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WATER RESOURCES—AN OVERVIEW OF THE WORLD DESERTS

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INTRODUCTION

The natural resources of arid regions particularly water is limited, and is often in a delicate envrionmental balance. Abundant ground water may be available in some areas but with small natural recharge this raises the problem of mining a non-renewable resource. Desertification due to a lack of conservation planning, and the dangers of destroying and/or depleting the water resources beyond recovery, are evident at the present time and may be disastrous if development is based on short term expediency rather than the long term stability. Therefore, it is imperative that an inventory of the water resources available in the deserts of the world (Fig. 1) may be prepared for the long term use, so as not to deplete this prime resource beyond redemption. The present review makes an effort in this direction. Water resources in the chief low latitude deserts of the world (Cloudsley-Thompson 1977) are as follows :

THE SAHARA

Apart from their scantiness water resources in the Sahara are variable. Rainfall varies between 30-50 mm yr^{-1} in the middle of the Sahara, increasing slightly in the mountains of the western Sahara—the Atlas, Adrar, Hogar, Tassilli, Ennedi and also on Jebel Marra in the Sudan. Tendency of sudden rain storms at irregular intervals result in an average of one flood a year in the semi-arid parts of the Sahara, but in the more arid region only six to seven floods in ten years (Goudie and Wilkinson 1977). The flow is both short lived and irregular. Saharan floods seldom succeed in flowing more than 300 km (Goudie and Wilkinson 1977). High flows with discharges of 20-60 m^3s^{-1} are separated over a short time span by periods of no flow at all. The average *wadi* runoff coefficient is 1-2% of the rainfall. Thus, total annual rainfall in the Sahara has been estimated to be $0.02x10^9$ m^3 (Ezzat 1982). In the areas of almost total aridity the *wadis* (dry valleys) may stay ten years without conveying water.

Hydrological data of the major Saharan rivers are given in table 1.

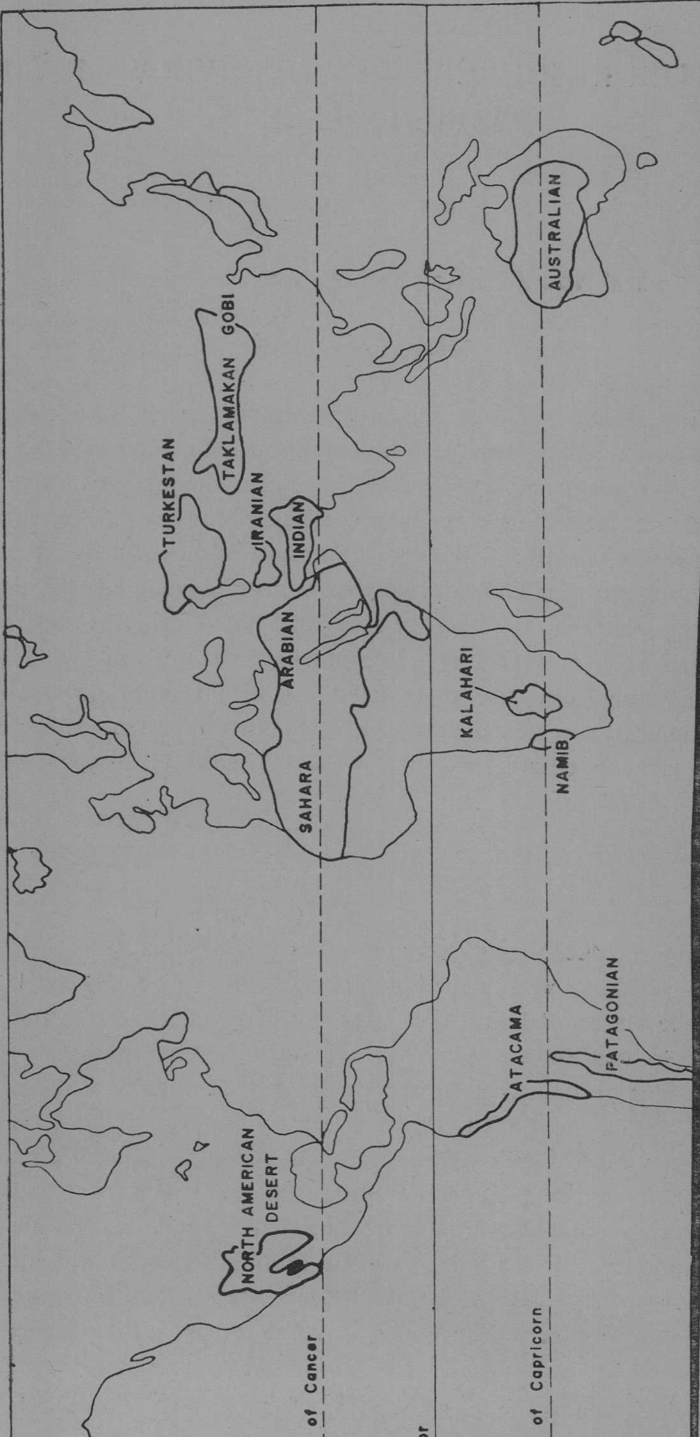

Fig. 1 The distribution of world deserts (Loopold 1959)

Table 1. Flow characteristics of the Saharan rivers (Gischler 1976).

