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# The Depletion of the Groundwater Resources in Wadi As-Safra, Saudi Arabia

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ABSTRACT. Unprecedented development in the Kingdom of Saudi Arabia gave rise to groundwater depletion problems in many arid regions. In order to avoid such an undesirable situation, a comprehensive investigation and assessment of groundwater resources should be carried out with utmost importance. Wadi As-Safra basin has been chosen as a pilot area for extensive study of groundwater potentiality. In the past, there were many small villages along this wadi, where the people used to work mainly in local agriculture. In fact, in the previous and current five-year plans, a great emphasis was given to the agricultural activities which can be achieved only by carefully presenting and exploiting the existing groundwater resources.

It has been found that the total available groundwater storage in the wadi is about $7.5 \times 10^6$ m$^3$.

## Introduction

Groundwater occurrence in the western part of Saudi Arabia is highly dependent on local functioning of the hydrological cycle. Rarity in the rainfall occurrences in this arid region requires preservation of every single drop of rainfall by any means. To this end, man-made depressions, sand and concrete dykes and diversion channels are formed on the surface so as to increase the surface retention and consequently groundwater recharge. On the other hand, high rate of evaporation and evapotranspiration cause groundwater storages to have direct losses. Hence, as a whole, preservation, exploration, exploitation, development and management of groundwater resources, especially in the wadi alluviums of arid region, play a vital role for the prosperity of local and regional activities.

The aim of this paper is to present a systematic approach for groundwater quantity and quality evaluations in arid regions of the Kingdom of Saudi Arabia. To this end, wadi As-Safra has been selected as a pilot area and has been studied in detail.

## Study Site

The wadi As-Safra catchment is located within the southern Hijaz Quadrangle, and it is an elongated area extending in the SW-NE direction. It lies between latitudes 23°30′-24°15′N and longitudes 38°30′-39°30′E, Fig. 1. The main portion of the wadi is located on the Arabian Shield of Precambrian rocks and in the downstream it enters the coastal plain of Bader Ḥunyan. The total catchment area is about 2660 $km^2$. At places, the wadi is very narrow such as from Mafrak to Bader Ḥunyan up to Al-Mosijid. However, it is considerably wider at Mosijid where another branch, Wadi Qaha, confluences with Wadi As-Safra. Average height of the upstream is about 500-600 meters above the mean sea level.

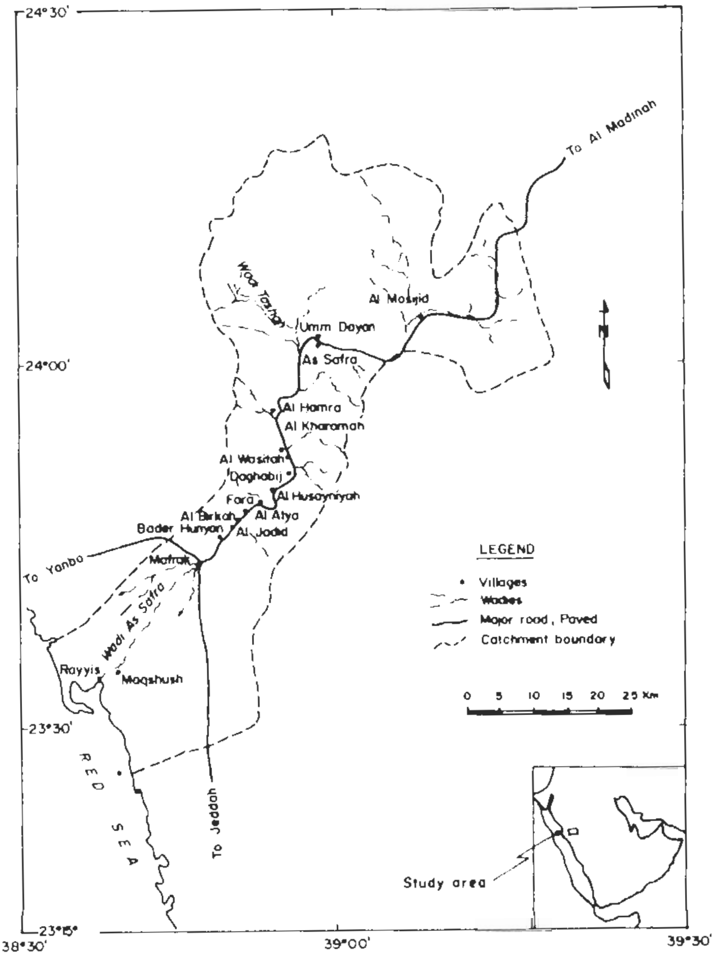



FIG. 1. Location map.

## Climate and Rainfall Pattern

The Arabian Peninsula lies between the two of the world's hottest regions, namely, Sahara in the African continent and the northwest Indian subcontinent which provide heat reservoirs, (Şen 1983a). The study area is characterized by its low rate of rainfall, high temperature and relative humidity. The average annual rainfall is about 60mm over the basin. The rainfall amount increases relatively towards the east due to the higher topography.

The climate of the study area seems to be a transition between Mansoon and Mediterranean types. It is modified by the Red Sea influence. In winter cold air originating from the Mediterranean and Atlantic Ocean cyclonic belts is guided and diverted by the Red Sea graben, (Al-Hajeri 1977). On the other hand, in summer the climate is continental with hot periods, and the air temperature reaches 43°C and monthly average is 36°C. The atmospheric humidity is always low, for instance annual average is 27% (El-Khatib 1980).

