# MAJOR ION DISTRIBUTION IN KHOBAR AQUIFER, EASTERN SAUDI ARABIA

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الخلاصـة :

تعتبر خرائط توزيعات الأيونات الرئيسة من الخرائط الشائعة، التي وضُعت لمعظم خزانات المياه الجوفية في المملكة العربية السعودية. وعلى الرغم من تداول بيانات كيميائية المياه فإنَّ دقتها كانت دائماً عرضة إلى الأخطاء سواء من الأفراد أو من أجهزة القياس. ولّما وكان من الضروري عند تحليل وضع كيميائية المياه لأي خزان أن تكون البيانات متسقة. ومن أجل الحصول على بيانات متسقة من مجموعة بيانات التحليل الكيميائي لخزان (الخُبر) بالمنطقة الشرقية، فقد أُجريت ثلاث عمليات غربلة متتالية، وعُرضت حزمة البيانات الناتجة في شكل خرائط توضّـح توزيعات الأيونات والكاتيونات الرئيسة.

أظهرت الكاتيونات الرئيسة في خزان الخبر أنماط توزيع متماثلة. وعلى الرغم من أن هذه الكاتيونات تختلف في كمياتها تحت خط عرض ٢٠° ٣٠′ فإنَّ هذه الكميات تزيد ناحية المصب (ناحية الخليج العربي). أما الأنيونات فقد أظهرت اختلافاً أكبر في التوزيع. فبينما الكلوريديات لها نفس نمط التوزيع مع الصوديوم تقريباً، فإن تركيز البيكربونات عالياً في وادي المياه والهفوف. وأظهرت الكبريتات نطاقا من التركيز المنخفض (٢٦° ٣٠′ - ٢٧° ١٠٠′) محاطاً بمنطقتين من التركيز العالي.

وعموماً فإن خزان (الخُبر) يُظهر مياه من نوعية كبريتات / كبريتات - كلوريدات في المنبع ثم تتحول إلى مياه من نوعية كلوريدات في منطقة التصريف. ولكن على الرغم من هذا التعميم فإنه يوجد بعض الاختلافات والتي تتمثل في اختلاط أنواع المياه والتبادل الكاتيوني وكذلك بعض الذوبان المحدور لمعادن الكبريتات. بناءً على الرسوم الثلاثية فإنه يوجد خمس سحن لكيمياء المياه في خزان الخبر.

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## ABSTRACT

Major ion distribution maps are very common and they have been previously plotted for almost all of the Saudi Arabian aquifers. However, commonly, hydrochemical data is prone to instrumental and human errors. So it is very important to look for a consistent data set in analyzing an aquifer's hydrochemical setting. In order to get a consistent data out of a set for Khobar aquifer's chemical analyses data in Eastern Saudi Arabia, three successive screening steps were undertaken. The resultant data set is presented in isocons of major cations and anions.

Major cations in Khobar aquifer show similar patterns. Although they differ in their magnitudes below the latitude 20° 30′, all the three cations increase downstream (towards the Arabian Gulf). The distribution maps of the anions show big differences. Chloride has a more or less similar distribution pattern as sodium. Bicarbonate concentration is high in the Wadi Al Miyah and Hofuf areas; whereas sulfate shows a stream of low sulfate concentration (26° 30′ – 27° 00′) area bordered by two high sulfate areas.

Generally, Khobar aquifer water shows sulfate/sulfate–chloride type water in the upstream, evolving into chloride type water in the discharge area. There are interruptions of this general pattern which involve mixing of waters, cation exchange, and localized dissolution of, probably, disseminated sulfate minerals. Based on the trilinear plot, there are five hydrogeochemical facies in the Khobar aquifer.

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## 1. INTRODUCTION

Most of Saudi Arabian land is an arid desert; however, conspicuously, the aridity of the land is contrasted by the presence of vast aquifers of relatively good quality water. One such aquifer is the Khobar aquifer, which is present in the Eastern Saudi Arabia. The aquifer is dependable and relatively shallow [1]. Although the Khobar aquifer is no match for the underlying Umm Er Radhuma aquifer, its potentiality is undeniable. In short, Khobar aquifer, like many other aquifers in Saudi Arabia, is an asset for the future. For proper utilization of the aquifer's resources, a knowledge of its physical, chemical, and hydrogeochemical natures are absolutely indispensable. Understandably, most previous studies have focused on the hydraulic properties of the aquifer [2, 3] and less attention was given to the chemical and hydrogeochemical properties. Among the few researchers who have studied the chemical nature of the aquifer, Naimi [1] in a classic paper discussed the regional hydraulic characteristics and general water quality of the aquifer. Job [4] described, near Qatif, the mixing of lower-mineralized water from the south with a groundwater stream of highly mineralized waters from the north. Italconsult [5] in their final area IV report included hydrochemical distribution maps.

The evaluation and exploitation of an aquifer needs an integrated study. Among other things, the hydrochemical evaluation of an aquifer is essential. It involves basically the studies of areal distribution, ionic strength, evolutionary sequence pattern, and saturation indices of the major ions and their compounds. Major ion distribution maps for all the major aquifers of the Kingdom of Saudi Arabia were prepared by the Ministry of water and agriculture. So Khobar aquifer and all the other Eastern Saudi Arabian aquifers are not new to such maps, however, factors such as human fault and difference in the employed laboratory methods could introduce errors. It is nearly impossible to get an error free data set, so the aim should be how to get a consistent data set. In this study three successive screening steps were undertaken in order to come up with a consistent data set. In addition, the kriging gridding method was employed to reduce further introduction of errors.

The main objective of this study is to analyze the areal distribution of the major ions in Khobar aquifer in Eastern Saudi Arabia (Figure 1) and present them as *isocon* maps. The distribution maps presented here could serve as a base for further hydrochemical evaluations. It could serve also for generating a new random data set.

## 2. GEOLOGY AND HYDROGEOLOGY

The Eocene Dammam Formation in Eastern Saudi Arabia consists of five members (from top to bottom): Alat, Khobar, Alveolina Limestone, Midra, and Saila Shale members (Table 1). Alat and Khobar which are mainly carbonate members constitute aquifers of regional importance [6].

The Khobar Member is subdivided into two units, the lower and upper units. The lower unit consists of light gray to tan dolomitic marl, whereas the upper unit consists predominantly of limestone with subordinate marly layers [7]. The Member conformably overlies the Alveolina Limestone Member and bounded at the top by the Alat Member (Table 1). It crops out at the south–southwest of Dhahran and on the 'Dammam Dome' around Dhahran (Figure 1).

In the study area, the Khobar Member is karstfied and fissured, and provides water for domestic and agricultural purposes [8]. The aquifer is confined at the top by a lower marly unit of the Alat Member, and it is bounded at the bottom by a set of aquitards consisting of the lower three members of the Dammam Formation and the underlying Rus Formation. The aquifer's average depth below the ground level is 100 m with the maximum depth being 241 m at Ras Tanura and the minimum being zero near Dhahran [5, 9].

Khobar aquifer has a transmissivity of $7.06 \times 10^{-3} - 2.9 \times 10^{-1}$ m$^2$/s and storativity value of $1.3 \times 10^{-6} - 7.8 \times 10^{-3}$ [1, 3, 5]. The low storativity reflects the overall confined nature of the aquifer.

## 3. HYDROCHEMICAL DATA

The hydrogeochemical data used for this study were taken from the chemical analyses published by the Ministry of Agriculture and Water [10], and Groundwater Development Consultants [9]. The data consisted of 250 wells from MAW and 14 wells from GDC.

Three successive steps were undertaken in order to get a relatively reliable data set. First, out of hundreds of data points the samples with less than 5% charge balance error were selected [11]. Secondly, the outliers which were most likely resulted from an artifact were eliminated. Thirdly, the data were declustered by randomly picking up a representative sample from a specified grid (1.5 × 1.5 km). This method of screening has eliminated the scattered, isolated, and abnormally anomalous samples without destroying the overall variability of the data (Figure 2).

