WATER RESOURCES AND AGRICULTURAL DEVELOPMENT PROJECT

QATAR

THE WATER RESOURCES OF QATAR AND THEIR DEVELOPMENT : VOL I

FOOD AND AGRICULTURE ORGANIZATION
OF THE UNITED NATIONS, DOHA: 1981

VIII

HYDROCHEMISTRY

8.1 INTRODUCTION

The chemical composition of the groundwater contained within the aquifers underlying Qatar reflects the influence of a number of factors. Among these are the chemical composition of the recharge water; the soluble minerals contained in the soil and rock and their spatial variation; the structure, transmissivity and permeability of the aquifer; the degree of contamination by mixing with either more saline groundwater or seawater; solution and precipitation reactions occurring under differential concentration and the temperature and pressure gradients within the aquifer. If the processes and factors affecting the composition of the water are understood, a study of the groundwater chemistry provides a valuable aid to the understanding of the whole groundwater system. For this reason a consideration of the hydrochemistry preceeds that dealing with the hydrogeology.

The usable groundwater resource of all except south-western Qatar is derived from rainfall over the peninsula which has established a body of meteoric water within both the Rus and Umm er Radhuma Formation aquifers in northern Qatar. The extent of this fresh meteoric water is defined both laterally and vertically by saline groundwaters. In northern Qatar, where the thinner, carbonate facies of the Rus Formation overlies the Umm er Radhuma Formation, there is a hydraulic continuity between these two Formations such that they form one aquifer system. Where the thicker gypsiferous, argillaceous facies of the Rus Formation predominates, over the greater part of Qatar except the Dukhan structure, vertical hydraulic continuity is confined to relatively small discrete depression areas caused by dissolution of gypsum in the Rus Formation and consequent collapse; horizontal continuity is minimal.

Within the Umm er Radhuma Formation, which is in excess of 300 m thick, lithological variations and selective karstification have given rise to a multi-layered aquifer system elsewhere but it is only the uniform upper part of the Formation which is of hydro-geological significance in Qatar.

The saline waters which bound the meteoric water body are in part of modern sea water origin, but higher salinities are also due to dissolution processes within the Rus Formation. In the Umm er Radhuma Formation ancient saline waters are also present particularly at depth.

In the extreme south-western part of Qatar the Alat aquifer of upper Dammam Formation age contains a mixture of deeper Umm er Radhuma waters and recharge from the overlying formations within Saudi Arabia which together provide an artesian source of brackish water.

The principal aquifer systems are defined as follows :

Aquifer I — Rus Formation, chalky and marly limestones, with thick anhydrite and gypsum in the south, of low transmissivity and storage, low yield from boreholes except in depressions. EC 500-4000 in recharge area, up to 10,000 elsewhere, from 15 to 120 m thick, generally 30-50 m in recharge area.

Aquifer II — Upper Umm er Radhuma Formation, dolomitic limestone, porous, fractured and karst weathered, high transmissivity and storage, good yields from boreholes, EC 1000 to 4000 in freshwater body, up to elsewhere, 300 m thick, but maximum of 70 m contain freshwater at centre of body.

8.2 THE DATA BASE

Hydrochemical observations in Qatar, outside the Dukhan oil and gas field and associated water supplies, were initiated by Le Grand Adsco in 1959 when water samples from exploratory drilling were analysed for major ion chemistry. With the advent of intensified hydrogeological investigations by FAO in early 1972, regular sampling of some 100 wells was initiated and has been maintained by successive FAO projects since the, including two programmes of isotope sampling in 1975 and 1978. A large amount of data has therefore been accumulated but no detailed analysis or interpretation has been carried out, previous reports having been confined to a purely descriptive presentation.

In the first FAO report (1974) an interpretation of Qatar's groundwater chemistry was presented consisting of a classification based on Piper diagram plots. This analysis was made without the benefit of later understanding of the complex origins of groundwater in Qatar. Anomalies arose when the composition of water from deep boreholes was compared with that from shallow boreholes and hand-dug wells which reach only just below the water table. It was later decided that a much more detailed analysis of the hydrochemistry was required to elucidate the hydrogeological analysis. A renewed and closely supervised programme of hydrochemical sampling was therefore initiated in 1978 together with additional environmental isotope sampling. These samples were despatched to the Department of Geological Sciences of the University of Birmingham, England for minor ion analysis and to the International Atomic Energy Agency (IAEA) in Vienna for isotope analysis.

Early project sampling was made by simple grab methods on the surface of the water in the well or from pumped discharge but from 1974 onward the sampling method was improved by the introduction of 'depth' samplers. Further data were provided by the logging of electrical conductivity and temperature throughout the profile. The analysis for major ion chemistry and some minor ions have been performed throughout by the Water Department laboratory of the Qatar Government at the Ras Abu Aboud desalination plant using the following methods of analysis and equipment.

Parameters	Method of Analysis and Equipment Used
Total Dissolved Solids	Weight of residue of sample evaporated at 180^{o}C.
Electrical Conductivity	Conductivity meter at standard 25^{o}C.
Sodium	Flame photometer or atomic absorption spectrophotometer.
Potassium	" " " " " "
Calcium	Complexometry with EDTA and related reagents.
Magnesium	" " " " " "
Sulphate	Calorimetry where SO_4 exceeds 20 mg/l or gravimetry as $BaSO_4$.
Bicarbonate	Standard acid-base titration using methyl orange indicator.
Chloride	Titration with $AgNO_3$.
Nitrate	Reduction to NH_3 and Nessler colorimetry.
Silica	Colorimetry using silicophasphomolybenum yellow.
Boron	Colorimetry using carmine.
Flouride	Specific ion electrode with citrate buffer.
Iron	Colorimetry using orth-phenanthroline.

Source : Water Chemist, Water Department, Ministry of Electricity and Water.

Arising out of the renewed and closely supervised sampling programme undertaken in 1978, a detailed hydrochemical study was carried out in co-operation with the Department of Geological Science of the University of Birmingham, England. For this study a total of some 300 major ion, 60 minor ion, 80 oxygen-18 and deterium, 54 tritium and 9 carbon-14 and carbon-13 analyses from 120 monitoring wells were made available. From these data a selection for inclusion in the study was made, based on the following criteria;

(a) Major ion analyses to be as recent as possible, preferably 1978.

(b) Minor ion analyses (iodide, strontium, flouride, bromide, boron) to be available for the same well.

(c) Where oxygen-18 and deuterium data were available these to be automatically included for interpretation provided at least a major ion analysis was available.

(d) All tritium data for wells belonging to the above to be used.

(e) All analyses of carbon-14 and carbon-13 to be used.

(f) Analyses of samples taken prior to 1978 from wells falling within the above categories to be included to provide a time related aspect.

(g) Accuracy of the analysis : This criterion is the most difficult to assess with any certainity as field conditions, methods of sampling, contamination, laboratory methods and equipment all combine in various ways to affect the resulting accuracy. As a purely subjective test only full analyses with an ionic imbalance of less than 5% were used. Upto 10% imbalance was accepted in the cases where isotope or minor ion chemistry data were available. The minor ions were analysed by XRE Spectrometer at the University of Birmingham and repeated three times with an estimated accuracy within 5%. Isotope and radiocarbon samples were analysed by IAEA with reported measurement errors of ± 0.02% for oxygen-18, ± 0.1% for deterium and less than 0.01% for carbon-13.

By application of these criteria to the total data base only 76 wells were finally considered in the interpretation (Fig. 8.1). Borehole details are given in Appendix and the analyses for each are presented in Appendix IV.

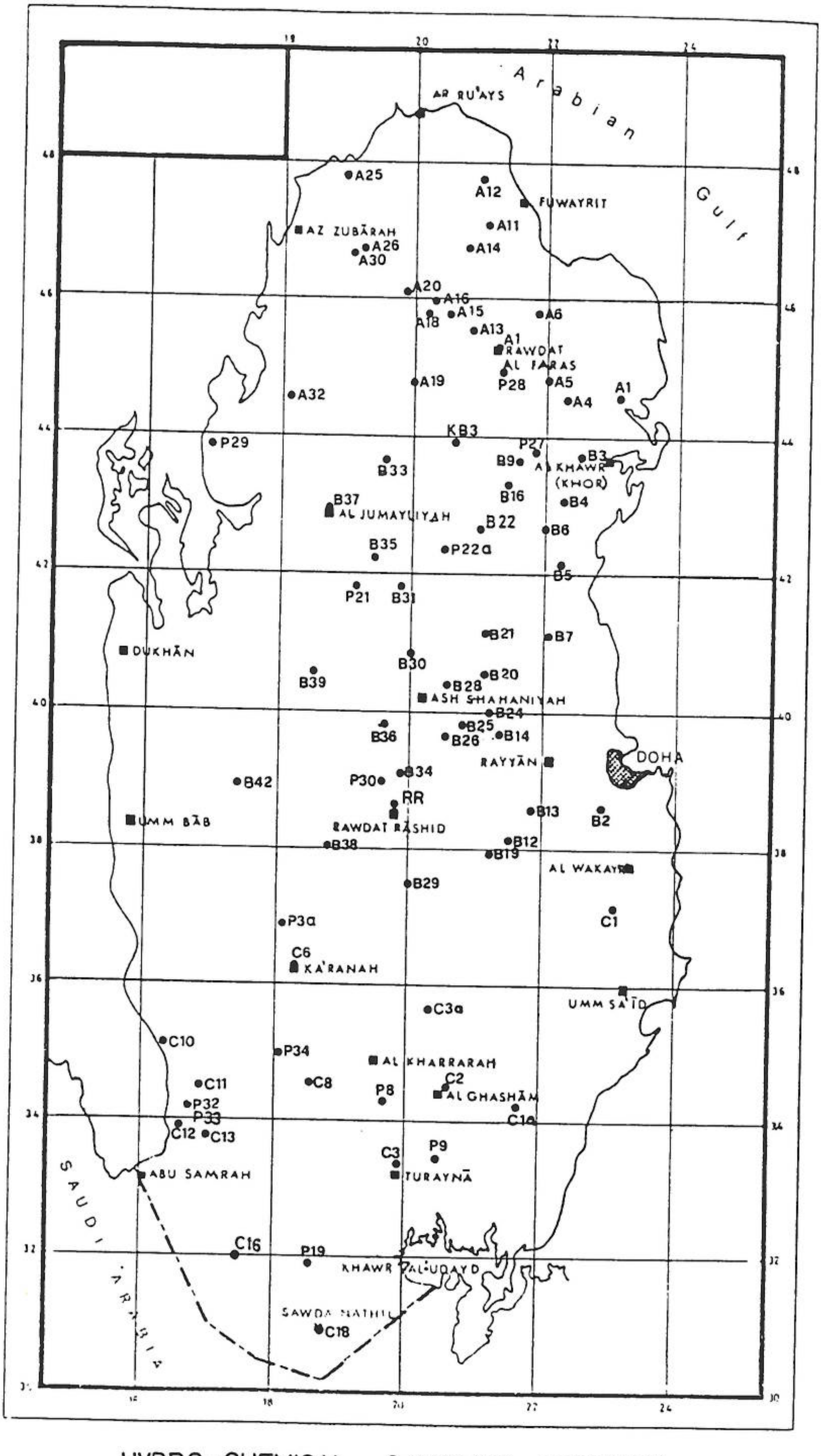
8.3 GENERAL PRINCIPLES

There are several chemical laws and principles, such as the law of mass action, which can be used to evaluate the chemistry of groundwater and these are referred to in the appropriate sections which follow. There is, however, one assumption underlying the approach to the study and which needs to be stated. It is assumed that groundwater is in equilibrium with aquifer matrix at the time it is drawn into the well and collected for analysis. The equilibrium is in fact disturbed during the sampling process and disequilibrium particularly affects the values determined for the more unstable chemical parameters particularly those affecting the carbonate stability. However, it must be assumed that the analytical results for the more stable parameters will represent their equilibrium values in the aquifer.

8.4 MAJOR ION CHEMISTRY

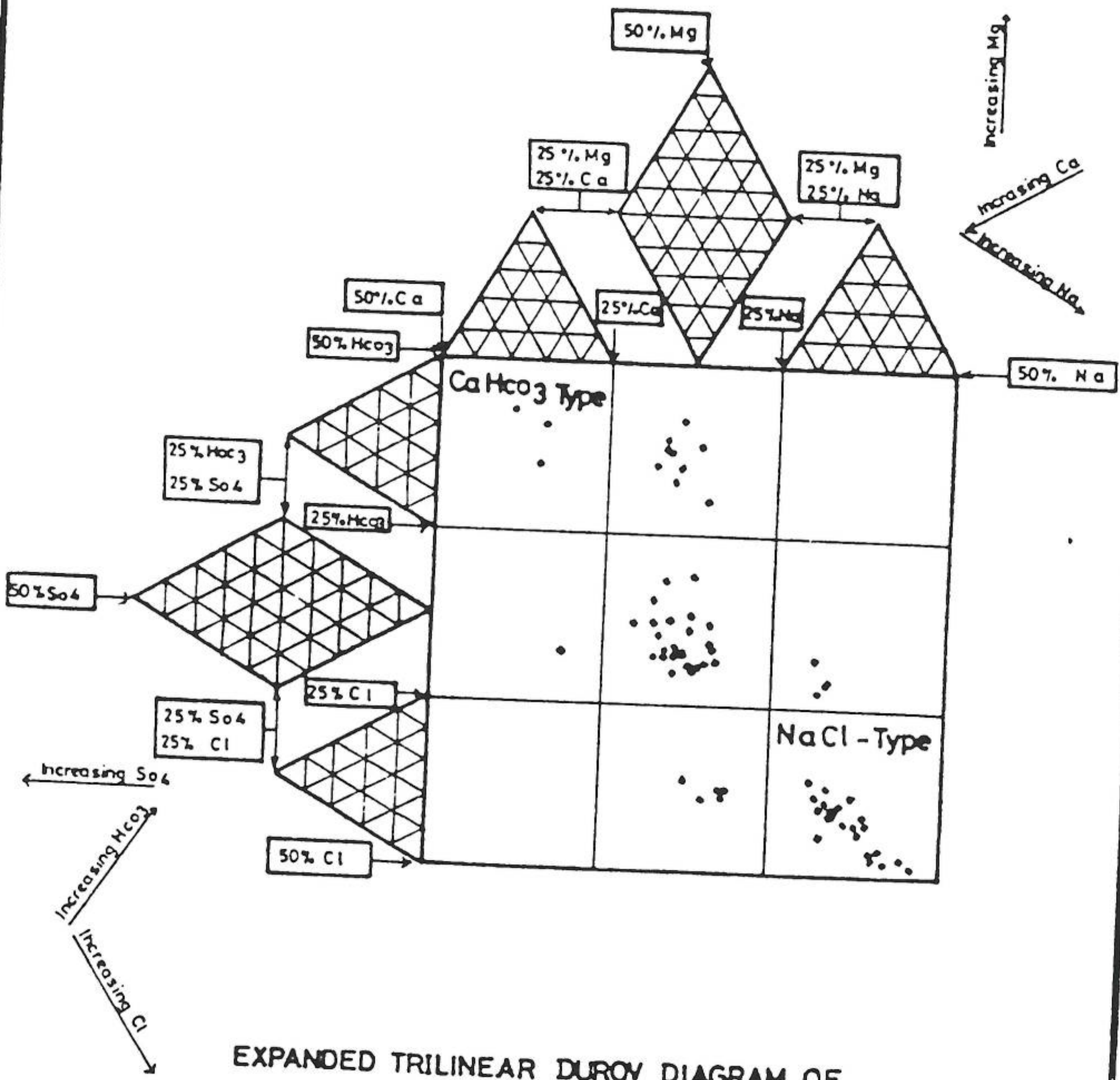
8.4.1 Durov Diagram and Classification of Groundwater

The following major cations and anions were analysed; Calcium (Ca^{2+}), Magnesium (Mg^{2+}), Sodium (Na^{+}), Potassium (K^{+}), Bicarbonate (HCO_3^{-}), Sulphate (SO_4^{2}) and Chloride (Cl^{-}). As an initial appraisal the major ion content of all samples has been presented on a Durov diagram which is a double trilinear plot of the major anions and cations. Fig. 8.2 shows an expanded form of a Durov diagram upon which all samples used in this study are shown and plotted. The concentrations (as percentages) of the cations Na + K, Ca and Mg are plotted on the upper expanded triangle. Lines drawn from these two points for any one water sample intersect at right angles in the square. It will be noted that most samples fall [illegible]



HYDRO.-CHEMICAL SAMPLING NETWORK

FIG 8.1



EXPANDED TRILINEAR DUROV DIAGRAM OF GROUNDWATER IONIC PROPORTIONS

An expanded, half-scale, double, trilinear plot of major cations and anions as percentages. Lines drawn from proportional plotting positions in the triangles meet within the square to indicate families of similar water types.

Fig. 8.2

fields whereas only relatively few points fall within the Mg-HCO_3 and the Ca-HCO_3 fields.

The grouping of the analyses into different water types cannot be accomplished by a simple inspection of the Durov diagram and for further interpretation a classification system was specially designed for this purpose. To classify waters into groups has always the disadvantage that boundary lines have to be defined which may often prove to be both arbitrary and unnatural. Furthermore, most standard classification systems have the disadvantage that stagnant, rather than dynamic, features of the groundwater chemistry are included. In an attempt to overcome these problems a classification system based on the following terminology was therefore devised;

- SEQUENCE has been adopted to represent the variation of chemical composition of waters, controlled by lithology, from the recharge area to the coastal saline zone. No specific flow direction of waters is inferred; rather it denotes a typical chemical evolution of waters reconstructed from various samples at different locations.

- ZONE has been adopted for an area where a certain chemical processes is dominant. This is often, but not necessarily, associated with the range of total dissolved solids.

- AQUIFER are the hydrogeological units.

The two terms SEQUENCE and ZONE which encompass the entire range of available chemical variation, are not fixed by one chemical parameter nor by composition. Thus chemical composition of the water may change within one ZONE and the dominant chemical process may change within one SEQUENCE.

Fig. 8.3 shows the application of this terminology to the aquifer system.

SEQUENCE 1 represents the range of chemical composition of water entirely within the carbonate facies of the Rus Formation (Aquifer 1) and SEQUENCE 2, the composition of water within the sulphate facies. Both may be seen as envelopes to the actual chemical composition since mixing between carbonate and sulphate facies waters takes place.

The three zones shown in Fig. 8.3 were defined only after the full analysis had been completed as they were not obvious at the outset. These are now defined as;

- ZONE A the recharge zone containing low salinity waters. It is the zone where no ion exchange or reverse ion exchange occurs and is approximately contained by the 1000 mg/l isosalinity line (Encl. 2).

- ZONE B Ion exchange (EX) processes, accompanied by a rapid increase in salinity, due to the solution of evaporites are the principal features of this zone where the salinity ranges from 1000 mg/l to 5000 mg/l. Some significant recharge is believed to occur.

- ZONE C The high salinity zone adjacent to the coast where salinities range from 3000 mg/l to greater than sea water values (40,000 mg/l). These waters may be classified as 'reversed ion exchanged' when compared to sea water composition.

The zones are also shown in Fig. 8.4. The area where ZONE B and ZONE C overlap has been denoted the 'interface zone' in the TDS range of 3000 mg/l to 5000 mg/l. It should be noted, however, that these are limiting values and not a fixed range and that the position, as well as the width, of the 'interface zone' varies from place to place.

All samples identified as belonging to Aquifer II, or to the Alat Formation are plotted on separate major ion diagrams. All basic chemical plots as well as some of the Durov plots have been produced by a computerised graphic plotter from a computer programme specially developed for this study. The symbols used in these computer plots are :

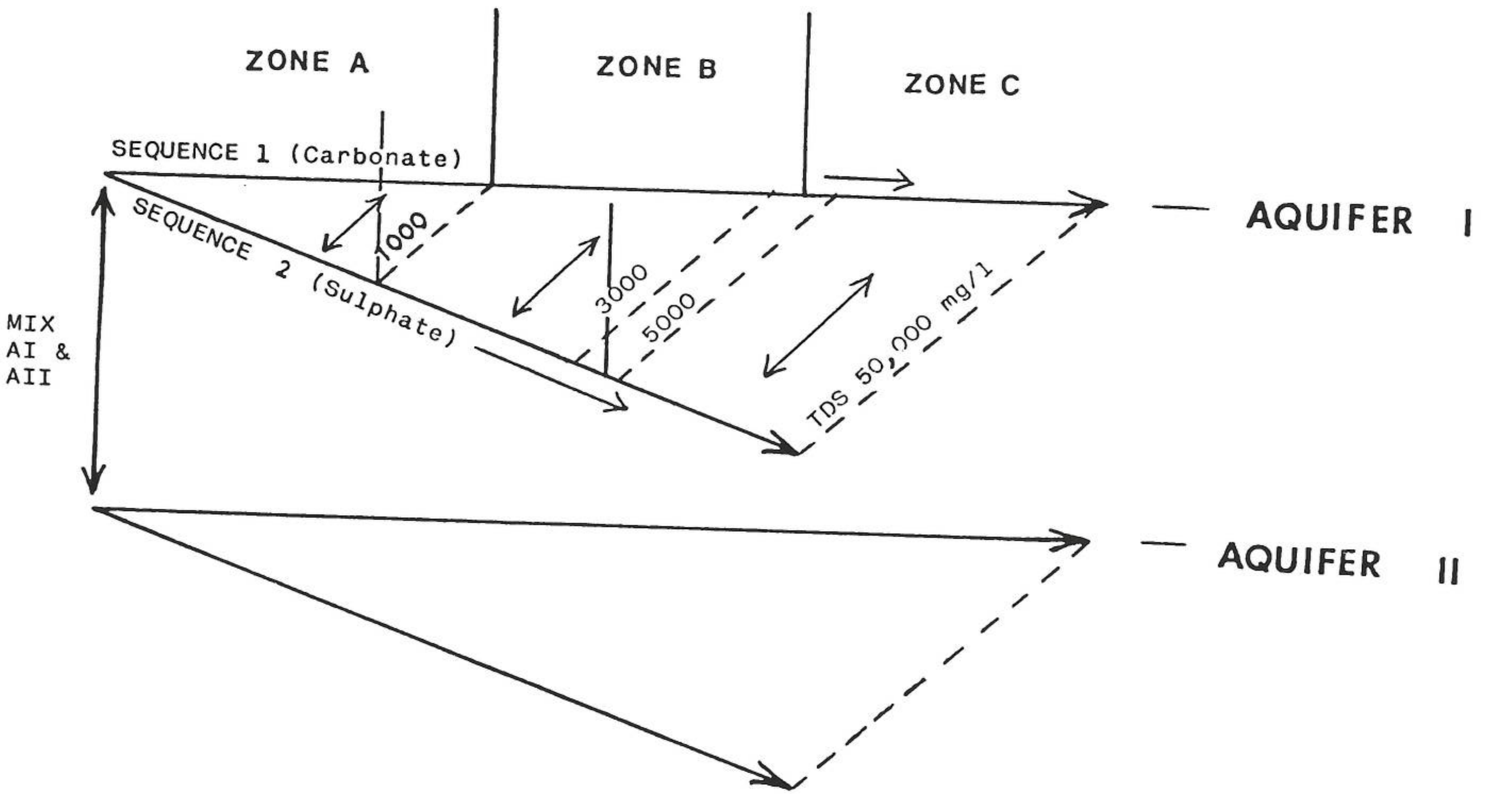
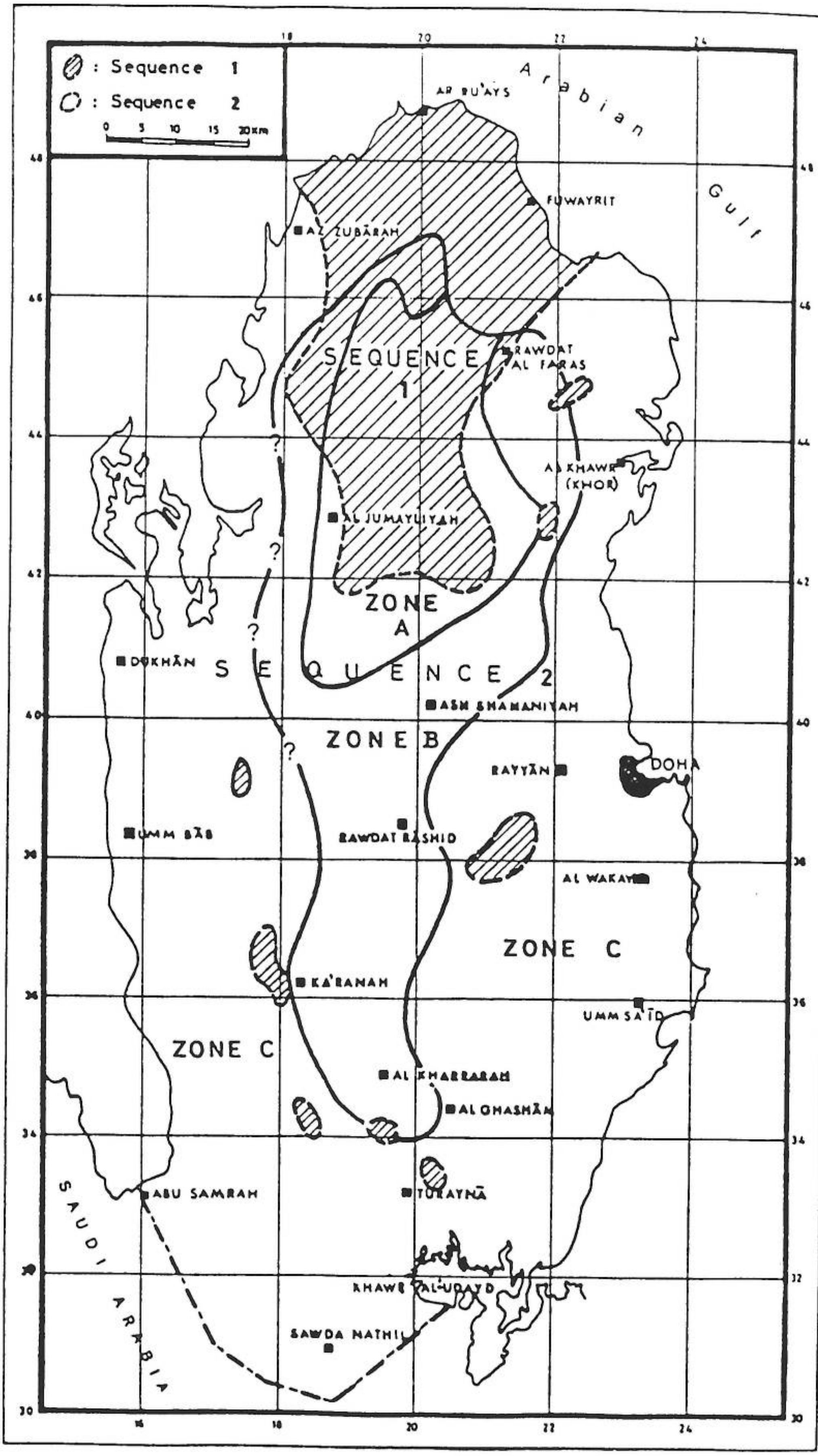


FIG 8.3 CONCEPTUAL DIAGRAM FOR HYDROCHEMICAL ANALYSIS



WATER TYPE DISTRIBUTION

Fig. 8.4

△	=	AQUIFER I SEQUENCE 1 (carbonate)
□	=	AQUIFER I SEQUENCE 2 (sulphate)
◇	=	MIX between AQUIFER I and AQUIFER II
○	=	AQUIFER II
⊞	=	ALAT AQUIFER
⊠	=	SEA WATER (Doha or Salwah)

8.4.2 Total Dissolved Solids (TDS)

The addition method was used to calculate TDS values since those obtained by the evaporation method were in considerable error especially for the low TDS waters.

The calculated value of each of the samples, together with other data, have been used to construct the Isosalinity recharge zone to over 10,000 mg/l towards the coast. If the 1000 mg/l isohaline (line of equal concentration) be regarded as the higher limit of the recharge zone, it may be noted that it not only encloses the carbonate facies area but extends into the sulphate facies of the Rus Formation as well. Small localised bodies with water salinities of 1000 mg/l are also found in the sulphate facies are of southern and south-western Qatar indicating recharge through collapse structures and in deflated areas. West of Doha, the isohalines curve inland from the east coast and are associated with the generally low piezometric levels where over-extraction and saline water intrusion or up-coning are taking place.

8.4.3 Electrical Conductivity (EC)

Electrical conductivity, or conductance, provides a method whereby the total effect of the presence of charged ion species may be measured simply and directly. The standard unit for expressing conductance (EC) is Siements/metre ($S.m^{-1}$). The Siemens is the inverse of the Ohm, the measure of electrical resistance. Because of its fairly recent introduction this new unit has not yet been widely adopted and it has been found convenient to retain the well known unit "micromho" (as $\mu mho.cm^{-3}$) which is equivalent to $\mu S.cm^{-3}$. The conductance of the solution increases with increase in ion concentration and EC values are strongly correlated with the TDS content of the water. This is commonly taken as TDS (mg/l) equivalent to 0.54 x EC ($\mu mho/cm^{-3}$ at 25°C.); although this relationship does not hold for high TDS values where the factor may exceed 1.00 (See Sec, 11.1.1).

For Qatar, the following linear relationship has been determined for salinity levels less than 10,000 EC.

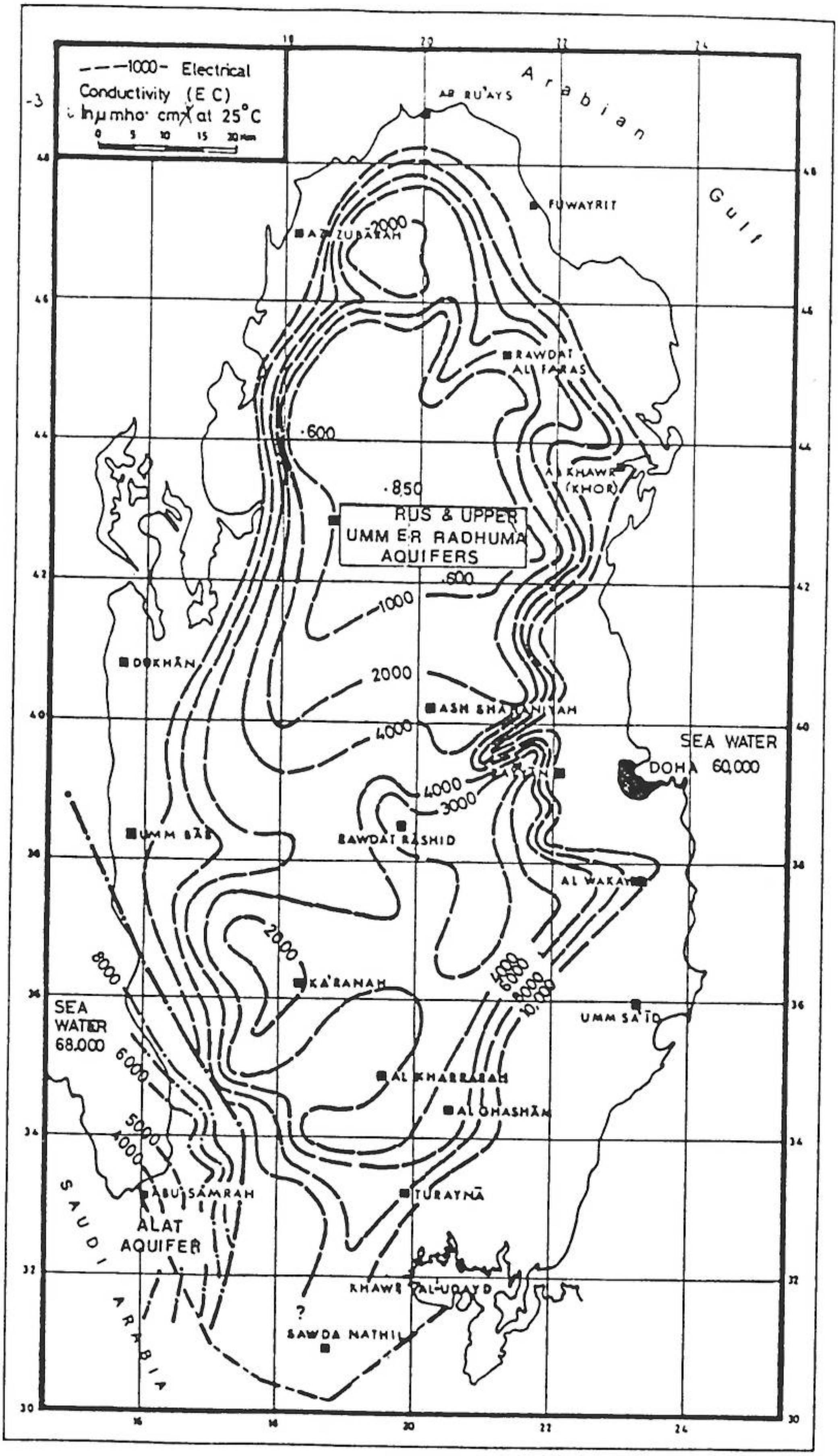
$$(TDS/mg/l) = 0.81\ EC\ (\mu mhos.cm^{-3}\ at\ 25^{o}C.) - 39.43$$

with a coefficient of determination of 0.98.;

A simplified factor, with a somewhat lower coefficient of determination, but of general application is

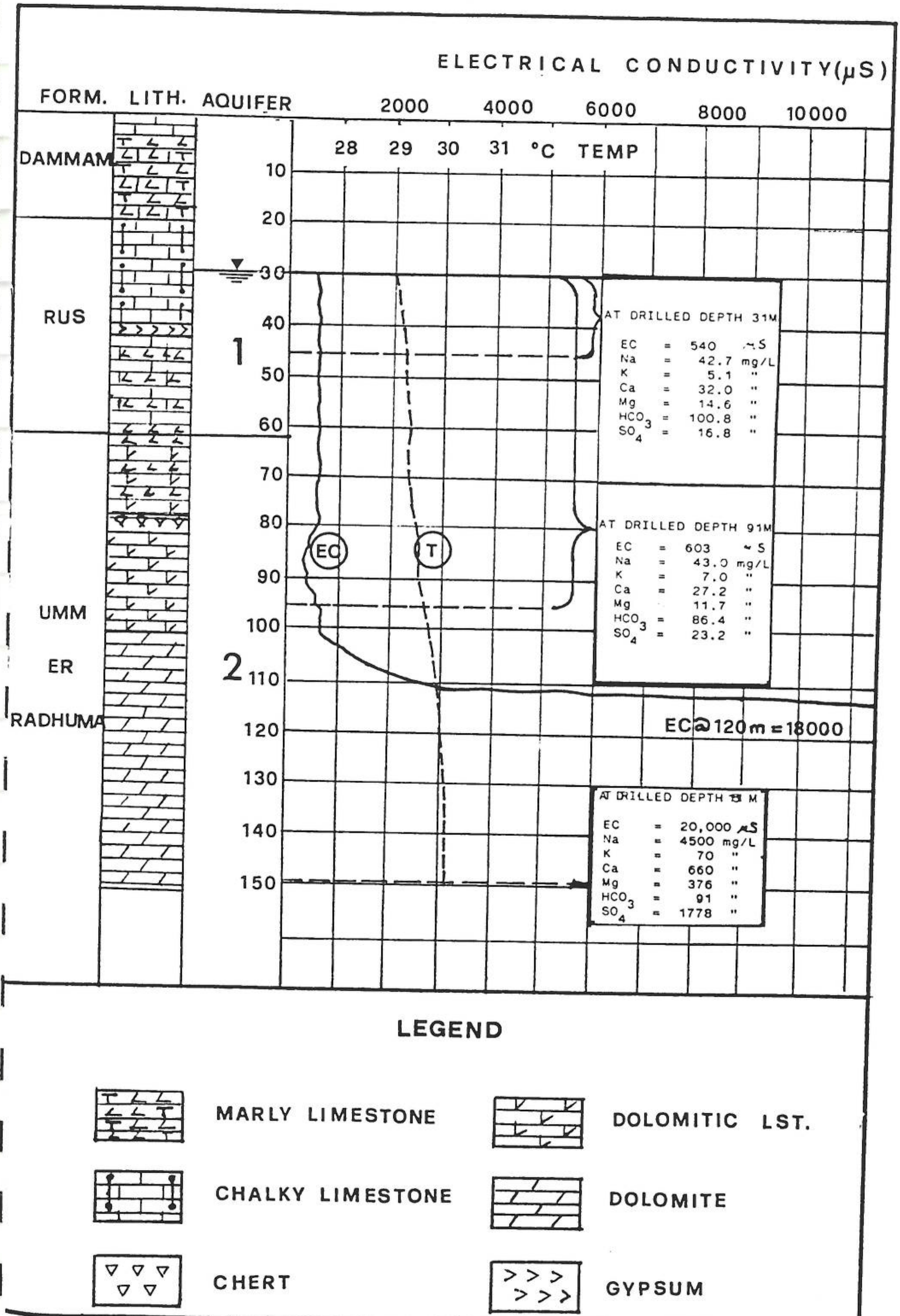
$$TDS = 0.75\ EC\ at\ 25^{o}C.$$

Fig. 8.5 shows the electrical conductivity of groundwater underlying Qatar which, as is to be expected, closely follows the map bases on TDS with the lowest values in the northern recharge zone, increasing towards the coast. Both these maps portary the spatial distribution of the salinity of the mixed waters from both the Rus and the upper Umm er Radhuma Formations which together constitute Aquifer I. In considering the TDS and EC maps note must be made of the fact that certain of the samples probably represent mixed waters drawn by pumping from different aquifer levels.



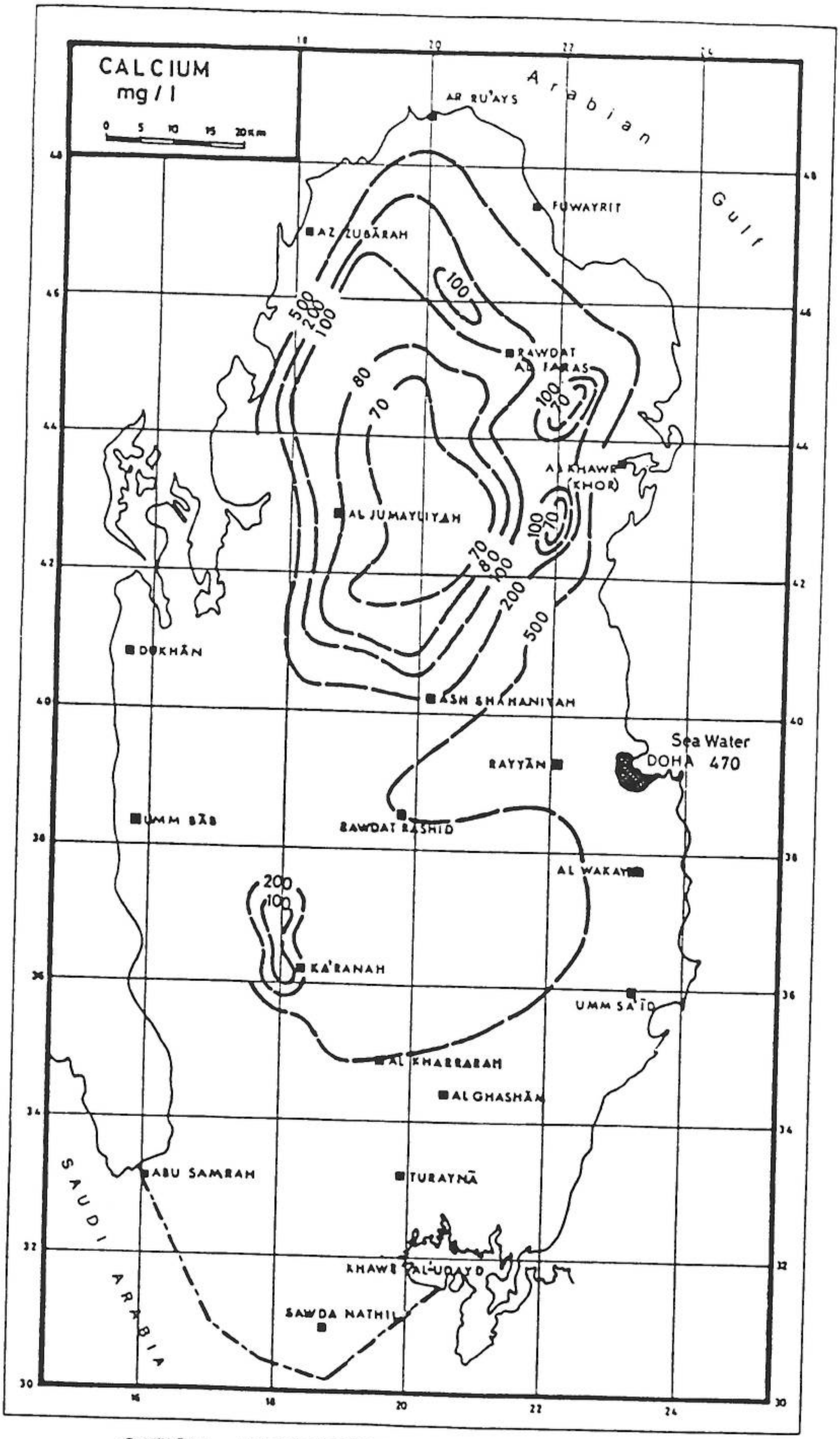
ELECTRICAL CONDUCTIVITY OF GROUNDWATER (SEPT-OCT 1980)

Fig. 8.5



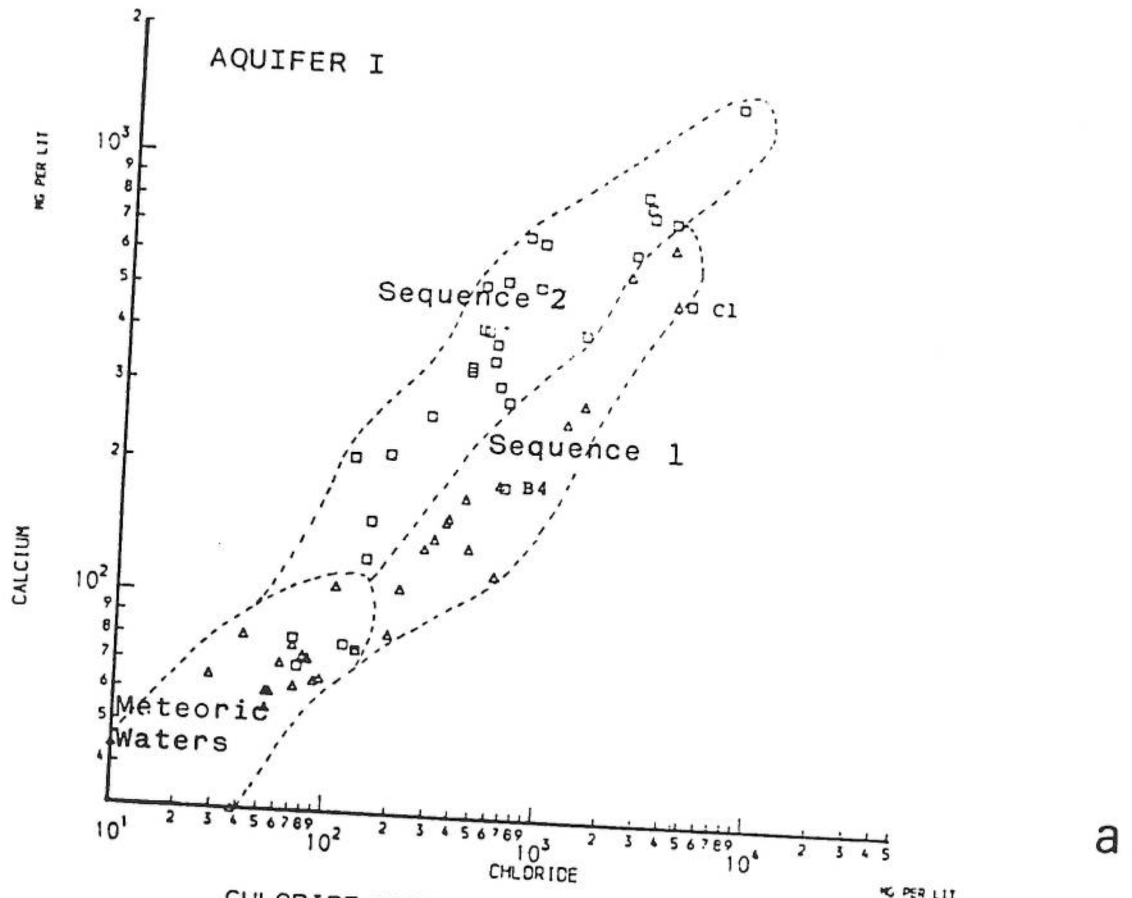
ELECTRICAL CONDUCTIVITY, TEMPERATURE AND HYDROCHEMICAL DATA — WELL No. P22A

Fig: 8.6

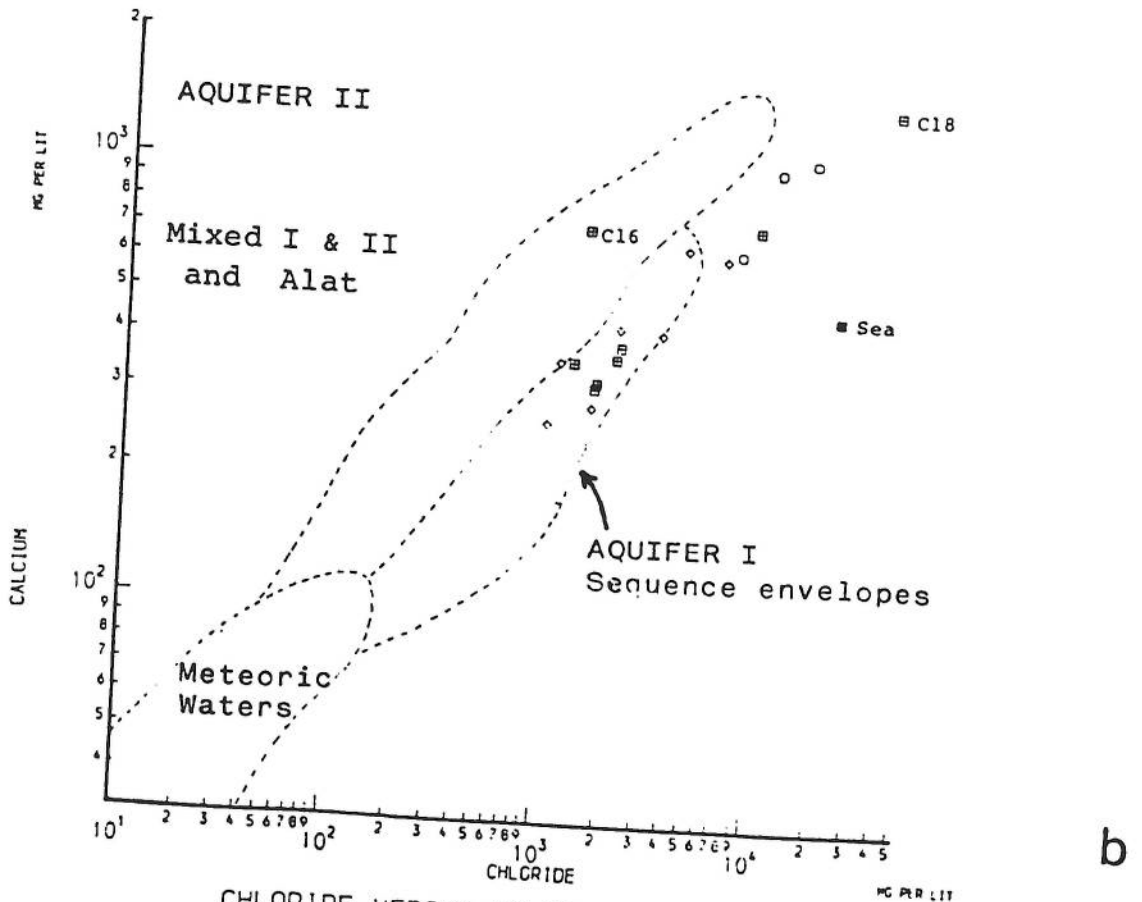


CATION DISTRIBUTION MAP

Fig. 8.7



CHLORIDE VERSUS CALCIUM



CHLORIDE VERSUS CALCIUM

An example of salinity change with depth is given as Fig. 8.6 which shows electrical conductivity and temperature profiles for the Project exploration well P22a together with hydrochemical, lithological, formational and aquifer information. Vertical groundwater movement between Aquifers I and II is retarded by the higher than usual clay content of the Rus Formation and some residual gypsum. A marked and abrupt change in salinity is noted within the Umm er Radhuma Formation, which is considered to be associated with hydraulic continuity layering within the formation. The diffuse or transitional salinity zone often associated with an aquifer of uniform permeability conditions is not apparent.

8.4.4 Calcium (Ca^{2+})

Calcium most commonly occurs in sedimentary rocks as the carbonates; calcite ($CaCO_3$), dolomite ($CaMg(CO_3)_2$ and the sulphates; gypsum ($CaSO_4.2H_2O$) and anhydrite ($CaSO_4$) and invariably enters into solution as the divalent Ca^{2+} ion.

In Qatar the limestones of the Rus Formation carbonate facies, the dolomites of the Umm er Radhuma Formation and the gypsum and anhydrite beds of the Rus sulphate facies is shown in (Fig. 8.7) by lines of equal concentration. Within the northern recharge area concentrations are usually less than 100 mg/l. Within the carbonate facies of the Rus Formation 500 mg/l calcium ion concentration coincides with a TDS of about 7000-8000 mg/l, whereas, outside the carbonate area, (especially towards the south-east), the 500 mg/l concentration is found at TDS values of about 3000-4000 mg/l. This suggests that outside the recharge zone the major calcium sources are the gypsum and anhydrite beds of the sulphate facies as would be expected.

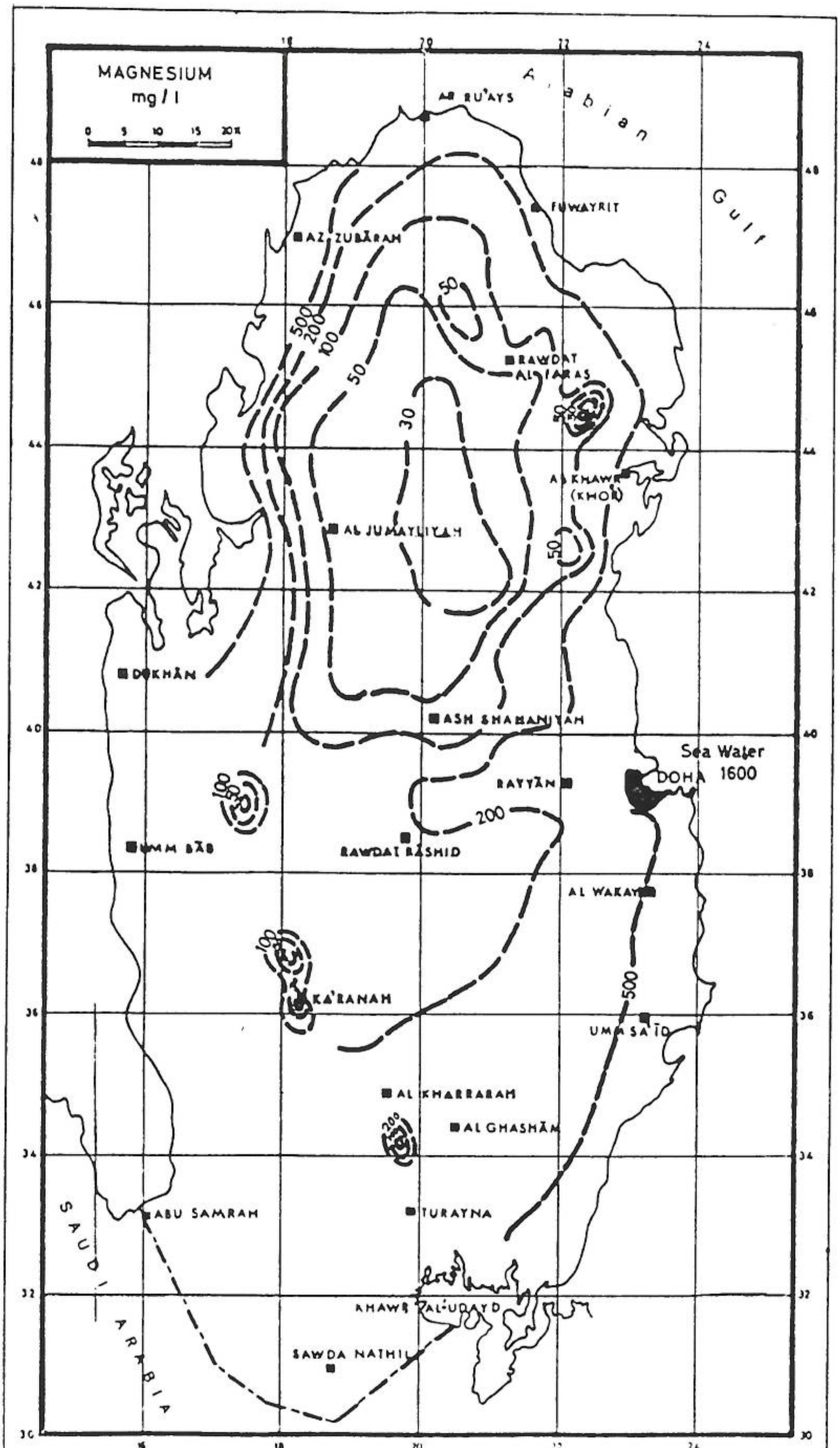
Fig. 8.8 shows plots of chloride versus calcium for Aquifer I (in a) and Aquifer II (in b). For the low chloride (or meteoric) waters of Aquifer I there is little variation in calcium content between Sequences 1 and 2. However, for chloride values above 100 mg/l as the water travels further from the point of recharge, the two different flow paths are clearly distinct; higher calcium is found in Sequence 2 waters,due to the higher solubility of gypsum and anhydrite, compared to the carbonates present in Sequence 1. Only the analyses for well C1 from the Sequence 2 area, (but believed to be contaminated by sea water), show a chloride/calcium ratio similar to Sequence 1. Fig. 8.8(b) shows that the mixed Aquifer I and II waters (and the mixed Aquifer I and II waters, Aquifer II waters (and the Alat aquifer water which are included because of strong similarities) all have a lower chloride/calcium ratio than Aquifer I Sequence 2 due to the relative absence of sulphates in these formations.

8.4.5 Magnesium (Mg^{2+})

Sedimentary occurrences of magnesium inclue mixtures of magnesium with calcium carbonate. This is mainly dolomite, $CaMg(CO_3)_2$, where calcium and magnesium are present in equal amounts, although other forms of magnesium may exist particularly in association with sulphate.

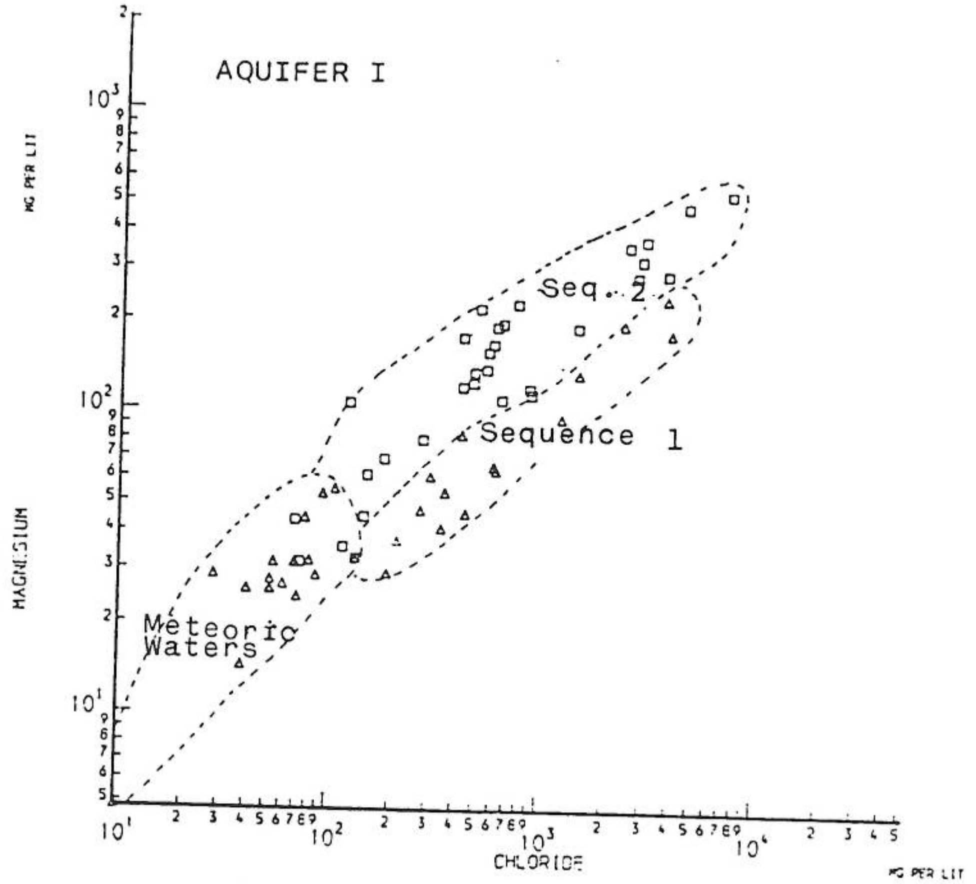
Fig. 8.9 portrays magnesium ion distribution which closely follows that of calcium. The lowest values (<50 mg/l) occur within the recharge zone with the highest values near the coast to the north west and south east. However, unlike calcium, magnesium shows only a slight increase within the sulphate facies of the Rus Formation. At about 3000 mg/l TDS the magnesium ion concentrations are 100 mg/l in the carbonate area and 130-160 in the sulphate area.

Fig. 8.10 shows the distribution of the magnesium ion over the whole chloride range and once again the grouping is similar to the calcium/chloride plot. To determine the importance of magnesium in relation to calcium, the calcium/magnesium ratio was plotted against chloride (Fig. 8.11) using a conversion from calcium/magnesium (mg/l) to milliequivalents per litre (meq/l) of 1.648. If pure dolomite dissolution was taking place the Sequence 1 waters would lie along this line indicating the contribution of the Umm er Radhuma waters. However, this is only valid for the lower TDS waters since the higher TDS waters are probably mixed with seawater as indicated by decreased calcium/magnesium ratio. The Aquifer I Sequence 2 waters indicate a large variation in lithology within the gypsiferous Rus Formation. The samples of C1 and B4, believed to be mistures with sea water have a low calcium/magnesium ratio trending towards the low sea water value. In the Aquifer II waters, dolomite dissolution whithin the



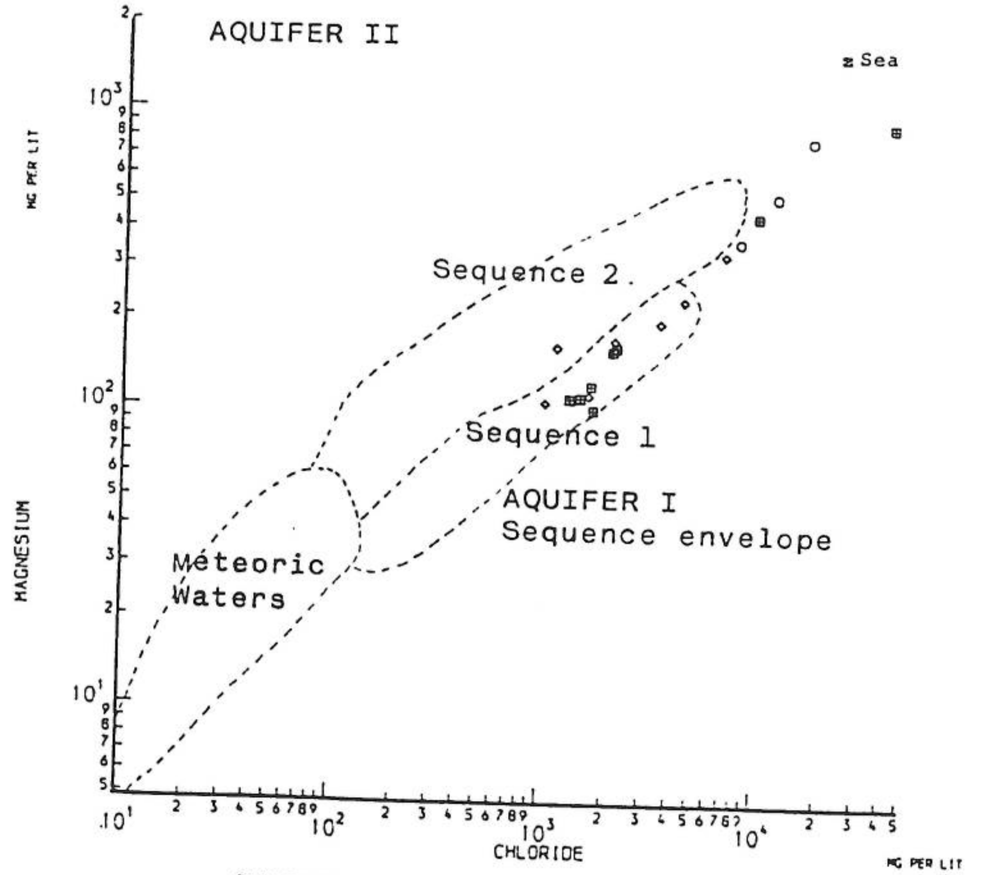
CATION DISTRIBUTION MAP

Fig. 3.9



CHLORIDE VERSUS MAGNESIUM

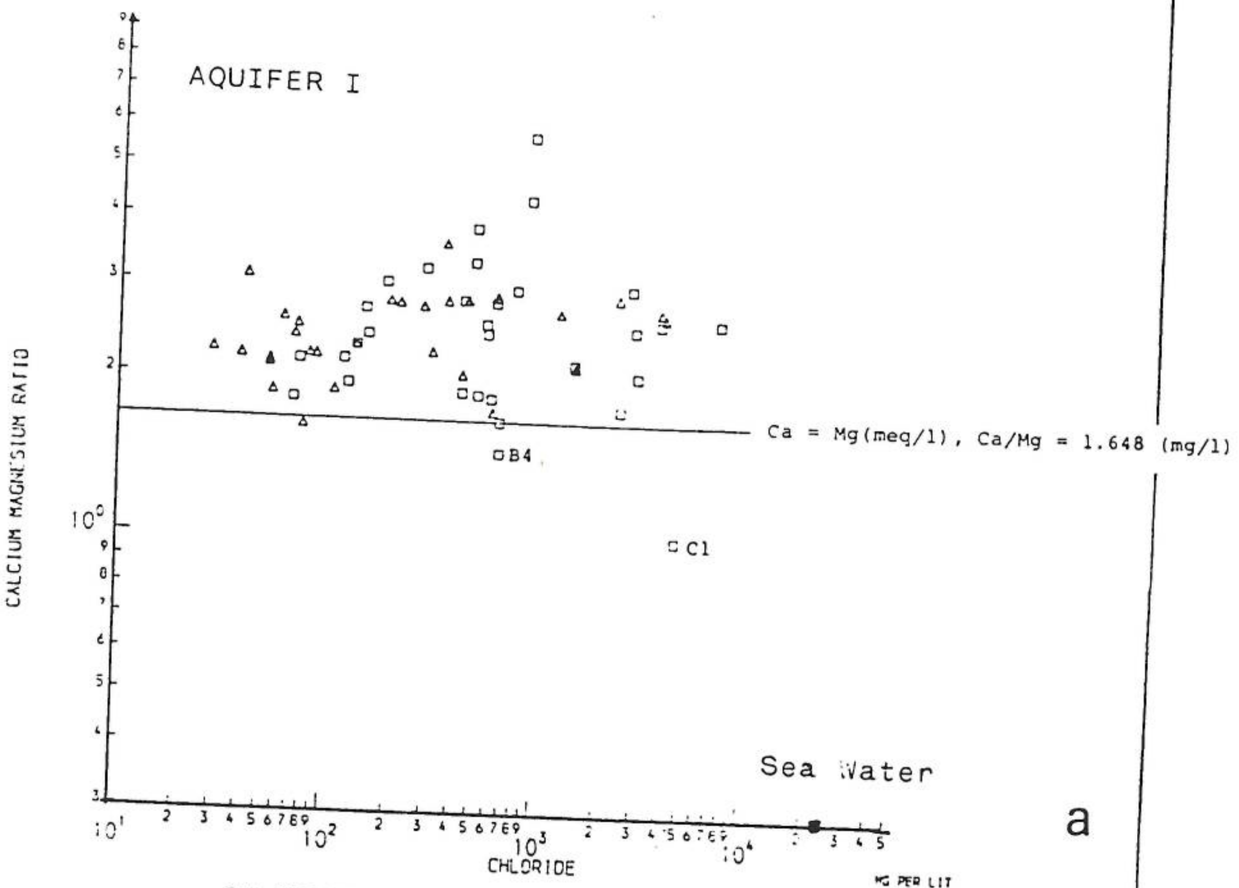
a



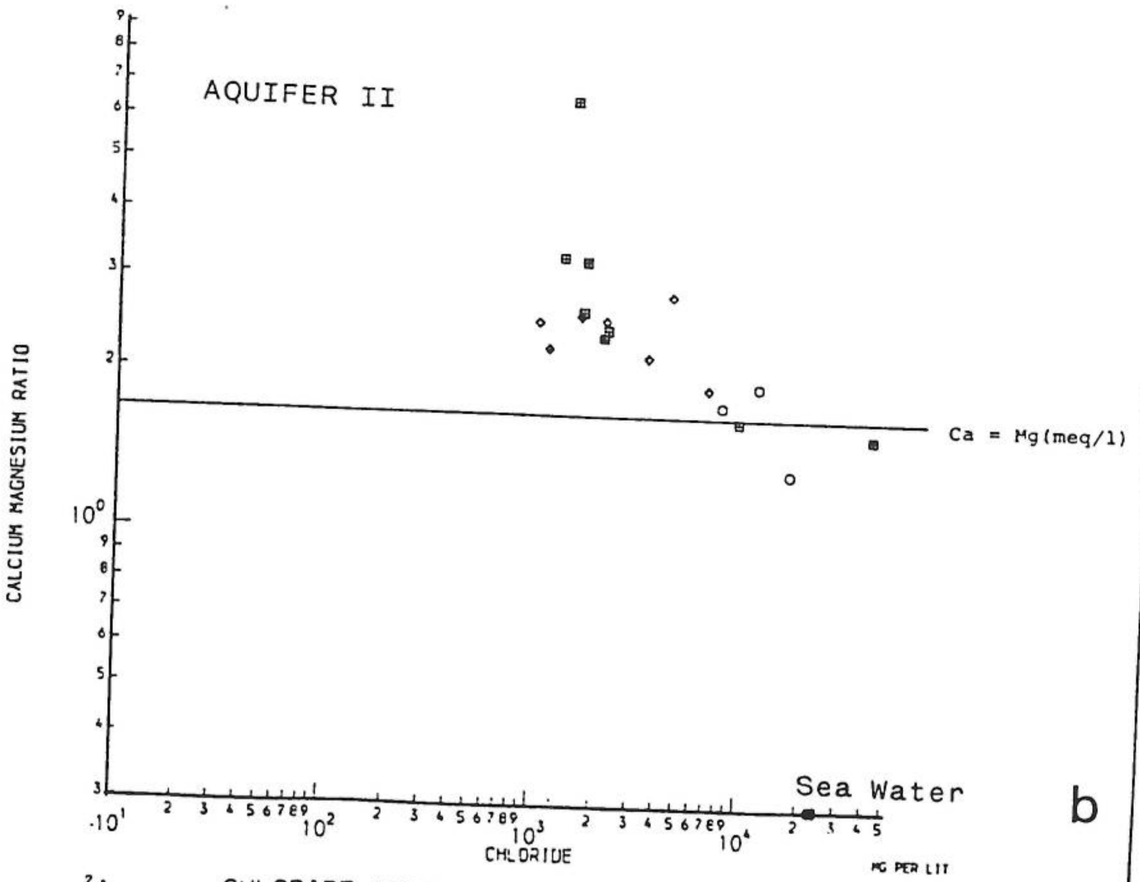
CHLORIDE VERSUS MAGNESIUM

b

Fig. 8.10

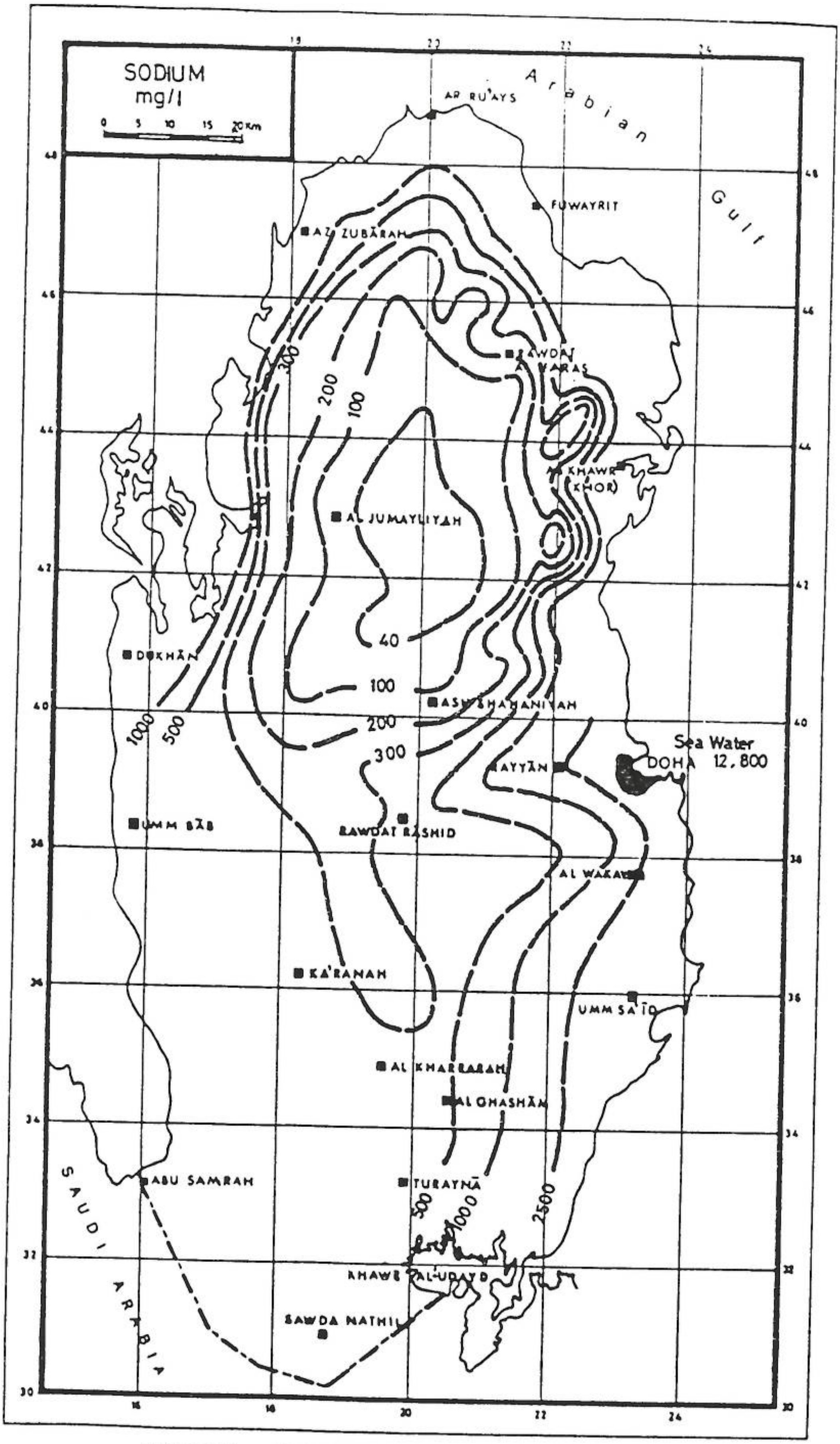


CHLORIDE VERSUS CALCIUM/MAGNESIUM RATIO



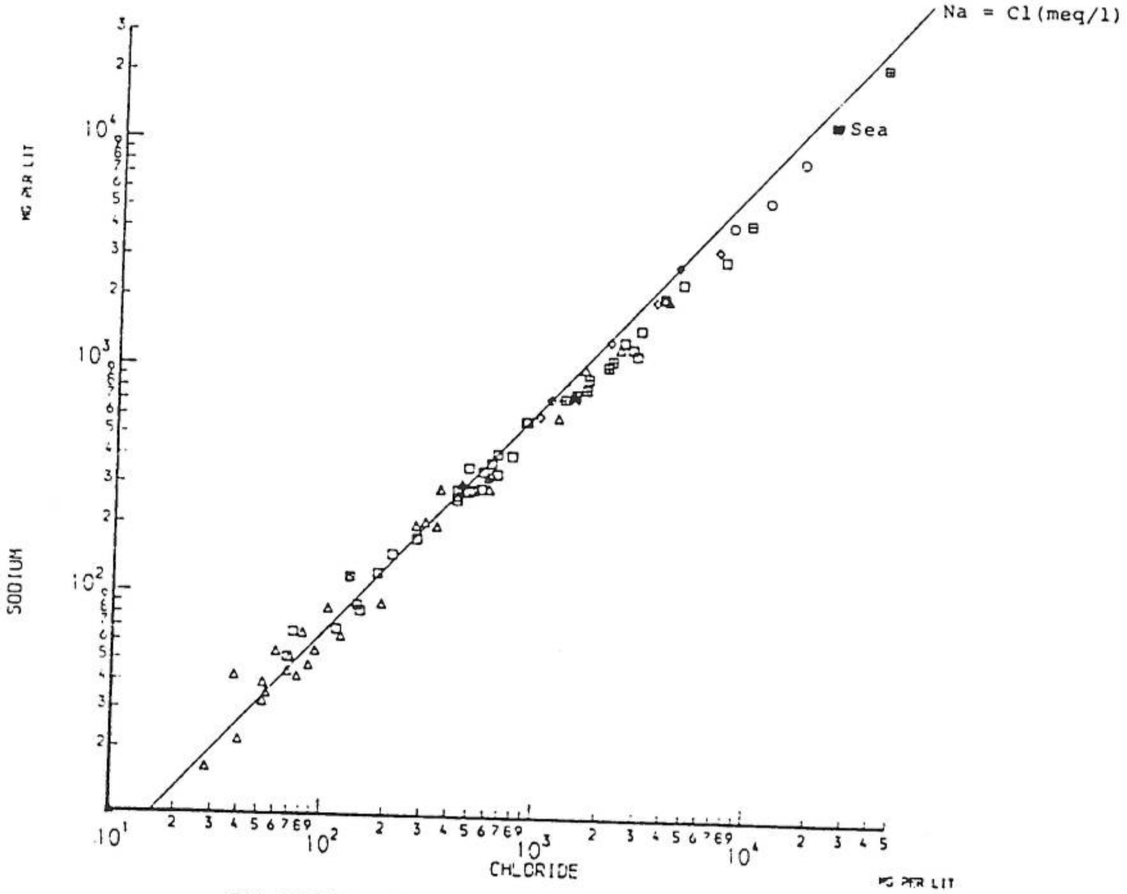
2. CHLORIDE VERSUS CALCIUM/MAGNESIUM RATIO

Fig. 8.11



CATION DISTRIBUTION MAP

Fig. 8.12



CHLORIDE VERSUS SODIUM

Fig. 8.13

Umm er Radhuma Formation is evident from the low calcium/magnesium ratios from these samples. The Alat Aquifer samples show higher ratios than the underlying Umm er Radhuma which would tend to indicate mixing with recently recharged water. This is somewhat anomalous as one of the same samples also shows a depleted isotope content, indicating the considerable age of the sample (see Table 9.2). However, within the area of well No. P32, from whence the sample was taken, there is an anomalous mound which could only be derived from recent recharge, possibly from the eastern outcrop of the Alat aquifer.

