STRATEGIC SUSTAINABLE DEVELOPMENT OF GROUNDWATER IN THAR DESERT OF PAKISTAN

*Nayyer Alam Zaigham**

ABSTRACT

Thar Desert forms the extreme southeastern part of Pakistan, covering about 50,000 km^2 area. It is one of the densely populated deserts of the world. Population of Thar is living primarily on limited agricultural products and by raising goats, sheep, cattle, and camels. The region is characterized by parallel chains of the NE-SW trending parabolic stable sanddunes having desertic varieties of vegetation, generally on windward sides, upto the crests. Interdunal areas are favourable for agricultural activities, where crops are mainly dependent on rainwater. Average rainfall is significant but inconsistent, due to recurrent drought-cycles causing inverse impact on food-production and socio-economic development. In spite of extensive groundwater-exploration projects, accomplished by a number of organizations, the water-crisis of the region could not be controlled, most probably due to lack of systematic exploration & development of deep groundwater potential. Management of the available water- resources is also not adequate, even to sustain a short period of drought-cycle. On recurrence of a drought-cycle, a significant section of the population is compelled to migrate towards other parts of the Sindh province, which affects their socio-economic stability.

An integrated research study, based on geo-electric scanning, drilling and seismic-data analyses, has been carried out to delineate subsurface hydro-geological conditions beneath the Thar Desert. Regional gradient maps of surface elevation, top of subsurface Oxidized Zone, top of coal-bearing formation(s) and the deeply buried basement have been prepared, covering almost the whole of Thar Desert. These gradient maps, analyzed in conjunction with the annual rainfall data, reveal the existence of encouraging subsurface hydrogeological conditions, associated with the sedimentary sequences and the basement. From the results of the study, it is observed that perch water aquifers, commonly being utilized throughout the Thar, are present at the bottom of the dunesand-zone, with fluctuating yield controlled by the annual rainfall cycles. At places, vertical electric-soundings indicate good prospects for the better water, associated with the basement complex. The strategic development of groundwater, based on scientific exploration and exploitation, from the deep sedimentary and basement aquifers, can de-desertify the Thar, accelerating the socio-economic stability of the people of the region.

INTRODUCTION

In the northeast, the desert extends towards Punjab Province and eastward across the Indo-Pakistan border, spreading over an area of about 200,000 km^2 (Figure-1). In the Pakistani part of Thar, the habitations are concentrated in the form of small villages scattered all over the desert. This desert is one of the most densely populated in the world. The population of Thar ranges between 850,000 to 950,000 (Baanhn Beli, 90; SAZDA, 1988; Qadri, 1983). Stabilization of the sanddunes and siltification in the interdunal valleys have provided good environment for cultivation and, consequently, raising of goats, sheep, camels, cattle, etc., which is the primary source of living in the Thar Desert.

Physiologically, the study area is bounded by the Punjab Plains in the north, by the Indian border in the east and south, and by the irrigated Indus Plains in the west. In the south, there are salt marshes and mud flats of the `Rann of Kutch', a former shallow arm of the Arabian Sea. In general, the terrain is topographically higher in the northeastern part of the Thar Desert. The elevation ranges from sea level in the south to more than 200 m in the northeast around Gadro area.

Parallel chains of NE-SW trending, large stabilized dominantly parabolic dunes form steep ridges 5-16 km long, with an average relief of 50m, locally up to 80m. Dunes have vegetation (grasses, shrubs, bushes, and trees) on windward sides up to crests (Figure-2). The interdunal valleys are wide and filled with silty and clayey sediments, useful for cultivation where crops are mainly dependent on rainwater. These valleys constitute almost one third of the total area.

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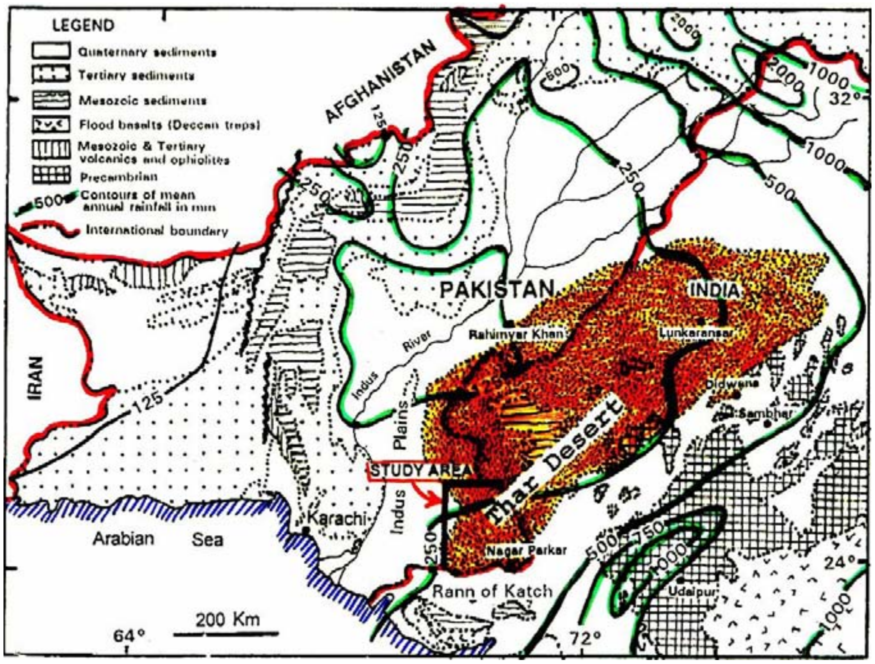


Figure 1: Index map of Pakistan showing location of study area, regional geology, contours of annual rainfall and eastward extent of the Thar Desert.

In Thar Desert, the rainfall is significant (average 350 mm annual) but capricious and uncertain; drought cycles have inverse impact on food-production and socio-economic development. On commencement of a drought-cycle, people of Thar usually migrate with their animals, temporarily, to other parts of Sindh due to poor management of the available water, which consequently affects their socio-economic stability.