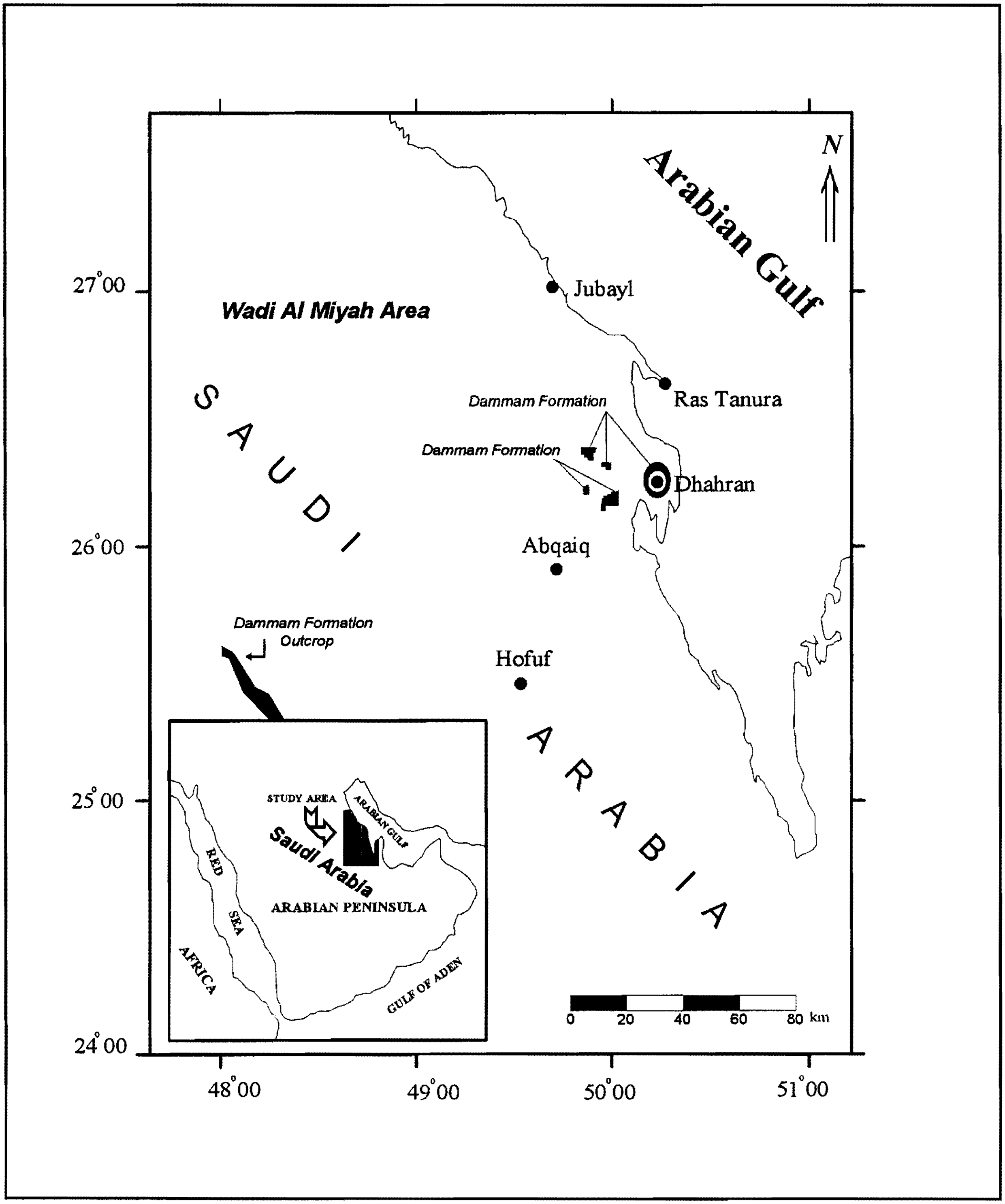


*Figure 1. Location Map of the Study Area.*

## 4. SPECIES DISTRIBUTION

The nature, the presence, and the strength of an ion in an aquifer depends mainly on the aquifer's overall setup. Such factors include the aquifer host-rock, the type of the aquifer, the overlying and underlying rock units, the water residence time and finally the aquifer's groundwater evolutionary sequence pattern. Major ions could enter in an aquifer system in different ways and commonly they are the ones that characterize the geochemistry on an aquifer.

**Table 1. Generalized Lithostratigraphic Succession of the Study Area (Modified After [6]).**

| AGE | FORMATION | MEMBER | ROCK UNIT | GENERALIZED LITHOLOGIC DESCRIPTION | THICKNESS (m) | HYDROGEOLOGIC UNIT |
|---|---|---|---|---|---|---|
| Quaternary | Surficial Deposits | | | Gravel, Sand, and Silt | 3 – 30 | Variable productivity depending on recharge |
| Tertiary / Neogene | Hofuf | | | Sandy marl and sandy limestone | 0 – 95 | Neogene Aquifer (Limited productivity) |
| Tertiary / Neogene | Dam | | | Sandy marls, silty clays, and skeletal limestones | 0 – 100 | Neogene Aquifer (Limited productivity) |
| Tertiary / Neogene | Hadrukh | | | Silty marls and shales, sandy limestones | 0 – 90 | Neogene Aquifer (Limited productivity) |
| Tertiary / Eocene | Dammam | Alat | Limestone | Skeletal detrital limestone | 0 – 110 | Aquifer |
| Tertiary / Eocene | Dammam | Alat | Marl | Dolomitic marls with limestone intercalations (orange color) | 0 – 35 | Aquitard |
| Tertiary / Eocene | Dammam | Khobar | | Skeletal, detrital, porous and friable limestones, dolomitic limestone | 0 – 75 | Aquifer |
| Tertiary / Eocene | Dammam | Alveolina Limestone | | Limestones interbedded with shales and marls | 0 – 20 | Aquitard |
| Tertiary / Eocene | Dammam | Midra and Saila shales | | Blue and dark grey, fissile shales with gypsiferous lenses | 0 – 20 | Aquitard |
| Tertiary / Eocene | Rus | | | Chalky limestones; anhydrite, dolomitic limestones & shales | 20 – 110 | Aquitard |
| Tertiary / Paleocene | Umm Er Radhuma | | | Partially dolomitized chalky limestones, detrital, skeletal limestone | Average 320 | Aquifer |
| Cretaceous | Aruma | | | Variocolored limestone, subordinate dolomite, and shale | | Poor Aquifer |

Bicarbonate in groundwater is normally derived from a soil zone and from dissolution of calcite and dolomite. The availability of calcite and dolomite, and their rapid dissolution in contact with $CO_2$ makes bicarbonate the dominant anion in recharge area. The most common sulfate-bearing minerals are gypsum and anhydrite which dissolve readily in the presence of water. Gypsum and anhydrite are more soluble than calcite and dolomite but less soluble than chloride-bearing

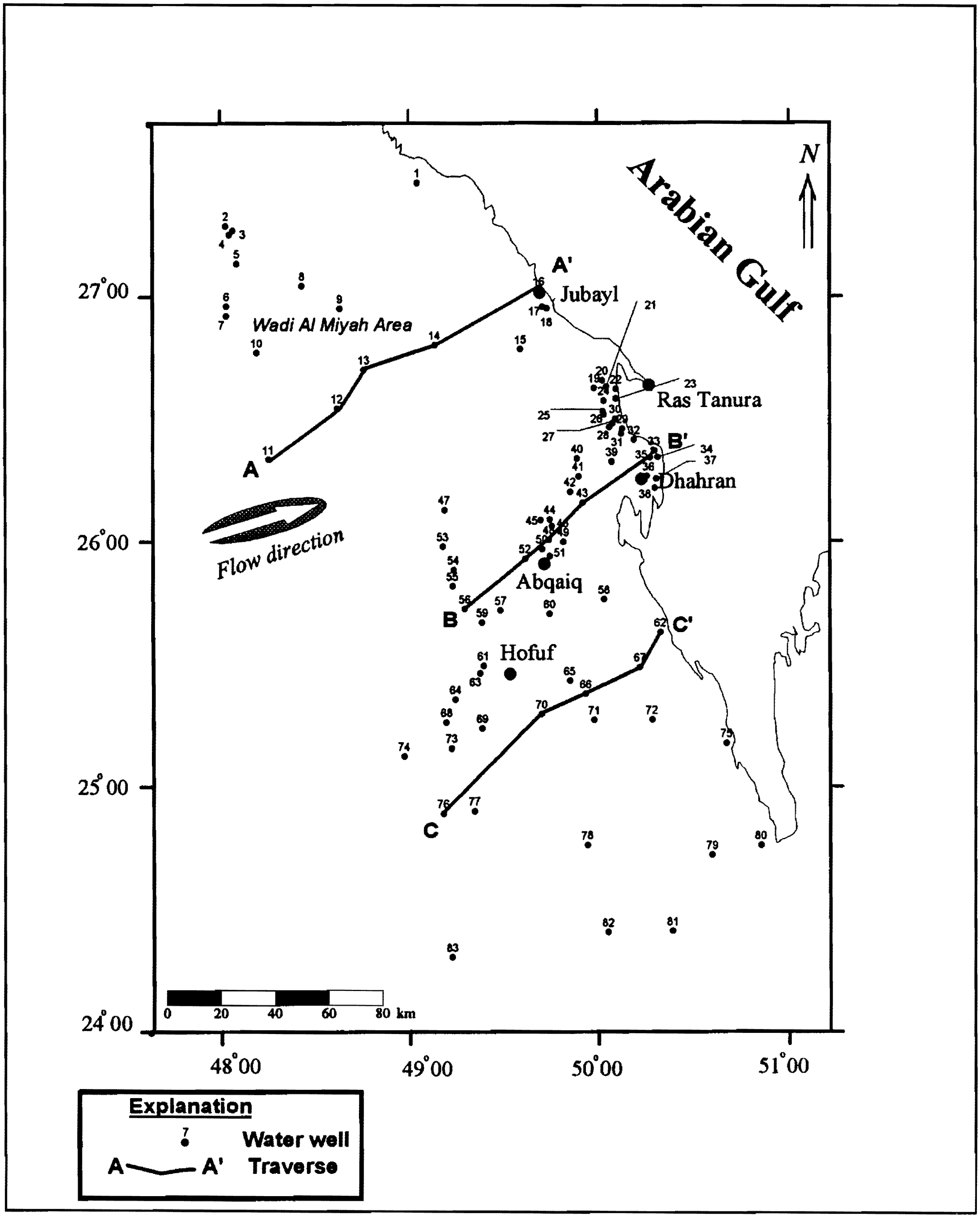


*Figure 2. Location Map of the Water Samples and Traverses.*

minerals. Chloride minerals of sedimentary origin dissolve readily in water. However, they are scarce in sedimentary basins. In clastic and carbonate rocks, chloride minerals occur in trace amounts, so chloride dissolution is mainly controlled by the process of diffusion. Generally, chloride is the predominant anion in deep groundwater and in discharge areas [11].

For the Khobar aquifer, the distributions of major ions are presented in *isocon* maps.