8.4.6 Sodium (Na^+)

Sodium invariably occurs in the form of Na^+ cations and is generally associated with Cl^- anions as NaCl. When sodium is dissolved, it tends to remain stable in solution since no natural precipitation reactions, which can maintain low sodium concentrations in water, are known although clays may retain sodium adsorbed to their surface and may possibly exchange it for other cations, e.g. calcium or magesium (Hem, 1970).

The sodium ion distribution map (Fig. 8.12) is similar to that of other major ions with low values in the recharge area and rapid increases towards the coast, as well as in the area to the west to Doha.

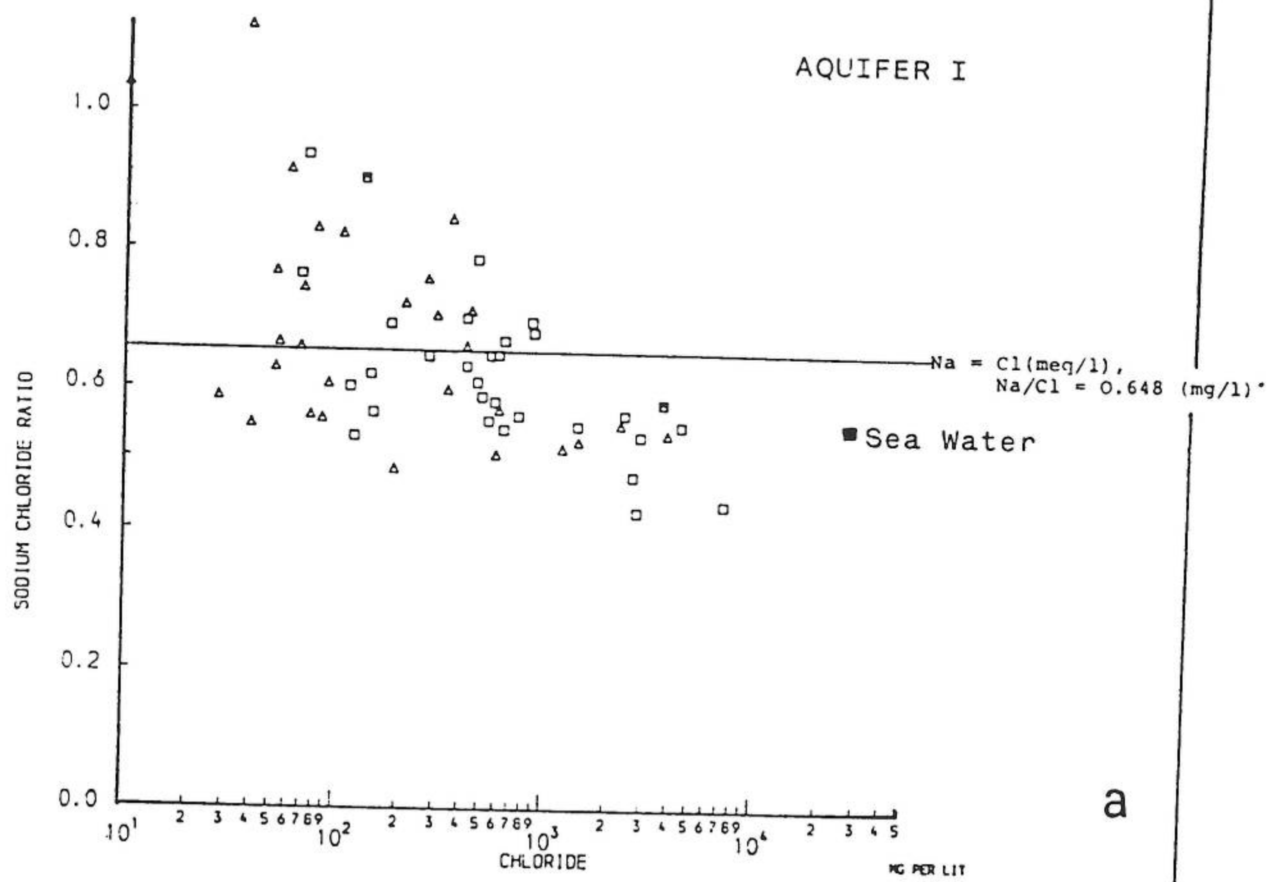
The typically close correlation between sodium and chloride is shown in Fig. 8.13. However, as the scales are logarithmic, only relatively large variations may be apparent and any evidence for possible ion exchange should therefore be sought in Fig. 8.14 (a) and (b) which shows plots of the sodium/chloride ratio against chloride (mg/l) for both aquifers. While there is an apparent large variation in this ratio for low chloride waters, (due to the low concentration of sodium and chloride in the meteoric waters), the higher chloride waters ($>$ 1,000 mg/l) in ZONE C show a considerable deviation from the Sodium/chloride (mg/l) line, suggesting the possibility of reversed ion exchange. The plotted position of the seawater sample serves to indicate that the sodium/choride ratios of most high chloride waters are not to mixing betweeen imbalanced seawater and a balanced recharge water, but rather reversed ion exchange as part of the process of modern seawater intrusion into the Rus Formation. Similarly, plot (b) also shows higher chloride waters of the Umm er Radhuma and the Alat aquifers which can also be considered to have suffered reversed ion exchange when compared to sea water.

8.4.7 Potassium (K^+)

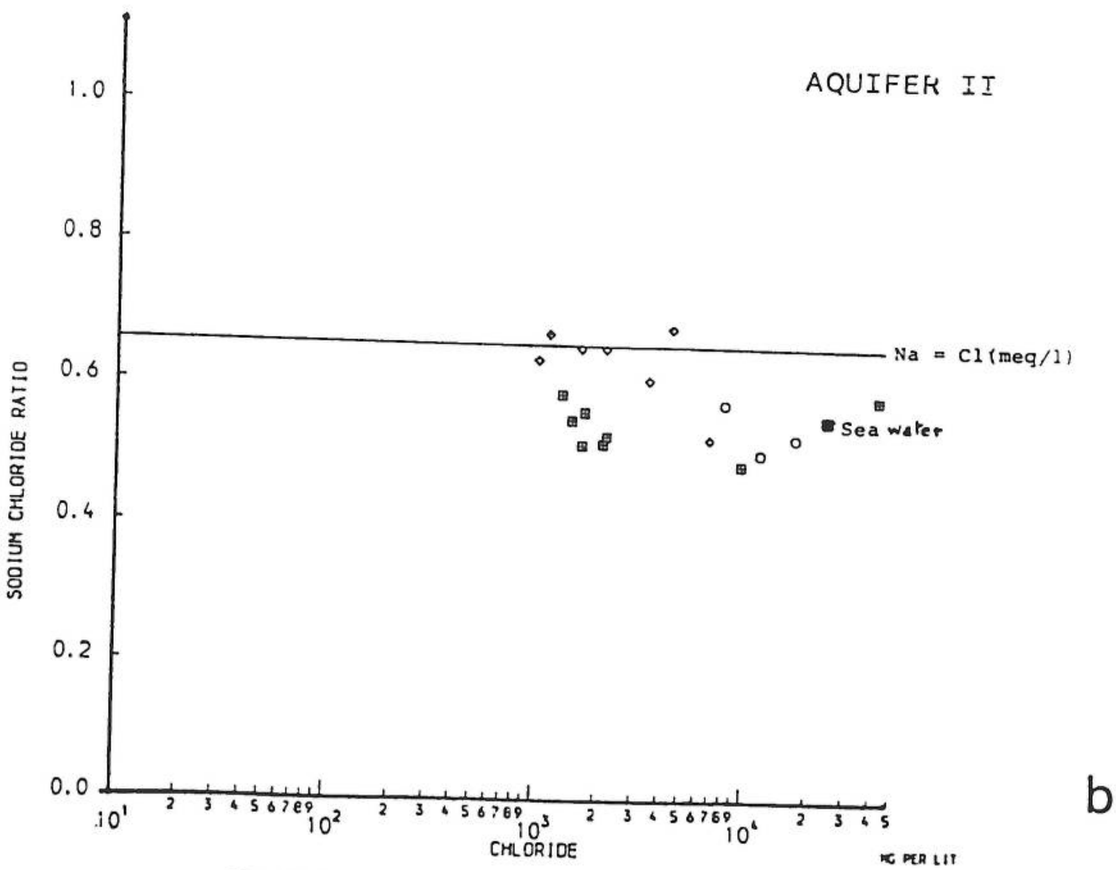
Although chemically similar, potassium has a very different hydrochemical behaviour to that of sodium and in natural waters its concentration is very much lower. Qatar groundwaters show concentrations of 10 mg/l in the northern recharge area which increase rapidly to about 200-300 mg/l towards the coast. The most probable source of potassium is minor occurrences of potassium salts in evaporite deposits, although their distribution in Qatar does not show any apparent relationship to known lithological provinces. For Aquifer I, potassium correlates well with chloride occurrence as shown in Fig. 8.15 (a) where the plots group in a fairly narrow cluster along the straight fitted dissolution line. The same applies for potassium in Aquifer II (the Umm er Radhuma and the Alat (in (b)) with a slight tendency to lower values.

8.4.8 Chloride (Cl^-)

Chloride is widely distributed in natural waters and accounts for a high proportion of the anions in high TDS waters. Possible sources of chloride are sedimentary rocks, particularly the evaporites. Any marine sediment that has been flushed completely by freshwater will contain remnants of salts, mainly sodium chloride. Since chloride ions remain chemically unreactive in the groundwater environment the chloride content of water can be used to normalize various other parameters as well as a calibration for comparisons between different waters. All major and minor ions have therefore been plotted against chloride to provide a means of comparison between different parameters.



CHLORIDE VERSUS SODIUM CHLORIDE RATIO



CHLORIDE VERSUS SODIUM CHLORIDE RATIO

Fig. 8.14

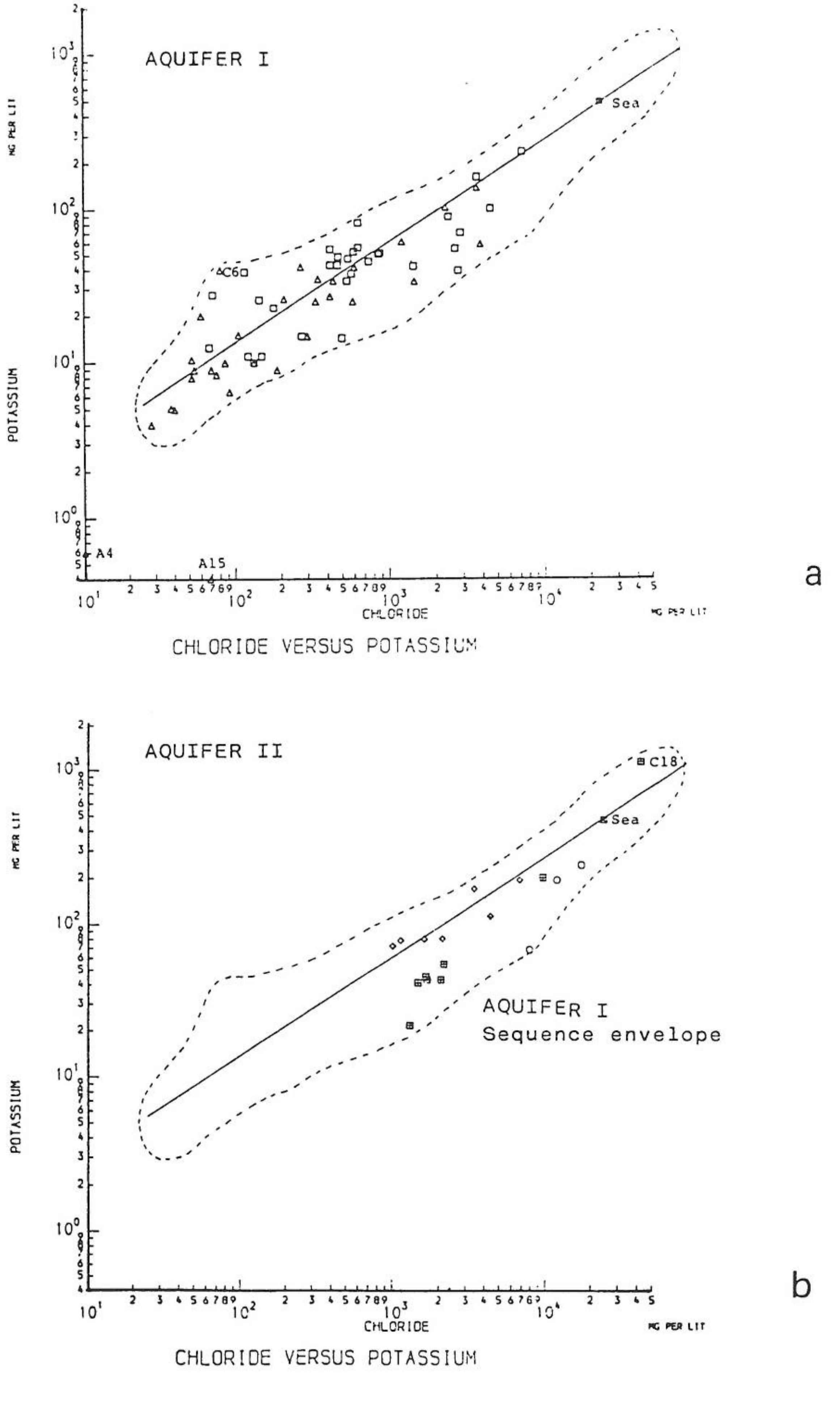

AQUIFER I
Sea
C6
A4
A15
POTASSIUM
MG PER LIT
CHLORIDE
MG PER LIT
CHLORIDE VERSUS POTASSIUM
a
AQUIFER II
C18
Sea
AQUIFER I
Sequence envelope
POTASSIUM
MG PER LIT
CHLORIDE
MG PER LIT
CHLORIDE VERSUS POTASSIUM
b

Fig. 3.15

Fig. 8.16 shows the distribution of the chloride ion over the peninsula where it ranges from less than 40 mg/l in the recharge zone to about 17,000 mg/l on the coast, in pattern closely resembling that of sodium. The chloride levels are higher within the carbonate facies of the Rus Formation and, as it is to be expected, the high TDS waters within this area contain a greater percentage of chloride than water in the sulphate facies area and a similar percentage of sulphate.

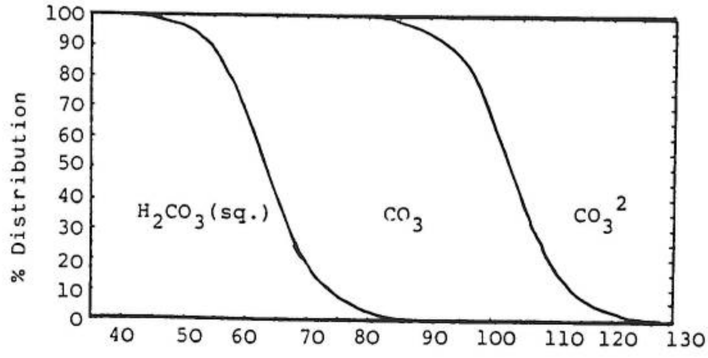
8.4.9 Sulphate (SO_4^{2-})

Sulphate may become a major, if not predominant, anion in waters where gypsum and anhydrite deposits are under active dissolution; the case in waters of SEQUENCE 2 in areas of the sulphate facies. Sulphate ion concentrations in waters of the same TDS are higher in these areas (Fig. 8.17A) than in the carbonate facies area. A similar patter is shown in Fig. 8.17B where the gypsum saturation index (SIG) is plotted. Gypsum saturation is often reached at sulphate values of about 2000-2500 mg/l although it can occur at 1200 mg/l in freshwater dependent upon the Ionic Strength of Water. For example, seawater is undersaturated with gypsum at a level of 2650 mg/l because the calcium is relatively low for such a high TDS, thus reducing the ion activity product of Ca^{2+} and SO_4^{2-}.

The relationship between chloride and sulphate is shown in Fig. 8.18 (a) and (b) where it may be noted that Sequence 2 waters have higher sulphate/chloride ratio than the Sequence 1 waters mixing line shows that high sulphate concentrations in the groundwater cannot be caused simply by mixing with seawater, but that significant gypsum or anhydrite dissolution must be taking place. A similar plot for the Umm er Radhuma and the Alat aquifer indicates that they contain water with a sulphate/chloride ratio similar to Sequence 1 waters which may be expected, considering their predominant carbonate lithology.

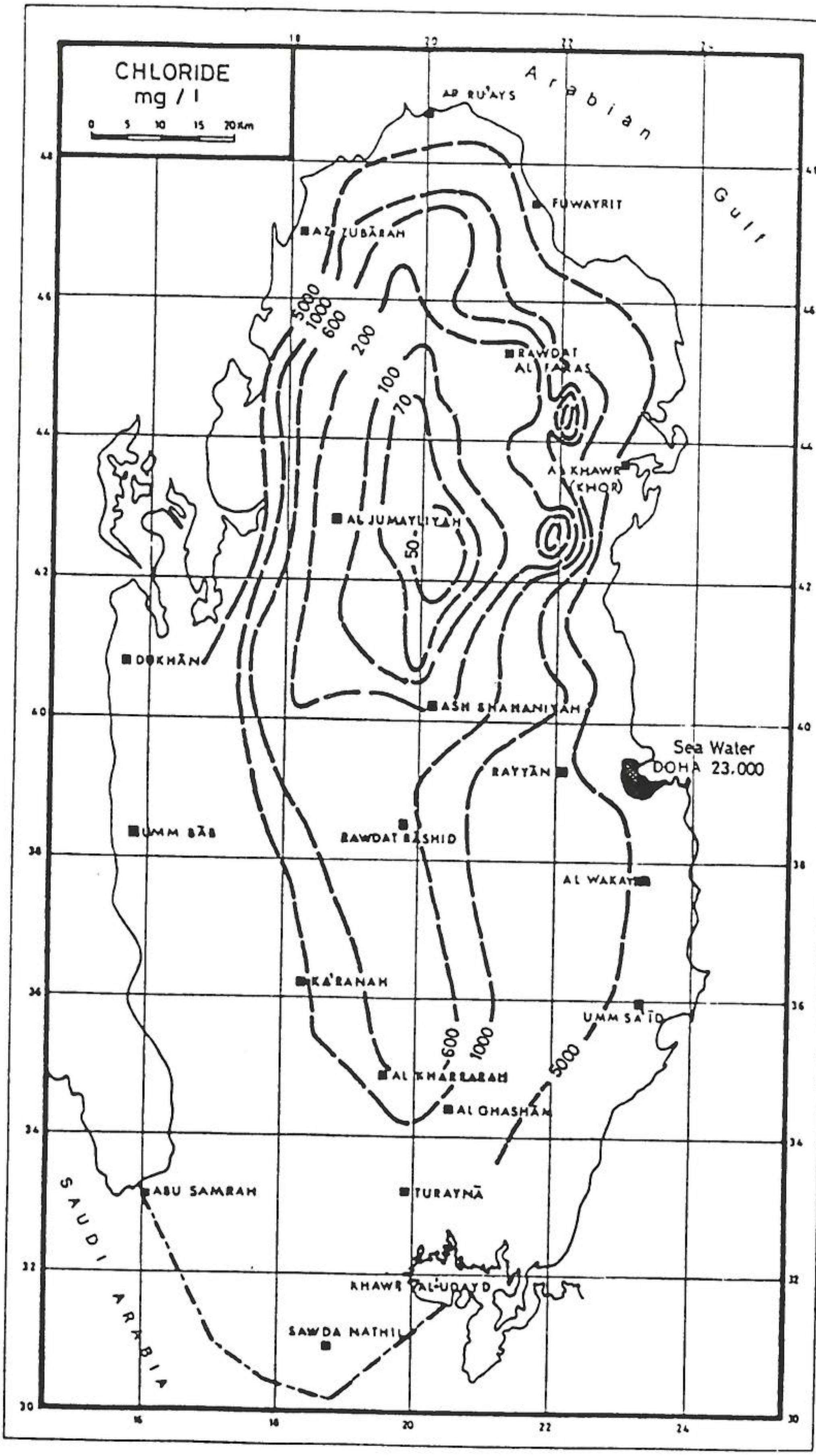
8.4.10 Bicarbonate (HCO_3^-)

The bicarbonate (alkalinity) concentration is an indication of the amount of dissolved carbonates in the water. Under near natural pH conditions HCO_3^- is the major equilibrium species of the total dissolved oxidised carbon (see Fig. 8.19). At a pH of 7, about 18% of the total is H_2CO_3 and 82% is HCO_3^-, whereas at a pH of 8.5 nearly all dissolved carbonate exists in the form of HCO_3^-. The sources of HCO_3^- ion in the water are mainly the limestones and dolomites which make up the greater part of the geological formations of Qatar.



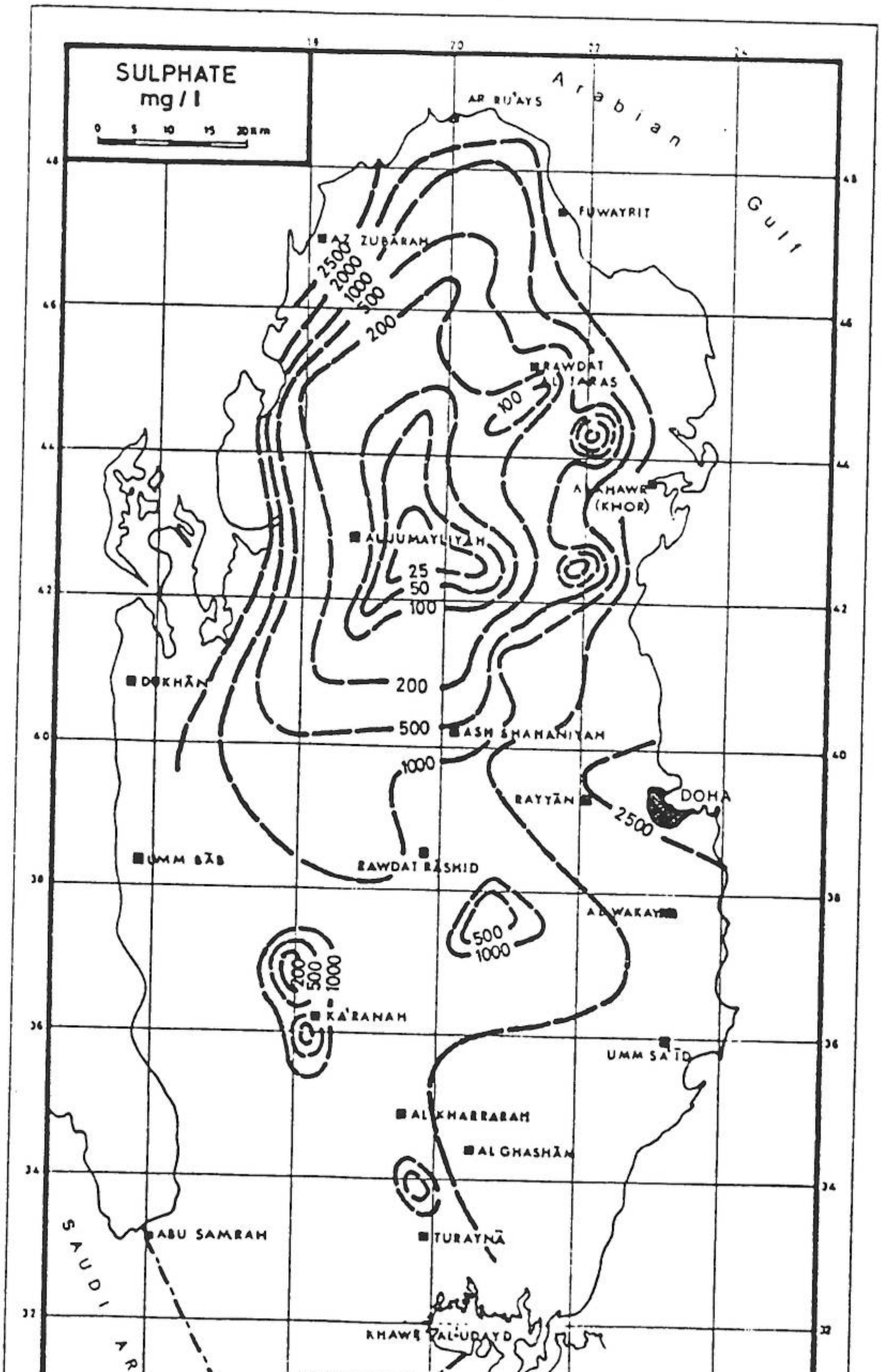
Percentage of total dissolved carbon dioxide species in solution as a function of pH, 25°C., 1 atm. (Hem.1970)

Soil and atmospheric carbondioxide produce a low pH recharge water which reacts to dissolve limestone and dolomite. This process is controlled by the saturation indices of calcite and dolomite - both pH and temperature dependent. As the data show a very high variation over short distances, it is not possible to discern any pattern of distribution of



ANION DISTRIBUTION MAP

Fig. 8.16



ANION DISTRIBUTION MAP

Fig. 8.17a

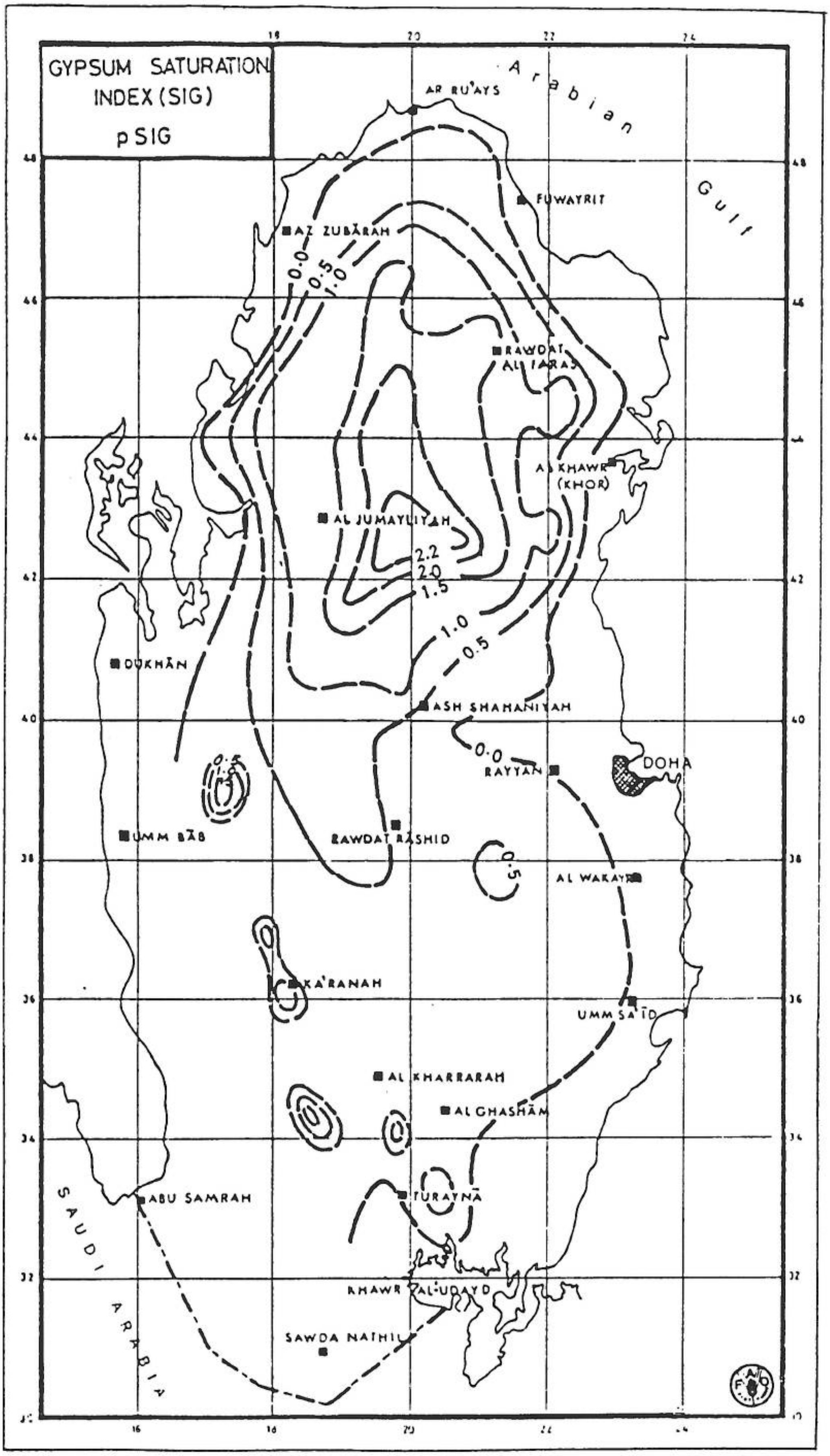

GYPSUM SATURATION INDEX (SIG)
p SIG
Arabian Gulf
AR RU'AYS
FUWAYRIT
AZ ZUBĀRAH
RAWDAT AL FARAS
AL KHAWR (KHOR)
AL JUMAYLIYAH
DUKHĀN
ASH SHAHANIYAH
RAYYAN
DOHA
UMM BĀB
RAWDAT RĀSHID
AL WAKRAH
KA'RANAH
UMM SA'ĪD
AL KHARRARAH
AL GHASHĀM
ABU SAMRAH
TURAYNĀ
KHAWR AL-UDAYD
SAWDA NATHIL
SAUDI ARABIA
0.0
0.5
1.0
1.5
2.0
2.2

Fig. 8.17b

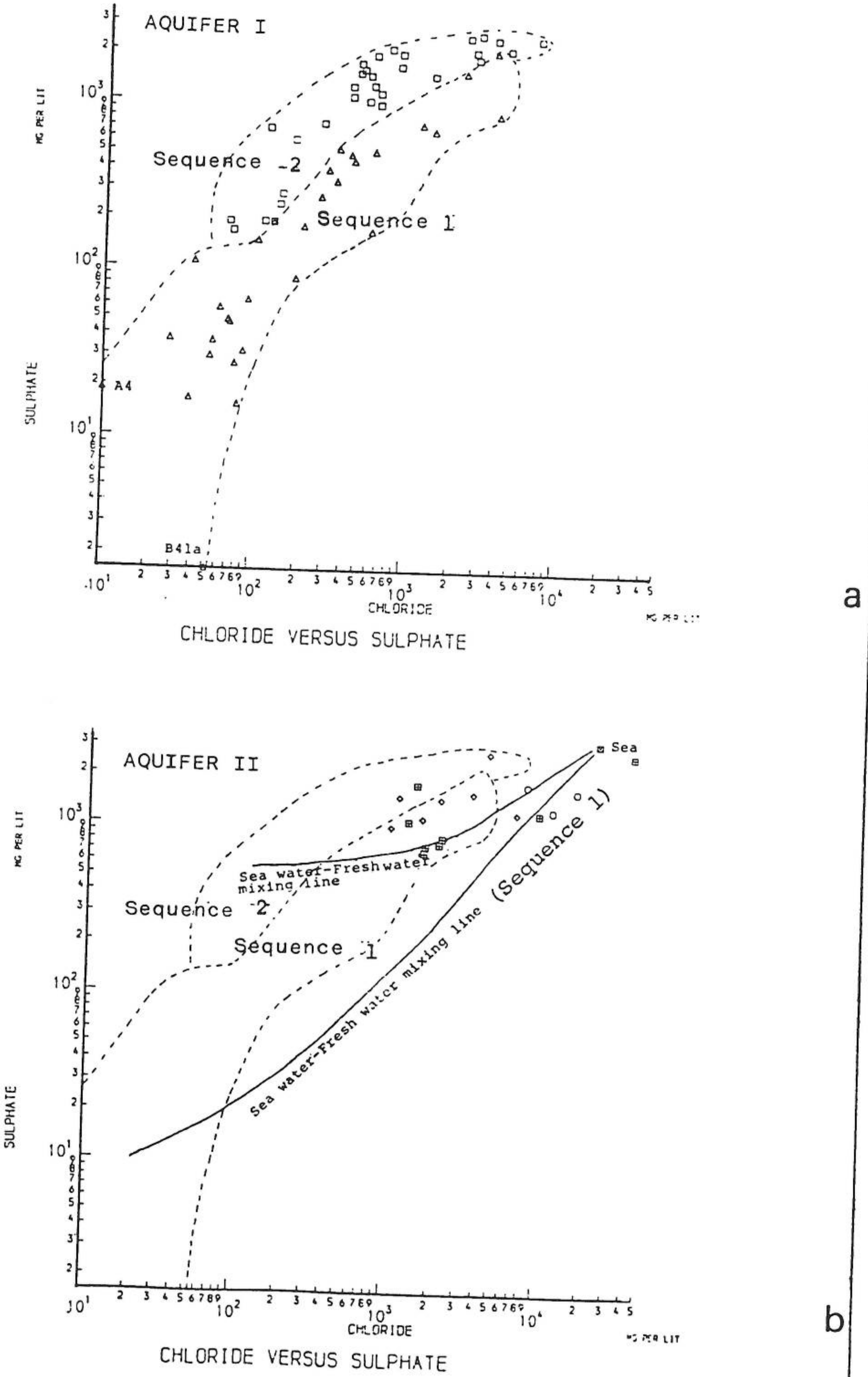
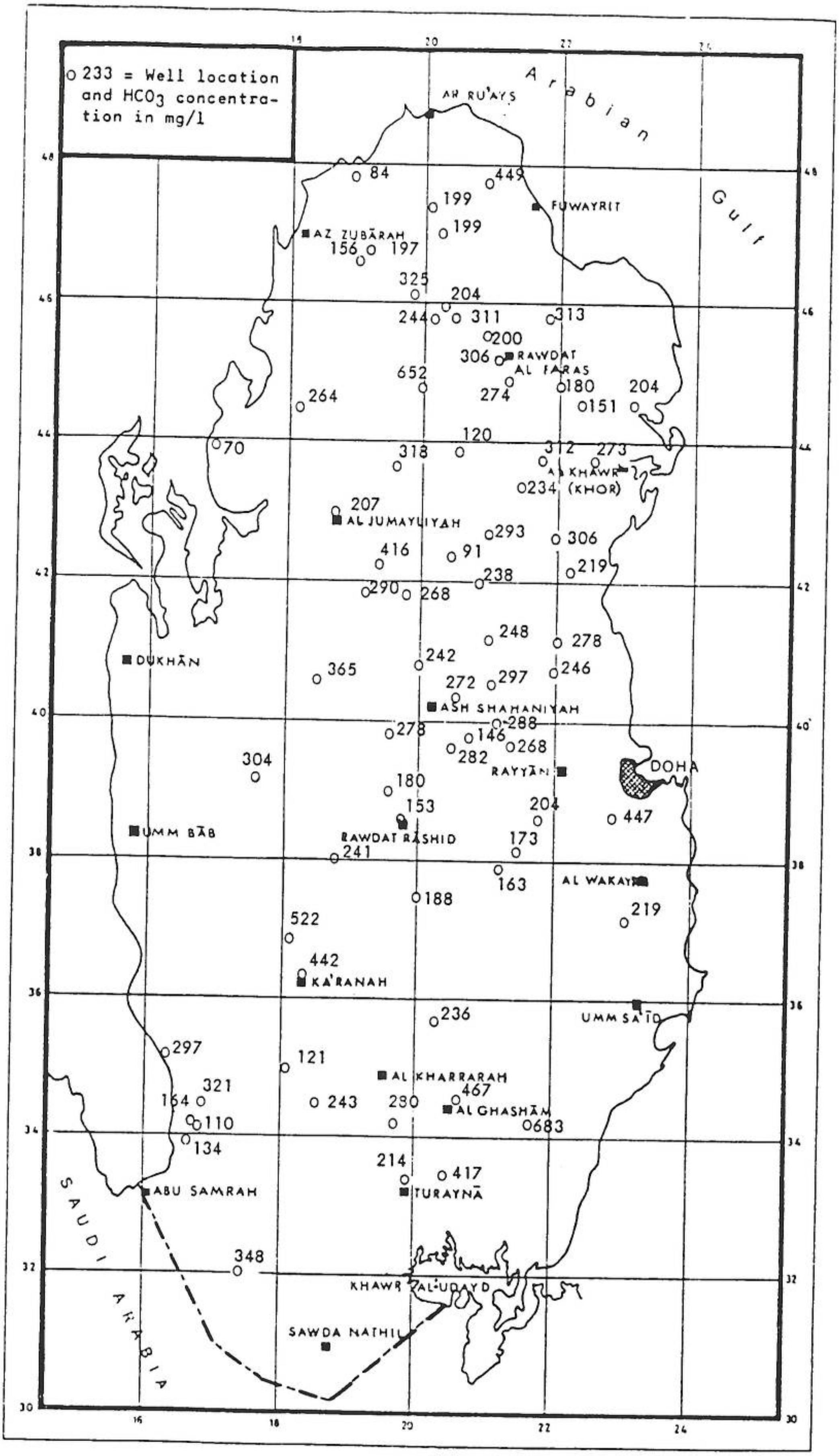

AQUIFER I
Sequence -2
Sequence 1
A4
B41a
SULPHATE
MG PER LIT
CHLORIDE
CHLORIDE VERSUS SULPHATE
a
AQUIFER II
Sea
Sea water-Freshwater mixing line
Sequence -2
Sequence 1
Sea water-Fresh water mixing line (Sequence 1)
SULPHATE
MG PER LIT
CHLORIDE
CHLORIDE VERSUS SULPHATE
b

Fig. 8.18



BICARBONATE (HCO_3) DISTRIBUTION Fig. 8.20

bicarbonate concentration and Fig. 8.20 shows the individual values plotted at their locations. This lack of uniformity is caused by the large number of different chemical processes affecting the dissolution of calcite and dolomite. Among these are the respective saturation indices, possible ion exchange reactions which may alter the cation composition of the waters and affect the equilibrium concentration, and a general decrease in partial pressure of CO_2 away from the recharge area.

8.4.11 Conclusions arising from a Consideration of Major Ion Chemistry

With foregoing analysis and discussion, the major ion chemistry has revealed that, while it has been possible to identify two different evolving groundwaters within the Rus Formation of Aquifer I which may be related to the controlling lithological facies, it has not been possible to separate the high TDS (ZONE C) Sequence 1 waters from the high TDS Umm er Radhuma or Alat aquifer waters of Aquifer II.

Minor ion chemistry and environmental isotope interpreations have therefore been applied to confirm the major ion conclusions, to clarify evidence on mixing processes and to elucidate the uncertainities in the origin of the more saline waters.

8.5 MINOR ION CHEMISTRY

The understanding of minor constituents has become increasingly important in groundwater studies, particularly to assist in clarifying problems associated with saline water intrusion (Howard 1979, Howard and Lloyd 1978). To this end all samples taken during the renewed sampling programme of 1978 were analysed for the minor ions Iodide (I^-), Strontium (Sr^{2+}) and Flouride (F) and some were also analysed for bromide, boron and lithium.

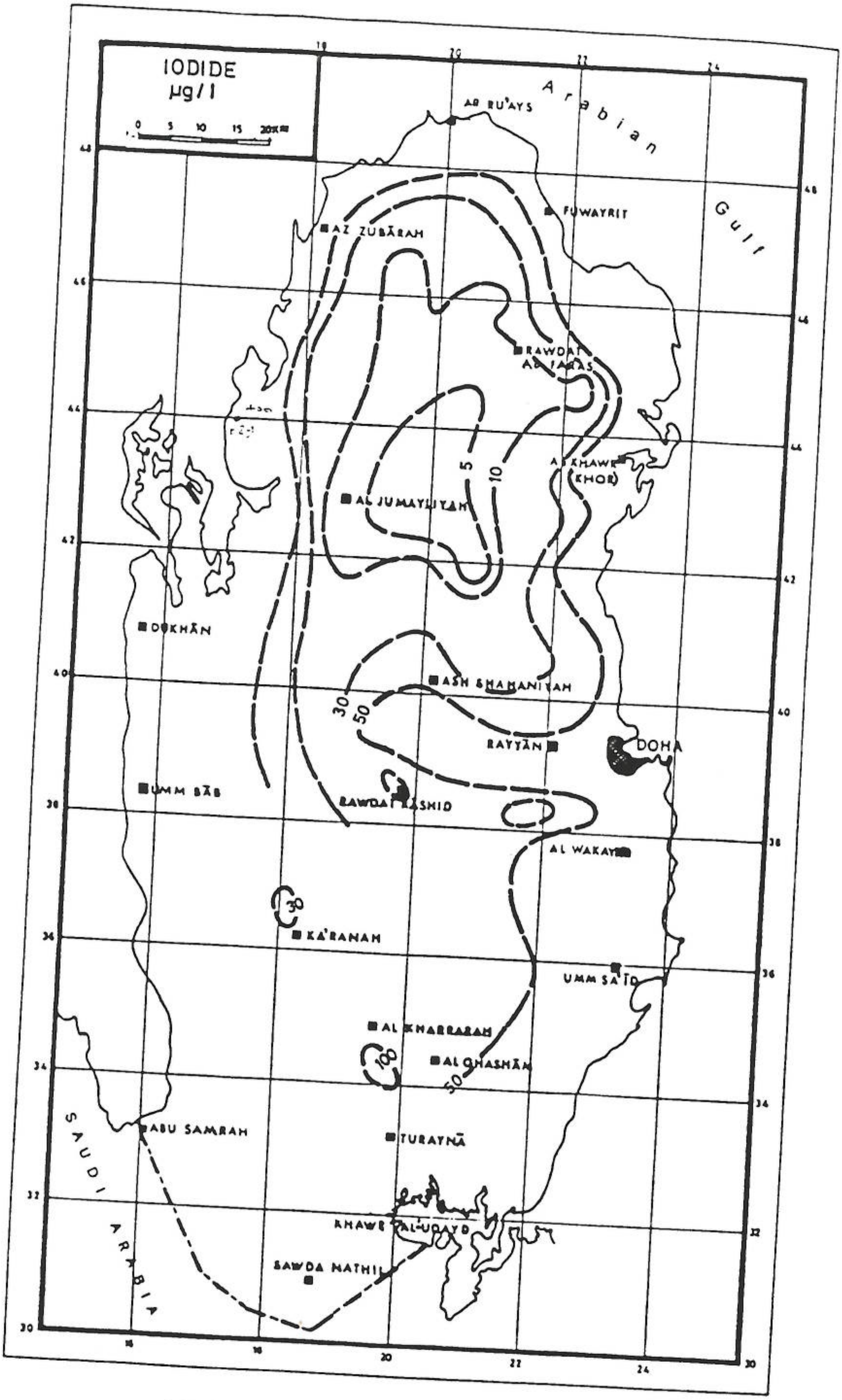
8.5.1 Iodide (I)

Iodide is concentrated in modern marine and oceanic sediments rich in organic material. Sea water usually contains about 70 µg/l of iodide although samples of sea water from the Gulf show slightly higher concentrations ranging from 85 to 90 µg/l. Because of the lower amounts of the minor elements, iodide concentrations are expressed in microgrammes per litre (µg/l) rather than milligrammes per litre (mg/l). One microgramme is one thousandth of a milligramme. (µg/l = 0.001 mg/l). In saline groundwater from carbonate aquifers, iodide values tend to be higher owing to the relatively higher amount of organic material and it is also believed that iodide enrichment may result from a prolonged period of groundwater residence (Howard and Lloyd, 1978).

In Qatar the sampled iodide values range from 3 µg/l in the northern recharge zone to approximately 400 µg/l in P29 a deep Umm er Radhuma aquifer borehole situated on the west coast. The distribution is shown in Fig. 8.21 and higher concentrations are evident in the high salinity waters along the coasts and in southern Qatar. Unexpectedly high values are reported from B16, P30, C6, P34, P29 and B42a. While the lithology of B16, C6 and B42a are known, the three Project exploration wells (P) penetrated very low permeability Rus Formation before the good aquifer at the top of the Umm er Radhuma Formation. The recharge waters of the sulphate area have higher iodide values than the respective waters from the carbonate area (Fig. 9.22). For chloride concentrations above 200-300 mg/l, (TDS 1500 to 2000 mg/l) the two groups merge into one cluster.

An interesting feature of Fig. 8.22 (a) is that the iodide concentrations for Sequence 2 do not increase with TDS whereas in the Sequence 1 area they do and attain the concentrations found in the Sequence 2 area, particularly for high chloride waters.

This suggests a control process whereby iodides would be taken into solution fairly rapidly during the recharge process in the sulphate facies of the Rus Formation, but then remain at a constant level, possibly because saturation with respect to the major iodide bearing ...



MINOR ION DISTRIBUTION MAP

Fig. 8.21

governing the dissolution and precipitation of iodide minerals.

It is noted that the samples from B4, B6 and B16 have fairly high iodide concentrations although all are from localised recharge mounds. Mixing with a proportion of Umm er Radhuma water is suspected. The Umm er Radhuma and Alat samples (Fig. 8.22 b) indicate that iodide concentration in these aquifers is significantly higher, with the mixed waters (Aquifer 1 with Aquifer 2) showing the relatively high iodide levels of the high salinity waters of the Umm er Radhuma. This may be related to a long residence time in this aquifer, upto 28,000 years B.P., indicated by carbon-14 age determination (Table 9.2).

8.5.2 Strontium (Sr^{2+})

Strontium (Sr) is an alkali earth metal and is similar to calcium and magnesium in its chemical behaviour (Skougstad 1971). In the range of samples from Qatar strontium shows an similar overall distribution to iodide although some of the local recharge mound, with high iodide levels (C6, B42a), show the typical low strontium values of recharge waters. Wells with anomalously low iodide concentrations do not have similarly distorted strontium levels. Low strontium values are found in waters of the northern recharge area and the local recharge mounds and is noted that carbonate waters have a lower Sr/Cl ratio (see A16, A14a, A17a) than the sulphate waters.

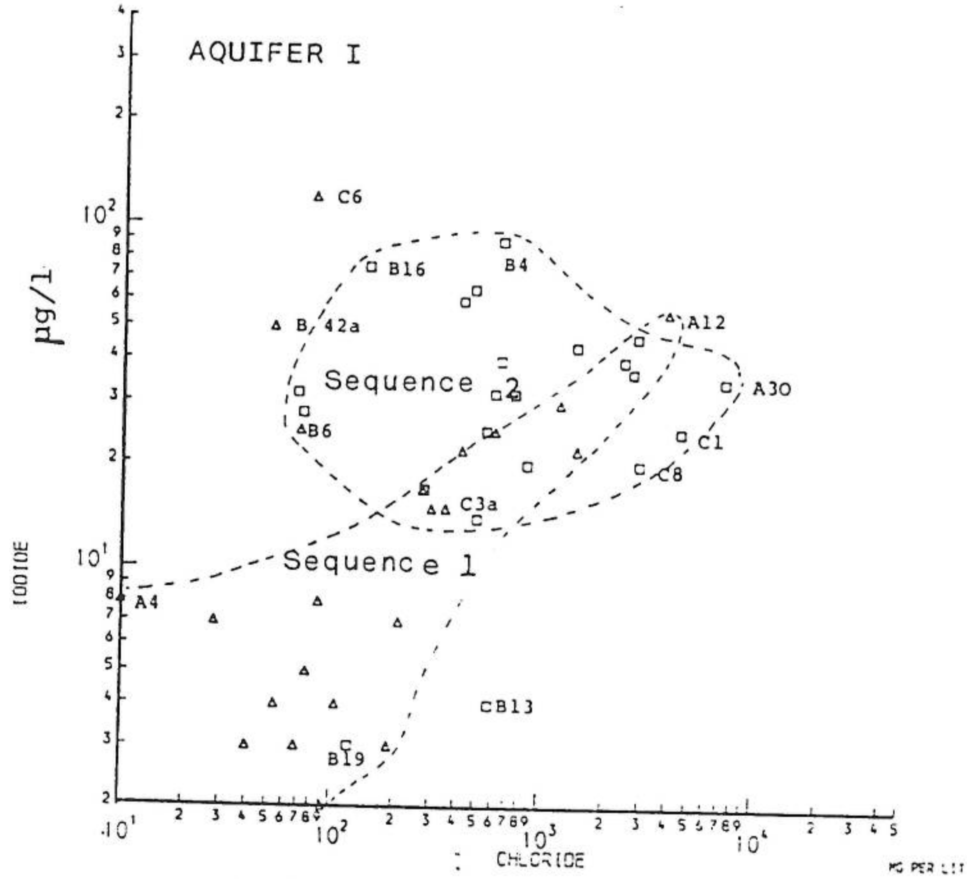
Possible sources of strontium in the waters are the minerals strontianite ($SrCO_3$) and celestite ($SrSO_4$) where, in both cases, strontium replaces calcium. Celestite is known as to occur in the limestones of the Dam Formation (Enclosure 1). The close relationship between strontium and calcium is shown on Fig. 8.23(a) where it will be noted that, for the low Ca- low Sr waters, the variation in the ratio is still fairly large but with increasing calcium levels the correlation with strontium improves.

It will also be noted that Sequence 1 and Sequence 2 waters do not separate on this plot, which is a reflection of the higher calcium levels in the gypsiferous area, and the Umm er Radhuma and the Alat aquifer samples lie within the group for those of the Rus aquifer. Sea water concentrations cannot account for the strontium levels found in high calcium - high TDS waters are dissolution of strontium-bearing minerals, present within the aquifers must therefore be taking place.

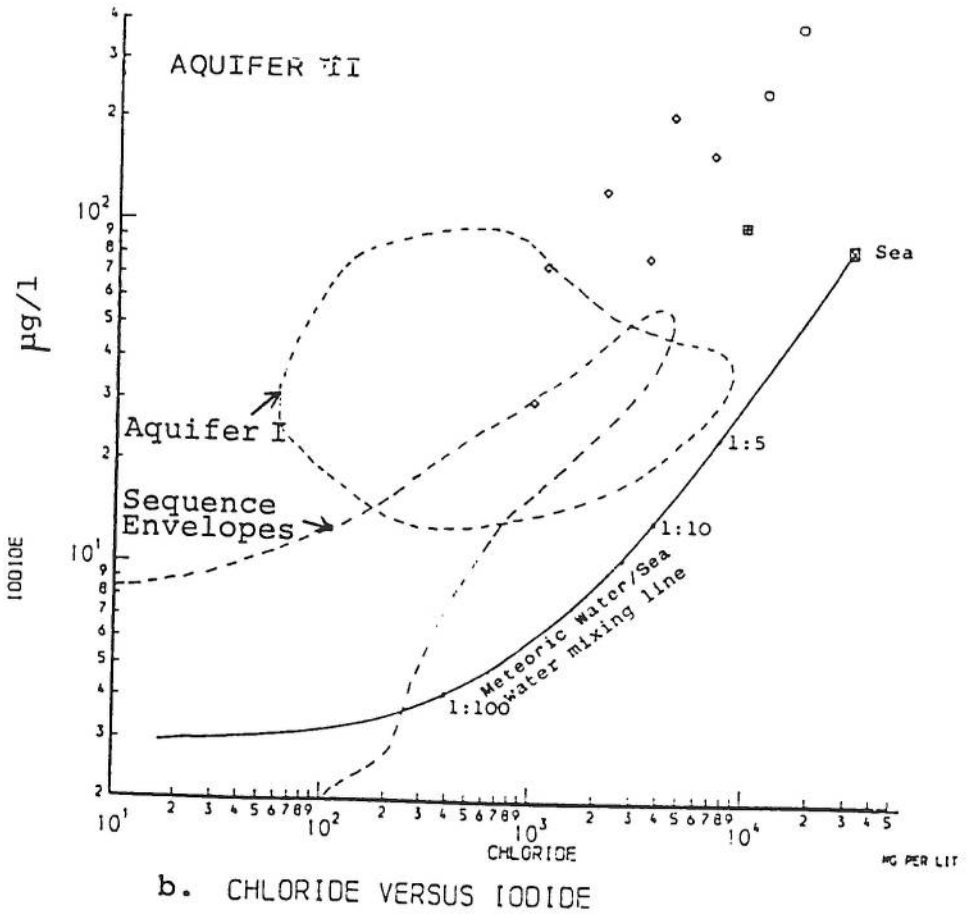
Strontium levels in groundwater are also correlated with sulphate concentration (Fig. 8.23(b)). Since high calcium concentrations are associated with gypsum dissolution, strontium and sulphate also correlate in a similar way to strontium and calcium. However, it will be seen that strontium values continue to increase beyond where saturation values continue to increase beyond where saturation with respect to gypsum is already reached and a second mechanism must be responsible for the further increase in strontium levels. All analyses showing high strontium concentrations in the sulphate range of 800-2500 mg/l also reveal a high chloride content, indicating long residence in the aquifer, and the extended contact time is therefore indicated.

The strontium-strontium/chloride ratio (Fig. 8.24(a)) has proved to be a reliable parameter to separate Sequence 1 and Sequence 2 in the moderately high TDS waters of ZONE B. The plot shows that the ratio is variable in the recharge waters, probably due to the large variation in the chloride and calcium levels, but in the chloride range from 100 mg/l to 2000 mg/l the plot provides a useful separation between the carbonate and the sulphate waters. For high chloride waters the difference diminishes to zero as the calcium levels in both facies are high and the strontium concentration is therefore virtually equal for both sequences.

The residence time effect on both iodide and strontium levels can be best demonstrated on the strontium-iodide plot (Fig. 8.24(b)). The Umm er Radhuma and the Alat aquifer samples have higher values than the Rus due to longer residence times in the aquifers.

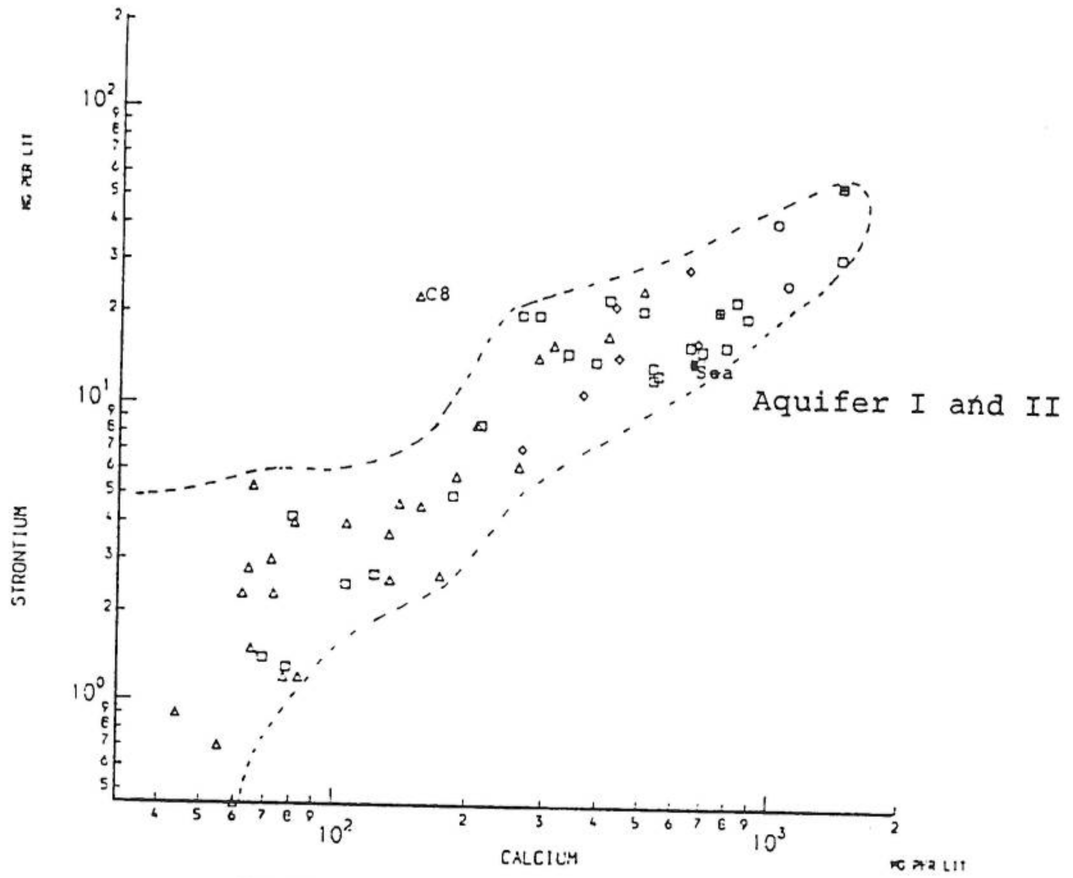


a. CHLORIDE VERSUS IODIDE

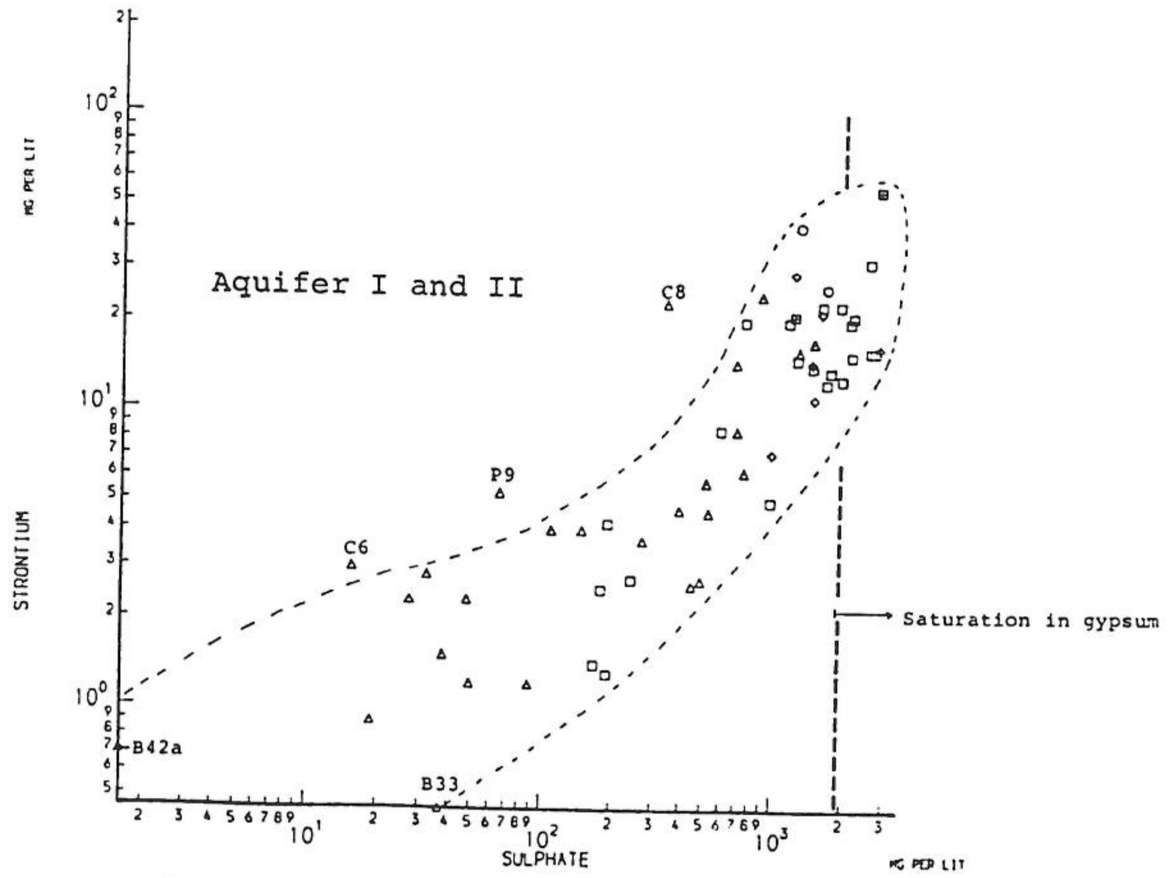


b. CHLORIDE VERSUS IODIDE

Fig. 8.22



a. CALCIUM VERSUS STRONTIUM



b. SULPHATE VERSUS STRONTIUM

Fig. 8.23

8.5.3 Fluoride (F)

Fluoride is typically incorporated in carbonates in the form of calcium fluoride (CaF_2) and coccolith plantes usually accumulate some CaF_2 in their structure during growth. In laboratory experiments it has been demonstrated that clay minerals are able to extract fluoride ions from aqueous solutions (Carpenter 1969). Sea water samples from the Arabian Gulf show a fluoride concentration of 1.25 mg/l which is within the range normally encountered in other sea waters (1.0 to 1.4 mg/l).

Fig. 8.25 shows the Fluoride distribution over Qatar. Low concentrations (< 1.0 mg/l) occur in the northern recharge area and in some local recharge mounds. Higher fluoride levels appear in wells located in south and central Qatar whilst a lower content can be found in wells with a high calcium concentration near the coast. It is believed that the saturation of waters with respect to calcium fluoride could be the reason for low fluoride levels in some high calcium waters though calculations of saturation limits by the technique of Howard (1978) do not appear to confirm this.

Both the Chloride-Fluoride and the Sulphate-Fluoride plots (Fig. 8.26 and 8.27) show that fluoride is rapidly taken up in the Sequence 2 area, and remains fairly constant even with increasing sulphate and chloride. In the Sequence 1 area the fluoride levels increase with both increasing sulphate and chloride indicating a fluoride ion saturation control mechanism similar to that proposed for iodide. It is noted that the Umm er Radhuma and Alat aquifer analyses do not differ in fluoride ion concentration from the rest of the high TDS waters and there is no evident residence time effect suggesting a saturation control.

The difference in the mechanisms controlling strontium and fluoride are shown in Fig. 8.28; both are well correlated in the Sequence 1 area where both ions occur in low concentration and values normally increase with increasing TDS. The group of long residence groundwaters (Fig. 8.31) are shown shifted to the right as strontium levels in these waters are higher than in the younger waters, whereas fluoride concentrations are approximately stable at an upper limit of 3.0 mg/l probably due to some form of solubility control.

8.6 HYDROCHEMICAL EVOLUTIONARY SEQUENCE

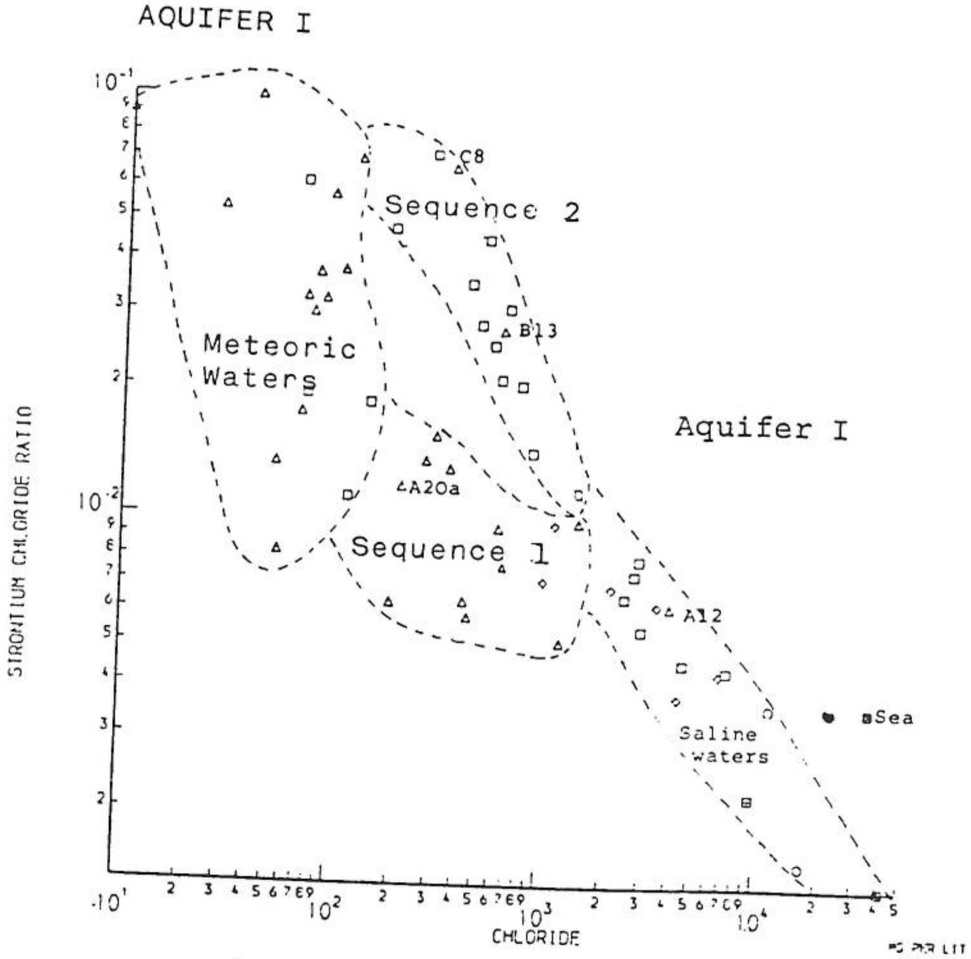
A large proportion of recharge takes place over northern Qatar through the carbonate facies of the Dammam and Rus Formations to form Sequence 1 waters. Recharge also occurs to the adjacent sulphate facies and via a number of collapsed structures in the south to form Sequence 2 waters. From the main recharge areas with typical low TDS waters the following sequence of chemical processes is believed to take place and is used to distinguish between the different types of groundwater.

(a) Due to the relatively higher solubility of gypsum, the TDS content of Sequence 2 waters tends to increase faster than for Sequence 1 waters. Throughout the evolutionary sequence, the sulphate waters also have higher calcium, sulphate and magnesium levels which indicates that the major source is the gypsum of the Rus Formation. Fig. 8.29 illustrates the separation of Sequence 1 and Sequence 2 waters and demonstrates the mixing between them at the low TDS level.

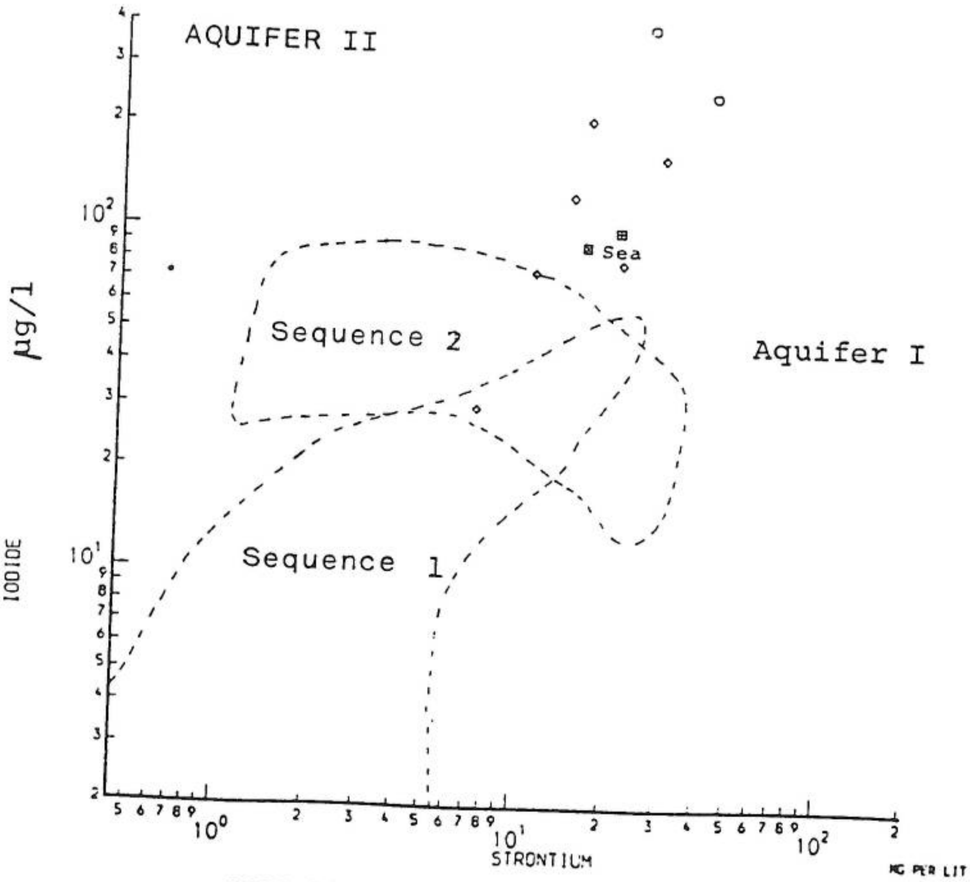
$$" \frac{(Na-Cl + Mg + Ca}{HCO_3} "$$

in meq/l accounts for all cations possibly associated with HCO_3, including any exchanged calcium. For a pure calcite ($CaCO_3$) dissolution process, the ratio should yield a value of unity. Where gypsum dissolution is also important, the ratio will be larger than unity since part of the Ca will be derived from gypsum ($CaSO_4.2H_2O$).

