contact with the water.

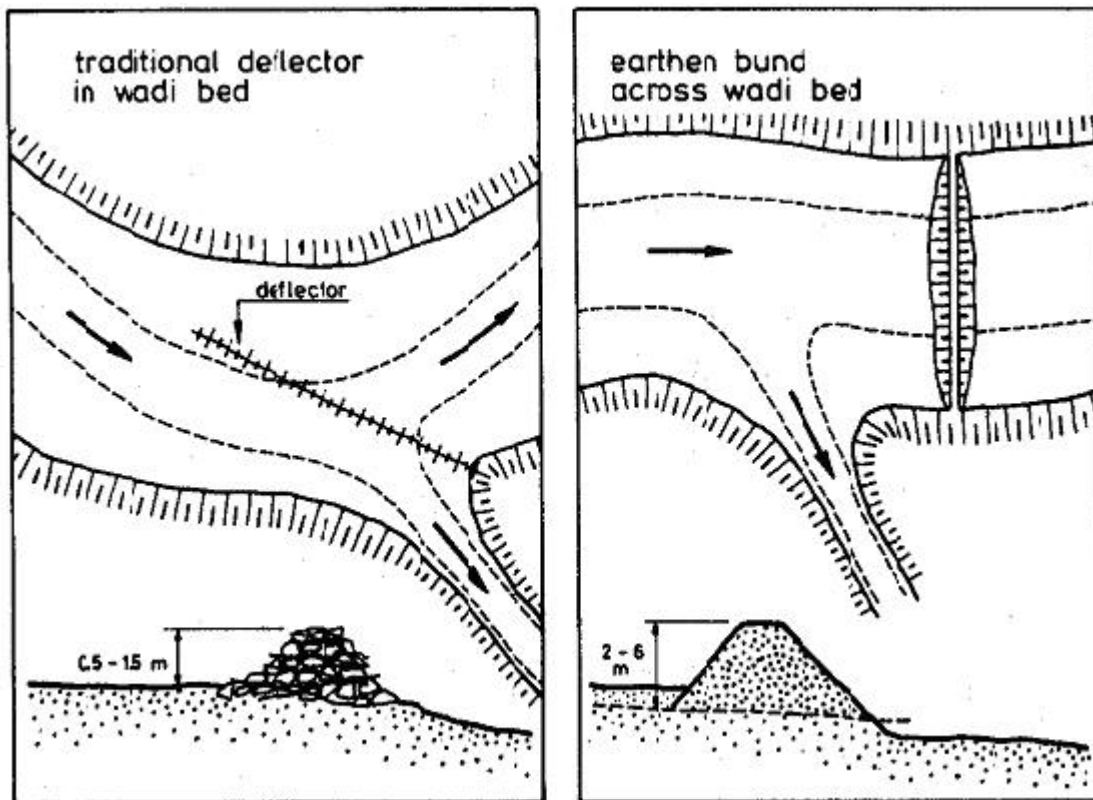


Fig.28 Schematic layouts of the traditional spate irrigation in Yemeni wadis (Oosterman, 1986)

## SOCIO-ECONOMIC FACTORS

### *Participation*

Rainwater harvesting projects are to assist farmers to improve their production systems; therefore, it is important that the farmer's priorities are being considered. If the priority is irrigation water, the response will be then for water harvesting systems for crop production. Once the priority is defined, it is becoming more widely accepted that people should actively involved in the projects development. It is important that the beneficiaries participate in every stage of the project; planning, construction and operation and maintenance stages.

Yemeni farmers in wadis have been practicing participation for centuries. During flood seasons, they involved intensively in the preparation of traditional deflectors or earth bonds where they the farmers in the area participate in the construction either by providing labor, tools or money. Each farmer has to pay his share in these activities according to his commitment and property (Tahir, et al, 1996).