There exist three raingauge stations within the wadi itself, whereas other five are distributed close to the area. Monthly rainfall averages for stations within and around the wadi are shown in Fig. 2. They all have two peak values respectively during winter and summer periods. In the upstream, the maxima occur during the winter period, in fact, in January, indicating the Mediterranean sea effect. However, in the downstream at Bader Ḥunyan, the maximum rainfall is observed during the spring period, in April, which shows the dominance of Indian Ocean Mansoon effects. The driest period of the year in As-Safra area occurs from June to October. However, February-March period corresponds to transition from the Mediterranean to Mansoon type of effects. As a result of this, the rainfall amounts are relatively smaller. Figure 2 has the characteristics of rainfall pattern in an arid region, in that they are irregular and unpredictable. In addition, unpredictable occurrences of flash floods coincide with winter period.

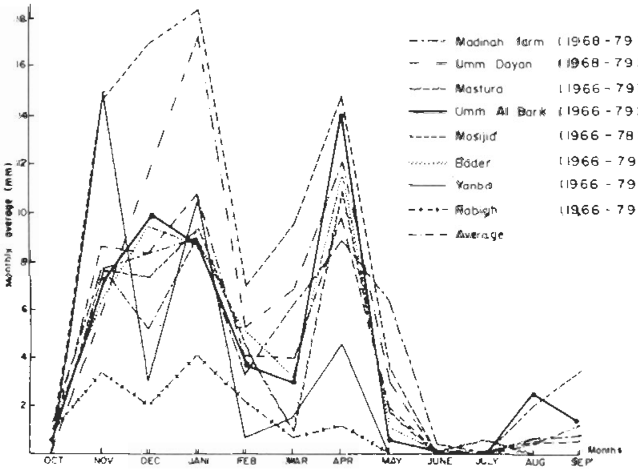



FIG. 2. Monthly rainfall averages.

Histograms of monthly rainfall are shown in Fig. 3 for these stations. Small intensity rainfalls are most frequent in each station. These histograms have exponential distribution characteristics which indicate that the monthly rainfall amounts are highly unpredictable and irregular. It is obvious from Fig. 3 that Mosijid has comparatively very rare occurrences of high rainfall amounts between 125-140mm.

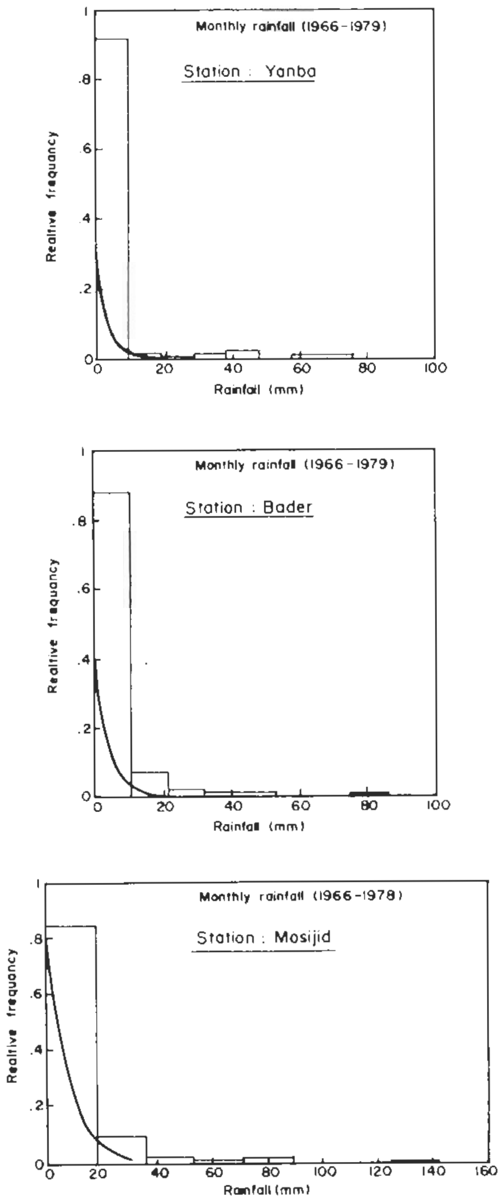
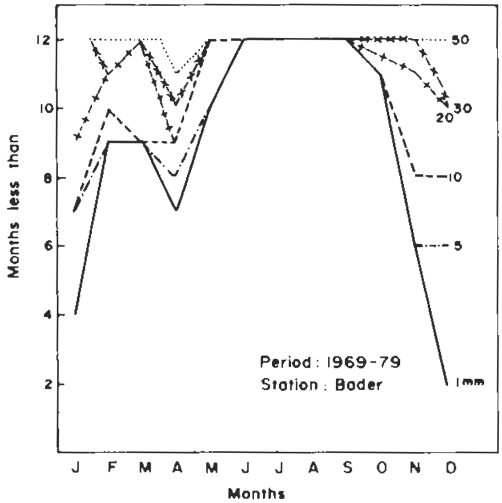



FIG. 3. Monthly rainfall histograms.