Considering the unfavourable climate and its impact on agricultural practices, the magnitude of population, the livestock, and the cultivated areas are surprisingly large. The crops grown are mainly millets and pulses. The agricultural crops are Bajri (Pennistum Typhoideum), Guar (Cluster beans, Cyamopsis Psoralioides) and Til (Sesamum Indicum). The breeding of livestock is the main source of livelihood in the region. According to an agricultural census the livestock population is more than 0.35 million.

A number of organizations have worked for the development of groundwater-resources, but the water-crisis of the region could not be controlled,

Figure-2: A general panoramic view of Thar Desert showing broad interdunal valley and typical vegetational growth.

Figure 3: Water crisis compels people of Thar with herds to migrate temporarily during drought period.

most probably, due to lack of systematic exploration & development of shallow and deep groundwater-resources. Almost the entire Thar Desert has been reconnoitered geologically, through test-drilling supported by the geophysical exploration under the coal- exploration program (Fassett and Durrani, 1994; JTB, 1994; Zaigham and Ahmad, 1996). The northeastern part of Thar Desert was also hydrologically investigated in a joint WAPDA-BGR venture (Ploethner, 1992). Technical management of the so far developed water-resources seems inadequate, because this has not provided sustainability, even against a short period of drought. On recurrence of the last spell of drought-cycle persistent during 1996-2000, a significant section of the population was compelled to migrate from Thar area, due to acute water-shortage even for their domestic needs (Figure-3).

Present study has been concentrated on the possible occurrences of the ground-water associated with the sedimentary rocks, at moderate depth, and hard rocks at deeper depth, and also to the factors controlling the recharge of groundwater at shallow and deeper depths. It is hoped that the study would provide guidelines to back up water-deficiencies for the socio-economic development in one of the less- developed regions of Pakistan, where population is rapidly growing and the environments are already conducive to food productivity as compared to other desert regions.

CLIMATIC CONDITIONS

Thar desert has semi-arid to arid climate. The present climatic situation in Pakistan is mainly influenced by the circulation of the monsoons, which depends on the movement of the intertropical convergence-zone. Strong, humid and cold southwest-monsoons prevail in the summer months from May to September. The strength of the southwest monsoon depends mainly on the pressure-gradient between the low air-pressure in Central Asia and high air-pressure above the Indian Ocean.

Rate of annual rainfall increases from northwest to southeast (Figure-1). In the north of the Thar Desert, a, low rainfall region (with an average annual rainfall of less than 100 mm), exists around

Figure 4: Typical blooming morning view of Thar Desert after heavy rain (September 1994). Geophysical logging was in progress under GSP coal exploration project in interdunal valley flanked by stabilized sand dunes, which look like green

Rahimyar Khan. On the other hand, in the southeast, comparatively high annual rainfall, up to 1000 mm, is received on the Indian side, across the border, around Udaipur. At western margin of the desert at Umarkot, an average of 208 mm/yr rainfall was observed for a period of 42 years from 1897 to1929/1938 to1946 (Radojicic, 1980), but an average of only 160 mm/yr rain was recorded from 1944 to 1958, indicating a cyclic fluctuation of precipitation. To the southeast at Nagarparkar, about 360 mm/yr rainfall was recorded. However, the rainfall is erratic and continuous spells of droughts, lasting for up to four years, have been experienced.

Practically, no rivers or streams exist in the Thar and the drainage is internal. Rainwater flows to the nearest topographic low, as sheet flow that eventually either evaporates and/or infiltrates. Most of the rains occur during July-August monsoon from southwest direction, whereas the prevailing winds are from the northeast during the rest of the year. During a good rainy-season, the area becomes "Green Hilly Thar" (Figure-4).

The winter rains are insignificant. Dust storms are common, with winds of 140 to 150 km/hr from April to June in the desert. The maximum temperature rises to over 45°C during the hot months of April, May and June. The mean maximum and minimum temperatures average 35°C and 19°C, respectively, over the year.

GENERAL GEOLOGY

The Thar Desert lies in the southeastern part of Pakistan, on the western edge of the stable Indian Peninsula. The whole area is covered with extensive & thick cover of duned-sands, extending down to an average depth of 80m. Surface rock exposures are almost absent, except limited outcrops of granitic basement in Nagarparkar. A few scattered outcrops of Mesozoic and Tertiary strata are exposed across the Indo-Pakistan border in the Jaisalmer and Rann of Kutch areas of India. Due to lack of surface-exposures of the prevailing subsurface geological sequences, the geology of the Thar Desert has been poorly understood. Mainly, geophysical and drilling data have provided subsurface geology (Figure-5).

The interpretation of seismic-data (Zaigham and Ahmad, 1996) shows that the Thar Desert rests upon a structural platform where granitic basement is at shallower depths (Figure-6). The granite basement has pre-Jurassic rifting, which caused flexure and the ultimate development of the Thar basin. The basement shows rise towards southeast and deepening towards northwest, as a result of Paleozoic-Mesozoic divergent tectonics. The consistent depositional trends of the stratigraphic sequences from Mesozoic to Tertiary periods indicate that the incipient rifting of the basement was pre-depositional. The younger formations are preserved and overlie the older in