### 4.1. Calcium

There are two low calcium areas which are Wadi Al Miyah and Hofuf areas (Figure 3). In Wadi Al Miyah the calcium concentration is about 10 meq/l whereas calcium drops to less than 6 meq/l around Hofuf. The calcium concentration is

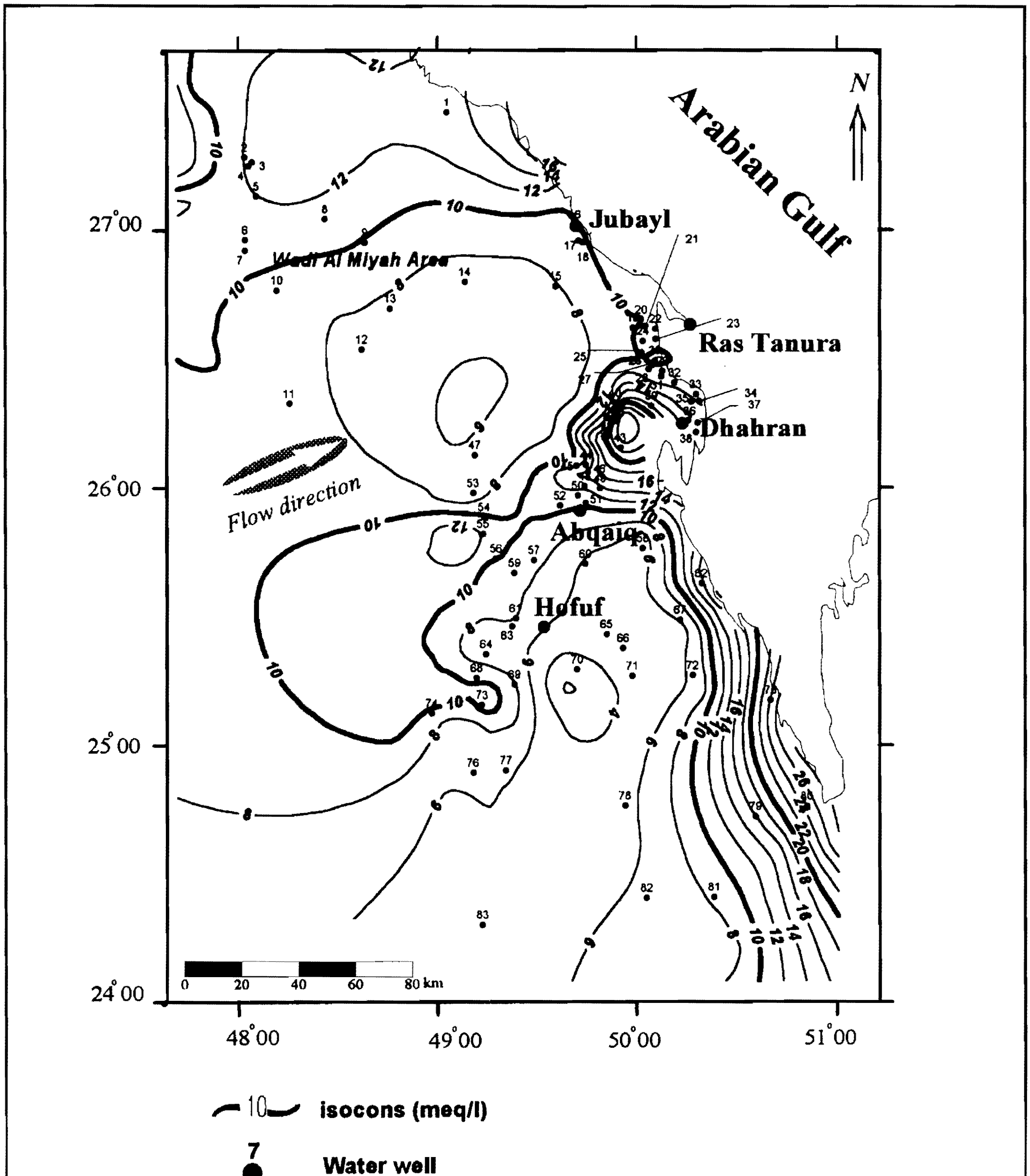


*Figure 3. Distribution Map of Calcium in Khobar Aquifer, Eastern Saudi Arabia.*

high from Ras Tanura on the north down to Dhahran and all along the southern coastal belt. Southwest of Hofuf shows a slight increase in calcium, however, the southernmost part of the study area shows low calcium values which are increasing towards the Arabian Gulf coast.

### 4.2. Magnesium

Magnesium follows the distribution pattern of calcium (Figure 4). The lowest magnesium concentration (less than 5 meq/l) occurs mainly in the south. However, towards the Arabian Gulf coastal belt the magnesium strength increases reaching more than 15 meq/l. Hofuf area has a relatively low magnesium. Also its magnesium concentration is lesser than its adjacent Abqaiq area.

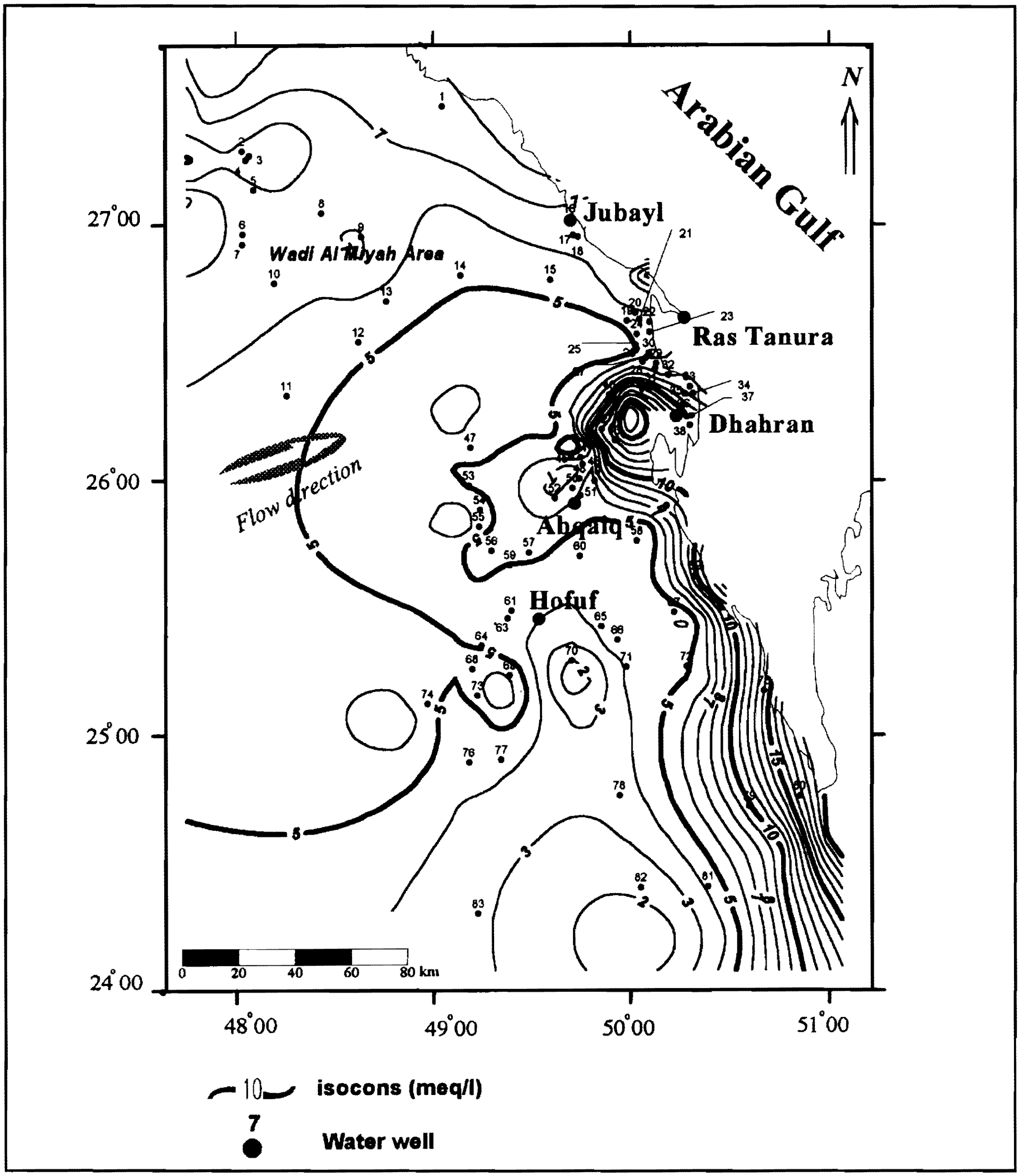


*Figure 4. Distribution Map of Magnesium in Khobar Aquifer, Eastern Saudi Arabia.*

### 4.3. Sodium

Sodium is the most abundant cation in the Khobar aquifer. Its concentration varies from 5 meq/l to more than 80 meq/l (Figure 5). In Wadi Al Miyah area it attains 15 meq/l. South of this area, in Dhahran–Ras Tanura, a wedge of high sodium