Comparison of these histograms leads to the conclusion that number of frequent rainfall occurrences with small amounts decreases towards the northeast in the study area. On the contrary, the number of rare rainfall occurrences with large amounts increases in the same direction. This is tantamount to saying that groundwater recharge is rich in the upper parts of the wadi. Figure 4 exhibits distribution of months that have rainfall amounts smaller than a given threshold value during the whole record period. Their comparison shows that for any given threshold value upstream rainfall station (Mosijid) has shorter duration of dry periods.



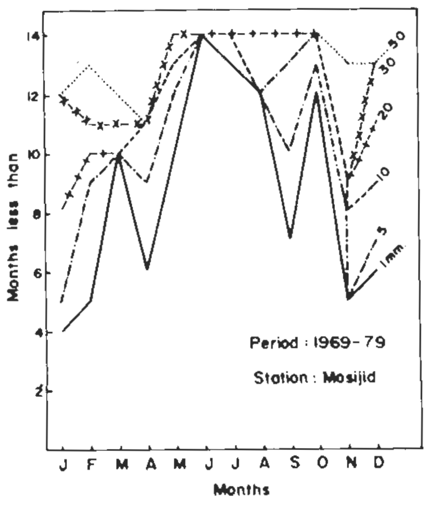




FIG. 4. Monthly rainfall distribution.

Due to rough terrain, especially in the middle and upstream of the area, isohyetal method has been applied for constructing areal rainfall distribution map. All of the eight raingauge stations are used in this procedure. The result is shown in Fig. 5 for 1970-1979 period. It is clear that the maximum rainfall occurs at Mosijid with annual average value of about 90mm. However, annual average rainfall is found to be 60mm. Potential evapotranspiration for the area is estimated by Thornthwait method. The annual potential evapotranspiration is about 1550mm, which is comparable with the values obtained for Saudi Arabia by Oberlander (1979).

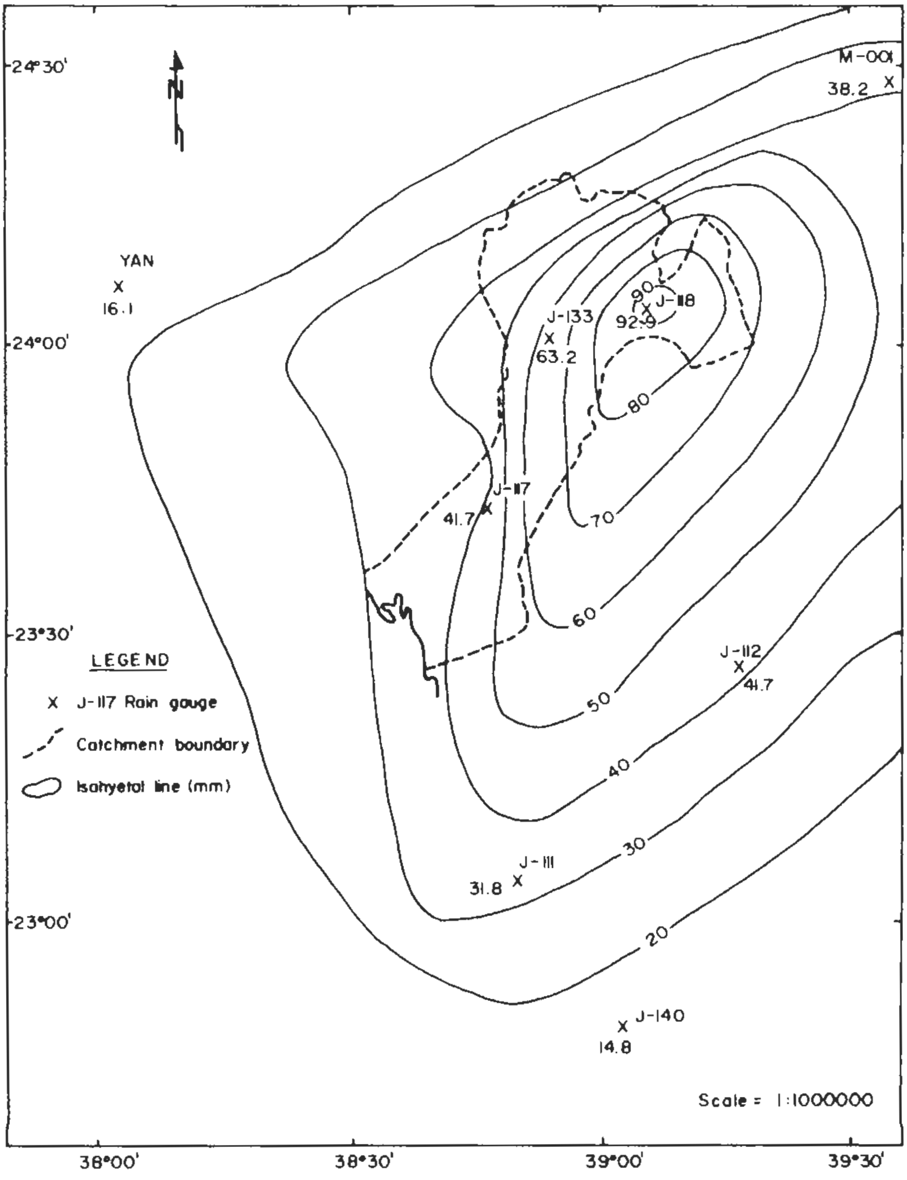



FIG. 5. Isohyetal map.