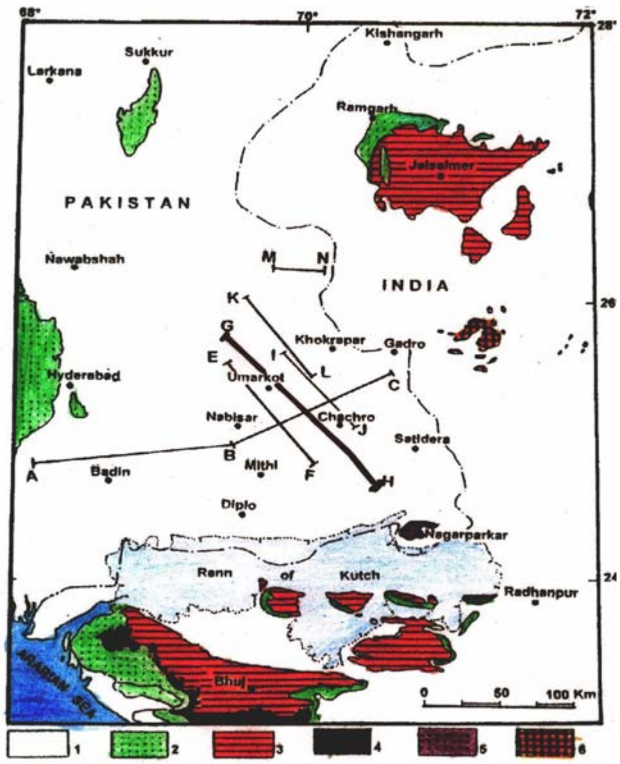


Figure - 5: Map shows general geology, locations of seismic profiles and geological cross-section. Geologic legend: 1) Quatemary sediments/Desert dune-sands, 2) Tertiary sequences, 3) Mesozoic-Jurassic sequences, 4) Lavs flows-Deccan traps, 5) Pre-Cambrian units, 6) Rhyolites-Malani beds

the northwestern part, where geological sequences are well developed. The older formations may be encountered at greater depths towards the basin and shallower on the continental shelf area towards southeast.

Results of the geo-electric, drilling and geophysical/geological log data (Rehman et al., 1993: Fassett and Durrani, 1994; Zaigham and Ahmed, 1996) indicate four major divisions of lithological sequences almost throughout the Thar Desert (Figure-7).

***Dune Zone*:** This zone consists of well-sorted eolian sand. The soils of the desert contain about 8 % clay and silt, near the surface and about 15 % clay and silt in the subsoil (Kazmi, 1985; Qadri, 1983). The thickness of this sand-zone varies from north to south. It is thinner in the northern part of the desert, about 5 to 15 m thick in Gadro-

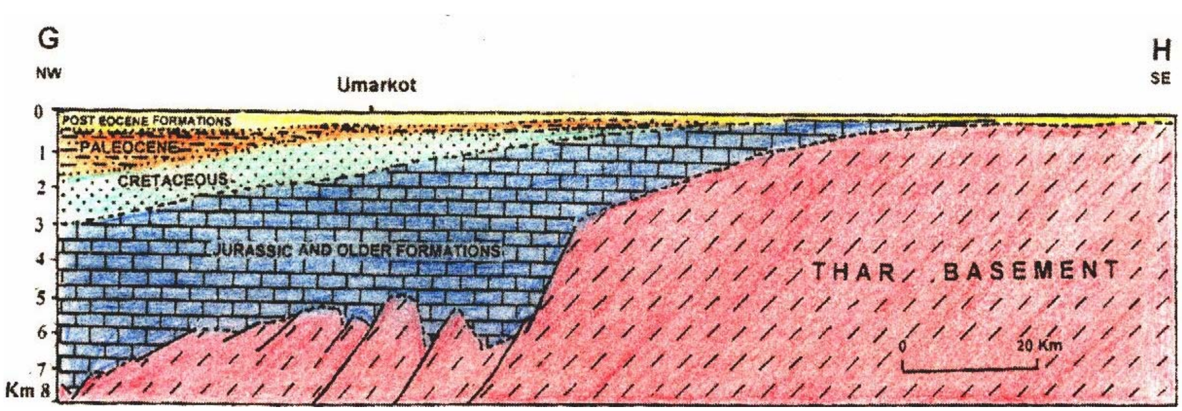


Figure 6: Geological cross-section of the Thar Rift interpreted from seismic data (after Zaigham and Ahmad, 1996).

Khokhrapar area. The thickness increases from about 40 to 93 m in the central and southern Thar in Chachro-Islamkot-Mithi area.

***Oxidized Zone*:** It consists of compact and loose clays, silts and sands with ironstone concretions and siderite nodules. This litho-unit is distinguished from other subsurface units by its iron oxide and limonite stainings. The thickness of this zone ranges from 11 to 209 m. The age of this unit is considered Sub-Recent (Fassett & Durrani, 1994). This oxidized zone lies unconformably over the coal-bearing formation.

Coal-Bearing Formations: The coal-bearing sequence consists of claystones, siltstones, sandstones and lignite, with intercalations of siderite bands, nodules and granite-wash at places. The thickness of this sequence ranges from zero to 185 m, hosting lignite beds with a cumulative thickness ranging from 0.5 to about 34 m.

Basement Complex: Granitic basement is encountered at depths ranging from 112 to 279 m in holes drilled in the east and southeast of Chachro (Fassett & Durrani, 1994). On the other hand, rhyolitic/basaltic basement was reported in a well near Pabban locality, about 8 km south of Gadro (Hindel, 1980). Further south along the border with India, the dioritic basement was reported, encountered at 253 m depth in a drill hole (Ploethner, 1992).

Based on the geoelectrical resistivity survey, this basement complex, having high resistivity of 50 to 150 Ωm, was interpreted to be a deep fissured sandstone aquifer, bearing fresh water, by Schildknecht & others (1991) under the WAPDA-BGR Groundwater Exploration Project. On the