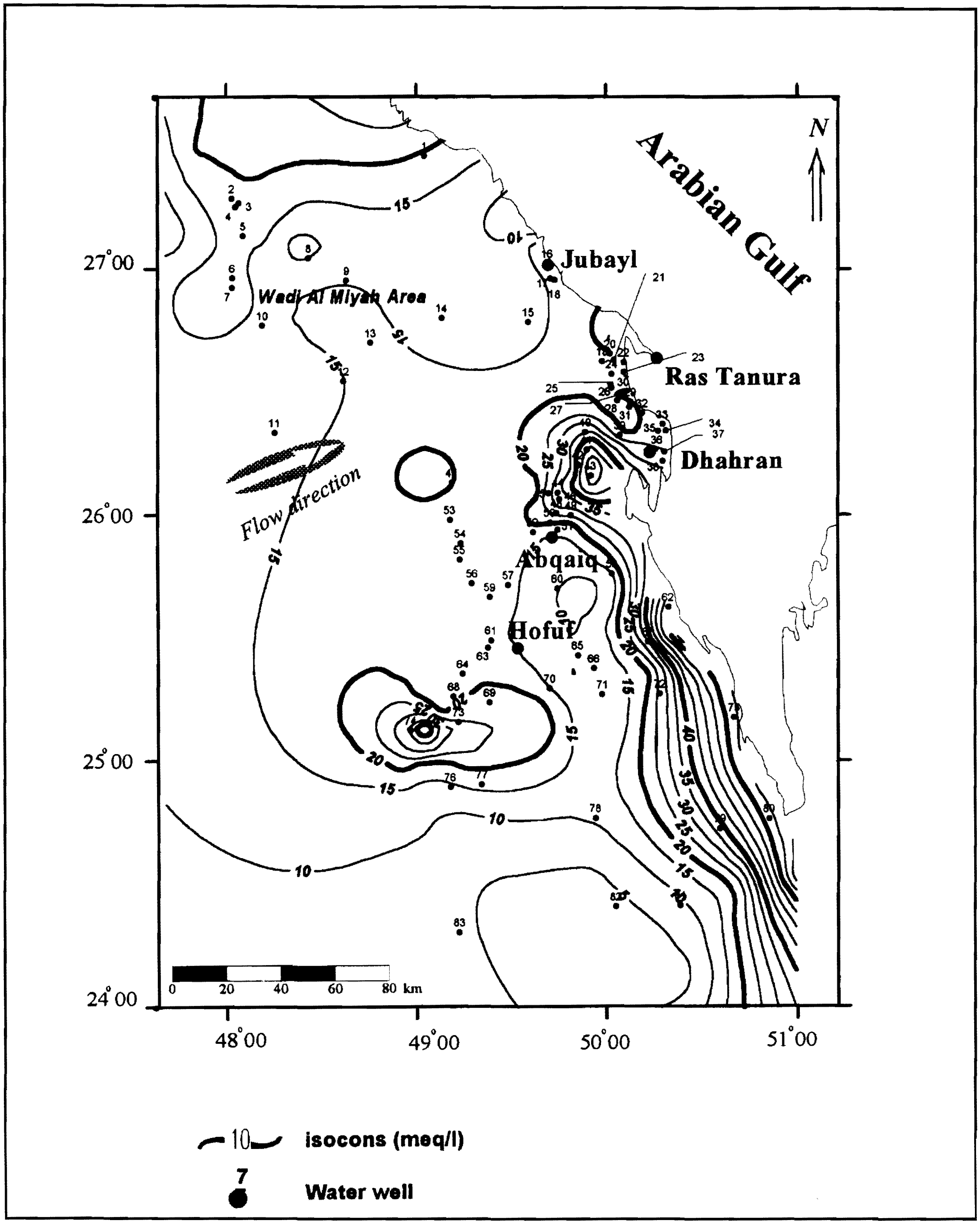


*Figure 5. Distribution Map of Sodium in Khobar Aquifer, Eastern Saudi Arabia.*

concentration protrudes westward. South of Dhahran, along the Arabian Gulf coast, sodium increases tremendously seaward. Around Abqaiq and Hofuf, the concentration drops to about 10 meq/l, reflecting a reasonably low sodium area. Southwest of Hofuf, in a localized area, the concentration reaches up to 40 meq/l. The lowest sodium concentration is found in the extreme south of the study area. The distribution could be generalized into two low sodium areas which are Wadi Al Miyah and Hofuf area accompanied by high sodium concentration area along the southern coastal belt.

### 4.4. Bicarbonate

Khobar aquifer has an average bicarbonate concentration of 3.0 meq/l (Figure 6). Bicarbonate is anomalously high in Wadi Al Miyah (north) and in Hofuf (south). The highest bicarbonate values of more than 5.0 meq/l are located in Hofuf.

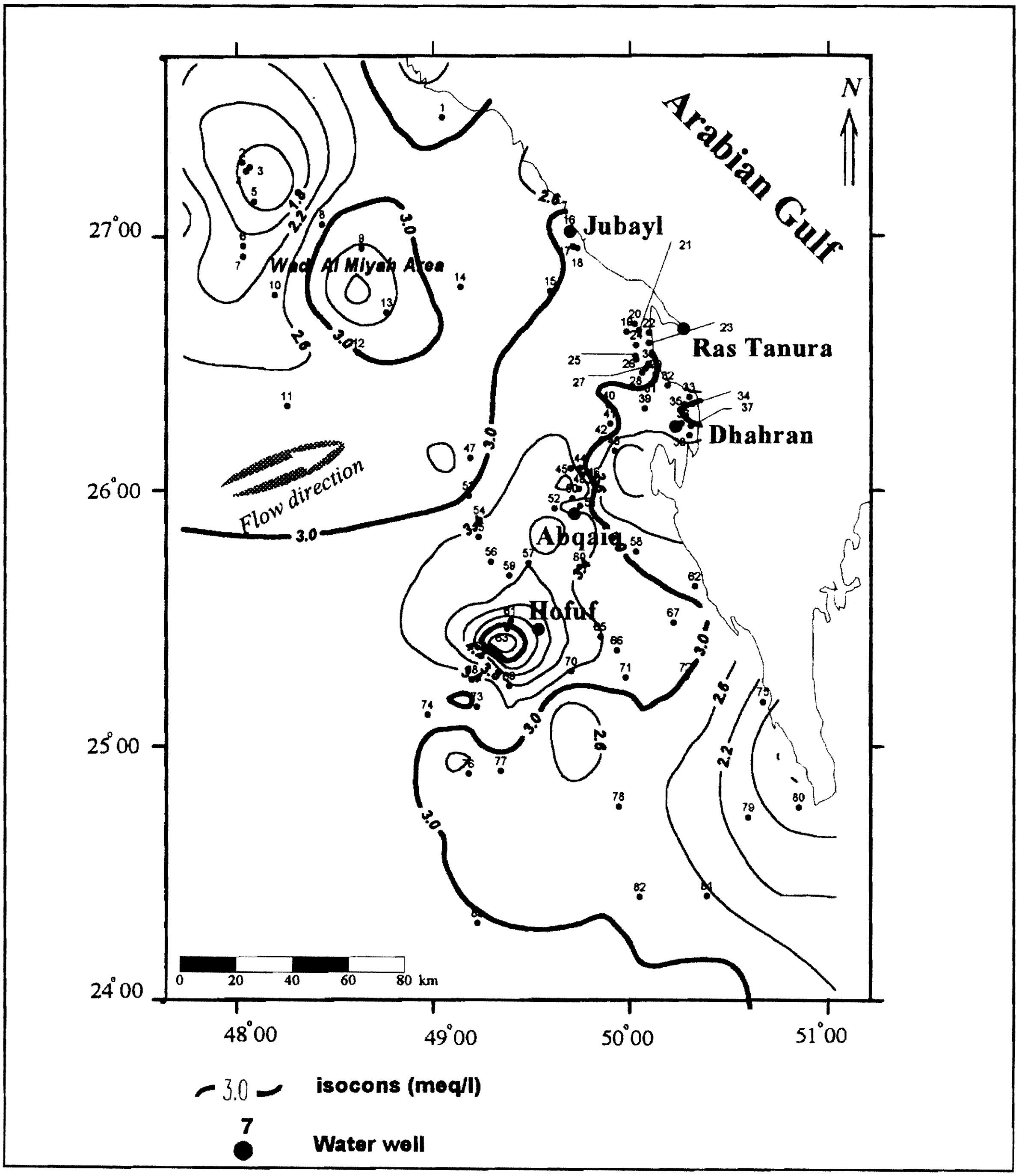


*Figure 6. Distribution Map of Bicarbonate in Khobar Aquifer, Eastern Saudi Arabia.*

Between the two high values there is an area of 3.0 meq/l which extends towards the Arabian Gulf. The southernmost part of the study area in contrast with the north and center shows a decrease of bicarbonate concentration towards the sea. This is, most likely, due to the normal groundwater evolution.

### 4.5. Sulfate

Sulfate concentration varies from 6 meq/l to 30 meq/l (Figure 7). In the extreme north the concentration increases seaward. Below this area, from Wadi Al Miyah all the way to Jubayl, the sulfate concentration is low. This low sulfate tongue is

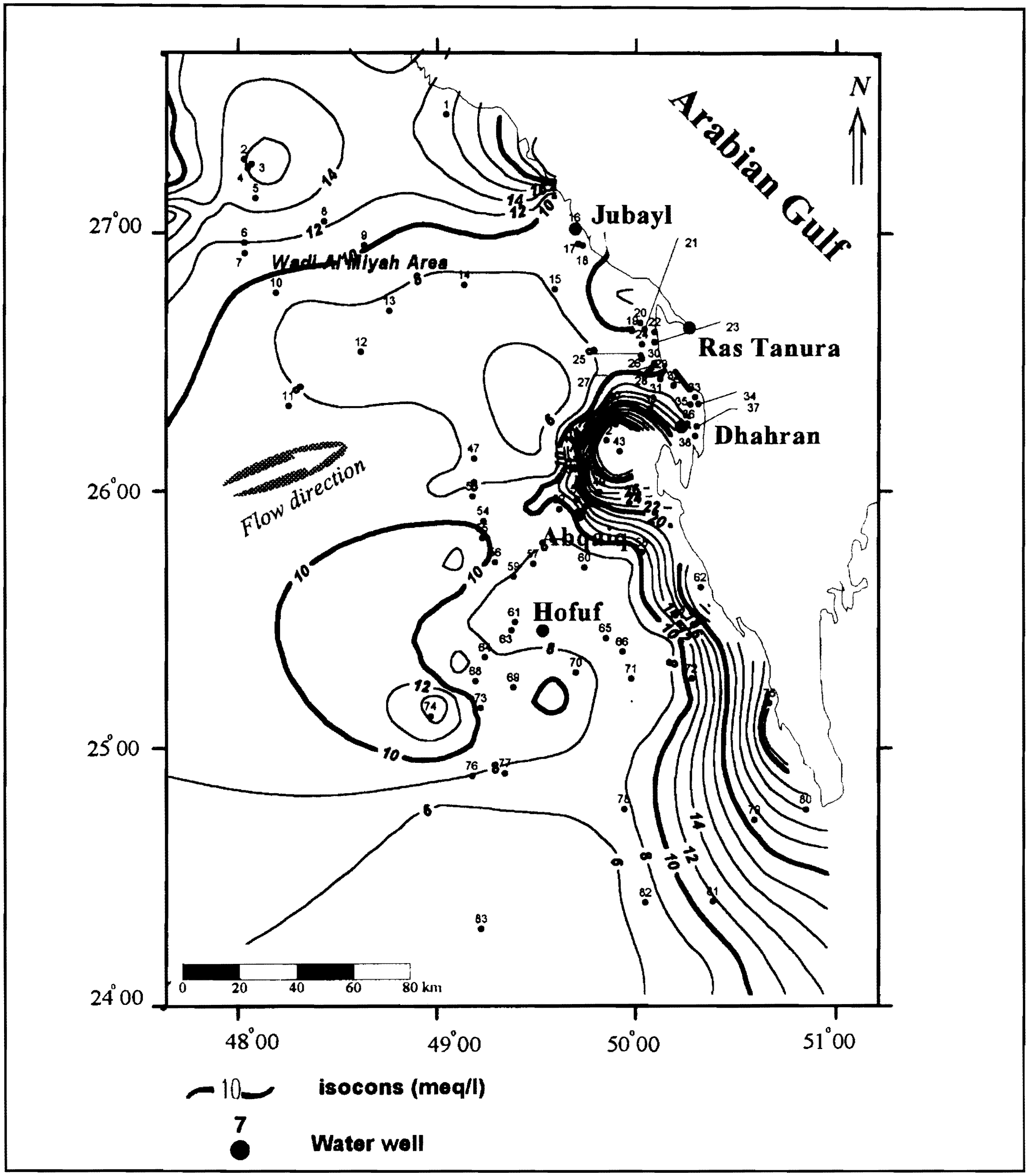


*Figure 7. Distribution Map of Sulfate in Khobar Aquifer, Eastern Saudi Arabia.*

bordered in the south, Dhahran area, by a very high sulfate area. Hofuf shows relatively low sulfate; however, the concentration increases tremendously towards the Arabian Gulf. Most of the Arabian Gulf coastal belt is characterized by high sulfate, with the exception of the area between Jubayl and Ras Tanura.