River	Annual discharge ($m^3 x 10^9$)	Specific Annual runoff (mm)	Years of observation
Senegal	24.5	123	72
Niger	49.1	409	70
Chari-Logone	40.5	66	39
Nile	84.0	3	96
Volta	37.8	96	28

Saharan rivers originate in more humid regions and traverse through the Sahara. Their flow regime is extremely variable (Gischler 1976); peak flow occurring during August-September. The river Nile risese in Burundi, an equatorial region at a height of 2000 m, and passes through lake Victoria. This branch is known as White Nile and has a more evenly distributed discharge (Rao 1975). The White Nile passes through the extensive Sudd swamps; the resultant flow contributed to the Nile is only 2/7th of the total inflow (ICID 1969). The main contribution comes from the Blue Nile taking off from lake Tana in Ethiopia as a result of seasonal rainfall. Therefore, the flow hydrograph is highly flashy (Rao 1975). Another tributary of the Nile is the Atbara which joins the Nile 325 km north of Khartoum and contributes 1/7 of the total flow. From Khartoum to the Mediterranean, a distance of 3000 km, there is no perennial tributary. The quantity of water in the various tributaries and the main Nile is 173 x 10 $^9m^3$ (Rao 1975).

The records show fluctuation in annual discharge between 120 and 25 x 10^9m^3 yr^{-1} (Ezzat 1982). The High Aswan dam was constructed in the year 1971 with a capacity of 164 x 10^9m^3 nearly twice the annual flow of the river. Besides, the lake Chand—a natural water body in the Sahara, has a capacity of 75 x 10^9m^3 and an annual inflow of 25.42 x 10^9m^3 yr^{-1} (Gischler 1976). The Gash river basin lies in the eastern part of Kassala Province, Sudan (Saeed 1978). The average annual precipitation is 341 mm. The mean annual seasonal runoff of the Gash river in the town of Kassala is 48 x 10^9m^3 and the mean average period of the flow is 88 days per year.

All water in the Negev desert of Israel is derived from rainfall, which occurs only during the winter season. Rainfall varies from 300 mm in the semi-arid northern Negev to less than 25 mm in the south of the region (Schechter and Galai 1980). The eastern part, in the rain shadow behind the mountains of Judea and Galilee, has a steppee like climate with a rainfall of 300-400 mm yr^{-1}. The only sizeable river, the Jordan has an average annual flow of abouts 60 x 10 $^9m^3$. It is regulated by Lake Kinneret, the operative storage of which is, however, only about one year's average annual flow of the river. Israel utilizes over 95% of its potential water supply. This amounts to only about 160 x 10 $^9m^3$ yr^{-1}, which is the annual rate of replenishment of all water sources.

The perennial rivers while traversing through the Sahara are subjected to heavy transmission losses (Anonymous 1978) which replenish the ground water basin. In Egypt, to the west of the Nile (new valley scheme) some recharge may still be taking place from the direction of the tropical plateau in the northeast Chad where the rainfall ranges from 250-625 mm yr^{-1} (Goudie and Wilkinson 1977). It has becn calculated that the total recharge from the borders of the Sahara into all the confined aquifers which underline this desert of nearly 8 x 10^6 km^2 is only 4 x $10^9 m^3$ yr^{-1}, that is somewhat less than 5% of the average annual flow of the Nile. In case of eastern aquifers the recharge areas are within the districts of very sparse rainfall and the recharge is negligible.

The bulk of the total water reserve stored under the Sahara is found in the western desert: in the deeper northern part of the Nubian sandstone aquifers with a total area of 1.8 x 10^6 km^2; the Narzng basin (0.7 x 10^6 km^2); the west Sahara basin (0.8 x 10^6 km^2) and Tanazrouft (0.25 x 10^6 km^2) (Gischler 1976). Probably not more than 20% of the total volume is stored in the southern shallow basins. Among these the most important are, from east to west: the southern shallow part of the Nubian sandstone aquifers (about half of the total area), the Chad basin (1.4 x 10^6 km^2) and the Niger basin (0.525 x $10^6 km^2$). Radiocarbon dating has revealed that the water contained in these basins is between 10,000 and 35,000 years old (Mandel 1977). Apparently, after the last pluvial, about 10,000 years ago, recharge to these basins ceased almost entirely. The total amount of water reserves stored in the above aquifers is estimated to be 60000 x $10^9 m^3$. Average salinity of this water is 2-4 g l^{-1} (Gischler 1976). The water bearing formation in the western desert (Nubian sandstone) ranges from Precambrian till middle Creteceous (Ezzat 1982). This sandstone, which in many places is inter bedded with shale, is 400-800 m thick in the Kharga depression, 1400 m in Dakhla depression and over 2000 m in Farafre depression. The ground water reservoir is a confined aquifer overlain by a semi-impermeable stratum. The top of the aquifer is within 50 m below ground level. It has an artesian flowing area of 57,000 km^2 including the Qattara depression. Average discharge of the wells is 200-350 m^3h^{-1} (Ezzat 1982). The annual recharge to the Nubian ground water reservoir is about 8.16 x 10^9 m^3 yr^{-1}. The aquifer in addition to a safe yield of about 8.16 x $10^9 m^3$ yr^{-1}, has a capacity of 6x10^9 m^3 of dead storage accumulated during the past 50,000 years.