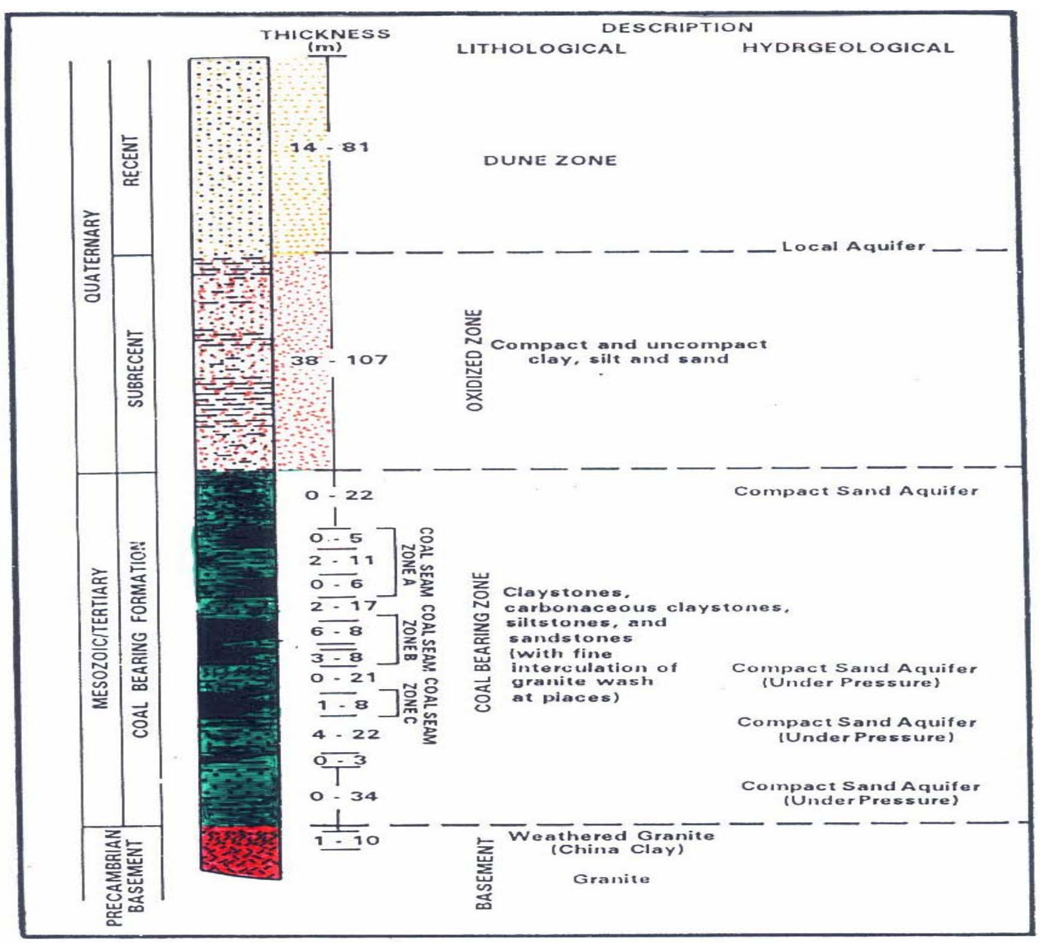


Figure 7: Generalized lithological column representing the stratigraphic units encountered in holes drilled for coal exploration and also showing hydrogeological conditions in the Thar Desert (modified after JTB, 1994).

other hand, results of the deep vertical electric soundings (VES) indicate two trends of apparent resistivity values at different sites in the area south of Chachro (Zaigham & Ahmed, 2000). One trend indicates massive granitic basement and the other trend reveals the presence of layered Archean metasediments.

HYDRO-GEOLOGICAL CONDITIONS

There is no surface perennial water available in the Thar. Based on the results of dug-wells' inventories, covering about 8500 km^2 area between Gadro and Virawah in the eastern Thar along the Pakistan border, it is observed that the perched aquifers are hosted in friable sandy/silty layers sealed underneath by clay-layers (Ploethner, 1992). The depth to water-table varies from 5 to 15 m in and around Gadro area, 30 m to 45 m in Chachro area and goes even deeper in areas west of Chachro. Their thickness and lateral extent are limited. The majority of the dug wells have a depth to groundwater ranging from 20 to 80 m (Figure-8). In general, the quality of groundwater ranges from saline to brackish.

Based on the analysis of integrated groundwater data, collected during GSP-USGS-JTB-USAID Coal Exploration Programme, the following facts have been interpreted (Figure-7):

- In general, the perched aquifers occur at the interface of dune-sand zone and subrecent sediments (Oxidized zone) with fluctuating yield controlled by the annual rainfall cycles.
- The subrecent sediments of Oxidized Zone hold saline aquifers with very limited yield. Practically, this unit is considered non-water bearing.
- The coal-bearing sedimentary sequence hosts a number of confined aquifers under artesian pressure, with significant yield and acceptable quality [range: 4000 - 5000 µS/cm].
- The upper part contains generally thin layers of aquifers, but the lower part contains significantly thick and brackish aquifers.
- Analyses of the geophysical logs show that coal-bearing formations generally contain a significant sandstone aquifer above the Coal Seam Zone-A, with thickness ranging from zero to 22 m. Occasional sandstone aquifer is also reported between Coal Seam Zone B and C, with thickness ranging from zero to 21 m. A large sandstone aquifer is encountered below the Coal Seam Zone C, with thickness ranging from zero to 34 m. All aquifers in the coal formation are under pressure (Figure-7).
- Electrical conductivity values of the ground water associated with deep aquifers are in acceptable range, between 4,000 and 5,000 µS/cm. The measurements of the field-conductivity indicated brackish quality of these aquifers.
- Results of pumping-test indicate nearly