### 4.6. Chloride

The overall chloride distribution pattern in the Khobar aquifer is identical to the sodium distribution, however, there are areas where the two differ slightly, such as west of Dhahran (Figure 8). To the west of Dhahran the Cl/Na ratio is more than 1, indicating probably:

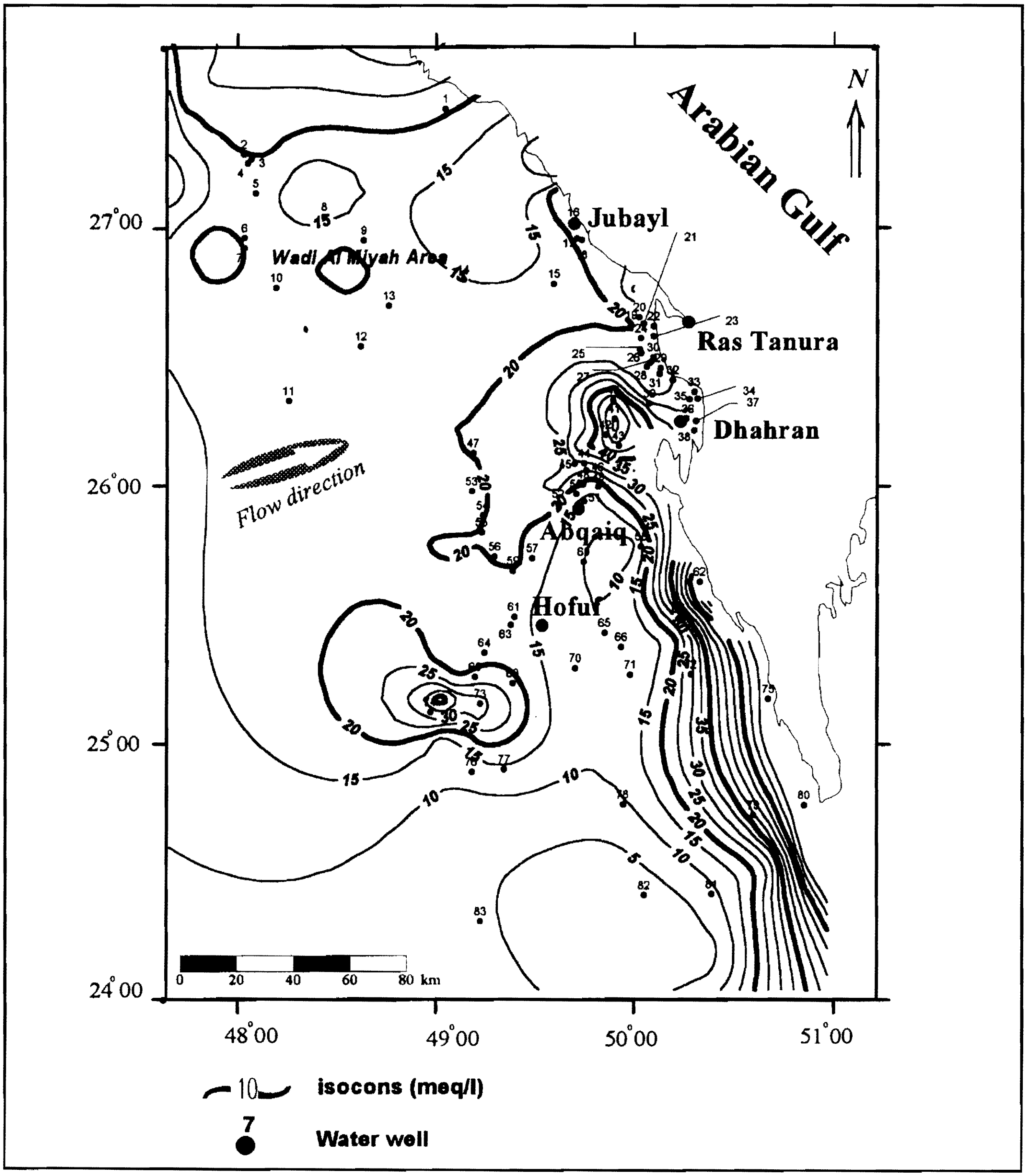


*Figure 8. Distribution Map of Chloride in Khobar Aquifer, Eastern Saudi Arabia.*

(1) The contribution of non NaCl salts to the system;

(2) The loss of sodium to ion exchange.

Around Wadi Al Miyah the chloride concentration varies from 15 to 20 meq/l. Chloride increases around Dhahran area reaching 50 meq/l. In the southwest of Hofuf, the chloride concentration increases to a maximum of 40 meq/l. Eastward along the Arabian Gulf coastal belt, chloride reaches its maximum value of 60 meq/l.

## 5. STATISTICAL ANALYSIS

Sodium and chloride show identical statistics. They have a similar mean values as well as similar variability. The strong positive skewness suggests the abundance of the low concentration values over the high values (Figure 9). The slight difference between sodium and chloride distributions could be attributed to the susceptibility of sodium to ion exchange. The histograms of sodium and chloride could be divided into: (1) a major group (less than 40 meq/l) which shows more or less a gaussian distribution; and (2) a minor group (more than 40 meq/l) which shows a more random behavior.

The histograms shapes for calcium, magnesium, and sulfate are similar (Figure 9). All the three histograms are unimodal and positively skewed. However, they differ in their mean, minimum, and maximum values (Table 2). Bicarbonate too is unimodal and positively skewed but it has a very small variance.

## 6. SATURATION INDICES

Saturation index is expressed as:

$$SI = \log \frac{IAP}{K_T} ,$$

where $IAP$ is the ion activity product of the components of the solid or gaseous phase, and $K_T$ is the solid or gaseous phase solubility equilibrium product at the specified temperature. The $SI$ value indicates the departure from equilibrium, when it is not equal to zero. The solid or gaseous phase is undersaturated and has a thermodynamic potential to dissolve when the $SI$ value is less than zero (*i.e.* negative). When it is greater than zero, the solid or gaseous phase is oversaturated and has the potential to precipitate or volatile. Sprinkle [12] mentioned the likeness of dissolution, although slow, when negative saturation indices are calculated. This indicates an association of undersaturation with mineral dissolution. However, oversaturation does not necessarily mean mineral precipitation. Drever [13] explained other factors such as mineral surface topography, surface poisoning, and nucleation energy that may inhibit the formation and growth of mineral.

A non-generalized aqueous model (WATEQ version) [14] that employs the successive approximation approach is used for the hydrochemical equilibrium condition analysis. In this study, the Khobar aquifer saturation indices pattern is evaluated in five areal sectors: Wadi Al Miyah, Jubayl, Ras Tanura–Dhahran, Abqaiq, and Hofuf areas (Figure 2). Wadi Al Miyah is almost oversaturated with respect to calcite and dolomite except in wells 8 and 10 (Figure 10). Well 8 shows undersaturation with respect to dolomite and it is in equilibrium with respect to calcite. Well 10 is undersaturated with respect to carbonate minerals (calcite and dolomite). In Wadi Al Miyah the aquifer is undersaturated with respect to gypsum. Jubayl area is oversaturated with respect to carbonate minerals and undersaturated with gypsum, however, well 16 is in a quasi-equilibrium condition with gypsum. The third area (Ras Tanura–Dhahran) shows persistent oversaturtion with respect to carbonates and undersaturation (with almost constant $SI$ values) with respect to gypsum. There is only one well (well 22) where the dolomite saturation drops anomalously. Abqaiq area is characterized by undersaturation with respect to gypsum and oversaturation with respect to carbonates (calcite and dolomite). However, the overall carbonate oversaturation of this area is interrupted in wells 48 and 54. Hofuf area shows interestingly high variability in the saturation indices. Well 66 is the most undersaturated,

**Table 2. Statistical Parameters of Major Ions in Khobar Aquifer, Eastern Saudi Arabia.**

| Parameter | | Ca | Mg | Na | $HCO_3$ | $SO_4$ | Cl |
|---|---|---|---|---|---|---|---|
| Mean | (meq/l) | 10.72 | 6.52 | 20.60 | 2.96 | 11.33 | 23.38 |
| Std. deviation | (meq/l) | 5.08 | 3.60 | 14.12 | 0.75 | 6.64 | 16.73 |
| Minimum | (meq/l) | 1.00 | 0.40 | 3.70 | 0.80 | 4.70 | 3.60 |
| Maximum | (meq/l) | 31.50 | 23.10 | 76.30 | 6.60 | 45.80 | 101.60 |
| Skewness | | 1.88 | 2.31 | 2.31 | 0.92 | 2.95 | 2.50 |