The Kufra basin (60,000 km^2) in the southeast Libya, Chad, Sudan and Egypt is occupied by the Nubian sandstone—an unconsolidated sandstone interbedded with varying amounts of silt, clay and silty shale (Ahmad and Eddib 1975). The ground water reserve in Kufra basin is estimated to be 3000 x $10^9 m^3$ (Pallas 1980). The groundwater is of excellent quality—total dissolved solid upto 0.5 g l^{-1}. The most probable age of the main groundwater unit is around 40,000 years, whereas the age of the water table aquifer may be around 2000-5000 years. The ground water level at

Sarra (300 km southwest of the Kufra region) is 491 m above mean sea level whereas the water level at Kufra varies from 390 to 410m above mean sea level. The transmissivity, storage coefficient, hydraulic conductivity and the discharge rate of the Kufra basin varies from 300-3500 m^2 day^{-1}, 0.02—$1 x 10^{-4}$, 0.006—8.6 gpd m^{-1} and 7000-8500 l s^{-1}. The safe yield of this aquifer is estimated at 0.37 x 10^9 m^3 yr^{-1}.

Some 1.38 x 10^9 m^3 are estimated to recharge the major groundwater basins in the Sudan annually (Saeed 1978); only 0.14 x $10^9 m^3$ of this recharged water is used. The groundwater reserves in Sudan are estimated to be 41.8 x 10^9 m^3. The Gash alluvial deposit, which have variable thickness ranging from 20 to 60 m, constitute the principal aquifers in the area. The average transmissivity of this aquifer is 240 x $10^4 m^2$ day^{-1}. The storage capacity of the ground water reservoir is about 0.60 x 10^9 m^3 in the Kassala river basin. The annual discharge from the ground water reservoir is about 0.09 x $10^9 m^3$. This aquifer is recharged seasonally from the Gash river during the flood season by influent seepage. The storage change is estimated to be 0.08 x $10^9 m^3$. In the western part of the Kassala area the water table shows an average decline in level of about 0.5 m yr^{-1}. In the eastern part of the town of Kassala the water table level is more or less stable. The total dissolved solids of ground water are about 0.25 g l^{-1} and the water is suitable for irrigation and domestic use.

In the Negev desert two separate ground water systems occur. The sandstone aquifer (Issar et al 1972) of the coastal plain draining directly into the sea has an average annual replenishment of about 0.21 x 10^9 m^3 yr^{-1}. Estimates of sustained yield is about 0.16 x 10 m^3 yr^{-1} (Schneider 1964) with a total thickness of about 700 m, is replenished through outcrops on the western flanks of the Judean mountain and drains mainly through the Yark on spring near Tel Aviv which yields about 0.20 x $10^9 m^3$ yr^{-1}.

THE ARABIAN, IRANIAN AND TURKESTAN DESERTS

The Arabian peninsula, falls under arid and semi arid zones, subject to local topographical conditions and distance from the sea. The Mediterranean influence and winter precipitation govern almost the entire northern half. The southern portion is hot in all seasons and is influenced by the monsoonal effect. Scanty rainfall can be expected at any season. Rainfall amounts of less than 20 mm yr^{-1} are experienced in the extremely arid areas. Table 2 shows the annual mean precipitation in different country of the region (Anonymous 1978).

There are three sources of water in the Arabian countries; rivers and springs, *wadi* floods and groundwater. In the countries of the northern subregion, by far the major part of water is conveyed through canals which divert water from major rivers such as the Euphrates, Tigris, Khabour, Droutes, Litani, Jordan as well as

Table 2. Average annual precipitation in the Arabian peninsula (Anonymous 1978)

Country	Region	Precipitation (mm)
Bahrain	—	75
Iraq	Desert plateau	50-150
	Lower Mesopotamia	100-200
	Upper plains and foothills	300-500
Jordan	West highland	300-700
	East highland	300-600
	Jordan valley-	—
	Dead Sea	Negligible
	South desert	<250
	East desert	<150
Kuwait	—	120
Lebanon	Bakaa valley	250-1500
Oman	—	40-180
Qatar	—	60
Saudi Arabia	North region	80-120
	Northeast region	50-70
	Centre	85-110
	Red Sea Coast	250
	Mountains	400
Syria	—	50-500
UAE	—	65
Yemen (YAR)	Plains	200
Yemen (PDR)	Coast	>50
	Northeast	Negligible

from a number of smaller rivers of local importance (Abu Khaled 1977). The flow varies both in quantity and nature throughout the region. In Iraq, Syria, Jordan and Lebanon data on stream stage and discharge are good. In Kuwait, Bahrain, Qatar and in portions of other countries no measurable surface runoff occurs. In Yemen, Saudi Arabia, and in portions of some countries there is a heavy reliance on *wadi* flood waters which approximate to 1.5 $10^9 m^3$ (Abu-Khaled 1977).