Widespread adoption of water harvesting techniques by the farmers is the only way that significant areas of land can be treated at a reasonable cost on a sustainable basis. It is therefore important that the systems proposed are simple enough for the people to implement and to maintain. To encourage adoption, apart from incentives in the form of tools for example, there is a need for motivational campaigns,

demonstrations, training and extension work (Critchley, et al. 1991). Throughout the course of the season it is helpful to involve people in monitoring, such as rainfall and runoff and recording tree mortality.

After the first season it is the farmers themselves who will often have the best ideas of modifications that could be made to the systems. In this way they are involved in evaluation of the water harvesting systems.

### ***Gender and equity***

If water harvesting is intended to improve the lot of farmers in the poorer, drier areas, it is important to consider the possible effects on gender and equity. In other words, will the introduction of water harvesting be particularly advantageous to one group of people, and exclude others. Perhaps water harvesting will give undue help to one sex, or to the relatively richer landowners in some situations. These are points a project should bear in mind during the design stage. It is apparent from farming experience in several of the Arab countries such as Egypt, Syria, Yemen, etc. that women are involved extensively in helping the man in the fields and that she is a complete partner with the man.

### ***Land ownership and management***

Land ownership issues can have a variety of influences on water harvesting projects. On one hand it may be that lack of ownership means that people are reluctant to invest in water harvesting structures on land, which they do not formally own. Where land ownership and rights of use are complex it may be difficult to persuade the cultivator to improve land that someone else may use later. On the other hand there are examples of situations where the opposite is the case - in some areas farmers like to construct bunds because it implies a more definite right of ownership.

The most difficult situation is that of common land, particularly where no well-defined management tradition exists. Villagers are understandably reluctant to rehabilitate areas, which are communally grazed. Land management by communities has recently been acknowledged to be extremely important. Degraded land can only be improved if the communities themselves face land management issues. Water harvesting is one of the techniques- amongst several others- that can assist in rehabilitation of degraded land.

## **FUTURE ROLE OF WATER HARVESTING**

Appropriate systems should ideally evolve from the experience of traditional techniques. They should also be based on lessons learned from the shortcomings of previous projects. Above all it is necessary that the communities appreciate the systems where they are introduced. Without popular participation and support, projects are unlikely to succeed. During recent years some developments took place in regard to water harvesting which might have some impact on the future role of water harvesting in general and may expand to other areas in the world:

#### *Supplemental water system:*

Runoff water is collected and stored offside for later application to the cropped area using some irrigation method. The water stored allows a prolongation of the cropping season or a second crop.

#### *Dual purpose systems:*

In a dual purpose system the runoff water flows first through the crop area, then the excess water is stored in some facility for later irrigation use. In Arizona, USA, runoff irrigation was combined e.g. with trickle irrigation, using sealed soil surfaces to increase runoff rates.

#### *Combined systems:*

If the irrigation water from aquifers or from rivers/reservoirs is not sufficient for year-round irrigation, a combination with runoff-irrigation (during the rainy season) is feasible. The combination of runoff- and furrow irrigation is reported from North Central Mexico (Frasier 1994).

#### *Modeling:*

If more information on hydrological, soil and crop parameters is available, models can be developed and applied to water harvesting for certain environments.

#### *Soil storage:*

The water is being stored in the soil profile. A high storage capacity of the soil (i.e. medium textured soils) and a sufficient soil depth (> 1 m) are prerequisites here (Huibers, 1985). The water retention capacity has to be high enough to supply the crops with water until the next rainfall event.

## **NON-CONVENTIONAL WATER RESOURCES**

Data in this issue is very limited. A brief study carried by the university of Sana'a 1995 shows that the total sewerage flows for the seven major cities in Yemen were estimated in 1995 as 43550m<sup>3</sup>/day =16million m<sup>3</sup>/year. The flow for the seven cities is expected to reach in the year 2005 a rates of 105895 m<sup>3</sup>/day or=39 m<sup>3</sup>/year.

The sewage treated water quantity is small but it has a strong impact on environment. It is used in agriculture without restrictions. It does not match with the standards and causes pollution to groundwater and deteriorates the soil structure.