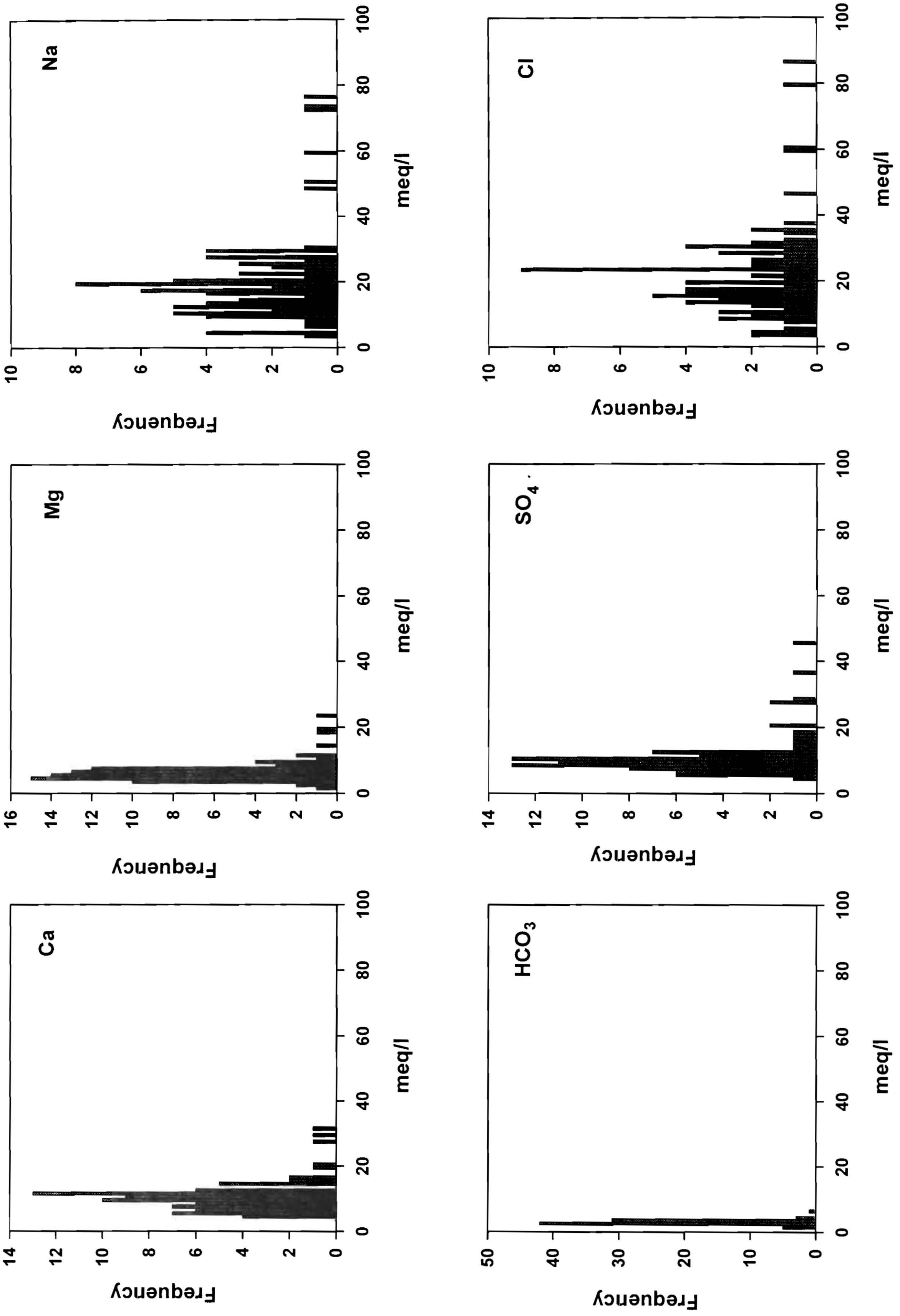


*Figure 9. Histograms of Major Ions in Khobar Aquifer, Eastern Saudi Arabia.*

in the whole aquifer, with respect to the carbonate minerals. Similarly, well 70 is the most undersaturated with respect to gypsum, meanwhile it has the highest oversaturation values with respect to dolomite.

## 7. HYDROGEOCHEMICAL FACIES

The trilinear plot (Figure 11) of the Khobar aquifer depicts the presence of five hydrogeochemical facies (Figure 12):

(1) Ca–$SO_4$ Facies

(2) Na-Ca-$SO_4$–Cl Facies

(3) Na-Ca-Cl–$SO_4$ Facies

(4) Na–Ca–Cl Facies

(5) Na–Cl Facies.

The Ca–$SO_4$ facies is present at the extreme south of the study area (Figure 12). In the trilinear diagram, more than 50% of the anions of this water type are sulfate and more than 40% of the cations are calcium. The second facies (Na–Ca–$SO_4$–Cl facies) is somewhat similar to the third facies (Na–Ca–Cl–$SO_4$ facies). Their only differences lie on the $SO_4$ : Cl ratio. Combined the two facies make up the second largest facies and they occupy south of the latitude 25° 30′. The western portion (the extrapolated area) of the two facies are not reliable due to the lack of data points, however, the kriging method used by the contouring software made the best realization that could be approximated to the actual pattern. The (Na–Ca–Cl) facies is the biggest facies and occupies almost 50% of the study area. Also most of the cities and heavily inhabited areas of the study area fall in this facies. Chloride is the dominant anion, whereas sodium and calcium with varying proportions make up the cations. The fifth facies (Na–Cl) occupies two distinct areas, Mid-north (Jubayl–Ras Tanura) and southeastern coastal belt. The two Na–Cl facies are separated by a Na–Ca–Cl facies tongue.

## 8. GROUNDWATER EVOLUTIONARY PATTERN

Total dissolved solids and most of the major ions increase when groundwater moves along its flow path. Investigations [15, 16] have shown that shallow ground-water in recharge areas is lower in TDS than deeper zone water in the same area; likewise the water in recharge areas (geochemically) is different than the water in discharge areas.

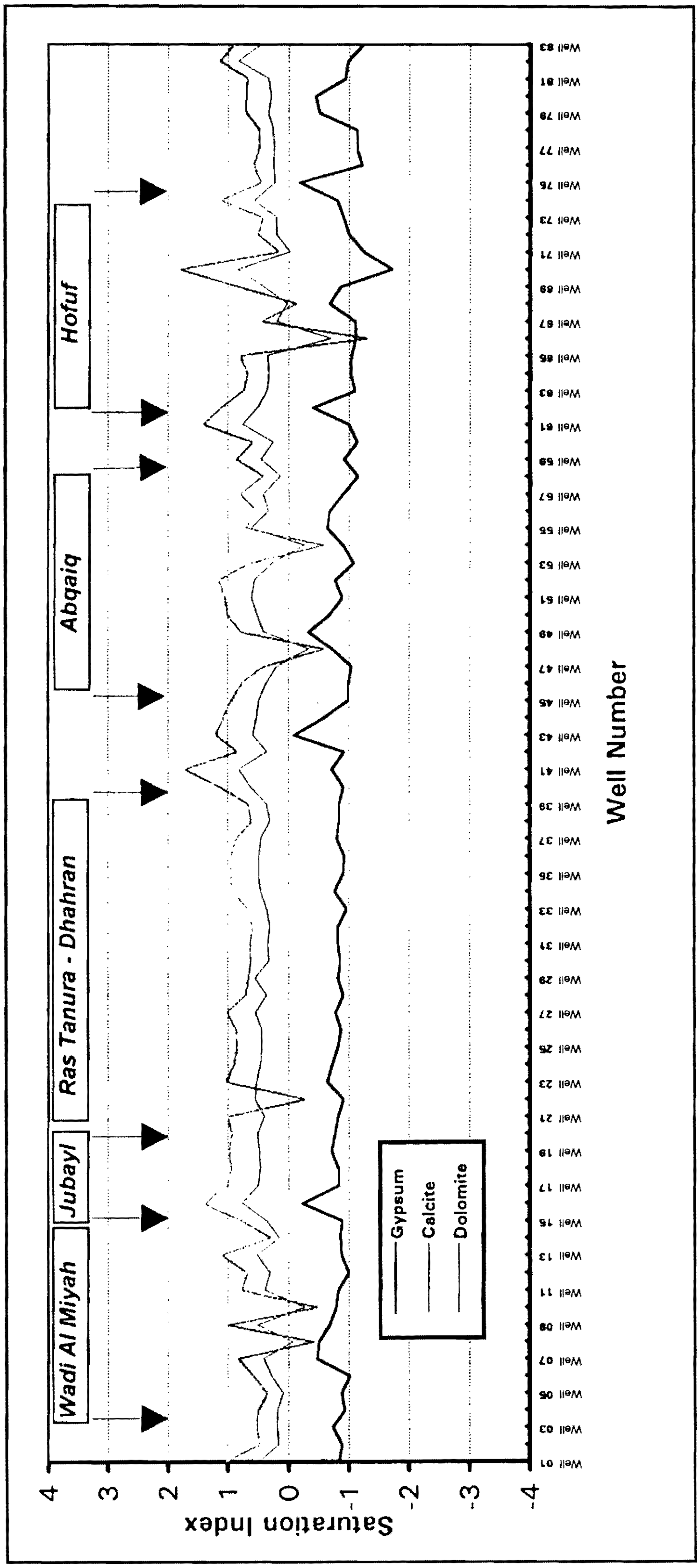


*Figure 10. Calcite, Dolomite, and Gypsum Saturation Indices in Khobar Aquifer, Eastern Saudi Arabia.*

Chebotarev [15] in a detailed investigation concluded that groundwater tends to evolve chemically towards the composition of sea-water. He indicated that the evolution was normally accompanied by regional change in the proportion of major anions along the flow path as shown below:

***Travel along flow path***

$$HCO_3^- \rightarrow HCO_3^- + SO_2^- \rightarrow SO_2^- + HCO_3^- \rightarrow SO_2^- + Cl^- \rightarrow Cl^- + SO_2^- \rightarrow Cl^-$$