Among the Arabian countries, Iraq has the highest surface water potential. This is because two mighty rivers—Euphrates and Tigris constitute the main water resource of the country. The mean annual flow of the Euphrates at Hit is estimated at an average of 30 x $10^9 m^3$ within a range of fluctuation between 10 x 10^9 and 40 x $10^9 m^3$ depending on the cycle of wet and dry years (Badry et al 1980). The annual flow of Euphrates river during the flood season from March to July is estimated at 60 to 70% of the total annual flow. Its lowest flow is during the period from August to Ocober at 110 to 230 $m^3 s^{-1}$ or a total of 2.5 x $10^9 m^3$, which is 9% of the mean annual flow. The mean annual flow of the Tigris river as it enters Iraq from Turkey is 31.5 x $10^9 m^3$. The mean annual flow generated inside Iraq at the confluence of the Diyala river with the Tigris river is 27.9 x $10^9 m^3$ (Greater Zab 14.2 x $10^9 m^3$, Lesser Zab 7.4 x $10^3 m^3$, Al-Adhaim 0.7 x $10^9 m^3$ and Diyala 5.6 x $10^9 m^3$). Thus the mean annual total flow of the Tigris river develops to 59.4 x $10^9 m^3$. The Teeb, Dewarage and Shehabi river waters are highly saline and thus, of limited use. In the flood season, the Karkha river flows into the Hur-Al-Hewali but this water is not available for use. In summary, the total annual water resources of the country are estimated as 115.8 x $10^9 m^3$ (Anonymous 1978).

In absolute terms Iraq's water resources are estimated to be 106 x $10^9 m^3 yr^{-1}$ (Anonymous 1978). The country's guaranteed water supply at 50%, 75% and 90% of times is assessed at 77.5, 64 and 53.2 x $10^9 m^3 yr^{-1}$, respectively.

Incidentally, Saudi Arabia is the largest country (2,253,000 km^2) in the world without any perennial river (Hajrah 1982). The average annual rainfall is less than 100 mm and only about 10% of the land gets 100 mm or more. Morocco (60.7 to 65.3 $m^3 s^{-1}$) and Jordan (1.7 to 7.8 $m^3 s^{-1}$) do have perennial rivers traversing through the country due to a favourable rainfall and topographic conditions (Anonymous 1979).

Groundwater reservoirs occur in two principal ways in the Arabian countries—deep aquifers with little or no recharge, and valley alluvium which is recharged periodically from stream flows (Anonymous 1978). Some of the deep aquifers have limited recharge but data are scanty and much research and study is needed to adequately assess the total quantity of water in storage and the recharge potential. Some countries depend upon deep aquifers for their principal water source e.g. Kuwait, Bahrain and Qatar (Taha 1980). Several countries have both deep aquifers and *wadi* alluvium as water supply sources. The *wadi* alluvium provides large sources of water, and have been managed well. Table 3 shows known quantities of ground water in the Arabian peninsula.

Good quality subterranian water has been found at the foot hills of the mountains in the northeast of Iraq and in the area along the right bank of the Euphrates (Badry et al 1980). The aquifers in the northeast of the country, having an estimated sustained discharge between 10 and 40$m^3 s^{-1}$, lies at depth of 5-50 m. Its salinity increases towards the southeast of the area till it reaches between 0.5 and 1 g l^{-1}. The aquifers on the right bank of the Euphrates river. trapped between gypsum and dolomite at depths increasing towards the west, where the water is found at 300 m depth (at Abu - Al jear), have an estimated total discharge of 13 $m^3 s^{-1}$. In the western part, the salinity of water is only 0.3g l^{-1} compared with 0.5 to 1.0 g l^{-1} in the eastern sections. In other areas of the country good quality groundwater is limited due to high levels of salinity.

Table 3. Water protential in the Arabian countries (Anonymous 1978)

Country	Surface water $(m^3) \times 10^{-9} yr^{-1}$	Groundwater Yield $(m^3) \times 10^9 yr^{-1}$	Total dissolved solids $(g\ l^{-1})$	Remarks
Bahrain	Neglgiable	0.20		Water table drop markedly
Iraq	80	0.13	0.2 - 3.0	Ground water contamination
Kuwait	Negligible	0.13	0.3 - 5.0	
Lebanon	3 80	0.05	Good	—
Oman	0.01	0.65	0 - 0.2	—
Qatar	Negligible	0.05	0.5 - 5.0	North part
Saudi Arabia	2.20	—	—	
Eastern part	—	1.72	0.35 - 0.87	28,000 wells
Wajid aquifer	—	0.10	0.53 - 0.82	—
Minjur aquifer	—	0.46	—	Level drop 45 m, in 1956-66
Saq aquifer	—	N.A.	—	
Tabouk aquifer	—	N.A.	—	—
Syria	32.0	1.67	—	Overdraft
UAE	0.16-0.27	0.27	—	—
Yemen	1.50	0.35	—	—

Desalinisation has come into prominance in recent years as a new source of supply in the Arabian countries. Quantities of desalinised water are appreciable and in many coastal areas is the principal source of supply. Usually, such water is mixed with local brackish water, keeping the mixture within, acceptable chemical standards, to form a new source of supply. The prospective supply of desalinised water in the region varies from 0.01 to $0.17 \times 10^9\ m^3\ yr^{-1}$ (Anonymous 1978).

Iran is a semiarid to arid country, 90% of the area is affected by inadequate precipitation. With the exception of the Caspian sea littoral, between the Alburz mountains and the sea, and some areas in the southwest, the average annual precipitation amounts to 250 mm. With a runoff coefficient of 0.25, the average annual runoff in the country is estimated to be $117.5 \times 10^9 m^3$ (Anonymous 1978). The annual dependable water supply in the country is $84.8 \times 10^9 m^3$ as surface water and $22.7 \times 10^9 m^3$ as groundwater. Nineteen large dams and reservoirs regulate more than $13 \times 10^9 m^3$ of water annually out of the $20.1 \times 10^9 m^3$ annual river flow.