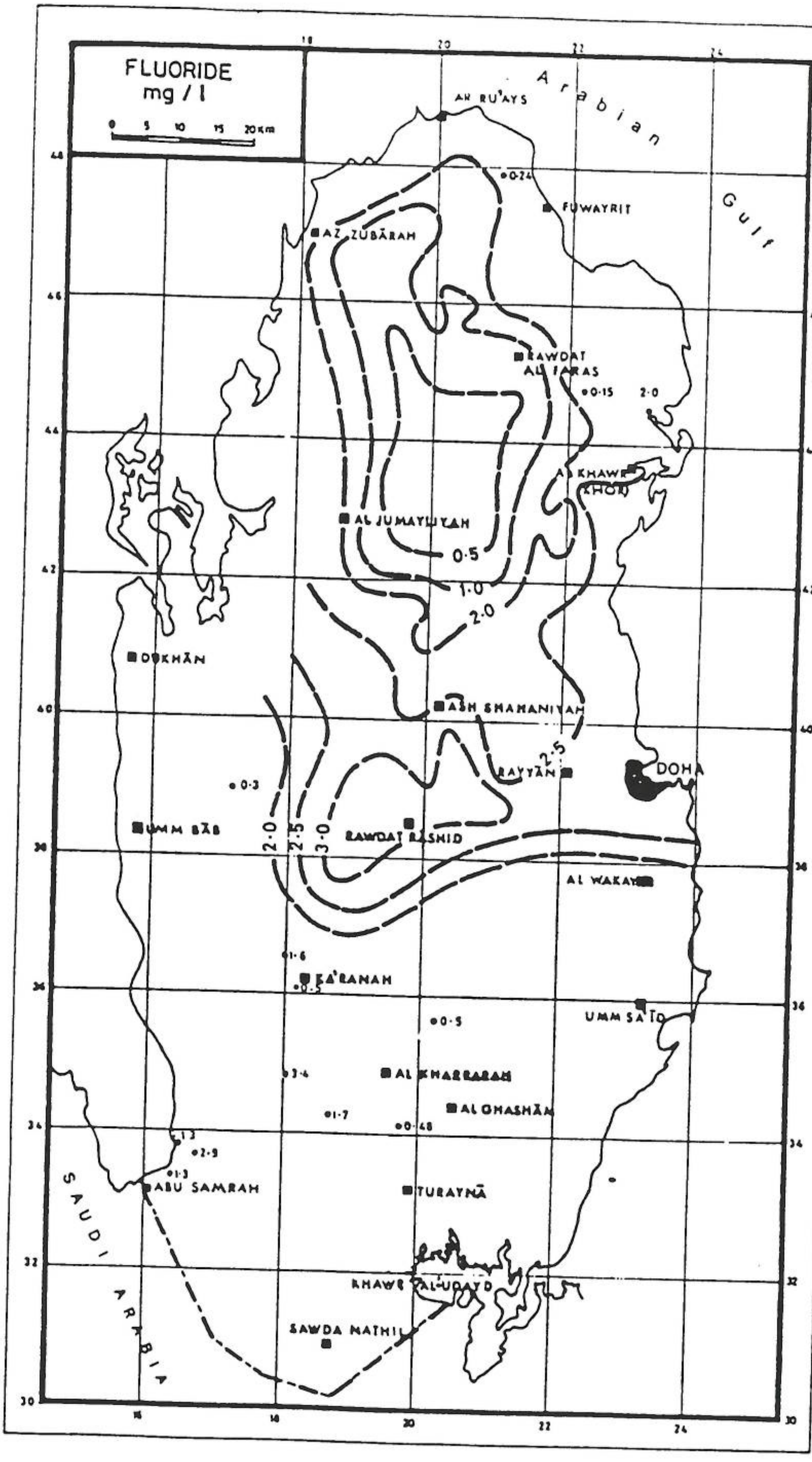
At a later stage in the evolutionary sequence calcite and dolomite saturation are reached, though the waters continue to dissolve considerable amounts of gypsum and



a. CHLORIDE VERSUS STRONTIUM/CHLORIDE RATIO



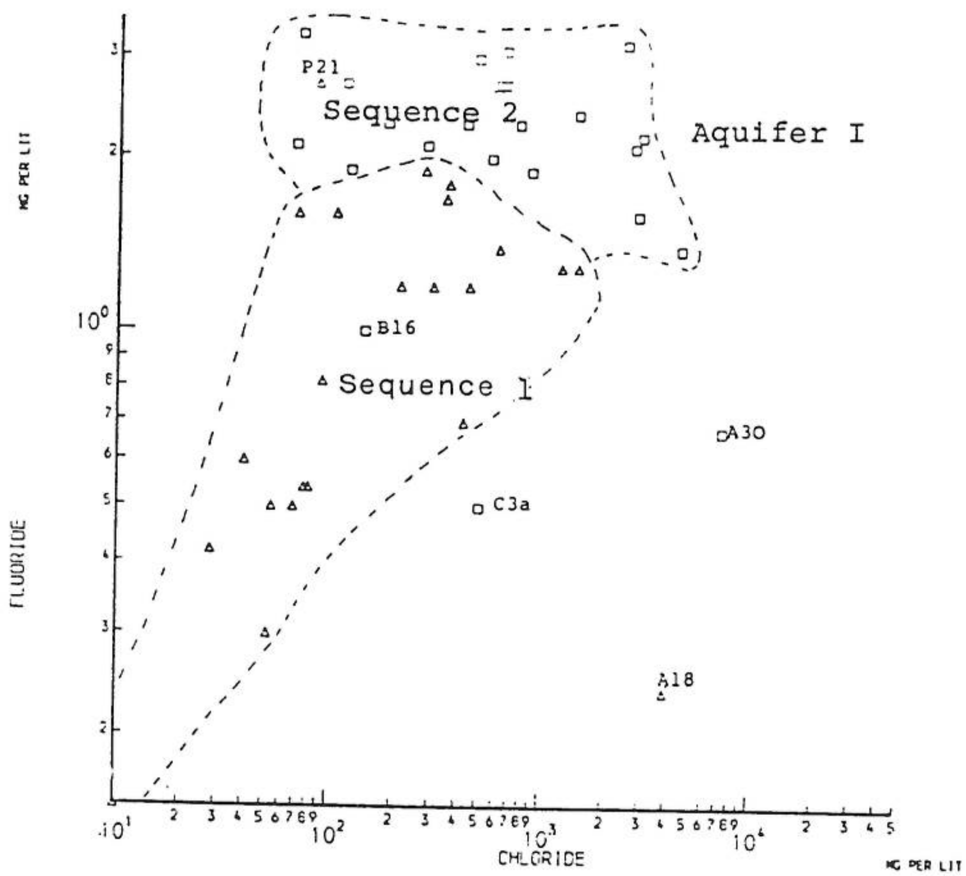
b. STRONTIUM VERSUS IODIDE



MINOR ION DISTRIBUTION MAP

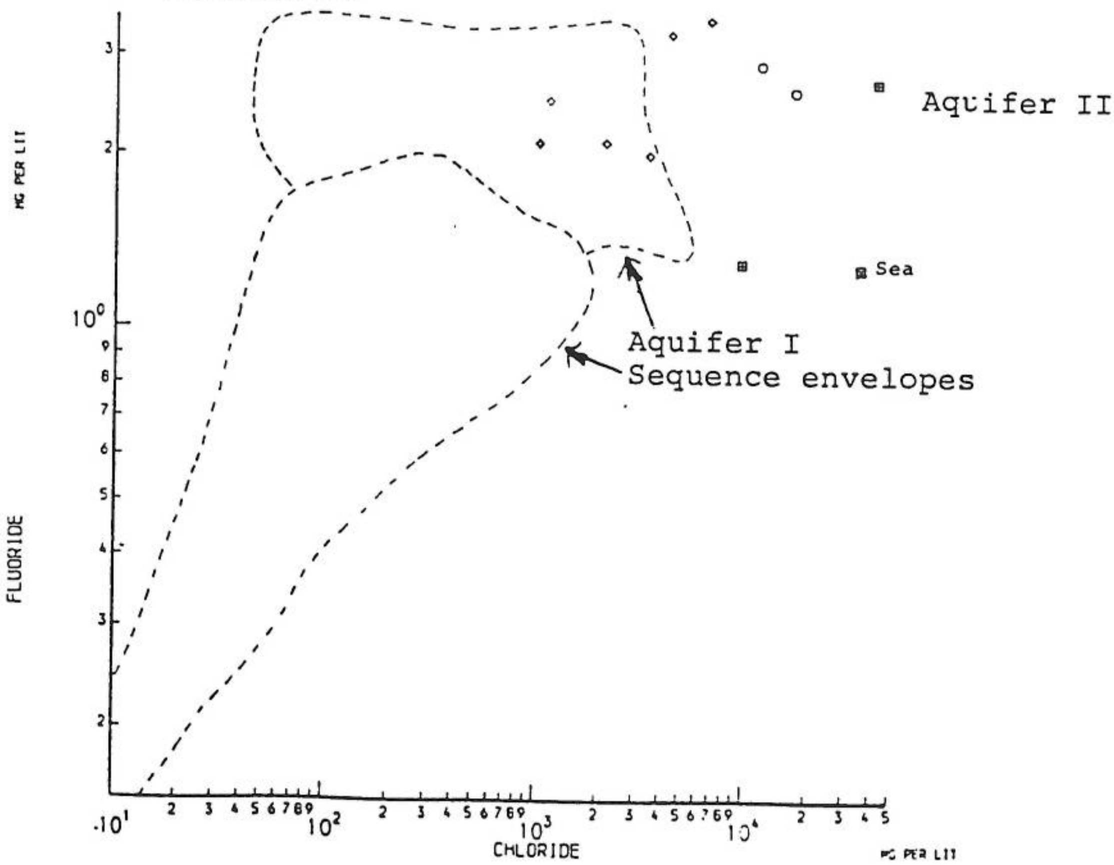
Fig. 8.25

AQUIFER I



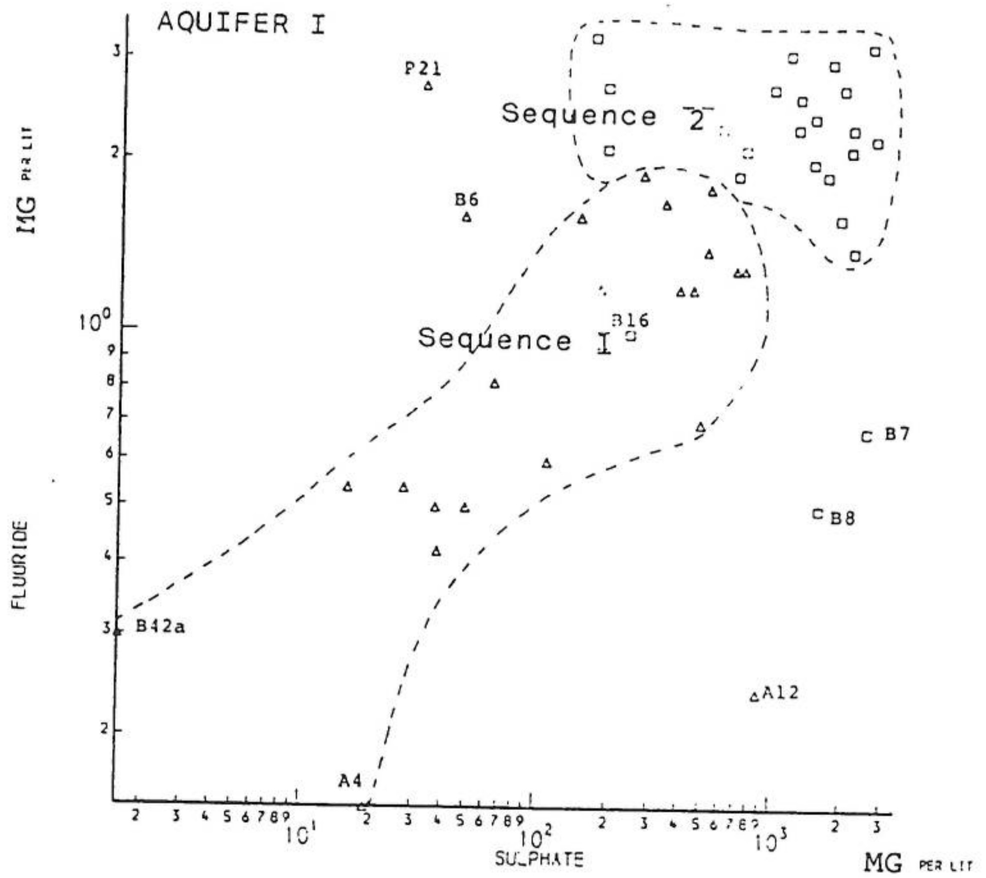
a. CHLORIDE VERSUS FLUORIDE

AQUIFER II

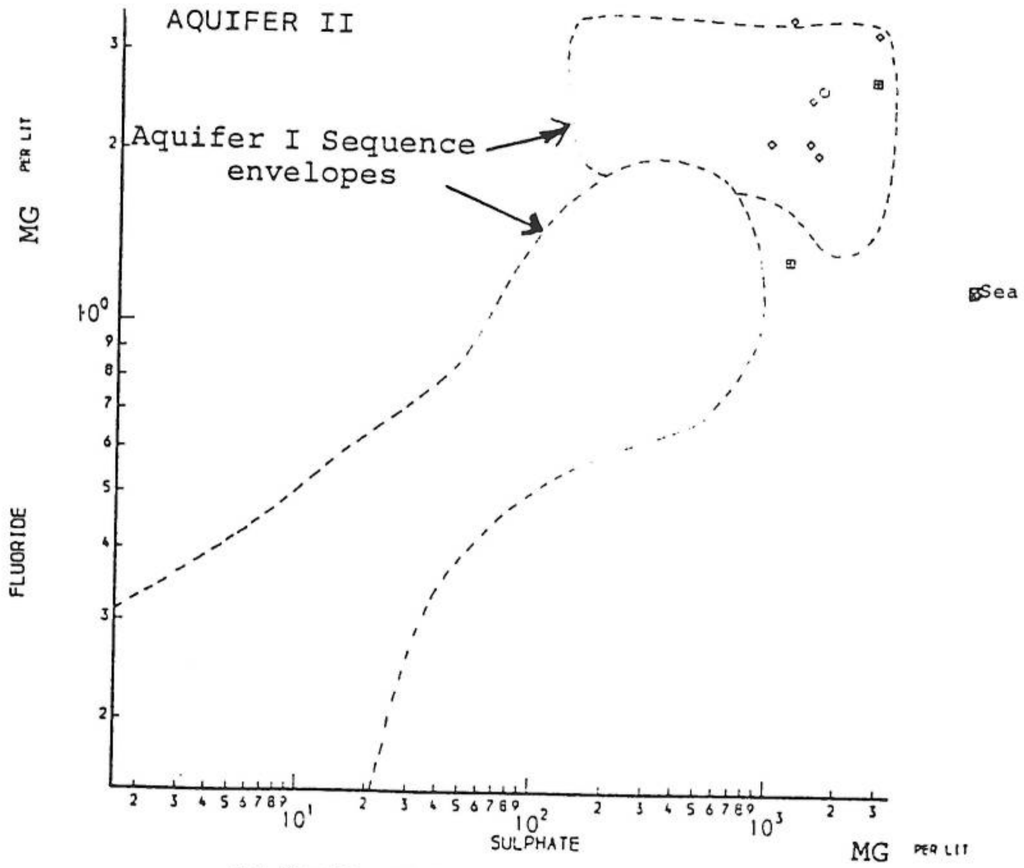


b. CHLORIDE VERSUS FLUORIDE

Fig. 8.26

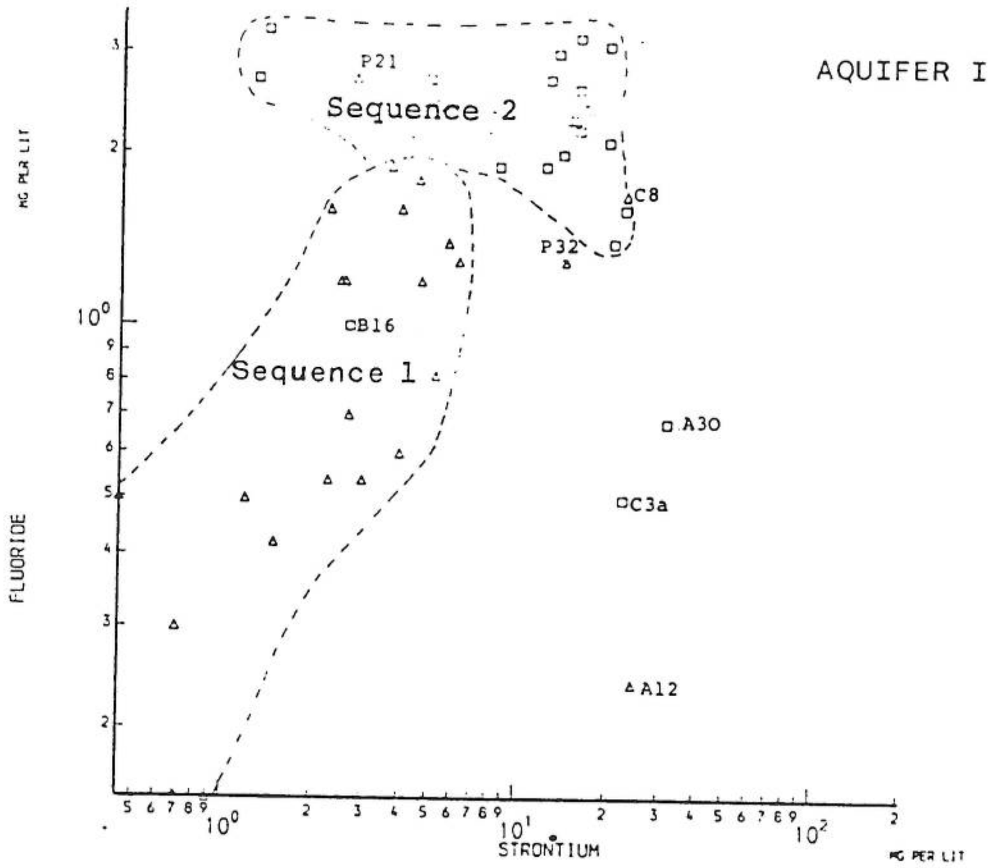


a. SULPHATE VERSUS FLUORIDE

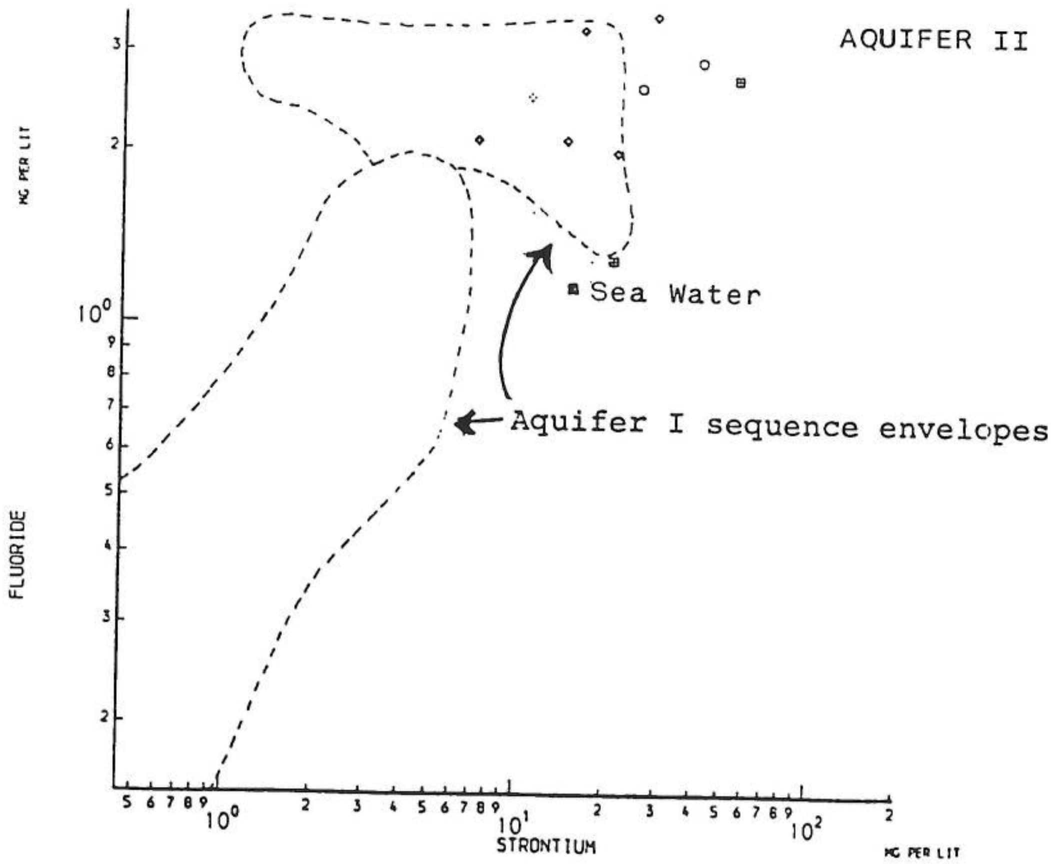


b. SULPHATE VERSUS FLUORIDE

Fig. 8.27



a. STRONTIUM VERSUS FLUORIDE



b. STRONTIUM VERSUS FLUORIDE

Fig. 8.28

anhydrite whilst the calcite gradually precipitates, causing a loss of calcium and bicarbonate as the sulphate increases. This process of incongruent dissolution of gypsum is believed to occur both as the carbonate waters enter the gypsiferous area and also as they flow to the northern coast. This process causes bicarbonate/TDS ratio to decrease rapidly as the sulphate/TDS ratio increases. Continuing dissolution of gypsum may lead to supersaturation with respect to calcite and dolomite.

(b) In ZONE B (See Fig. 8.3) TDS increase and ion exchange process may be inferred with calcium and magnesium ions possibly being exchanged for sodium ions on the surface of clay minerals present in the carbonate as well as the sulphate facies. The almost constant chloride/sulphate ratio in ZONE B then increases towards the value of sea water where it rises to 7. In the range 5000-7000 mg/l TDS, the waters becomes saturated with respect to gypsum when sulphate values of about 2000 to 2400 mg/l are reached, and chloride and sodium increase due to mixing with sea or saline groundwater.

(c) Reverse ion exchange waters of higher chloride/sulphate ratio are inferred for ZONE C (Fig. 8.3). Figs. 8.30 and 8.31 illustrate the concept of ion exchange and reversed ion exchange. In the case of ion exchange, (Na-Cl) should balance for $(Ca+Mg)-(HCO_3+SO_4)$ and, if plotted in meq/l, should lie on a slope of -1 in the upper left quadrant. In the case of reversed ion exchange the same relationship applies but the points should lie on a slope -1 in the lower right quadrant. In Fig. 8.30a most points plot at the intersection of the axes, indicating balanced waters, while a few samples, including the sea water sample, lie in the reversed ion exchange field. This was, however, found to be misleading as samples with mixtures between balanced waters and sea water will erroneously be classified as reversed ion exchanged. However, as the plot shows absolute values in meq/l and low TDS waters are not clearly discernable a normalised plot was introduced (Fig. 8.30(b)). This distinguishes the waters of the three zones. Balanced recharge waters of ZONE A plot close to the intersection and within the circle, the ion exchange waters of ZONE B in the upper left quadrant and the reversed ion exchanged waters of ZONE C plot in the lower right quadrant.

Similarly, the waters of the Umm er Radhuma and Alat aquifers are plotted in Figs. 8.31a and b and show reversed ion exchanged tendencies, although appear as 'balanced' waters where the vertical mixing between the Rus and upper Umm er Radhuma takes place in northern Qatar.

8.7 SUMMARY, CONCLUSIONS AND HYDROGEOLOGICAL INFERENCE

In the foregoing sections of this Chapter both the major and minor ion chemistry of Qatar's groundwater has been presented in some detail. Results have been based on samples from 76 observation wells selected to meet certain criteria, eliminating where possible uncertain laboratory analyses without obscuring true anomalies. A more detailed sampling programme would obviously refine the hydrochemical interpretation but, given the size of the country and its relative position within the overall regional groundwater systems of eastern Arabia, the sampling network is considered adequate and the data obtained sufficient at this stage as a basis for the hydro-geological interpretation.

Analysis has confirmed that recharge takes place principally over northern Qatar and through the carbonate facies of the Dammam and Rus Formations to form the Sequence 1 waters. It also takes place over the adjacent sulphate facies areas and a number of local recharge mounds to form Sequence 2 waters. Fig. 8.32 shows three separate zones; ZONE A coinciding with the northern recharge and where the waters are balanced; ZONE B representing waters of moderate total dissolved solids and indicating ion exchange; ZONE C representing waters of higher total dissolved solids in the saline intrusion region and adjacent to the coast and which appear reversed ion exchanged compared to sea water. Fig. 8.33 presents a series of expanded Durov plots which summarise all available data.

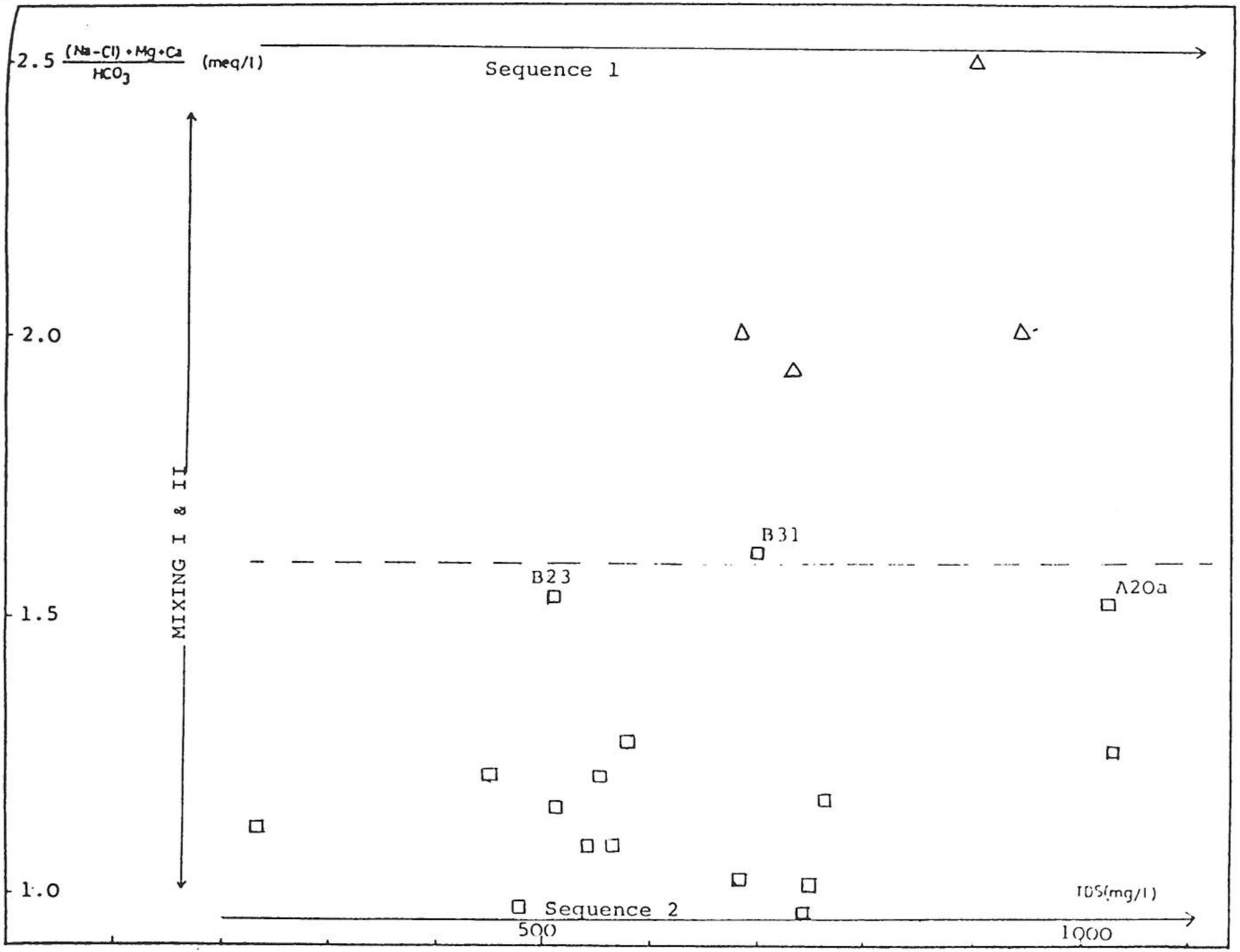
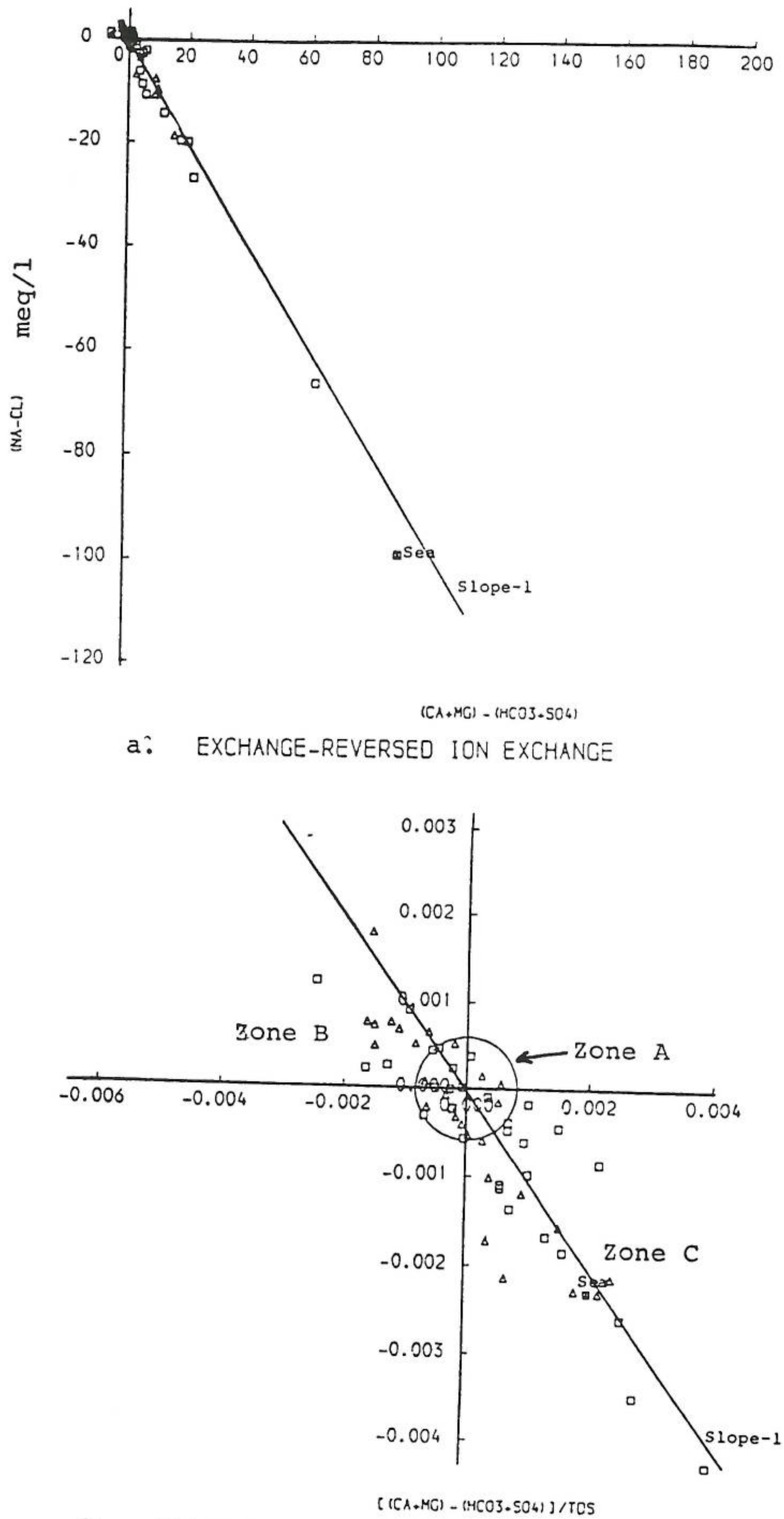


FIG. 8.29 SEPARATION OF SEQUENCE 1 and 2 WATERS AND MIXING BETWEEN THEM IN LOW TDS WATERS

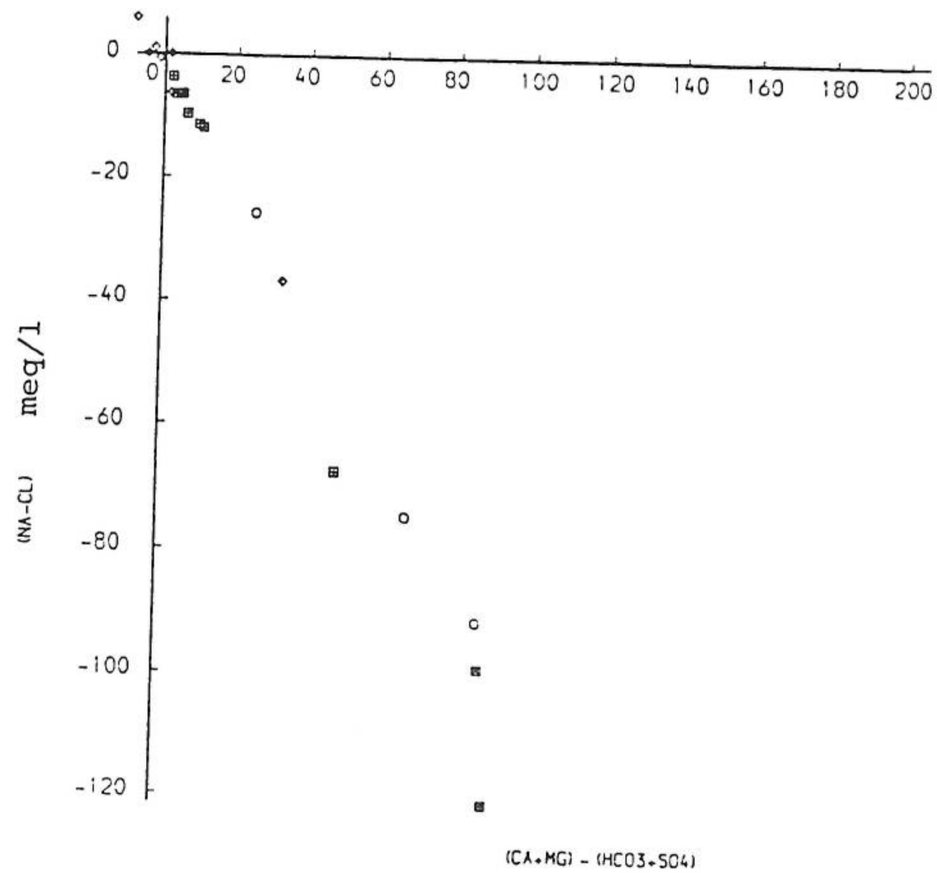


a. EXCHANGE-REVERSED ION EXCHANGE

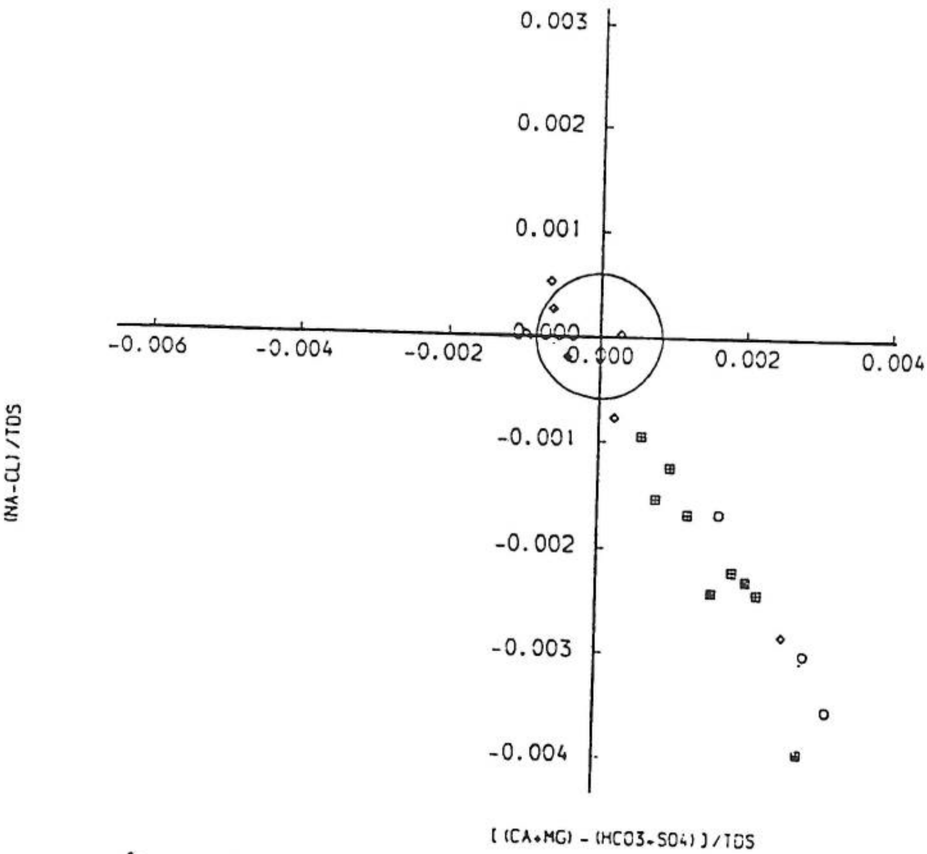
b. EXCHANGE-REVERSED ION EXCHANGE (NORMALISED)

Aquifer I

Fig. 8.30



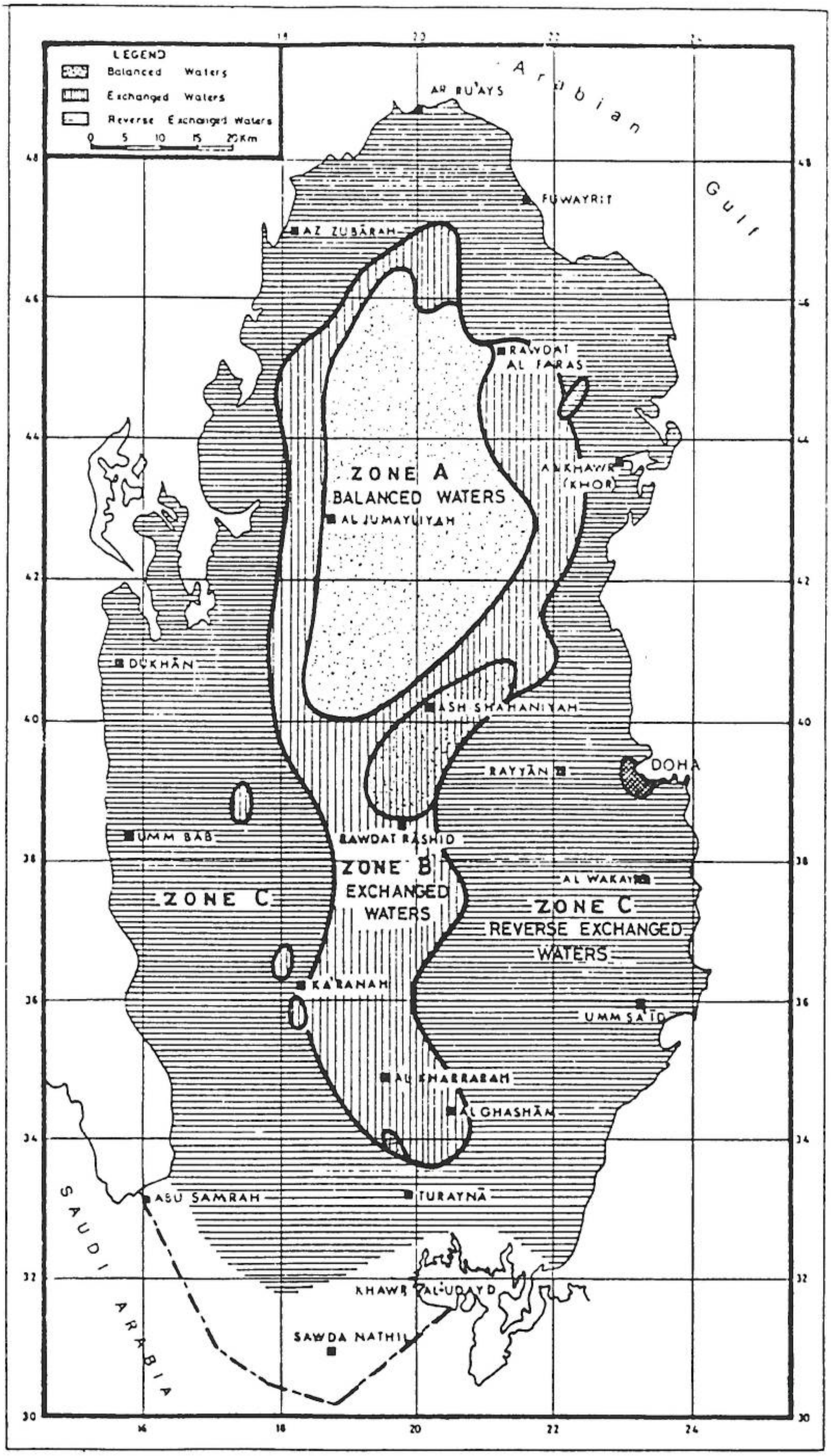
a. EXCHANGE-REVERSED ION EXCHANGE



b. EXCHANGE-REVERSED ION EXCHANGE (NORMALISED)

Aquifer II and Alat Aquifer

Fig. 8.31



GROUND WATER ZONING

Fig. 8.32

SUMMARIZED HYDROCHEMICAL CHARACTERISTICS

Parameter	ZONE A Seq.1	ZONE A Seq.2	ZONE B Seq.1	ZONE B Seq.2	ZONE C Seq.1	ZONE C Seq.2	MIX & UER	Alat Aquifer
Ca/Cl	-	-	low	high	low	high	low	low
Mg/Cl	-	-	low	high	low	high	low	low
Ca/Mg	-	-	-	-	-	-	low	-
SO_4/Cl	low	high	low	high	low	high	low	low
I^-	low	high	low	high	-	-	V. high	V.high
Sr/Cl	-	-	low	high	-	-	-	-
F^-/Cl	low	high	low	high	low	high	high	high
$O^{18}D$	← high →						← depleted →	

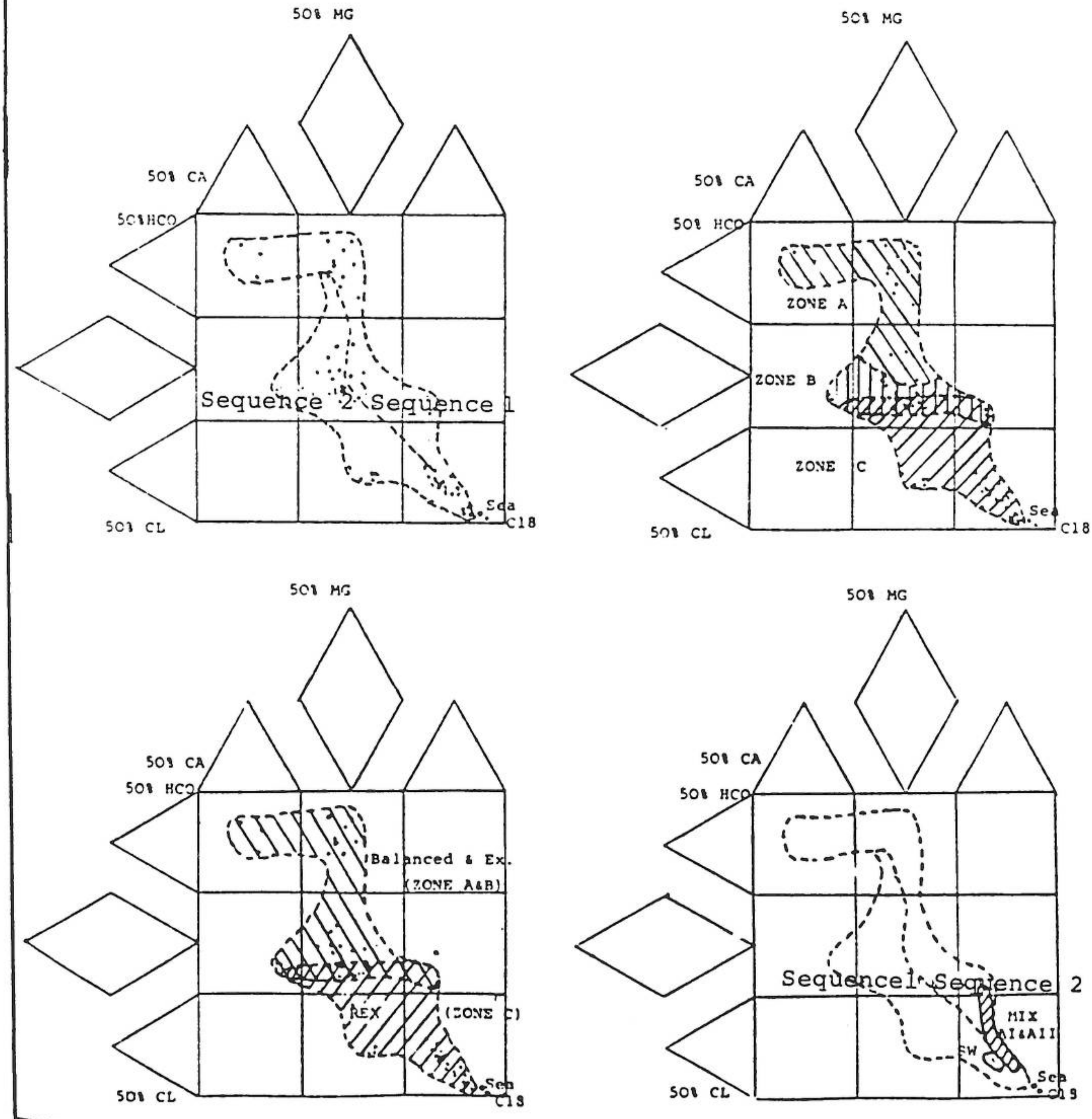


Fig. 9.22

A combination of the chloride/sulphate ratio against TDS and exchange or reverse ion exchange features leads to a diagram (Fig. 8.34), which clearly demonstrates the concept of Sequence 1 and 2 separation and the ZONE B/ZONE C inter-relationship. The freshwater/salt water interface is placed on chemical evidence, in the transition zone between 3000 and 5000 mg/l TDS where ion exchanged waters occur together with reverse ion exchanged waters.

The minor ion chemistry strongly supports the interpretation based on the major ion chemistry. As is to be expected, iodide, strontium and fluoride ion concentrations are significantly higher in the sulphate areas although, with increasing TDS, this difference diminishes to zero. This suggests control mechanisms for minor ions since their concentration remains constant at a high level in the sulphate waters.

In southwest Qatar, the waters of the Umm er Radhuma and the Alat aquifers cannot be separated chemically from ZONE C/Sequence I waters of the Rus aquifer elsewhere and the only distinguishing parameter was found to be the chloride/sulphate ratio. A long residence period and presumed absence of gypsum or anhydrite deposits gave a significantly higher chloride/sulphate ratio. There is a chemical similarity between the waters of the Umm er Radhuma and the Alat aquifers which has previously been taken as evidence of upward leakage of Umm er Radhuma water in the area. Exploratory drilling by the Project has however shown that the two aquifers are in fact separated by over 100 m of dry gypsiferous Rus Formation in this area which provides an effective aquiclude. The evidence of environmental isotopes and hydrochemistry from Saudi Arabia (Fig. 8.35) has however revealed that upward leakage is taking place from the Umm er Radhuma through 'windows' in the Rus Formation where the evaporites are absent or have been removed by solution.

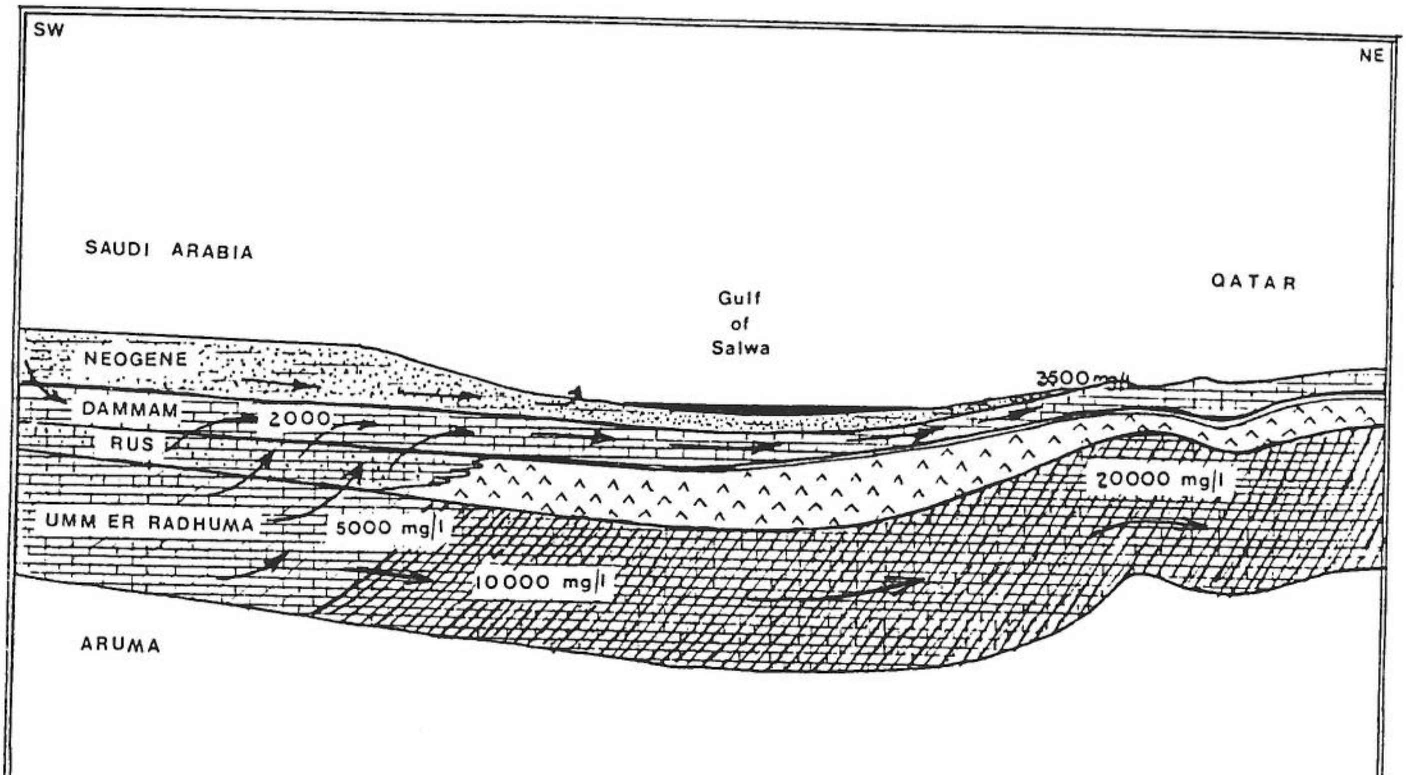
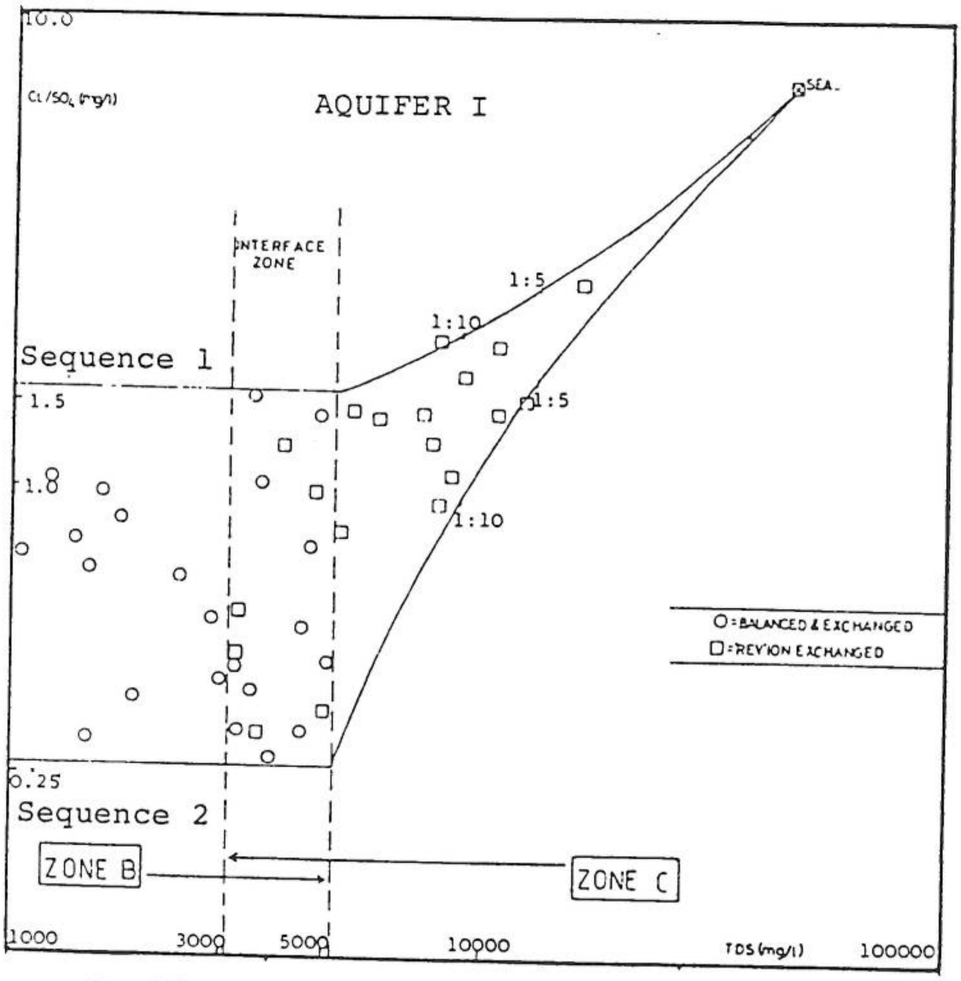


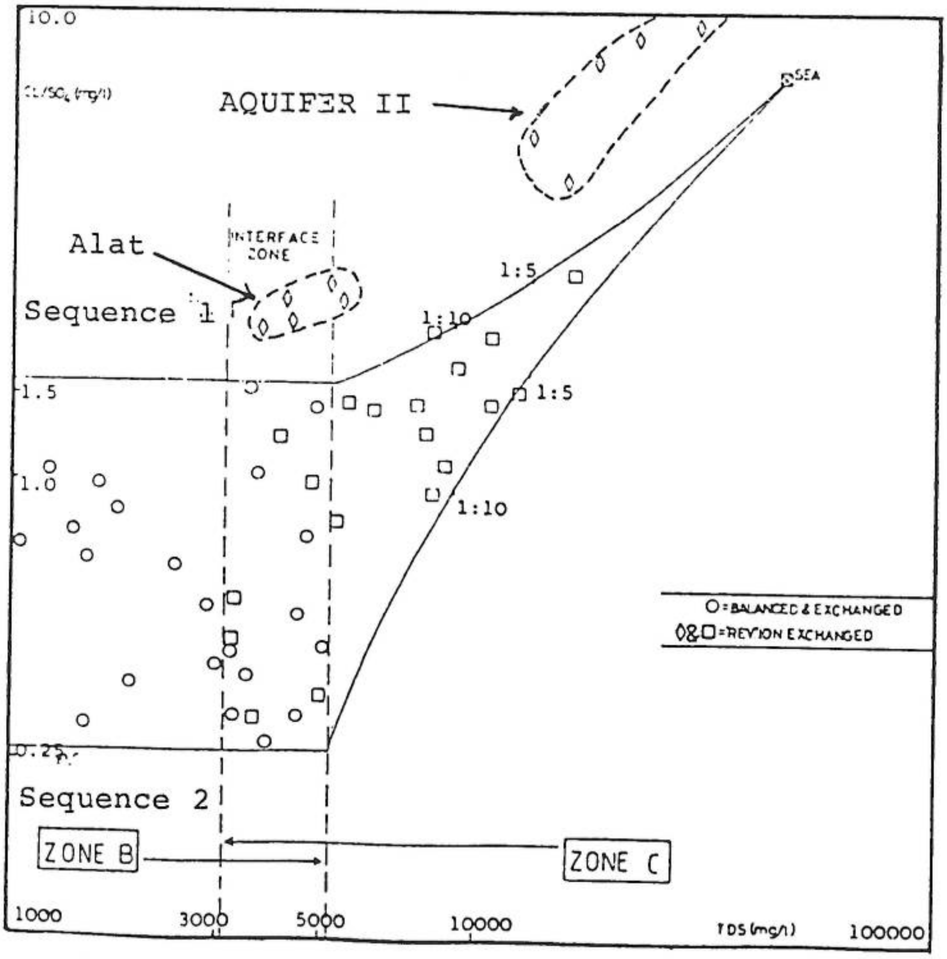
FIG. 8.35 IDEALISED SECTION : PROBABLE UPWARD LEAKAGE OF UMM ER RADHUMA WATERS INTO THE DAMMAM AQUIFER IN SAUDI ARABIA

(Not to Scale)

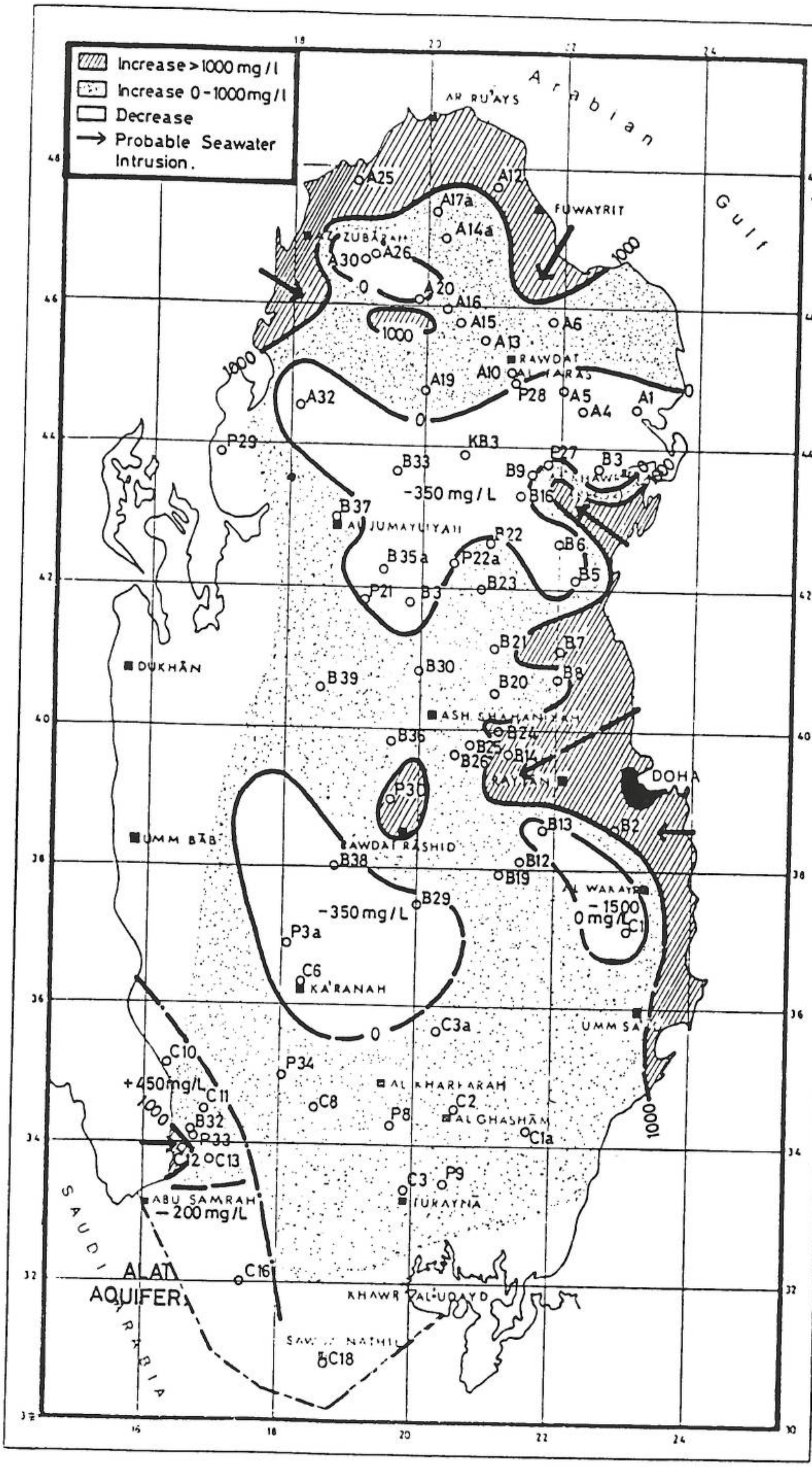
Compiled from project data and data provided by the Ministry of Agriculture & Water, Saudi Arabia from the work of Groundwater Development Consultants Ltd.



a. Aquifer I Sequence, Zone and Exchange Trends



b. As a. with Aquifer 2 and Alat Data



CHANGE IN GROUNDWATER SALINITY 1972-80

Fig. 8.36

The minor ion analyses of the Umm er Radnuma and Alat aquifers show significantly higher levels of iodide and strontium due to the residence effect.

8.8 CHANGE IN GROUNDWATER SALINITY 1972-80

Fig. 8.36 illustrates the distribution of change in total dissolved solids in mg/l observed by the project since 1972 within the Rus/Upper Umm er Radhuma aquifer and the Alat aquifer in the south-west. This shows that groundwater in the eastern coastal area, particularly near Doha is seriously affected by sea water intrusion. Tongues of sea water intrusion south of Khor and in the extreme northern coastal areas are also apparent. South of well A20 at Sulamania (A18) and at Rawdat Rashid in south central Qatar there has been a serious deterioration in water quality within the past few years probably due to displacement by saline waters caused by the heavy and sustained pumping in these areas.

The principal recharge area of northern Qatar, identified hydrologically and hydrochemically, is confirmed by long-term decrease in TDS over the main central area with an outlier to the north and similar zones of decreased TDS in southern Qatar reflecting an above average recharge (17%) during the past 5 years. The northern central area is of particular interest as it shows decreased TDS values towards possible outflow points at Khor bay on the north eastern coast and at Al-Swaihliyah on the north western coast both indicating the movement of fresher waters towards these points. Locally near Khor, Vicennia marina (mangrove) grow in certain areas around the present shore-line indicating a dilution of sea water at the coast as the mangrove requires a regular flushing by fresher water to survive. In the same area Williamson and Pomeroy (1935) noted freshwater springs along the foreshore and in the immediate vicinity archeaological surveys have recently identified well-preserved remains of an Ubaid settlement dated at 6900 B.P., pointing to human settlement in the area over a long period and by implication, a source of freshwater. Off the north-west coast, the principal small crustacean fishing grounds occur, and these animals thrive best in diluted sea water.

In south western Qatar there has been a general increase in TDS of an average 450 mg/l at each well in the northern sector of the Alat aquifer although in wells C15 and C16 in the southern sector there has been an improvement in quality of the order of 200 mg/l or 5%.

IX

ENVIRONMENTAL ISOTOPES

9.1 INTRODUCTION

The environmental isotopes used in this study of groundwater in Qatar include (a) the stable isotopes of oxygen and hydrogen and the radioactive isotope of hydrogen, tritium, which all form a part of the water molecule and (b) the carbon isotopes carried as dissolved carbonate species in the water. Changes in the concentrations of these isotopes can be used to characterise the water, to examine the mixing or stratification of waters and to provide some indication of age of the water since it was recharged or the residence time in the aquifer.

The sampling and interpretation are, however, not without their difficulties. Firstly, many samples are mixed by pumping from two unseparated aquifers and a single measurement therefore relates to a water whose composition is of intermediate value between original waters; secondly, the characteristics of the water at the time of recharge are unknown which limits the quantitative interpretation which can be made from the isotope measurements; thirdly, while the stable isotopes oxygen and hydrogen and the radioactive tritium are component parts of the water molecules and are, therefore, not subject to direct chemical reactions, the carbon isotopes of the carbonate species are part of the complex groundwater chemistry. They must, therefore, be considered as part of the overall chemical system, and the chemical and isotopic reactions have to be considered for each state of the development of the water.

With the above reservations and qualifications, isotope measurements do however, provide valuable information which can supplement that provided by hydraulic and hydro-chemical data. The data base has already been described in Chapter VIII and all analytical results are presented in Appendix VI.

9.2 STABLE ISOTOPES OF OXYGEN AND HYDROGEN

Oxygen consists primarily of the stable isotope oxygen-16 (^{16}O) together with a small component of a heavier isotope, oxygen-18 (^{18}O) (approximately 1 part in 500). Hydrogen is principally the isotope of mass 1 (^{1}H) together with deuterium (^{2}H) in the concentration of approximately 1 part in 6,400. The mean isotopic composition of environmental water is entitled Standard Mean Ocean Water (SMOW), and it is against this standard that the small changes of composition of individual samples are measured. Measurements are expressed in terms of deviation from the standard (δ) in parts per thousand (o/oo)[1].

Deviation from SMOW occur throughout the hydrological cycle and are caused by evaporation and condensation processes - the lighter isotopes evaporating more radily and the heavier isotopes condensing preferentially in a process known as isotopic fractionation. The climatic conditions of temperature and humidity control the degree of fractionation, and hence variations in isotopic composition offer the possibility of associating the groundwater composition with the climate prevailing at the time of recharge. The aquifers of eastern Arabia were recharged during pluvial periods extending over the past 50,000 years and there are clearly no direct data on climatic conditions during that time and an absolute time scale cannot be deduced from isotope measurements. It is, however, sometimes possible

---

1/ $$\delta x = \frac{Rx - Rstd}{Pstd} \times 1000 \text{ o/oo}$$

where δx = sample deviation

Rx = sample isotope ratio

$Rstd$ = standard isotope tatio

Table 9.1

ISOTOPE DATA

Well	Date	δO^{18}	δD	Tritium (T.U.)	δC^{13}	C^{14} (% mod.)	C^{14} corrected age (years)
A19	26/10/72	-2.66	-6.3	0.6			
A10	25/02/75	-2.18	-8.6	5.6			
C6	27/02/75	-1.66	-1.3	59.4			
C6	18/03/75	-1.96	-3.3	57.5			
C6	12/04/76	-1.51	-1.5	46.3			
A25	09/03/75	1.4	16.4	16.1			
B22	17/12/75	-2.29	-10.3	5.0			
C8	27/12/75	-1.56	-7.0	1.3			
B24	26/02/75	-2.03	-11.6	11.6			
B26	26/02/75	-1.77	-8.60	4.2			
B34a	26/02/75	-1.76	-9.1	6.3			
R.R.	26/02/75	-1.95	-6.6	6.7			
B31	26/02/75	-1.96	-4.7	17.5			
B29	24/12/75	-1.9	-8.4	0.3			
B29	10/04/76	-1.95	-8.0	0.3			
B37	23/12/75	-1.51	-4.0	0.1			
B39	23/12/75	-2.2	-4.2	12.4			
C1a	23/12/75	-1.44	-12.1	1.6			
C2	23/12/75	-2.2	-8.8	0.5			
C2	12/05/76	-2.29	-9.2	1.1			
C3	23/12/75	-2.52	-12.3	1.4			
B2	24/12/75	-1.97	-9.6	5.1			
A5	26/10/72	-2.76	-12.1	0.3			
A5	09/03/75	-2.95	-19.3	1.1			
A5	27/04/76	-3.49	-20.7	0.7			
A1	26/10/72	-2.33	-12.3	3.2			
A1	27/04/76	2.38	13.2	15.8			
A32	09/03/75	0.1	4.7	38.4			
B5	09/03/75	-3.62	-23.8	5.2			
B5	05/05/76	-3.85	-22.7	3.2			
C16	13/07/75	-0.82	-6.0	5.4			
C16	13/04/76	-1.0	-4.6	4.6			
C18	12/07/75	-3.57	-42.3	0.3			
C18	27/04/76	-3.76	-41.3	0.1			
A6	23/12/75	-3.05	-21.9	0.5			
A6	27/04/76	-2.92	-19.5	0.3			
A18	23/12/75	-2.66	-16.2	0.1			
C12	26/10/72	-4.1	-34.6	0.1			
C12	12/07/75	-2.66	-28.9	0.4			
C12	31/03/76			0.0	-7.1	8.9	7850
C12	12/04/76	-2.73	-30.1	0.8			
C12	12/05/76	-1.37	-8.0	2.0			
C10	12/07/75	-4.59	-39.0	0.1			
C10	10/03/76				-7.2	4.8	13100
C10	12/04/76	-4.79	-38.8	0.8			
C11	12/07/75	-4.81	-37.2	0.4			
C11	18/04/76				-7.2	-0.7	18150
C11	12/04/76	-4.74	-38.9	0.2			
C13	13/07/75	-4.58	-36.9	1.3			
C13	27/04/76				-7.7	3.0	17750
C13	27/04/76	-5.2	-38.5	0.4			
C14	13/07/75	-3.79	-34.4	2.4			
C14	13/04/76	-3.79	-31.6	0.9			
C15	13/07/75	-4.07	-34.5	1.1			
C15	13/07/76	-4.07	-32.3	0.4			
Sea-Doha	26/10/72	2.16	15.5	0.0			
Sea-Salwah	27/02/75	4.53	28.9	0.0			
Surf. Pond	27/02/75	-1.25	1.5	21.4			
Surf. Pond	01/03/75	-0.6	2.4	0.0			
Precipitation	28/01/75	-0.72	14.4	33.5			
Temp. Surf. Pond	04/03/75	0.31	8.+	0.0			
Temp. Surf. Pond	10/03/75	2.04	15.3	0.0			
Temp. Surf. Pond	18/03/75	5.57	33.9	0.0			
Temp. Surf. Pond	25/03/75	11.51	59.3	0.0			
P30	04/79	-1.77	-9.25	0.0	-12.21	23.3	5050
P29b	02/79	-3.81	-32.3	0.0	-4.1	3.6	7750
P33	12/79	-5.69	-42.4	0.8	3.34	2.4	7150
P32	08/79	-4.97	-38.8	0.9	-6.87	1.3	23350
P32a	11/79	-2.73	-27.0	0.9	-9.03	3.9	17350

to infer a timescale from paleoclimatic conditions, with archaeological, palynological and other studies, e.g. Edmunds & Walton (1980).

The stable isotope access to the groundwater system is via rainfall, either directly or indirectly and individual rainfall events vary in isotopic composition depending upon the climatic conditions producing the rain.

Data have been collected throughout the world for nearly two decades by the International Atomic Energy Agency and the World Meteorological Organization and published in the IAEA Environmental Isotope Data Series of reports. There is a linear relation between the world-wide concentrations of the two stable isotopes ^{18}O and ^{2}H and this can be expressed as the 'World Mean Precipitation Line' (WMPL) or 'World Meteoric Water Line' (WMWL) (Craig, 1861) such that

$$\delta^2H = 8\,\delta^{18}O + 10$$

and this line is plotted on Fig. 9.1.

This relationship is not always universally applicable, particularly in hot and arid areas where rainfall is limited and sporadic. The nearest international monitoring station to Qatar is Bahrain where the isotopic relation has been determined by IAEA as

$$\delta^2H = (4.98 \pm 0.29)\,\delta^{18}O + (9.8 \pm 0.8)$$

(IAEA Technical Report Series No. 206 (1981) and this line is also indicated on Fig. 9.1.

Stable isotope data from wells sampled during the 1975/76 and 1979/80 programmes are plotted. The group of samples enclosed by the rectangle are taken from the combined Rus and upper Umm er Radhuma Formations of north central Qatar with a mean isotopic composition of $\delta^{18}O$ = -2.0 o/oo and δ^2H = -6.2 o/oo. These values are close to the average for the World Mean Precipitation Line (line A-B, Fig. 9.1) whose values are -2.3 and -7.2 respectively, thus confirming that recharge to the upper aquifer (SEQUENCE 1, ZONES A and B waters) is by a relatively direct process or by waters apparently little affected by evaporation. The only exceptions to this general observation are the samples from wells A25 and A32 (see Table IX.I) situated in the north western coastal area which show an enriched stable isotopic composition related to the Bahrain Meteoric Water Line suggesting evaporation. Their low chloride content, determined from a chemical analysis of a sample taken at the same time, precludes any possibility of seawater intrusion despite their proximity to the coast. The high tritium concentrations also point to recent recharge and it is therefore very likely that recharge to these two wells took place from ponded run-off some time after rainfall occurred.

These data tend to confirm that recharge is predominantly, but not exclusively, the direct process postulated in Chapter VI whereby rapid infiltration occurs through the shallow coarser soils around the periphery of depressions during and soon after flooding, by interception of run-off and not as a residual after ponding and isotopic enrichment due to evaporation. However, the analysis of samples taken from ponded flood water at Karanah in February 1975 (Table IX.I) shows that isotopic enrichment by evaporation is significant only after about 10 days and some ponded waters could have been recharging for a few days without showing any enrichment.

Where samples show an isotopic composition which deviates significantly from the above mean values, there is clear indication that processes, other than evaporation, have taken place and usually points to sea water intrusion or mixing with deeper, isotopically depleted waters. Fig. 9.1 shows two distinct groupings of samples, with a mixed group linking the two. The upper set refers to the recharge waters of north central Qatar discussed in the preceding paragraph, whilst the lower group are from the deeper, and sometimes confined, Umm er Radhuma Formation and also from the shallow confined Alat aquifer of SW Qatar. The line AB represents the mixing line between the recharged aquifer and the deeper aquifer.

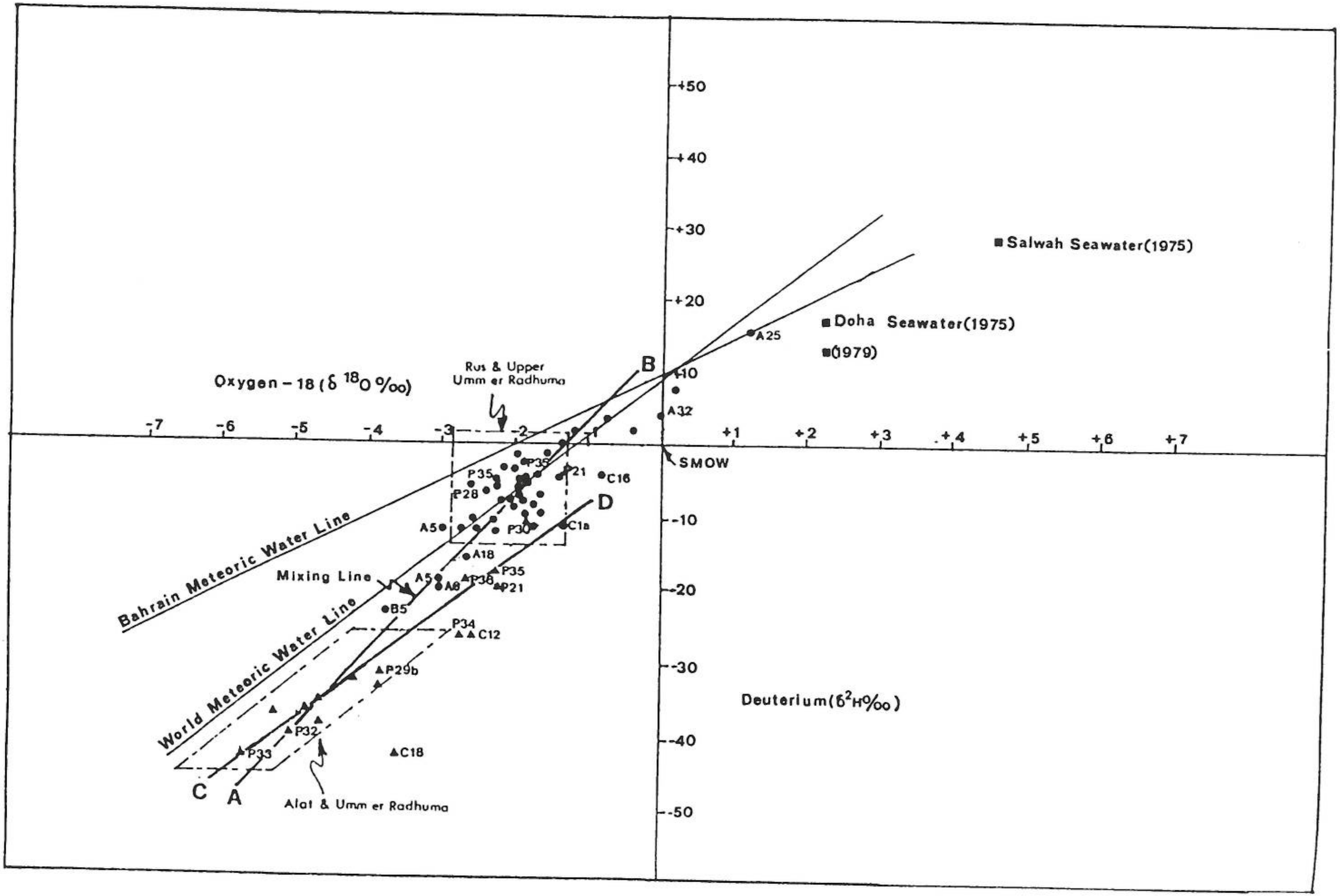


Fig. 9.1 OXYGEN-18, DEUTERIUM COMPOSITION OF QATAR GROUNDWATER

Both P33 and P29b were drilled to the Umm er Radhuma Formation along the west coast of Qatar. Old brackish groundwater is confined by a thick gypsiferous Rus aquitard.

Well Nos. P32, C13, C11, C10, C14, C15 all tap the Alat aquifer of SW Qatar and display a similar isotopic composition to that of the deeper Umm er Radhuma waters thus lending weight to the supposition that these younger waters have been augmented by deeper Umm er Radhuma waters migrating upwards through gypsum-and anhydrite-free 'windows' in the Rus Formation in Saudi Arabia (See Fig. 8.35). The parallelogram (hatched in Fig. 9.1) enclosing these samples is also the envelope for analyses for samples from the Umm er Radhuma Formation both in Al-Hasa and Qatif in Saudi Arabian (Zötal et al, (1978)) and Bahrain (Walton-pers. comm.) confirming a regional uniformity of isotopic composition for the Formation in areas not in hydraulic connection with the upper aquifers of Qatar.

The line C-D is seen to lie parallel to the World Meteoric Water Line indicating different climatic conditions at the time of recharge to the deeper aquifers. In general, rainfall occurring in colder climatic conditions is isotopically lighter with more negative values of δ^2H and $\delta^{18}O$ and, on this basis, the data indicate that recharge to the deeper aquifer must therefore have taken place during an earlier pluvial period when the mean temperature was probably lower and the relative humidity somewhat higher than it is today.