## **INSTITUTIONAL ENVIRONMENT**

There are many entities, which deal with irrigation water in the country. They can be grouped into the following:

- General Directorate of irrigation (MAI).
- The Regional Development Authorities (TDA), (EDA), (NDA).
- Regional offices of agriculture.
- Department of Irrigation in Aden.
- Governorates and local community Offices.

Government has been trying three times to pass laws related to water since 1990. The traditional and customary roles are prevailing. These are mostly taken from the Islamic law (al-Sharia'a) and practiced to allocate, distribute water and solve dispute on water. These roles confirm that water is free for drinking and the priority for use is those who first reach water and develop it. Traditional roles are not enough to face the water needed by local communities for different purposes (Industry, Tourism), and the presentation of new crops.

## REFERENCES

Achouri Moujahed. 1998. *Participatory Watershed Management Towards Integrated Water Resources Management*.

Al-Hemiary A. Maged. 1999. Yemeni Experience in the Watershed Management. YEM/97/200. Sana'a ROY.

Bamatraf A. M, 1987. *Supplemental Irrigation in Yemen Arab Republic*; pp561-598, In: "supplemental Irrigation in the Near East and North Africa", Eds. E. R. Perrier & A. B. Salkini. Publ. Kluwer Academic, London.

Bamatraf A. M. 1994. *Water Harvesting and Conservation System in Yemen*; pp 169-188, In: "Water Harvesting for Improved Agricultural Production". FAO Expert consultation Cairo 21-25 Nov. 1993. FAO. Rome.

Bruggeman H.Y. 1997. *Agro-climatic Resources of Yemen*. Part 1. Agro-climatic Inventory. FAO proj. GCP/YEM/021/NET, Field doc. 11. Ministry of Agri. & Irrigation., Agri. Res. & extension Authority, Dhamar, Yemen.

Food and Agriculture Organization of the United Nations Rome, 1997. *Irrigation in the near east region in figures*

General Department of Agricultural Statistics. *Agricultural Statistics Yearbooks 1988-1992* . Ministry of Agriculture and Water Resources.

International Service for Agricultural Research (ISNAR). 1993. A Review of the Agricultural Research System in the Republic of Yemen. ISNAR, The Netherlands.

Ministry of Agriculture and Irrigation (MAI). 2001. *Agricultural statistics year- book 2000*. MAI, Sana'a, ROY.

Ministry of planning and Development (MPD). Statistics year-book 1998. Central Stat. Organisation. Sana'a, Yemen.

Mohamed Fara M. 1998. *The water Resources of Yemen*. Paper presented to environmental Information System for Natural Resources Conservation and use. Dec.1998., Sana'a ROY.

Richard Tutwiler. 1990. *Agricultural labour and Technological Change in the Yemen Arab Republic*; pp 229-251 In: Labor and Rainfed Agriculture in West Asia and North Africa., Eds., Dennis Tully. Publ. Kluwer Academic, London.

TS/HWC-UNDP/DESD., 1995. *Final reports. Volume III: Surface water resources; Volume IV: Groundwater resources; Volume VI: Water supply, wastewater and sanitation.*

Bamatraf, M. A. (1994). "Water harvesting and conservation systems in Yemen". FAO Proceedings of the Expert Consultation about "Water Harvesting for Improved Agricultural Production", Water Report 3.

Bazza, M., (1994), "Operation and management of water harvesting techniques". FAO Proceedings of the Expert Consultation about "Water Harvesting for Improved Agricultural Production", Water Report 3.

Bruins, H. J.; Evenari M. and Nessler. U. (1986). "Rainwater-harvesting for food production in arid zones". *Applied Geography* (6), 13-32, (<http://fadr.msu.ru/rodale/agsieve/txt/vol2/8/art1.html>).

Camacho, R. (1986). "Traditional spate irrigation and wadi development schemes". proceedings of the subregional expert consultation on wadi development for agriculture in the natural Yemen. Aden-Yemen.

Critchley, W. and Siegert, C. (1991). "Water harvesting manual". FAO Paper AGL/MISC/17/91.