## Groundwater Storage

Quaternary deposits, weathered and fractured Precambrian rocks are major geological formations which include groundwater storage within the study area. Well inventory in the area indicates that almost all of the wells have large diameters. They are dug mostly around some major towns as well as agricultural lands. The average thickness of unconfined aquifer is about 9 meters. In order to determine the aquifer properties, such as the storage coefficient, ($S$), and the transmissivity, ($T$), three pumping tests have been carried out, one in each down, middle- and upstreams, (Fig. 6-8). In the evaluation of field data, three methods, namely, Papadopulos and Cooper (1967), Şen (1982), and Şen (1983b) are used. The results are presented in Table 1. Transmissivity values show that the down and upstreams are highly potential, whereas the middle-stream is moderate potential according to Gheorghe (1979) criterion.

TABLE 1. Aquifer characteristics.

| Location | Transmissivity ($m^2$/min) | Storativity | | |
|---|---|---|---|---|
| | | Papadopulos and Cooper (1967) | Barrier effect Şen (1982) | Volumetric Şen (1983*b*) |
| Upstream | $7.1 \times 10^{-1}$ | - | $1.0 \times 10^{-1}$ | $5.0 \times 10^{-1}$ |
| Middle-stream | $1.4 \times 10^{-1}$ | $0.6 \times 10^{-2}$ | – | $1.0 \times 10^{-2}$ |
| Downstream | $8.1 \times 10^{-1}$ | $1.0 \times 10^{-2}$ | – | $3.0 \times 10^{-2}$ |

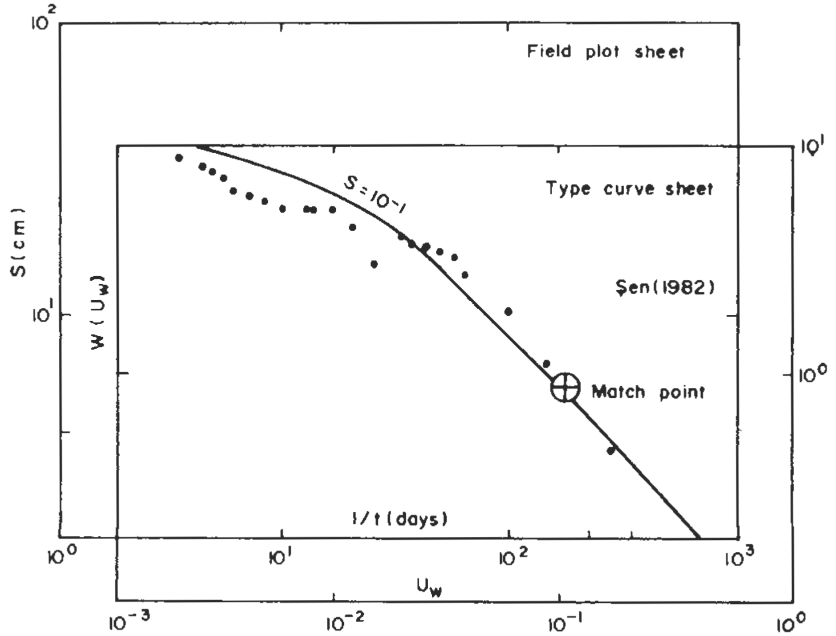



FIG. 6. Pumping test in upstream.

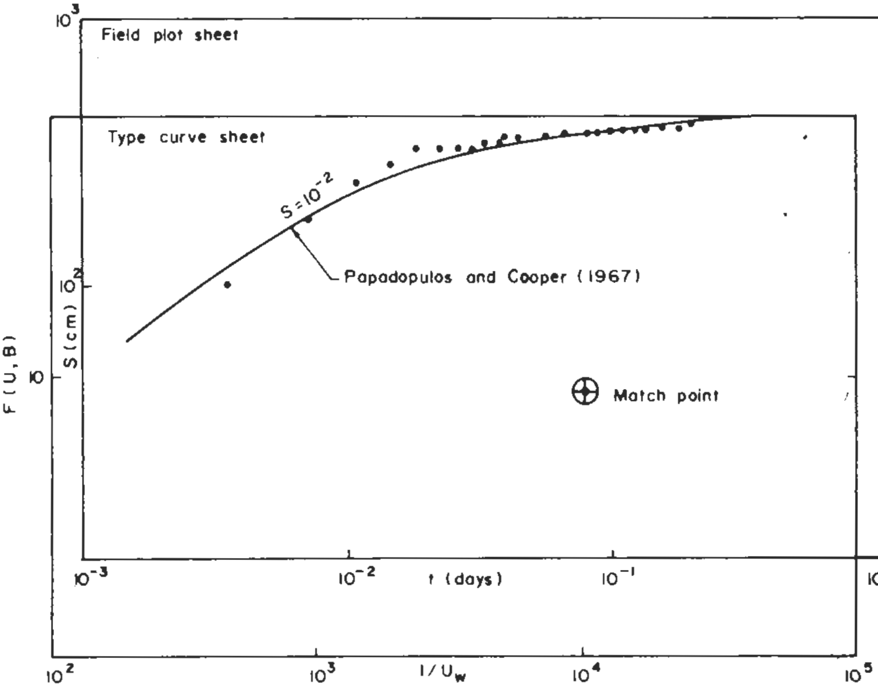



Fig. 7. Pumping test in middle-stream.