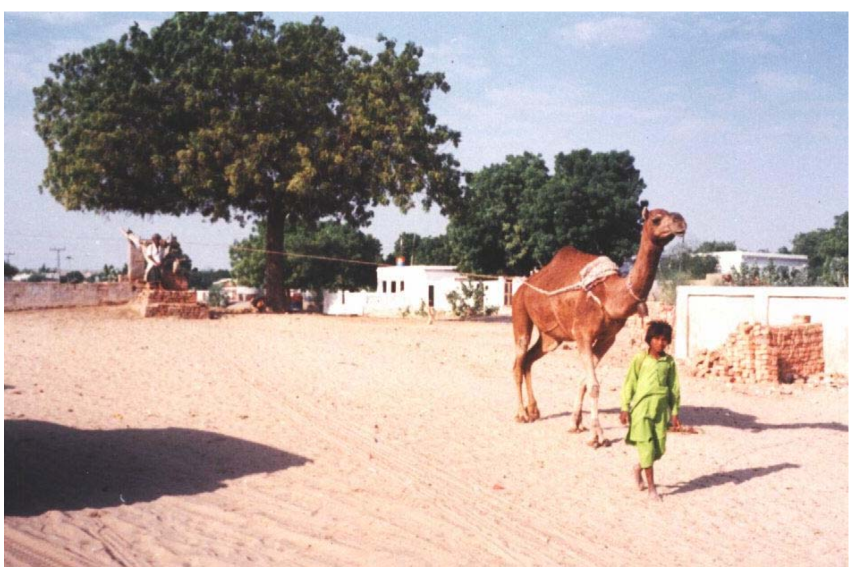


Figure 8: People of Thar Desert use camel-power to take out water from relatively deeper dug-wells.

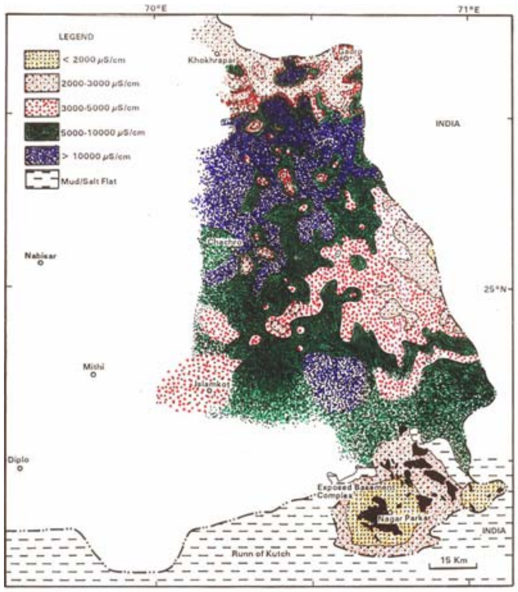


Figure 9: Distribution of electrical conductivity of groundwater in the Thar Desert. Source of data: JTB, 1994; Ploethner, 1992; GSP, 1962)

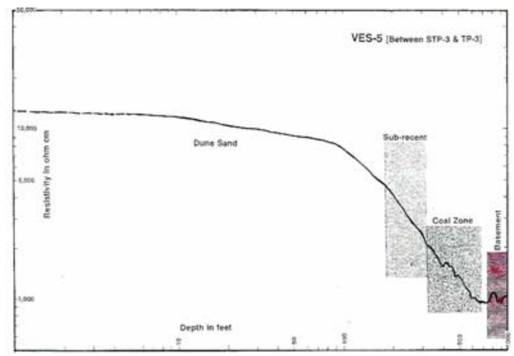


Figure 10: Deep vertical electric sounding shows layered basement indicating groundwater potential in basement units.

immediate recharge of the aquifers. It has also been found that, after a longer pumping, the quality of deep ground water aquifers improves.

GROUNDWATER QUALITY

In Thar Desert, the ground water tapped by 83 % of dug wells has an electrical conductivity (EC) value ranging from 2000 µS/cm to more than 10,000 µS/cm. Thus, under normal standard, such quality of water is unfit for human consumption, but the water with EC of 5,000 µS/cm is considered drinkable under duress for the arid region. As such, 48 % of the water in the dug wells may be considered fit for human consumption in the area.

Figure-9 shows the distribution of electrical conductivity (EC) of groundwater in the Thar Desert. The distribution-pattern indicates three prominent good-quality groundwater zones. In the northern part, EC values less than 3000 µS/cm prevail, exclusively associated with the perched aquifers encountered in the shallow dug-wells. The perched aquifers contain mostly fairly good to brackish groundwater, but show extreme lateral variation in ground-water salinity over small distances.

The area between Gadro/Khokrapar and Chachro is dominated by EC values greater than 10,000 µS/cm, indicating poor groundwater prospects. In the central part, south and southeast of Chachro extending from Pakistan-India border to Islamkot, EC values between 2,000 and 5,000 µS/cm are found, particularly in the relatively deeper aquifer(s). The hydrogeological data indicate good groundwater prospects, particularly associated with deep-seated sedimentary aquifers. Another good prospective area is reflected by the EC values ranging from less than 2,000 to 3,000 µS/cm, in and around Nagarparkar, where the basement units are exposed. In the area between the central zone and Nagarparkar, EC measurements of the dug well water (values mainly range from 5,000 to 10,000 µS/cm) indicate brackish to saline water- quality. In this area, deep sedimentary aquifers have not been explored in detail.

Occurrences of better groundwater (EC: < 2000 µs/cm) are associated only with the exposed granite unit in Nagarparkar area (Fig.9), where basement is exposed otherwise no good-quality groundwater is so far exploited, associated with the basement at deeper depths throughout the Thar region. At places, vertical electric soundings have indicated good prospects for the good quality groundwater associated with the basement complex (Figure-10).

REGIONAL GRADIENTS

Basic tendency of water is to flow to the lowest topography on the down slope. In view of this physical property, the regional gradient-maps of surface and major subsurface interfaces have been generated to study the surface and the subsurface water-movements in the Thar Desert. For this study, the spot elevations and the collar elevation of the drill holes have been used. The drill holes are located more or less on uniform grid, covering almost the whole Thar Desert. Moreover, all the holes were drilled in the interdunal valleys.

Surface Gradient

Figure-11 presents the smoothened topographic map to illustrate the regional surface-gradients. Three surface-gradient trends are distinct across the Thar Desert. Originating from northeastern corner of the study area, one trend is towards west, approaching Nabisar-Umarkot area, and the other trend is towards south, approaching Islamkot area. There is a significant change in regional gradient striking in east-west direction along Mithi-Islamkot area. South of Mithi-Islamkot alignment, there is a west-trending gradient, starting probably from the western edge of the subsurface continuation of the Nagarparkar basement complex.