FAO, (1997), "Irrigation in the Near East Region in Figures. *Water Report* (9).[www.fao.org](http://www.fao.org).

Frasier, G. W. (1994). "Water Harvesting/Runoff Farming Systems for Agricultural Production". Water Harvesting For Improved Agricultural Production. Expert Consultation, Cairo, Egypt. 57-73.

Gary, W. F., (1994), "Water harvesting/ runoff farming systems for agricultural production". FAO Proceedings of the Expert Consultation about "Water Harvesting for Improved Agricultural Production", Water Report 3.

Huibers, F. P. (1985). "Rainfed agriculture in a semi-arid tropical climate: aspects of land and water management for red soils in India". Doctoral Thesis, Agric. Univ. Wageningen, NL.

Kutsch, H. (1982). "Principle features of a form of water-concentrating culture on small- Holdings with special reference to the anti-atlas". *Trierer Geogr. Studien* 5. Trier.

Nasr, M. (1999). " Assessing desertification and water harvesting in the Middle East and North Africa: policy implications", Center for Development Research, (ZEF), (10) 59.

Oosterman, J. (1986). "Diversion structure and protection works" proceedings of the subregional expert consultation on wadi development for agriculture in the natural Yemen. Aden-Yemen.

Prinz D., (1996). "Water harvesting - history, techniques and trends". Z. f. Bewässerungswirtschaft 31(1) 64 – 105.

Tahir T. M. (2002) "Rainwater harvesting systems: a community based managed systems". *Journal of Science and Technology*, (JST), 7(1), 1-8.

Tahir, T. and Depeweg, H. (1996) "Traditional Water Rights Versus Water Availability- a Case Study Wadi Siham" Water Resources Conference in the Arab World , Tripoli, Libya.

Van der Gun,. & Ahmed A., (1995). "The water resources of Yemen", Report WRY35, TNO, Delft.

[http://www.greekorthodoxchurch.org/wfb1998/yemen/yemen\\_geography.html](http://www.greekorthodoxchurch.org/wfb1998/yemen/yemen_geography.html)

**Yemen - The Statistical, Economic and Social Research and Training Centre for Islamic Countries (SESRTCIC)**

<http://www.sesrtcic.org/members/yem/yemhome.shtml>

**COUNTRY PROFILE OF YEMEN: NATURAL RESOURCES : MINERAL, NON METALLURGICAL, AGRICULTURE AND FISHING**

<http://www.bisnetworld.net/bisnet/countries/yemen4.htm>

**Yemen - UN SYSTEM-WIDE EARTHWATCH Web Site, ISLAND DIRECTORY**

<http://www.unep.ch/islands/CDY.htm>

**Yemen Landuse/Land Cover - 1M - E00 Format - GISDataDepot.com**

<http://www.gisdatadepot.com/catalog/YM/group113.html>

annotation: "....." [editor's note, 02feb2002]

**Yemen Sector Strategy Paper (PDF document)- World Bank**

[http://lnweb18.worldbank.org/ESSD/essdext.nsf/18DocByUnid/0B03BAE363FB1E1685256BAB0073CB07/\\$FILE/WRSSDraftSection11.pdf](http://lnweb18.worldbank.org/ESSD/essdext.nsf/18DocByUnid/0B03BAE363FB1E1685256BAB0073CB07/$FILE/WRSSDraftSection11.pdf)

**Yemen - The Science of Biodiversity and Conservation - University of California, Irvine**

<http://darwin.bio.uci.edu/~sustain/h90/Yemen.htm>

**Exploitation of Groundwater Resources - IFAD**

[http://www.ifad.org/evaluation/public\\_html/eksyst/doc/lle/pn/l103nrme.htm](http://www.ifad.org/evaluation/public_html/eksyst/doc/lle/pn/l103nrme.htm)

**SUSTAINABLE WATER RESOURCES MANAGEMENT**

<http://www.y.net.ye/undp-yem/WTR-OTLN.html>