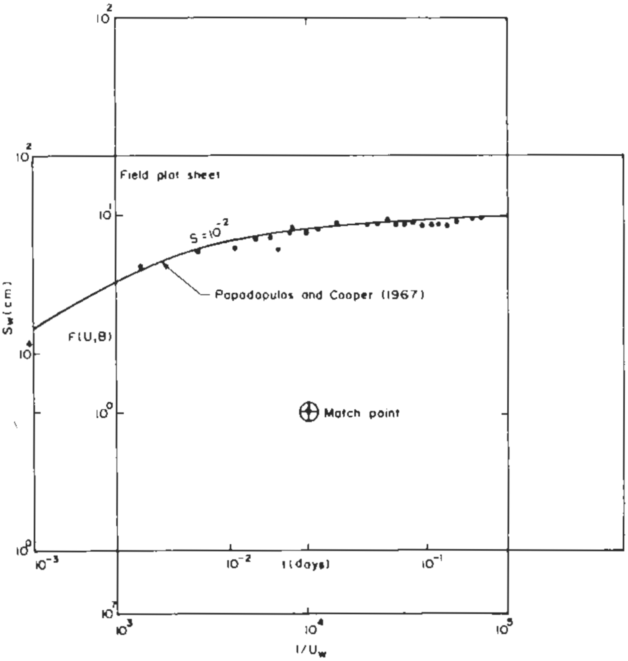



Fig. 8. Pumping test in downstream.

Groundwater potential of the area includes two major calculations. These are the available water storage in the saturation zone and groundwater movement rates at different cross-sections. According to the locations of important towns along the Wadi As-Safra, the area has been divided into 6 subareas as shown in Fig. 9. Since the quality of water is not good, and there are no towns or agricultural activities, the groundwater potential of downstream subarea 6 is not considered herein. The available groundwater storage in each subarea can be calculated from

$$V = A.D.S.$$

where $V$ is the groundwater volume in $m^3$, $A$ is the water table area in $m^2$, $D$ is the thickness of saturated zone in m, and $S$ is the storage coefficient. It is indeed not reliable to determine the storage coefficient from the pumping test as explained by Papadopulos and Cooper (1967) due to difficulties in finding the observation wells in the actual field work. However, herein, the volumetric approach has been used. This approach is suitable for the unconfined aquifers and especially without any observation well. On the other hand, the natural flow of groundwater that passes through downstream cross section of each subarea can be calculated as:

$$Q = TWI \qquad (1)$$

in which $Q$ is the discharge in $m^3$/min, $T$ is the transmissivity in $m^2$/min, $W$ is the cross section width in m, and finally $I$ is the hydraulic gradient.

The results of these calculations are shown in Table 2. The total available groundwater storage in the area is about $7.5 \times 10^6$ $m^3$. The last column in Table 2 indicates the natural flow from one subarea to the following one. The decrease from subarea 2 to 4 is due to the decrease both in the width and the depth of saturated zone in the cross section as well as the surface area.

TABLE 2. Water potential.

| Subarea | Mean aquifer thickness (m) | Surface area $\times 10^6 (m^2)$ | Saturated volume $\times 10^6 (m^3)$ | Available water storage $\times 10^6 (m^3)$ | Natural flow ($m^2$/min) |
|---|---|---|---|---|---|
| 1 | 4.0 | 35.0 | 140.0 | 1.1 | 8.3 |
| 2 | 5.0 | 40.0 | 200.0 | 1.6 | 8.3 |
| 3 | 10.7 | 17.2 | 184.0 | 1.5 | – |
| 4 | 10.8 | 16.6 | 179.3 | 1.4 | 0.5 |
| 5 | 9.9 | 22.2 | 219.8 | 1.8 | 1.7 |

**Groundwater Quality**

As the water is very necessary in our life for any use, its quality should be at a required standard. The groundwater contains dissolved salts in the form of solutions which may control its quality at any place and time. The factors can be explained as the source of water, its contact with various rocks and soils as well as time of precipitation and discharge in addition to the environmental conditions.