Gradient at Top of Oxidized Zone

Figure-12 shows depth-contours on top of the zone of subrecent sediment or the bottom of the dune zone. The trend of contours shows that the gradient-pattern is more or less similar to the surface-gradient trend. Thus, it is inferred that the depositional environments for the Oxidized Zone were initially similar to those under which the Dune Zone was deposited. In the southeast of Chachro, there is a significant subsurface mound-like body, indicating a possible differential erosional feature. Moreover, there is also a marked change of south-trending gradient in Mithi-Islamkot area. South of this area, the main gradient is towards the west, as in the case of the surface-gradient trend.

Compaction of the deposited sediments and the surface oxidization seem to be due to the prevailing last glaciation, earlier to about 22,000 years BP. Perched aquifers occur at the bottom-part of the dune-zone on the top of the Oxidized Zone consisting of mainly clays as underneath seal.

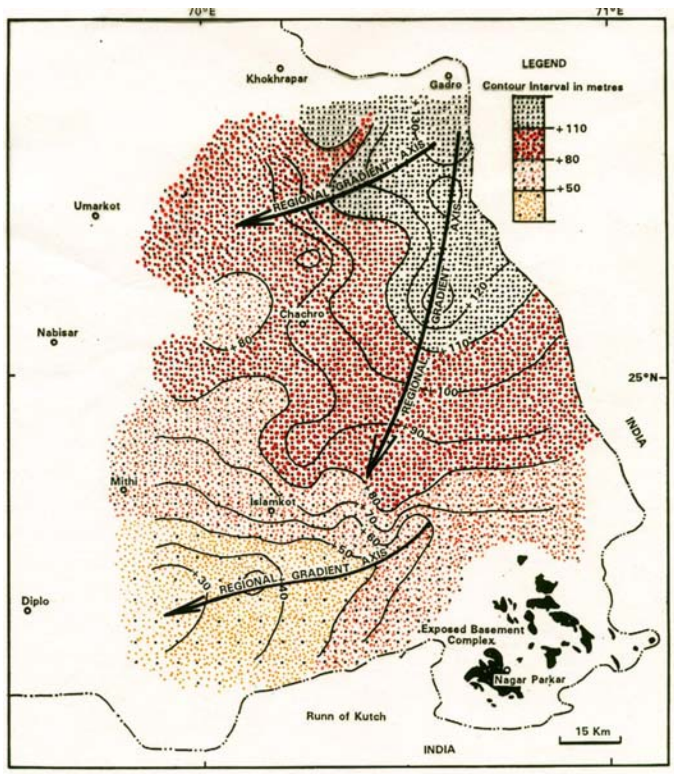


Figure 11: Map showing smoothened topography of the Thar Desert illustrating regional gradient trends which control over-all movements of water-recharge conditions

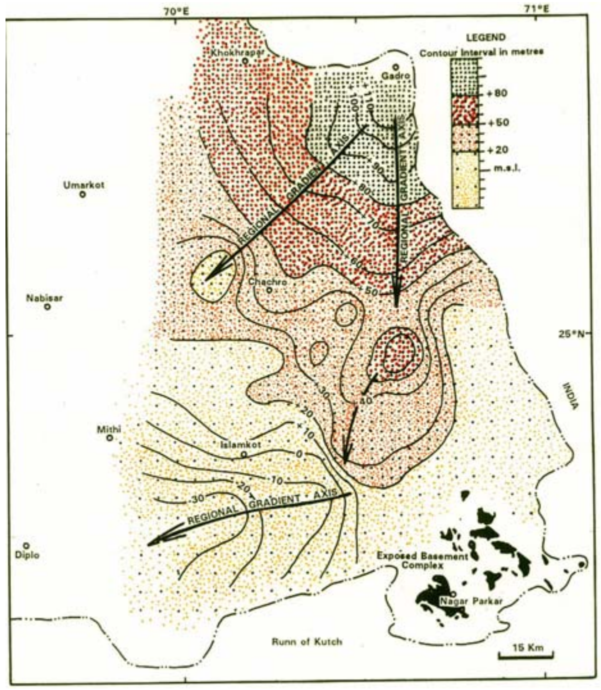


Figure 12: Subsurface configuration of top of the Oxidized Zone in Thar Desert. Arrows show major gradient trends.

Gradient at Top of Coal-Bearing Formation

Configuration of the top of the consolidated sedimentary sequence, underneath the subrecent Oxidized Zone, shows a different gradient trend (Figure-13). It is almost trending NNW, perpendicular to the trends of the overlying zones of unconsolidated sediments. It is interesting to note that between Islamkot and Chachro there is a ridge-like structure, striking in regional gradient direction bounded by elongated depressions on either side. To the east, both the depressions

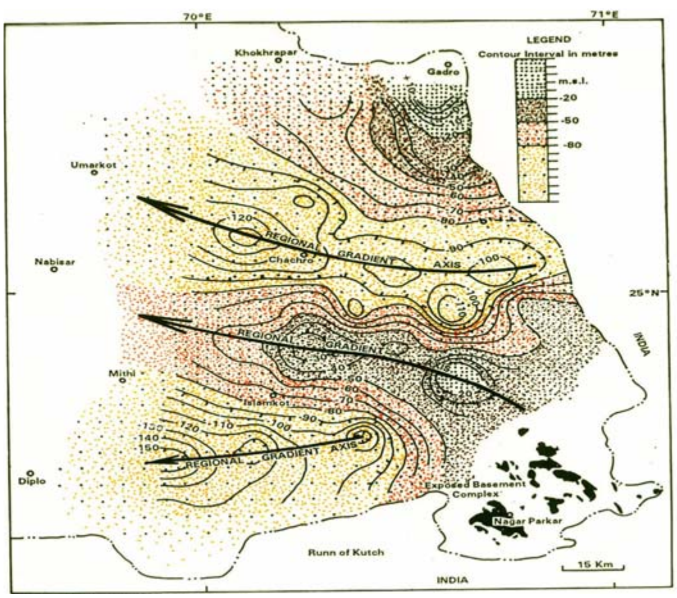


Figure 13: Subsurface configuration of top of coal-bearing formation beneath the Subrecent Oxidized Zone in the Thar Desert.

appear to terminate, possibly against the subsurface continuation of the basement complex, but westward they are broader and continuous. Based on the available data, two possible interpretations are proposed here:

- *Either*, the area between Islamkot and Chachro represents a horst block and the depressions on its northern and southern margins are the counter-graben blocks;
- *Or*, the depressions are the buried palaeo-channels representing deeper erosion of the coal-bearing formation, whereas the central part, between Islamkot and Chachro, represents the area where the formation was relatively less eroded.