***Increasing residence time***

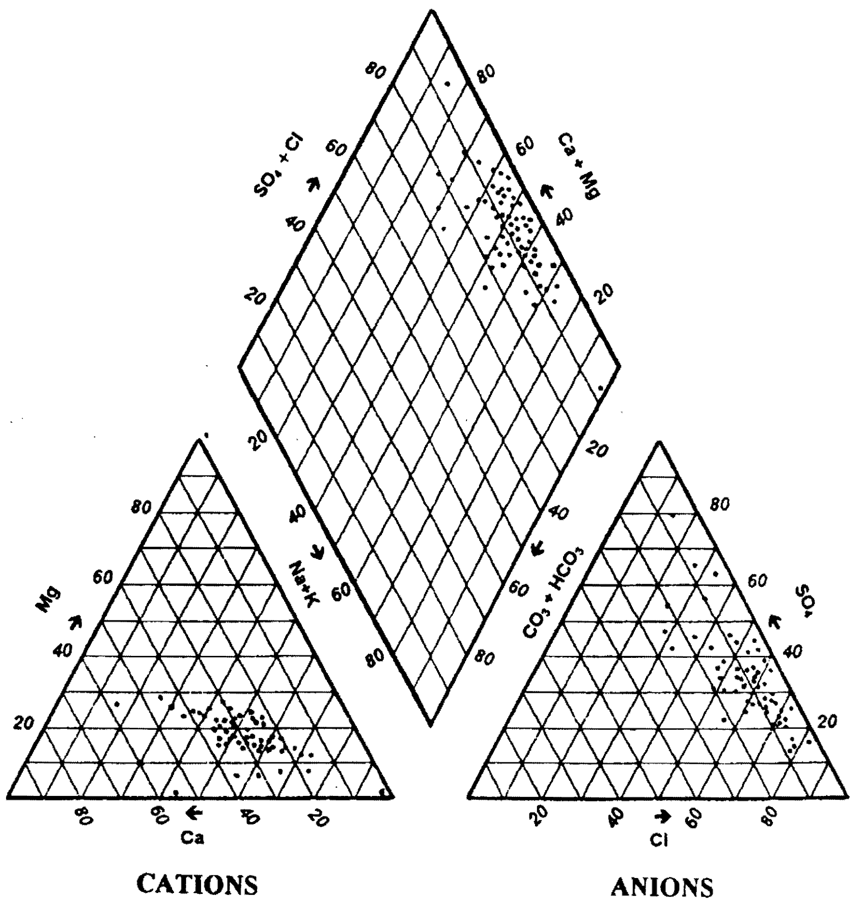


*Figure 11. Trilinear Diagram of the Water Samples.*

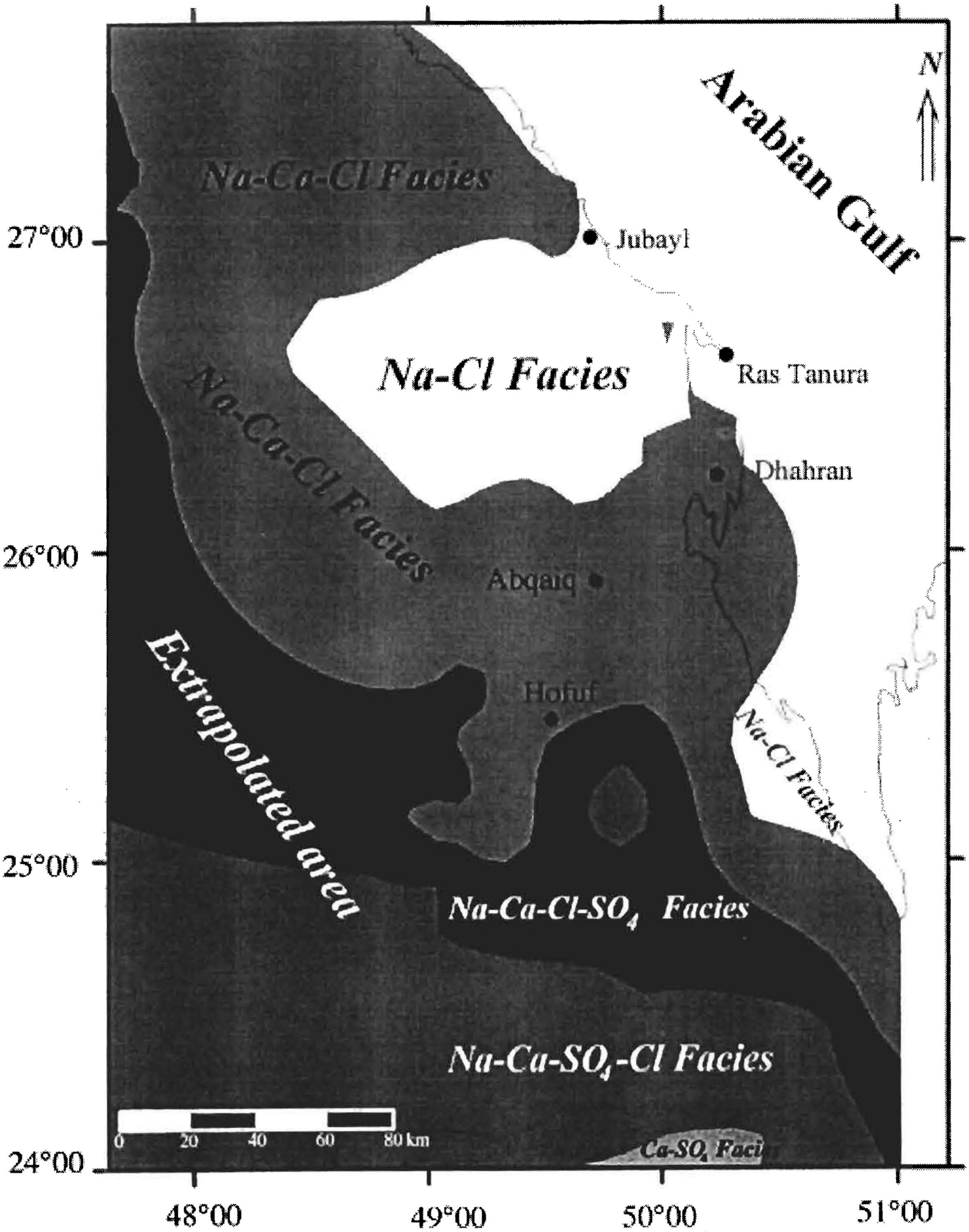


Figure 12. Distribution of the Hydrogeochemical Facies.

Schoeller [16] referred to the above sequence as "Ignatovich and Souline Sequence" in recognition of the fact that two hydrogeologists in the former Soviet Union had developed similar generalization independent of the contributions by Chebotarev [11, 15].

Three parallel traverses (*AA′*, *BB′*, and *CC′*) along the regional flow direction are selected. Due to the nature of the spatial data distribution, the traverses are not in an exact geometrical parallelism with the flow direction (Figure 2). The traverses are 60–80 km apart and 80–110 km long.

### 8.1. Traverse AA′

Chloride concentration seems constant with the exception of well 13 and well 16 (Figure 13). In well 13 chloride increases, similarly sulfate too increases. The only major cation which increases with chloride and sulfate is sodium. The reaction involved seems mixing of different water. Around well 14 and well 15 (which is projected on the traverse) the water composition seems somewhat constant. In well 16 the rapid increase of sulfate accompanied by the calcium increase suggests, dilution with localized gypsum type water. Along this traverse there is no evident cation exchange. The drop of sodium accompanied with chloride drop and calcium increase at well 16 could not be attributed to cation exchange. The overall calcium and sulfate concentration, along the whole traverse, appears somewhat related. This suggests that although the aquifer skeleton is carbonate some disseminated evaporitic minerals have played a role in contributing to the calcium and sulfate concentrations.

### 8.2. Traverse BB′

Major anion evolution is evident along wells 56, 52, 50, and 48 (Figure 14). Sodium increases steadily whereas sulfate relatively decreases. This indicates, as shown on Figure 12, that $SO_4$–Cl facies water evolves and gives way to a Cl facies water. The pattern is interrupted at well 43 where the Dammam Formation is exposed (Figure 1) or thinly covered. This leads to an interaction with surficial waters that could be affected by sabkha. The composition of well 35 and well 33 follows the general trend of the flow path. Also, there is no cation exchange.

### 8.3. Traverse CC′

Along this traverse (Figure 15), the water evolves from $SO_4$–Cl facies to pure chloride facies. Sulfate and chloride have somewhat similar concentrations (less than 10 meq). In well 70 sodium is exchanged with divalent cations (Ca and Mg). Most likely this exchange takes place in subsurface argillaceous lenses. The rest of the profile shows a steady increase of chloride which becomes the dominant anion.

## 9. CONCLUSIONS

A statistically representative data set was produced from the original raw data by taking three successive screening steps. Major cations in the Khobar aquifer show a similar pattern. Although they differ in magnitude below the latitude 26° 30′, all the three cations increase seaward (down stream). Above 26° 30′ there is no clear increase of calcium and magnesium, while sodium slightly drops. The chloride distribution is more or less identical to sodium. Bicarbonate is high in Hofuf and Wadi Al-Miyah area. There is a stream of low sulfate (26° 30′ – 27° 00′) area bordered by two high sulfate areas. The statistics of the aquifer show positive skewnesses, indicating the prevalence of low concentration values over the higher ones. The aquifer is generally oversaturated with respect to carbonate minerals and undersaturated with respect to sulfate minerals.

In the Wadi Al Miyah–Jubayl area (*AA′*), there is a mixing of water probably with localized gypsum type water. The Abqaiq–Dhahran flow path (*BB′*) shows the evolution of $SO_4$– Cl facies water into Cl facies water. There is an interruption of the general pattern where the Dammam formation crops out or is thinly covered. Similarly, the Hofuf flow path (*CC′*) shows groundwater evolution ( $SO_4\text{–Cl} \rightarrow \text{Cl}$ ); it also shows an ion exchange, which involves the replacement of sodium by divalent cations (Ca and Mg).