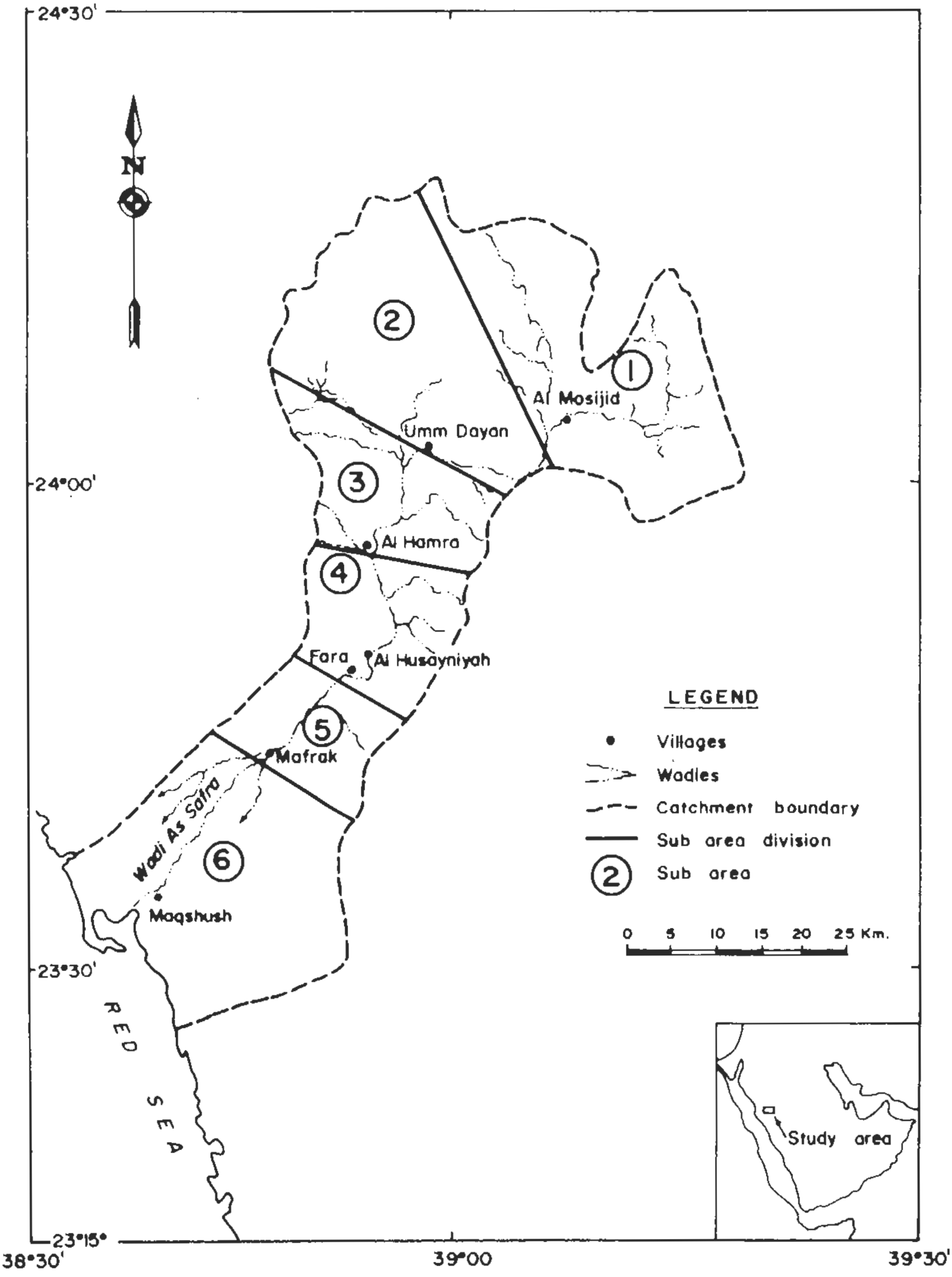



FIG. 9. Water potential subareas.

In Wadi As-Safra area some people work in agriculture and they need water for domestic, irrigation or agriculture uses. So it is necessary to make quality studies, in order to know the extent of water that can be used in this area. In all, 30 water samples were taken from different representative location of wells along the wadi and the Electrical Conductivity (EC) was also measured for all the inventoried wells in the area.

The chemical analyses were done for those collected samples to determine the major cations which are $Ca^{++}$, $Mg^{++}$, $Na^{+}$ and $K^{+}$ and also major anions such as $SO_4^{--}$, $Cl^{-}$ and $HCO_3^{-}$. The analysis was carried out by the flame photometer Model 510 and titration methods. The results are shown in Table 3.

TABLE 3. Chemical analysis results.