Gradient of Thar Basement

Figure-14 shows the basement configuration interpreted from the seismic data, deep-resistivity data and drilling data (Zaigham and Ahmad, 2000; 1996; Fassett and Durrani, 1994). Depth contours show three distinct anomalous zones of curvatures. The first zone lies in the southeastern part of the map, i.e., southeast of Chachro, where the contours indicate gentle dipping with 0.7% gradient. Further southeast of 200-meters contour, the basement appears at shallower depth, i.e.,less than 200 meters. The pattern of shallow depth contours also indicates that the lateral extensions of geological formations in the northeast and in the southwest are bounded by relatively steeper gradients.

In the second zone, which lies to the northwest of Chachro, there is a sharp gradient of depth-contours trending northeast-southwest, indicating steep slope of the basement in northwest direction. In this zone, the basement gradient ranges from 4% (between 500 and 1000-meters (Contours) to 9.8% (between 1000 and 3000-meters contours).

The pattern of the basement depth-contours abruptly changes beyond contour of 3000-meters, which, in fact, is the third anomalous zone. The trend of the gradient beyond 3000-meters contour indicates a steep large-scale offset of the basement in the northwestern side. There are very steep slopes, with limited lateral extent, indicating irregular surface of the basement. The

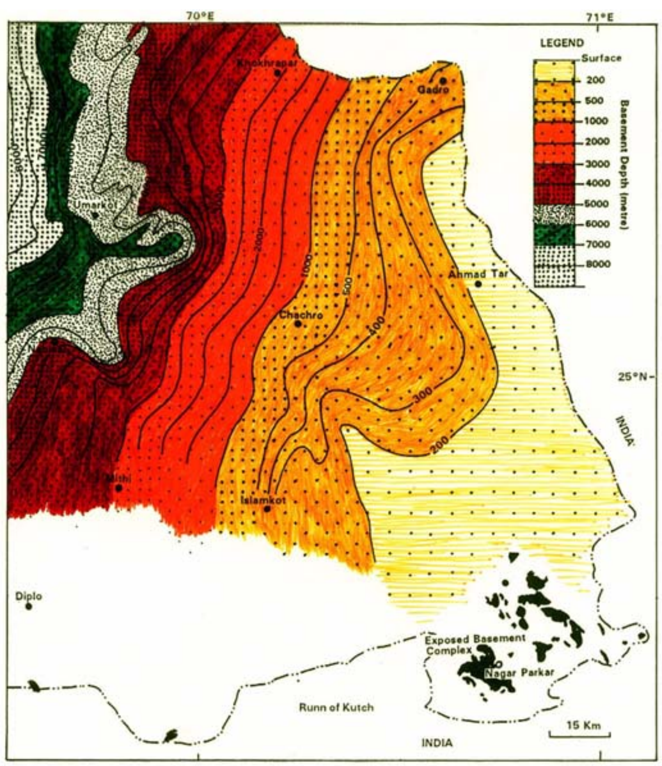


Figure 14: Thar Basement configuration analyzed from seismic, resistivity and drilling data.

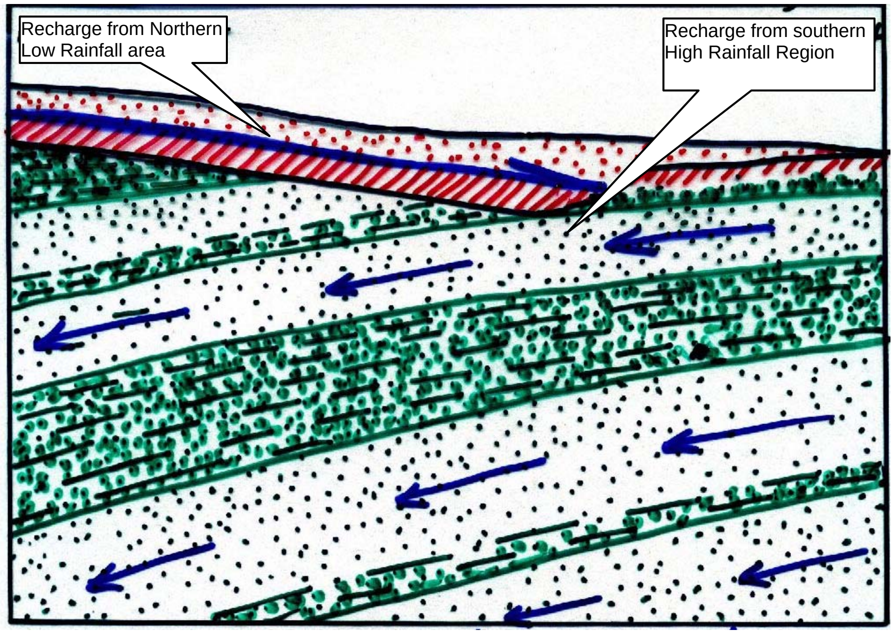


Figure 15: Schematic model shows the relationship between the regional gradients and the recharge conditions (groundwater flow) based on the rainfall conditions.