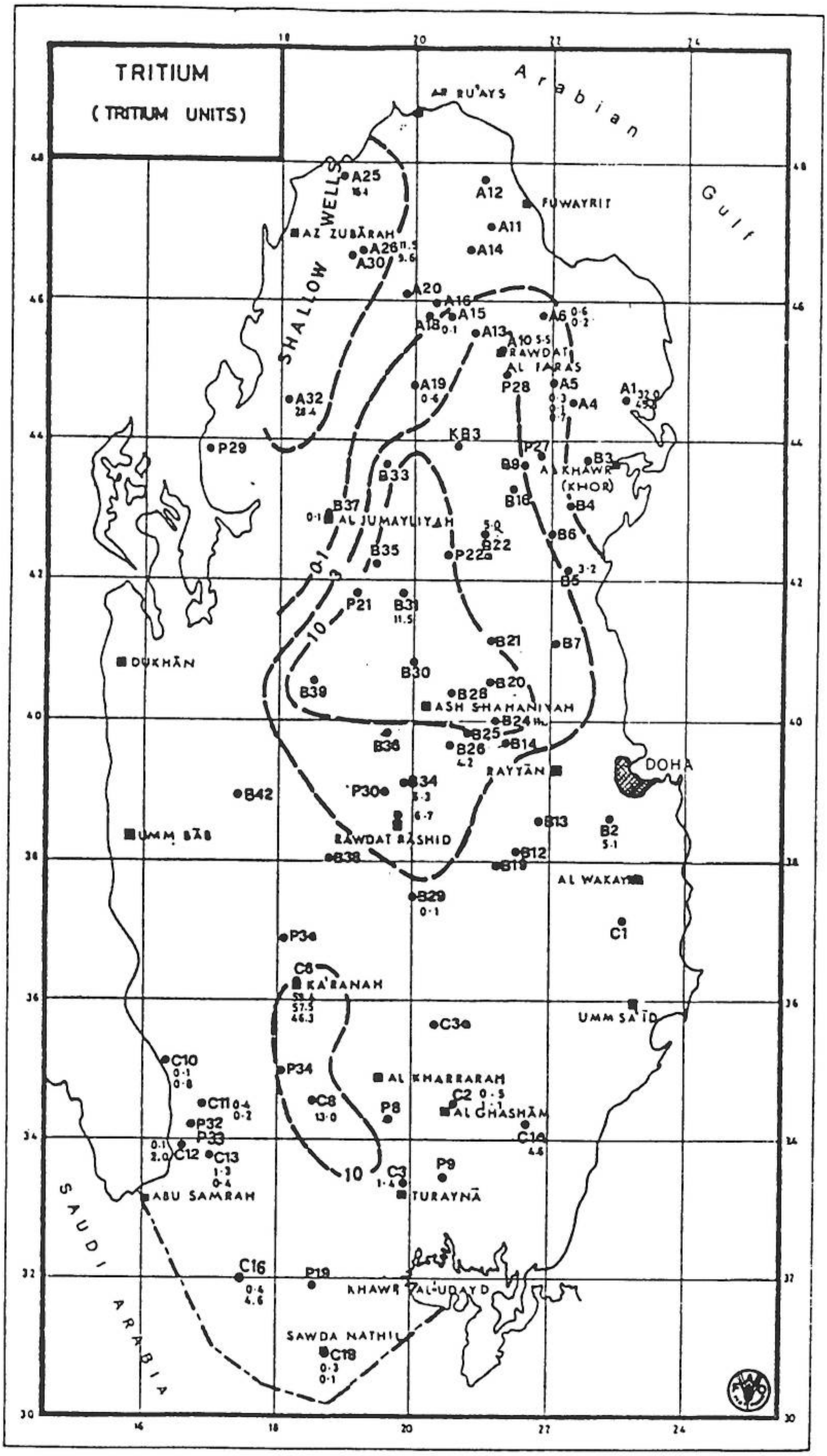
A second feature of this plot is the anomalous position of the sample from C18. Generally there is a reasonable correlation between increasing negativeness in the stable isotope composition and salinity but, in a series of samples with a salinity of 72,000 mg/l drawn from a mixture of Aruma and Umm er Radhuma waters in this well, a reversal of this trend is evident. This very saline water has a less negative isotopic composition, particularly in the ^{18}O deviation, than less saline waters elsewhere. Samples from well No. C18 shows a mean ^{18}O value of -3.7 o/oo whereas elsewhere in Qatar such a value is associated with a salinity level of the order of 4000 mg/l. The ^{18}O and ^2H ratios, when considered together with the salinity data, suggest that this very saline ater, which is in fact a brine, is neither part of the modern meteoric groundwater system nor, because of its very high salinity, can it indicate a modern sea water intrusion. It is therefore likely that these deep waters of the Aruma and Umm er Radhuma Formations underlying Qatar are essentially brines of ancient meteoric, connate and marine origin, with a component linked to the original precipitation of the Rus Formation evaporites.

9.3 TRITIUM

Tritium (^3H) is a radioactive isotope of hydrogen with a mass of 3 units and a half life of 12.43 years. It is naturally produced in the earth's upper atmosphere by cosmic ray bombardment which maintains a natural background level of 2 to 5 Tritium Units (TU)*. The atmospheric concentration of tritium increased by several orders of magnitude with the advent of thermonuclear testing in 1954 with peak values of 1000 TU at Bahrain occurring in 1963. Because of its comparatively short half-life, groundwater recharged prior to 1954 should show tritium concentrations below about 2 to 4 TU.

Fig. 9.2 shows the location and the tritium concentration of all samples collected and analysed during the 1975 and 1978 sampling programmes. The tritium content of the groundwater (See Table 9.1) exhibits quite large variations, within the range of near zero to 59.4 TU. The waters may be classified into three general groups; (A) those containing more than 10 TU, (B) those containing 3 to 10 TU, and (C) those containing less than 3 TU. Although the selection of tritium levels for each group is rather arbitrary, the above range of values signifies the time span involved in the replenishment of the groundwater and may be used in semiquantitative interpretation of the turn-over rate. This Group A waters would indicate very recent recharge, within the last few years; this group includes the majority of wells in northern Qatar with the exception of those wells along the eastern

* TU = 1 tritium atom in 10^{18} atoms of hydrogen.



GROUNDWATER TRITIUM Fig 9.2

coast where increasing salinity has reduced the tritium content by a dilution effect. Group B would indicate some recharge during the post-thermonuclear period, i.e. at sometime during the past 20 years and includes a number of wells in all areas of Qatar which, in some cases, may also exhibit such dulution effects. Group C waters include all the deeper wells located in south western Qatar, the majority of which tap the Umm er Radhuma aquifer and where there is little evidence of recent recharge.

An attempt has been made to derive an estimate of the turn-over rate of the freshwater body from tritium data to provide an independent check on the recharge estimates arrived at by mofe conventional hydrological methods. This approach was first presented to the Project in a report (Yurtsever and Payne (1978)) by IAEA who undertook the field collection and analysis of samples. The basic theoretical framework of this approach relies on the fact that the observed tritium contents of groundwater are the result of the response of the system to a known tritium input from precipitation. If the response can be described by certain dynamic parameters then the tritium input can be related to the observed output to estimate the dynamic parameters.

A mathematical expression of such an approach was given as the following convolution integral.

$$C_o = \int_o^t f_i(t-T).f(T).e^{-\lambda t}.dT$$

where

C_o	=	tritium output concentration
$f_i(t-T)$	=	tritium input concentration
$f(T)$	=	system response function (transit time distribution function)
$e^{-\lambda t}$	=	decay correction factor for a radioactive isotope
t	=	time
T	=	transit time
dT	=	unit time (1 year)

In applying the above general convolution integral a major difficulty is the definition of a proper system response function f(T) for a given aquifer system. In this evaluation, an exponential type of system-response function was used which is given by

$$f(T) = \frac{V}{Q}.e^{-\frac{Qt}{v}}$$

where V/Q is the turn-over rate.

As it is difficult to estimate the tritium input concentration of recharging water from each year, owing to variations in both space and time of individual major storms, two extreme cases were used in the calculations : <u>a Minimum input concentration and</u> <u>a Maximum input concentration</u> to provide an order of magnitude of the range in the recharge. By applying the extreme tritium input concentration curves (Fig. 9.3), derived from precipitation samples, and the exponential transit-time distribution function, the tritium output concentrations that may be expected at the sampling date are computed by the convolution integral for various values of the V/Q parameters. The mean values for each case are 152 (minimum output) and 515 (maximum output). Alternatively, the average TU value for the entire system (4,5 TU) may be used to approximate the parameter V/Q which is shown to be 150 and 500; very close to the former calculated values.

The estimates made for the average value of the V/Q parameter of the upper freshwater body of Qatar may be said to represent an average turn-over rate in years of the water in the system, and have therefore been used to arrive at an estimate of the annual recharge volume. By applying an early (1974) estimate of the total volume of freshwater in storage as 5250 Mm^3 the upper limit of the average annual recharge volume is calculated to be $5.25 \times 10^9/150 = 35$ Mm^3 and the lower limits as $5.25 \times 10^9 \times 515 = 10$ Mm^3. This result is difficult to assess as it is derived from a storage volume calculated on the earlier assumption that the freshwater body extended into southern Qatar. If the northern area only is considered the recharge volumes become 16 and 5 Mm^3 respectively.

Recharge to the northern area is calculated to be of an average annual volume of 27 Mm^3 within the range 0.5 - 85 Mm^3yr^{-1} somewhat beyond the range of figures indicated by isotope data. However, as Yurtsever and Payne (1978) have themselves pointed out, the above estimates are merely imprecise indications of the possible order of magnitude and may be subject to significant error in view of the simplifying assumptions made in the computations. In particular, the basic assumption· that the system is in a steady-state condition, implying discharge equals recharge; that recharge equivalent to an average value occurs each year; that the system function for each compartment defined by a samples well is of the exponential type and that the discharge/recharge ratio for each compartment is 1 (Siegenthaler 1978).

None of these assumptions is met; neither the system nor each compartment is in a steady state condition that many of the sampled wells show the effects of dilution of tritium by incursions of more saline water. In the absence of this mechanism the average TU content would increase and the V/Q parameter would be decreased. Other uncertainities in the calculation are the estimates of the volume of the freshwater body, calculated on the basis of geophysical profiles deep boreholes, and the assumed storage coefficient (15%) of a fractured karst limestone aquifer, may vary considerably. If a 2% storage coefficient is assumed, for instance, the minimum and maximum annual recharge limits become 6.45 Mm^3 and 22 Mm^3 respectively. Similarly, if only two additional modern water samples were to be added to the data base, the value of V/Q would differ by 45%, thus indicating the sensitivity of certain input parameters in the equation.

As a valid alternate method of calculating recharge the foregoing has its limitations. However, with a continued belief that isotope techniques do offer the means whereby recharge may be determined to within acceptable limits of accuracy, a recently developed geochemical and isotopic technique is now being applied in Qatar. This is based on the work of Edmunds and Walton (1980 (a,b)) in Cyprus and Libya where solute profiles of the unsaturated zone were interpeted to provide estimates of the direct palaeo-and recent recharge component, using chloride and tritium levels, in a steady state, mass-balance approach. The field technique is relatively simple and has recently been introduced in Qatar by one of the authors (N.R.G. Walton) now with the Qatar Ministry of Electricity and Water.

9.4 CARBON ISOTOPES

Carbon-14 is a radioactive isotope of carbon with a half-life of 5,730 years and is present in the carbon dioxide of the atmosphere being produced at a fairly constant rate by the action of cosmic rays on nitrogen in the upper atmosphere. Unlike the isotopes of hydrogen and oxygen, carbon is subject to chemical reactions as it moves with the groundwater, being involved mainly in the carbonate buffer control system. Changes in the carbon-14 concentration are partly due to its radioactive decay but also due to the chemical behaviour of bicarbonate. The carbon-14 in the recharging water is associated with other stable carbon isotopes (^{12}C and ^{13}C) which are normally quite distinct from that of the rock. Rather than absolute values, the presence of ^{13}C is expressed as a deviation, hence $\delta^{13}C$, from the internationally accepted PDB standard. The $^{12}C/^{13}C$ ratio of a certain fossil belemnite was deemed the fixed point from which all other ratios would differ, as with SMOW (9.2), and be expressed in parts per thousand (o/oo). Hence any subsequent changes of carbon-14 concentration not due to radioactive decay also occur proportionately in the $\delta^{13}C$ value. The $\delta^{13}C$ concentration can therefore be used to evaluate the losses of carbon-14 due to causes other than the radioactive decay.

The $\delta^{13}C$ values for materials which enter the water-carbon cycle are shown in Table 9.1.

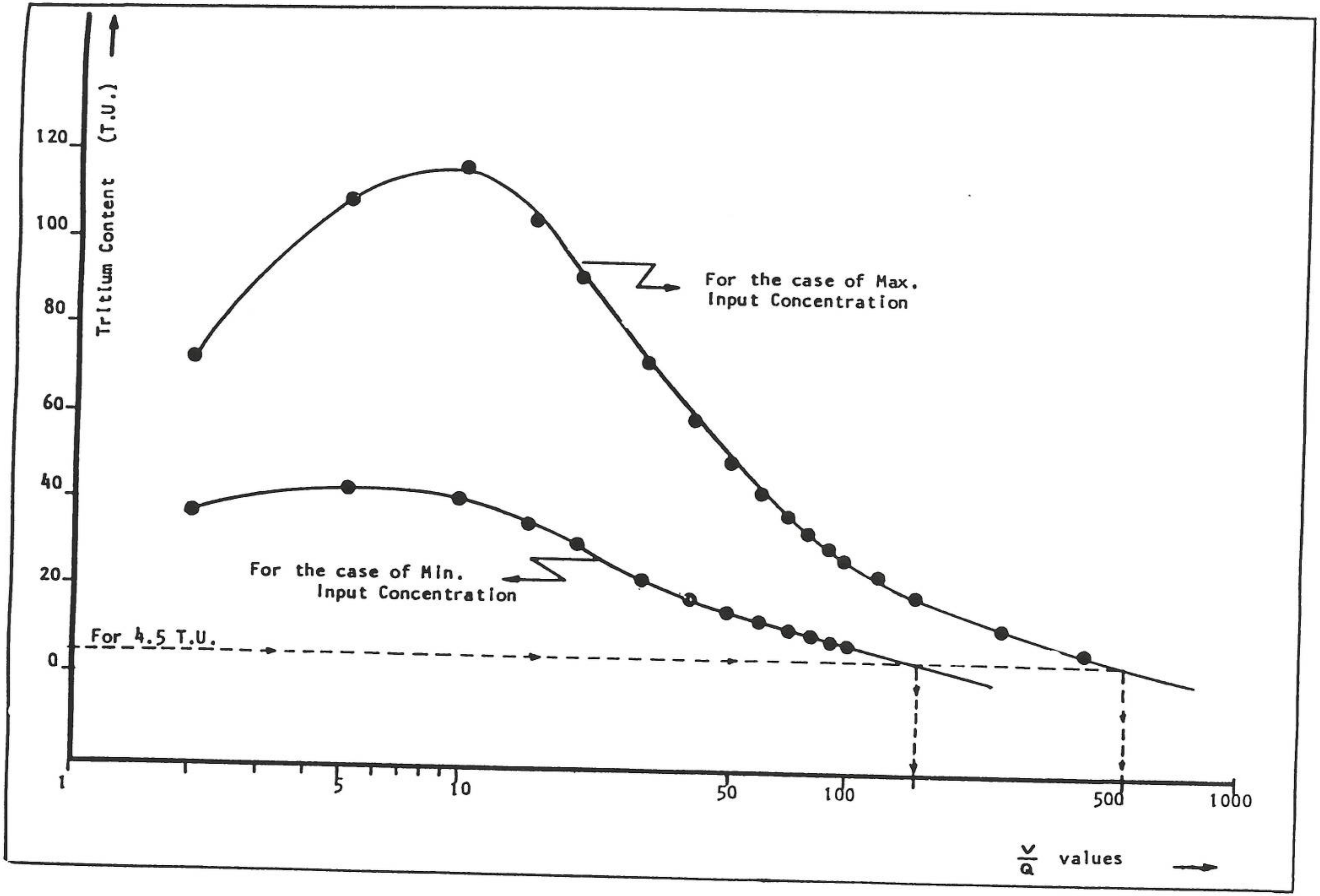


FIG 9.3 COMPUTED TRITIUM OUTPUT CONCENTRATION FOR 1975

Table 9.2

$\delta^{13}C$ Values of Carbon Sources in Groundwater

(after Wigley 1976)

Material	$\delta^{13}C$ o/oo
Carbon dioxide (air)	-7 approx.
Marine limestone	+1 to -1 approx.
Plant humus	
(a) C3 Calvin Cycle (temperate)	-26
(b) C4 Hatch Slack Cycle (arid)	-13
Fossil humic material in limestone	-25 approx.

The input of carbonate species at the outcrop is a complex process and is critically dependent on hydrological and humic conditions prior to and during infiltration. These are discussed briefly in order to provide a basis for interpreting the groundwater data. Several models are possible and no single model may be applicable over the long time span of the groundwater ages under conditions of changing but, in detail, unknown climate.

The classical chemical reaction which produces the bicarbonate ions in groundwater is :-

		H_2O	+	CO_2	+	$CaCO_3$	=	$Ca(HCO_3)_2$
		(recharge)		(biogenic)		(rock)		(bicarbonate dissolved in groundwater)
	^{14}C			100% modern		0% modern		50% modern
Calvin Cycle	^{13}C			-26 o/oo		0 o/oo		-13 o/oo
Hatch Slack Cycle	^{13}C			13 o/oo		0 o/oo		- 7 o/oo

Any exchange between the dissolved bicarbonate and the rock due to precipitation and re-solution during movement of the water through the aquifer will result in the $\delta^{13}C$ values approaching more nearly that of the rock. By using the $\delta^{13}C$ value, allowance can be made for the changes in ^{14}C. The method of correction in common use is that of Pearson and Hanshaw (1970), modified by Wigley, Plummer and Pearson (1978) and simplified by Evans and Otlet (1978). Recent work (Reardon and Fritz 1978, Freeze and Cherry, 1979) has suggested that a ^{14}C activity of 100% modern instead of 50% modern would be more appropriate since partial pressure CO_2 is assumed to be constant within the open system under equilibrium conditions.

Alternative methods have, however, now been adopted by the IAEA (Payne, 1981) whereby two estimates are given. The first is based on the approach described by Reardon and Fritz (1978), referred to above, and the second on carbon isotope data. Essentially the latter approach assumes isotopic equilibrium between carbon dioxide gas in the unsaturated zone and disslved bicarbonate taking into account the appropriate fractionation factor for ^{13}C and the great excess of carbon dioxide. Comparison of the computed carbon-13 of the HCO_3^- with the actual measured value provides an estimate of the dilution by 'dead' carbon.

Table 9.3 shows stable isotope, Tritium, $\delta^{13}C$ and ^{14}C data from a number of wells in Qatar designed to provide age determination of the deeper waters of the lower Umm er Radhuma, the Alat and the combined Rus and upper Umm er Radhuma.

Table 9.3

Stable Isotope, Tritium, ^{13}C and ^{14}C Data

Well No.	Formation	$\delta^{18}O$ o/oo	$\delta^{2}H$ o/oo	^{3}H T.U.	^{14}C o/oo modern	$\delta^{13}C$ o/oo	Age 1/ years	Age ± 2σ 2/ years
P32	Alat	-4.97	-38.8	0.9	1.3	- 6.87	25,800	21,700 ± 7,300
P33	UER	-5.69	-41.8	0.8	2.4	- 3.34	21,200	28,500 ± 5,330
P34	UER	-2.73	-27.0	0.9	3.9	- 9.03	16,700	17,500 ± 6,700
P30	UER	-1.77	-9.25	–	23.3	-12.21	6,500	9,400 ± 2,200
P36	UER	-2.61	-18.2	0.2	8.9	-11.79	16,400	17,100 ± 1,200
P29b	UER	-3.81	-30.7	–	3.6	- 4.10	17,300	15,900 ± 3,000
P35	RUS	-2.19	- 5.7	8.7	65.2	-10.05	–	700 ± 1,200
	Upper UER	-1.88	- 5.7	0.5	14.7	- 9.51	9,200	11,200 ± 1,300
	Lower UER	-2.18	-18.4	0.3	13.2	- 7.77	–	10,400 ± 1,450
P21	Rus/UER	-1.31	- 4.1	0.5	21.4	- 7.71	7,000	6,300 ± 1,450
	Lower UER	-2.19	-19.5	0.6	3.7	- 5.53	16,500	18,100 ± 2,150

Analysis of samples by IAEA, Vienna.

1/ Corrected age estimated according to the method of Reardon and Fritz (1978).

2/ Corrected ages obtained from carbon isotope data.

In south western Qatar P32 and P33 are two exploratory wells drilled alongside each other, P32 cutting the Alat aquifer only. In P33 the Alat was cased out and drilling continued through thick dry gypsiferous chalky limestones of the Rus Formation to the Umm er Radhuma Formation. The two ages given for samples from these two aquifers are however similar at about 21,000 yr and 28,000 yr respectively and offer further confirmation of augmentation of the Alat aquifer by waters from the Umm er Radhuma in Saudi Arabia.

Well No. P34 is located six km northeast (see Fig. 3.12) of P32/33 on the southward extension of the Dukhan structural high. Here too dry gypsiferous Rus Formation was also encountered overlying the Umm er Radhuma Formation although an age of about 17,500 yr is somewhat younger than that obtained from P33. Despite the fact that the Rus appears to be an effective aquiclude in this borehole, the interpretation of chemical and isotope analyses suggests a mixture of waters of three origins; local recharge (± 79%), sea water (± 13%) and deep brackish water (± 8%) (Payne 1981). While a sea water component is unlikely, recharge may well have taken place in the large depression areas to the east of the borehole. The ground surface lies some 20 m lower indicating the surface removal of a considerable thickness and volume of gypsum which resulted in the deflation of the land surface and permited recharge to gain access to the upper Umm er Radhuma aquifer via a limited area of permeable Rus Formation. Spreading of this freshwater recharge below areas where Umm er Radhuma Formation aquifer is overlain by impermeable Rus Formation gypsum is postulated. Similarly, wells P30, P36 and P29b are located within the gypsiferous facies area of western and southern Qatar where the Umm er Radhuma is confined below the dry gypsiferous Rus aquiclude. The dates for P36 and P29b are similar at about 16,000 - 17,000 yrs but that of P30 where a younger age is indicated, showing implying recent recharge possibly by dilution via abandoned boreholes associated with irrigation within the immediate vicinity.

Well P35 is located within the central northern recharge zone and is the only well in which three separated samples were obtained from the aquifer profile. The Rus aquifer shows a stable isotopic composition and tritium content indicative of recent recharge with an apparent age of 700 yrs. The sample from the upper part of the Umm er Radhuma, the formation immediately below and in hydraulic continuity with the Rus aquifer, has an isotopic composition similar to that of the upper sample (although the tritium concentration is effectively zero) with an age of about 10,000 yr.

The third sample was taken from the more saline underlying waters and has a depleted isotopic composition. The chloride concentration of this sample is relatively low suggesting that mixing with deeper brackish water is the cause of the chlorinity. The samples taken from this well indicate a hydraulic continuity throughout the profile with meteoric waters overlying or 'floating' on deeper, brackish groundwater.

A similar interpretation may be made in the case of the samples from P21, located within the same general area. The upper section, composed of water from both the Rus and upper part of the Umm er Radhuma has a characteristic stable isotope composition showing a slight evaporation effect whereas the sample from the deeper lower Umm er Radhuma aquifer is similar in composition to that from P35. The ages of the two waters are about 7,000 yrs and 17,000 years respectively. This well was originally drilled into the upper Umm er Radhuma Formation in 1975 and then later deepened in 1980.

X

HYDRO-GEOLOGY

10.1 INTRODUCTION

10.1.1 Project Objectives

The prime objective of the Project was the definition of the limited fresh groundwater reserves of Qatar and the planning for the optimisation of their exploitation concurrently with the development of agricultural production. This planning also required the integration of the existing and future demands on the some reserves in the provision of domestic and industrial water supplies. Despite the rapidly expanding facilities for the desalination of sea water, which was displacing the former complete reliance on low salinity groundwater alone, the provision of a piped distribution of potable water accelerated the rate at which the rise took place and more and more groundwater was required to satisfy the blending and distribution requirements as well as to fulfill the needs of an expanding agricultural sector.

It is thus clear that from 1958, when the several natural factors contributing to the water balance stood in near equilibrium, with man's activities of only very limited influence, the situation had changed markedly by 1974, at the beginning of the second phase of studies. Water balance estimates (see also Chapters 6 & 13) have placed the long-term annual average natural recharge at 28 Mm^3yr^{-1} with a range from as little as 8 to as much as 64 Mm^3yr^{-1} dependent upon rainfall amount, frequency and intensity. Of this, average outflow losses to the sea around the coast of Qatar and to evaporation from sabkha surfaces may have stood as high as 25 Mm^3yr^{-1} in 1958 when only small quantities of groundwater were exploited for agriculture, but by 1974 the total groundwater extraction had probably reached some 40 Mm^3yr^{-1} which, with irrigation return on that part of the total used for crops, is equivalent to a net extraction of some 33 Mm^3yr^{-1}. With the extraction already in excess of the recharge from about 1971 onwards, water levels began to decline and the outflow to the sea and sabkhas fell in consequence with the original hydraulic head, required to drive such a volume of water coastwards, no longer available.

During the period of the Project Second Phase vital changes in the manner and quantity of groundwater exploitation have occurred. The capacity to desalinise sea-water has expanded greatly and ground water is theoretically required for blending to the required level of dissolved salts only. However, is has been found that large volume of low salinity groundwater are still required to make up for sector shortages and for temporary supplies in the incomplete sections of the distributions network.

Thus, while domestic and industrial requirement from groundwater had reached a peak of about 6 Mm^3yr^{-1} in the years 1975-78, by 1980 the total potential requirement for Doha and its environs had risen to about 55 Mm^3yr^{-1}, of which some 90% or 48 Mm^3yr^{-1} was actually met, with groundwater required for blending and as stop-gap supplies at about 8% of this total or nearly 4 Mm^3yr^{-1}. In addition, more of the other towns of Qatar and the outlying rural areas are being provided with a reliable water supply and the well fields which once supplied Doha only are now returning to active use to meet the expanding nation-wide demands. It must therefore be assumed that the well-field exploitation of groundwater will return to a peak capacity of 5 Mm^3yr^{-1} providing that no further large well-field development takes place or that no deliberate action is taken to reduce the extraction from such sources.

Overall groundwater extraction for agricultural use had reached some 77 Mm^3yr^{-1} in 1980 which, with irrigation return, is equivalent to net extraction in excess of 60 Mm^3yr^{-1}. It is likely that coastal discharge of freshwater reserves has now ceased and that the annual sea ward discharge has now declined to about 12 Mm^3yr^{-1}. Such an outflow cannot be regained as the positive head it represents is essentially controlled by the lower aquifer and as freshwater reserves decline saline rather than freshwater will be discharged coastwards. In addition it is believed that an average of 3 Mm^3yr^{-1} was transferred from the upper to the lower aquifer under the influence of the declining head difference between them to replace water pumped from the lower aquifer. This low rate of flow was controlled by the very limited vertical transmissivity between the aquifers compared to the higher horizontal transmissivity within the aquifers, which has permitted, in the case of the lower aquifer in recent years, up to 20 Mm^3yr^{-1} of saline groundwater to replace the fresh groundwater removed from the reserves. However it is likely that this downward vertical flow has now ceased and even reversed as the head of the upper aquifer has declined. Thus the likely average "safe yield" of freshwater available from the natural recharge has in fact improved with the decline in the losses of freshwater to the sea and could now be of the order of 25 Mm^3yr^{-1} with the possibility of a range from a negative value to some 2 or 3 times this average dependent upon recharge.

It is thus clear that from 1958, when the several factors contributing to the water budget stood in near balance, to the situation is 1980 when groundwater was being extracted at about 2.5 times the long term average "safe yield", and the reserve depleted at the rate of 30 Mm^3yr^{-1}, very large amounts have been exploited from the overall reserves, computed to be some 250 or 10% of the calculated original total of 2500 Mm^3. At the present rate of depletion, assuming that little or no change takes place in quantity of groundwater extracted due to expanding agriculture, the remaining reserves will be depleted to zero in 64 years. However it is considered likely that only 50% of this freshwater storage will be extractable before mixing with surrounding and underlying saline groundwater is sufficient to contaminate the remainder beyond usability and the period therefore reduces to 32 year i.e. by 2012.

10.1.2 History of exploration

Natural collapse structures (dahl), in which fresh and brackish groundwater could be reached from the surface, were amongst the first sources of perennial potable water available to nomadic herdsmen and coast-dwelling fisherman. It is likely that coastal and even off-shore springs also provided valuable supplies but with the decline in freshwater levels, these have dried up and there is little written or verbal history which allows an inter-pretation of the locations of such flows, the quantities involved and period of their final decline to zero flow.

Inventiveness lead to the development of simple hand-dug wells to serve the needs of an early settled population, their animals and the beginnings of seasonal agriculture. These first developments took place in surface depressions where the depths to water were least and cultivable soils were at hand. The power required to lift the water was provided by human and animal muscle and inclined walk-ways utilising gravity assistance in hauling of full skins of the surface, may still be found in the long-established gardens.

With the advent of the exploration for petroleum in the 1930's an adequate and permanent supply of water was required and the drilling for water and its extraction by pumping started in 1938 and increased with the expanding oil operations. Williamson and Pomeyrol (1938) listed 118 water sources, inventoried for the Qatar Petroleum Company, of which only 3 were drilled wells, and in so doing provided the first indications of groundwater levels and the locations of the first extraction sites. They also recorded standing water at the bottom of Dahl el Misfer and Dahl el Mudlam in central Qatar at probable elevations of +4 to +5 m. These caves are now dry.

As the population grew and it was realised that groundwater could be exploited for agricultural use, farms and gardens were developed. Good quality water was discovered suffi-ciently close to Doha to permit piped supplies to be installed, thus replacing early primitive animal-powered water transport. The capital city and port expanded rapidly and soon over took the earlier centre of Rayyan where the water resources for Doha were developed. With a concentration of source development in Rayyan and around Doha itself, the water quality deter-iorated due to incursion of sea water and the exhaustion of the limited thickness of freshwater overlying more saline water in an area, relatively close to the sea and where the geological and hydrogeological conditions did not provide for adequate reserves or annual recharge.

Large volumes of potable water were thus required from much further afield.

The first definitive survey of the groundwater resources of Qatar was undertaken by Le Grande Adsco Ltd. for Messrs J.D. and D.M. Watson, consultants to the Water Department of the Ministry of Electricity and Water, between February 1958 and May 1959. They were required to

1. find the form, quantity, quality and position of the freshwater resources of Northern Qatar;
2. estimate the present replenishment;
3. recommend how this might be improved;
4. prepare a geological map on a scale of 1:100,000.

The area surveyed lay to the north of a line between Doha and Dukhan only and thus was limited to about half of the total land area of Qatar, though the choice of this northern sector must have been based upon an early recognition of the over-riding importance of the Northern Groundwater Province in the general water resources of the nation. Groundwater levels near the centre of the peninsula generally lay some 3-4 m above sea level, with some isolated areas reaching 10 and even 15 m. The principal extraction areas were the well fields at Al Sinnah and Al Jumailiyah from where some 230,000 $m^3.yr^{-1}$ were pumped to the oil field area.

The connection between land surface depressions and higher well yields was quickly realised and all the major depressions were surveyed using surface resistivity methods and classified according to the quality and estimated reserves of potable water. 47 boreholes were drilled with a total depth of 1534 m and a further 8 small diameter cored holes were also drilled with a total of 728 m for general structural and stratigraphic exploration in areas away from the depression drilling.

Chemical analysis of water samples, lead to a division into three groups of groundwater :-

- Depression Water, underlying the principal depressions and of lowest salinity; less than 1500 EC, and of bicarbonate type. On the basis of geophysical surveys and drilling results the reserves of all surveyed depressions were calculated.

- Mound Water of higher salinity, up to 4500 EC and basically a sulphate type with a varying chloride component. This water was found to be of better quality near the centre of the peninsula, deteriorating coastwards. Two boreholes were sunk in inland areas remote from depressions and the Mound Water was found to be of good quality and chemically similar to Depression Water, thus finding, for the first time, evidence of the potential for a peninsula-wide freshwater resource not related to depression infiltration. Although not evaluated, this discovery pointed clearly to the general recharge potential and the existence of reserves and their replenishment, unrestricted by the depression run-off requirements. The statement "No reserves have been calculated for mound water, but as the areas where it can be found are not limited to the immediate vicinity of depressions, it would seem that the reserves are large" was of profound importance.

- Intrusive Saline Water, groundwater variably contaminated with sea water and therefore of chloride type.

The general conclusion reached was that away from depression areas, borehole yields would be lower and salinities higher. A general trend was for a deterioration of water quality with depth. It was not felt that the relationship between fresh and saline groundwater was affected by gravity-controlled interfaces, the Ghyben-Herzberg phenomenon, and the highly saline nature of the water beneath the fresh groundwater reserves was not identified.

A very rapid expansion in the development of shallow groundwater resources in the early 1960s drew attention to the still unknown lower limits of the freshwater reserves. In nearby Saudi Arabia potable reserves were being located in the Upper Cretaceous and Lower Tertiary formations and those rocks were known to underly Qatar. In 1962, Parsons Engineering carried out an interpretation of the data then available and, coupled with their knowledge of conditions in Saudi Arabia and Bahrain, recommended that the Umm er Radhuma aquifer underlying Qatar along the northern coast and southern borders as well as the Wasia aquifer along the southern border be studied by exploratory drilling to determine the quality of the water present and the hydrogeological characteristics of the aquifer systems. Their study postulated that at the then (1961) rate of extraction of about 4 $Mm^3.yr^{-1}$, the shallow renewable groundwater reserves were fully committed and that additional groundwater supplies could only be obtained by the economic utilisation of brackish water resources or by the successful exploration and development of deeper aquifers.

The subdivision of 'Shallow Zone' and 'Deep Zone', groundwater was introduced. The 'Shallow Zone' reserves, between 75 and 100 m thick in central regions, thinning northwards (and, though unstated, presumably east and west) to the coast, were stated to be contained in the Simsima Member and the Rus Formation. No emphasis was placed upon the separation of the lowest salinity waters below the depression the 'Depression waters' of Adsco (1959) and the 'Mound waters' into which they merged laterally, as these divisions arose from the way in which Adsco had used 1500 EC as a limit for classification. Parsons thus postulated the existence of freshwater reserves up to 100 m below sea level in central Qatar, an important feature implying isostatic control and salinity interfacing which had not been recognized by Adsco 13 years earlier. The lowest salinities occurred near the centre of peninsula with deterioration coastwards. The abundance of gypsum in the south accounted for the poor quality groundwater there. Deeper drilling to improve well yields resulted in the extraction of water from both zones and a consequent decline in quality.

The limited recharge potential, while unquantified, was noted as were the erratic variations in static water levels, particularly in the south and the generally low well yields. A tritium age determination for water pumped at the Jumailiyah well field indicated that the recharge had later place within the preceeding 10 years.

Parsons also provided the only well founded information on the Fasht ad Dibal 'spring' an offshore source of freshwater from a reef between Bahrain and Qatar. It was found to be a borehole drilled for structural control purposes, flowing at about 0.6 lts $sec.^{-1}$ from the Damman Formation (probably the Khobar member) and, at 2500 mg/l was slightly brackish though potable.

The 'Deep Zone' reserves were thought to be within the Umm er Radhuma and Wasia Formations for up to 300 m below the Shallow Zone with groundwater quality and flow conditions projected from the results of exploration in Saudi Arabia and Bahrain between the outcrop and the coastal areas. The flow direction was deemed to be east or northeasterly with the possibility that, despite the distances from the recharge area, the Deep Zone groundwater would still remain potable beneath Qatar. The higher rainfall conditions of the Pleistocene Pluvials were thought to have had a flushing effect thus improving the potential for Deep Zone potable reserves. Umm er Radhuma water of 4000 mg/l, had been encountered in Saudi Arabia only 10 km south of the Qatar border and, following a precept of structural control of groundwater flow, it was suggested that flow might be diverted to the north and the south of the Dukhan anticline and even be influenced by the much gentler Qatar Arch. Thus the areas selected as most promising were the extreme boundaries of the State, the northern and southernmost limits of the anticlinal structures.

During the first half of 1963, three deep holes were drilled by the contractor Almojil. The first at Ruwais, on the northern tip of Qatar, reached a total depth of 495 m. The conductivity of numerous samples taken during drilling, from a progressively increasing cut section, averaged 70,000 in a range from 24,000 to 100,000. At Sauda Nathil on the southern border, drilling to 1180 m penetrated the Umm er Radhuma, Wasia and Aruma Formations and a strong artesian flow reached the surface. EC ranged between 45000 and 88000. At Qarn Abu Wail, in the south west, at 495 m the full Umm er Radhuma was penetrated but the water conductivity was 25,000 to 30,000. The resultant detailed drilling reports have provided much valuable data which is included in Appendix I.2 and Appendix V.1.2 The general interpretation was of the complete absence of potable water supplies in the Umm er Radhuma and older formations below Qatar.

However, a shallow borehole was drilled at Qarn Abu Wayil for a water supply to the rig and revealed a source of groundwater of useable quality at shallow (> 50 m) depth in the Abarug (Alat) Member of the Upper Dammam Formation and under sufficient artesian head to induce a moderate flow at ground surface. A total of 8 shallow wells were drilled to depths ranging from 21.6 to 79.5 m. Artesian head rises in water levels were recorded and the conductivity of all waters was less than 7000 except for one site where it exceeded 16,000. mmhos. m.

The specific capacities of the boreholes varied between 3 and 1300 $m^2.day^{-1}$ indicating the very considerable control exerted by lithology over groundwater movement. Low salinity, water reserves were calculated for the Alat aquifer, assuming 15% average rock porosity and effective aquifer thickness of 10m, for the area within Qatar only, at 250 Mm^3. That the recharge area and further storage lay in Saudi Arabia was recognized, though no attempt was made to calculate the rate of recharge and the transmissivity which would control the rate of replacement of any groundwater exploitation.

Pencol (1965), in a 'Study of Project for Extension of Water Supplies to Doha', considered the implications of the estimated totals, and replenishment of groundwater reserves, made by Adsco for northern Qatar and by Parsons, with the Almojil drilling results, for the southwestern area. Despite the higher costs of supply from north central Qatar wellfields, compared to distillation of sea water near Doha, development of several new well fields, pumping stations and pipe lines went ahead in the late 1960's presumably to match the ever increasing demand.

Indeed, Sogreah (1966) in a report 'Improvement of Doha Water Supply', placed the problems of an adequate and expanding system to supply water to Doha with those of the management of the water resources of Qatar as a whole. Sogreah's 1966 estimate that the shallow well fields could yield up to 5 to 6 $Mm^3\ yr^{-1}$, based upon the estimates of Adsco and Pencol, proved remarkably accurate for, by 1975-76 and at a peak of 6 $Mm^3\ yr^{-1}$, the dynamic water levels in some of the shallow aquifer fields had declined to 10 m or more below sea level.

The estimates of useable water reserves in the Alat aquifer of the south west were recalculated at 50 Mm^3 for a 10 m thickness, 15% porosity and an area of about 500 Km^2, partly in Qatar and partly in Saudi Arabia. The replenishment was also estimated at 3.3 Mm^3 from a recharge of 10% of rainfall over the whole outcrop area and this was proposed as a safe yield for the source. Five alternative water supply schemes were proposed and costed, integrating the sources for shallow well fields, the Alat aquifer, distilled sea water, treated sewage effluent and singe and double distribution systems.

In 1971, M.E. Johnson, of Glenn A. Brown and Associates, reported on a review of the UNDP/FAO Hydro-Agricultural Resources Survey, then underway, from the point of view of groundwater resources. The results obtained and the recommendations for additional activities including drilling and aquifer testing required to bring the Project to a successful conclusion were detailed. During 1972, the consultants made several visits to the Project, totalling 5 months and presented a Technical Report on the Hydrogeology of Qatar by M.E. Johnson and G.R. Stern (1972). Among many other data collection requirements suggested by the consultants, a total of 110 observation wells had been selected to cover the whole of Qatar and accurately surveyed. Regular water level and quality observations, starting in 1971, have permitted an evaluation of the changes brought about by the interaction between exploration and recharge. By 1972, the consultants recognized a decline of 3 to 4 m in the central area water levels since 1958 and, assuming a 3% specific yield for the aquifer systems postulated a total overdraft of 222 Mm^3. Average aquifer recharge was estimated by Pike (1971) to be of the order of 20 $Mm^3.yr^{-1}$ and the excess of extraction over recharge was thought to be some 37 Mm^3 for the year 1971-72. Total extraction was estimated to have exceeded recharge by some 200 Mm^3 between 1958 and 1971 and the remaining reserves of freshwater were calculated to be between 220 and 350 Mm^3. The importance of the brackish water reserves of south west Qatar were also recognized. Test pumping of 5 wells was carried out and the specific capacities of 43 of the monitoring programme wells were determined. They ranged widely between 0.14 and 52 Lts $sec.^{-1}m.^{-1}$ or 12 to 4500 $m.^2day^{-1}$.

In January 1975, a consultant hydrogeologist L.W.Hyde visited the Integrated Water and Land use Project and prepared a Hydrogeological Evaluation and Test Drilling Proposal (1975). The report presented a detailed set of conclusions from the data available but made specific recommendations for improvements in the data collection network. Improvements were suggested in the equipping, data collecting and staff training requirements of the climatological network. The need for water level recorders and accurate measurements of water consumption on farms as well as extraction rates from wellfield was stressed. The need for recharge studies and geophysical surveys was also stated and a detailed programme of exploratory drilling and testing drawn up.

In mid 1977, at the end of the UNDP/FAO Integrated Water and Land Use Project, J.G.Pike (1977), Project Manager and Water Resources Specialist, prepared a detailed survey report, The Water Resources of Qatar and their Development, but, with the Government of Qatar's decision to continue the Project for a further 3 years, to implement many of the specific recommendations, this report was not issued. The present work therefore contains the essence and results of the long period of wide-ranging and intensive study which was started in July 1974.

10.1.3 General Groundwater Conditions

The Qatar peninsula forms with Bahrain, and the eastern province of Saudi Arabia, an integral part of the south-western coastal area of the Arabian Gulf. A fall in the Gulf sea level of only a few meters would create a new land area uniting the parts and stretching far out north eastwards into the Gulf. The existance of a connection between the groundwater of eastern Saudi Arabia and Bahrain on the one hand and Saudi Arabia and Qatar on the other has long been understood. Many valuable data have been made available from contemporary groundwater studies undertaken in Bahrain and the Eastern Province of Saudi Arabia. This information has not only permitted an integration of the Qatar situation into its overall position in the regional setting but has also provided insight and explanation of many of the conditions that would otherwise remain enigmatic.

The results of geological, geophysical and hydrochemical investigations both in Qatar and in the adjacent onshore and offshore areas of neighbouring States have lead to a generally accepted classification of widespread and traceable stratigraphic units into a complex series of aquifers and aquitards within which groundwaters of varying compositions move and are directed by the influence of lateral and vertical hydraulic pressures. Lateral flow takes place, within these aquifers and vertical flow occurs in both aquifers and aquitards where lithological changes in aquitard conditions permit the interchange of flow, dependent upon the prevailing pressure patterns. Recharge of meteoric water to the aquifers of the systems takes place by the direct infiltration of a proportion of the rainfall occuring over the outcrop, by infiltration into superficial deposits such as soil cover, weathered rock crust, wind blown sand etc.... with a delayed transfer to the underlying aquifer by the run-off transfer from lower-rate to higher-rate infiltration areas and, particularly in the Qatar context, by the accumulation and delayed infiltration of water ponded in the shallow depressions which are a widespread and frequent landscape feature.

Amounts of recharge are dependent upon the amount, intensity and frequence of rainfall, the infiltration rate and the soil or rock moisture conditions prior to each rainfall event. Measurements of the parameters and estimates of recharge are dealt with in Chapter 6. The results of recharge have been the development of a freshwater flow into and through the aquifer units in Saudi Arabia with a submarine flow to the island of Bahrain and possibly during Pluvial times to Qatar and beyond as well as the accumulation of freshwater, supported and surrounded by more saline water, by direct recharge from rainfall over the peninsula of Qatar.

An interpretation of the overall Central Arabian Gulf groundwater flow pattern and the most important factors influencing such flow, are depicted as Fig 10.1.

Central Arabian Gulf Groundwater Flow Pattern

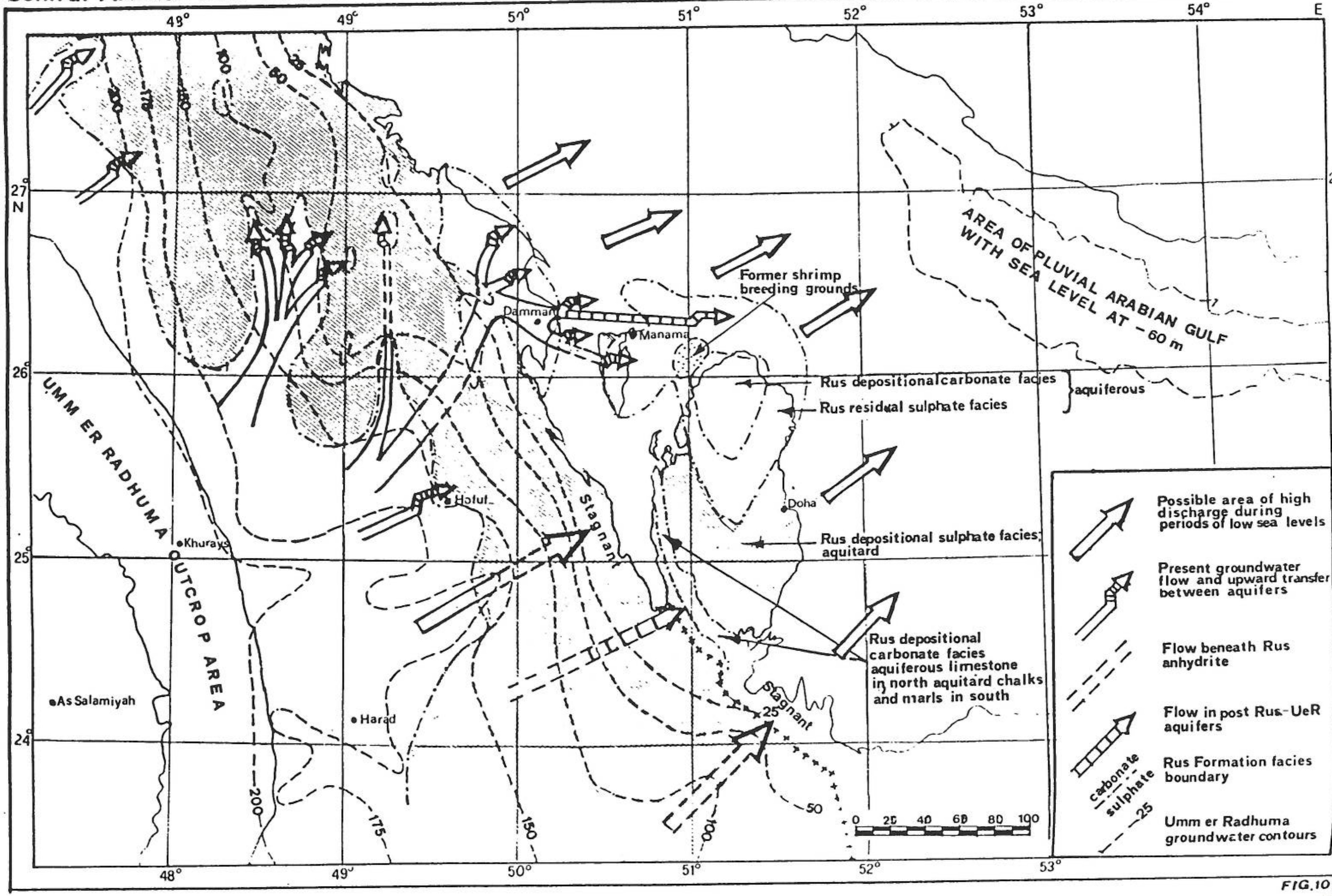


FIG.10.1

10.2 THE AQUIFER SYSTEM PIEZOMETRY AND GROUNDWATER MOVEMENT

10.2.1 Introduction

The fabric of the aquifers and routes taken by moving groundwater are demonstrated in several ways. Formation outcrops, collapse caverns and hand dug wells provide visible evidence of the nature and variation of aquifers as do drill cuttings and cores. Drilling reports, where rates of penetration, variation in drilling conditions and circulation fluid requirements, are recorded as well as geophysical logs, are indirect evidence. The analysis of aquifer test pumping, by calculating the porosities and permeabilities required to provide the water to a discharging well also permit comparison between visual and suppositional evidence.

Carbonate and evaporite rocks have a primary depositional porosity formed by the voids between the chemically precipitated grains, even though the grain size may be very small, as well as between the fragments of shells which form biogenic deposits. Post depositional consolidation reduces this void to solid ratio in all cases. Secondary porosities and permeabilities develop as diagenesis takes place and water moves between the grains either to be expelled during the process of consolidation or in response to pressure fronts generated by hydraulic head. Elements of the original material are removed and others may be brought in dependent upon a complex inter-relationship of chemical and physical factors. Changes brought about in carbonate rocks, particularly by solution, are described as karstification. Solution enlargement of primary sedimentary features such as joints, bedding planes and fractures increase the void to solid ratio, which may have been reduced to infinity by compaction. Interconnected, enlarged joints, fractures, bedding planes, voids and solution cavities provide the generally high permeabilities which are a feature of karstification, though rapid and considerable variations in void to solid ratios and degree of inter-connection of the voids, both vertically and horizontally, is usual. These features continue to develop in the zones of most active groundwater circulation, the upper meters of the saturated zone and frequently above,providing evidence of the movement of groundwater levels during very recent geological history.

Palaeokarst features, present at depths no longer related to the phreatic water table, point to changes in the levels at which such karstification has taken place.

The several aquiferous horizons present in the rocks of Qatar are developed in the carbonate and sulphate facies by these solution and redeposition effects (diagenesis) that moving water has upon such materials. The creation of the Simsima Dolomite facies from the original chalky limestone by the redistribution and concentration of calcium magnesium carbonate is of great importance. Itself a product of exposed-rock alteration by weathering the Simsima Dolomite accepts infiltration at higher rates and acts as a near-surface reservoir for the storage of larger quantities of recharge than the unaltered chalky limestone beneath. Thus while recharge may take place only once or twice per year at times of effective rainfall, penetration to the Rus Formation and below may continue, for a considerable period after the rainfall event and at a rate dictated by vertical permeabilities in the chalky limestone facies, of water held in the more porous duricrust above. The same mechanism may also be effective over the approximately 500 km^2 where the Rus Formation actually outcrops and a similar dolomitic duricrust has developed.

10.2.2 The Aquifer System

A brief summary of the coastal area aquifer regimes, as defined in the Eastern Province, Bahrain and Qatar, inreverse stratigraphic order, is :-

- <u>The Neogene Complex</u> The post-Eocene rocks form an important recharge and aquifer complex, up to 120 m thick in the El Hasa Oasis. A lower shale with thin limestones (Hadrukh formation) is overlain by, generally areneacous, marls, shales and porous skeletal limestones (Dam Formation). The finer grained components act as aquitards impeding vertical flow and splitting the complex into several discrete units. The Dam is karstified and has very high transmissivities. The Dam is probably absent in Bahrain except as the 'Jebel Cap' but the Hadrukh, as a claystone underlain by a sandy limestone and together some 10 to 60 m thick,forms with the Alat below the so-called 'A' aquifer. In Qatar the Neogene occurs as a limited number of outliers, only in the southwest and generally at a high topographic level, except in the Abu Samra area where the complex and very variable, thin limestones, clays, mudstones, chalks and gypsum act as a confining aquiclude to the Alat Formation aquifer below.

- <u>The Upper Dammam Complex</u> The Alat and Khobar Limestones, both between 20 and 50 m thick in Saudi Arabia are separated,as they are in Bahrain and Qatar, by the thin Alat marl, 10 to 20 m thick and an important aquitard, though the three members are generally modelled in Saudi Arabia as one unit. They form an important aquifer at El Hasa. The Khobar Marl below is the top member of a very thick aquitard complex which reaches down to the top of the Umm er Radhuma Formation. In Bahrain the 'A' aquifer is principally the Alat Limestone, 15 to 25 m thick and a partly dolomitised fossiliferous carbonate sequence, bounded above by the Hadrukh claystone and below by the Alat Marl, 10 to 15 m thick. The 'B' aquifer of Bahrain is a combined Khobar Dolomite above, some 30-40 m thick and the Alveolina limestone, a friable brown dolarenite, about 10 m thick below. The aquifer, which is usually confined, is very highly permeable in the top 10 m and forms the most important water bearing unit of the island.

  In Qatar, the Abarug Dolomitic limestone (the equivalent of the Alat limestone), which, other than the southwest, occurs only on the flanks of the Dukhan Anticline where it reaches about 2 m in thickness, is of hydrogeological significance in the Abu Samra area where it consists of up about 12m of grey, friable dolomitic limestone of high permeability. This aquifer, which may be a conduit to groundwater storage in both older and younger formations is believed to have a safe-yield throughout of up to 2 $Mm^3.yr^{-1}$ without resort to overpumping. It is underlain by up to 10 m of yellow clays and marls, the Abarug Marl member (equivalent to the Alat or Orange Marl) which acts as a supporting aquiclude.

  The Simsima Dolomite and Limestone (equivalent to the Khobar in Saudi Arabia and Bahrain), from 10-30 m thick forms the outcrop over 80% of Qatar's surface. The Dolomite is a diagenetic replacement of part or all of the original chalky limestone and is an important aquifer near the coast as is the undolomitised but still vuggy original chalky limestone. Elsewhere the phreatic water levels are generally below the Dammam Formation - Rus Formation contact.

- <u>The Lower Dammam Aquitard</u> In Saudi Arabia the several, generally clay and marl, members of the Lower Dammam some 10 to 40 m thick are grouped with the underlying Rus Formation. The Lower Dammam aquitard of Bahrain is some 10-20 m thick and consists of shale with some silty dolomitic limestone, the Sharks Tooth Shale Group.

  In Qatar, the Lower Dammam consists of marls, clays and shales with thin, 1 m, subordinate limestones at the top and bottom of a sequence rarely exceeding 12 m in thickness, though still an important aquitard. The absence of this aquitard, either by non-deposition or pre-Upper Dammam erosion, from the northern part of country, and about ½ of the total area, is of profound hydrogeological significance.

- Rus-Umm er Radhuma Complex In Saudi Arabia the Rus Formation may be between 40 and 200 m thick where it consists principally of anhydrite and is an aquitard. Over anticlines and where evaporite solution has been active it is formed of limestone dolomite and marl, only 20 to 30 m thick, locally fissured and a minor aquifer in hydraulic continuity with the Umm er Radhuma Formation below.

The Umm er Radhuma aquifer, some 300 to 600 m thick, increasing from west to east, and formed of porous fissured limestone and dolomite with some anhydrite in the northwest is an important though variable aquifer. The top 30 to 50 m are karstified and may have been subjected to subsequent infilling with clay thus causing a debasement to a poor aquifer. The unaffected calcarenite facies below has a higher yield typical of the upper meters where clay infilling has not occurred.

In Bahrain, a similar interpretation applies. The full anhydrite facies aquitard sequence, confined to the north and west of the island may be up to 150 m thick, of of which the anhydrite may form 25% and combined anhydrite and shale more than 50% of the total. Elsewhere to the south and east between 30 and 50 m of chalky limestones with quartz concretions and frequent large voids and solution cavities, form an aquifer continguous with the Umm er Radhuma Formation below. It is believed that the anhydrite, and much clay, has been removed in solution and suspension by circulating groundwater and that this thinner aquifer is a residual deposit formed by the collapse and compaction of resistant layers. The underlying Umm er Radhuma Formation, between 100 and 350 m thick and a dolomitic limestone with calcarenite and often argillaceous and bituminous, forms a variable aquifer sequence. Transmissivities in the clays are very low yet porosities may exceed 30% in the calcarenites. However, the Rus - Umm er Radhuma complex contains only brackish or saline water and therefore has little or no development potential.

In Qatar, the Rus Formation, varying between 20 and 110 m, also consists of the two distinct facies. Sulphate Facies of thick anhydritic marls with thin limestones that are an aquiclude in structurally negative areas and the Carbonate Facies of thin, altered chalky dolomitic limestone over structurally positive areas. The absence of anhydrite, either due to non-deposition or post-depositional removal by groundwater and the consequent collapse of overlying strata, is of profound groundwater significance. The thin residual Rus Limestones are in hydraulic continuity with the underlying Umm er Radhuma Formation. The boundary within the northern area where the Lower Dammam is absent is also significantly near and aligned with the boundary between the thin, Carbonate Facies, aquiferous Rus to the north and the thicker, Sulphate Facies, aquitard Rus to the south, indicating that the Lower Dammam marls and shale have impeded the infiltration and circulation of groundwater and thus prevented the general removal of Rus Formation anhydrite from the area to the south. The Umm er Radhuma dolomites and limestones beneath are in hydraulic continuity with the carbonate Rus in the north. Up to 80 m of the Umm er Radhuma may contain freshwater reserves and yields are high. In the south, where the Rus is an aquitard, Umm er Radhuma groundwater is confined. Only the top 100 m of the Umm er Radhuma have been investigated for groundwater and to this depth only in 2 boreholes. As in Saudi Arabia, in some areas the top 10-20 m, though karstified, have suffered subsequent clay infilling and significant yields may be obtained only below this layer. Elsewhere, particularly in the south, the yield of even the topmost meter may be very high. Detailed information on the lithology of the upper 10 to 20 m of the Umm er Radhuma is insufficient to permit this important lithological variation to be mapped and predicted.

The lithostratigraphic and groundwater properties of the various units are summarised in Table 3.4 (See Chapter 3)

10.2.3 Piezometry

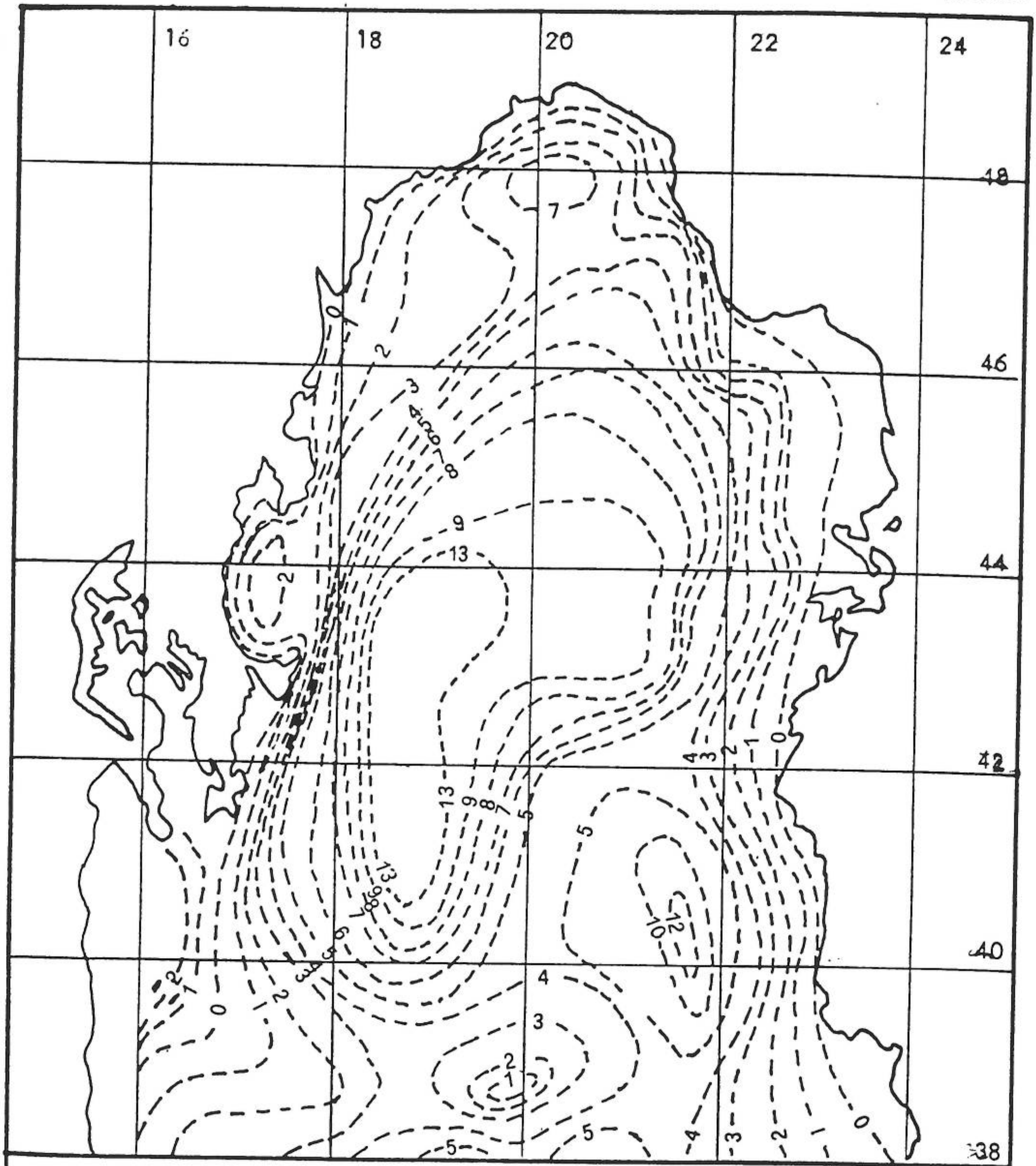
In the Northern Groundwater Province, phreatic water levels occur generally within the Rus Formation except in the coastal areas where the geological structure brings the Dammam Formation down to the water table zone. The groundwater surface conforms to the general topography though retains a flatter profile and groundwater levels are easily predictable. In the Southern Groundwater Province considerable variation occurs related to the lateral and vertical changes in aquifer lithology and permeability so that discreet bodies of water at differing levels and of varying quality are separated by extensive areas in which groundwater is almost absent. Drilling the sulphate facies of the Rus Formation in both Groundwater Provinces, does not generally encounter lost circulation horizons indicating the overall aquiclude character of the facies.

Figure 12.2 indicates the overall quantity and density of boreholes in Qatar and Enclosure 4, the location and title of all boreholes and wells for which stratigraphic and aquifer data are available and has been utilised in the production of this report. Historic details of water levels recorded during the monitoring programme conducted by the staff of the Project are given as Appendix 5.2 and cover a 10 year period from 1971 to 1980. As a basis for comparison, to which changes in groundwater level may be related, the piezometric surface configuration for 1958-59, developed from data collected by the Adsco survey, with corrections based upon subsequent more accurate topographic details, is presented as Figure 10.2. The groundwater contours have also been smoothed as the data available to Adsco were obtained principally from existing hand-dug wells and boreholes in developed depressions as well as from their own exploratory drilling programme which concentrated upon the assessment of the groundwater resources of major depressions. Their water levels are thus likely to reflect for example, the effect of heavy rainfall which occurred in January 1959. Despite the limited number of rain gauge sites (5 only operative), falls of 75 to 100 mm were registered over much of the country and this is likely to have had a considerable though haphazard effect upon pre-rainfall groundwater levels.

The phreatic surface culminated at + 13 m to the west of the centre axis of the peninsula and this displacement is thought to be an early reflection of the expansion of agriculture along the eastern flank and the effect of the concentrated extraction from the first of the well fields to be brought into production. Thus the 'lows' in the block 20-22E, 40-42N are due to the extraction from Al Khurayb and Umm al Quhāb well fields, those in block 20-22E, 38-40N by extraction around Al Rayyan, Mu'aydhir and As Sayliyah and the considerable decline at 20E 39N due to the concentrated extraction from the Rawdat Rashid wellfield and the Umm al Mawaqi farming complex where up to 10 farms were active, pumping up to 10,000 m^3 day^{-1} from a total of 60 wells. Some modification of the regular order of contours also appears in the north of the peninsula related to the early development of agriculture in that area. Attention is drawn to the below-sea level values for the water surface in the area just east of the Dukhan anticline associated with the very large inland sabkha area of Zgain al Bahth. This approximately 100 km^2 area of salt flats at or just below sea level is believed to be an important area for the natural discharge of groundwater by evaporation.

Energy balance studies over sabkha surfaces where the potential piezometric level is above ground level have shown that evaporation from the moist and saline salts may take place at 20-25% of the potential open water evaporation rate which is calculated as 2260 mm $yr.^{-1}$ for the western coastal area of Qatar. Evaporation does not take place from the whole sabkha surface as the evaporation of the groundwater surface leaves behind salt crusts and pans which inhibit further upward water rise until the dried salt is blown away by wind action. However,

Piezometric Surface: 1958 — Northern Qatar



---4--- COMPOSITE PIEZOMETRIC CONTOURS IN METERS ABOVE SEA LEVEL

0 4 8 12 16 20 km

FROM LEGRAND ADSCO 1959
CORRECTED FROM REVISED TOPOGRAPHIC DATA

it is believed that up to 10 $Mm^3.yr^{-1}$ may have been lost to evaporation by this means at times of balanced steady-state conditions declining with reduced coastward groundwater movement, to some 7 $Mm^3.yr^{-1}$ in 1980. The remaining sabkha areas of Qatar, which amount to a further further 200 km^2 are, with minor exceptions, covered by considerable thicknesses of dry silt and wind blown sand and are deemed to be no longer active, particularly following the decline of water levels with the trend away from steady-state balanced recharge-discharge conditions.

An important embayment in the contour pattern stretches from the negative area of the sabkha near Dukhan eastwards towards Umm al Marwaqi and, to a less marked degree, on to the south of Doha. This feature is considered to be a result of the enhancement of permeability in the Rus Formation in the area of active anhydrite solution in the border zone between the Northern and Southern Groundwater Provinces in the stage prior to the overall collapse which leads to the deflated landscape typical of the Northern Groundwater Province. The reduced aquifer losses of a higher transmissivity zone result in a more rapid dissipation of recharge and therefore a flatter groundwater profile.

Monitoring of water level changes has been continuous since the initiation of the Project programme in 1974. The general configuration of the piezometric surface for 1980 is given as Figure 10.3 and Enclosure 4 presents more detailed information at a scale of 1 : 250,000. Water level data is collected over a period of several weeks, two times per year, and can therefore only provide a generalised impression. The proximity of many of the monitoring wells to irregularly pumped farms enhances this variability. A comparison of the 1958 and 1980 conditions for the comparable area of Qatar, north of the Grid N38, indicates the marked decline of the highest groundwater levels from + 13 to + 6 in the west of centre area and the now only very slight positive elevation of the groundwater surface elsewhere. While few of the boreholes, which provided data for the 1958 map, penetrated to the Umm er Radhuma Formation, a large number of such boreholes are used in the monitoring programme as farm production wells are generally sunk to the Umm er Radhuma to provide an adequate yield. Thus the 1980 surface is truly composite, presenting an integration, at most sites except the well fields, between the regional groundwater level of the Umm er Radhuma Formation which declines from about + 5m in the southwest to + 2m in the north east of the peninsula and is related to storage and potential groundwater movement from Saudi Arabia north eastwards and the Rus Formation levels. These are allied to recharge and discharge conditions of recent meteoric waters and are much effected by the annual variations in these conditions as well as groundwater abstraction.

Thus in areas where the levels of the phreatic Rus Formation have been drawdown by extraction in the near-coast area to equal those of the Umm er Radhuma below, groundwater from the Umm er Radhuma will have gained a new route of discharge to the sea. Coastal area water levels will therefore be maintained at levels balancing the Umm er Radhuma head and the drawdown created by such a discharge but water quality will deteriorate with time to that of the regional Umm er Radhuma water, as the feather-edge of meteoric water thins and recedes inland in areas where the recharge-discharge volume are un-balanced.

Figure 10.4 portrays the changes in groundwater levels over the period of the monitoring programme, 1974 to 1980. This indicates that only minor changes have taken place during this time and thus that the major declines took place in the period prior to 1974 during the major expansion of agricultural activity. Comparison with the Groundwater Conductivity Map (Enclosure 5) shows that the fresher groundwater salients in the areas of Wells A2 and B6, where losses of recharged meteoric water to the sea are still likely, have sustained a major decline of over 2 m during 1974 to 1980. With a reduction in wellfield extraction the

Piezometric Surface: 1980

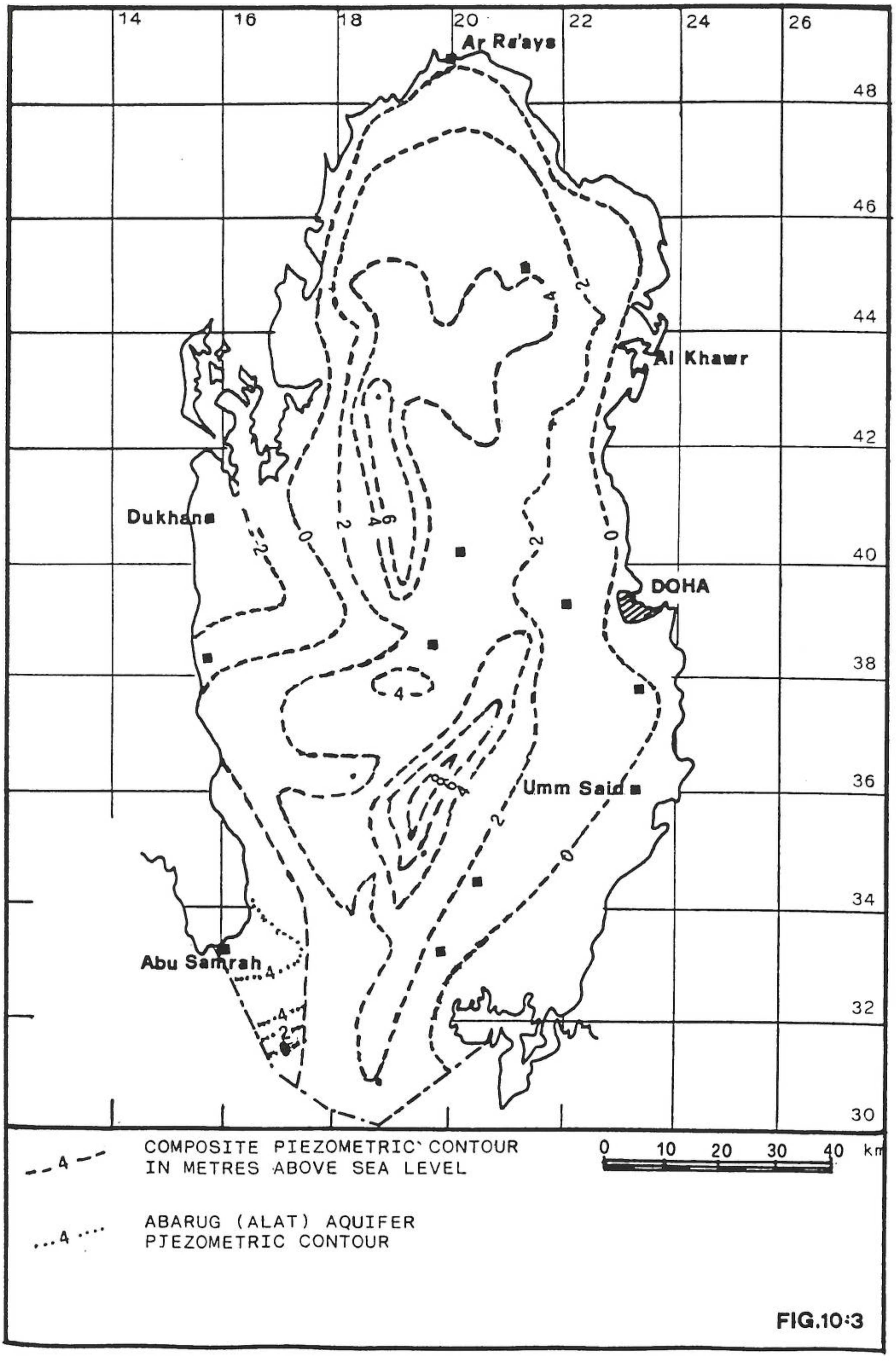


FIG.10:3

Change in Groundwater Level - 1974-80

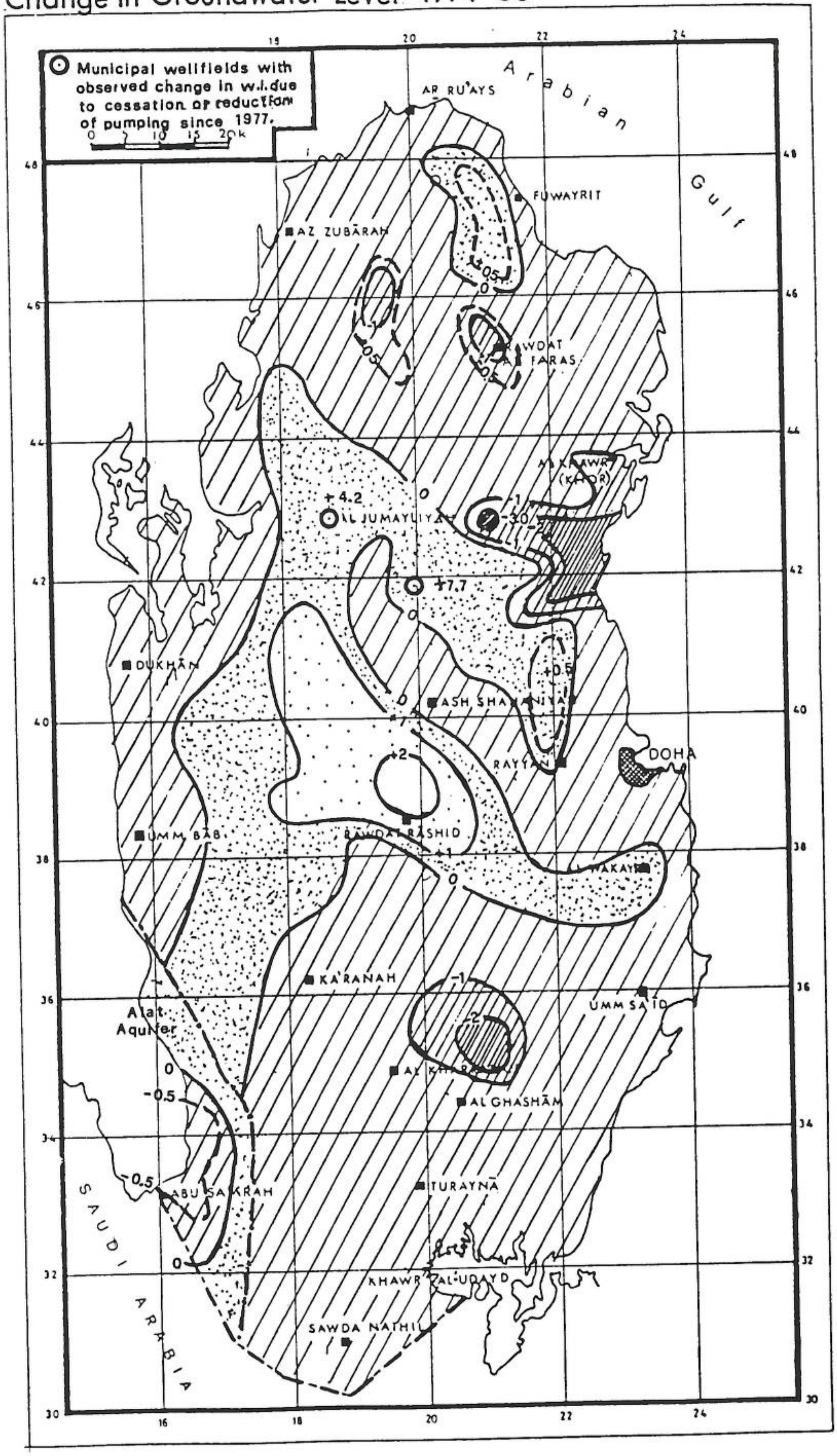


FIG.10:4

areas of Al Utoriyah and Rawdat Rashid have shown a degree of recovery and that with an expansion of the well field area and a rationalisation of extraction the phreatic level near Al Jumailiyah has also risen. With little potential for development in the Southern Groundwater Province, few changes have taken place but the slight decline in the artesian head of the Alat aquifer near Abu Samrah is significant as the safe yield of that resource is approached. The decline of 2 m around well C2a north of Al Ghashām may have been caused by an anomaly in the rainfall, and therefore recharge, pattern as there has been little change in the extraction regime of that area.