| Sample No. | $Mg^{++}$ epm | Na epm | $K^{+}$ epm | $Ca^{++}$ epm | Total Cations epm | $SO_4$ epm | Cl epm | $HCO_3$ epm | Total anions epm | SAR |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Downstream | | | | | |
| 1 | 9.4 | 29.2 | 0.2 | 15.6 | 54.4 | 18.0 | 32.7 | 3.2 | 53.9 | 8.2 |
| 2 | 9.6 | 27.9 | 0.3 | 18.0 | 55.8 | 8.5 | 32.9 | 2.4 | 53.8 | 2.0 |
| 3 | 12.2 | 40.2 | 0.3 | 22.4 | 75.1 | 25.6 | 47.5 | 3.6 | 76.7 | 9.7 |
| 4 | 10.1 | 33.9 | 0.2 | 17.9 | 62.1 | 21.1 | 36.6 | 3.2 | 60.9 | 9.1 |
| 5 | 5.9 | 21.1 | 0.2 | 8.5 | 35.7 | 10.2 | 20.4 | 3.1 | 33.7 | 7.9 |
| 6 | 13.2 | 43.5 | 0.3 | 25.8 | 82.8 | 27.4 | 49.3 | 4.7 | 81.4 | 9.9 |
| 7 | 10.2 | 30.0 | 0.2 | 15.6 | 56.0 | 19.6 | 32.4 | 4.0 | 56.0 | 8.4 |
| 8 | 11.2 | 30.7 | 0.2 | 21.6 | 63.7 | 21.2 | 35.2 | 4.3 | 60.7 | 7.6 |
| 9 | 8.0 | 27.2 | 0.2 | 17.0 | 52.4 | 17.4 | 28.7 | 4.1 | 50.2 | 7.7 |
| 10 | 11.3 | 25.8 | 0.2 | 24.5 | 61.8 | 19.2 | 35.94 | 3.2 | 58.34 | 6.1 |
| | | | | | Middle-stream | | | | | |
| 11 | 5.4 | 29.9 | 0.2 | 36.8 | 72.3 | 15.3 | 54.3 | 2.0 | 71.6 | 6.5 |
| 12 | 6.4 | 16.7 | 0.2 | 12.0 | 35.3 | 11.5 | 18.3 | 4.2 | 34.0 | 5.5 |
| 13 | 6.9 | 26.7 | 0.2 | 15.9 | 49.7 | 16.7 | 26.1 | 5.2 | 48.0 | 7.9 |
| 14 | 5.0 | 18.5 | 0.1 | 11.2 | 34.8 | 10.3 | 16.4 | 6.8 | 33.5 | 6.5 |
| 15 | 3.7 | 10.9 | 0.1 | 6.1 | 20.8 | 5.8 | 9.4 | 4.7 | 19.9 | 4.9 |
| 16 | 4.1 | 8.7 | 0.1 | 4.2 | 17.1 | 4.9 | 7.0 | 3.5 | 15.4 | 4.3 |
| 17 | 3.8 | 12.6 | 0.1 | 9.4 | 25.9 | 8.3 | 12.2 | 5.2 | 25.7 | 4.9 |
| 18 | 3.2 | 8.5 | 0.1 | 4.8 | 16.6 | 4.2 | 6.6 | 3.7 | 14.5 | 4.2 |
| 19 | 4.0 | 7.6 | 0.1 | 3.8 | 15.5 | 3.7 | 6.8 | 3.5 | 14.0 | 3.9 |
| 20 | 1.6 | 7.4 | 0.1 | 5.0 | 14.1 | 3.6 | 6.1 | 3.7 | 13.4 | 4.1 |
| | | | | | Upstream | | | | | |
| 21 | 6.9 | 28.3 | 0.1 | 13.4 | 48.7 | 16.4 | 26.3 | 2.9 | 45.6 | 8.9 |
| 22 | 4.0 | 15.2 | 0.1 | 8.0 | 27.3 | 8.9 | 13.2 | 3.2 | 25.3 | 6.2 |
| 23 | 0.9 | 1.3 | 0.2 | 2.0 | 4.4 | 0.9 | 1.3 | 2.3 | 4.5 | 1.1 |
| 24 | 2.3 | 17.4 | 0.1 | 8.6 | 28.4 | 9.8 | 14.6 | 3.3 | 27.7 | 7.5 |
| 25 | 0.7 | 3.0 | 0.1 | 5.2 | 8.9 | 0.9 | 2.4 | 3.8 | 7.1 | 1.8 |
| 26 | 5.2 | 9.6 | 0.2 | 17.4 | 32.4 | 11.1 | 16.8 | 3.5 | 31.4 | 2.9 |
| 27 | 5.8 | 7.0 | 0.1 | 5.0 | 17.9 | 5.1 | 7.5 | 2.6 | 15.2 | 3.0 |

TABLE 3. (Contd)

| Sample No. | $Mg^{++}$ epm | $Na^{+}$ epm | $K^{+}$ epm | $Ca^{++}$ epm | Total Cations epm | $SO_4$ epm | Cl epm | $HCO_3^-$ epm | Total anions epm | SAR |
|---|---|---|---|---|---|---|---|---|---|---|
| 28 | 0.7 | 1.7 | 0.1 | 4.2 | 6.7 | 0.9 | 2.3 | 3.6 | 6.8 | 1.1 |
| 29 | 3.0 | 6.1 | 0.1 | 4.4 | 13.6 | 2.2 | 4.2 | 3.8 | 10.2 | 3.2 |
| 30 | 2.6 | 7.6 | 0.1 | 3.4 | 13.7 | 3.4 | 7.8 | 2.3 | 13.5 | 4.4 |

These results can be interpreted in many ways. The total dissolved solids (TDS) concentrations in the downstream are in the range from 2150 ppm to 4700 ppm. Its range in the middle-stream varies between 925 ppm to 430 ppm, whereas in the upstream from 480-2900 ppm. According to the classification of water, which is based on the total concentration of dissolved solids by Davis and De Wiest (1966), it can be noticed that in the upstream of the Wadi As-Safra the quality of waters tends to be fresh to brackish. However, in the middle-stream, it becomes more brackish with few wells being fresh. These wells are located at Al-Hamra village where the necessary water for drinking purposes is transported to the surrounding areas by water tankers. In addition, as expected, the water in the downstream is completely brackish.

Chemical analyses show that $Ca^{++}$ and $Na^{+}$ have more concentration than other cations. Especially, $K^{+}$ is the lowest in its concentration. The reason for having $Ca^{++}$ in large concentrations is because of the surrounding igneous rocks which have been metamorphosed at various locations along the wadi. Similar reasons are valid for $Na^{+}$. On the other hand, anion concentrations are much more than the cations. $Cl^{-}$ as the most existing anion indicates the saline nature of the groundwater. The chloride concentrations at the investigation wells are generally high, and it is decreasing from downstream towards upstream. The high concentration at very downstream may be due to possible sea water intrusion from the Red Sea. This increase of salt water in the downstream may also be due to two sources. First of all, high rate of evaporation and evapotranspiration causes salinity, and secondly the water coming from long distances accummulates in the downstream after solving different minerals during its journey. Bicarbonates in the upstream are more than those in the middle-stream and downstream. This is due to the relatively higher rainfall amounts in the up and middle-streams. Most of the wells which are located at the upstream of Wadi As-Safra contain calcium amounts which are somewhat bigger than other parts of the wadi.