The water resources in the USSR deserts include precipitation, local surface runoff, allochthonous rivers and groundwater (Anonymous 1983). During a year of average annual rainfall the deserts in central Asia and south Kazakhstan receive nearly $240 \times 10^9 m^3$ water (Babayev 1977). However, potential sources of local water continue to be used inadequately, despite the fact that there has been widespread use of fresh underground water which has been discovered over considerable territories in the deserts in recent years.

Man made impervious sites or natural Takyr (clay) catchment may yield in different regions an annual average of 5,000 to 35,000 m^3 of rainwater from 1 km^2 (Lyeshinki 1974). In the Karakum alone, where Takyr or Takyr-type areas account for 3.1 x $10^6 m^2$, the total runoff of freshwater equals 35 x 10^9 m^3 yr^{-1}, which is almost equal to the Syr Darya runoff. Kudelin et al (1970) estimated the surface runoff in Kazakhstan as 88 x $10^9 m^3$ yr^{-1} out of which 57.3 x $10^9 m^3$ yr^{-1} occurred as base flow.

The drainage network of Central Asia is extremely poor, with many rivers being lost in the sands and forming dry beds and deltas. The Syr Darya river is the most important water source in the USSR's central Asia (Dukhovny and Litvak 1977). Rainfall in the Syr Darya basin fluctuates from 575 mm in the upper collecting areas to 100-150 mm in the lower parts of the river basin. The surface runoff of the Syr Darya river is estimated as 37.2 x $10^9 m^3$ yr^{-1}; 52.9% of this from Narin river, 15.4% from the Kara Darya river and 3.17% from side tributaries of the Syr Darya. The average specific discharge of the whole basin is 8.1 1 s^{-1} km^{-2}. Syr Darya river has a characteristic alternation of 4-5 years of dry and wet cycles. A situation may occur when extra dry years run in succession.

Over the four years (1970-1973) the water demands have been met only by usage of underground and return waters in addition to the regular river runoff (Dukhovny and Litvac 1977). Present seasonal flow contiol is being carried out by means of a cascade of large reservoirs constructed on the Syr Darya river and its tributaries. Their combined storage capacity is 37.0 x $10^9 m^3$ out of which 27.9 x $10^9 m^3$ is the available water. Another important river of the USSR's desert is Amu Darya whose annual runoff measures around 60 x $10^9 m^3$. Both the Syr Darya and Amu Darya join the Aral sea. The worlds' largest desert hydrotechnical project the Karakum canal with a discharge capacity exceeding 400 m^3 s^{-1} in its upper reaches and with 12 storage reservoirs with a combined capacity exceeding 1.6 x $10^9 m^3$ also lies within the USSR's desert (UNESCO 1980).

Most of the ground water in the USSR's deserts has a high mineral content. In some areas mineralisation reaches high value of 50 to 100 g 1^{-1} (Lyeshinski 1974). Geographically the desert groundwater salinity is not uniform : in the western part of Turkmenistan from 0.1-3.0 g l^{-1} to 15-50 g l^{-1}, in Kyzylkum 3-15 g l^{-1} and in Karakums from 1.5-3.0 g 1^{-1} to 30 g 1^{-1}. Most wells are not deep : 98% are upto 30m. 1.5% from 31-99 m and the rest 0.5% are 100 m and deeper.

THE TAKLA MAKAN AND GOBI DESERTS

In Takla Makan desert several rivers flow from the Tienshan and Kunlunshan; the mountain ranges surrounding it. Annual rainfall over these mountains ranges from 200-450 mm (Cloudsley-Thompson 1977). The river Quang Ho with a water yield of $47 \times 10^9 m^3 yr^{-1}$ is the major river in this desert. The Turfan depression in Sinkiang is protected by the Tienshan range in the north and has a mean annual rainfall of only 16.6 mm. Permanent snow cover on this range provides an important perennial supply of surface water @ $0.3 \times 10^9 m^3 yr^{-1}$ (UNESCO 1980). The basin also has important artesian groundwater resources with an annual discharge of $0.2 \times 10^9 m^3$.

In Gobi desert water is found only in wells or in occasional small alkaline lakes. The average annual rainfall of the region is 220 mm. With an estimated runoff coefficient of 0.07 the Gobi desert has a runoff potential of $24.6 \times 10^9 m^3 yr^{-1}$ (Anonymous 1978).

THE INDIAN DESERT

The countries sharing parts of this desert are Afghanistan (southern part, Dasht-i-Margo region), Pakistan (Baluchistan, Sind and Indus plain) and India (north-western part). The arid part of Afghanistan receives an annual rainfall of 324 mm. With an estimated runoff coefficient of 0.24 the average annual runoff in the region is $50 \times 10^9 m^3$ (Anonymous 1978). The Helmand river, one of the worlds' few major streams, with an annual flow of $22.0 \times 10^9 m^3$ flows through this extensive desert (Lustig 1967).