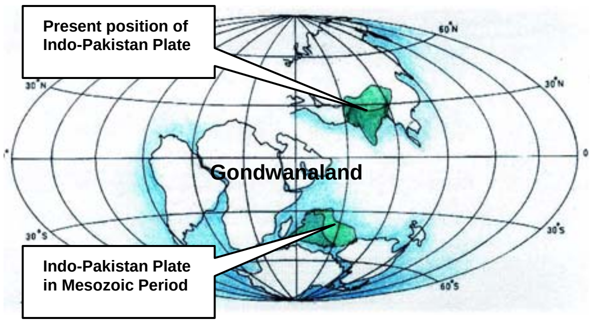
basement is deepening around Umarkot area continuously towards northwest, with an average gradient of 11.3%.

DISCUSSION

From the integrated surface and subsurface study, it is found that the regional gradients associated with the Dune Zone and the Oxidized Zone are from north to south, southwestward and westward. This study reveals that, regionally, the groundwater recharge to the unconsolidated sediments, i.e. the Dune Zone and the Oxidized Zone, is from the areas lying in the north of the Thar Desert (Figure-15). Figure-1 shows very arid areas in the north of the Thar Desert, where average rainfall is reported about 100 mm/yr or less. Moreover, in the northern part of the Thar Desert itself, the average rainfall is about 160-200 mm/yr with occasional drought cycles. The whole rainfall picture of the areas in the north of the Thar Desert and northern part of the Thar Desert itself indicates very poor recharge-conditions to the perched water aquifers throughout the area. That is why, any drought cycle affects the living activities of the Thar Desert immediately and adversely.

On the other hand, the regional deep-seated gradients associated with the sedimentary sequences and the basement are almost in the opposite directions to that of surface gradient and the subsurface gradient on the top of the Oxidized Zone. Moreover, the average rainfall conditions are also reverse, as compared to the northern and northwestern areas. In the southeast, i.e. the Nagarparkar area (where the basement rocks are only exposed) the average rainfall is about 360 mm/yr. Further southeast, the rainfall goes up to 1000 mm/yr in Udaipur area of India across the border. The higher precipitation in the southeastern Thar, i.e. Nagarparkar and surrounding areas, provides good recharge conditions to the confined aquifers of the consolidated sequences and the basement.

Moreover, aquifers associated with the Nagarparkar basement complex may also provide good- quality connate water. Palaeomagnetic study (Klootwijk, 1979) indicates that the area had remained in the southern polar region at about latitude 40°S, covered with ice from time, to time as a part of the Gondwanaland during Paleozoic-Proterozoic time (Figure-16). During Paleozoic time, intracontinental rifting developed flexure basins and associated fault systems, with a number of fracture zones, due to the stretching of the upper crustal part of the Gondwanaland (Zaigham et. al, 2000). Such rift-basins and ice-covers created a number of sweet-water lakes, which might have served as the source of sweet water for the basement aquifers. Seismic study illustrates the presence of the deep-seated pre-Mesozoic fossil rift in the Thar Desert of Pakistan



Drifting of Indo-Pakistan

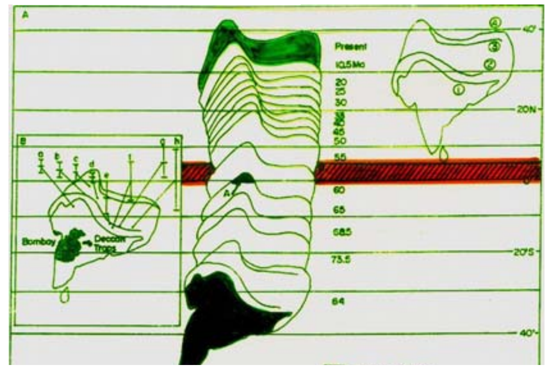


Figure 16: Left inset shows papaeo-Mesozoic position of Indo-Pakistan subcontinental plate comparing it with the present-day position. Inset on the right shows northward drifting of Indo-Pakistan plate from late-Mesozoic time to present-day.

(Figure-6). In addition, at places, the earth-resistivity soundings have also indicated good prospects for good-quality groundwater associated with the basement complex (Zaigham and Ahmed, 2000).

Based on exploitation of the deeper water resources associated with sedimentary sequences and the basement rock units, the better socio-economic development of Thar Desert could be possible. If due attention is paid to the results of the present investigations, significant sustainable agricultural targets could be achieved since already Nature has created environments to stabilize sanddunes, siltification in interdunal valleys, and significantly encouraging rainfall conditions.

CONCLUSIONS

1. The present study indicates remarkable groundwater potential in the Thar Desert. Three sources have been identified: the bottom of the Dune Zone, the coal-bearing sedimentary units, and the basement.

2. In general, the regional gradients of the surface and top of the subrecent zone are towards south and southwest. The aquifers at the bottom of the Dune Zone significantly vary in quality (Saline to brackish) as well as in their yield being dependent on rainfall in the northern areas, where the annual average is about 150 mm. The quality of water ranges from bad to marginal, but is usable under duress. These aquifers are the main source of water in the Thar at present.

3. The regional gradient of the tops of the coal-bearing sedimentary units and the basement are towards northwest. The rainfall conditions in the southeast are generally good; the annual average is 360 mm around Nagarparkar. Moreover, further southeast, it increases up to 1000 mm in the Udaipur area. The recharge condition of the aquifers associated with the coal-bearing sedimentary units and basement are excellent, as compared to that at the bottom of the Dune Zone. The quality of water found in coal-bearing sedimentary units is generally brackish whereas in the basement it is sweet.

4. In general, research-approach is lacking; in order to boost socio-economic development in Thar Desert, more detailed research studies are imperative for the formulation of a scientific systematic future strategy for exploration and development of deep water resources associated with sedimentary sequences and basement.

5. Due attention for groundwater-research activities can de-desertify the area, since Nature has already created conducive environments to stabilize dune sands, better siltification in valleys, and significantly encouraging rainfall conditions.

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