The likelihood of a regional decline with time of the Umm er Radhuma aquifer head also exists and Groundwater Development Consultants Ltd (1980) in a study of the Umm er Radhuma Aquifer in Eastern Saudi Arabia on behalf of the Saudi Arabia Government, have modelled a fall of 10m. in both the Umm er Radhuma and Dammam aquifers of the coastal province between 1940 and 1980 during a period when the extraction from the Umm er Radhuma has risen from 0.6 to 72.4 $Mm^3.yr^{-1}$ and from 87 to 352 $Mm^3.yr^{-1}$ from the Dammam. The apparent similarity in head decline is due to the balance response to exploitation with a vertical flow between the aquifers via high permeability 'windows' where the Rus Formation is non-anhydritic.

10.2.4 Groundwater Movement

The regional pattern of groundwater movement and the implicating of such flow have been discussed in Section 10.1.3 and only the flow within Qatar itself will be defined. The dominant direction of this flow is normal to the lines of head equipotential or piezometric contours depicted in Enclosure 4 and Figures 10.2 and 10.3. From the interpretation of the near steady state conditions of 1958 it is clear that the flow was coastwards, north, east, west from the centre of the peninsula. This flow pattern followed closely that of the surface topography and the isosalinity contours showed very similar gradients. The results of concentration of extraction in the wellfields and in the intensive farming areas of the eastern and northern districts have modified this flow, in many areas inducing changes and reversals particularly where wellfield depletions had caused Rus phreatic level to fall to well below sea level. The much changed shape of the water table is clearly evident from Figure 10.3.

In the Northern Groundwater Province general declines are not pronounced in deeper wells tapping the Umm er Radhuma aquifer as extraction has resulted in a reduction in fresh-water reserves by the upward displacement of the fresh-saline interface as the Rus head differential, above that of the Umm er Radhuma, has been reduced. Those wells tapping only the Rus show greater declines due to the aquitard conditions which exist at the base of the Rus and, in certain areas, within the top 15 m of the Umm er Radhuma aquifer also. Low groundwater levels in a belt stretching from Doha via Rayyan to Rawdat Rashid, Umm Bab and Dukhan may be related to two groundwater movement features. The Groundwater Model (Chapter 13), due to mathematical restrictions, was not able to include this area. The first, eastwards from Rawdat Rashid towards Doha, the movement is to replace water extracted in the recent past along the Doha to Rawdat Rashid corridor, which has caused the edge of the freshwater body to recede inland with replacement laterally by sea water incursion and vertically by saline ground water from the Umm er Radhuma. The second, less marked, is westwards towards the groundwater sink area of the large Dukhan sabkha area, where groundwater levels decline to 2 m below sea level. The near Surface Apparent Resistivity Map (Figure 7.5) indicates an area of higher than 16 ohm.m resistivity in the path of such groundwater movement but reference to the Geological Map, Enclosure 1, shows that this anomaly is caused by the presence of large area of dry, high-resistivity, aeolian sand covering the southern end of the sabkha which masks the subsurface conditions but are in fact only superficial. The small area of higher apparent resistivity north west of Doha is due to the presence of a small areaof high ground (over 20 m) near Duhail camp increasing the below-surface depth to the high salinity groundwater below.

That this groundwater movement is parallel to the Anhydrite Solution Scarp is indicative of the continuing solution activity and the development of higher porosities and permeabilities along rather than across the scarp during the process before total collapse takes place and the overall void to solid ratio is subsequently reduced. Within such a belt of higher transmissivity, high groundwater levels cannot be sustained and any natural upward leakage of Umm er Radhuma water (white this is not thought to be great due to the fact that active solution is taking place only in the overlying Rus) will also be transferred laterally under the influence of the lower head levels at the Dukhan sabkha and towards the sea near Doha.

The continued existence of a limited discharge of land-derived meteoric recharge at the coast is indicated by the presence of extensive growths of the coastal marsh plant mangrove which requires a regular flushing in water of a lower salinity than sea water to survive, in the tidal flats of Al Dhakira bay, just north of El Khor.[1/] The salinity and groundwater contours of the area support the phenomenon. The groundwater contour pattern near the north west coast between Grids 44N and 46N suggests a flow which may have supported the prolific shrimp feeding grounds which have only recently declined in that area. A freshwater discharge from the Neogene aquifers between Bahrain and Qatar may also be implicated.

In the south west, the direction of groundwater flow in the Alat aquifer is assumed to be east-northeast wards, following the regional pattern, towards the centres of extraction. Reference to Enclosure 4, the regional and detailed piezometric surface map for that aquifer Figures 10.5 and 10.7 and as well as appropriate conductivity maps, Enclosure 5 Figures 10.6 and 10.8 indicates certain anomalies. The isosalinity contours support the principle of a general east-northeast ward flow, but the piezometric head culminates at + 5 m between wells WA9 and WA11, declining both northeast wards and southwest wards towards the Gulf of Salwah. While a freed discharge of an artesian flow would exhibit such a trend, as the head was dissipated to sea level in aquifers above the confining aquiclude, the decline is also apparent in boreholes that are cased and cemented to the top of the Alat aquifer, WA9, WA8 and C12. The secondary peak, centred around borehole C14 in the south of the Alat Groundwater Province, it anomalous as this borehole penetrates deep into the Umm er Radhuma Formation and is cased indicating the general piezometric level of that aquifer and not the Alat. The anomaly may be related to lateral and vertical thickness, lithology and permeability variations in the Alat aquifer as indicated by the results of aquifer testing Table 10.3.

In the Southern Groundwater Province, and more specifically south of a line between Doha and Umm Bab, the apparent flow pattern is rendered more complex by a number of factors : the relative paucity of actively cultivated areas and therefore the limited number and scattered nature of the monitoring wells available; the lower density and smaller relative size of the depressions within and beneath which potable water reserves have accumulated and the very low horizontal and vertical permeability of the upper Rus aquifer so that recharge is not dissipated to form an extensive groundwater unit.

1/ See Chapter VIII, p8/48

Alat Aquifer–Regional Salinity

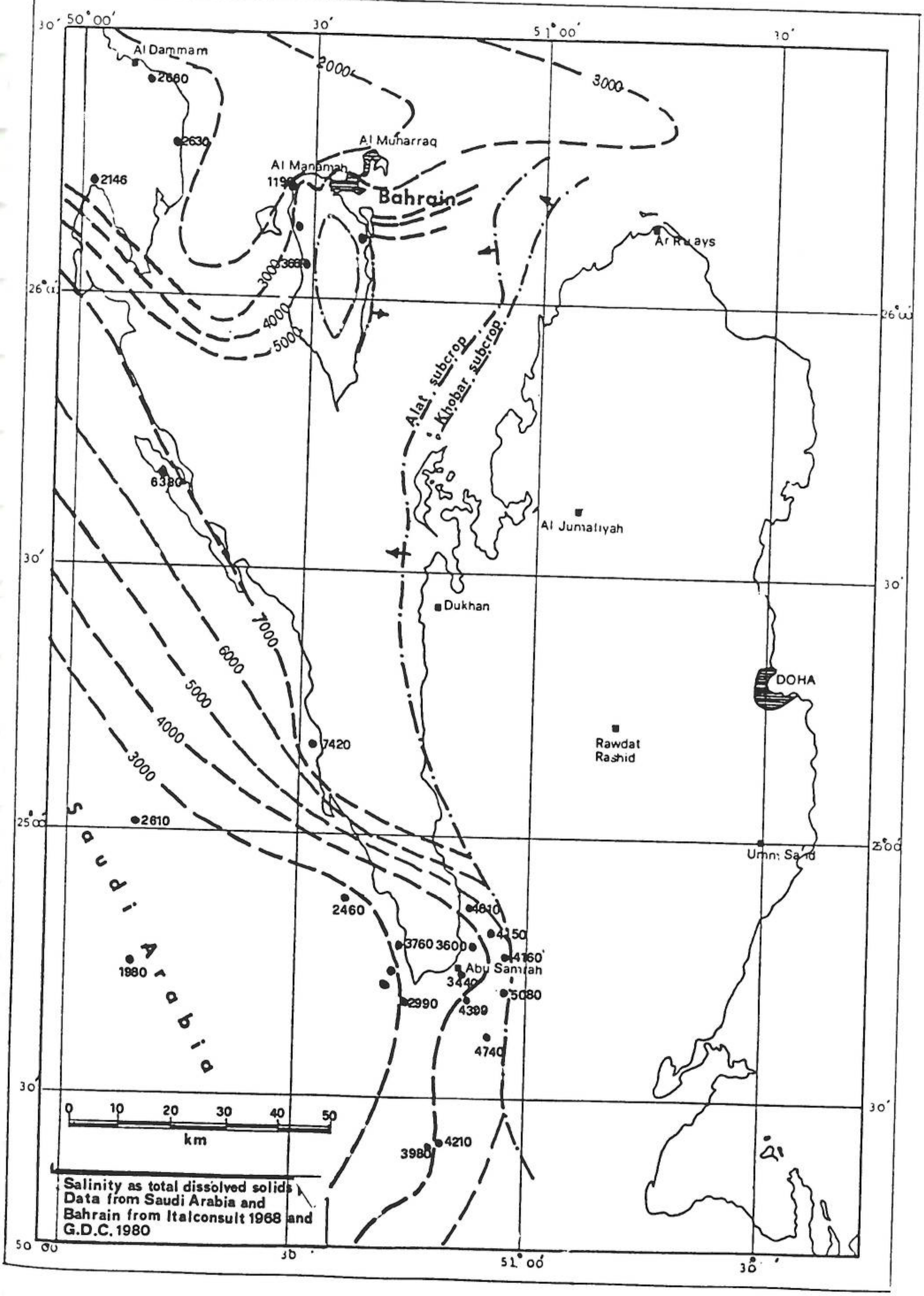


FIG.10:5

Alat Aquifer - Regional Piezometric Surface (m.a.s.l.)

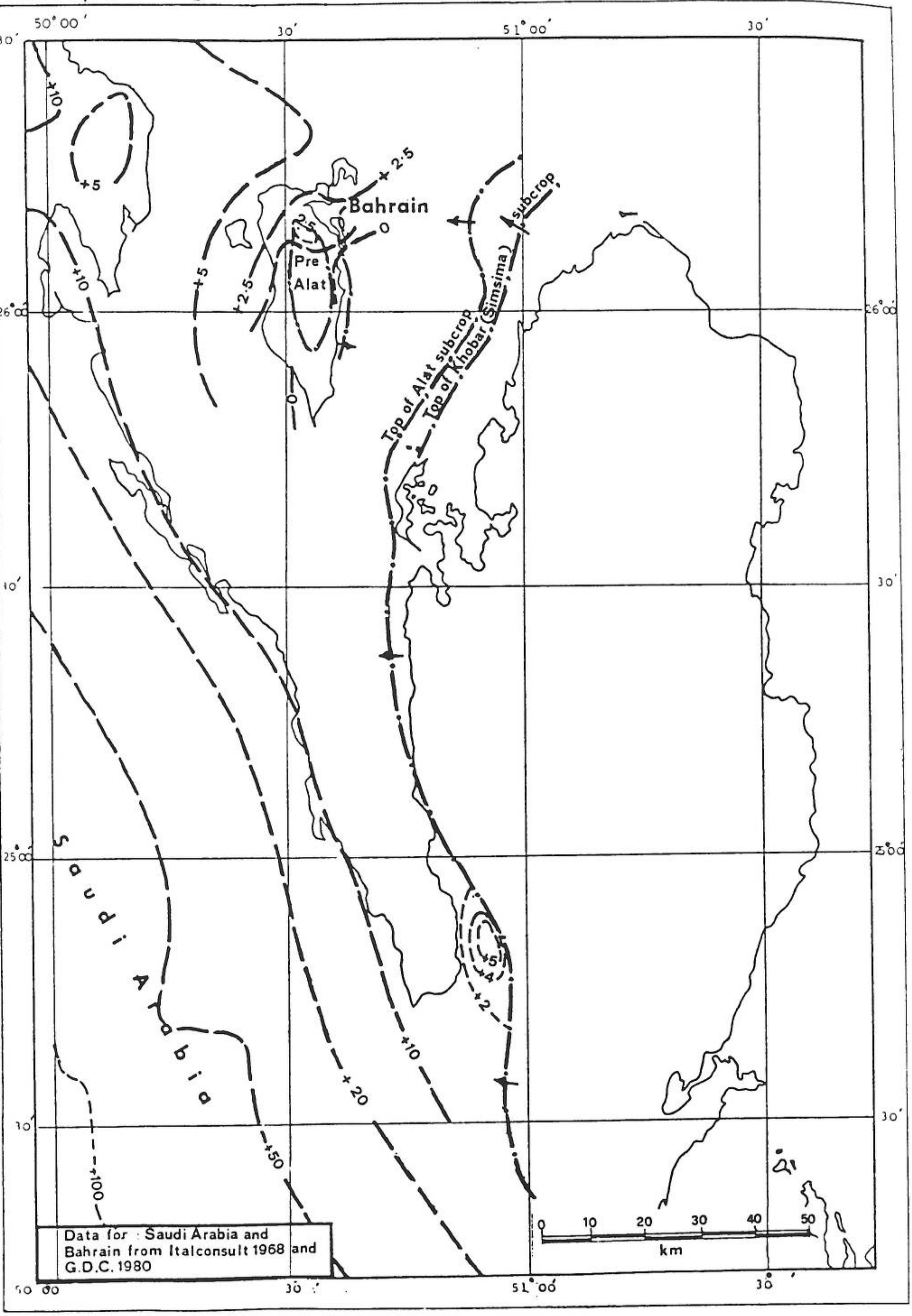
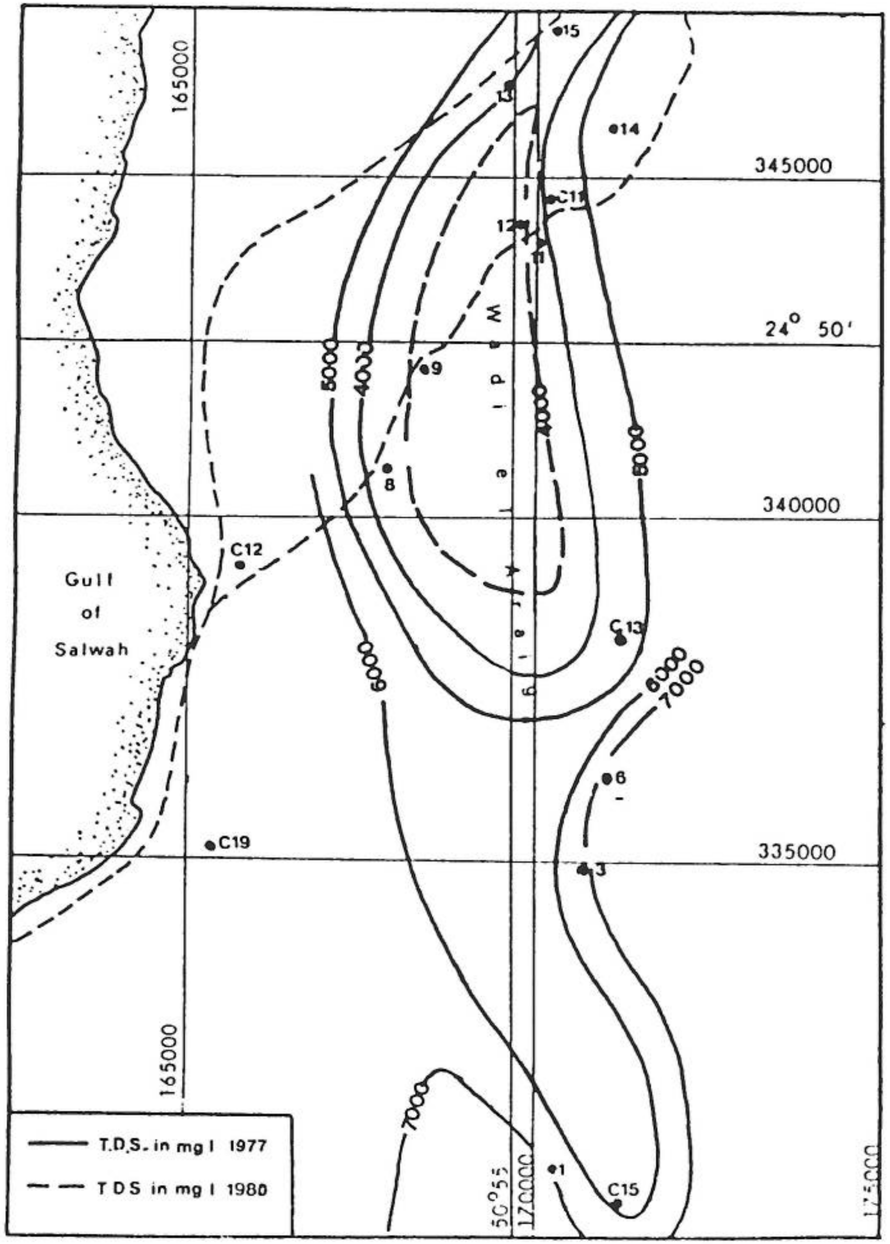
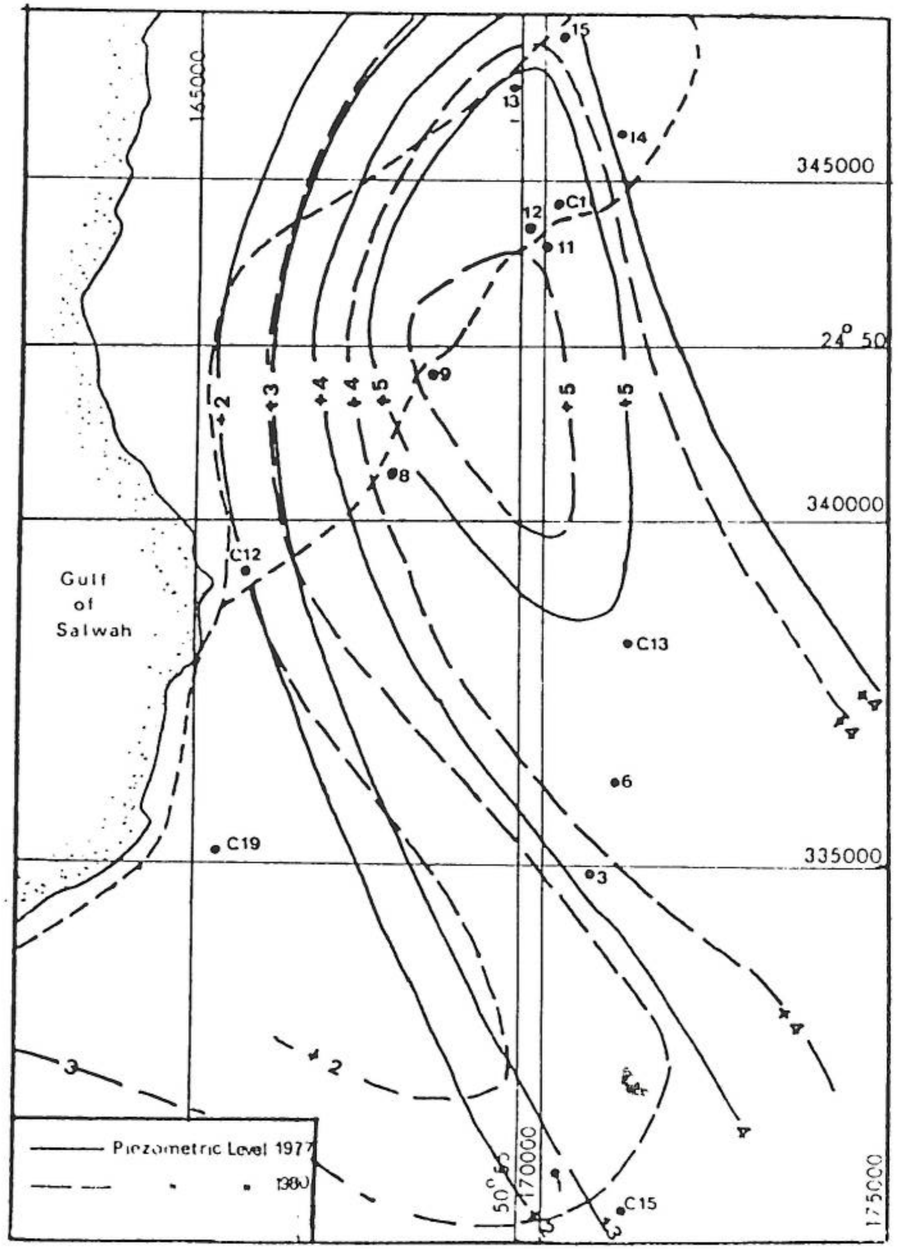


FIG 10:6



SALINITY

FIG: 10.7



PIEZOMETRIC LEVEL (m)

FIG: 10.8

The relationship between the groundwater salinity and piezometric data is confused and contradictory. As an example, at Al Kharrarah high water levels coincide with low salinities whereas at Karanah low salinities occur in an area of low ground water levels.

10.2.5 Alat Member Aquifer Unit

The Alat Member as an aquifer occurs only in the southwest of Qatar. The equivalent Abarug Member of the Upper Dammam Formation occurs elsewhere in Qatar as isolated outliers generally of small thickness and of no hydrogeological significance. The subcrop in southwestern Qatar has a synclinal form, the Salwa Gulf syncline, with a gently dipping western limb, most of which lies in Saudi Arabia, and a small remnant area of the eastern limb, isolated from the remainder of the peninsula by the Dukhan structure, in the Abu Samrah and Wadi el Araig areas as indicated on the several Enclosures and other maps. The western boundary is unknown as it lies in Saudi Arabia, but from studies in that country the Alat and underlying Khobar Formations are linked as a confined aquifer unit of considerable importance. In Qatar the Alat does not have a readily discernable outcrop at its eastern margin and, as depicted in the enlarged cross-section of South Western Qatar, Enclosure 2, it is deemed to be overlain uncomformably by the Lower Dam Formation, which rests directly on the Simsima Dolomite and Limestone Member further inland.

The Alat (Abarug) Dolomitic Limestone, the aquifer, is thin (from 10 to 25 m) and rests upon the Abarug or Orange Marl, a plastic marly clay which is also about 10 m thick and acts as the supporting aquiclude. Overlying the aquifer are the lithologically variable clays, marls, limestones and shales of the Lower Dam Formation which form an effective confining aquiclude. It is likely that the Alat limestone itself varies considerably in lithology and permeability as it does in thickness and the wide range of specific capacities indicated by test pumping, (Table 10.4) are clear evidence. The heterogeneity is probably confined to the eastern most limits of the formation area as the combined Alat and Khobar are relatively uniform in thickness and composition in Saudi Arabia.

Recharge occurs over the outcrop of the Upper Dammam in Saudi Arabia and the piezometric gradient appears constant at about 0.015 as far as the border area west of Salwah where an increase to 2 to 3 times this value is apparent, though the cause is not obvious. The regional groundwater salinities and piezometric levels are presented in Figure 10.5 and 10.6 respectively and show the important relationship between the recharge, storage and flow and the connections between Saudi Arabia and Bahrain and southwestern Qatar. More detailed groundwater information from boreholes in the Qatar zone are given in Appendix 5 and Figures 10.7 and 10.8 illustrate the Salinity and Piezometric Contours respectively of the small Qatar area of this aquifer unit. Changes in groundwater salinity and piezometric level between 1977 and 1980 are also shown in these figures indicating that the extraction, which is approaching the $2Mm^3.yr^{-1}$ level, has already caused departures from the steady state conditions.

It seems probable that the Alat aquifer unit in Qatar had no landward discharge prior to the drilling of boreholes and only limited groundwater movement and discharge is deemed to have taken place upward via vertical leakage through the confining Dam Formation beneath the Salwah Gulf. The age of the Alat water, between 22,000-26,000 years (Table 9.2), suggests the remoteness of the recharge area and consequently the potential volume of storage. That the Alat water is of a similar apparent age to the Umm er Radhuma water from P33, also in the southwest, provides evidence of the possible interflow between the two aquifers in the Hofuf area of Saudi Arabia where the Umm er Radhuma water is of low salinity and changes in the Rus lithology provide a connection. The age of the Alat groundwater and the stratigraphic relationship of the several Formation Members which form the eastern limb of the synclinal structure suggest that direct recharge to reserves by rainfall occurring over the adjacent outcrops, is unlikely. The absence of the Alat Marl in the area of wA14 would permit a southwesterly transfer of groundwater from the Simsima to the Abarug Limestone but this is uncertain.

10.2.6 Rus Formation Aquifer Unit

The Rus Formation forms the surface outcrop or underlies younger beds over the whole of the area of the Qatar peninsula. It is recognisably contiguous with the Rus Formation of Saudi Arabia and Bahrain and similar changes in lithology, thickness and structure are common to all areas. The sub-division into a Northern and Southern Groundwater Province based upon the variations in these characteristics of the Rus, and particularly the recognition of Carbonate, Sulphate and Residual Facies zones as of fundamental importance, is however peculiar to Qatar and has been developed and refined during the lifetime of the Project as a logical model of the hydrogeological circumstances. Eastwards from Qatar the Rus Formation continues in its sulphate facies, except in the north and northeast, beneath younger members and groundwater circulation is probably very limited. It is in the north, where the Depositional Carbonate Facies or Residual Sulphate Facies are in direct connection with the sea via the variably permeable Simsima Limestone and Dolomite member and without the protection of the intermediate lower Dammam shales and clays, that the groundwater reserves are at greatest risk of lateral sea water contamination.

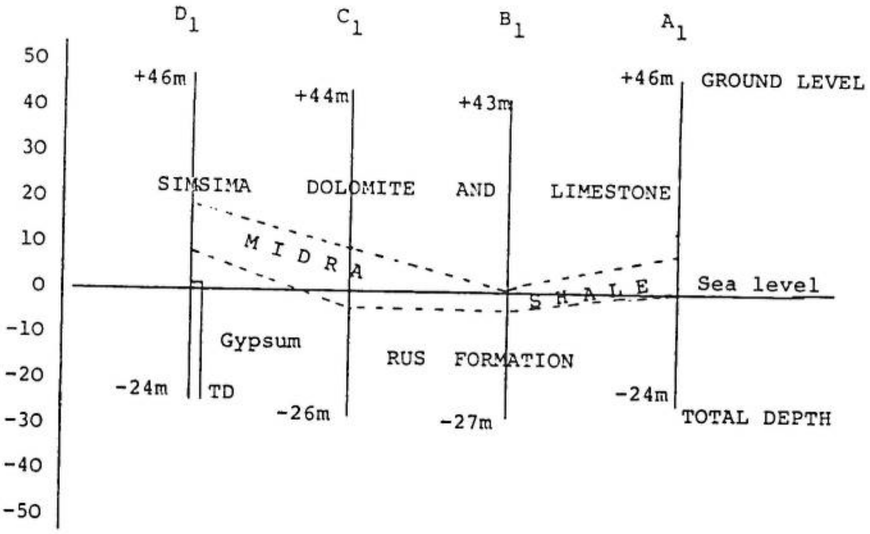
Details of the areas of each facies and the variations in thickness and structural position have been given in Chapter 3 and depicted in Figure 3.13. In the Northern Groundwater Province, in the absence of the intermediate Lower Dammam aquitard, the Rus and Upper Dammam form one continuous aquifer unit with the Upper Dammam of minor importance as only near the coast do phreatic water levels occur within the limestones and dolomites of the Simsima. In the Southern, with the Lower Dammam shales protecting the underlying gypsiferous Rus from penetration and solution by circulating groundwater, the cover has been broached by minor faulting or joint plane slip only in certain areas and there have been an accumulation of low salinity groundwater from recharge beneath the resultant solution depressions. While the Depositional Carbonate Facies of the Dukhan structure is in most respects suitable for the accumulation of a fresh water body of smaller area than in the north, it is narrow and open to sea level discharge to the west and to a sub-sea level sabkha area to the east and does not therefore contribute to the Rus groundwater reserves. The southern extension of the Dukhan structural area, while not gypsiferous, is of a soft chalky marl and limestone facies and only limited reserves have accumulated, such as in the Al Amriyah area.

The lower boundary conditions of the Rus at its contact with the Umm er Radhuma Formation, are complex and dealt with in the following Section 10.2.7. Despite the major removal of soluble gypsum from the residual sulphate facies of the Rus in the Northern Groundwater Province, the high clay content of the argillaceous lower Rus of both sulphate and carbonate facies is the cause of the low vertical permeability of the Formation. The higher horizontal permeability is developed in a relatively thin layer, about 10 to 15 m thick, from the present (or earlier steady-state) static water level downwards. It is suggested that this karstic form of fracture permeability has developed in response to the energy of the seaward drainage of locally infiltrated meteoric water. The lower but important vertical and horizontal permeabilities below, down to the top of the Umm er Radhuma Formation are a product of the groundwater circulation conditions created by higher rainfall and infiltration rates and the lower base levels of the Pluvial periods.

Recharge to the Rus Formation aquifer occurs throughout the peninsula directly via outcrop or through the overlying Simsima. From the work by Adsco (1959) it was recognized that recharge amounts were greatest beneath the depressions because of the runoff concentration and the enhanced recharge via the depression floors to form mound water bodies. While it is now felt that the depression floor silts may inhibit recharge rather than enhance it, from the clear evidence of ponding and slow decline of the ponded water level at or near potential open water evaporation rates (see Harhash (1979)), the significance of the depression is still accepted though with the principal amounts of recharge taking place through the coarser depression deposits around the margins and downwards via the high permeability zones of the collapse-induced fractures which underly them.

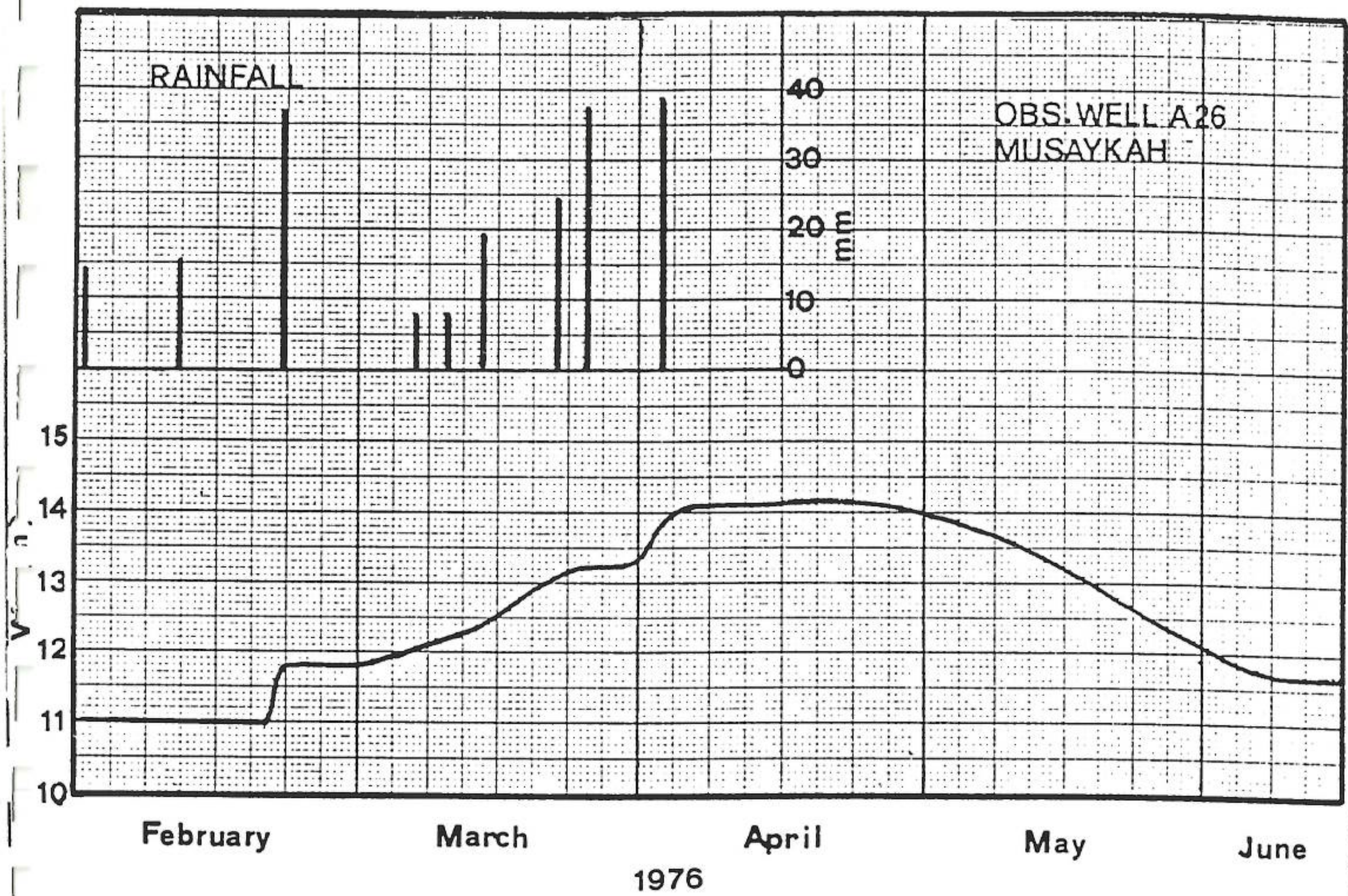
The response of Rus aquifer water levels to rainfall and recharge are clearly indicated by the hydrographs plotted as Figure 10.9, both of which are for boreholes in depression areas on the Northern Groundwater Province. At Bayd al Qa', a roughly circular depression 1 km in diameter and the southernmost of a series of depressions associated with the Al Markiyah deflated area, where there is a 20 m height difference between the floor and the surrounding area, a number of pilot pre-production holes were drilled and carefully tested for an eventual water supply to the Sand Processing Plant. Series A, B and C, each consisting of a production well, a cored observation borehole and two uncored piezometric boreholes, were sited within the depression area and had rest water levels of + 8.5m + 8.1m and + 8.2m respectively. A fourth series D, at the southern boundary of the depression, had a rest level of + 6.4m some 2m lower than inside the depression. As the measurements were made during the Winter and Spring seasons of 1976 and 1977, before groundwater extraction started in the area, they provide clear evidence of the accumulation of a recharge mound beneath a depression following the infiltration of Winter rainfall.

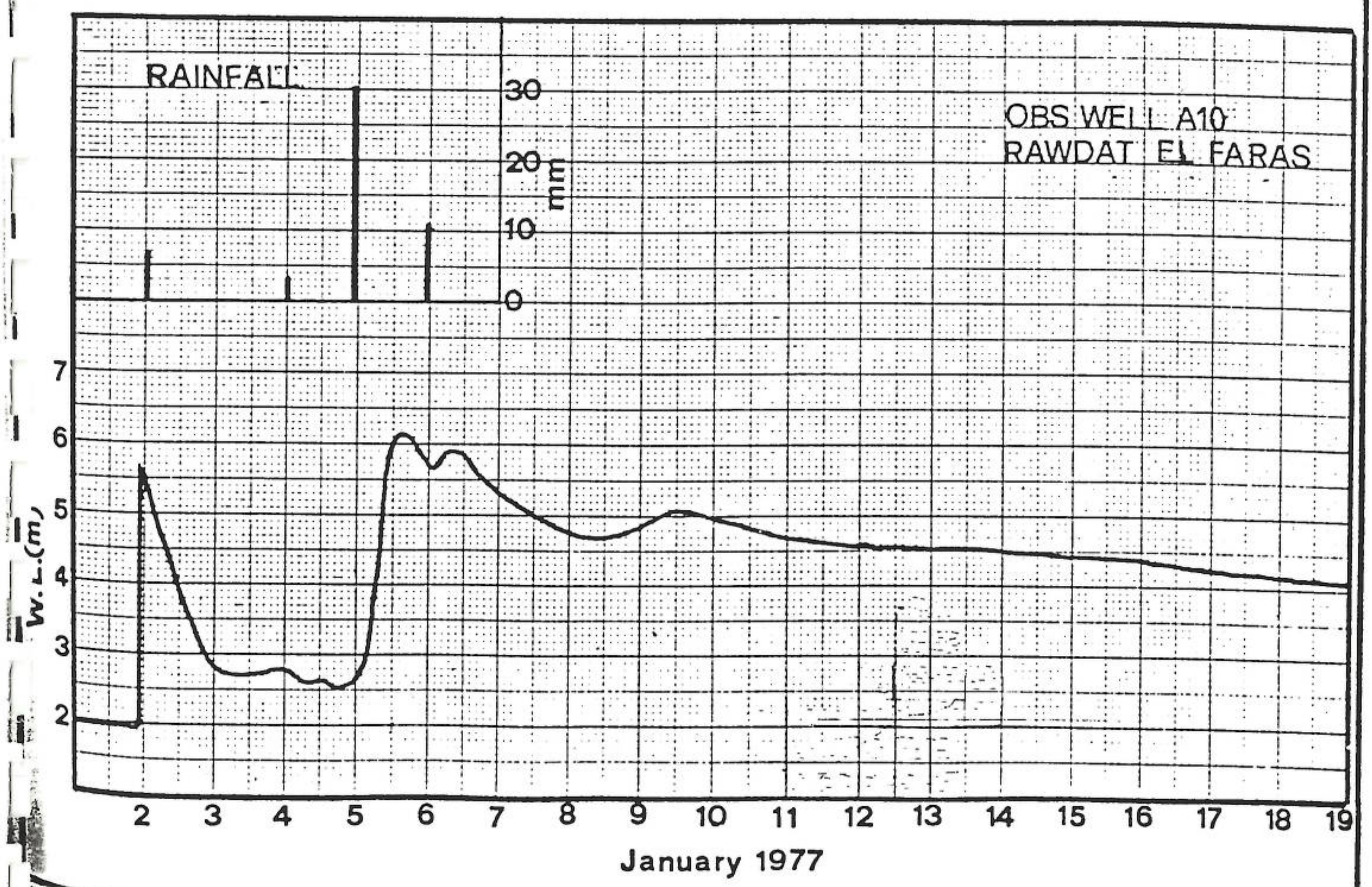
The pattern of exploratory drilling for the Sand Washing Plant provided valuable evidence of the removal of gypsum from the Rus Formation and the consequent subsidence to form a distinct depression.



In cored hole D_1, sited at the edge of a depression some 1.2 km in diameter and 10 m lower than the surrounding land, gypsum, forming more than 50% of the core, was recovered from the lower 25m. No gypsum was encountered in any of the other holes, which are all within the depression. In D_1 also the Midra shale Member of the Lower Dammam Formation lies some 15 m higher than in the other holes.

Recharge - Water Level Response





There is a marked vegetation difference between the larger coallesced and shallow depression north of the anhydrite solution scarp and the smaller steeper ones to the south. In the north, vegetation is generally absent, indicating poor retention in the rocks and subsoil and therefore recharge to the aquifer below. In the south the vegetation is more abundant permitted by a higher retention of infiltration near the surface. (See Chapter IV)

Variations in depression transmissivity and storage capacity is considerable. Both are high at the margins of collapse structures, where evaporites have been removed but accommodation collapse has not been complete. Near the centres of large depressions, where few large subsurface cavities remain and collapse has reached the stage where the amount by which the floor of the depression is lower than the surrounding area is equal to the thickness of the evaporite removed, transmissivity is likely to remain high though storage capacity will be lower. In the area of unaffected gypsiferous Rus between major depressions both transmissivity and storage are low.

Results of test pumping of boreholes in the Umm er Shukut depression and the non-depression area of Khor Park, indicate considerable differences in the aquifer characteristics between the two environments although both are in the Northern Groundwater Province where gypsum removal has been complete. It seems likely that initial depression areas, where fracturing first allowed recharge water to gain access to the gypsum, have retained their higher transmissivity and permeability values despite the eventual general removal of gypsum and the production of a deflated landscape.

As the majority of boreholes which fully penetrate the Rus Formation also continue into the upper high yield zone of the Umm er Radhuma, the two aquifer zones are inter-connected and differences in piezometric levels are obscured. Details of Rus aquifer boreholes are given in Appendix and the composite groundwater contours for the linked Rus - Umm er Radhuma units are presented in map form as Enclosure 4 and as a reduced diagram in Figure 10.3. The related composite water conductivity map forms Enclosure 5. In Project boreholes, where casing was inserted to separate the Formations and thus distinguish head differences and potential vertical transfers between aquifers across aquitard units, the pattern was inconsistent. In some, the Rus head exceeded the Umm er Radhuma and in others the opposite was observed and it must be concluded that localised differences in lithology and thus permeability cause such alternations together with the combined aquifer response to pumping. A head differential between the two aquifers in the Northern Groundwater Province where the Rus gypsum has been eliminated, or never deposited, presupposes an aquitard between the Rus and Umm er Radhuma Formations. The variably argillaceous nature of the Lower Rus and the clear indications that the principal water-bearing unit is generally the 10 to 15 m at and below the static water depth, with only slight increases in transmissivity below, are accepted as the origins of such variations.

The head characteristics of the Northern Groundwater Province are therefore modelled as a balance between the recharge accumulation head and the regional level of the Umm er Radhuma below which declines from + 6 m at the border area with Saudi Arabia to + 3 m at Al Ruwais. A decline in the combined head levels to below the minimum of + 3 m, which occurs in the coastal areas, implies that Umm er Radhuma groundwater is also being discharged to the present sea level via the vertical connections between the aquiferous units and through the horizontal flow network which formally carried the meteoric recharge as a flow to the sea at times of high phreatic groundwater levels.

10.2.7 Umm er Radhuma Aquifer Unit

The Umm er Radhuma aquifer unit, which has no outcrop in Qatar, is the northeastward continuation of a very extensive, thick, gently dipping and in general homogeneous formation which has a long curved outcrop in eastern Saudi Arabia and underlies most of the Gulf area eastwards to the U.A.E. It has no lateral lithological boundaries beneath Qatar and its coastal waters, though there is regional evidence to indicate that a gradual change from a carbonate to an argillaceous facies takes place eastwards. There is insufficient, accurate, subsurface data from Qatar to state with certainty that this is significant across the width and length of Qatar, but the eventual eastward change to shales and clays brings about a decline in the groundwater circulation within the Formation and an upward migration to stratigraphically higher aquifers via lithological windows and eventual discharge to the Gulf sea where this is possible.

The base of the aquifer are the shales of the Aruma Formation but as only the upper meters of the Umm er Radhuma have been explored and exploited for groundwater, little is known of the geometry and significance of this lower boundary. It is believed to lie at depths ranging from less than 300 m to perhaps 1000 m below sea level, depending upon the effect that structural control has had on the thickness and level of the formation. The Umm er Radhuma thickens generally eastwards but imposed upon this trend are the results of folds active during the accumulation of the Formation and both younger and older rocks. Thus it may range from over 500 m thick in the synclinal areas of the Salwa Gulf and the off-shore area east of Qatar to les than 300 m over the positive areas of the Dukhan anticline and Qatar arch. Figure 3.20 shows the considerable variation in the elevation of the upper surface of the Formation ranging from sea level or slightly above near the centre of the Qatar Arch and as much as 50 to 60 m above sea level at the Dukhan Anticline, to about 200 m below sea level in the southwest and southeast of the peninsula. The two positive structures merge in the south of Qatar, maintaining the upper surface of the Umm er Radhuma at about sea level until the rapid plunge southwards to an uncertain depth.

The upper boundary of the Umm er Radhuma is hydrogeologically more complex and can be categorized as follows:-

- Umm er Radhuma overlain by a thick Rus succession of up to 50% anhydrite and shales.
- Umm er Radhuma overlain by a thinner residual Rus succession from which most if not all the soluble anhydrite has been removed.
- Umm er Radhuma overlain by a depositional carbonate Rus sequence with little or no anhydrite and shale.

The first condition occurs over more than 50% of Qatar, in the south and west of the country, and is designated the Southern Groundwater Province. The second and third form the Northern Groundwater Province. An area of the third category is also formed by the Dukhan Anticlinal Structure and its southeastward extension. Whilst in the north of the structure the Rus Formation is of typical depositional carbonate facies, south of grid 36^{O} North, it consists of a very fine-grained, chalky limestone of aquitard properties. In addition the narrowness of the structure, the more rugged topographic expression inducing a greater percentage of runoff and the proximity to the Salwa Gulf and the flanking sabkha have not permitted the accumulation of significant freshwater reserves and the area is therefore linked with that which surround it, the Southern Groundwater Province.

The reservoir characteristics of the Umm er Radhuma are controlled by lithology. In the main it consists of fine-grained, green and olive limestones, dolomites, dolomitic limestones and mudstones, with some marls and shales. While basically therefore open water deposits, some areas of lagoonal, stagnant water deposition are recorded : argillaceous carbonates with anhydrite beds. This facies occurs in Saudi Arabia, near the Kuwait border and also south of the Qatar border.

At borehole P29, a thick sequence of grey, soft argillaceous carbonates with beds of white, crystalline anhydrite and some pale, hard limestone and dolomites were observed. This is unlike the Umm er Radhuma elsewhere in Qatar and from its position is evidence that stagnant lagoonal conditions occurred between the positive areas of the Dukhan Anticline and the Qatar Arch. Porosities are high in both facies but primary permeabilities are low due to the overall fine grain-size of the carbonates and the presence of clays and marls. Post-depositional diagenesis has resulted in a redistribution and recrystallisation of the dolomites and a considerable increase in the overall permeability. Powers et al (1966) report a more pronounced dolomitisation away from the areas of the argillaceous, anhydrite accumulation due to the greater facility for groundwater circulation. However a high permeability was encountered in the Umm er Radhuma Formation at P29 and it appears that the argillaceous anhydrite facies of that area, while of considerable thickness, may be of limited extent. The restructured, dolomitic limestones containing the groundwater are in overall connection with the 'normal' facies of the Umm er Radhuma Formation elsewhere in Qatar and the clay and anhydrites induce limited control on vertical permeabilities with a tendency to layering of the groundwater circulation.

The 'standard' lithology of the Umm er Radhuma elsewhere in Qatar — a highly porous, vuggy, restructured, grey to olive dolomite — has a well developed secondary intergranular porosity and permeability as well as a fracture permeability evidenced by cores and rates of drill-bit penetration. The upper meters of the Formation are believed to have very high porosity and permeability values everywhere due to the karstic nature of the aquifer. However, low permeability conditions may be present where the karst has undergone subsequent clay infilling thus extending downwards by up to 15 m the aquitard characteristics of the overlying Rus Formation. Aquifer details from boreholes are given in Appendix 5 .1 and the limited data on piezometric levels are plotted as Figure 10.10. While many boreholes penetrate to the Formation, the opportunity to obtain exclusively Umm er Radhuma head levels by carefully executed casing and cementing techniques has been relatively rare. The + 10 m contour at the Saudi Arabia coast, and parallel to it, is evidence of the degree of confinement beneath the aquitard Rus of the Salwah Gulf. The evidence that the contours do not continue parallel the NNW-SSE trend, declining east-north eastwards, is regarded as a firm indication of discharge to the present sea level in the area of the northern part of the Dukhan Anticline where the Umm er Radhuma groundwater levels are unconfined and generally in the Northern Groundwater Province. That this discharge must take place via the overlying gypsiferous Rus Formation of an aquitard character everywhere except in the extreme north and north east of Qatar, maintains a positive Umm er Radhuma groundwater head of several meters. The very shallow groundwater gradients of 3×10^{-5} between south and north Qatar are indications of the very high horizontal permeability values of the upper zone. Other than in the central area of the freshwater body of the Northern Groundwater Provinces, the recharge origin of the groundwater of the Formation is the outcrop in Saudi Arabia. The low salinity water of meteoric origin in the north is entirely of local origin with a probable initiation of this accumulation during times of high Pluvial rainfall and contemporary low sea-levels. The base of this freshwater body reaches to some 100 m below sea-level near Grid E19 N43; that is some 60 m below the top of the Formation in the same area. Exploitation of this freshwater body at greater than the average rate of recharge is causing a lateral convergence of the fresh-saline interface as well as its upward vertical displacement as the volume of freshwater in storage declines. In borehole SH9 the interface appears to have risen by some 10 m between 1959 and 1976, the date of the geophysical survey.

Regional Salinity of the Umm er Radhuma is indicated on Figure 10.11 with only sparse data for Qatar due to the problems of obtaining exclusive samples. No pattern of increasing salinity is present.

Umm er Radhuma Aquifer – Regional Piezometric Surface (m.a.s.l.)

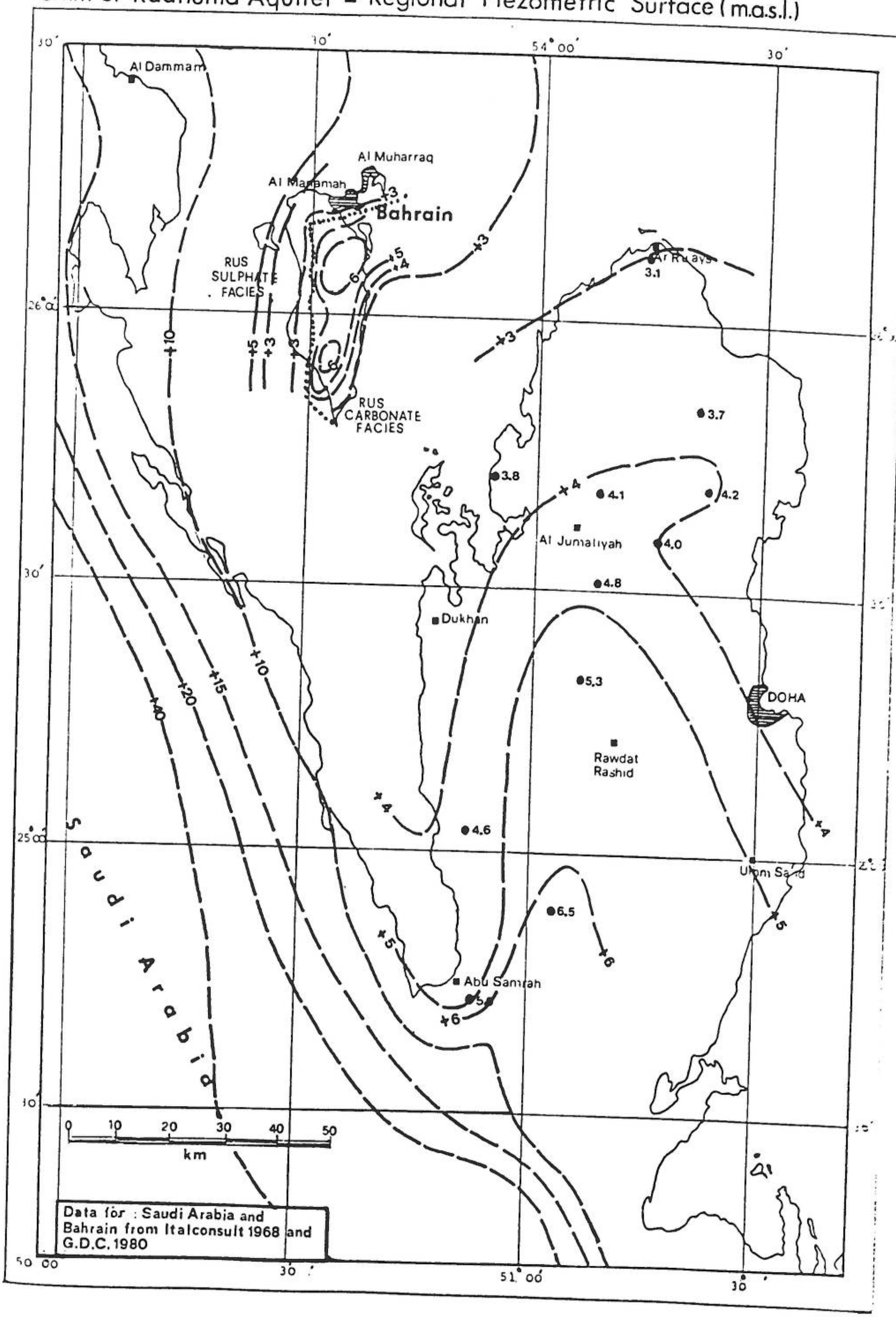


FIG. 10:10

Umm er Radhuma Aquifer - Regional Salinity

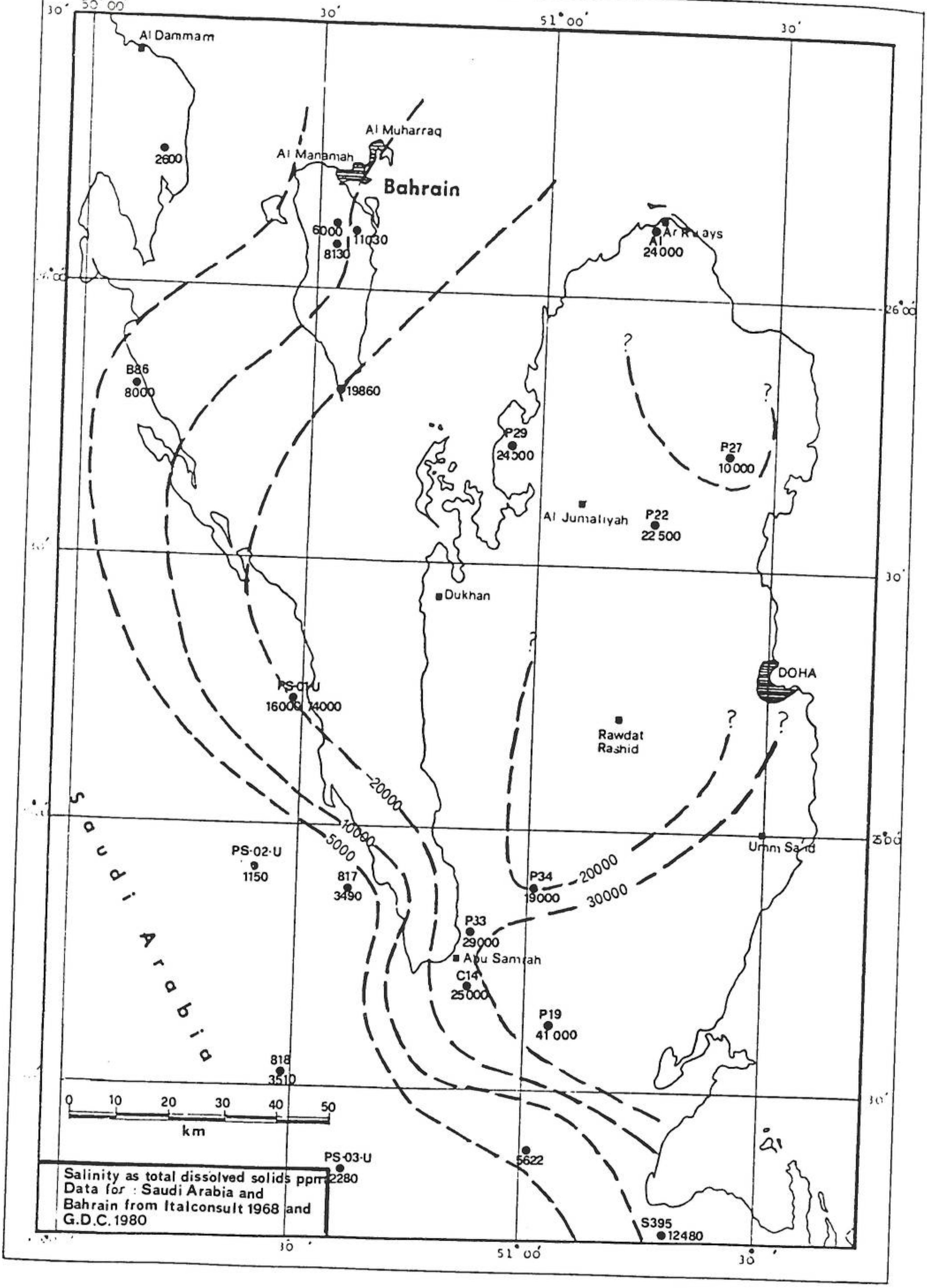


FIG: 10:11

10.2.8 Definition of the Aquifer System

The geological and hydrogeological connection between Saudi Arabia, Bahrain, and Qatar is demonstrated in a series of vertical cross sections presented as Figures 10.12, 10.13, 10.14, 10.15 and 10.16. Figures 10.12 and 10.15 illustrate the groundwater flow away from the inland recharge area of Saudi Arabia, 10.13 the sub-Gulf connections between Saudi Arabia, Bahrain island and northern Qatar. Figure 10.14 illustrates the typical hydrogeological conditions of the Northern Groundwater Province and Figure 10.16 the more complex situation of the Salwah Gulf and the Alat artesian aquifer.

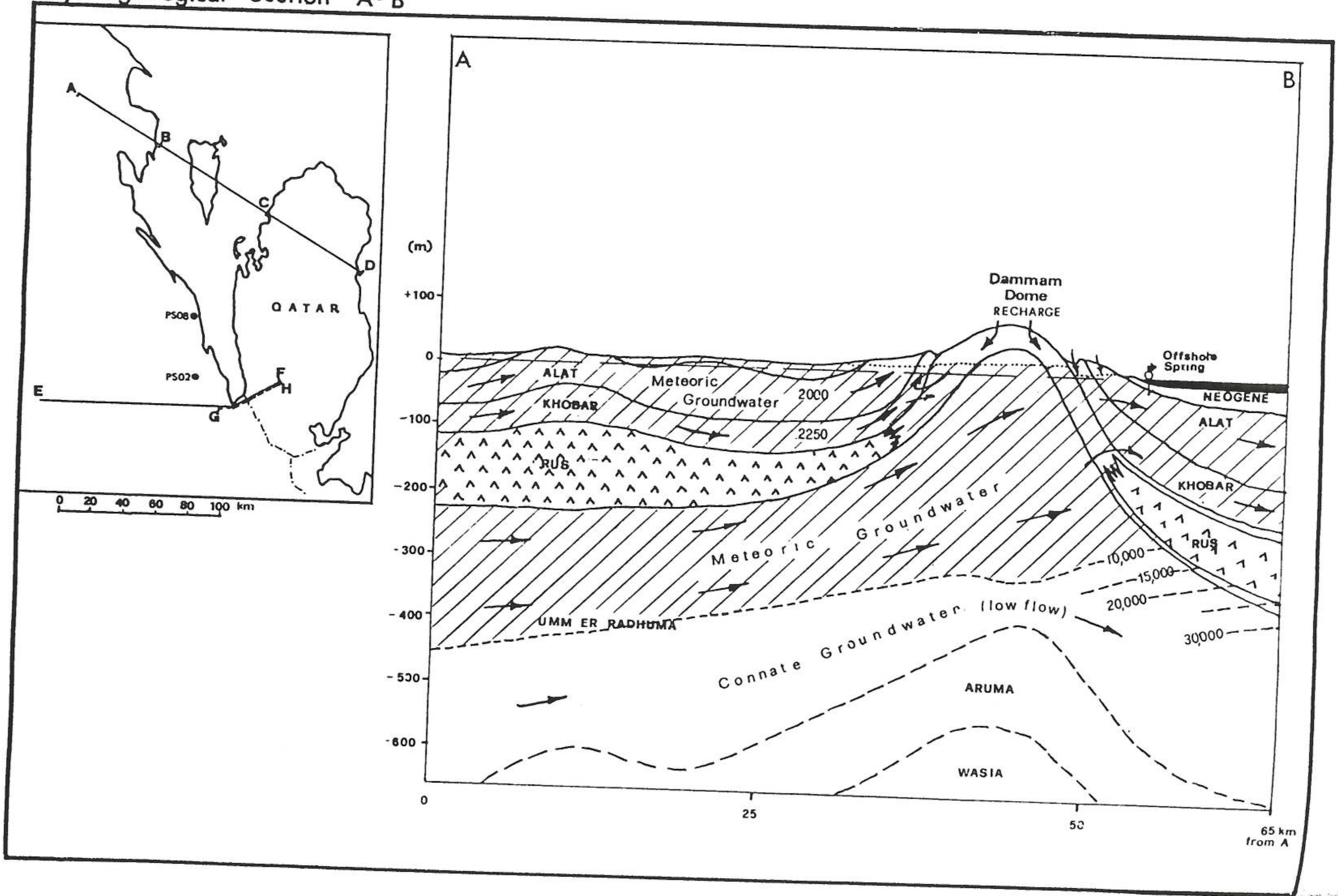
Lateral flow takes place within the sequence of aquifers and vertical flow occurs in both aquifer and aquitards where a breakdown in aquiclude conditions permits the interchange of flow dependent upon the requirements of changing pressure patterns. The seaward lateral flow of recharge in any one aquifer is limited by the presence of a fresh water-salt water interface. In the most superficial aquifers this contact occurs at the sea water boundary, in deep aquifers at the contact with connate water. Intermediate aquifers may have a sub-sea mixture of both sea water and connate water but in all cases there is a tendency for this fresh water-salt water interface to lie further inland with increasing depth. Thus lateral movement of groundwater towards the coast is converted to vertical movement upwards through both aquifers and aquitards towards the eventual discharge at the coast or at near-shore sites where flow is controlled by structure. Seawards, beyond the eventual discharge line, groundwater movement declines, to be reactivated only by natural changes in sea level creating a new pressure head situation or by the stress induced from massive artificial extractions of ground-water.

This basic model may be modified by the presence of near-coast confining conditions which protect and channel land-derived recharge towards remote off-shore discharge areas and thus permit the sea-ward displacement of the fresh water-saline water interface for considerable sub-sea distances. This condition is thought to apply in the case of the Alat aquifer of the Upper Dammam Formation of Bahrain where piezometric head data and groundwater salinities indicate a flow of freshwater from the Dhahran area of Saudi Arabia. The flow geometry has been much modified by extraction on the island as well as in the area of Dhahran but despite declining levels and increasing salinity the flow still supports the agriculture of the north west part of Bahrain. A similar flow of potable water in the Khobar Member of the Lower Dammam Formation may have continued into historic times but this also has declined with lower water levels and increasing salinity. A comparable onshore salinity contour configuration occurs for the Umm er Radhuma Formation of Saudi Arabia and, on Bahrain, the piezometric levels and the salinities indicate a former connection now trending towards isolation by changed hydrogeological conditions.

Other than the volume of usable fresh water reserves of the thin artesian Alat aquifer unit in the southwest, the stable groundwater reserves of Qatar may be defined separately from any historically recent connection to recharge and flow from Saudi Arabia. In the north of Qatar and within the area of the Northern Groundwater Province, the reserves have accumulated as a body of low salinity water surrounded and supported by higher salinity water. Despite the high salinity, 10,000 mg/l or more, of the underlying groundwater a positive piezometric level of up to 4 m above present sea level indicates the remote origin of this water. The potential thus exists for further lateral movement within the aquifer or, translated as a pressure head, for upward vertical transfer to higher aquifers where ever the levels of the upper unconfined and less saline groundwater are less than 4 m above sea level.

The overall shape of the freshwater body is controlled by variations in lithology and has been modified considerably by extraction. The removal of large volume of freshwater from certain areas only rather than uniformly over the Province, has resulted in the upward displacement of the freshwater salt water contact zone in some areas as well as the lateral incursion of sea water in others.

Hydro-geological Section A - B



Hydro-geological Section B - C

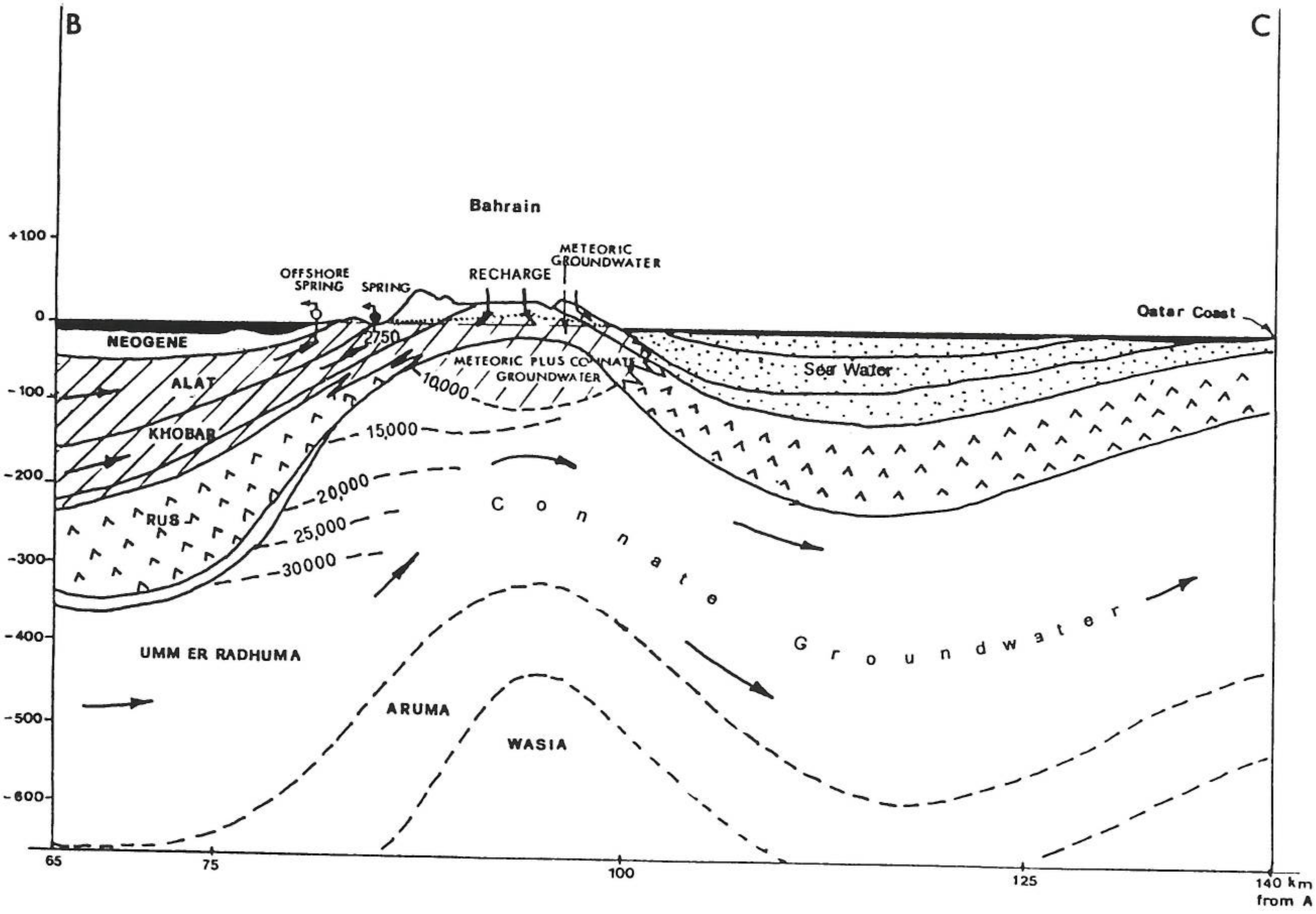


FIG. 10:13

Hydro-geological Section C-D

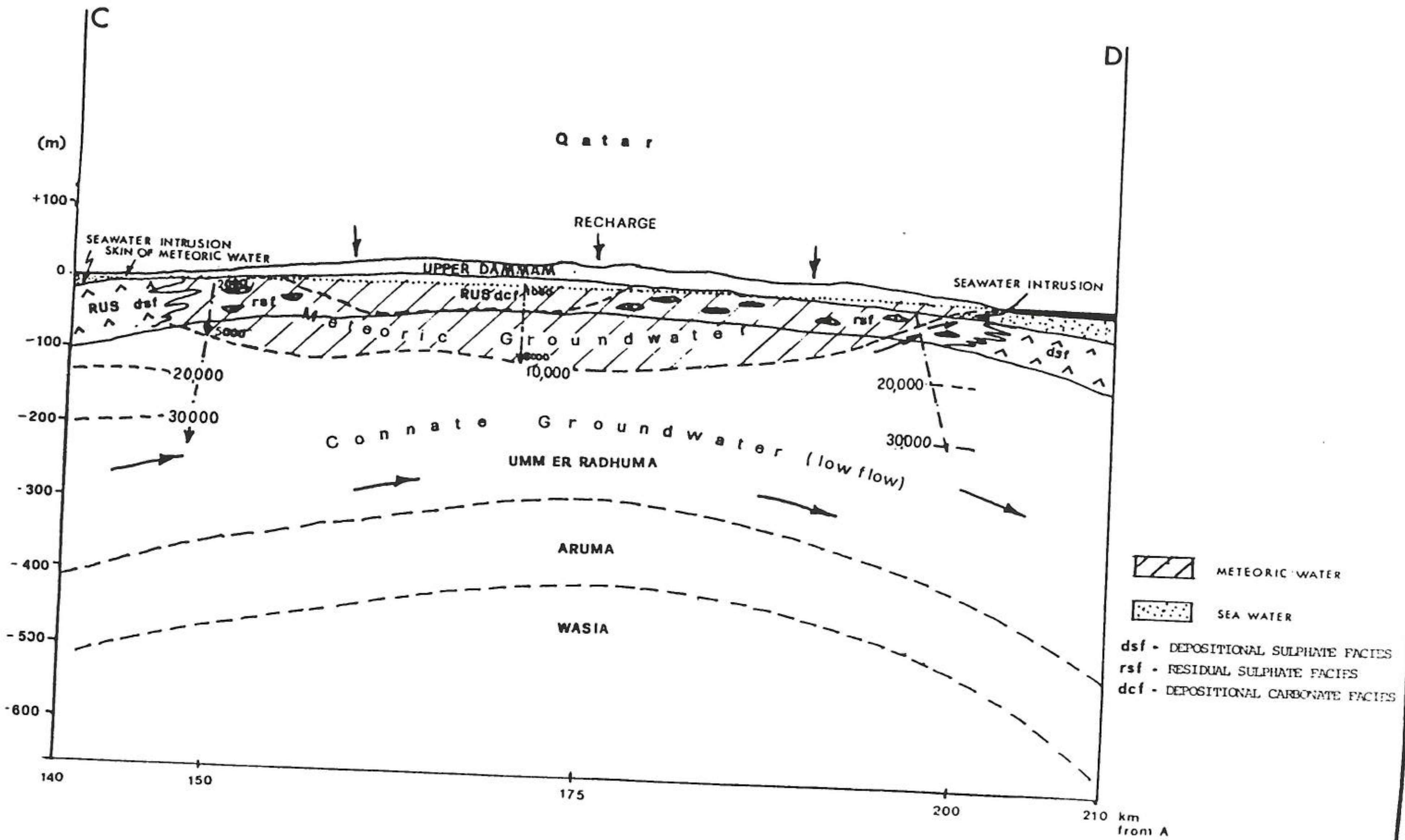
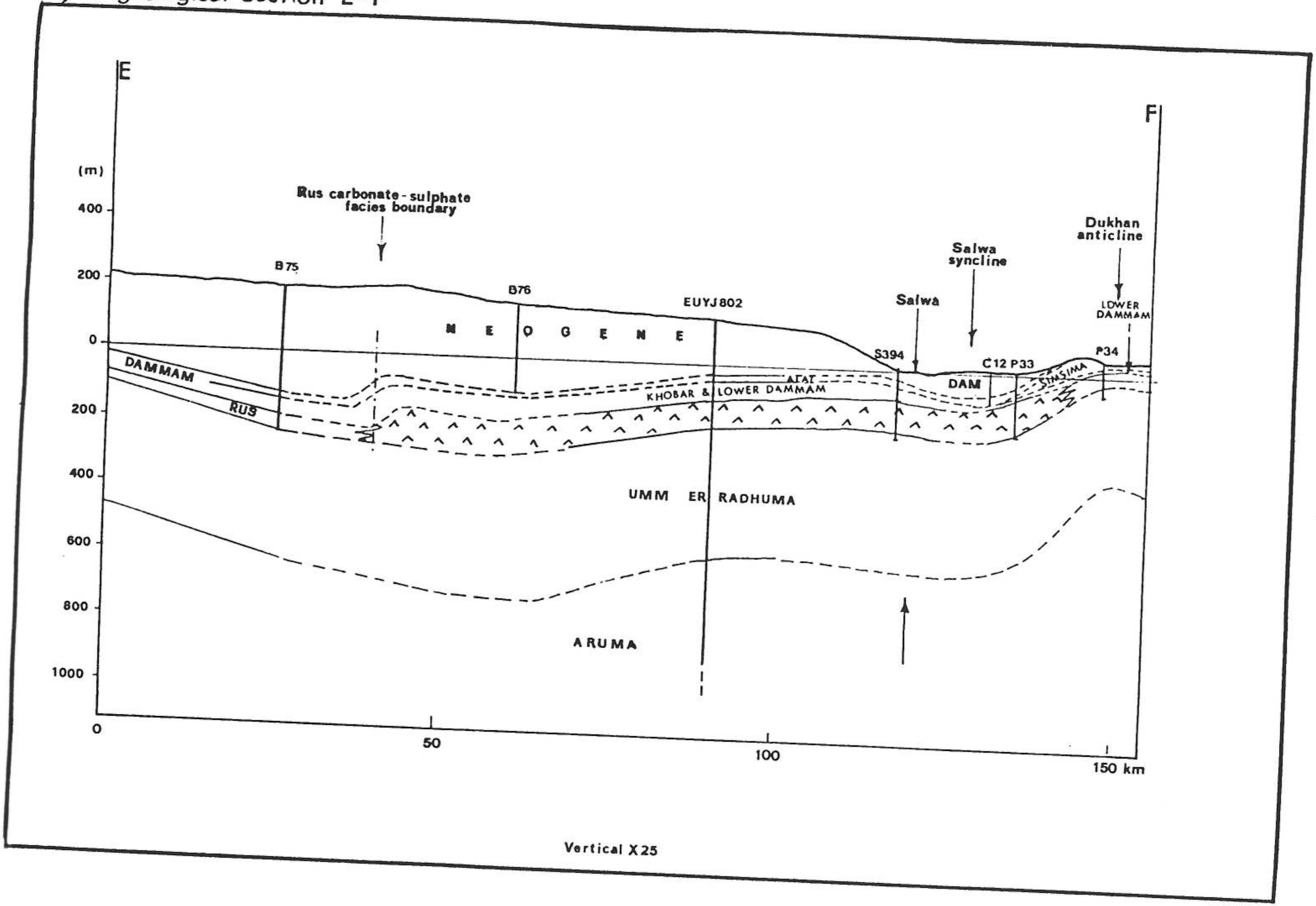


FIG 10:14

Hyaro-geological Section E-F



FIG,10 15

Hydro-geological Section G-H

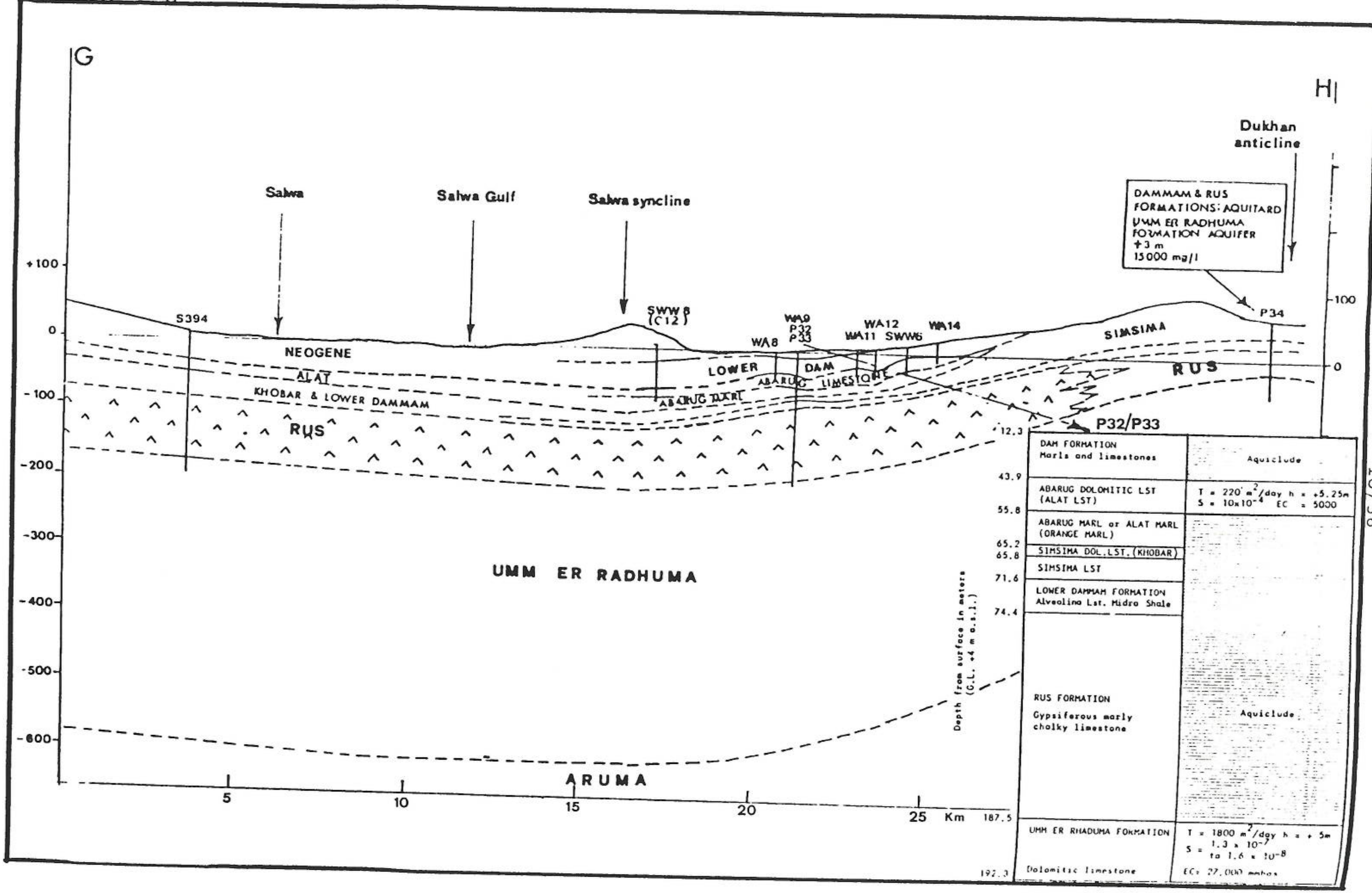


FIG. 10:16

Except for the Alat Member Unit, there is no evidence of the replenishment of fresh or brackish water reserves in Qatar by continuing through flow from Pluvial recharge in Saudi Arabia. The protrusion of better quality water of less than 2000 mg/l which extends, in the Alat aquifer, from Qatif in Saudi Arabia, passing to the north of Bahrain Island as far as Fasht Jebel, declines in quality before reaching northern Qatar and the equivalent of the containing formation, the Abarug Member in Qatar, possesses neither aquifer qualities nor a continuous large outcrop area. Similarly, the Khobar Formation, an aquifer of considerable importance in the Dhahran area with large potable water reserves, shows only a limited extension of better quality water towards northern Qatar. Although the equivalent Simsima Member has a very widespread outcrop of up to 80% of the surface of Qatar it is of importance as a fresh water bearing unit only in the lower elevation, coastal areas of Qatar in combination with the Rus Formation and there is no evidence of any throughput of freshwater from remote recharge areas in Saudi Arabia.