The water resources of Pakistan desert include water of the Indus river and its tributaries, local rainfall and usable groundwater from the aquifers underlying the Indus plains. The average annual rainfall in this region is 250 mm (range 100-600 mm). The rivers serving the Indus plains are the Indus and its tributaries-the Kabul on the right bank, and the Jhelum, Chenab, Ravi, Beas and Sutlei on the left bank. At present only the rivers Indus, Jhelum and Chenab have fallen to the share of Pakistan with the implementation of the Indus water treaty between Pakistan and India effective since April 1970. These rivers flow in shallow, meandering channels across the vast alluvial plains which gently slope towards the south and the southwest along the rivers with extremely flat gradients from about 0.02% in Punjab to 0.01% in Sind. The rivers have individual flow characteristics but they all rise in the spring and early summer with the snow melt and monsoon rainfall and have combined peak discharge in July or August. In winter, during the period November to February, flows are much lower being only about less than one-tenth of those in the summer monsoon. The winter flows consist almost entirely of regeneration or bank storage returning to the river after the summer has ended. The annual average flow in the rivers Indus, Jhelum, Chenab and Kabul is about $172.0 \times 10^9 m^3$ (Anonymous 1983). The mineral content (total dissolved solids) of the river waters range between 0.10

to 0.35 g l^{-1} from north towards south. Presently about 123.0 x $10^9 m^3$ of river flow is diverted out of which about 71.6 x $10^9 m^3$ is available at the heads of water courses.

The deep alluvium deposits of the Indus plains form an extensive groundwater aquifer. The physical characteristic of the alluvium are generally favourable to ground water development. Keeping in view ihe irrigation water quality constraints and gradual deterioration of groundwater, it has been estimated that about 50.0 x $10^9 m^3$ of groundwater can be developed annually, most of which would have to be mixed with canal water before use (Anonymous 1983). However, presently about 24.7 x 10^9 m^3 of groundwater is available for agricultural use.

The northwestern hot arid zone in India, occupying an area of 285, 680 km^2, can be divided into three hydrological zones (Fig. 2) viz. zone I-canal irrigated area (42,900 km^2), zone II - region with primitive/no stream net work (148,600 km^2) and zone III - region with integrated stream network (94, 280 km^2). The mean annual rainfall varies from 100 to 450 mm in Rajasthan, 300 to 500 mm in Gujarat and 200 to 450 mm in Punjab and Haryana.

In Zone I the designed capacity of the Ferozpur feeder (Murthy and Gulati 1978), Bhakra canal (Uppal 1978), west Jamuna canal Gupta (1987), and the Indira Gandhi canal (Kapoor and Rajvanshi 1977) is 314, 510, 79.3 and 524 cumec, respectively. These canals bring water from more humid regions by diverting the flows of Sutlej, Beas and Ravi in Punjab. The total water delivery in this zone through canals worked out to be 1.07 x 10^9 m^3 yr^{-1} (Sharma and Vangani 1979).

The Zone II comprises sandy plains, dune complex, eroded rocky/gravelly surfaces and isolated hillocks. The channels emanating from these hillocks and rocky gravelly surfaces get suffocated in deep alluvium and blown sand and form internal drainage basins. Jain (1968) estimated that approximately 0.28 x $10^9 m^3$ of surface water is available annually for utilisation in this zone. Mehta and Kashyap (1970) estimated the surface water potential of this region as 0.2 x $10^9 m^3$ out of which 0.13 x $10^9 m^3$ as the utilizable portion. Sharma and Vangani (1989) estimated the surface water potential of this area as 1.33 x 10^9 m^3 out of which 47% was the exploited water yield till 1987-88.

The Zone III comprises the Luni basin, Sahibi basin and the smaller basins in Gujarat. These are ephemeral drainage systems and convey water only in direct response to the torrential rainfall during the monsoon season. Sharma and Vangani (1989) estimated the water potential of this region as 4.09 x $10^9 m^3$ (Table 4). They also measured the actual runoff in the Luni basin during 1979-87 and reported the average flow as 0.84 x $10^9 m^3$.

In the Indian desert sandstone and limestone aquifers were found promising for tapping moderate to potential supplies of groundwater due to their porous and

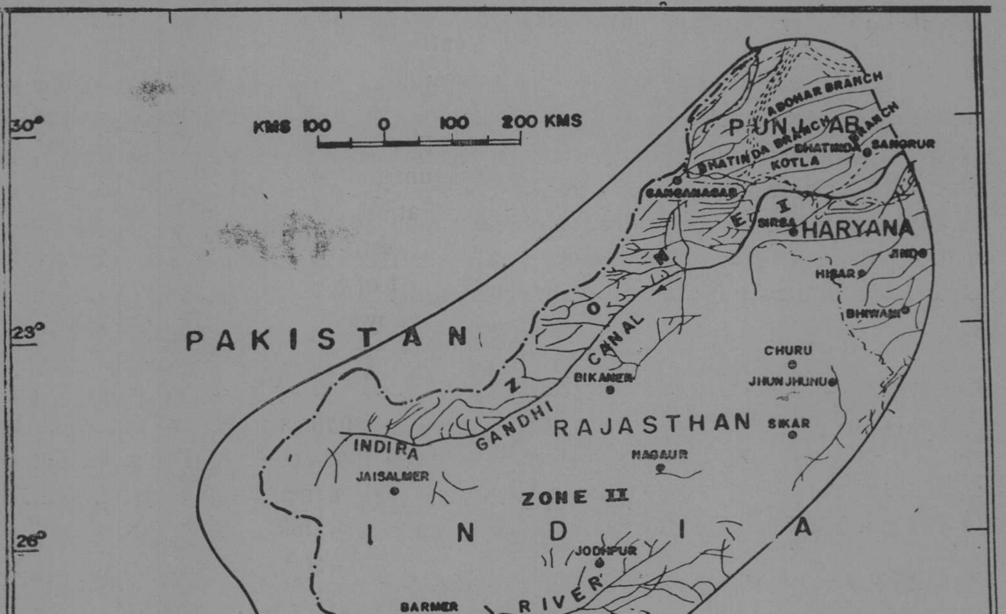

Fig. 2. Hydrological zones in the indian desert (Sharma and vangani 1989)