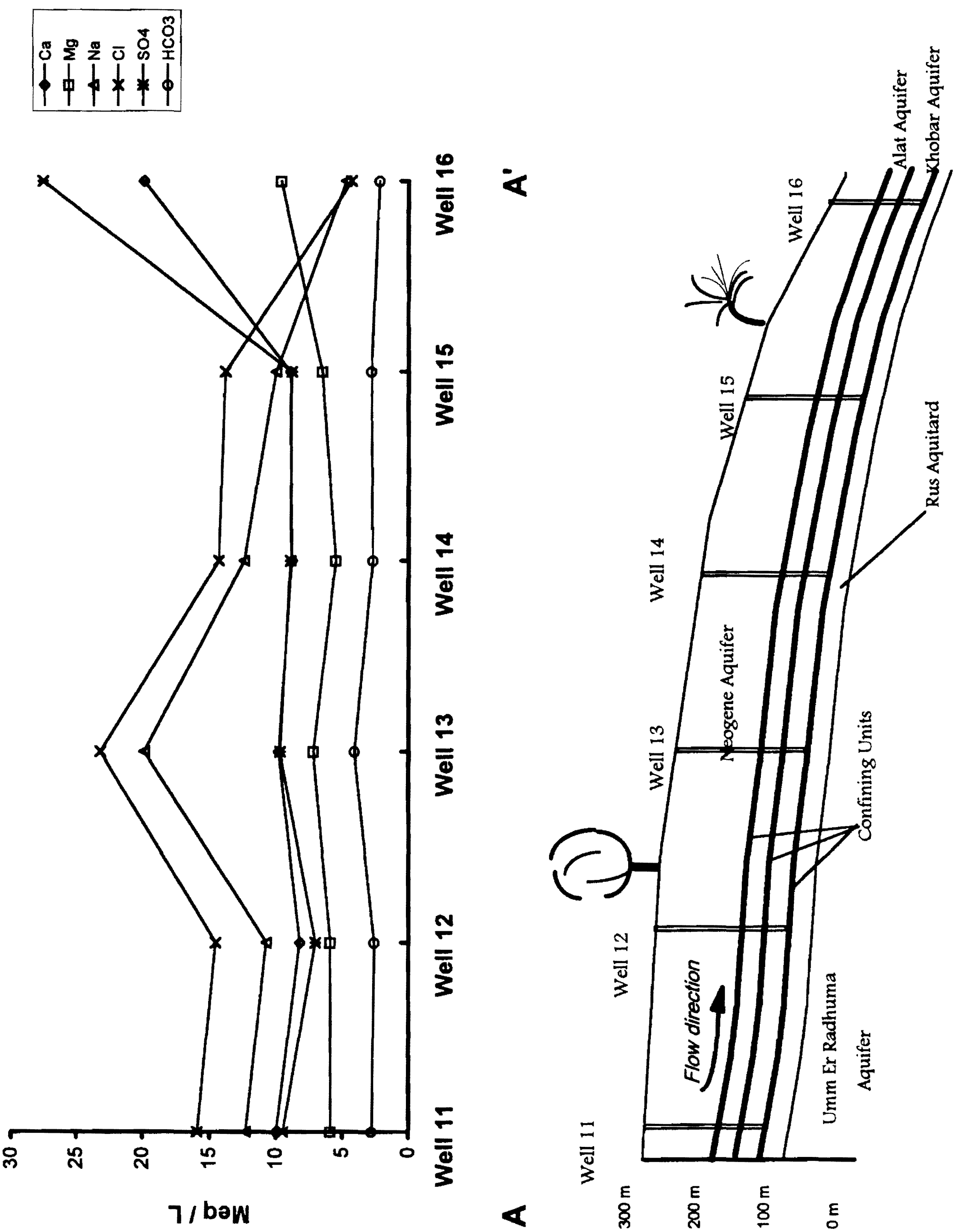


*Figure 13. Hydrogeochemical Traverse along Wadi Al Miyah–Jubayl Flow Path in the Khobar Aquifer (see Figure 2. for the Location of the Traverse).*

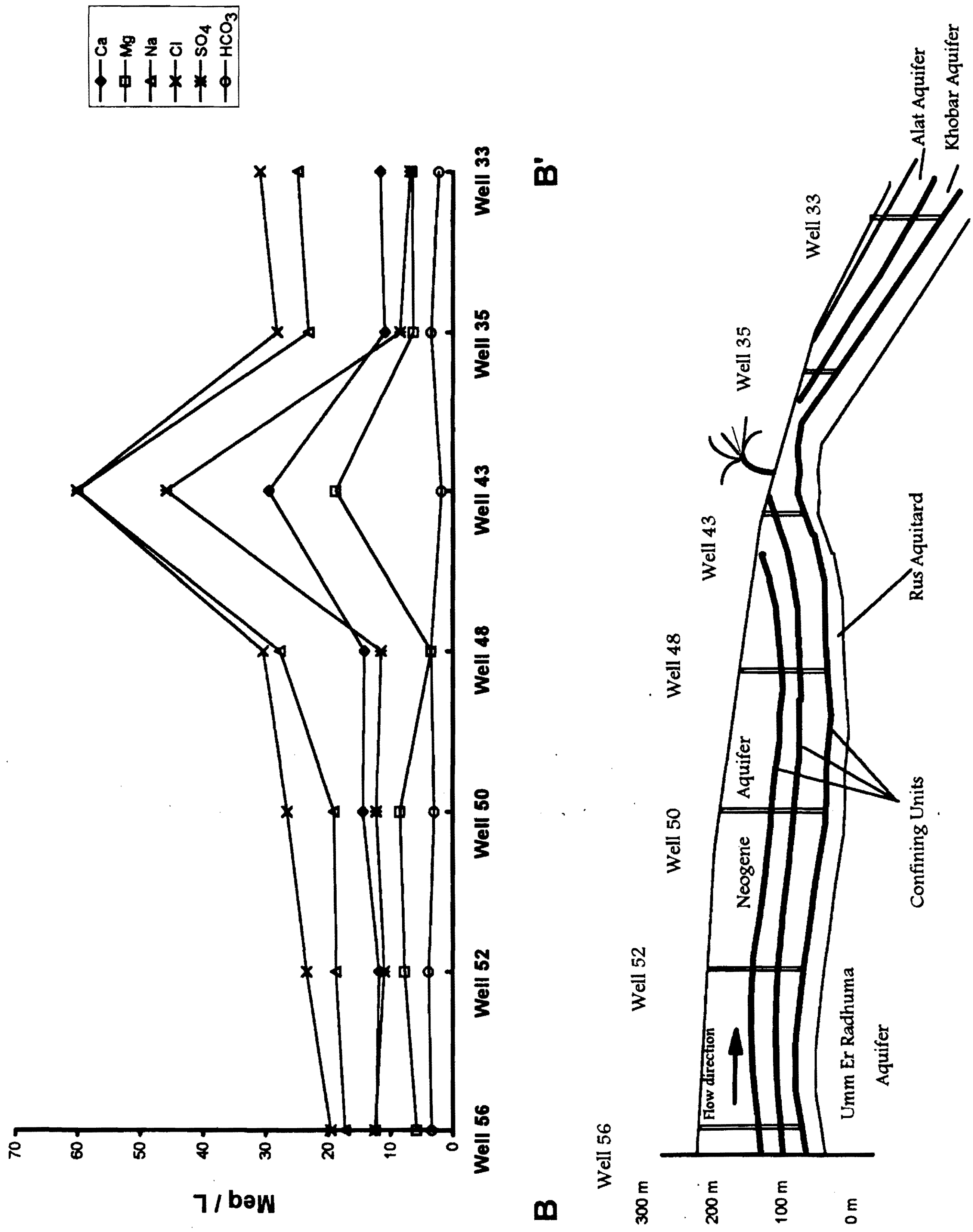


*Figure 14. Hydrogeochemical Traverse along Abqaiq–Dhahran Flow Path in the Khobar Aquifer (see Figure 2. for the Location of the Traverse).*

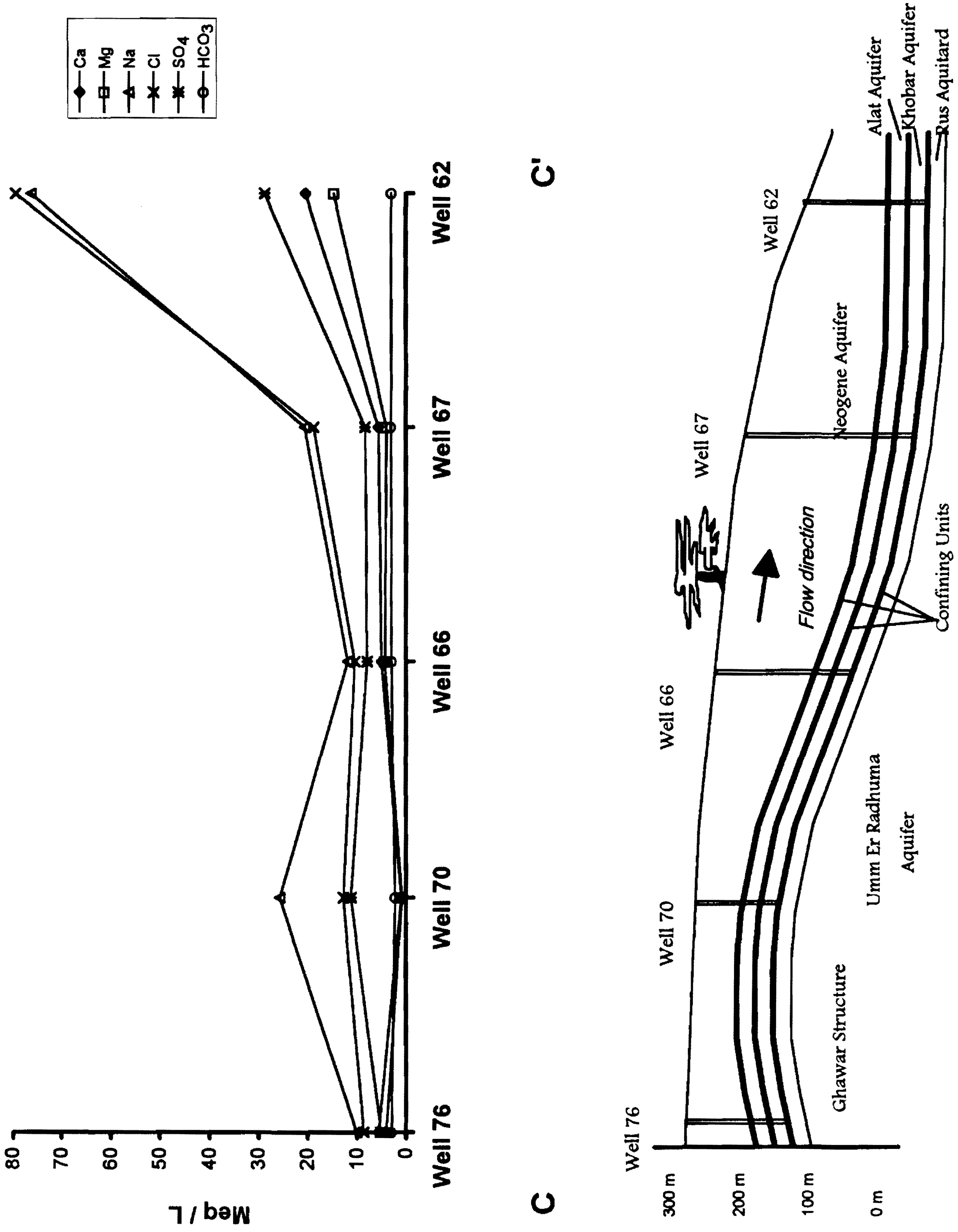


*Figure 15. Hydrogeochemical Traverse along Hofuf Flow Path in the Khobar Aquifer (see Figure 2. for the Location of the Traverse).*

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