Regional groundwater movement in the Rus Formation is complex and controlled by lithological variation. Thus the Formation occurs generally as a thick anhydrite-bearing aquitard or leaking aquiclude with some water-bearing potential in the thin limestones which separate the anhydrite and shale beds and in the relatively shale-and-anhydrite-free, chalky limestone of the upper Rus. Elsewhere, as a depositional carbonate or the thin anhydrite-free carbonate residual of a deflated evaporite facies, it is in hydraulic continuity with the Umm er Radhuma Formation below. From Figure 3.10 it may be seen that the potentially aquiferous areas of Rus Formation are restricted to inland areas of Saudi Arabia with the exception of the coast around Qatif and Dammam, the south and east of Bahrain Island and the Northern Groundwater Province of Qatar. The lack of hydraulic continuity between these areas and the Rus recharge area in Saudi Arabia precludes the lateral movement, either past or present, of freshwater in to the Northern Groundwater Province of Qatar via the Rus Formation itself.

The Rus of the Southern Groundwater Province is an aquifer of very poor and variable potential for these same reasons. The extensive and unbroken cover of the lower Dammam shales and clays have limited the potential for groundwater accumulation, via either the few depressions which have developed or more generally from the well-weathered and highly porous Simsima Member outcrop which forms the surface rocks. The non-anhydrite areas of Rus are in overall hydrogeological continuity with the under-lying Umm er Radhuma and may best be described together with that Formation. From recent work in Saudi Arabia and Bahrain, the Umm er Radhuma regional water quality is found to be generally good west of the Saudi Arabian coastal area and a remnant tongue of good water extends south eastwards under Dhahran and El Khobar towards Bahrain island. North of this tongue, the quality declines rapidly towards the coast, south of the tongue less rapidly but in general the 10,000 mg/l contour follows the Saudi Arabian coast. (GDC 198o)

In Bahrain the 10,000 mg/l contour is seen to follow closely the coast line and a remnant of low salinity water the contact between the Sulphate Facies Rus of the north and west coastal areas of the island and the Carbonate (or Residual Sulphate) Facies of the centre east and south. Two very small remnants of Rus/Umm er Radhuma water of less than 2000 mg/l remain (1980) in the zones of highest Rus/Umm er Radhuma piezometric levels; + 6 m a.s.l. Though not expressed as such by GDC it is conceived that the aquiclude nature of the Rus to the north and west protect this remnant of a formerly more widespread body of fresh water.

10.2.9 Formation of Freshwater Bodies and the Evolution of the Aquifer System

Geological, archaeological and historical evidence of climate changes during the Neogene Period (Miocene Epoch to Present Day) points to an irregular but gradual decline in global temperatures which was initiated in the Paloegene Period (Palaeocene and Eocene Epochs). The major growth of high latitude ice masses probably commenced 3 million years ago, in the late Pliocene, reaching the lower mid-latitudes at the beginning of the Pleistocene. The four major glaciations of the northern hemisphere took place between 1.6 million and 18,000 years ago. Changes in wind pattern and ocean currents brought far-reaching changes in climate with overall migration of temperate zone conditions towards the equator. It is likely that average temperature conditions in the Gulf were some 10^{o} cooler than today during glaciation maxima and similar to the present during interglacials.

Evaporation conditions are indicated by stable oxygen isotope ratios measured in ice-cores taken from present-day northern and southern polar ice masses and from numerous sea-floor sediment cores world-wide. The process of isotope enrichment and the value of varying ratios in the determination of recharge conditions are explained in Chapter 9.2. Marked decreases in the relative proportion of the heavier ^{18}O isotope, due to the reduced evaporation of the lighter ^{16}O, are indications of cooler and presumably wetter conditions. Increases in ^{18}O proportions signify warmer and drier periods. A considerable decrease in ^{18}O took place between 72,000 and 60,000 years ago followed by a long interval characterised by irregular fluctuations but still maintaining the trend of increasingly cooler and wetter conditions (Johnson et al (1972)). A sharp increase in ^{18}O content commenced about 15,000 years ago and, with minor variations the ratios had reached those of the present time by about 10,000 years ago. Undoubtedly, the level of the sea changed in relationship with the variations of climate during the Neogene. As the present day is part of an interglacial period, with relatively high sea levels, evidence of conditions and groundwater flow and discharge which occurred at these lower levels lies beneath the sea. While the advance and retreat of ice massess are time-transgressive the variations in isotope ratios and sea-levels are synchronous worldwide and the interpretation of evidence may be transposed with confidence. Thus wave-cut platforms and the crests of coral reefs, which grow and decay to remain at mean sea level, have been correlated, with excellent agreement, between Barbados and New Guinea; (Bloom et al (1974)) As with oxygen isotope ratios from Greenland and Antartica, a rapid decline in world wide sea levels is indicated. Starting about 70,000 years ago, and following a long and relatively stable period with levels similar to those of today, the decline continued, with minor variations, as more and more water was locked up in high latitude ice masses and expanding lakes elsewhere, until the abrupt reversal, following the glacial maximum, which occurred about 18,000 years ago. Sea levels had probably returned to those of the present-day about 5000 years ago.

During the period of decline several falls and rises have been documented and correlated with the several glacial and inter glacial periods, but at the glacial maximum, the sea levels lay more than 50 m below that of today and some evidence points to a maximum excusion to more than 100 m below present sea level. The whole of the Arabian Gulf, may, therefore have been converted to a land area and the position and dimensions of the remnant Gulf, when the sea level stood at 60 m below present, are indicated on Figure 10.1, together with an interpretation of the groundwater movement and discharge situation at present as well as some indication of features dominant during Pluvial times. Thus a very large area of the shallow Gulf littoral would have been exposed as dry land. Migration of climate belts would also have brought the Qatar area under the influence of a temperate regime with much higher rainfall than at present. Discharge of groundwater recharged over Saudi Arabia and the exposed littoral, including the present day Qatar peninsula, would have taken place at a relatively straight NW-SE oriented shore line which lay up to 100 km north of the present one. Increasing general recharge of considerable quantities of precipitation would have developed the groundwater circulation conditions which lead to the situation interpreted in a Groundwater Province separation seen today (Figure 3.13). The protective cover provided by the impermeable lower Dammam Shale, south of the centre of the present-day peninsula and in the west, restricted the solution and removal of the Rus gypsum to those areas where joints and fractures allowed recharge to penetrate and develop a network of connected waterways. In the north the absence of the shales resulted in the removal of almost all of the gypsum over a large area and the development of an aquifer of valuable porosity and permeability despite the fine-grained lithology of the chalky Rus limestone and the high high clay content.

It is believed that residual formation (or connate) water and sea water would have been scoured from the Rus and underlying Umm er Radhuma to a depth compatible with the lowest sea leve reached. This situation is illustrated as a development series in Figure 10.17. The sections are drawn in a SW-NE direction to relate to perferred paths of groundwater movement which would have been the prime route in Pluvial times. Stage I shows the situation during the advance of the interface, with increased recharge and declining sea levels, and Stage II the supposed position at the time of maximum extension. With the decline of the Pluvial period conditions and as the sea level rose, the coast line retreated towards the south west and the fresh water-saline water interface would also have reflected the changes. Where connections (lithological windows) existed the rising sea levels would have caused salt water incursions and the gradual isolation of the fresh water bodies. This is illustrated as Stage III. Sea water would have displaced the freshwater on a front which advanced into and beneath the freshwater (because of specific gravity differences) and in competition with the head and flow of the remaining connate water content of the Umm er Radhuma Formation thus creating the separated remnant freshwater bodies found today in the northern Qatar peninsula and to a lesser degree, Bahrain. The fourth and present stage in this series is illustrated by Figure 10.12, Hydrogeological Section A-B, where the meteoric body of water beneath Bahrain is a remnant only and the freshwater-saline water interface, relieved of head pressures by upward transfer and discharge, lies beneath the present Saudi Arabian coast line.

The U-shaped contact between the anhydritic and non-anhydrite Rus Formation in the north of Qatar could be the dry land part, with a submerged northern part, of what was a major discharge zone during Pluvial times. In Bahrain also the freshwater leakage from the Umm er Radhuma is all to the north of the island. A diagramatic illustration of the effects of changing sea levels on groundwater movement and discharge is given below as Figures 10.18, 19, and 20.

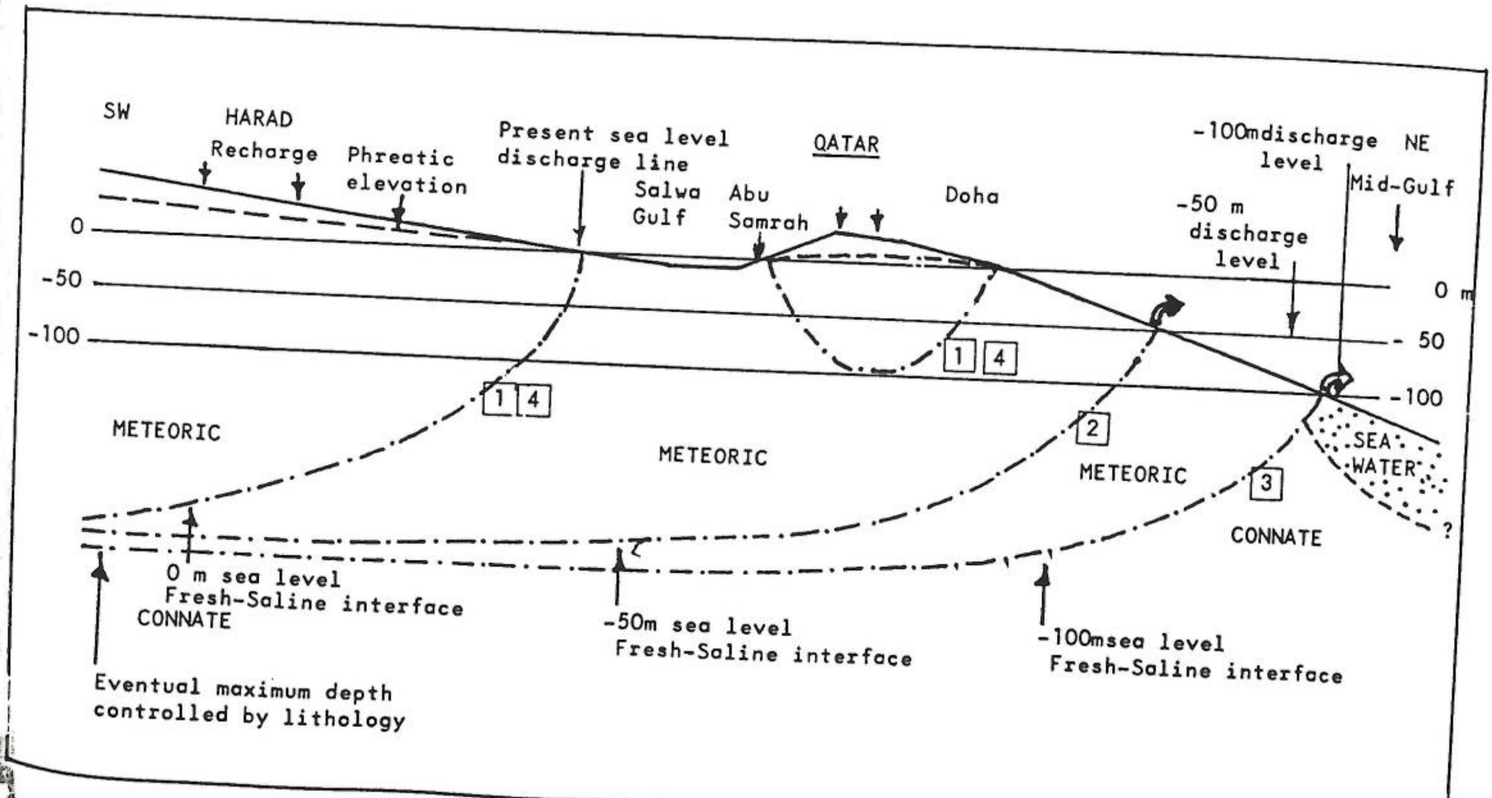


FIG. 10.18. STAGES OF DEVELOPMENT OF FRESHWATER BODY WITH DECLINING SEA LEVELS

Probable Hydro-geological Evolutionary Sequence

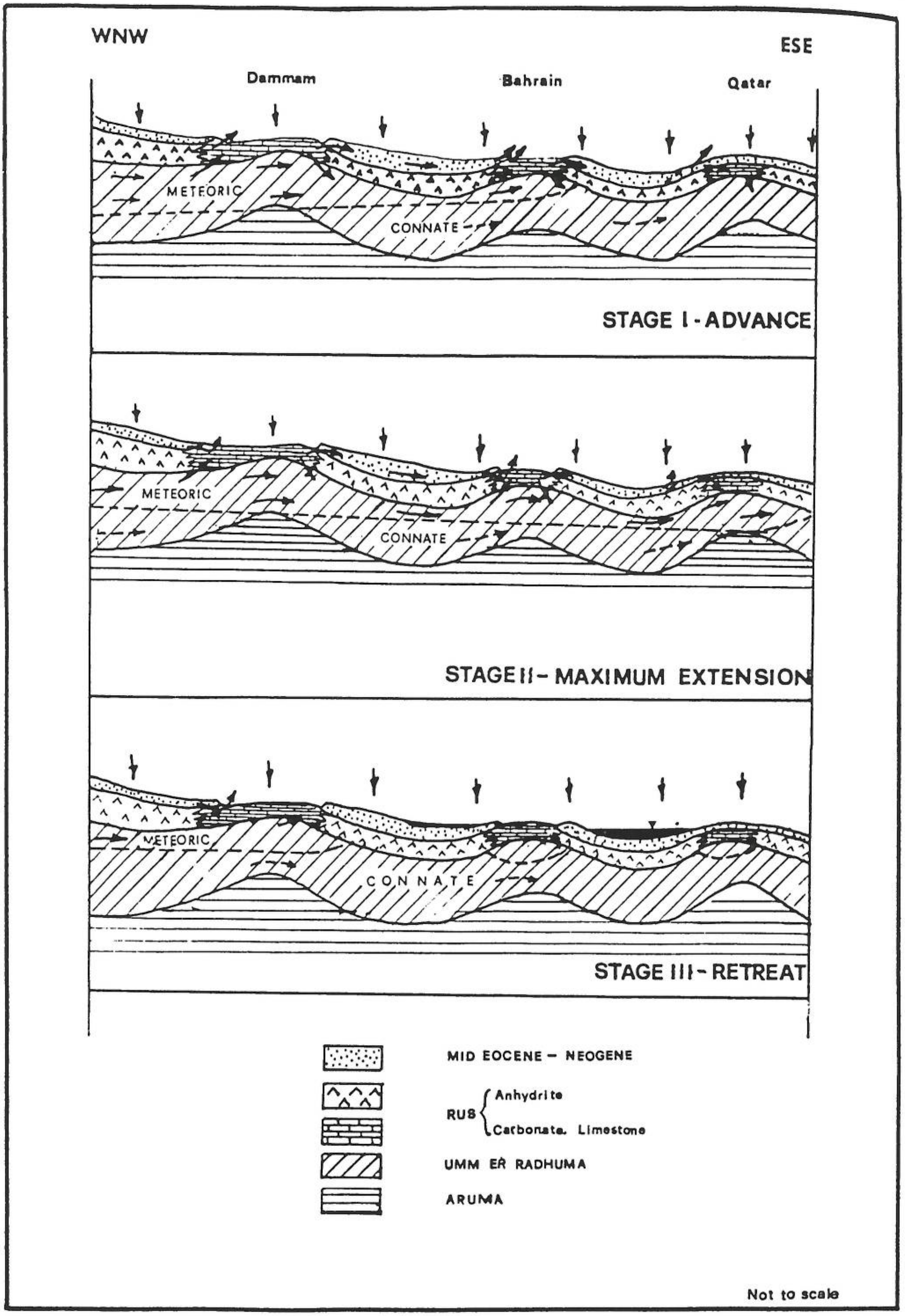


FIG. 10:17

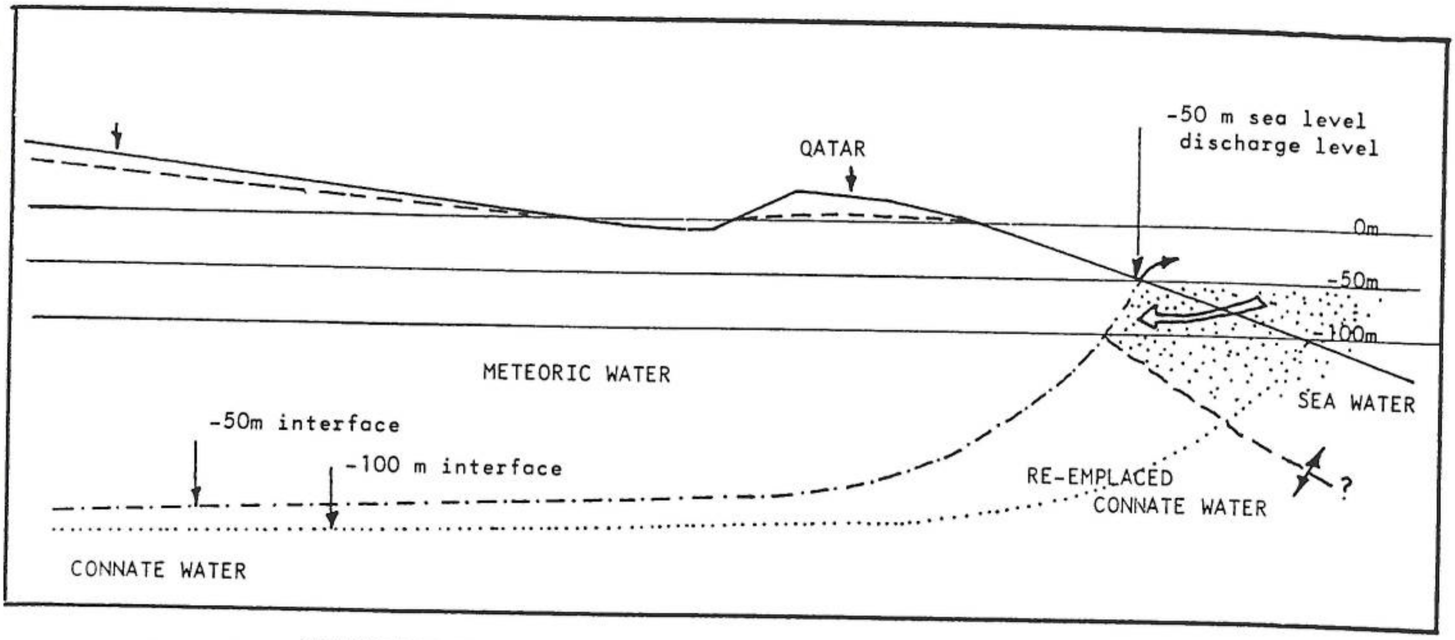


FIG. 10.19. STAGNATION OF AND INCURSION INTO FRESH-WATER BODY BELOW - 50 m DISCHARGE LINE AS SEA LEVEL RISES

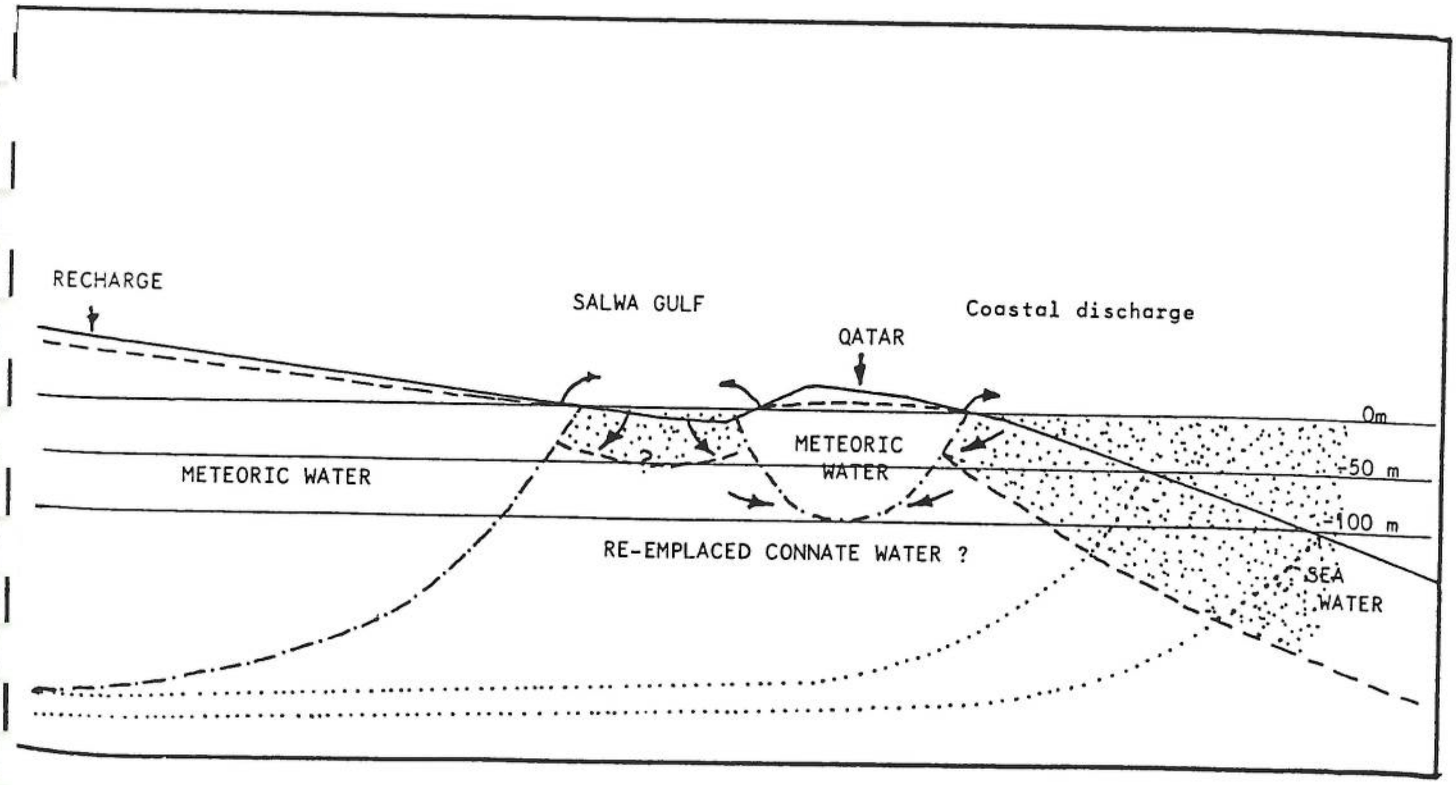


FIG. 10.20. FURTHER STAGNATION, INUNDATION AND SEPARATION OF FRESH-WATER BODIES AS SEA LEVEL RETURNS TO 0 m

The inter-relationship between the connate groundwater and intrusive sea water is not clearly understood due to the difficulty in obtaining uncontaminated samples for analysis. The methods of emplacement and replacement of meteoric by connate and/or sea water are therefore presented as an hypothesis awaiting further deep-level exploration and sampling. However, the evolution of chemical sequences (Chapter 8.4.1) tend towards limits which differ in the types of more saline groundwater and which could be explained by the above hypothesis. The considerable variation in ages determined for the deeper fresh and brackish groundwater may also be the result of admixture with recent sea water or reimplaced connate water of very considerable age.

At all stages, water levels of the Umm er Radhuma, volumes of freshwater and therefore the position of the interface, marginal discharge to the sea and recharge to the freshwater body tend to remain in equilibrium. Assuming steady stage conditions in 1958, prior to the start of large scale agricultural and domestic extraction, the balance between the fresh water body, which maintained an outflow to the sea equal to recharge, required a head in the centre of the northern area of about + 13 m to overcome aquifer friction losses with this head declining to zero at the coast. This is some ± 10 m above the supporting head of the Umm er Radhuma Formation near the centre of Qatar with the head of this aquifer also declining to zero at the coast as water flowed from it to the sea. (See Figure 10.2) That this piezometric surface was not everywhere uniform with contours equidistant and parallel to the coast is an indication of the variations in porosity and permeability and therefore the creations of corridors of enhanced flow induced by variations in lithology and geological structure. Historical aquifer pressure heads up to a maximum of 15 m in the Rus Formation and 4 m in the Umm er Radhuma would still have driven recently recharged water into the freshwater body even if the total volume of the body remained stable. Volume balance and the requirement for meteoric water discharge would have been met by marginal discharge of 'older' meteoric water to the sea at the coast, as indicated in Figure 10.21 below.

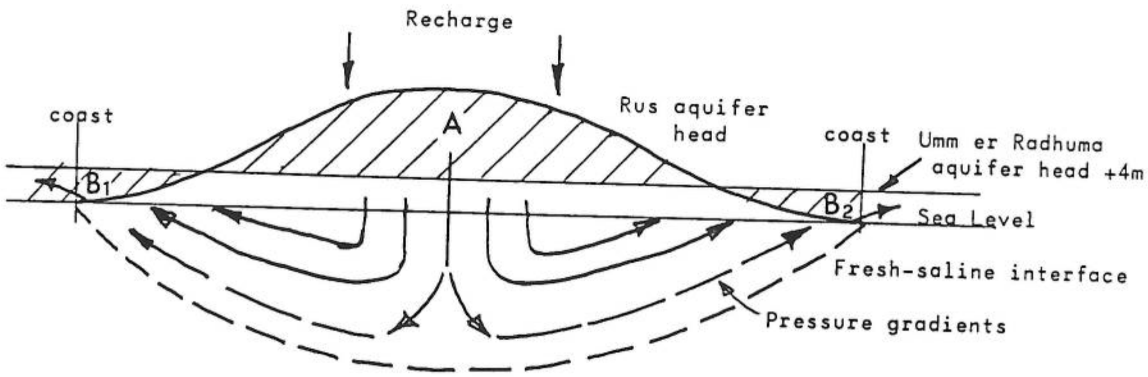


FIG: 10.21. HYDRO-DYNAMICS OF FRESH-SALINE WATER INTER-REACTION

Thus where the Volume in A exceeded the combined volumes of B_1 and B_2 by a sufficient amount to overcome aquifer friction losses discharge would have taken place. As the heads in the Rus Formation declined due to over extraction and with the head of the Umm er Radhuma aquifer remaining constant (or suffering only very slight decline) due to support from the distant recharge area and a stable volume in storage, the pressure head gradient gradient could be altered with a consequent change to upward displacement flows by the same preferred channels and a discharge of fresh and brackish water to the sea driven by the head of the deeper groundwater flows.

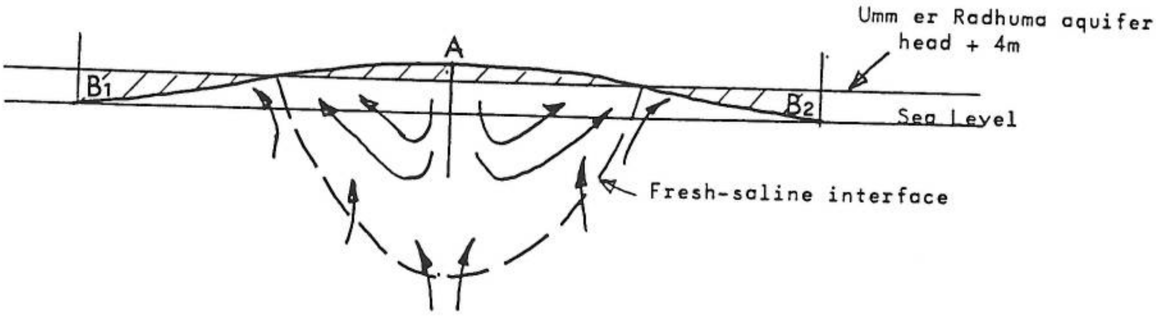


FIG: 10.22 HYDRO-DYNAMICS OF DECLINING FRESHWATER BODY

Where the volume at A is insufficient to exceed B_1 and B_2 plus the friction head losses, mixed, deeper, more saline goundwater will be discharged at a rate controlled by the limited pressure head available.

For the classical Ghyben-Hertzberg relationship an archimedian ratio of 1 : 40 occurs between the head above sea level of the surface of the fresh groundwater and the depth below sea level of the interface with the supportive saline water below according to the following formula which was first applied to floating lenses developed in oceanic islands.

$$D = \frac{h_f \ p_f}{p_s - p_f}$$

where D = depth to the interface below datum
h_f = head of freshwater above datum
p_f = freshwater density
p_s = saline water density.

The development of freshwater bodies within saline groundwater can also be modelled but rather than the uniformity of sea water density, a vertical gradient of salinity and therefore density is found within thick aquifer sequences. This is apparent in P27 as a linear gradient of about EC $1000.m.^{-1}$ over a depth of 40 m within the Umm er Radhuma, below an interface and EC $280.m.^{-1}$ for 32 m in P 22a. GDC (1980) found a gradient of about 180 mg/l in Saudi Arabia and thus while the data from P22a maybe related that for P27 probably indicates the profile is still within the lower part of a mixing zone.

Of the deeper drilling in the Northern Groundwater Province, where a Ghyben-Herzberg isostatic relationship could exist between the low salinity groundwater body and the supportive higher salinity below, conductivity profiles which illustrate such a phenomenon are available from Borehole P22a and P27 (Figure 8.6 and Appendix 1.3)

The data are as follows:-

Table 10.1

Groundwater Profile Data - P22a and P27

Borehole	Total Depth (m)	Ground Level (m)	Static Water Level (m)	EC 3000 Level * (masl)	Top of Transition Zone (masl)	Base of Transition Zone (masl)	1 : 40 G.H. Depth	Calcul-ation Ratio
P 22a	152.4	34.8	+ 3.65	- 82.2	- 75	- 85	- 146	1 : 23
P 27	137.2	18	+ 4.10	see text	- 66	- 96	- 164	1 : 23

* EC 3000 selected as the limit of potable water

In borehole P22a, some 23 km from the coast, the profile exhibits a sudden rise in salinity between the depth of - 75 and - 85 m rising from EC 600 to EC 12600, indicating a very thin transition zone.

In borehole P27 within 12 km of the east coast, the Mixing or Transition Zone is very much thicker. A relatively stable conductivity of about EC 3000 occurs between water surface and - 66 m, co-incidentally the level of the chert horizor some 15 m below **the** top of the Umm er Radhuma Formation, with a rapid rise to EC 7000 at - 69 m. The conductivity rises only slowly, reaching EC 9000 at - 96 m, but below that depth there is a constant rapid rise with depth to an eventual 46,000 at - 118 m. The base of the freshwater body is placed at - 66m and the Transition Zone from that depth to - 96 m.

Whatever the thickness of the mixing zone the depth to the top of the saline groundwater which exhibits a linear increase in salinity and temperature with depth, should therefore be related to the phreatic level of the freshwater zone above.

Table 10.2

Isostatic Ratios

Borehole	Freshwater Salinity at 25^{o}C ($mg.l^{-1}$)	Freshwater Density at 25^{o}C ($kg.l^{-1}$)	Saline Water Salinity at 25^{o}C ($mg.l^{-1}$)	Saline Water Density at 25^{o}C ($kg.l^{-1}$)	Present Sea Level Ratio	Umm er Radhuma Level Ratio	Geophysical Survey base Level (masl)
22a	500	1.0005	8000	1.0080	1:487	1:153	- 100
27	2000	1.0020	8500	1.0085	1:632	1:246	- 75

The ratio calculated by using present sea level as datum is clearly not viable and, using the known differences between the phreatic surface of the freshwater body at the two localities and the general + 3.5 m of the Umm er Radhuma piezometric surface for the Northern Groundwater Zone the depth to the base of the interface was recalculated and compared to the results of the geophysical survey and still indicating very considerable discrepancies.

It is therefore likely that the salinity interfaces encountered in both P22a and P27 are only intermediate in the complex relationship between fresh and saline groundwater which is not directly controlled by isostatic principles but more under the influence of lithological variations.

10.3 AQUIFER TESTING

10.3.1 Introduction

The evaluation of water level data and the test pumping of a limited number of exploratory boreholes drilled specifically for Project investigations have permitted estimations of water bearing properties of the several lithological and stratigraphic units. Transmissivities, permeabilities and storage coefficients have been calculated from test pumping and specific capacity estimates made where test pumping could not be carried out. Hydraulic heads and piezometric surfaces have been evaluated from water level data.

Some 36 boreholes were drilled during the various stages of the Project but only 12 of these have been fully tested and the results analysed. Specifically in the case of the boreholes exploring the artesian conditions of the Alat aquifer and in the more recent P27, P29 and P35 casing was used to separate varying aquifer conditions and also support the bore against collapse. It has been found that many of the boreholes in the group P1 to P26 have collapsed either partially or totally and a cleaning and protection programme would have been required before test pumping could be carried out. As the early wells also lacked strict lithological and stratigraphic control it was deemed more advantageous to use the very limited rotary rig and testing time and facilities available on new boreholes rather than on the recleaning of old ones. Details of aquifer testing and the evaluation of results are given as part of each individual Borehole Completion Report which make up Appendix 1.3 and 5.1.

Particularly in the case of the upper part of the Umm er Radhuma aquifer, and to a lesser degree the thinner band within the Rus Formation spanning the water table surface, it was found that steady stage conditions were reached very rapidly from the start of pumping. Without a sensitive water level recorder, it was impossible to obtain accurate hand held tape measurements of transient conditions prior to equilibrium as the limited drawdowns of 1 to 2 m took place within the first minute or two of pumping. As this is also the period when well storage has great influence over yield/drawdown relationships the value of transient data was further limited.

During drilling, evidence of the form of aquifer storage was provided by fluid circulation losses and the occurrence of large voids and cavities. This suggests that the high transmissivities are due to the presence of joints, fractures and inter-connected voids which form only a very limited proportion of the total rock volume which is therefore of low storativity. This fissure flow supposition is entirely compatible with the karstic nature of certain horizons within the complex of formations described in 3.6 and 10.2 though the results of test pumping from the Alat aquifer indicate the presence of a greater proportion of granular porosity. Confined fissure flow aquifers are greatly influenced by diurnal atmospheric pressure changes and chart records of pumped water level show clearly this effect. A further feature of such aquifer hydraulics is the very limited drawdown induced in adjacent piezometers by the pumping from a test borehole. This was noted during the testing of all the Project boreholes.

Calculations and estimates of the fundamental aquifer parameters are essential to the understanding of groundwater hydraulics and for the calculations of reserves and rates of replenishment. The most accurate calculation of these factors comes from the results of long-term well-controlled test pumping of wells with accurate water level measurements in the pumped well and in adjacent boreholes of a similar depth acting as piezometers.

10.3.2 Groundwater Terminology

The definition and significance of some terms used to express the nature of groundwater flow and the results of testing, are as follows:-

10.3.2.1 Water Bearing Properties of Aquifers

(a) Porosity is the property of a soil or rock in possessing voids and may be expressed quantitatively as the ratio of the volume of voids to the total volume, usually as a percentage. The origin of the porosity may be two fold and the total porosity of an aquifer may be derived from a varying proportion of either or both types. Primary (or intrinsic) porosity results from the voids remaining following the accumulation and compaction of a sedimentary siliclastic, carbonate or evaporite deposit. The amount of spaces between grains will vary considerably during the geological history of a rock unit and will generally decrease with time until weathering processes reverse such a trend. Secondary (or diagenetic) porosity is openings created by the separation of the faces of joints, fractures, faults, bedding planes and cleavage. These tend to increase with geological time and the process is much accelerated during the weathering cycle. Many dense and consolidated rocks with low primary may have an appreciable secondary porosity which is the mode for storage and movement of groundwater. The solution of carbonate rock by the chemical action of atmospheric carbon dioxide dissolved in moving groundwater, and taking place along widening joints, fractures and bedding planes may result in very high effective porosities as does the process of removal in solution of anhydrite from evaporitic formations.

(b) Permeability is the measure of the ability of a rock or soil to transmit water under the influence of a pressure gradient. In as much as this is a property of the medium alone, the term intrinsic permeability (k) is used to indicate the facility of a sample of rock to permit the flow of a gas or liquid under controlled laboratory conditions of temperature, viscosity, pressure etc., created during the testing of core samples. The permeability of a water bearing rock unit, in its natural state, is termed hydraulic conductivity (K) as here the properties of natural groundwater are included as well as those of the aquifer.

(c) Hydraulic Conductivity (K) may be defined as the property of a medium to conduct, in unit time, a unit volume of groundwater at the prevailing viscosity through a cross section of unit area, measured at right angles to the direction of flow, under a hydraulic gradient of unit change in head through unit length of flow.

Therefore $$K = \frac{Q}{Ai}$$

or $$K = -\frac{m^3}{m^2.day.(-m.m^{-1})} = m.day^{-1}$$

where

K	=	unit length per unit time	.... $m.day^{-1}$
Q	=	cubic metres	.... m^3
A	=	area	.... m^2
i	=	hydraulic gradient ($\Delta h / \Delta l$)	.... ratio

The negative signs result from the fact that water moves in the direction of decreasing head.

Thus the rate of water flow through a porous medium is proportional to the head loss, inversely proportional to the length of flow path and proportional to the coefficient K.

That is $Q = KiA$

For the average water particle <u>velocity</u>, $\bar{v}$, the porosity of the medium is also required.

Thus from $Q = \bar{v}A\varnothing$

where

Q	=	volume of flow	.... m^3/day
$\bar{v}$	=	velocity	.... m/day
A	=	cross sectional area	.... m^2
$\varnothing$	=	porosity	.... %

and the relationship that

$$Q = KiA$$

then $\bar{v}A\varnothing = KiA$

and $\bar{v} = \frac{Ki}{\varnothing}$

<u>Transmissivity</u> (KD) is the product of the average hydraulic conductivity (K) and the thickness (D) of the water bearing section. It is the rate of flow under a unit hydraulic gradient through a cross section of unit width over the whole thickness of the aquifer.

thus $$KD = -\frac{m^3.m}{m^2.day\ (-m.m^{-1})} = m^2.day^{-1}$$

10.3.2.2 <u>Water Yielding Properties of Aquifers</u>

(a) <u>Specific Yield</u> (Sy) is the water given up by a medium under the influence of gravity drainage or more specifically, the volume of drainable water per unit volume of rock. It is dimensionless and usually expressed as a decimal fraction.

<u>Storage Coefficient</u> (S) is the volume of water released or taken up by an aquifer per unit surface area, per unit change in hydraulic head. The storage coefficient of unconfined aquifers is virtually equal to the <u>Specific Yield</u> (Sy) which is also the

effective porosity (as opposed to the total porosity) of the aquifer varying between 0.1 and 0.3 with 0.2 being a generally accepted value. The term Storage Coefficient (S) is usually retained in reference to the confined parts of an aquifer where the yield is not derived by dewatering and depends upon the elasticity of the medium and the fluid contained. It is generally in the range of 10^{-3} to 10^{-5} and may be assumed at 30^{-6} per metre of aquifer thickness.

(c) Unconfined Aquifer is a permeable unit, partly filled with water overlying a relatively impermeable layer. Its upper boundary is formed by a free water, or phreatic, surface, under the influence of atmospheric pressure. Water in a well penetrating an unconfined aquifer does not generally rise above the phreatic level, whatever the well depth except where there is vertical flow.

(d) Confined Aquifer is a completely saturated unit where the upper and lower boundaries are impermeable. As all rocks are to some degree permeable, a truely confined aquifer is unusual and the preferred terms are semi-confined and semi-unconfined aquifers and the confining layers, aquitards rather than aquicludes. The water pressure within the aquifer is higher than atmospheric and the water level rises when released by drilling to stand at a level above the top of the aquifer. Artesian is used to describe confined groundwater which is free flowing at the ground surface. The potentiometric surface is an imaginary one connecting all points to which the confined groundwater level would rise in non-leaky boreholes.

10.3.2.3 Groundwater Flow Conditions

As well as being a source of much valuable information, the test pumping of a borehole is an interference (as is the borehole itself) with the natural groundwater conditions. The disequilibrium conditions induced by pumping create flow regimes of two types.

(a) Steady State Flow where there is equilibrium between the discharge of the pumped well and recharge to the aquifer from a source outside the radius of pumping influence. This may occur in unconfined aquifers where the regime of natural recharge and discharge has settled to a new balance. Thus changes in drawdown with time are negligible and the hydraulic gradient has reached equilibrium. Such a regime gives no information on the likely storage coefficient since no water is being drawn from adjacent storage where measurements are possible.

(b) Nonsteady State Flow occurs from the instant pumping starts until equilibrium is reached. In the case of a truely confined aquifer, non-steady state conditions will continue without limit as the water is provided by shrinkage due to the elasticity of the medium and the water and not to dewatering. Generally however, steady state conditions are eventually reached due to enhanced recharge, inter-aquifer transfer or sea-water intrusion, all of these being un-natural conditions induced by the pumping.

10.3.2.4 Analysis of Test Data

In the situation of the long-established wellfields, which penetrate and utilise the Rus Formation aquifer, so as to exploit the low salinity water only, steady state conditions have been developed. The methods of analysis of data proposed by Dupuit (1863) for steady state flow in unconfined aquifers, and later modified by Thiem (1906) to include steady state flow in confined aquifers also, require that:-

$$Q = \frac{2\pi KD\ (s_1 - s_2)}{\ln\ (r_2/r_1)}$$

in which

Q	=	discharge	....m^3/day
K	=	permeability	....m/day
D	=	aquifer thickness	....m
$s_1 s_2$	=	steady state drawdown	....(m) in piezometers at distances $r_1 r_2$ from the pumped well.

thus

$$KD = \frac{Q}{2\pi\ (s_1 - s_2)} \ln \frac{r_2}{r_1}$$

In addition to the assumption of steady state conditions, the method requires that the water flow to the pumped well is horizontal and uniform in the vertical section through the axis of the well. While the latter assumption is rarely met the larger than usual scale of assuming a Qatar water supply wellfield, consisting of up to 200 separate wells up to 50 m apart, to be the equivalent of a single pumped well smooths the errors introduced by the lack of homogeneity in the aquifer.

The basic assumption of Darcian flow in aquifers (Darcy 1856) is based upon the following precepts.

- the aquifer has a notionally infinite areal extent.
- the aquifer is homogeneous, isotropic and of uniform thickness over the area influenced by the pumping test.
- the piezometric or phreatic surfaces are horizontal over the area influenced by the pumping test.
- the aquifer is pumped at a constant discharge rate.
- the pumped well penetrates the complete thickness of the aquifer, as do the adjacent piezometers, and thus receives water from the entire thickness by horizontal flow.

In fissured aquifers such precepts are not entirely applicable in that the aquifer is not homogeneous and isotropic and the flow to the well is not entirely horizontal. The drawdown in the pumped well is not linear with discharge and the additional drawdown induced by rising velocities and consequent friction losses as the water travel through the limited number of fissures intersected by the well as the rock/open hole interface, are termed well losses. Such losses may be high in fissured aquifers and should be isolated from aquifer losses for reasonable determinations of transmissivity and permeability.

Rorabaugh (1953) determined for particulate aquifers; that

$$s_w = BQ + CQ^2$$

where

s_w	=	total drawdown
Q	=	discharge
B	=	aquifer loss coefficient which varies with time until steady state conditions are reached.
C	=	well loss coefficient

These coefficients may be determined by calculation from step tests in which the well is pumped at more than one discharge rate for equal time periods. Attempts to subject step-test data to analysis by the Jacob (1946) method and the modified Jacob method proposed by Eden and Hazel (1973) were unsuccessful as the increase in drawdown induced by increases in yield were not complementary. However, GDC (1980) have calculated that apparent well losses induced by pumping from the Khobar and Umm er Radhuma aquifers represent a very large proportion of the total drawdown, ranging from 35 to 98% for yields of 25 lit/sec or about 2000 m^3/day. It is likely that the Rorabaugh method does not accurately represent the relationship between aquifer losses and well losses for fissured aquifers and Clark (1978) has stated that there is no accurate method for analyzing for well losses from step tests of fissure rocks as the vertical variation of permeability invalidates the method.

While the degree of the well loss contribution to drawdown is uncertain it is still believed to be an important factor and thus the steady state calculations of aquifer transmissivities and permeabilities may in reality be under estimates. The values are therefore conservative estimates of the aquifer characteristics but are those that will be obtained from all typical boreholes.

When only one piezometer is available, adjacent to the pumped well, the drawdown was also measured in the pumped well and the basic Thiem equation applies

$$Q = \frac{2 \pi KD (s_w - s_1)}{\ln (r_1 / r_w)}$$

where r_w and s_w are the effective radius of and the drawdown in the pumped well.

In most cases test pumpings were carried out without the benefit of any adjacent piezometers and for limited periods only. Unsteady state flow regimes were thus deemed to apply and the methods of analysis, first introduced by Thies (1935) include the factors of time and storage coefficients.

The method, originally developed for confined aquifers, utilizes the principal that the influence of discharge extends radially with time. The rate of decline of piezometric head, multiplied by the storage coefficient and summed for the expanding area of influence is equivalent to the yield. The water is removed from storage and the piezometric level will therefore continue to decline with time. However the rate of decline decreases with time as the area of influence expands until virtual steady state conditions are reached. The Theim equation is extended by the factors 't' (time) and a well function 'u' representing the expanding influence. Type curves for theoretic analogy of groundwater flow are matched against measured data for the calculation of KD (the transmissivity) and S (the storage coefficient).

The elimination of the exponential integral by curve matching reduces the Thies equations to

$$Kd = \frac{Q}{4 \pi s} W(u)$$

$$= \frac{0.08 Q}{s} W(u)$$

where Q = discharge .... m^3/day

W(u) = expanded integral of 'u' the relationship between radius influence, coefficient of storage transmissivity and time, the Theis well function and other units are as before.

$$S = 4\ KD\ (t/r^2)u$$

$$= \frac{4\ KD\ tu}{r^2}$$

where t = time .... days.

The value of 'u' decreases as the length of pumping time 't' increases and for large values of 't' and for measurements close to the pumped well, or in the pumped well itself, the value of 'u' becomes negligible. Chow (1952) introduced a simplification of the classical Theis method which avoids the matching of plotted against type curves by the use of a log - log nomogram.

The plotting of drawdown 's' against the logarith of 't' is a straight line and if the asymtotic plot is extended to the intercept were 's' = O at time 't_o' the storage coefficient may be found from

$$s = \frac{2.25\ KD}{r^2}$$

in the simplified method of analysis introduced by Jacob (Cooper and Jacob 1946).

The substitution of 's' by 'Δ s', the drawdown difference per log cycle of time, permits the calculation of KD

$$KD = \frac{2.30\ Q}{4 \pi\ \Delta\ s}$$

where the units are as before. This method is limited in application as the value of 'r' should be small and those of 't' large. These methods have been applied to drawdown in the pumped well where adjacent piezometers were not available with the understanding that well losses may have had a substantial effect upon the data and therefore the under estimation of aquifer permeability and transmissivity values. The reduction of the value of 'u' to insignificant may occur within a matter of minutes for a confined aquifer but may take several hours of pumping for an unconfined aquifer. By the substitution of a corrected drawdown value 's′' for 's' to take into account the fact that, unlike the confined aquifer condition, water is being drawn from storage when an unconfined aquifer is pumped, the Thiem method for analysis may be used for both steady state and unsteady state conditions in unconfined aquifers. The Jacob simplified method may also be utilized for unsteady state conditions.

The corrections required to the drawdown values are obtained from

$$s' = s - \frac{s^2}{2D}$$

to compensate for the violation of the basic assumption that the thickness of the aquifer is constant which is caused by the dewatering of the cone of depression around the pumped well.

The sites where well-controlled tests could be undertaken were limited, and estimates of permeability, and therefore transmissivity, were obtained from the approximation methods proposed by Logan (1964) for other wells where confined aquifer steady-state conditions were assumed to exist. By using 'Q' (yield) 'r_w' (radius of the pumped well) and 'r_{max}' (radius of influence, i.e. to the outer-edge of the cone of depression) and 's_{max}' (the maximum drawdown in the pumped well), Logan reasoned that

$$KD = \frac{2.30\ Q \log\ r_{max} / r_w}{2 \pi\ s_{max}}$$

Again, well losses may have a profound effect upon the values of 's_{max}' which are used and the ratio of 'r_{max} / r_w' cannot properly be determined without the use of piezometers. While the ratio may be uncontrolled the logarithm of the ratio is relatively insensitive and, assuming typical radii conditions and a log ratio approximation of 3.33, the formula may be simplified to

$$KD = \frac{1.22\ Q}{s_{max}}$$

This method may also be applied to unconfined aquifer using the corrected drawdown method of

$$s'_{max} = s_{max} - \frac{s_{max}^{2}}{2D}$$

Logan also postulated that an approximation of K values for an aquifer may be based upon Specific Capacity data (yield per unit drawdown : $m^2.day^{-1}$) via the following formula

$$K = \frac{R\ C_s}{d}$$

where C_s = specific capacity ...... $m^2.day^{-1}$

R = constant varying between 1 and 1.5 and usually taken as 1.3

d = aquifer penetration ...... m

'KD' values for the aquifer may then be obtained by multiplication using the thickness 'D'. Again well losses lead to varying under estimation of the true aquifer horizontal permeability and transmissivity.

10.3.3 Tests of the Alat Formation Aquifer Unit

Aquifer Parameters

Test borehole P32 was drilled, cased and cemented specifically to permit the testing of the Alat aquifer in the southwestern area. Appropriate borehole data are given in Appendix 1.1 & 1.3. The water level data for the pumped well from the constant rate pumping are plotted as drawdown (normal) - time (log) on Figure 10.23 and the summary of analysis results are as follows:-

Table 10.3

Alat Aquifer Testing Results

	Permeability K(m.day^{-1})	Transmissivity KD(m^2.day^{-1})	Storage Coefficient S	Method
				Chow's Method
	15.45	156	16.2×10^{-4}	Log cycle 0.01 - 0.1 t (min)
	16.83	170	2.5×10^{-4}	0.1 - 1.0 t
	21.29	215	21.7×10^{-4}	100 - 1000 t
				Jacob's Method
	16.34	165	1.0×10^{-4}	Log cycle 0.01 - 0.1 t (min)
	30.89	312	7.3×10^{-4}	100 - 1000 t
Accepted Value	20	200	10×10^{-4}	

During the Shallow Water Well drilling programme (1963) the following data were generated and aquifer parameters have been calculated:-

Table 10.4

Shallow Water Well Project Tests Results

Well No.	Total depth (m)	Aquifer Cut Section (m)	Specific Capacity (m^2.day^{-1})	Perm (K) (Constant 1.3) (m.day^{-1})	Perm (K) (Constant 3.25) (m.day^{-1})	KD using (Constant 1.3) (m.day^{-1})	KD using (Constant 3.25) (m.day^{-1})
SWWI C16	22.6	7.7	1341	226	566	1740	4358
2 C17	31.1	14.3	DRY	-	-	-	-
3 C14	44.2	10.5	297	37	92	389	966
4 C15	35.7	14.9	80.5	7	18	104	1550
5 C13	29.0	24.4	559	30	74	732	1806
6 C11	35.1	18.3	19.7	1.4	3.5	26	476
7 C10	39.6	16.8	3.2	0.2	0.6	3.4	57
8 C12	79.2	18.3	8.9	0.6	1.6	11	201

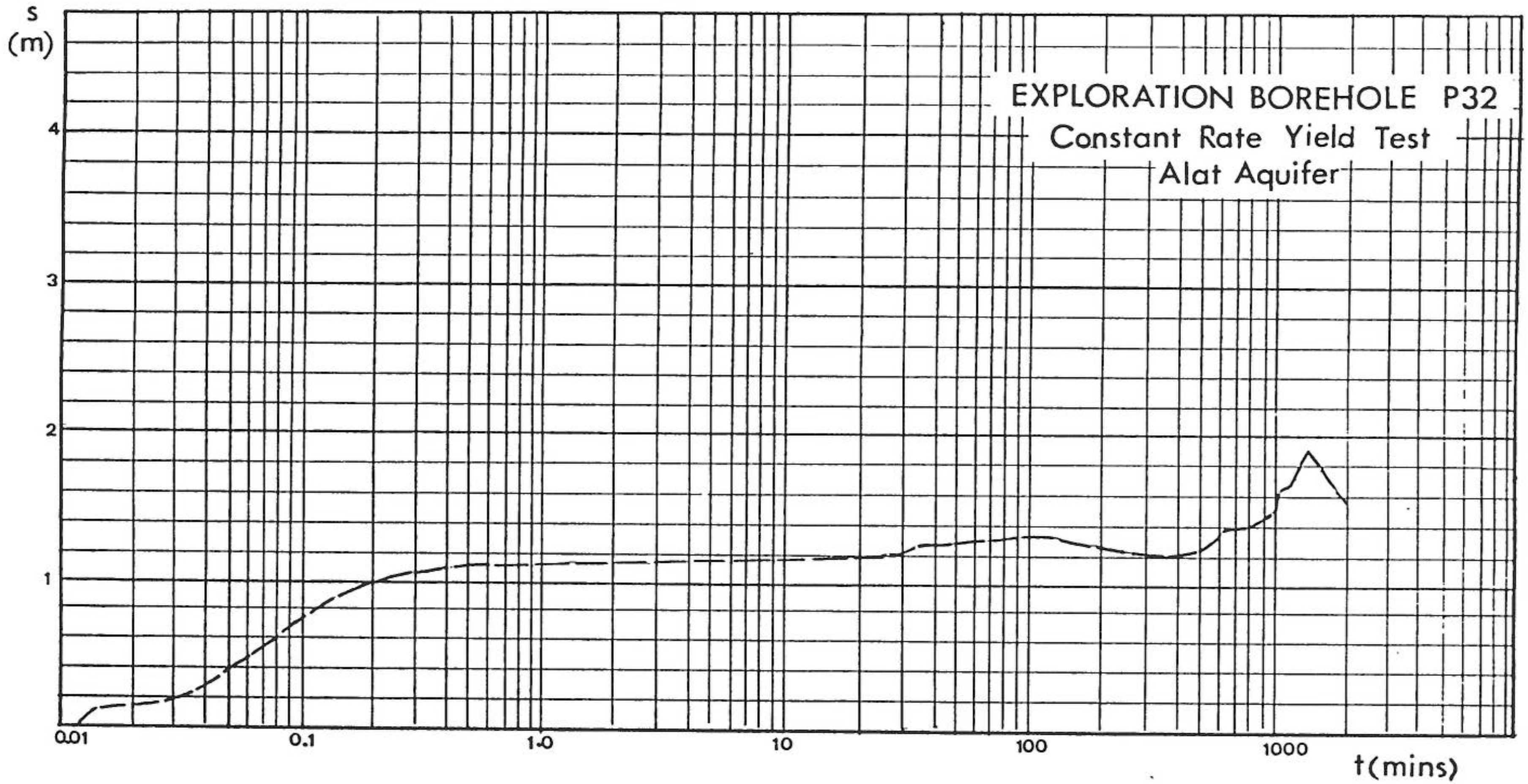

EXPLORATION BOREHOLE P32
Constant Rate Yield Test
Alat Aquifer
s (m)
4
3
2
1
0.01
0.1
1·0
10
100
1000
t (mins)

Fig:10.23

It would appear that the test pumping calculations of aquifer values fall within the range of values derived from specific capacity data and that, for the Alat aquifer, the generally accepted constant of 1.3 gives an appropriate approximation of transmissivity values. The constant 3.25 is one selected in 10.3.5 for combined Rus - Umm er Radhuma aquifer specific capacity data.

Studies in Saudi Arabia and Bahrain have indicated that the Alat is a granular aquifer wiht a vertically uniform permeability. Characteristics by transient data analysis for wells in the Saudi Arabia coastal belt area KD values of 150-250, K of 3.0 to 7.0 and a Storage Coefficient of 5.7×10^{-4} which compare with those of P32, indicating the horizontal homogeneity of the aquifer.

10.3.3.b Alat Aquifer Yield

Based upon the test results of P32, and the supporting evidence from Saudi Arabia the following average values may be selected:

Average Transmissivity (KD)	200 m^2 day^{-1}
Average horizontal permeability (K)	13 m. day^{-1}
Mean aquifer thickness (D)	15 m.

The piezometric slope between the outcrop area and Abu Samrah andalso between the Hofuf area of probable aquifer interconnection and Abu Samrah is :-

Mean groundwater gradient (i)	0.0015

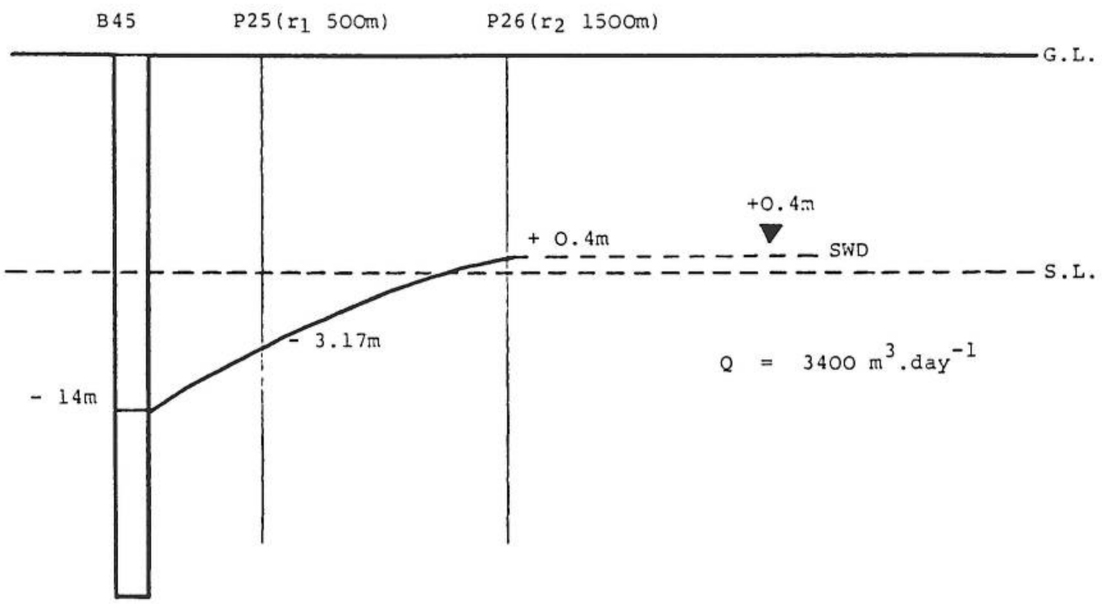
Assuming a flow front of 20 km length as the total available in Qatar then the throughput (Q) is approximately 6000 $m.^3 day^{-1}$ or 2.2 Mm^3 yr^{-1}.

However, the piezometric slope near the border may be much greater than the overall value. The reserves may not be calculated from the characteristics of the Alat aquifer alone as vertical transfer at points of aquifer interconnection may permit Umm er Radhuma water to flow northeastwards via the Alat conduit. If the present piezometric levels in the southwest of Qatar are drawdown by overpumping the throughput maybe increased by a steepening of the hydraulic gradient without greatly influencing the long term volume in storage.

10.3.4 Tests of the Rus Formation Aquifer Unit

Boreholes which penetrate the Rus aquifer only and are therefore suitable for the analysis of Rus hydraulic parameters, are limited. The majority of wellfield boreholes were sunk to 60 m which in almost all cases was fortuitously just short of the total thickness of the Rus in several scattered wellfields. These wells are constructed, closed and linked for production and testing has not been possible. However, at Rushaidah Wellfield, steady state conditions have developed over many years of regular extraction from the Rus only and exploratory wells P25 and P26 were drilled to investigate the lithological and hydraulic conditions which permitted the piezometric level to be reduced to - 14 m without a rise in salinity due to sea water intrusion. They were drilled at 500 m and 1500 m from the edge of the wellfield which may be taken as a single well of large diameter.

Given that steady state drawdown existed in an observation wellfield borehole, B45, (induced by pumping from adjacent wells but not from B45 itself) and using P25 and P26 as piezometers, then as depicted below:



two basic assumptions may be made.

<u>A</u> Assuming (1) that <u>P26</u> was not effected by pumping in the wellfield and

(2) that the Rus regional water level is therefore + 0.4 m. and

(3) the drawdown in B45 is typical of the wellfield and

(4) r_1 and r_2 are correct (with the uncertainty of where exactly the edge of the cone of depression lay) then drawdowns were as follows:-

water level B45 = - 13.95., s = 14.35 m.

water level P25 = - 3.17 m., s 2 3.57 m.

and water level P26 = + 0.40 m.

These values were taken at the time when both P25 and P26 were 36.6m deep and therefore not influenced by water from the Umm er Radhuma aquifer under ahigher head. Both piezometers are shallower at 36.6 m than the pumped wells around B45 at 61 m and therefore not of full aquifer penetration.

Using all combinations of r and s values, then

	r_1 m	r_2 m	s_1 m	s_2 m	KD $m^2.day^{-1}$
1	500	1500	3.57	0	167
2	0.15	500	14.35	3.57	407
3	0.15	1500	14.35	0	347

Because the assumptions that B45 is typical of the whole area of the wellfield and the cone of depression rises away from B45 and not from some point closer to or further from the first piezometer P25, cannot be sustantiated, the calculations are on indication only and therefore the lower value of 167 m^2/day is taken as typical as only the piezometers are involved and the uncertainties are eliminated.

B If it is assumed that P26 is affected by pumping in the Rushaydah wellfield and that the Rus regional water table is at + 3 m not + 0.4 m as indicated by P26 the calculation of KD provides the same value of 167.

The additon of Well No. 4, some 300 m from B45 and 200 from P25, (for which no record is now available) indicates that the wellfield boundary cone may be very steep.

Based upon Logan's Assessment Method, the values of KD are 300 or 350 $m^2.day^{-1}$ using either + 0.4 m or 3.0 as the static water level.

In Fig.10.25A the results of testing at P35, which lies just outside a well-defined depression, indicate the very low permeability values that may occur even in the Depositional Carbonate Facies area of the northern Groundwater Province. Aquifer properties of the Rus Formation in typical depression conditions in the Southern Groundwater Province, where generally aquifer values are poor, may on the other hand show localised areas of higher yield. Such a case is illustrated by the results of testing at the Sand Processing Plant carried out in two wells each with 3 piezometers.

The drawdown data for those tests are plotted as Figure 10.24 B and analysis, using the several combinations of pumped well and observation boreholes, for confined or semi-confined conditions has yielded:-

	WELL A	WELL C	
KD m^2 day^{-1} range:-	101-236	98-283	
mean:_	166	191	
Selected value:-	170	190	
Storage Coefficient, S range:-	-	$3.6x10^{-3}$	$4.x10^{-7}$
mean:-	-	$8.4x10^{-5}$	
Selected value:-	-	$8x10^{-5}$	

The transmissivity and storativity values for the Rus obtained from tests carried out by other investigators are given in Table

Rus Aquifer Tests

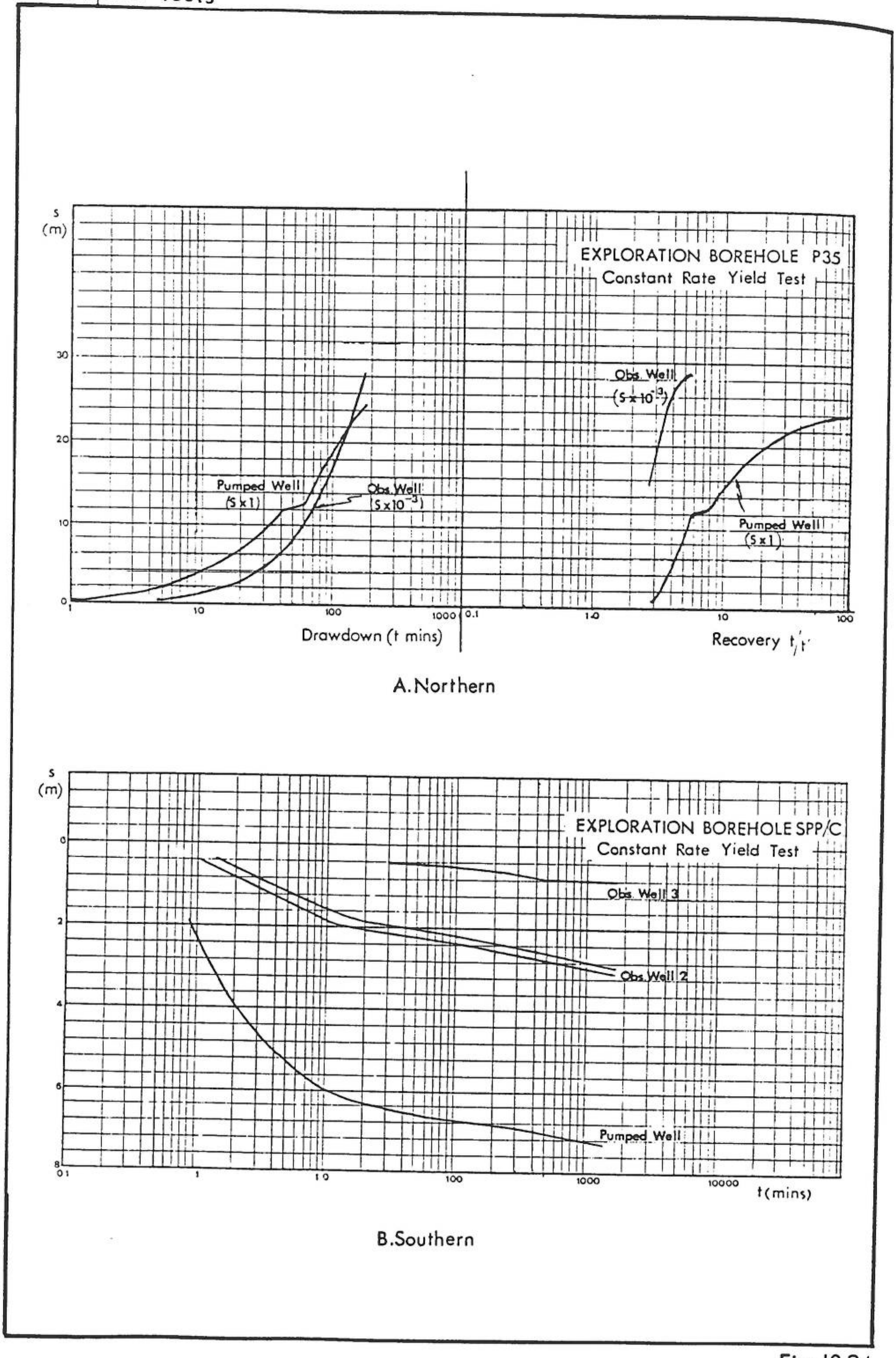


Fig: 10.24

Rus Aquifer Test Results

Well No.	Discharge $m^3.day^{-1}$	Specific Capacity $m^2.day^{-1}$	Transmissivity KD $m^2.day^{-1}$	Storage Coefficient S $(x10^{-4})$	Remarks
Wimpey 1	674	136	23	-	Pumped well only
2	674	129	26	-	" " "
Decca 1	112	-	2	-	" " "
3	968	-	37	-	" " "
P5	207	-	14	-	" " "
Al Utoriyah 75	43	-	48	0.4	Piezometer
74	43	-	97	0.4	Piezometer
76	43	-	63	-	Pumped Well
Al Rushayda 60a	95	-	35	7.7	Piezometer
71	95	-	60	1.2	"
61	95	-	166	3.9	"
48	95	-	150	2.1	"
60	95	-	44	-	Pumped well
Musaykah 2	683	-	228	0.1	Piezometer
3	683	-	714	8.6	"
4	683	-	380	0.8	"
- Combined	683	-	67	6.1	Distance/drawdown
A6	1702	555	480	-	
A12	605	195	140	-	
A30	605	125	82	-	
B3	294	452	380	-	
B5	363	227	170	-	
P15	156	195	140	-	
B17	389	54	31	-	
B23	66	12	-	-	
C1	112	400	310	-	
C4	225	96	60	-	
C6a	225	26	12	-	
Airport Reservoir Blending	1728	414	-	-	Coastal area
Ras Abu Fontas Blending	1728	1900	-	-	" "
Umm Said Blending	1728	250	-	-	" "

For comparison, GDC (198)) report the transmission values of Rus Formation boreholes in the centre and east of Bahrain island, where the lithology is equivalent to the Residual Sulphate Facies of Qatar, as follows:-

Table 10.6

Rus Aquifer Tests Results : Bahrain

Well No.	Total Depth (m)	Aquifer Penetration (m)	Yield ($m^3.day^{-1}$)	Draw down (m)	Specific Capacity $m^2 day^{-1}$	Trans missivity ($m^2.day^{-1}$)	Permeability ($m.day^{-1}$)
CWW30	146	31	5400	7.78	694	846	27
CWW45	140	35	4900	6.25	798	974	28
860/861	67	20	1780	0.86	2070	2525	126 *
882	104	52	650	7.31	90	110	2.1
925	49	33	1020	1.18	864	1050	32

NB The values were estimated by the Logan Method.

* It is likely that 860/861 penetrates the top of the Umm er Radhuma aquifer.

These values are higher than those found for the Rus aquifer in Qatar where, in summary, the full range and typical range values would appear to be :

Specific capacity	12-1900	100-500	$m^2.day^{-1}$
Permeability	6.1-70	20-30	m.day
Transmissivity	2-1000	100-500	$m^2.day^{-1}$
Storage Coefficient	$4x10^{-3}$ $4x10^{-7}$	$4x10^{-4}$	

10.3.5 Tests of the Umm er Radhuma Aquifer Unit

The very high potential yields of the Umm er Radhuma have made testing and analysis for hydraulic characteristics very difficult.