Table 4. Water potential of Zone III in the Indian desert (Sharma and Vangani 1989)

Region	Basin area (Km^2)	Total runoff ($m^3 \times 10^9\ yr^{-1}$)	Total utilization ($m^3 \times 10^9\ yr^{-1}$)
Luni river basin	34639	0.87	0.39
Sukri river basin	945	0.06	0.01
Sahibi river basin	5885	0.19	0.13
Streams of Jalor district	471	0.01	0.01
Basins of Gujarat	59414	2.95	0.57

permeable nature (Anonymous 1986). The blown sands also form moderately potential aquifers in places. In the hard rock terrain, the valley fills along the streams consisting of river alluvium often contain highly productive aquifers although their productivity is limited and yield is low (5-25 m^3h^{-1}). The alluvium contains the most productive aquifers in the region but locally the quality of groundwater is poor. Among the semi-consolidated formations the Lathi sandstone (Anonymous 1981) is found to contain moderately to highly productive aquifers (water yield varying from 25-150 $m^3\ h^{-1}$). Overall, the groundwater resources in this region is estimated to be $4.54 \times 10^9 m^3$ out of which net recoverable recharge is $3.83 \times 10^9 m^3$. In Gujarat the groundwater bearing formations are shale and limestone and thus, the quality of groundwater is poor in general. According to an estimate (Anonymous 1986) the recoverable recharge from all aquifers in the Gujarat desert is $1.27 \times 10^9 m^3$. The range of total dissolved solids was found to be 0.5 to 2.5 $g\ l^{-1}$. Wells tapping the alluvium and hard rock aquifers in Punjab and Haryana yield 3.6 to 10 m^3h^{-1} and 1.7 to 3.3 m^3h^{-1} respectively (Anonymous 1981).

THE KALAHARI AND NAMIB DESERTS

The Kalahari desert is intersected by the beds of ancient rivers (fossil river valleys) with extensive mud flats and deposits of alluvium. After rain, these form pans and lakes and retain water for several months (Lustig 1967). In Kalahari there is a little permanent surface water except a perennial river traversing it-the river range with a water yield of $90 \times 10^9 m^3\ yr^{-1}$. In Namib desert the annual rainfall averages only 23mm. Kuiseb is a major ephemeral river that crosses the Namib.

THE AUSTRALIAN DESERT

The great deserts of Australia include the Simpson, Gibson and great sandy deserts and are comparable in severity to the Sahara, the Kalahari and the desert areas of Arabia. Australia's average rainfall is only 432 mm yr^{-1}. It is the driest continent; 35% of the area receives less than 250 mm yr^{-1} rainfall which is both low and unreliable (Clark 1978). Over most of the mainland, river flow is either intermittant or non-existant. Furthermore, flat topography and high evaporation losses reduce the flow of streams.

The river Murray and its tributaries form the largest river system in the arid tract of Australia. Though its catchment covers nearly one-seventh of the total area of Australia i.e. 1,036,000 km² yet the runoff per unit area from the system is extremely low in comaprision with other major rivers of the world (e.g. only 14% of the Nile; Hotes and peargon 1977). The average annual flow in the river Murray totals 16.04 x $10^9 m^3$ (Maver and Michels 1975). Another important river in the Australian desert is Burdekin river draining a catehment area of 130,000 km². The annual discharge is extremely variable ranging from 28 to 85 x $10^6 m^3$; periods of no flow upto six months are not uncommon. Similarly, the river Darling, the longest tributary of the Murray with an average annual discharge of 2.655 x $10^6 m^3$ shows extreme variability of flow from 1230 m^3 to 0.01 x $10^9 m^3$ in different years. These vairations are caused by the extreme changes in the year to year rainfall (Clark 1978). Discharge of selected rivers in the Australian desert are given in Table 5. With an estimated runoff coefficient of 0.096 the average annual runoff in the Australian desert was found to be 343.0 x 10^9 m^3 (Anonymous 1971). The annual dependable water supply was estimated to be 125.0 x $10^9 m^3$ from the surface water and 72.0 x $10^9 m^3$ from the groundwater.

Table 5. Discharge of selected rivers. of Australian and American deserts (Anonymous 1979)

River	Location	Average annual discharge (m^3 s^{-1})	Water yield (m^3 x 10^9 yr^{-1})
	Australian desert		
Fitzroy	Diamond Gorge	57.2	1.80
Fitzroy	The Gap	996 1	31.41
Ord	Homestead	69.5	2.19
Murray	Lock 9	704.4	22.21
Burdekin	Clare	740.7	23.36
Victoria	Coolibah	1.8	0.06
Daly	Gourley	281.5	8.88
	American desert		
Sabive	Ruliff, Texas	369.7	11.7
Neches	Evadale. Texas	282.3	8.9
Trimty	Ramayor, Texas	337 0	10.6
Brazos	Richmond, Texas	290.0	9.1
Colorado	Wharton, Texas	116.3	3.7
Nevces	Mathis, Texas	23.5	0.7
Colorado	Less Ferry, Arizona	351.0	11.1
Colorado	Yuma, Arizona	23.7	0.7
Humboldt	Imley, Neveda	19.6	0.3
Sevier	Jnab, Utah	7.4	0.2
San Joaquin	Vernalis, California	108.3	3.4
Sacramento	Sacramento, California	929.0	29.3
Eel	Scotia, California	313.3	9.9
Klamath	Klomath, California	641.0	20.2
Mexico	Grande	158.5	5.0