In addition, the chemical analyses are presented graphically by trilinear diagram in Fig. 10. From this diagram, it is noticed that most of the waters have more than 70 percent of sulphate and chloride. On the other hand, it contains calcium and magnesium from 40-60 percent, while few samples, from locations at upstream, have less than 50 percent of sulphate and chloride. In addition, it is obvious, from this figure, that the most waters in the study area are either of non-carbonate alkali (primary salinity) type or there is no one cation-anion pair, which exceeds 50 percent according to Piper (1953). For these samples, which are non-carbonate alkali, the chemical properties are dominant by alkalies and strong acids. It is, therefore, expected that these waters are saline and possibly of brine type.

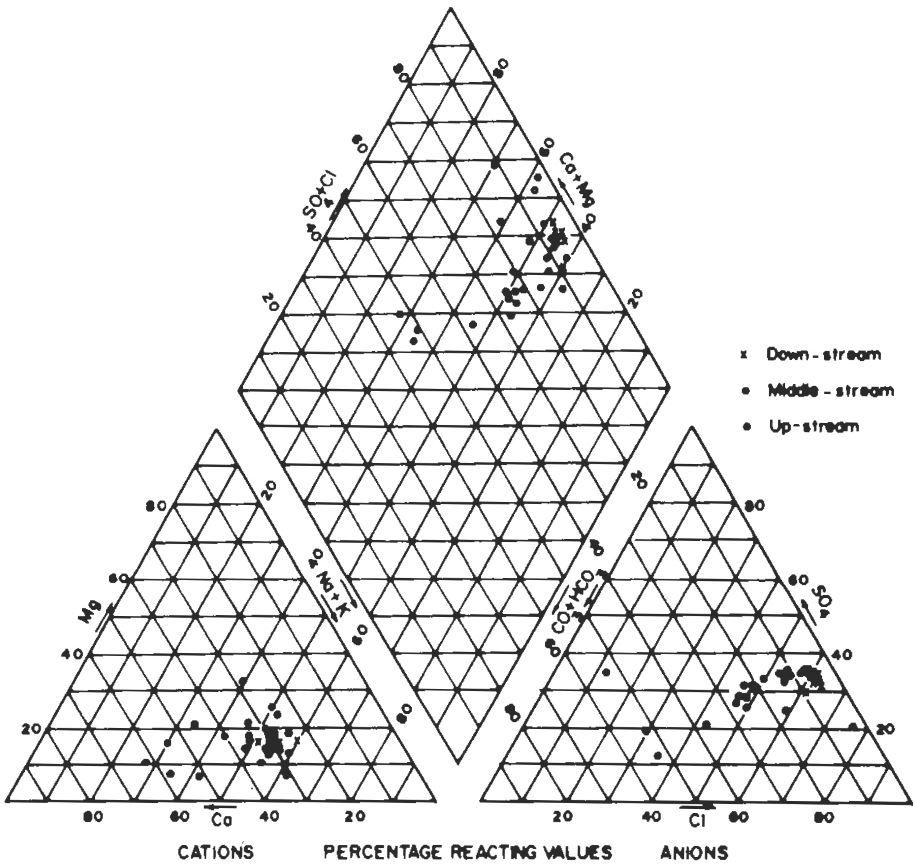



FIG. 10. Trilinear diagram.

The sodium-adsorption ratios (SAR), in Table 3, are all less than 10, which, as mentioned by Todd (1980), means that water in this area is excellent for irrigation purposes. It has been observed in the field that the main activity along the wadi is agriculture. The SAR increases from 1.1 in the upstream up to 9.9 towards downstream. By the same classification scheme, the groundwaters would be high to very high in salinity hazard for irrigation use. It should only be used on well-drained soils. In fact, using Fig. 7.9 in Todd (1980), most of the waters in Table 3 would be of medium to high sodium hazard because of their high salinity.

## Conclusion

The study in this paper indicates that Wadi As-Safra groundwater is suitable for agricultural activities. The number of existing wells in the wadi must not be increased. Otherwise, interference of depression cones may result in decrease of the safe yield. Especially, at Al-Hamra village, the pumping should be strictly controlled. If it is not, then the overpumping may give rise to the intrusion of relatively poor quality water from the surrounding areas.

Occasionally occurring floods must be regulated by small surface dykes to enrich the groundwater.

### *Acknowledgement*

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# نضـــوب مصـــادر الميـــاه في وادي الصفـــراء

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**مستخلص .** أدى التطور الملموس في المملكة العربية السعودية إلى نقص المياه الجوفية ، خاصة في المناطق الجافة . ولأجل اجتناب مثل هذه المشاكل غير المرغوب فيها ، لابد من دراسة شاملة وتقويم لمصادر المياه الجوفية . اختير حوض وادي الصفراء كمنطقة للبحث عن جهد المياه الجوفية والتي ستكون نتائجها مفيدة للمملكة . في الماضي كانت هناك قرى صغيرة تقع على امتداد الوادي يعتمد أهلها على الزراعة . في الخطة الرابعة والخامسة للدولة ، أُعطيت أهمية كبرى للزراعة ، والتي بلا شك تعتمد على استخدام مصادر المياه الجوفية . وفي هذه الدراسة ، حسب حجم المياه في منطقة الدراسة الذي قدر بسبعة ملايين ونصف ($٧,٥ \times ١٠^{٦}$) متر مكعب .