Borehole P27 was tested at a total depth of 70.71 m with an Umm er Radhuma cut section of only 1.91 m. Borehole and testing details are given in Appendix I.2 and the log drawdown to log time graph is presented as Figure 10.25. Analysis of the data has yielded the following results.

Table 10.7

P27 Combined Rus-Umm er Radhuma Aquifer Test

Permeability K $(m.day^{-1})$	Transmissivity $(m^2.day^{-1})$	Storage Coefficient	Method
1654	3160	-	Pumped well Jacob's Method
827	1580	-	Log cycle 2.5 - 25 t (min)
150	286	2.5×10^{-4}	25 - 250 t
1690	3227	5.2×10^{-4}	Pumped well; Recovery
1536	2934	3.2×10^{-4}	Observation well; Jacob
1334	2547	4.6×10^{-4}	Observation well; Chow
			Observation well; Theis/ Walton

The results of the tests may be used for comparative purposes only as the Rus and Umm er Radhuma aquiferous zones were linked in the pumped well but not in the piezometer and thus the drawdown in the piezometer would have been affected by the horizontal permeability of the Rus zone and the rate at which the head loss was sensed in that zone. However, as equilibrium conditions were reached and maintained and because there is agreement between one analysis from the pumped well data and others from the piezometer, the results are deemed acceptable.

At a total depth of 121.9 m., but before casing was installed and therefore with the Rus Formation and post-chert and pre-chert Umm er Radhuma aquiferous horizons connected, a maximum and stable drawdown of 1 m occurred within the first 1.5 minutes of pumping at an output of 9 lts. sec.$^{-1}$ and was constant for the 1440 minutes of pumping. The high yield zone of sub-chert Umm er Radhuma must therefore have a permeability several orders of magnitude higher than the other levels above, including the post-chert Umm er Radhuma.

When the Rus aquifer and the top, high yield, unit of the Umm er Radhuma were cased and cemented out to one metre below the chert horizon to investigate the sub-chert conditions, draw-down in the pumped well reached a maximum of 3.5 m at a yield of 5 lts. sec.$^{-1}$ within the first 30 seconds of pumping and then gradually reduced throughout the 2 day (2880 min.) test period to stand at 2.5 m at the end. No drawdown was detected in the Rus Formation water level measured outside the casing which lined the pumped well nor in a Rus Formation piezometer at a horizontal distance of 175.40 m.

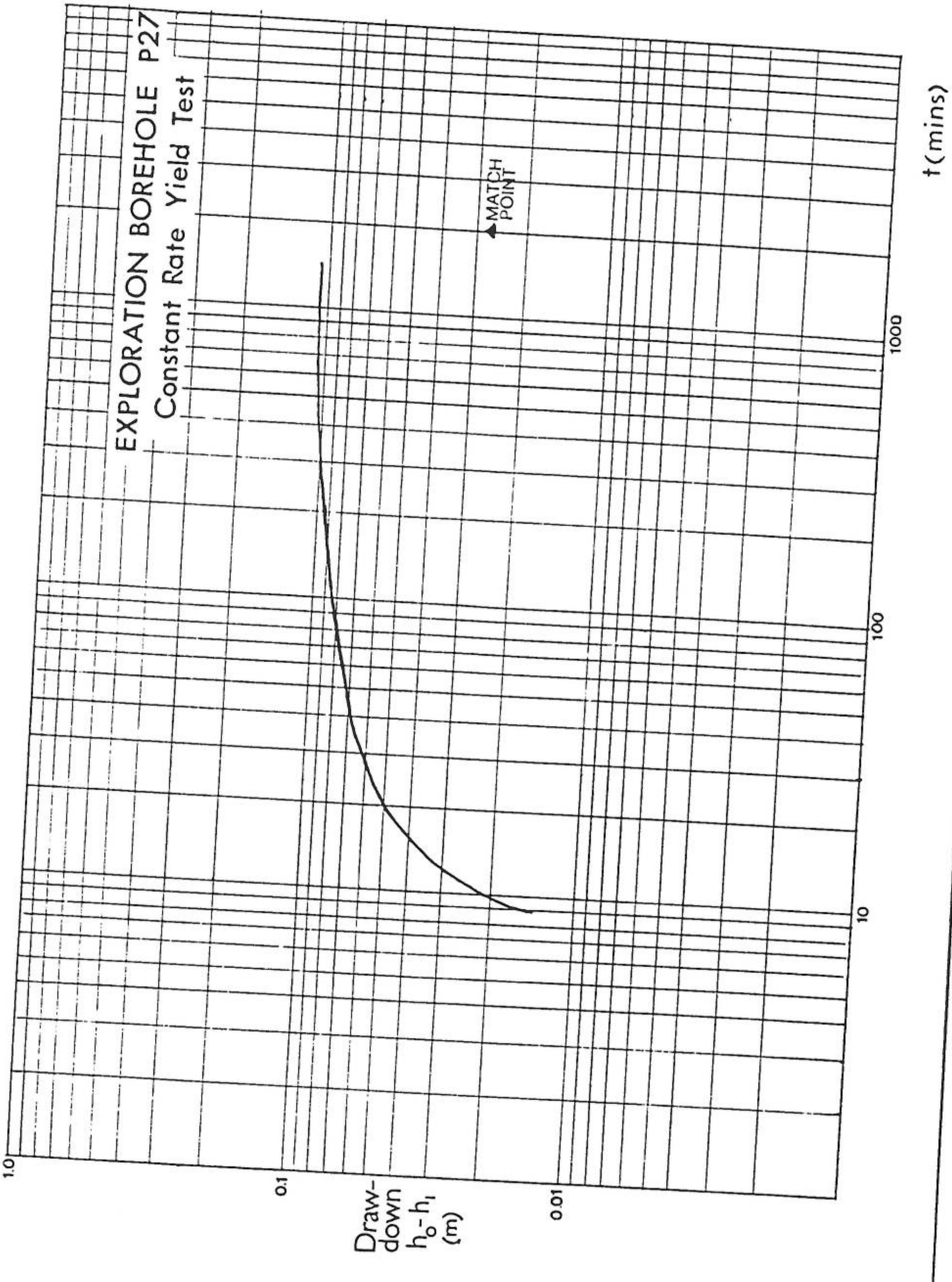

EXPLORATION BOREHOLE P27
Constant Rate Yield Test
MATCH POINT
t (mins)
10
100
1000
1.0
0.1
0.01
Draw-down h_o-h_1 (m)

Fig 10:25

The results of tests in other Project Rus - Umm er Radhuma aquifer boreholes are presented as Table

Table 10.8

Hydraulic Properties of Combined Rus - Umm er Radhuma Aquifers - Project Testing

Well No.	Transmissivity Range	(m^2 day^{-1}) Average	Permeability K (m day^{-1})	Storage Coefficient x 10^{-4}
I.D.T.C 1 - 4a	3 7 - 543	425	-	40
" 6a	-	587	-	40
" 6b	433 - 836	634	-	70
" 8a	-	1673	-	200
Govt. Farm RW2	-	3600	-	13
" " Obs Well	-	536	-	15
P 21	824 -1644	-	22 - 44	-

In boreholes where the Rus Formation contained little or no groundwater, the results of testing apply exclusively to the Umm er Radhuma aquifer. In others the Rus Formation water was excluded by casing. At P27 and P35 the upper part of the Umm er Radhuma aquifer was also cased out to investigate the conditions below. Notes of the results are given below the following Table 10.9

Table 10.9

Hydraulic Properties of Umm er Radhuma Aquifer from Project Pumping Tests

Well No.	Groundwater Province	Cut Section Thickness (m)	Transmissivity Estimates KD($m^2.day^{-1}$)	Permeability K($m.day^{-1}$)	Storage Coefficient S	Specific Capacity $m^2.day^{-1}$	Remarks
P 27	Northern	52.2	232	4.4	-	190	Upper part of Umm er Radhuma aquifer cased out see note.
P 29	Southern	60	673	11.2	-	690	See note
P33	Southern	4.8	1800-6700	375-1396	0.2×10^{-8}	2100	
P34	Southern	20	378-850	19-43	$1.26-1.77x10^{-8}$	206	
P35	Northern	20	233	-	-	-	Upper part of Umm er Radhuma aquifer cased out see note.
P35	Northern	54	2635	49	-	2160	
P21	Northern	33.9	8433	249	-	1728	See note
P36	Northern	3.6	485-520	135-144	-	96.5	

Notes:

P27 Peak drawdown of 3.5m at a yield of 475 $m^3.day^{-1}$ was reached after 0.5 mins of pumping. This declined to 2.5 m at the end of the 2880 min. test. Recovery to above the original static water level occurred within 0.5 min. of the pump being switched off. No analysis possible.Logan Estimate of KD etc., but low values indicate limitations of method.

P29 Peak drawdown of 1.25 m. at a yield of 864 $m^3.day^{-1}$ was reached within 1 minute and remained constant for the 300 minutes of the test. Water level returned to within 0.13 m of static levelafter 0.5 minutes of the recovery period and then oscillated as depicted on Figure 1027 No analysis possible, Logan Estimation of KD etc.

P35 With 54 m. of Umm er Radhuma cut section, the stable drawdown was 0.20m., for the 1340 mins. of pumping at a yield of 432 $m^3.day^{-1}$., following a one minute period of oscillation. The recovery was complete after a 2 minute period of oscillation above and below the static water level. No analysis possible. Logan Estimation of KD etc.

P21 Peak drawdown of 0.25 m at a yield of 432 $m^3.day^{-1}$ was reached after one minute of oscillation and then remained stable for the 2820 minutes of the test. Recovery was instantaneous. No analysis possible. Logan Estimation of KD etc.

Figures 10.26 and 10.27 illustrate the time-drawdown relationship for two Umm er Radhuma tests in the Southern Groundwater Province. In P34, Figure 10.26, the transmission value are such that the resultant curve may be analysed but in the case of P33, Figure 10.27, the aquifer characteristics would require a very high yielding pump to establish a meaningful and stable drawdown. Such aquifer conditions, which so far have not been subjected to analysis, were also found in P21, 27, 29 and P35.

Much information is also available on aquifer characteristics from specific capacity tests.

Table 10.10

Combined Rus-Umm er Radhuma Aquifers

Transmissivity Estimates from Specific Capacity Data - Northern Area

Well No.	Total Depth (m)	Aquifer Cut Section (m)	Specific Capacity ($m^2.day^{-1}$)	K Perm (Constant 1.3) ($m.day^{-1}$)	K Perm (Constant 3.25) ($m.day^{-1}$)	KD with (Constant 1.3) ($m^2 day^{-1}$)	KD with (Constant 3.25) ($m^2 day^{-1}$)	KD * ($m^2 day^{-1}$)
IDTC 1-2a	58.4	14.3	11.23	1.0	2.5	14.6	36.5	-
" 3a	58.0	15.0	18.14	1.6	4.0	23.6	59	-
" 4a	61.7	18.7	41.47	2.9	7.3	53.9	135	-
" 5a	60.6	18.6	54.43	3.8	9.5	70.8	177	425
" 6a	31.1	-	160.70	-	-	208.9	522	-
" 6b	58.0	16.0	194.4	15.8	39.5	253	632	587
" 8a	57.4	15.4	541.73	45.7	114.3	704	1760	634
" 9a	75.0	26.0	109.72	5.5	13.8	143	357	1673
A9	61.0	? 15	361	31	78	465	1170	-
A10	61.0	? 15	449	39	97	585	1455	-
A13	61.0	? 15	453	39	98	585	1470	-
B9	61.0	? 15	164	43	36	645	540	-
B22	56.7	? 15	51	4.4	11	66	165	-
B30	61.0	? 15	35	3.0	7.6	45	114	-
B31a	61.0	? 15	43	3.7	9.3	56	140	-
B33	61.0	? 15	820	71	178	1065	2670	-
B35	61.0	? 15	308	27	67	405	1005	-
B36	61.0	? 15	88	7.6	19	114	285	-
B43	61.0	? 15	368	32	80	480	1200	-

* KD values are from test pumping analysis given in Table

The average thickness of the yield zone of the Rus aquifer is 11 m and with a variable but shallow penetration of the Umm er Radhuma aquifer below the total aquifer cut section is a composite. The variations in yield of the upper metres of the Umm er Radhuma aquifer over a short horizontal distance is illustrated by the inverse relationship between specific capacity and aquifer cut section seen in Wells 8a and 9a.

The constant in the simple equation $KD = \frac{Q \text{ constant}}{sw}$ which is generally regarded as ranging from 1 to 1.5, may, in the case of wells 6a, 6b and 8a, be as high as 3.25 when the KD from high SC data is compared to KD by calculation.

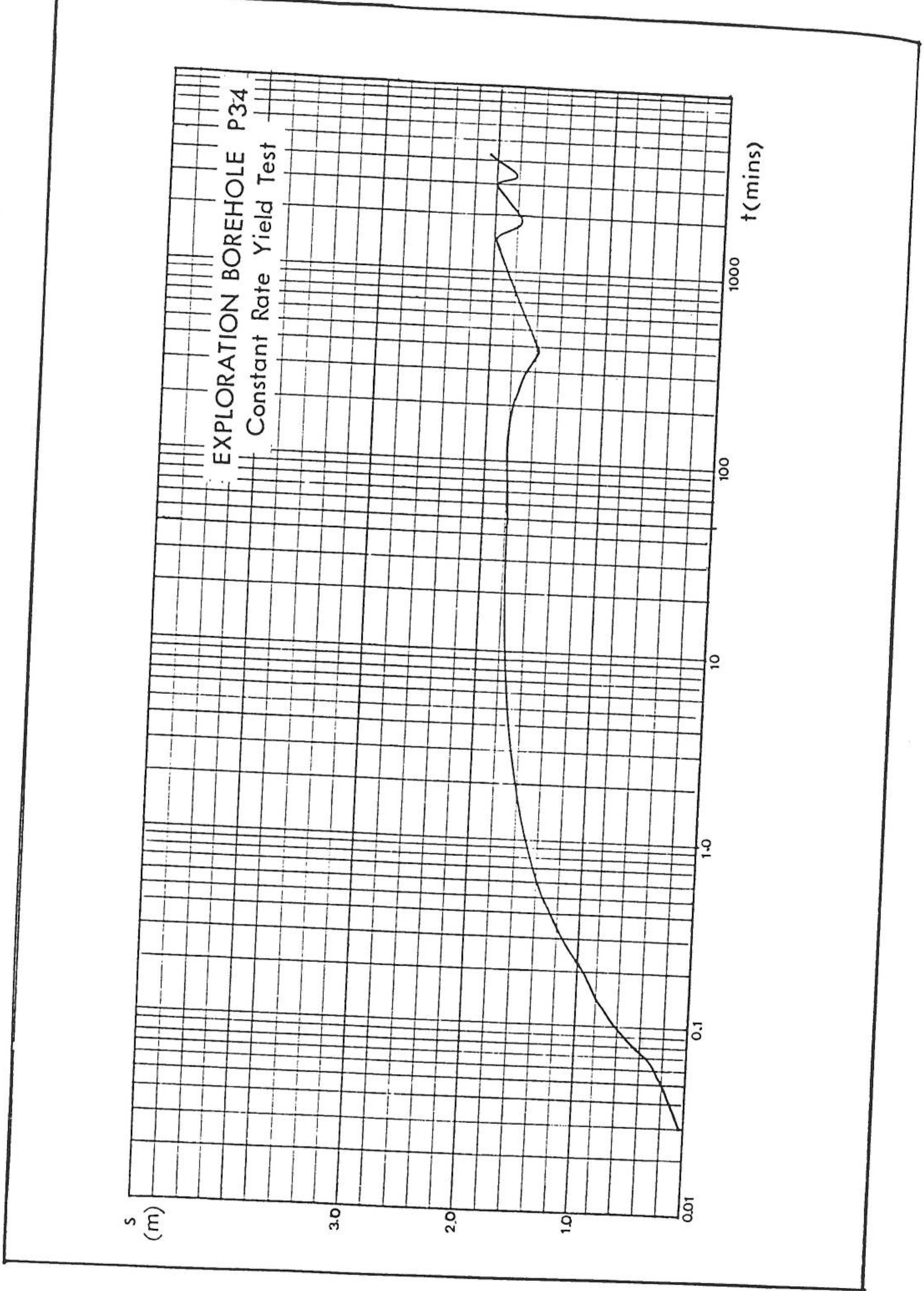

EXPLORATION BOREHOLE P34
Constant Rate Yield Test
t (mins)
1000
100
10
1.0
0.1
0.01
s (m)
3.0
2.0
1.0

Fig.10.26

Umm er Radhuma (S.W.) Aquifer Test

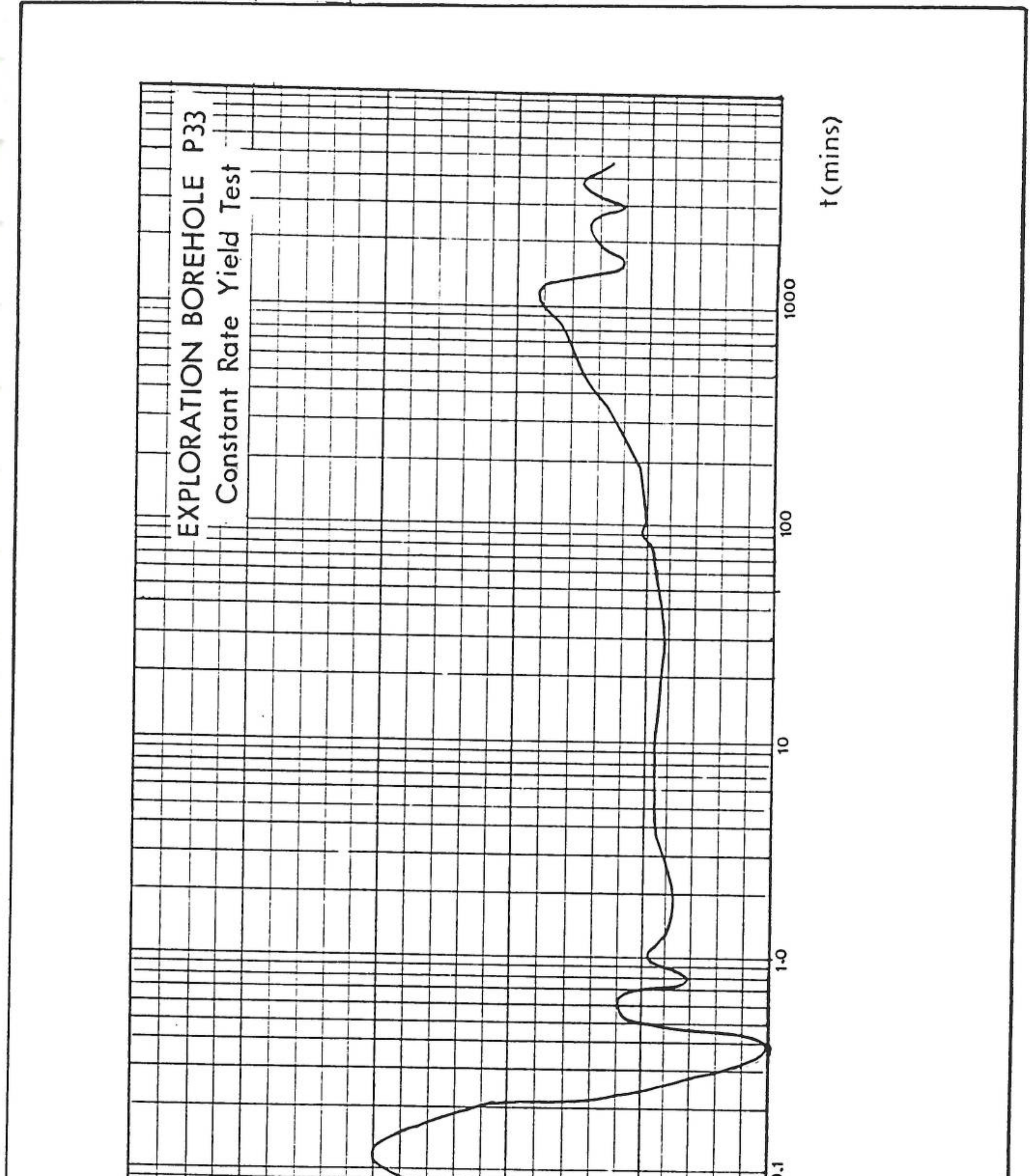


Fig: 10.27

Table 10.11

Combined Rus - Umm er Radhuma Aquifers

Transmissivity Estimates from Specific Capacity Data
Central and Southern Area

Well No.	Groundwater Province	Total Depth (m)	Aquifer Cut Section (m)	Specific Capacity ($m^2.day^{-1}$)	K Perm (Constant 1.3) ($m.day^{-1}$)	K Perm (Constant 3.25) ($m.day^{-1}$)	KD with (Constant 1.3) ($m^2 day^{-1}$)	KD with (Constant 3.25) ($m^2 day^{-1}$)
IDTC 2-2	Central	65.6	5	415	108	270	540	1350
" 4	"	55.4	5	432	112	281	560	1405
" 6	"	61.3	5	475	124	309	620	1545
" 7	"	56.0	5	320	83	208	415	1040
B39	"	61.0	? 5	40	10.4	26	52	130
B34b	"	61.0	? 5	209	54	136	270	680
B28	"	61.0	? 5	230	60	150	300	750
B21	"	61.0	? 5	50	13	33	65	165
B6	"	69.5	? 5	63	16	41	80	205
B7	South	61.0	? 5	140	36	91	180	455
B10	"	61.0	? 5	117	30	76	150	380
B12	"	61.0	? 5	579	151	376	755	1880
B14	"	61.0	? 5	1151	300	748	1500	3740
B18	"	61.0	? 5	819	213	532	1065	2660
B24	"	61.0	? 5	731	190	475	950	2375
B25	"	61.0	? 5	4490	1167	2918	5835	14590
B26	"	61.0	? 5	35	9.1	23	45,5	115
B27	"	61.0	? 5	848	220	551	1100	2755
B32b	"	61.0	? 5	484	126	315	630	1575
B43	"	61.0	? 5	368	96	239	480	1195

The first 4 wells extract water from the Umm er Radhuma below dry gypsiferous Rus Formation from a high yield zone about 5 m. thick. The cut section of the remainder is an estimation only.

Several groundwater studies carried out in Saudi Arabia have also reported the same very wide range in aquifer parameters for the Umm er Radhuma. Transmissivities from less than 10 to more than 50,000 $m^2.day^{-1}$ and storage coefficients of 10^{-4} to 10^{-5} for confined conditions and 10^{-2} to 10^{-3} for unconfined conditions. Permeability values also varied considerably from .001 to 400 $m^2.day^{-1}$ with an average of between 1 and 5.

For Bahrain Island tests the transmissivities also varied from 10 to 40000 $m^2.day^{-1}$, the storage coefficients from 1 to 3 x 10^{-4} and horizontal permeabilities from less than 1 to more than 500 $m.day^{-1}$.

Problems of analysis of the unusual drawdown-time relationships exhibited by the Umm er Radhuma tests and the very wide range of all calculations preclude the selection of mean values for the aquifer and also the accurate prediction of areal variations in storage and reserves.

XI

WATER QUALITY

11.1 WATER QUALITY FOR IRRIGATION

Groundwater intended for irrigation must be assessed in relation to the soil type, crops and the climate and for this reason there is no uniform water quality classification for agriculture. In setting local standards of water quality the chemical characteristics of the irrigation waters and the soils to which they are to be applied are therefore of primary importance. The most important characteristics of irrigation water are;

- Total concentration of dissolved salts or salinity
- Concentration of sodium relative to other cations
- Anionic composition of the water, especially the concentration of bicarbonate and carbonate anions
- Concentration of boron or other elements that may be toxic to plant growth
- Concentration of calcium and sulphate ions.

11.1.1 Total Salt Concentration

The effect of salt on crop growth is believed to be largely of an osmotic nature which is related to the total salt concentration rather than the concentration of individual ionic species. The total salt concentration is reported as total dissolved solids (TDS) in mg/l values or as electrical conductivity (EC) in the basic unit $mho.m^{-1}$. The revised internationally agreed standard is now in SI units as Seimens/meter ($S.m^{-1}$) at 25°C. However, to avoid confusion in the interpretation of the large volume of data available, the well-known term specific conductance (which is the electric conductance of a one centimetre cube of a substance), expressed in thousandths of mhos or mmhos (to avoid inconvenient decimals and according to the standard practices for soil and soil water analyses) is retained for this report. There is a variable relationship between TDS and EC but for a mixture of salts in the range up to 10.0 $mmhos.cm^{-3}$ there is a linear relationship, which for Qatar has been determined as

$$TDS\ (mg/l) = 0.81\ EC(\mu mhos.cm^{-3}) - 39.43 \quad \text{.......Eq. 11.1}$$

with an coefficient of determination of 0.98 (See Chapter 8.4 & 3). Because of the wealth of existing data, expressed as conductivity which is parameter that may easily be measured in the field with a portable EC meter, EC have been used as the basis of the water salinity classification.

Fig. 8.5 (Chapter VIII) shows the electrical conductivity of groundwater in Qatar and refers to the mixture of Rus Formation and Upper Umm er Radhuma Formation waters. As a general guide for the heavy calcareous soils of northern Qatar, the satisfactory upper limit is of the order of EC 2.3 mmhos through, with decreasing crop yields, up to EC 3.5 is tolerable; beyond this soil salinity problems become increasingly apparent. For the sandy unconsolidated dune sands of south west Qatar the upper limits are considerably increased to a limit of approximately EC 6.0 with a probable upper unsatisfactory limit of EC 10.0 although agricultural trials have yet to fully substantiate this. The above limits are based on actual field data from Qatar and this experience confirms the findings of Bernstein (1974,1976), Maas and Hoffman (1977) and Meiri and Shalhevet (in Yaron et al, 1973) that the salt tolerance standards recommended by the US Salinity Laboratory staff (Richards, 1954), and in common use today, require re-evaluation and adjustment. Generally, therefore groundwater in the northern and central part of Qatar is satisfactory for irrigation but the waters from the upper Umm er Radhuma and partly from the Rus elsewhere in Qatar are marginal for sustained crop production as evidenced by the low level of farming activity in southern Qatar even where sufficient water has been discovered.

In south-west Qatar the higher salinity waters of the Alat Formation (EC 5.0-6.0) are at present being utilized to produce high yields of fodder and field crops at the Project experimental farm at Wadi el Araig on normally sterile and partly unconsolidated sands. These waters do however have some special features of importance to irrigation. Firstly, they show a high nitrate (NO_3) concentration in the range 20 to 30 mg/l in contrast to concentration of less than 20 mg/l found in the groundwater of the Rus and Umm er Radhuma aquifer of north central Qatar. This may therefore explain these high experimental yields of forage and field crops. These waters also show a very high chloride concentration, ranging from 1200 to 1600 mg/l compared to less than 500 g/l over most of central Qatar, which is certainly responsible for the excessive rate of corrosion in aluminium sprinkler irrigation pipes. As future irrigation of this area will probably be based on sprinkler systems pipe work will have to be of a different material.

11.1.2 Sodium Hazard

The absolute concentration values of the various cations in irrigation water are however, insufficient for estimating potential hazards and an important consideration is the extent to which the exchangeable sodium percentage (ESP) of the soil will increase as a result of adsorption of sodium from the irrigation water. This increase, depends on the radio of soluble sodium to the divalent cations in solution; the higher the ratio, the higher the hazard.

For the purpose of assessing the danger of cation exchange in soils with a significant proportion of clay, the sodium hazard is usually expressed in terms of the sodium adsorption ratio (SAR) given by

$$SAR = \frac{Na^{+}}{\sqrt{\frac{Ca^{++} + Mg^{++}}{2}}} \qquad \text{............ Eq. 11.2}$$

where the ionic concentrations are expressed in meq/l.

SAR values of irrigation water in Qatar (Fig. 11.1) have been calculated for all wells and, as is to be expected, the lowest values are those found in the northern central recharge zone. In general, however, the hazard increases towards the coast in all directions except in the coastal regions of the south-west where the groundwater is confined within the Alat Formation. Waters with SAR values in excess of 8 may cause a reduction in soil permeability as the calcium ions absorbed on the clay particles are replaced by sodium ions, although, in areas where gypsum is present within the soil, this will tend to neutralize the effect of any sodium excess in the irrigation water. This is particularly relevant to the unconsolidated sands of the south-west where the SAR is high (7.0-7.5) but where there is considerable gypsum within the sands.

It should, however, be noted that the SAR of irrigation water is a measure of its sodicity hazards provided it can be related to the resultant SAR of the equilibrated soil water. The concentration of the soil solution is increased by root water uptake and by evaporation. Depending on the frequency of irrigation, and the amount of water applied, the concentration of the water drained from the root zone may be two to ten times that of the irrigation water. However, the average concentration of the soil solution in the main root zone is not normally more than two to three times that of the irrigation water (See Table 11.11).

11.1.3 Bicarbonate Hazard

A major factor affecting the final SAR value of soil water is the change in calcium and magnesium concentration due to precipitation or dissolution of alkaline earth carbonates. In irrigation waters containing a high concentration of bicarbonate ions, there is a tendency for calcium and, to a lesser extent, magnesium to precipitate in the form of carbonate as the soil solution becomes more concentrated, thus leading to an increase in the SAR of the soil solution and consequently to an increase in the exchangeable sodium percentage (ESP) of the soil and a reduction in permeability.

By assuming that all calcium and magnesium would precipitate as carbonates, Eaton (1950) proposed the concept of residual sodium carbonate (RSC) as derived from the following equation;

$$RSC = (HCO_3^- + CO_3^{--}) - (Ca^{++} + Mg^{++}) \qquad \text{.......(Eq. 11.3)}$$

ere all ionic concentrations are expressed in terms of milliequivalent per litre (meq/l).

In Qatar the concentration of calcium and magnesium invariably exceeds the bicarbonate and rbonate concentration except in three sampled wells (A19, B22, B42a) located along the central ch. Bicarbonate concentrations elsewhere are all within the range 2.5 - 7.0 meq/l with a median value of 3.5 meq/l despite a wide range of total salinity values. By Eq. 11.3 there would pear to be little bicarbonate hazard in Qatar's groundwater.

However, even though the concept of residual sodium carbonate is widely used in water quality work it has not in practice proved to be very useful, mainly because of the assumption quantitative precipitation. Shainberg and Oster (1978) contend that a better estimate of the precipitation tendency of carbonates is provided by the so-called "Saturation Index" (SI). Bower et al (1965, 1968) proposed the use of Langelier's Saturation Index to estimate carbonate cipitation from irrigation water as a function of the degree of $CaCO_3$ saturation of the soil solution. The index as applied to soil is :

$$SI = (8.4 - pH_c^*) \qquad \text{.......(Eq. 11.4)}$$

here 8.4 is the approximate pH of a nonsodic saline soil in equilibrium with $CaCO_3$, and is stituted for the pH of the water as originally proposed by Langelier. This substitution ects the high buffering effect of calcareous soils. The pH_c^* is defined by

$$pH_c^* = (pK_2 - pK_{sp}) + p(Ca + Mg) + p(CO_3 + HCO_3) \qquad \text{.......(Eq. 11.5)}$$

ere p(Ca + Mg) is the negative logarithm of the molar concentration of Ca + Mg; $p(CO_3 + HCO_3)$ he negative logarithms of the second dissociation constant of H_2CO_3 and the solubility uct of $CaCO_3$, respectively, both corrected for ionic strength. The prediction equation for changeable sodium, for adjusted SAR values (SAR_{adj}) as given by Bower et al (1968) is

$$ESP = SAR_{adj} = SAR_{iw} [1.0 + (8.4 - pH_c^*)] \qquad \text{........(Eq. 11.6)}$$

Eq. 11.6 is the recommended equation for estimating the increased sodium hazard and places Eq. 11.3. Increasing problems in soil salinity and permeability become apparent at lues of between 6.0 and 9.0 with severe problems becoming apparent beyond this threshold. j values have been computed for some 76 wells in Qatar, the distribution of which is seen losely follow that of SAR values although the proportional increase is higher in the northern ion than the south.

4 Calcium and Sulphate Ion Concentrations

The calcium and sulphate ion concentrations in groundwater are not generally considered to teria in the determination of the quality of irrigation water but calcium sulphate (gypsum) often found in large quantities in certain soils of Qatar. In particular, the sandy soils plateau area and the unconsolidated dune sands of south west Qatar are both examples of ype of soil and where future agricultural development is planned.

If gypsum is in a crystalline form, the crystal mesh maintains a permeable soil structure order to preserve this the gypsum saturation index of the irrigation water needs to be n in account. Gypsum saturation indices have been calculated for all sampled wells in Qatar the distribution shown in Fig. 8.19. The lower salinity waters of northern Qatar is usually aturated with respect to gypsum but the moderate quality waters are usually saturated, at 2500 mg/l. Thus, excessive application of low salinity ...

For the two cases mentioned above, the Al Ashara area is to be developed and irrigated with treated sewage effluent water from Doha which is desalinised water in origin with accretion of sodium chloride and undersaturated in gypsum. Unless adequately amended, this water could pose problems to soil structure. In the case of Wadi el Araig in SW Qatar, a similar situation arises as these groundwaters derive from the Alat aquifer and are also undersaturated with respect to gypsum whereas the unconsolidated dune sands at present being developed for agriculture do contain significant amounts of gypsum. As these sands are however loose and structureless the problem of collapse following solution is not potentially serious.

11.1.5 Specific Ion Toxicity

There are several important trace elements required by plants for healthy growth and these may be found in either the soil or irrigation water. In most cases the quantity required is very small but under certain circumstances excessive concentrations may be harmful to both crop growth and to humans. The most common problem is the occurrence of boron in groundwater, although in recent years some concern has also been expressed over the occurrence of heavy metals, particularly cadmium, in the Doha sewage effluent waters which are to be utilized for irrigation.

Boron has been determined for all groundwater samples and the distribution of its concentration shown in Fig. 11.1 Plant species vary in their boron requirements and in their tolerance to excess and Table 11.1 shows limits of boron in irrigation waters derived from Shainberg and Oster (1978).

Table 11.1

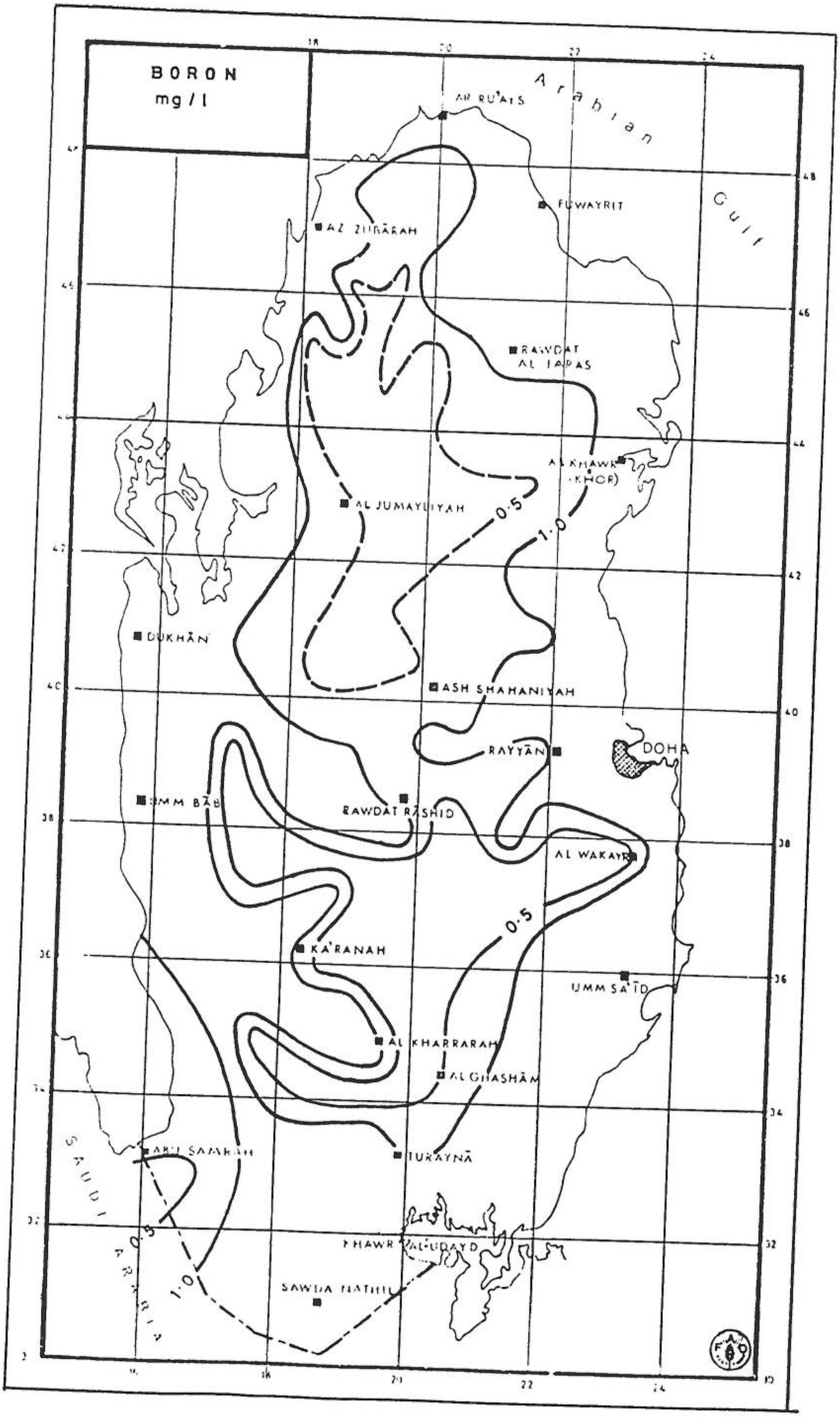
Limits of Boron in Irrigation Waters

Sensitive 0.3-1 mg/l Boron	Semi-tolerant 1-2 mg/l Boron	Tolerant 2-4 mg/l Boron
Citrus	Lima bean	Carrot
Apricot	Sweet potato	Lettuce
Peach	Pepper	Cabbage
Cherry	Oat	Turnip
Fig	Milo	Onion
Grape	Corn	Broad bean
Navy bean	Wheat	Alfalfa
Jerusalem artichoke	Barley	Garden beet
	Olive	Mangel
	Field pea	Sugar beet
	Radish	Palm
	Tomato	Asparagus
	Potato	
	Sunflower	

In each group the crops are arranged in descending order of tolerance within the range indicated.

Source :- Shainberg and Oster (1978)

The areas of lowest boron concentration coincide with the northern recharge zone and in south central Qatar. There is a close correlation between salinity and boron concentration and, in the higher salinity areas, (particularly in the agricultural areas of eastern Qatar), boron levels are in excess 1.5 mg/l. It should be noted that citrus is sensitive to boron at very low concentrations, yet citrus trees are being grown in areas of eastern Qatar where the levels are well in excess of the suggested limits.



BORON CONCENTRATION IN GROUNDWATER

Dissolved iron is not present in the natural groundwater but is often present in the discharge from wells by corrosion of the well casing and other equipment. Dissolved iron in well discharge is in the ferrous state which, upon exposure to the atmospheric oxygen, precipitates as ferric hydroxide. Water containing appreciable amounts of ferrous hydroxide may effect irrigation methods, crop growth and quality and in particular cause clogging of drip-irrigation nozzles. Other heavy metals have not been detected in Qatar groundwater but significant amount of zinc and iron have been detected in Doha sewage effluent water. These metals are thought to be derived from galvanized roof storage tanks which, though subjected to corrosion by the alkaline distillate from sea water, are a common feature of every household in Doha. Two samples of re-cycled garbage compost, washed with treated sewage effluent, revealed excessive concentrations of cadmium though further monitoring since has failed to confirm this hazard.

As treated sewage effluent will be utilized for irrigation it is essential that these waters be analysed for soluble noxious trace elements and heavy metals. Table 11.2 shows recommended levels prepared by the United States Committee on Water Quality (Branson et al, 1975).

Table 11.2

Recommended maximum concentrations of trace elements in irrigation water[1]

Elements	For waters used continuously on all soil mg/l	For use up to 20 yrs. on fine-textured soils at pH 6.0 to 8.5 mg/l
Aluminium	5.0	20.0
Arsenic	0.10	2.0
Beryllium	0.10	0.50
Boron	0.75	2.0 - 10.0
Cadmium	0.010	0.050
Chromium	0.10	1.0
Cobalt	0.050	5.0
Copper	0.20	5.00
Fluorine	1.0	15.0
Iron	5.0	20.0
Lead	5.0	10.0
Lithium	2.5	2.5[2]
Manganese	0.20	10.0
Molybdenum	0.010	0.050
Nickel	0.20	2.0
Selenium	0.020	0.020
Vanadium	0.10	1.0
Zinc	2.0	10.0

1. These levels will not normally have an adverse effect on plants or soils. No data available for mercury, silver, tin, titanium, tungsten.
2. Recommended maximum concentration for citrus is 0.75 mg/l.

Source :- Branson, R.L., Pratt, P.F. Rhoades J.P. and Oster J.D. (1975) Water Quality in Irrigated Watersheds J. Environment Quality 4:33-40.

11.1.6 Crop Growth and Salinity

Maas and Hoffman (1977) concluded, from an extensive review of salt tolerance data, that crop yield is not affected until a threshold salinity level is exceeded, beyond which the yield decreases. The salt tolerance values given in Table 11.3 have been calculated from the data of Maas and Hoffman (1977) and have been expressed according to the weighted average concept of Ayers and Branson (1975). Plant yields are largely determined by salinity levels in the upper part of the root zone which accounts for 2/3 of the water uptake. Through this depth increment the irrigation water is assumed to concentrate threefold. Plant response to salinity also depends on such plant factors as stage of growth, variety and rootstock, on soil factors such as fertility, water content and aeration, and on climate.

Salinity effects in many crops depend mainly on the length of time plants are exposed to salinity regardless of the specific stage of growth (Shalhevet, 1970). Some other plants, however, are more sensitive at specific stages of growth, particularly in the case of cereals (Bernstein, 1974; Maas and Hoffman, 1977). Barley, wheat and maize are most sensitive during the early seedling stage. However, localized high salt concentrations at seedling root depth, rather than a specific sensitivity, may be the immediate cause of germination failure, which is common in saline soils. Bernstein (1974) suggests a maximum permissible soil salinity of about EC 8.0 during the salt-sensitive state of growth. The salt tolerance data in Table 11.3 were obtained from salinity treatments given after seedling establishment in nonsaline plots, so they do not necessarily apply to the germination and early seedling stages.

Table 11.3

SALT TOLERANCE OF AGRICULTURAL CROPS

Yield Decrease to be Expected due to Salinity of Irrigation Water

(after Maas and Hoffman, 1977)

Crop	Yield Decrement 0%			10%			25%			
	EC_e [2]	EC_{iw} [3]	LR [4]	EC_e	EC_{iw}	LR	EC_e	EC_{iw}	LR	EC_d [5]
Fruit Crops										
Date	4.0	2.7	4	6.8	4.5	7	11	7.3	12	64
Orange	1.7	1.1	7	2.3	1.6	10	3	2.2	14	16
Grape	1.5	1.0	4	2.5	1.7	7	4	2.7	12	24
Vegetable Crops										
Beet	4.0	2.7	9	5.1	3.4	11	7	4.5	15	30
Broccoli	2.8	1.9	7	3.9	2.6	10	6	3.7	14	27
Cucumber	2.5	1.7	8	3.3	2.2	11	4	2.9	15	20
Tomato	2.5	1.7	7	3.5	2.3	9	5	3.4	13	25
Cabbage	1.8	1.2	5	2.8	1.9	8	4	2.9	12	24
Potato	1.7	1.1	6	2.5	1.7	8	4	2.5	13	20
Sweet Corn	1.7	1.1	6	2.5	1.7	8	4	2.5	13	20
Pepper	1.5	1.0	6	2.2	1.5	9	3	2.2	13	17
Lettuce	1.3	0.9	5	2.1	1.4	8	3	2.1	12	18
Onion	1.2	0.8	5	1.8	1.2	8	3	1.8	12	15
Radish	1.2	0.8	5	2.0	1.3	7	3	2.1	12	18
Carrot	1.0	0.7	4	1.7	1.1	7	3	1.9	11	16
Forage Crops										
Bermudagrass	6.9	4.6	10	8.5	5.6	13	11	7.2	16	45
Barley	6.0	4.0	10	7.4	4.9	12	10	6.3	16	40
Tall fescue	3.9	2.6	6	5.8	3.9	9	9	5.7	13	46
Sudangrass	2.8	1.9	4	5.1	3.4	7	9	5.7	11	52
Alfalfa	2.0	1.3	4	3.4	2.2	7	5	3.6	12	31
Berseem Clover	1.5	1.0	3	3.3	2.2	6	6	3.9	10	38
Field Crops										
Barley	8.0	5.3	10	10.0	6.7	12	13	8.7	11	56
Sugarbeet	7.0	4.7	10	8.7	5.8	12	11	7.5	16	48
Wheat	6.0	4.0	10	7.4	4.9	12	10	6.3	16	40
Peanut	3.2	2.1	16	3.5	2.4	18	4	2.7	20	13
Sesbania	2.3	1.5	5	3.7	2.5	8	6	3.9	12	33
Corn (grain)	1.7	1.1	6	2.5	1.7	8	4	2.5	13	20

1. After Maas and Hoffman (1977).
2. EC_e is the electrical conductivity of the saturation extract (mmho/cm at 25°C) in the root zone where about two-thirds of the water uptake occurs. For 0% yield reduction, EC_e is the threshold salinity at which yield is expected to begin to decline.
3. EC_{iw} is the electrical conductivity of the irrigation water and was calculated from EC_e according to the expression $3EC_{iw} = 2EC_e$; the irrigation water is concentrated threefold in the root zone, which is equal to two times EC_e.
4. Leaching requirement is calculated from Eq. (V.4).
5. EC_d is the maximum electrical conductivity that can develop due to water uptake by the crop. At this EC, crop growth ceases.

11.2 WATER QUALITY FOR DOMESTIC USE

According to international standards, proposed by F.A.O., (Table 11.4) suitable groundwater for domestic consumption is found only in the northern recharge zone containing waters of less than 1500 mg/l or EC 1.9 (see Fig. 8.3). Elsewhere, groundwater should not be supplied directly to the consumer and in particular in those areas of central and southern Qatar where magnesium exceeds 30 mg/l in waters and where the sulphate concentration is in excess of 250 mg/l. While these standards tend to err on the safe side as criteria for the design of domestic water undertakings, in practice there is a wide range of TDS values in some remote rural drinking water supplies. For most rural communities, however, low salinity water for domestic use is available either by pipeline or by tanker distribution.

Table 11.4

Drinking Water Standards

Chemical Constituent	Concentration (mg/l)				
	WHO International (1958)			WHO European (1961)	
	Permissible limit	Excessive limit	Maximum allowable	Recommended limit	Tolerance limit
Ammonia (NH_4)	–	–	–	0.5	–
Arsenic	–	–	0.2	–	0.2
Cadmium	–	–	–	–	0.05
Calcium	75	200	–	–	–
Chloride	200	600	–	350	–
Chromium (hexavalent)	–	–	0.05	–	0.05
Copper	1.0	1.5	–	3.0[1]	–
Cyanide	–	–	0.01	–	0.01
Flouride	–	–	–	1.5	–
Iron	0.3	1.0	–	0.1	–
Lead	–	–	0.1	–	0.1
Magnesium	50	150	–	125[2]	–
Magnesium + Sodium Sulphates	500	1000	–	–	–
Manganese	0.1	0.5	–	0.1	–
Nitrate (as NO_3)	–	–	–	50	–
Oxygen, dissolved (minimum)	–	–	–	5.0	–
Phenolic compounds (as phenols)	0.001	0.002	–	0.001	–
Selenium	–	–	0.05	–	0.05
Sulphate	200	400	–	250	–
Total solids	500	1500	–	–	–
Zinc	5.0	15	–	5.0	–

1 After 16 h contact with new pipes; but water entering a distribution system should have less than 0.05 mg/l of copper.

2 If there are 250 mg/l of sulphate present, magnesium should not exceed 30 mg/l.

Source :- International Source Book on Irrigation and Drainage of Arid Lands. FAO, Unesco. Paris, 1967.

In recent years the Qatar Ministry of Health have become increasingly concerned regarding the absence of fluoride in desalinised water and, on the other hand, its excessive concentration in groundwater in certain areas. Fluoride in small quantities (less than 1 mg/l) has been shown to be beneficial in the prevention of dental caries in humans. However, fluoride in larger concentrations and with prolonged consumption may be harmful and cause mottling of the teeth with crippling decalcification of the bones at very high concentrations. The average maximum daily air temperature is frequently used as a guide in defining the maximum recommended concentration as people in hotter climates tend to consume more water. The United States Senate,(1975) has defined the following limits.

Average Maximum Daily Air Temperature	Maximum Recommended Fluoride Concentration (mg/l)
12 and below	2.4
12.1 - 14.6	2.2
14.7 - 17.6	2.0
17.7 - 21.4	1.8
21.5 - 26.2	1.6
26.3 - 32.5	1.4

Fig. 8.25 shows the fluoride concentration determined by the Project from regular groundwater sampling from which it will be seen that the limit of fluoride recommended for Qatar (1.4 mg/l) is not exceeded over most the northern recharge zone. However, in the central area to the west of Doha and in some wells tappling the Alat aquifer in SW Qatar this limit is exceeded.

11.3 GROUNDWATER POLLUTION

With increasing development in both the urban and rural sectors, pollution of groundwater has become a distinct probability and early signs of this are already apparent. In the agricultural sector all irrigation is presently supported by groundwater pumped at the site where it is used within the farms located within depressions. These are also the focii of storm water run-off and indirect recharge, and irrigation return, infiltration also takes place near the production wells. Various salts precipitated on the surface due to evaporation are therefore leached downwards to the aquifer and in some cases, such as on government experimental farms, there has been an significant increase in nitrate derived from nitrogenous fertilizers.

In Doha, freshwater bodies are now accumulating over the normally saline groundwater, which has a TDS in excess of(10,000 mg/l) and are clearly derived from leaking freshwater mains, garden irrigation return and from sewers. A flow of fresh water encountered in 1978 in an excavation near the sea shore at the Qatar National Museum was found to be highly contaminated by E. coli and it is possible that the high quality water being recharged to the aquifer is being contaminated by sewage effluent.

The widespread pollution of Qatar's inshore areas and coast line from an offshore oilwell accident in late 1980 also posed problems in the disposal of oil deposits from beaches. The Project was called upon to advise on this problem at the time and clearly there is an ever-present danger of the recurrence of such episodes. Not only does this pose a serious hazard to the desalinisation works but the uncontrolled disposal of residues on land could introduce toxic substances into the groundwater system.

11.4 HEALTH HAZARDS OF SEWAGE EFFLUENT UTILIZATION

Proposals for the use of Doha sewage effluent for irrigation at Al-Ashara on central Qatar have been accepted and construction of the engineering works is expected to commence in 1981 (See Chapter XV). The re-use of this water does however pose potential health hazards and it is essential that these be known and precautionary measures instituted. The major components of the waste-water collected by the existing Doha sewage system is domestic effluent. Industrial or trade wastes are not considered to contribute significantly to the chemical or bacterial composition of the effluent in the existing sewer network serving Doha. It is not envisaged that they will do so in the future as this would be prevented where necessary by compelling industries, producing potentially troublesome effluents, to install specialised treatment plant to process their effluents before discharge into the sewer network.

The major health hazard presented by domestic effluent are the pathogens it contains, which can cause a variety of diseases. The major pathogens present in crude domestic sewage are bacteria, viruses, protozoa and helminths.

The most important diseases caused by bacteria and conveyed in effluent and sludge are typhoid, paratyphoid, cholera, bacillary dysentery, enteritis, salmonella plus other less serious diseases. The infection risk which seems most relevant in Qatar are Salmonella spp and S. typhi both of which are known to occur. The bacteria are much reduced by effluent treatment but are still present after biological treatment which precludes the use of effluent in this form for uncontrolled purposes. Their inability to survive and multiply in the environment of a sewage treatment works is the principal reason for their reduction in numbers. Adequate chlorination is highly effective in the elimination of bacteria from effluent, as also is lagoon treatment where the incidence of sunlight is a major contributory factor.

Information on the transmission of viral disease through waste-water is limited but pathogenic viruses are normally present in such waters. Diseases which could be transmitted this method include infectious hepatitis, polimyelitis, enteric diseases and some respiratory and eye diseases. Infectious hepatitis and polimyelitis are known to occur in Qatar where the incidence of the former is high. In general, the viral content of waste-water is much less than the bacterial but viruses are more resistant to treatment processes and a lesser degree of removal is achieved, even with chlorination. It is believed however, that viruses cannot survive for more than approximately 7 days in effluent.

Untreated sewage can be expected to carry the cysts of the more common protozoa such as Entamoeba histolytica which causes amoebiasis and amoebic dysentery. No definite figures are available on the instances of these diseases in Qatar but Entamoeba histolytica almost certainly occurs and Giardia lamblia is probably also common. The protozoa cysts which cause the disease to be transmitted are unlikely to be present after tertiary treatment filtration, but will remain in the sewage sludge.

Helminths are parasitic in man and animals and are probably present in effluent. The mechanism of transmission of the disease is through the eggs, which can survive for long periods. They are deposited on soil or crops and picked up by physical contact, before being ingested. Typical of the diseases thus caused are tapeworm and hookworm infections, schistosomiasis and ascariasis. Ascaris is an important consideration and a variety, Taenai saginata, which is not a common human infection, could have a serious effect on cattle fed on fodder crops irrigated with effluent treated only to secondary standards. The eggs of the worms are resistant to first stage treatment processes, but can be removed from the effluent by a combination of sedimentation and tertiary treatment. However, eggs of ascaris would still be present in sludge after digestion and can only be killed by heating to about 55°C for two hours, or more slowly, by dessication or prolonged exposure in direct sunlight.

In addition to the pathogenic agents discussed above there are aquatic insects which can also present risks to public health. Of these the most important is the ...

can only survive in water. Malaria is not endemic in Qatar but any large open bodies of effluent such as oxidation or maturation ponds storage basins and evaporation or infiltration lakes, would need to be monitored at regular intervals to check on the incidence of malaria-bearing mosquito larvae.

There are three main groups of the general population that would be at risk from the use of insufficienty treated sewage effluent. They are the agricultural workers employed at the sites irrigated by such effluent, residents living near the sites and consumers of the crops produced at the sites. However refined the tertiary treatment and disinfection techniques applied to the effluent there will inevitably be a degree of health risk to all three groups. The aim should be to reduce this risk to acceptable minimal proportions.

The health of the farm workers should be regularly monitored. A safety code for the workers together with a continuing health education programme is recommended. A medical centre for the surveillance of the health of the work force is a necessity, for primary healthcare, immunization and as a health survey and record analysis centre.

The health hazard to people living near the sites of farms using treated effluent can be avoided both by siting the proposed farms away from residential development and by refusing to allow new constriction to take place close to the irrigated areas. The El Ashara development is a good example of appropriate siting so as to minimise health risk as it is well away from residential areas and is sufficiently isolated so as to prevent unauthorised access by members of the general public.

The only means of reducing the health risks to the consumers of the crops produced from any agricultural development using treated effluent is by the action taken at the tertiary treatment stage and at the point of application of the effluent. In practice it requires constant monitoring of effluent quality, the health of the farm workers (to prevent them from becoming carriers of pathogens), irrigation techniques, irrigated soil characteristics, and the quality and preparation of the crops produced.

Public health criteria for effluent are required to ensure the protection of the community by preventing the dissemination of disease through direct or indirect contact with effluent. It is essential to establish standards from the outset of any effluent utilization project, and then, by long term monitoring, revise these standards as necessary to control any secondary effects on public health. It may not be possible to predict with certainity the long term secondary effects that might, for example, occur from undesirable trace elements entering potable water supplies from deliberate, or inadvertent, recharge of effluent to ground. Hence there is a need for continuous monitoring over the entire lifespan of any project.

Whilst in theory it is possible to design a scheme where different effluent qualities are available to serve different uses, such a policy would be technically inappropriate in Qatar. The tertiary treatment processes proposed for all works should therefore aim to produce consistently high quality effluent.

The quality standards recommended where food crops will be grown using the treated effluent are :-

- The effluent must be substantially free of all pathogens.
- The total coliform count must not exceed 100 per 100 ml in 80% of samples.
- The effluent must contain a detectable chlorine residual at the point of use.
- The effluent must not be used for potable purposes.
- The effluent should not be used on salad crops or other crops usually eaten raw and without peeling.
- Distribution systems, whether underground or not, must be clearly marked to show that they are carrying nonpotable water.
- The quality of the effluent must be regularly monitored.

XII

WATER USE AND PRODUCTION

12.1 INTRODUCTION

There are two aspects to the problem of water in the Arabian Region. Firstly, there is the absolute scarcity caused by the historic lack of capital to tap groundwater reserves and secondly, essentially in the long-term, the absolute scarcity commensurate with the heavy demand now being placed upon them. Historically, groundwater in Qatar was obtained from shallow wells, springs near the coast and in caverns (dahl) developed in the Rus Formation in the immediate hinterland of Doha. The exploitation of groundwater has paralleled oil production activity which introduced both well-drilling technology and capital resources for the purchase of mechanical pumps and ancillary equipment.

From the late 1950' onward therefore there has been a steady increase in groundwater abstraction for both municipal and agricultural use rising from about $5 \times 10^6 m^3$ in 1958 to $79 \times 10^6 m^3$ in 1980. The level of abstraction in each year (Q) may be represented by

$$Q = 1.06(3 + 2.5 x - 0.0075X^2) \quad \ldots\ldots\ldots\ldots \quad (12.1)$$

where Q = annual rate of groundwater abstraction ($m^3 x 10^6$)

t = years since 1958.

The above equation describes the growth of gross groundwater abstraction for both domestic and agricultural use between 1958 and 1980 and has been used in the development of the groundwater model (Chap. XIV).

12.2 GROUNDWATER

12.2.1 Municipal and Commercial Abstraction

In the years prior to the early 1960's all municipal water supplies were based on pumped groundwater. For minor settlements this was from small local wells but Doha was supplied from a member of well-fields in east-central Qatar sited and designed by Le Grand Adsco. From 1964 onwards these groundwater supplies augmented increasing supplies of distilled sea water to reach a peak in 1975 when, as the result of an FAO (1977) recommendation, extraction was reduced with the aim of phasing out groundwater extraction from existing well-fields within the northern fresh-water aquifer area and developing other, possibly more brackish, sources nearer Doha for distilled water blending purposes. This recommendation was made when the full extent of over-extraction of the northern aquifer was determined by the project and was the first direct measure taken towards groundwater conservation.

Fig. 12.1 is a time-series histogram showing groundwater extraction for municipal (Doha and Umm Said) purposes over the period 1964-80 which clearly illustrates the growth and decline of annual pumping for municipal supplies from the northern freshwater aquifer.

These abstractions are made from 10 well fields located in the northern groundwater province and at Rowdat Rashid in central Qatar (Fig. 12.2). Some additional quantities ($2.50 \times 10^6 m^3$) of brackish groundwater are extracted from small well-fields at Musherib, Garrafah, Doha Airport and West Bay for blending purposes; from two well fields at Sinnah and Jumaliyah operated by the Qatar Petroleum Producing Authority (QPPA) and pumped to their main on-shore production centre at Dukhan; and at Al-Jadiyah for the supply to the Zubarah radio station and Umm al Shukut for the supply by tanker to outlying villages. The individual well fields are pumped at varying rates with water being piped quite considerable distances to supply principal centres.

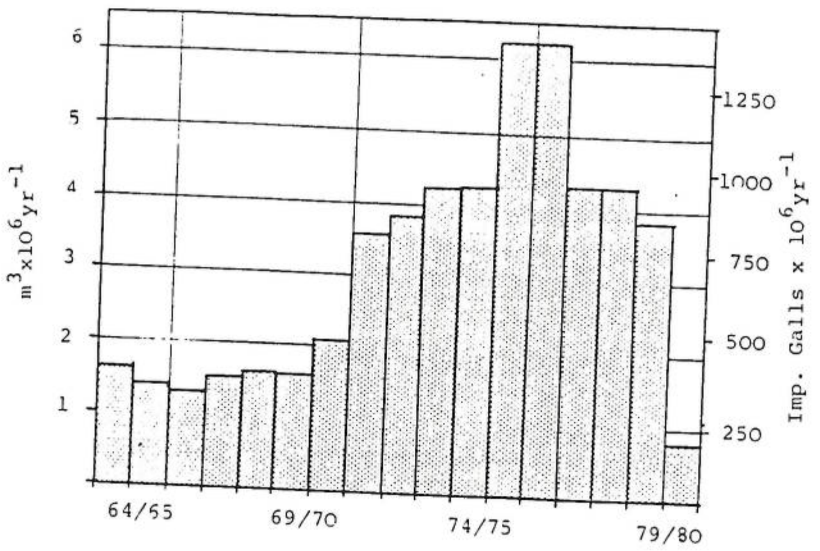


Fig. 12.1 THE GROWTH AND DECLINE OF GROUNDWATER EXTRACTION FOR NON-AGRICULTURAL USE FROM GOVERNMENT WELL-FIELDS

Source : Water Department.

The well fields at Umm er Ghab, Al-Otoriyah and Rashadah have consistently supplied approximately 60% of the total annual extraction of groundwater for municipal use. Since the phased reduction in pumping in 1980, only minimal supplies have been pumped for blending purposes and the maintenance of afforestation within the environs of the well-fields. They are nevertheless maintained in a stand-by condition as an emergency supply and with the prospect of domestic consumption in Doha and Umm Said exceeding distillation capacity in 1981/82 are ready to be brought back into production.

The following table shows the present level of extraction at each of the major well fields compared with that during the peak year of 1975.

Table 12.1

Groundwater Extraction from Well fields, 1975 and 1980

($m^3 \times 10^6 yr^{-1}$)

Well Field	1975	1980
Al Mazroah	0.239	Nil
Rawdat Rashid	0.150	0.060
Umm el Ghab	1.242	0.196
Al Shahaniyah	0.292	0.073
Al Khraib	0.209	0.066
Al Otoriyah	1.107	0.141
Abu Thailah	0.514	0.013
Al Deebiyah	0.847	0.086
Al Rashidah	1.222	0.146
Sunna } QPPA Al Jumaliyah }	0.388	0.388

Source :- Water Department Data and QPPA

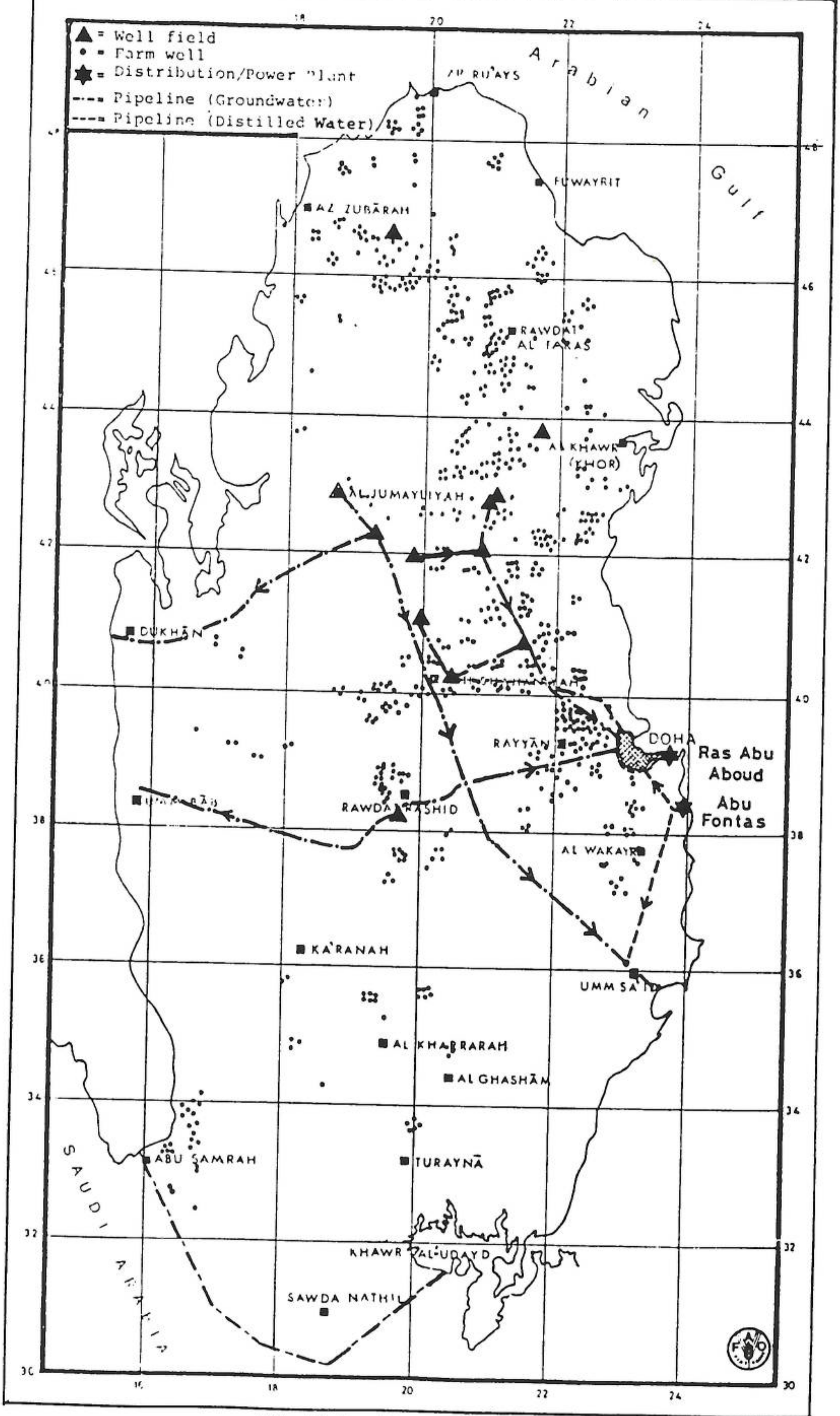


FIG. 12.1 WATER ABSTRACTION AND PRODUCTION SITES (1980)

12.2.2 Agricultural Abstraction

Agriculture in Qatar is based almost entirely upon irrigation from pumped groundwater and accounts for just over half the total of all water consumed in the State. This proportion has steadily declined from nearly 80% in 1976 as increasing volumes of distilled sea water have been made available from distillation plants to meet growing domestic demand.

The accurate determination of pumped groundwater for irrigation from over 900 wells throughout the State has proved to be difficult because of the variable number of hours pumped at each farm on each day throughout the year. Certain assumptions have therefore had to be made in computing the total pumped discharge from an annual survey undertaken by the Project. On the basis of large sample of farms this has been taken as 8.4 hours per day during winter months of November to March and 9.7 hours per day for the remaining seven months of the year.

The first farm well abstraction survey was undertaken by the previous FAO project in 1972 and repeated in 1976 by the Project when an enumeration of every farm in the State was undertaken, and data on the number of wells, discharge and hours of operation were obtained in every case. In addition, the 1976 survey was supplemented by data from the farm management survey where the analysis of farming systems included a detailed analysis of water use and irrigation efficiency from a sample number of farms. (Mitra and Flack, Farm Enterprise and Resource Use, Technical Note No. 39, 1976).

The original farm survey of 1972 recorded a total gross extraction for irrigation usage of 44.14 x $10^6 m^3$. On the basis of subsequent investigations whereby it was estim estimated that 20% of irrigation water is returned to the aquifer, total net extraction amounted to 35.0 x $10^6 m^3$. The farm management survey carried out in 1975/76 showd that agriculture in Qatar may be classified into three separate enterprises or systems; (1) vegetable farms (2) vegetable-orchard-forage farms and (3) orchard-forage farms. Data from sample farms in each category was then used to determine gross water extraction and consumptive use or net water requirement from meteorological data for each of the typical cropping patterns to derive an approximation of irrigation efficiency. Summarised data from this survey are shown in Table 12.2.

Table 12.2

Estimated Total Annual Extraction of Groundwater for Agriculture 1975/76

Farming System and No. of Farms	Av. Net Crop/ area/farm (ha)	Total Area (ha)	Gross Extraction (MCM)	Net Extraction (m)	Water Requirement (m)	Irrigation Efficiency (%)
1 (130)	7.62	990	28.53	2.30	0.81	35
2 (103)	6.06	624	17.63	2.32	1.26	56
3 (37)	4.66	172	4.90	2.26	1.27	58
Totals and weighted averages	6.6	1786	51.06	2.28	0.99	44

This survey showed a total gross extraction of 51.06 x $10^6 m^3 yr^{-1}$ which was within 6% of the total obtained by an enumeration and survey of every farm and this small discrepancy may be accounted for by sampling error.

In May/June 1980 a detailed survey of all farms in Qatar was undertaken by the project upon the instruction of a ministerial committee headed by H.E. The Minister of Education. The details have not been made public but permission was given to the Project to utilize certain basic data obtained from this survey. This revealed a total of 573 farms with a total aggregate summer irrigated area of 3050 ha. The Ministry of Industry and

Agriculture, in their annual publication '<u>Agricultural Statistics</u>' (1979), give a figure of 406 'active' farms with a total area of 3600 ha and with a modal farm size of 9.03 ha. The Project groundwater abstraction survey of November/December 1980 showed that there were 597 farms of which 377 were in operation or 'active'. Taking into account all data and reconciling these with irrigation demand and production data, the present situation is believed to be;.

Total number of farms	=	573
Total number of operational farms		377
Area under irrigation (maximum)		3300 ha
The groundwater abstraction		76.2 Mm^3

Agricultural production and marketing data, coupled with the records of the extension section of the Department of Agricultural Affairs, suggest that only about 100 farms may however be considered as production and abstract a estimated 52 Mm^3 of groundwater per annum. The remaining farms, which abstract a total of 24 Mm^3, may be regarded as amenity farms which serve as country estates for a number of leading citizens and do not participate in the production of crops for the market. This substantial amount of water, almost equivalent to the safe yield of the northern aquifer, is utilized in the irrigation of trees, landscaping, non-productive date palms and some vegetable and fodder for private consumption.

Table 12.3 is an estimate of areas under various crops on productive farms in Qatar.

Table 12.3

Estimated Crop Water Use - Qatar
1979 / 80

Crop	Area ha.	Average Water Use m^3/ha	Total Water Use Mm^3
Dates	410	24,000	10
Orchard	360	30,000	11
Afforestation	40	20,000	1
Alfalfa	400	44,000	18
Cereals	200	9,000	2
Winter Vegetables	550	11,000	6
Summer Vegetables	290	16,000	4
Total	1370	–	52

These data refer to groundwater abstraction on private and government farms throughout Qatar but exclude limited, but steadily increasing abstraction of brackish groundwater (3,500-4,000 mg/l) from the Alat aquifer in south-western Qatar for the Project experimental farm at Wadi el Araig and the Department of Agriculture's sheep station at Abu Samra.

The growth rate of groundwater abstraction for agricultural purposes is shown in Table 12.5. This shows a steady annual increase of approximately $2 \times 10^6 m^3 yr^{-1}$ until 1975 when the annual rate began to increase to reach an unprecedental annual rate of $76.2 \times 10^6 m^3$ between 1979 and 1980 to give a total annual net abstraction for agriculture of $63.6 \times 10^6 m^3$.

The trend in agricultura water use are also shown in Table 12.4 below whereby irrigation efficiency has remained constant at 43-44% but the average irrigated area per farm has increase from 6.6 ha to 8.1 ha over the past 5 years.

In 1980 an Emiri Decree prohibited any further development of groundwater for agriculture and all drilling rigs were impounded. The full effect of the measure will not become apparent for at least a further year but this major conservation measure will arrest the continued and accelerating over exploitation of the country's main freshwater reserves.

Table 12.4

Trend in Agricultural Use of Groundwater

Year	Average Net Crop Area/Farm (ha)	Total Area (ha)	Gross Extraction ($m^3 \times 10^6$)	Net Water Requirement (m)	Irrigation Efficiency %
1975/76	6.6	1986	51.1	1.00	44
1980	8.1	3300	76.2	1.00	43

12.3 SEA WATER DISTILLATION

The distillation of sea water has provided an increasing proportion of Qatar's domestic and industrial water needs since 1954 and by 1980 was amounted to 45% of all water consumed in Qatar. Distillate with a total dissolved solids concentration of 100 mg/l is blended with groundwater but since 1979 these freshwater supplies have been substituted with brackish groundwater.

The first distillation plant was completed in 1954 with a capacity of 0.099 x Mm^3yr^{-1} (60?000 g.p.d.) blended with an equivalent amount of groundwater. In 1958 a new plant was constructed on the sea front and the total output raised to 0.713 x Mm^3yr^{-1} (430,000 g.p.d.). In 1963 the first two multi-stage flash evaporation units at Ras Abu Aboud were commissioned with an initial production of 2.489 x Mm^3yr^{-1} (1.5 m g.p.d.). In 1974 and 1978 additional units were added and in 1977 the new power/distillation station as Ras Abu Fontas was commissioned, bringing the total production of distillate to 4435 x 10^6m^3 (26.7 m g.p.d.) from both distillation plants. In 1981 tenders were issued for the addition of 4 further units to bring the total production to 85 x Mm^3yr^{-1} (51 m g.p.d.) by 1983.

12.4 EFFLUENT WATER

Sewage effluent water from the Doha sewage treatment works has steadily increased since their completion in 1974 to reach a total daily discharge of 30,000 m^3 (10.9 Mm^3yr^{-1}) of secondary treated effluent by the end of 1980. Originally this effluent was discharged into a dam sited near Wadi Isameer depression. This arrangement soon proved to be a unsatisfactory one for not only were the growing boundaries of Doha encroaching upon the site it also infringed upon the Ras Abu Fontas main power gasline. As an interim measure, pending the construction of a pipeline to transfer the effluent to an agricultural development in central Qatar (See Chap. XV), the Wadi Imsameer site was abandoned in 1980 and the effluent transferred to a disposal area in the vicinity of Abu Nakhlah, some 12 km south west of Doha.

Since 1974 increasing amounts of secondary treated and chlorinated effluent have been made available for the irrigation of trees and public gardens in Doha. In 1980 this amounted to 4,500 m^3day^{-1} (1.64 Mm^3yr^{-1}) with a salinity concentration of 2800 mg/l, much of it accruing from leaking sewers along the city foreshore below high tide level.

12.5 TOTAL WATER USE AND PRODUCTION

Fig. 12.3 shows in the growth of water consumption in Qatar for the 1964-1980 divided between domestic and agricultural use. Whilst agricultural use has increased in recent years the domestic consumption has more than quadrupled since 1976.