Calcrete formations provide important aquifers in arid Australia. Their importance is accentuated by the aridity of the area, the average annual rainfall being about 210 mm. The average saturated thickness of calcrete is 4.46 m, hydraulic gradient 0.57×10^{-3}, transmissivity 5800 m^2 day^{-1} and specific yield is 0.26 (Williamson 1978). The total dissolved solids range from 0.71 to 1.33 g l^{-1}. The estimated underground flow is 9920 m^3 day^{-1}, which is equivalent to 0.04×10^9 m^3 yr^{-1} and the upstream storage to be 0.01×10^9 m^3.

THE NORTH AMERICAN DESERT

The North American desert lies in an essentially continuous arid area which extends southward from the western United States (the states of Nevada, North Mexico, Utah, Arizona, Texas and California) into Mexico. The Colorado river (catchment area 583,000 km^2) draining portions of Colorado, Wyoming, Utah, New Mexico, Arizona, Nevada and California as well as 510 km^2 in nortnern Mexico is the most important river in this region. The long term average annual virgin flow of the Colorado river is 18.38×10^9 m^3 (Rao 1975); of major importance too, are the large variations in annual flows which have ranged from 6.91×10^9 to 29.60×10^9 m^3 (Diskin and Lane 1972). Discharge data of the other rivers crossing through the North American desert are given in Table 5.

Generally large proportional differences between mean and median river flows in the North American desert are indication of the positive skewness of the annual runoff distribution. The statewise long term runoff in California averages about 87.6×10^9 m^3 yr^{-1}. Flows have varied from 22.2×10^9 to 166.5×10^9 m^3 (Jones 1981). These flows are distributed in numerous rivers, creeks and streams; many of them have intermittant flow only. In California 18.5×10^9 m^3 water is also available annually from the groundwater basins.

In an average year Arizona receives about 98.7×10^9 m^3 of water from rain and snow, out of which 2.47×10^9 m^3 is captured. About 7.40×10^9 m^3 is obtained from underground water reserves (Steiner 1982). Inflow into the Santa Cruz groundwater basin (5734 km^2) consists of natural recharge 0.08×10^9 m^3 yr^{-1} and seepage from the river 0.002×10^9 m^3 yr^{-1}. Some 3.70×10^9 m^3 of the groundwater occurs in the Gila sub-basin. The groundwater reserves available in Arizona's alluvial aquifers are aggregating approximately 1470×10^9 m^3 and to a depth of 366 m below land surface having total dissolved solids between 0.3 to 4.5 g l^{-1}.

THE ATACAMA DESERT

In the Atacama desert the precipitation along the Pacific coast and in the inner parts of the region is almost zero and in many places even a sprinkle of rain is a very rare occurrence. Precipitation increases towards the Cordillera in the east; it is about 100 mm at altitudes of 3000 m and 300-400 mm (mostly as snow) at the peaks of Colcanoes - altitude 5000 to 6000 m. The quantities of known and easy to tap water resources of the region are smaller than the projected needs. The 5 $m^3 s^{-3}$ of water is tapped from the surface water resources (Golani 1982). The hydrological and hydrogeological studies showed that 3-5 $m^3 s^{-1}$ water can be made available by exploiting the additional water resources of the area and by better water management. The Combarbala and Pama rivers in the Chile desert are supplied by rainwater as well as by snowmelt from the high mountains. These rivers have a regular regime and irrigate the low lying lands. Measurements of the Pama and Combarbala rivers show a mean annual discharge of 0.32 $m^3 s^{-1}$. The Chilean Water Board considers both rivers to have a similar rain dependent regime. Observations made during an 11 year period show that 70% of the discharge in one year comes from May to August (UNESCO 1980). The highest flow of 133 $m^3 s^{-1}$ was registered in 1958 on 4 June. The river supplies about 30% of the volume collected in the Cogoti reservoir, its mean annual discharge is 0 01 x $10^9 m^3$.

THE PATAGONIAN DESERT

The arid zone in central and southern Argentina is generally termed the Patagonian desert. The average annual rainfall in this desert vary from 320 mm in the Atlantic region to 410 mm in the closed region. The principal rivers traversing this desert are Negro and Senguerr-Chubut with an aunual water yield of 40 x $10^9 m^3$ and 3 x $10^9 m^3$, respectively (Anonymous 1979). However, data on the magnitude and frequency of runoff in the Argentinian desert and details on the channel characteristics of ephemeral streams as well as the information on the groundwater resources are largely lacking.

CONCLUSION

The surface water resources in the arid regions of world are extremely variable both in the quantity and quality, and are undependable. Withdrawal of groundwater, at present, reflects only a tiny proportion of the fossil and/or recharging water contained in the various potential aquifers throughout the region. However, quality of the groundwater is a constraint in the deserts for their enhanced use.

Available water resources in the arid region of the world have been stretched to the limit as a result of increased demand for drinking, agricultural and industrial use. If this trend continues there is a danger of destroying or depleting the water resources beyond recovery i.e. overuse, over pumping and increased salinity. Therefore, a long term planning of water use is a prime need.

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