Table 12.5 summarises the total water consumption for Qatar for the period 1964-1980. The original fresh groundwater source was supplemented by distilled sea water in 1964, the later growing in volume to provide almost 42% of total water consumption in the country by

TABLE 12.5

WATER CONSUMPTION - QATAR

1964-1980

($m^3 \times 10^6$)

YEAR	AGRICULTURE/FORESTRY					DOMESTIC/COMMERCIAL							TOTAL DOMESTIC COMM.
	GROUNDWATER			EFFLUENT	TOTAL AGRI-CULTURE	GROUNDWATER			DISTILLED SEA WATER			
	FRESH (NET) 1/	BRACKISH 2/	TOTAL			FRESH 3/	BRACKISH 4/	TOTAL	ABOUD	FONTAS	TOTAL	
1964	14.0	-	14.0	-	14.0	1.59	-	1.59	2.40	-	2.40	3.99
1965	16.0	-	16.0	-	16.0	1.37	-	1.37	2.85	-	2.85	4.22
1966	18.5	-	18.5	-	18.5	1.29	-	1.29	2.79	-	2.79	5.37
1967	20.5	-	20.5	-	20.5	1.54	-	1.54	2.30	-	2.30	3.84
1968	21.5	-	21.5	-	21.5	1.61	-	1.61	2.93	-	2.93	4.54
1969	24.0	-	24.0	-	24.0	1.58	-	1.58	4.50	-	4.50	6.08
1970	28.0	-	28.0	-	28.0	2.07	-	2.07	4.74	-	4.74	6.81
1971	30.0	-	30.0	-	30.0	2.58	-	2.58	5.34	-	5.34	7.92
1972	33.0	-	33.0	-	33.0	3.84	-	3.84	5.14	-	5.14	8.98
1973	35.3	-	35.3	-	35.3	4.26	-	4.26	5.90	-	5.90	10.16
1974	38.0	-	38.0	0.2	38.2	4.33	-	4.33	8 80	-	8.80	13.13
1975	40.0	-	40.0	0.5	40.5	6.21	-	6.21	10.40	-	10.40	16.61
1976	43.0	0.2	43.2	0.5	43.7	6.07	-	6.07	10.22	-	10.22	16.29
1977	45.6	0.9	46.5	0.6	47.1	6.00	-	6.00	10.06	4.74	14.80	20.80
1978	48.3	0.8	49.1	1.0	50.1	5.40	-	5.40	10.01	13.05	23.06	28.46
1979	49.8	0.9	50.7	1.5	52.2	4.07	0.50	4.57	8.46	23.49	31.95	36.52
1980	57.2	0.8	58.0	1.6	59.6	1.17	2.50	3.67	10.95	33.40	44.35	48.02

1/ Net after deduction 25% irrigation return

2/ Alat Aquifer. Abu Samra and Wadi el Araig

3/ Incl. Dukhan

4/ Doha blending water and Abu Samra reverse osmosis plant.

1980. Other sources are brackish groundwater derived from the Alat aquifer in south-western Qatar and used for limited agriculture and for the domestic supply to Abu Samra after treatment by reverse osmosis, effluent water used principally for the irrigation of trees and some public gardens in Doha and brackish groundwater from Doha (≈10,000 mg/l) utilized as blending water with distilled water. Table 12.4 summarises the total water use in Qatar on the basis of source.

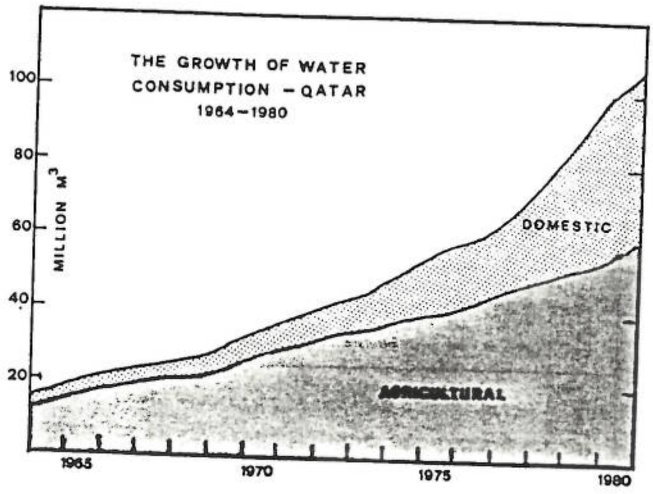


Table 12.4

Total Water Use by Source - 1980

($m^3 \times 10^6$)

Fresh groundwater (500-2000 mg/l) (Net)	62.37
Brackish groundwater (3500-10,000 mg/l)	3.30
Distilled sea water	44.35
Effluent water	1.60
Total	111.62

12.6 COST OF WATER

The cost of water from various sources in an important element in water resources and agricultural planning. In 1974, FAO (QAT/001 - Technical Report No. 1 - Water Resources and Use) estimated the cost distilled sea water, pumped groundwater for domestic use and pumped groundwater for agricultural use to be QR. 1.15, QR. 1.62 and QR. 0.10 per cubic meter respectively.

The cost of distilled water is difficult to assess and there is no definitive cost figure available. Major problems resides in the value which Government may wish to assign to energy, mainly natural gas, and the isolation of water from power generation. On the basis of energy at equivalent oil prices the consultants to the Ministry of Electricity and Water (Ewbank Ltd.) have estimated the cost to be QR. 4.00 ($ 1.10) per cubic meter. This cost is comparable with that of multi-flash distilled sea water elsewhere, [e.g. Japan $ (US) 0.85/m^3 and the Caribbean $ (US) 0.92/m^3 (World Water, 1979)] and a large (600,000 $m^3 day^{-1}$) reverse osmosis plant in Libya where the cost of product water is expected to be the present equivalent of QR. 4.32 m^3 made up of QR. 3.57 in capital and replacement cost, QR. 0.58 pre-treatment and QR. 0.17 in power (Ames Crosta Babcock, 1980).

Great care is, however, required in the comparison of costs of desalinized water when data are obtained from various sources, as the costs concerned are dominated by capital charges and energy costs. In view of recent rapid inflation it is necessary to specify the year of plant construction or to bring costs up-to-date to a specified base date, and this is seldom possible without extensive studies. Energy costs are a function of the source of heat and type of fuel, and costs quoted are often based on heavily subsidized transfer prices within particular countries. Calculations of the cost of distilled water based on full economic resource costs in Qatar by Shell International Gas Ltd. (Internal Energy Supply and Demand, 1980-2020, 1980) have been estimated to range from QR. 5.00 to QR. 8.00/m^3. The high capital and operating costs of any distillation plant ensure that water from this source can never be cheap although the use of waste heat, subsidized energy prices and judicious location all assist in reducing costs to a minimum. However an important parameter in the master planning study undertaken by Halcrow-Balfour on behalf of the project, was the true economic cost of distilled water and a detailed economic analysis was made. The results obtained may be summarised as follows :

Table 12.7

Cost of Distilled Sea Water

Plant Location	Unit Costs (QR/m^3)	
	with energy at world market price	with energy at zero cost
Ras Abu Fontas Ras Abu Aboud	6.00	4.15
Ras Laffan	5.30	4.25

To these production costs must be added the costs of transmission (conveyance) of the water from the plant to the farm gate. Based upon available cost data and schematic distribution systems, unit costs of water varying from 0.014 to 0.047 QR/m^3/km have been derived. These figures are analagous to the desalination costs and incorporate all capital, operating, maintenance and fuel costs (at the full economic price). If gas is taken to be free the corresponding water transport costs fall to 0.012 to 0.040 QR/m^3/km.

Similarly, the consequences of having to transmit power to a remote site for desalinisation may increase this cost by up to 40%. For instance, a possible development option discussed in Chapter XIV is the desalinisation by reverse osmosis of saline Umm er Radhuma groundwater in south-western Qatar to augment meagre groundwater supplies. The calculated cost of water at site would be QR. 2.87/m^3 but when the costs of power transmission are added the budget production costs would be raised to QR. 7.69/m^3 not including raw water pumping costs.

In 1976 an analysis of the cost of pumped groundwater for agriculture was undertaken by the Project and published in Technical Note No. 39, (Mitra). This survey consisted of a detailed assessment of both fixed and variatble costs of pumped groundwater on a random samples of 30 farms and resulted in the finding that the cost was QR. 0.05 ($ 0.0125) per cubic meter or half that of the previous limited survey. Fixed costs amounted to 47.6% and variable costs to 52.4% of the total. The variable cost element is higher than normally encountered and this is because many of the pumps and engines are old and require constant repair and maintenance to keep them in running order. This stems from an overall reluctance to keep them in running order. This stems from an overall reluctance of landowners (who are largely absentee landlords) to invest in agriculture where the opportunity cost of investment is much higher than the rapidly developing urban sector. If the present installations were to be replaced by new pumping plant it was calculated that the variable cost ...

Because of recent inflationary trends or revision of this estimate was undertaken in 1981 and it was found that the cost of pumped groundwater was QR. 0.156. This is confirmed by a study undertaken by Metcalf and Eddy International Inc. (MEI) in 1979[1], who found the cost of pumped groundwater to range from QR. 0.15 to QR. 0.20 at two demonstration farms. These costs include piped distribution systems and the higher of the two costs reflects a high level of supervision by comparatively better-paid Government staff.

These estimates were criticlly reviewed for the master planning study and it was concluded that although the calculation of a unit cost for raising well water is possible for one well, or a number of wells in the same neighbourhood, the figure obtained would be unlikely to be representative of well operations elsewhere. Moreover, costs will vary from place to place not only because of the type and size of installation, but also according to the numbers of wells in a particular contract. Accordingly, in collaboration with well contractors and equipment suppliers, well water abstraction costs for this study were based upon a 'notional' typical well, 60 m deep and operating 7 hours per day at a rate of 6 l/s. A well with this specification would be capable of serving a mixed farming area of about 4 ha. The true economic unit cost of production (including lifting costs) for such a duty was found to be QR 0.24 per m^3, reducing to QR 0.21 per m^3 with gas feedstock considered free. This is in reasonable agreement with the higher of MEI estimates given above.

Water is a major limiting factor in the national development of Qatar and each marginal unit of available water should be optimally allocated in order to derive the maximum economic return. An earlier investigation (FAO, 1974) has shown that on a well-managed farm, the value of water used is of the order of QR. 0.25 ($ 0.0625) per cubic meter. The <u>cost</u> of pumped groundwater at farm level has been shown to be QR. 0.15 per cubic meter and hence net returns to water on private farms are of the order of QR. 0.10 ($ 0.03) per cubic meter. Thus, if water from other sources (desalinised groundwater, distilled sea water or effluent water) were to be reallocated to agriculture, net returns to water in agriculture must either be equal to or more than the estimated figure of QR. 0.10 in order to derive a profit at present levels of agricultural practice. At the present time the unit cost of distilled water (at production site) exceeds the present value of agricultural water by as much as a factor of twenty and if it is to be used in supplementing groundwater for irrigation, this difference indicates the extent of subsidy required or loss on the undertaking.

The potential for raising the value of irrigated vegetable crops in terms of water applied has been demonstrated by both the project and IDTC (MEI) in a number of investigations[1]. These have shown that the net value may be raised considerably under improved irrigation practices and the allocation of high cost water to agricultural enterprises may therefore only be economically justified if there is a commensurate improvement in irrigation practices to the level demonstrated by the Project and other investigations, and only in the case of certain high value enterprises, such as winter vegetables (See Chap. XIV).

1/ Metcalf & Eddy International Inc., Economic Aspects of Crop Production in Qatar. Report No. 16, IDTC.

XIII

GROUNDWATER MODEL AND WATER BALANCE

13.1 MODEL CONCEPT

Models are important tools in groundwater studies and are now used at all stages of investigation. At the outset simple geologic and hydraulic principles are used to formulate a model or hypothesis relating these principles to the process of water movement through the ground. The initial model is used to guide the investigations, for example, where boreholes are to be located and what parameters and data are to be quantified. Later in the study the model is used to refine the original concepts and to interpolate and infer information which cannot be measured economically. At the final stage the model can be used as a predictive tool to assess the effect on the aquifer(s) of proposals for development, if these were to implemented. This enables the consequences of alternative proposals to be seen in advance, thus facilitating the choicc of the best possible proposal. The generalized approach described above has been adopted in use although quantitative mathematical modelling has been confined to the aquifer systems of northern Qatar only. This is in accordance with geological conditions and the model area approximately coincides with the main recharge zone of Qatar, characterised by the calcareous facies of the Rus Formation.

The aquifer system of northern Qatar are fully described in the Chapter IX. Briefly, the aquifer system is comprised of several separate layers which are locally hydraulically connected to each other. Where this connection is very good any two or more layers may be considered as one. The situation is further complicated by the presence of saline water in the aquifers near the coast and underlying the whole peninsula in the deeper layers. The surface or separation between the fresher water, which is of economic interest, and the more saline water may be controlled by the geological layering or the difference in density between the two waters (see Chap. IX).

The consequence of this complexity from the point of view of modelling is that not only must the model be able to take into account the transfer of water between connected aquifers but it should also take some account of the nature of the movement of the freshwater/saline-water interface.

GEOLOGY	MODEL
Dammam - - - - - Rus (permeable)	Layer I
Rus (impermeable)	Leaky in parts
Upper Umm er Radhuma	Layer II
Lower Umm er Radhuma	↑ Effective Boundary

FIG. 13.1 RELATIONSHIP BETWEEN HYDROGEOLOGY AND MODEL STRUCTURE

A mathematical model was developed which fully accounts for water movement in two connected aquifers and an approximate connection to a third. The basic data required for the model study is :

(a) the shape and extent of the aquifer;

(b) the aquifer hydraulic properties;

(c) the inputs and outputs;

(d) the conditions at the boundaries or edges;

(e) the pressure distributions in the aquifers at different times.

The effect on the movement of the saline water is dealt with separately.

The two main layers in the groundwater model correspond approximately to the upper Umm er Radhuma and Rus Formations respectively with the Rus overlying the Umm er Radhuma (UER). Towards the seaward boundary, and under the assumption that there is a free water surface in the upper modelled aquifer, water may be present in the Dammam Formation which overlies the Rus. However, for the greater part it has been assumed that the collapse structures in the Rus, which have their effect in the Dammam Formation, form zones of high permeability or conduits between the two aquifers which, from the point of view of modelling may be treated as a single layer. This is shown schematically in Figure 13.1.

13.2 AQUIFER GEOMETRY

The basic geometry of the mathematical model used was a 15 by 9 grid of squares each 7.5 km by 7.5 km. The grid has two definite layers. The upper grid was moulded to the shape of Qatar but the lower grid was left as a rectangle. The two grids were vertically connected to each other. Figure 13.2 shows the centres of each grid square in relation to Qatar. Because of the irregular shape of Qatar and the fact that the grid squares are of finite size and regular shape an exact match could not be made but it is nevertheless considered to be sufficiently accurate for modelling and predictive purposes.

Because of the complex geology of the peninsula and the difficulty in identifying precisely the levels of the different formations over the whole area, details of the vertical geometry have been explicitly included in the model.

13.3 AQUIFER HYDRAULIC PROPERTIES

The aquifer properties required for modelling are permeability and storage coefficient. In place of permeability, transmissivity may be substituted which is product of permeability and aquifer thickness. Measured values of transmissivity are given in Table 13.1.

By using transmissivity as the aquifer parameter to be modelled the necessity of having the detailed vertical geometry of each layer is avoided. In using transmissivity as the modelled parameter it is implicitly assumed that in the upper layer fluctuations in water level do not affect flow properties and in the lower layer that there is negligible vertical movement of any saline interface. In practice, it was assumed that the lower aquifer is bounded by a layer of low permeability.

In the case where aquifers are vertically connected a vertical permeability has had to be assigned. To simplify the problem of assigning a value to permeability a 'vertical permeability factor' is introduced which in the model has the units of $days^{-1}$. The rate of vertical flow is computed by multiplying the head difference in metres by the permeability factor and the area in square metres. This provides the flow in cubic metres per day. The values were chosen by first identifying areas where vertical connectivity was feasible, both geologically and from the hydrochemistry, and then by analysis of water level data through the running of the model.

Similarly, information on the storage coefficients for the aquifers is sparse. FAO (1977) gives values from approximately 1% to 0.01% or less, even for the water table aquifers. Very little information is available on the spatial distribution of this aquifer

Groundwater Model   Pattern of Abstraction

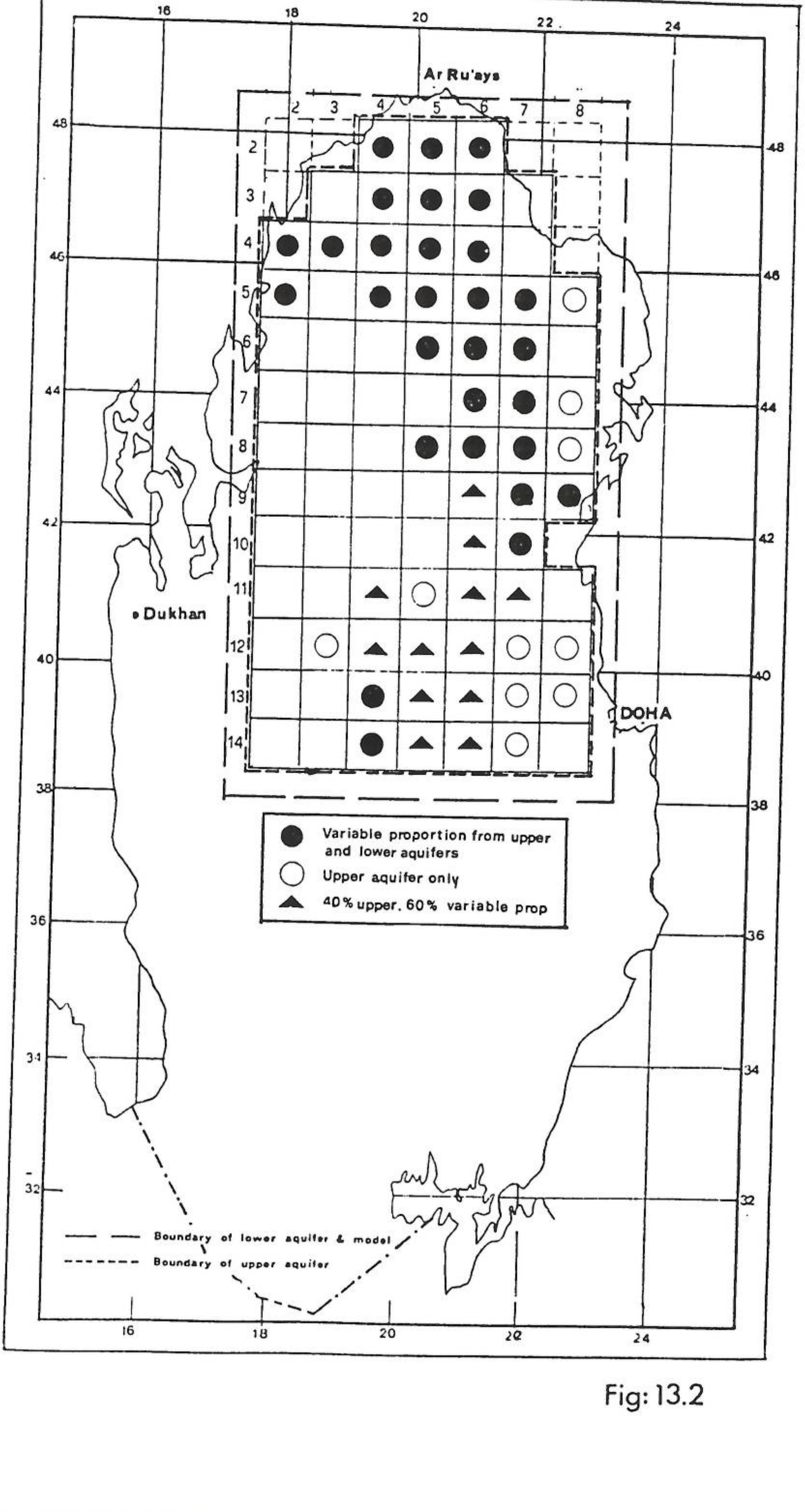


Fig: 13.2

Groundwater Model

Measured Transmissivities

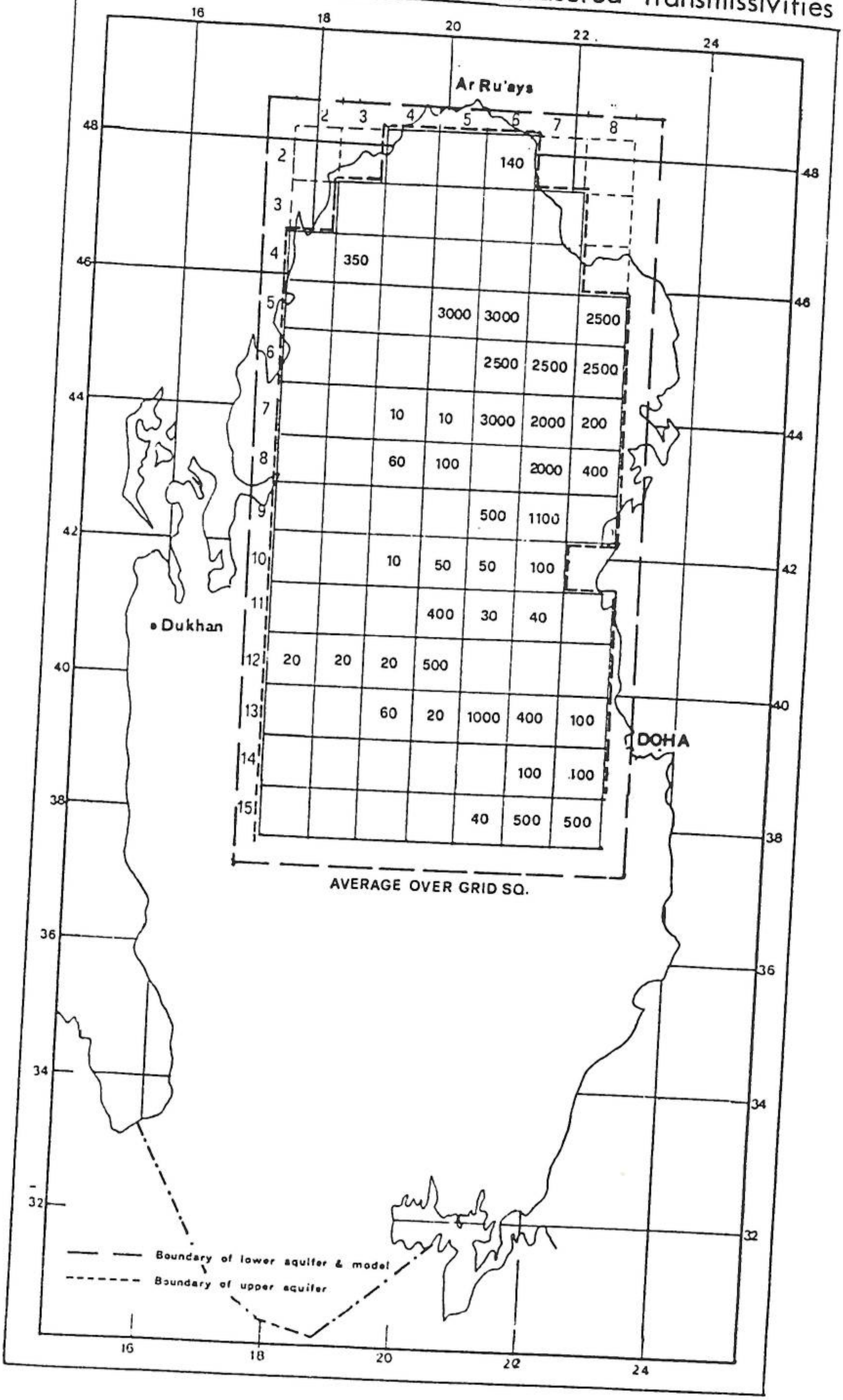


Table Fig: 13.1

parameter. It would appear that the storage coefficient is very small in the vicinity of the government well-fields (Rus Formation only) but is as much as two orders of magnitude higher in the northern area where both aquifers are tapped. This range of values and these general comments were borne in mind at the model calibration stage.

13.4 INPUTS AND OUTPUTS

In any aquifer study the inputs and outputs to the aquifers must be quantifiable. Water can enter or leave an aquifer by any or all of the following mechanisms :

(a) Direct recharge from rainfall

(b) Indirect recharge from/to water bodies

(c) Artificial recharge

(d) Irrigation return flows

(e) Transfer from one aquifer to another

(f) Underground flow

(g) Flow of springs

(h) Pumping

(i) Evaporation

Each one of these possibilities has been considered.

13.4.1 Direct and Indirect Recharge from Rainfall

Direct recharge is dealt with in Chapter VI and it is discussed here for its relevance to the model work. In order to simplify the data preparation for the model calibration a fixed percentage of the mean annual rainfall was taken as the input to the model by direct recharge. The mean annual rainfall was distributed in space over the surface of the upper aquifer. The annual rainfall in millimetres per year is shown in Table 13.2. Recharge was estimated to be 12 per cent of mean annual rainfall, except where indicated.

It was assumed that there was no direct recharge to the lower aquifer. When the model was calibrated actual estimates of recharge for the eight years 1971-79 were used. These values are shown in Tables 13.3-13.10. (Appendix II)

13.4.2 Indirect Recharge, Artificial Recharge

Recharge from ponded rainfall is the only source of indirect recharge but this is considered as recharge from rainfall in 13.4.1.

13.4.3 Irrigation Return Flows

It was assumed that 20 per cent of all water pumped for irrigation is returned to the upper aquifer. This has been determined from lysimetric observations.

13.4.4 Transfer from One Aquifer to Another

It was assumed that where geological information indicated that there was a possibility for water transfer between aquifers that water would flow from one to the other under the influence of the pressure head difference between the two aquifers and a vertical permeability factor. The groundwater model is used to estimate the actual quantities involved, historically and at present.

Groundwater Model Average Rainfall and Recharge

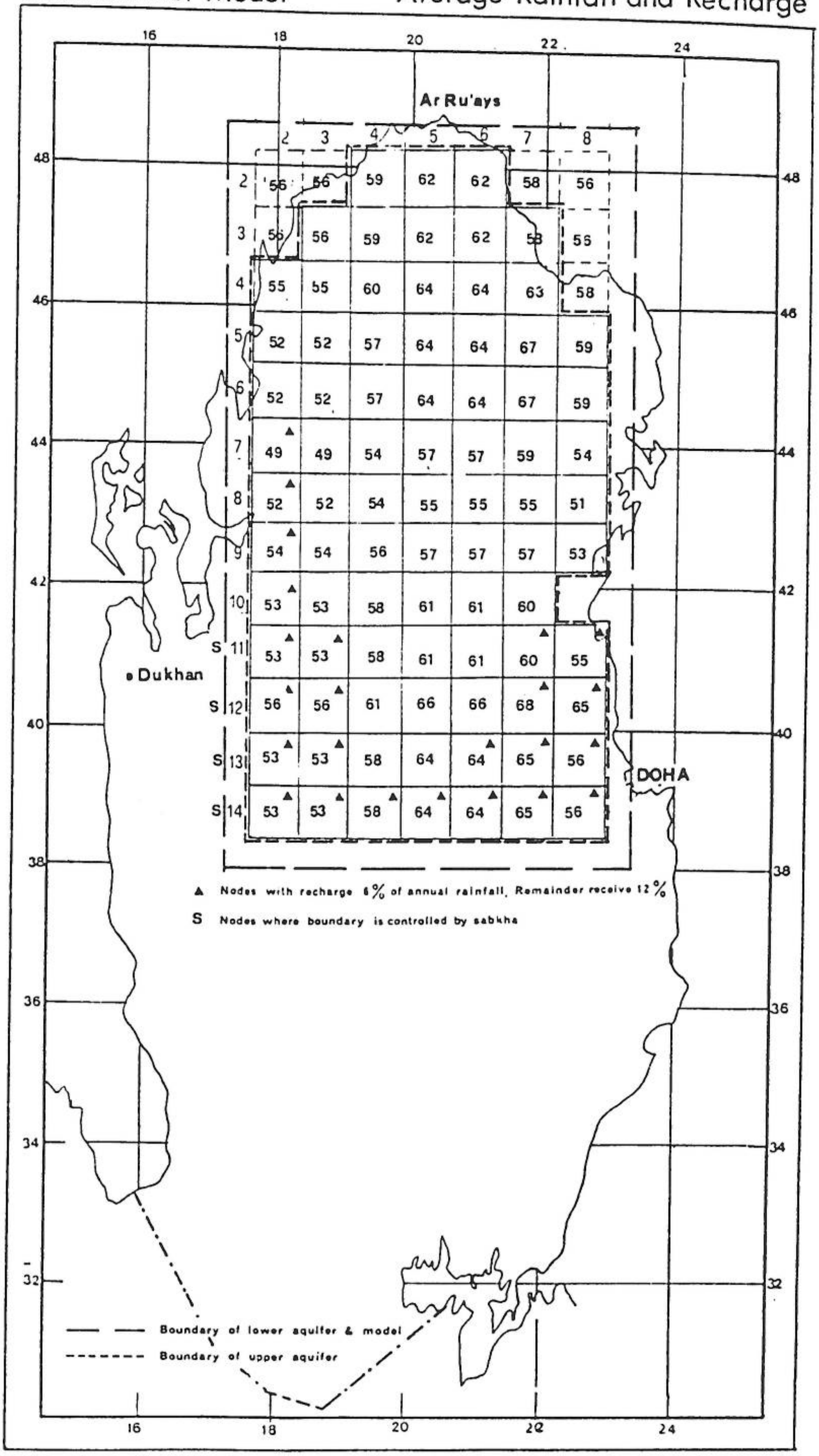


Table Fig: 13.2

1	2	3	4	5	6	7	8	9
			3.0	3.0	5.0			
			4.5	4.0	6.0			
		6.0	4.5	5.0	7.5	8.0		
		6.0	5.0	6.0	9.5	9.5		
	5.5	5.5	4.5	7.0	12.0	11.5	9.0	8.0
	5.0	5.0	4.5	4.5	11.5	11.5	9.5	7.5
	4.5	4.5	4.5	4.5	8.0	11.5	10.0	8.5
	4.0	4.0	4.0	4.0	6.5	4.5	10.0	9.0
	4.0	3.8	3.8	4.0	4.5	7.0	8.5	
.4	3.6	3.6	3.6	3.8	4.5	5.5	7.0	
.0	3.0	3.4	3.4	3.8	4.0	4.5	5.5	
.0	3.0	3.2	3.2	3.2	3.5	4.0	4.5	
.5	3.5	3.0	3.0	3.0	3.0	3.5	3.5	
.5	3.0	3.0	3.0	2.5	2.5	2.5	3.0	3.5
.5	3.0	3.0	3.0	2.0	2.0	2.0	3.0	3.5

TABLE 13.3 RAINFALL FOR 1971/72 (cm)

	1	2	3	4	5	6	7	8	9
1									
2				1.0	1.5	2.0			
3			1.0	1.0	1.5	2.0	2.0		
4			1.0	1.5	2.0	2.0	2.0		
5		1.0	1.0	2.0	2.0	2.0	1.5	1.0	1.0
6		1.5	2.0	2.0	2.0	2.0	1.5	1.5	2.0
7		1.5	2.0	2.0	2.0	2.0	2.0	2.0	2.0
8	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
9		2.0	2.0	2.0	2.0	2.0	2.0	2.0	
10	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	
11	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	
12	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
13	2.0	2.5	2.5	2.5	2.5	2.0	2.0	2.0	
14	2.5	2.5	2.5	2.5	2.5	2.5	2.0	2.0	2.0
15	3.0	3.0	3.0	3.0	2.5	2.5	2.5	2.0	2.0

TABLE 13.4 RAINFALL FOR 1972/73 (cm)

	1	2	3	4	5	6	7	8	9
1					3.0	2.0			
2				4.5	3.5	3.5			
3			6.0	5.0	4.0	3.0	3.0		
4		5.5	5.5	6.0	3.0	4.0	3.5	3.0	3.0
5		4.0	4.5	5.0	4.5	5.0	4.0	3.5	3.5
6		4.0	4.0	3.0	3.5	5.0	4.5	4.0	3.5
7	4.0	4.0	4.0	4.0	4.0	5.0	5.5	4.0	3.5
8	4.5	4.5	4.0	4.0	4.0	5.0	6.0	4.5	4.0
9	5.0	5.0	4.5	4.5	4.0	4.5	5.0	4.0	
10	5.0	5.0	5.0	5.0	4.0	4.0	5.0	4.0	
11	5.0	5.5	5.5	5.0	5.0	4.0	4.0	4.0	4.0
2	5.0	6.0	6.5	6.5	5.5	5.0	4.0	4.0	4.0
3	4.0	5.5	5.5	8.5	8.0	6.0	5.0	5.0	5.0
4	4.0	4.5	8.0	8.5	9.0	7.0	6.0	5.0	5.0
5	4.0	3.0	3.5	5.5	7.0	6.5	5.5	5.0	5.0

TABLE 13.5 RAINFALL FOR 1973/74 (cm)

QATAR GROUNDWATER MODEL

	1	2	3	4	5	6	7	8	9
1				7.0	6.5	7.0			
2			7.0	7.0	6.5	7.0			
3		7.0	7.0	7.0	6.0	5.0	5.0		
4		6.5	7.0	7.0	6.0	5.0	5.0	5.0	5.0
5		6.0	6.0	5.5	6.0	6.0	5.0	5.5	6.0
6		5.5	5.0	4.5	7.5	7.5	6.0	6.0	6.0
7	5.0	5.0	5.0	4.5	4.5	5.0	6.0	6.0	5.0
8	6.5	6.0	6.0	6.0	5.0	5.0	6.0	6.0	6.0
9	6.5	6.6	6.5	6.5	6.0	6.0	6.0	6.0	6.0
10	6.0	6.0	7.0	7.0	7.0	7.0	6.5	6.5	
11	6.0	7.0	6.6	6.0	6.0	6.5	7.0	7.0	
12	5.5	7.5	8.0	7.5	6.5	6.0	7.5	7.0	
13	5.0	7.0	8.5	8.5	8.6	7.0	6.0	7.0	
14	4.0	5.5	7.5	8.5	10.0	9.0	7.0	6.0	6.5
15	4.5	4.5	6.0	8.0	10.0	10.0	4.5	6.5	6.0

TABLE 13.6 RAINFALL FOR 1974/75 (cm)

	1	2	3	4	5	6	7	8	9
1					20.5				
2			22.0	22.0	20.5	22.0			
3			22.0	20.5	20.5	20.0	20.0		
4		21.5	20.5	20.5	20.0	19.5	19.0	18.5	
5		19.5	19.5	18.5	17.5	18.5	19.0	17.0	15.5
6		14.5	15.0	14.5	13.5	15.0	16.5	14.8	12.5
7	14.5	14.5	13.0	11.5	11.0	12.0	12.0	11.5	11.5
8	14.0	13.0	11.5	10.5	10.0	10.0	10.0	10.5	11.0
9	13.0	11.5	10.5	10.0	10.0	10.0	10.0	10.5	
10	11.5	10.5	10.0	10.0	10.0	10.0	10.0	10.5	
11	10.5	10.0	10.0	10.0	10.0	10.0	11.0	11.0	
12	11.0	10.0	10.0	10.5	10.0	11.5	11.5	12.5	
13	10.0	10.0	11.0	11.5	12.5	12.5	13.5	14.0	15.0
14	10.0	10.0	11.5	12.5	13.0	13.5	13.5	14.0	14.5
15	10.0	11.0	12.0	13.0	13.0	13.0	12.5	12.5	12.0

TABLE 13.7 RAINFALL FOE 1975/76 (cm)

	1	2	3	4	5	6	7	8	
1					13.0	14.5			
2			10.5	12.0	13.5	15.5			
3			11.0	13.0	15.0	16.5	17.5		
4		10.0	11.0	14.0	16.5	18.5	19.0	18.	
5		12.5	15.0	18.0	18.0	18.0	15.5	13.	
6		17.0	17.5	16.0	12.5	11.5	11.5	9.	
7	18.0	18.5	16.0	13.0	10.5	9.0	8.0	7.5	
8	14.0	14.5	12.3	10.5	8.5	7.5	7.0		
9	12.5	13.5	13.5	12.5	10.5	9.0	6.5	7.0	
10	11.0	11.5	12.0	11.0	9.5	8.5	7.5	7.0	
11	9.5	10.5	10.5	10.0	8.5	8.0	7.0	7.0	
12	8.0	8.0	8.0	8.0	7.5	7.0	7.5	7.5	
13	6.0	6.0	6.0	6.5	7.0	8.5	9.5	9.5	
14	6.0	6.5	6.5	7.0	7.5	9.0	10.5	10.0	8
15	6.5	7.5	8.5	8.5	8.5	9.5	11.0	10.0	9

TABLE 13.8 RAINFALL FOR 1976/77 (cm)

QATAR GROUNDWATER MODEL

	1	2	3	4	5	6	7	8	9
1				2.0	2.0	2.0			
2			2.0	2.0	2.0	2.0			
3		2.0	2.0	2.0	2.0	2.0	2.0		
4		2.0	2.0	2.0	2.0	2.0	2.0	2.0	
5		2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
6		2.0	2.0	2.0	2.5	2.5	2.5	3.0	3.0
7	2.0	2.0	2.0	2.0	3.0	2.0	3.0	3.0	3.0
8		2.5	3.0	3.0	3.0	3.5	3.5	4.0	4.0
9	3.0	3.0	3.5	3.5	-4.0	4.0	4.0	4.0	4.0
10	2.5	3.0	3.5	3.5	4.0	4.0	4.0	4.0	4.0
11	2.5	3.0	3.0	3.0	3.5	4.0	4.0	4.0	4.0
12	3.0	3.0	3.0	3.0	3.0	4.0	5.0	4.0	4.0
13	3.0	4.0	4.0	4.0	4.0	4.5	5.0	4.0	4.0
14	3.0	4.0	3.5	3.0	3.0	3.0	3.5	3.0	3.0
15	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0

TABLE 13.9 RAINFALL FOR 1977/78 (cm)

QATAR GROUNDWATER MODEL

	1	2	3	4	5	6	7	8	9
1									
2			4.0	4.0	4.0	4.0			
3			5.0	4.5	4.0	4.0	4.0		
4		6.5	6.0	5.5	5.0	5.0	5.0	6.0	7.0
5		7.5	7.0	6.5	5.5	5.5	6.0	8.0	7.0
6		7.5	8.0	8.0	7.5	7.5	7.0	6.0	5.0
7	7.0	7.0	7.0	7.0	7.0	6.0	5.5	4.5	4.5
8	8.0	6.0	6.0	6.0	5.5	4.5	4.5	5.5	6.5
9	6.0	6.0	5.5	5.0	4.5	5.0	6.5	7.5	
10	6.0	6.0	5.5	4.5	4.5	6.5	7.5	8.0	
11	7.0	6.0	6.0	4.5	4.5	7.5	7.0	7.0	
12	7.0	7.0	6.0	5.0	4.5	7.5	9.0	7.5	
13	7.0	7.0	6.0	5.0	4.0	4.5	7.0	5.5	
14	6.0	6.0	6.0	5.0	5.5	5.5	5.5	5.0	5.0
15	5.0	5.0	5.0	4.5	4.0	4.0	4.5	5.0	5.0

TABLE 13.10 RAINFALL FOR 1978/79 (cm)

13.4.5 Groundwater Flow

In the case of the lower aquifer the hydraulic boundaries are believed to extend beyond the boundaries of the Qatar land mass and the possibility therefore exists that water flows underground to or from the area being modelled. Very little information about these likely amounts is known and so certain assumptions have had to be made. These are based on the fact that Qatar forms a very small part of the extensive Umm er Radhuma aquifer and that anything that may have happened in Qatar to this aquifer over the last 20 years has had a very small effect on the regional pressure distribution in the Umm er Radhuma aquifer. The consequence of this assumption is that it may be assumed that the pressure in the Umm er Radhuma at the edge of the modelled area has remained constant. Observations from exploration wells base provided data on pressure in the aquifer and a constant boundary value of 4 metres has been used in the calibration runs with the exception of where the Umm er Radhuma is believed to be hydraulically connected to the overlying Rus aquifer (upper aquifer).

In the case of the upper aquifer it is assumed that the pressure distribution at the boundary of the modelled area is at sea level except at the south-east edge where the large Dukhan Sabkha surface is -1 m below sea level and acts as a local discharge to the Rus aquifer. It has been assumed that this sabkha forms a boundary to the Rus aquifer in this region. The implications of this assumption is that all discharge at the edge of Rus aquifer either flows into the sea or is evaporated in sabkhas situated near the coast.

In both cases the groundwater model provides estimates of the discharge across these boundaries.

13.4.6 Flow of Springs

There are no known onshore springs in northern Qatar but it is believed that offshore springs may be present. The facility for modelling the flow from artesian springs is included in the model and is used as a mathematical device to ensure consistent results for the lower aquifer. However, the physical presence of these springs is not known.

13.4.7 Abstraction

Apart from abstractions from the well-fields for the Doha water supply it is only in recent years that records of abstraction for agriculture have been available. The gradual build-up in abstraction has been discussed previously by FAO, (1977). The groundwater modelling has been carried out on the basis of there being an increase in total abstraction from 3 Mm^3 per annum to 50 Mm^3 per annum over a 22 year period leading up to 1979.

This total abstraction has had to be distributed between each aquifer and in both space and time. For the Doha water supply well-fields it is well established that abstraction is from the Rus or upper aquifer; locations of the abstraction points are also known. An approximation has been made that temporal build up of this abstraction has taken the same pattern as the total abstraction, though in the past two years there has been some reduction. Apart from this approximation, abstractions have been located in the model as close as possible to their actual locations.

The abstraction for farm use is immensely more complicated and is of far greater importance in total than potable supplies. The spatial distribution has been obtained by assuming that the distribution as in 1979 had been maintained for the previous 22 years and that the rate of increase was according to that described in Technical Report 1, (1977) which includes wellfield abstraction. This can be represented by

$$Q = (3 + 2.5t - 0.0075\,t^2)\ 1.06 \qquad \text{Eq. 13.1}$$

Q - annual rate of abstraction Mm^3

t - time in years from 1957

It is not known for certain for any of the farm wells from which aquifer the water is pumped because each well is open for its main length and may penetrate both upper and lower aquifers. A division was made on the basis of the estimated depth to the UER and the capacity of drilling equipment. This means that if the UER is very deep it is most likely that abstraction is from the Rus Formation or above. Where it is uncertain it has been assumed that the basic division between the two aquifers is equal and for all wells fully penetrating to the UER a variable percentage is assumed to be pumped from each aquifer. This percentage was decided by calibration of the model. The areas of each source of pumping are shown in Figure 13.2, and amounts attributed to the upper aquifer alone are shown in Table 13.11. The amounts from the combined aquifers are further divided at the time of running the model and are given in Table 13.12.

The well-field abstractions have been increased by 20% because in the model all farm abstractions are assumed to be reduced by this amount to allow for irrigation return. The wellfield water is removed from the aquifer area and there is therefore nothing returned.

It should be noted that where abstractions are from the combined aquifer it is assumed that 20% of the total pumping is returned to the upper aquifer as irrigation return. The consequence of this assumption is that if less than about 20% of abstraction is assumed to come from the upper aquifer there will be a net recharge to the upper aquifer due to pumping alone, apart from natural recharge.

13.4.8 Evaporation

Water can be lost from aquifers by direct evaporation from the water table and there are a number of such areas adjacent to the coast where this may take place. The geologic map (Encl. 1) shows the location of sabkha in Qatar, most of which are adjacent to the coast and could function as groundwater sinks or discharge areas. It is not known which of these sabkhas are presently active but it is known that there is sufficient area of sabkha in Qatar to more than evaporate all of the recharge to the country. The way in which these areas were treated in the groundwater modelling was to set the water to flow into them. As a matter of mathematics it is immaterial whether water moves directly to the sea or is evaporated in a sabkha.

For the large sabkha in the Dukhan area the level was set below sea level, ranging from 0 to -4 metres. Boundary heads in both upper and lower aquifers are shown in Tables 13.13, to 13.15 which also give the historic water levels in the upper aquifer which were used in the calibration of the model.

13.5 BOUNDARY CONDITIONS

It is important to define the boundaries of any model since these conditions have a large influence over what goes on in the interior of the model. For the upper aquifer it was been assumed that the water moves out of the aquifer to the sea or to coastal sabkhas. The water level at the boundary has therefore been set at zero except at the south-east where it was assumed that the discharge point is the Dukhan sabkha. During the model calibration some minor modifications were made to this general hypothesis to simulate the effect of a third aquifer on top of the upper aquifer.

It has been considerably more difficult to estimate the boundary conditions for the lower aquifer corresponding to the UER formation. The general hypothesis on this aquifer has been stated earlier whereby it has been assumed that the UER under Qatar is generally connected to the entire UER formation which extends throughout the region, and that the influence of the recharge mound in Qatar, and recent abstraction have had little effect on this larger aquifer. It has therefore been assumed that there is, for all practical purposes, no regional pressure gradient across the UER in Qatar either before abstraction started in the 1950's or since. The only changes have [illegible] boundary pressure was allowed to drop to 1.0 m where vertical discharge to the sea is believed to be operative because of poor confining conditions in the overlying Rus aquifer. Apart from this local variation, the boundary head pressure was set at 4 metres of fresh water.

13.6 PIEZOMETRY

The calibration or final refinement of concepts and determination of aquifer parameters is based upon the water pressure or water level distribution in the aquifer and it is essential that such data are available. Ideally, a complete history is required since the condition at any one time is serially correlated with a preceding condition.

For this study only two piezometric maps are available, and these are for, what is believed to be, either the upper aquifer or a mixed value. One is based upon measurements taken in 1958 by Le Grand Adsco and corrected to a common datum and the other is based upon the 1979 survey carried out by the Project.

The 1958 map has been assumed to represent the steady state in Qatar when the aquifer recharge was balanced by an equal flow out to the sea although an allowance was made for a small amount of pumping that was believed to be carried out at that time. Table 13..13 shows the 1958 levels for modelling purposes and Table 13.14 shows the 1979 values.

The piezometry in the southern part of the model is less reliable than that in the northern part especially for 1958. The model was extended into this area because of need to include the aquifers as a whole. However the results for this area should not be looked at too critically, their main value being to form a reasonable boundary condition for the rest of the model.

In order to obtain reasonable water levels in the upper aquifer at its seaward boundary the transmissivities have had to be locally increased. An alternative would have been to assume that the pressure heads in some coastal sabkha were below sea level. Only in the case of the large sabkha in the south west has this assumption been made. This illustrates the problem of trying to obtain very precise results from data that is limited in quality by practical and economic constraints.

The computed 1978-79 model water levels are anomalously high on the 'mound' areas. This could be due to a number of causes; firstly a certain amount of abstraction may have taken place in these areas which is greater than that allowed for in the modelling. Secondly the historic 1958 levels for those areas are not reliable. The calibration has endeavoured to obtain a balance between obtaining a good fit to the 1958 assumed steady state levels and measured 1978-79 levels. A slightly better fit to the 1978-79 levels may be achieved by increasing all transmissivity values by a few per cent. This will reduce high water levels by encouraging water to flow from high points to low points. The values actually selected and presented can therefore be regarded as giving conservative results when used in water development.

13.7 MATHEMATICAL DETAILS

A two layer groundwater model was devised and programmed for the Project HP 9830 computer. The model is based upon the principles of conservation of mass and momentum in which the following assumptions were made :

(a) Each aquifer is isotropic, though parameter values may vary from place to place;

(b) The pressure distribution within each aquifer is hydrostatic;

(c) Energy losses in the vertical direction are concentrated at a single hypothetical boundary between the two aquifers;

	1	2	3	4	5	6	7	8	9
1	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	120	0
6	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	440	0
8	0	0	0	0	0	0	0	531	0
9	0	0	242	117	378	2853	0	0	0
10	0	0	0	867	1310	852	0	0	0
11	0	0	0	110	496	274	1183	0	0
12	0	0	271	72	2805	746	681	369	0
13	0	112	0	0	186	127	106	193	0
14	0	0	0	94	332	0	726	316	0
15	0	0	0	0	0	0	0	0	0

TABLE 13.11 ESTIMATED ACTUAL ABSTRACTION FROM UPPER AQUIFER 1979 ($m^3 x 10^3$/year)

Notes :-

1. Well field abstraction increased by 20% to allow for non-return by irrigation.
2. Well field abstractions as at 1975.

	1	2	3	4	5	6	7	8	9
1	0	0	0	0	0	0	0	0	0
2	0	0	0	226	748	55	0	0	0
3	0	0	0	51	63	151	0	0	0
4	0	32	861	1737	808	1346	0	0	0
5	0	0	0	1800	5387	3060	1253	0	0
6	0	389	0	0	458	3711	1909	0	0
7	0	0	0	0	108	1004	1166	0	0
8	0	0	0	0	0	680	1875	0	0
9	0	0	0	0	0	400	544	1437	0
10	0	0	0	0	0	316	1781	0	0
11	0	0	0	164	0	412	1326	0	0
12	0	0	0	107	1332	1118	0	0	0
13	0	0	0	903	208	191	0	0	0
14	0	0	0	523	349	0	0	0	0
15	0	0	0	0	0	0	0	0	0

TABLE 13.12 ABSTRACTION FROM COMBINED UPPER AND LOWER AQUIFERS 1979 ($m^3 x 10^3$ /year)

Notes :- This abstraction is split between upper and lower aquifers at run time by a model parameter.

QATAR GROUNDWATER MODEL

	1	2	3	4	5	6	7	8	9
1	0	0	0	0	0	0	0	0	0
2	0	0	0	3.0	4.0	2.0	0	0	0
3	0	0	2.0	3.0	3.0	3.0	1.0	0	0
4	0	0	2.0	3.0	5.3	5.3	2.5	0	0
5	0	1.0	4.5	6.4	7.4	7.4	3.0	2.0	0
6	0	3.0	6.3	8.3	8.7	8.5	6.5	3.0	0
7	0	3.5	8.0	11.0	11.5	11.0	7.5	3.0	0
8	0	4.0	13.0	13.0	12.0	11.0	5.5	3.2	0
9	0	5.5	13.0	10.0	8.4	8.4	4.6	1.0	0
10	0	7.0	13.0	9.0	5.0	4.5	3.5	0	0
11	0	7.0	13.0	8.0	5.3	7.0	6.0	1.0	0
12	-2.0	6.0	8.7	7.3	5.4	8.0	10.0	3.3	0
13	-2.0	4.0	6.0	5.0	4.0	6.0	10.0	3.0	0
14	-4.0	1.0	3.0	3.3	3.7	4.0	5.0	2.0	0
15	-2.0	0	3.0	3.0	3.5	4.0	5.0	2.0	0

TABLE 13.13 WATER LEVELS IN UPPER AQUIFER 1958
(m ABOVE SEA LEVEL)

QATAR GROUNDWATER MODEL

	1	2	3	4	5	6	7	8	9
1	0	0	0	0	0	0	0	0	0
2	0	0	0	1.0	1.0	1.0	0	0	0
3	0	0	1.2	2.1	2.2	2.0	0	0	0
4	0	0	2.0	2.0	2.0	2.0	1.4	0	0
5	0	1.0	2.7	2.1	2.0	2.3	2.5	1.0	0
6	0	3.1	4.2	4.0	3.5	4.1	3.0	1.6	0
7	0	1.6	4.2	4.1	4.1	4.2	4.0	2.5	0
8	0	0.8	4.2	4.3	4.4	4.0	3.5	1.0	0
9	0	1.5	6.0	4.0	4.2	3.3	2.3	1.0	0
10	0	1.6	6.0	4.2	4.0	3.5	2.0	0	0
11	0	1.7	6.0	4.0	4.0	3.0	1.5	0.2	0
12	-2.0	1.6	4.0	4.0	3.0	3.0	1.2	0.4	0
13	-2.0	0.6	4.0	4.0	3.5	2.0	1.0	0.3	0
14	-4.0	0	2.2	2.5	2.5	2.0	0.9	0.2	0
15	-2.0	2.0	3.0	3.0	4.0	4.0	1.0	0.2	0

TABLE 13.14 WATER LEVELS IN UPPER AQUIFER 1978/79
(m ABOVE SEA LEVEL)

(d) Viscocity and density are uniform.

These principles and assumptions can be used to formulate a partial differential equation (pde) for the flow regime. However, since the 'pde' would be solved by a finite difference approximation of it, it is simpler to formulate the finite difference equations directly. The storage coefficients are denoted by S, the transmissivities by T, and the head or water levels by H. The subscripts '1' or '2' refer to the upper or the lower aquifer respectively. The vertical permeability factor between the two aquifers is P, and R is the net recharge or inflow to a nodal area.

Each aquifer is divided into a number of squares or blocks, each one sitting upon the one below it. By assuming that the flow between any two nodes in a single plane, or between two planes, is equal to the product of the difference in head and the transmissivity between the two points and the width of the flow path; or the difference in head, permeability factor and nodal area respectively, the equation of conservation of mass for each node in each plane may be written.

$$\Delta^2 . S_1(I,J) \; . \; \frac{d\,H_1(I,J)}{dt} \quad = \quad R_1(I,J)$$

$$- \;(H_1(I,J) - H_1(I-1,J)).(T_1(I,J) + T_1(I-1,J))/2$$

$$- \;(H_1(I,J) - H_1(I,J-1)) \;.(T_1(I,J) + T(I,J-1))/2$$

$$- \;(H_1(I,J) - H_1(I+1,J)).(T_1(I,J) + T_1(I+1,J))/2$$

$$- \;(H_1(I,J) - H_1(I,J+1)).(T_1(I,J) + T_1(I,J+1))/2$$

$$- \;(H_1(I,J) - H_2(I,J)).P(I,J).\,\Delta^2 \qquad \text{........................ Eq. 13.2}$$

A similar expression may be written for the nodes in the lower aquifer, with the subscripts 2 and 1 reversed. These equations can be written for each node within the area. At a boundary other conditions specifying the actual conditions there must be provided. For the most part in this work, the boundary heads have been fixed. Some modifications were introduced to allow for impermeable boundaries.

Given the boundary conditions these two sets of simultaneous ordinary differential equations can be solved. A simple approximation to the differential coefficient dH/dt is made. $(H(I,J) - H^1(I,J))/\Delta t$ is used, where $H^1(I,J)$ is head at time t and $H(I,J)$ is the head at time $t + \Delta t$. All equations are thus seen to be written in terms of the head at time $t + \Delta t$ with the exception of dH/dt term. The resultant set of simultaneous equations in $H_1(I,J)$ and $H_2(I,J)$ are solved by successive over (or under) relaxation.

$$(T_1 + T_2 + T_3 + T_4 + \Delta^2 \;.\; S_1(I,J)/\Delta t + \Delta^2 \,.\, P(I,J)).H(I,J) \quad =$$

$$T_1H_1(I-1,J) + T_2H_1(I,J-1) + T_3H_1(I+1,J) + T_4H_1(I,J+1) + H_2(I,J)$$

$$P(I,J)\Delta^2 + \Delta^2 S_1(I,J)\; H_1(I,J)/\Delta t \;\; \text{....... Eq. 13.3}$$

where $T_1 \; = \; (T_1(I,J) + T_1(I-1,J))/2$ etc.

Initial approximations of the H(I,J) are made by setting them equal to the initial conditions $H^1(I,J)$. New estimates are obtained using equation 13.3. The process is repeated until successive approximations to the solutions at the same time-step are essentially the same. Once the solution has been advanced by the time-step Δt the new heads are put equal to the old ones and the solution is moved forward a further time-step Δt.

Appendix II gives details of the model, run requirements and an example of an actual run.

13.8 MODEL CALIBRATION

13.8.1 Introduction

The model has been used since 1978 in assisting in the understanding of the aquifer systems of northern Qatar. It has been used interactively in formulating hypothesis. The model calibration reached at the termination of the Project is a synthesis of all information available prior to and acquired during its life. It is considered to have served its purpose in assisting with understanding and providing an adequate level of information on consequences of proposals for development.

Some of the proposed developments are of a very major nature and would require further studies, particularly, on the technology of water injection into the aquifers. Should some of these proposals be seriously considered for implementation, after being suitably screened for optimum choice,further hydrogeological information and model refinement would be necessary for the detailed design of the general proposals. The model would later become part of an overall monitoring and management programme.

The general calibration strategy has been to adjust the various hydrogeologic hypotheses and parameters so as to obtain as good a prediction of the water levels as possible for 1958 and 1979, at the same time taking into account known facts regarding the geology and groundwater chemistry of the area. It was assumed that in 1958 a steady state existed when inflow was balanced by outflow. The water levels in 1979 were assumed to be the result of 22 years of gradually increasing abstraction on the pattern of 1979 which was discussed earlier in this chapter. (In practice the modelling had to be carried out for the period 1957-79, assuming that the water levels in 1958 were the same as 1957).

An initial calibration was made to obtain the 1958 steady state water levels by adjusting vertical permeabilities, transmissivities and boundary heads, calibration being the adjustment of model parameters in a systematic fashion. This was followed by a series of calibration runs to further refine the choice of permeabilities and transmissivities and to determine the factors which affect the dynamic response of the aquifers. These are the distribution of abstraction between the two aquifers and the aquifer storage coefficients. As before, these adjustments were made to accord as far as possible with known facts.

13.8.2 Single Aquifer Model

The first series of model runs was carried out on the assumption that the system could be treated as a single aquifer. After careful consideration of the geology, hydrogeology, hydrochemistry and the operation of this model it was decided that the system must be treated as a two aquifer system with a partial vertical connection.

13.8.3 Two Aquifer Model

The first series of calibrations on this model were carried out on a 14 x 9 grid. Effort was concentrated on getting a good representation of the 1958 steady state. The area of vertical connectivity, its probable permeability and boundary head conditions were all examined, including an assumption that the lower aquifer was physically bounded (zero transmissivity) along parts of the western border. A similar condition was tried for the south edge of the upper aquifer but without conclusive results.

The second main series of calibrations was carried out on a 15 x 9 grid model. The extra row was introduced to obtain a better representation of the northern boundary. Effort in this series of calibrations was concentrated on obtaining values for factors affecting the dynamic performance of the model. During this series a number of trials were made to test the significance of the Dammam Formation overlying the Rus formation but no satisfactory result was obtained in resolving this. It should however be pointed out that for the major part of northern Qatar collapse structures are regarded as sufficient for the two formations to be treated as a single aquifer for hydraulic calculations.

13.8.4 Final Calibration

The results of the final calibration are presented in Tables 13.16 to 13.22. Appendix I shows the transmissivity in the upper aquifer, Table 13.21 shows the storage coefficient. Transmissivities and storage coefficients were assumed to be constant in the lower aquifer and these are shown in Table 13.23. Page 13.17 and 13.19 show the 1979 computed levels where boundary heads are given. Figures 13.3 and 13.4 show the water level contour maps for 1958 and 1979 together with measured values. Table 13.22 shows the vertical permeability factors used.

In examining the values, especially in those areas with pumping in the upper aquifer, it should be noted that abstractions in the model are assumed to be spread uniformly over an area of 7.5 x 7.5 km whereas actual point drawdowns will therefore be greater than computed values which are average values over a large area.

The additional drawdown (s in metres) due to the actual well being of smaller diameter than a model well (where abstraction points are represented by a whole grid square of side 7500 metres) is :

$$s = 0.111\ Q/T \log(a/(4.81.r)) \qquad \text{........... Eq. 13.4}$$

Q - discharge in m^3/day

T - transmissivity in m^2/day

r - diameter of actual well in metres

a - length of grid square side in metres.

For example, assume that a wellfield is a 'well' of effective diameter 0.4 km.

$$\text{Discharge} = 2\ Mm^3/\text{year}$$
$$T = 100\ m^2/\text{day}$$
$$a = 7500 \text{ metres}$$
$$r = 400 \text{ metres}$$
$$\therefore s = 0.111\ .\ 5479/100.\ \log(7500/4.81/400)$$
$$= 0.111\ .\ 54.79\ .\ \log 3.9$$
$$= 3.6 \text{ m.}$$

3.6 metres is therefore the amount needed to be added to the drawdown in a well which is computed from a model with a grid square of 7.5 km from which 2 Mm^3/year is being abstracted.

However, of greater importance are the overall water balance figures, the rate of drawdown and the relative drawdowns, rather than the actual computed drawdown. There are some anomalous high values in the computed values but most of these disappear after two or three years of additional pumping. The result is considered to be satisfactory considering that no accurate definition is possible of the aquifer from which abstraction was being made. These high levels could have been due to the assumption that the aquifer was in a steady state in 1958, whereas there may have been some local recharge in 1957-58 to give artificially high water levels in these areas. In modelling the steady state the long term rainfall distribution has been used. However, one run was made using actual rainfall figures for 1971-79 resulting in calibrated levels higher than for the run using mean rainfall. This reflects the higher than average rainfall (and hence recharge) for the period 1971-79 when the average recharge is estimated to have been [illegible]

QATAR GROUNDWATER MODEL

	1	2	3	4	5	6	7	8	9
1	4	4	4	4	4	4	4	4	4
2	4								1
3	4								1
4	4								4
5	4								4
6	4								4
7	4								4
8	4								4
9	4								4
10	4								4
11	4								4
12	4								4
13	4								4
14	4								4
15	4	4	4	4	4	4	4	4	4

TABLE 13.15 BOUNDARY HEAD VALUES LOWER AQUIFER 1958-79 (m above sea level)

QATAR GROUNDWATER MODEL

	1	2	3	4	5	6	7	8	9
1	0	0	0	0	0	0	0	0	0
2	0	0	0	2.8	3.9	1.8	0	0	0
3	0	0	2.5	3.6	3.8	3.3	1.8	0	0
4	0	0	3.2	4.1	4.4	4.2	2.8	0	0
5	0	1.8	3.9	4.7	7.2	6.7	5.0	2.1	0
6	0	3.0	6.0	9.1	10.9	9.2	6.7	3.0	0
7	0	3.5	8.8	14.1	13.6	11.1	7.8	3.2	0
8	0	3.8	13.0	13.8	13.0	11.2	7.6	3.2	0
9	0	5.0	11.8	12.0	11.0	9.1	5.3	1.0	0
10	0	7.1	12.7	10.9	9.9	7.9	4.3	0	0
11	0	7.1	11.5	10.9	10.1	8.8	5.7	.8	0
12	-2	6.3	10.7	10.8	10.5	10.0	9.2	2.9	0
13	-2	3.8	7.9	9.5	8.0	9.1	8.0	3.2	0
14	-4	1.2	4.6	6.2	6.5	6.7	5.7	2.7	0
15	-2	3	3	3	3.5	4	5	2	0

13.16 FINAL STEADY STATE CALIBRATION LEVELS 1958 Upper Aquifer

QATAR GROUNDWATER MODEL

	1	2	3	4	5	6	7	8	9
1	4	4	4	4	4	4	4	4	4
2	4	2.7	2.6	3.4	3.6	3.4	2.6	1.9	1
3	4	2.5	2.9	3.5	3.7	3.3	2.5	1.7	1
4	4	3.0	3.3	3.8	3.9	3.7	3.2	3.1	4
5	4	3.7	3.8	4.0	4.0	3.8	3.6	3.6	4
6	4	3.9	3.9	4.0	3.9	3.9	3.8	3.8	4
7	4	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4
8	4	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4
9	4	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4
10	4	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4
11	4	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4
12	4	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4
13	4	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4
14	4	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4
15	4	4	4	4	4	4	4	4	4

TABLE 13.17 FINAL STEADY STATE CALIBRATE LEVEL 19 Lower Aquifer

QATAR GROUNDWATER MODEL

	1	2	3	4	5	6	7	8	9
1	0	0	0	0	0	0	0	0	0
2	0	0	0	2.2	3.1	1.5	0	0	0
3	0	0	1.7	2.2	2.2	1.9	1.1	0	0
4	0	0	1.8	1.6	1.5	1.5	1.5	0	0
5	0	1.4	2.3	1.6	2.7	2.9	2.7	1.3	0
6	0	2.4	4.7	6.2	6.6	4.7	3.7	1.9	0
7	0	2.9	7.0	9.7	8.4	6.3	4.3	1.5	0
8	0	3.1	8.9	7.3	5.9	4.9	3.5	1.1	0
9	0	3.9	5.9	4.3	2.5	-.7	1.1	0.4	0
10	0	5.3	4.8	2.5	1.4	0.5	0.4	0	0
11	0	4.7	3.6	2.6	1.3	0.8	-0.4	.1	0
12	-2	3.7	3.4	2.9	0.1	0.6	-.8	-.2	0
13	-2	2.0	4.4	4.0	3.4	3.1	2.6	.6	0
14	-4	.5	3.1	3.6	3.4	3.6	.9	.3	0
15	-2	0	3	3	3.5	4	1	.2	0

13.18 FINAL DYNAMIC CALIBRATION LEVELS END 1979
Upper Aquifer

QATAR GROUNDWATER MODEL

	1	2	3	4	5	6	7	8	9
1	4	4	4	4	4	4	4	4	4
2	4	2.5	2.3	2.7	2.7	2.7	2.2	1.7	1
3	4	2.2	2.0	2.0	2.0	1.8	1.6	1.3	1
4	4	2.4	1.8	1.3	1.0	.9	1.5	2.3	4
5	4	2.9	2.1	1.1	-.1	0.0	1.0	2.5	4
6	4	3.0	2.4	1.5	.6	.1	.9	2.5	4
7	4	3.3	2.6	1.9	1.3	.9	1.3	2.6	4
8	4	3.4	2.8	2.2	1.8	1.4	1.6	2.7	4
9	4	3.5	3.0	2.5	2.1	1.8	1.9	2.7	4
10	4	3.6	3.1	2.7	2.4	2.1	2.1	3.0	4
11	4	3.6	3.2	2.8	2.5	2.3	2.5	3.2	4
12	4	3.7	3.3	2.9	2.5	2.5	2.9	3.5	4
13	4	3.7	3.5	3.1	3.0	3.0	3.3	3.7	4
14	4	3.9	3.7	3.5	3.4	3.6	3.7	3.8	4
15	4	4	4	4	4	4	4	4	4

TABLE 13.19 FINAL DYNAMIC CALIBRATION LEVELS END 1979
Lower Aquifer

QATAR GROUNDWATER MODEL

	1	2	3	4	5	6	7	8	9
1	∞	∞	∞	170	255	170	∞	∞	∞
2	∞	510	510	170	55	170	1360	170	∞
3	∞	680	680	340	170	170	1360	2040	∞
4	∞	510	510	510	170	170	850	1360	∞
5	1020	680	170	170	340	680	850	340	850
6	476	510	170	85	170	340	340	321	1020
7	510	425	85	85	170	255	340	321	1190
8	510	51	85	170	170	255	255	391	680
9	255	25	34	680	680	170	170	170	170
10	127	25	17	850	2720	2720	2720	4080	∞
11	127	42	34	1020	2040	1360	170	340	510
12	85	85	85	1020	340	340	34	85	255
13	85	85	85	340	340	170	34	83	340
14	340	340	340	340	340	170	340	340	680
15	340	340	340	340	340	340	170	340	680

TABLE 13.20 CALIBRATED TRANSMISSIVITY
UPPER AQUIFER M^2/day

QATAR GROUNDWATER MODEL

	1	2	3	4	5	6	7	8	9
1	.4	.4	.4	.4	.4	.4	.4	.4	.4
2	.4	.4	.4	.4	.4	.4	.4	.4	.4
3	.4	.4	.4	.4	.4	.4	.4	.4	.4
4	.4	.4	.4	.4	.4	.4	.4	.4	.4
5	.4	.4	.4	.4	.4	.4	.4	.4	.4
6	.4	.4	.4	.4	.4	.4	.4	.4	.4
7	.4	.4	.4	.04	.04	.4	.4	.4	.4
8	.4	.012	.04	.04	.04	.4	.4	.4	.4
9	.4	.012	.04	.04	.4	.4	.4	.4	.4
10	.4	.012	.04	.4	.4	.4	.4	.4	.4
11	.4	.012	.04	.4	.4	.4	.4	.4	.4
12	.4	.4	.4	.4	.4	.4	.4	.4	.4
13	.4	.4	.4	.4	.4	.4	.4	.4	.4
14	.4	.4	.4	.4	.4	.4	.4	.4	.4
15	.4	.4	.4	.4	.4	.4	.4	.4	.4

TABLE 13.21 CALIBRATED STORAGE COEFFICIENT
UPPER AQUIFER ($\times 10^{-2}$)

QATAR GROUNDWATER MODEL

	1	2	3	4	5	6	7	8	9
1	5	5	-	-	-	-	-	-	5
2	5	5	5	-	-	-	2.5	5	5
3	-	5	5	10	10	10	5	5	2.5
4	-	2.5	5	5	5	5	2.5	-	-
5	-	-	5	5	.25	.25	-	-	-
6	-	-	.25	.25	-	-	-	-	-
7	-	-	-	-	-	-	-	-	-
8	-	-	-	-	-	-	-	-	-
9	-	-	-	-	-	-	-	-	-
10	-	-	-	-	-	-	-	-	-
11	-	-	-	-	-	-	-	-	-
12	-	-	-	-	-	-	-	-	-
13	-	-	-	-	-	-	-	-	-
14	-	-	-	-	-	-	-	-	-
15	-	-	-	-	-	-	-	-	-

TABLE 13.22 VERTICAL PERMEABILITY FACTOR

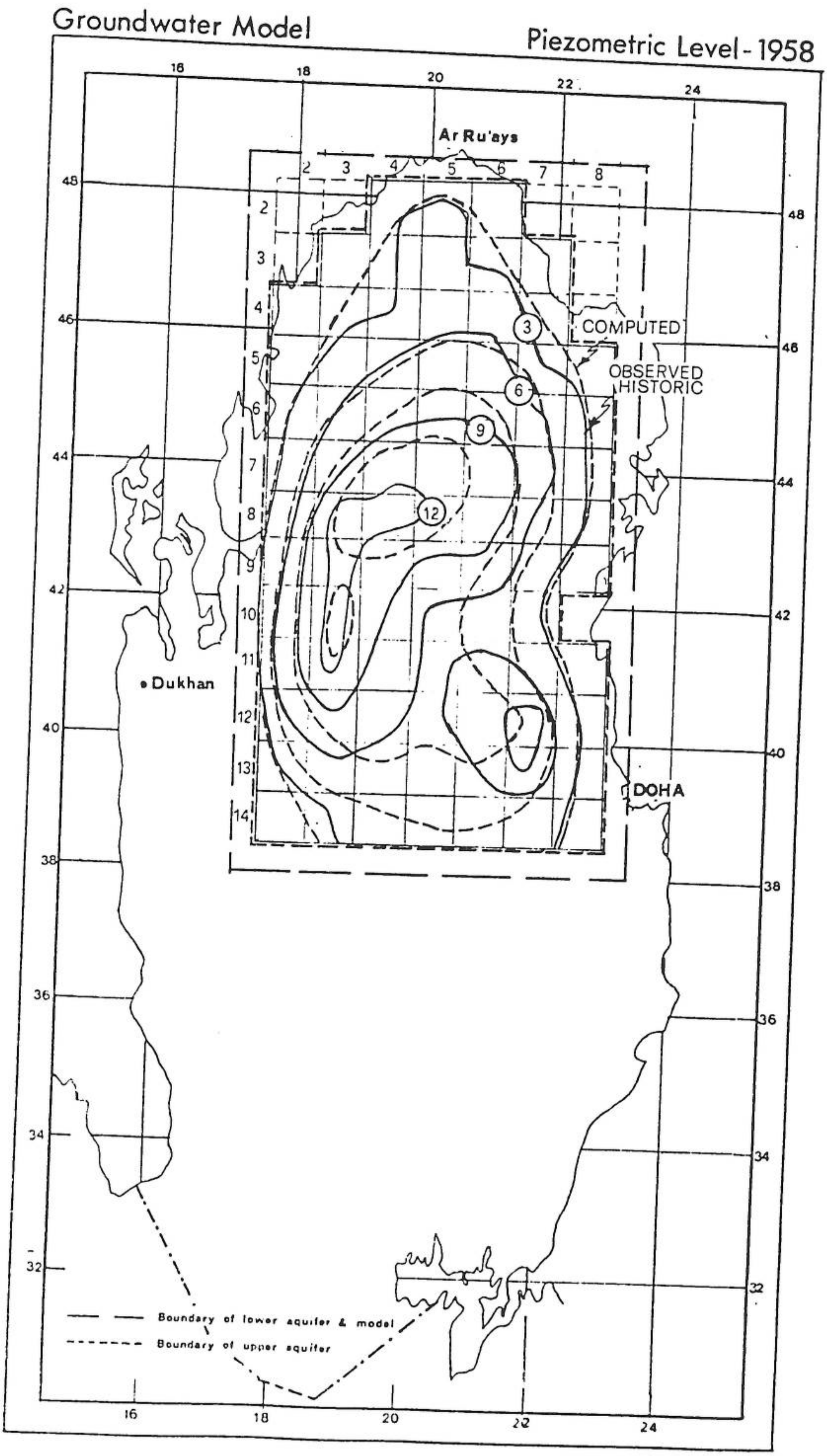

Groundwater Model
Piezometric Level - 1958
Ar Ru'ays
COMPUTED
OBSERVED HISTORIC
Dukhan
DOHA
Boundary of lower aquifer & model
Boundary of upper aquifer

Fig: 13.3

Table 13.23

COEFFICIENTS FOR FINAL CALIBRATION

1	Transmissivity in Lower Aquifer	3000 m^2/day
2	Storage Coefficients in Lower Aquifer	0.0001
3	Proportion of pumping from combined aquifers coming from upper aquifer	0.30

13.8.5 Water Balance

A water balance is presented in Table 13.24 for the 22 year period 1978-79. These data can
be used to calibrate the Lumped Parameter Model developed during the project which is of consider-
able use in gross evaluations of alternatives. Table 13.25 gives the water balance for the model
area using the detailed annual rainfall figures.

Interval (year)	Period (Calendar year)	Upper Aquifer						Lower Aquifer		
		Irrigation Returns	Total abstraction	Recharge Balance	Outflow	Transfer (upper to lower aquifer)	Change in Storage	Total abstraction	Change in Storage	Change in fresh water reserves
2	1958-59	1.2	2.9	25.9	22.9	2.2	-0.2	2.9	-.03	+ 0.5
2	1960-61	2.2	5.6	23.3	22.3	2.3	-1.2	5.4	-.03	- 2.8
2	1962-63	3.2	8.2	21.7	21.3	2.5	-2.0	8.0	-.03	- 5.3
2	1964-65	4.3	10.8	20.2	20.2	2.5	-2.5	10.5	-.03	- 7.8
2	1966-67	5.3	13.3	18.6	18.9	2.6	-2.8	13.0	-.03	-10.2
2	1968-69	6.3	15.9	17.1	17.6	2.7	-3.1	15.5	-.03	-12.6
2	1970-71	6.6	18.3	15.6	16.2	2.8	-3.3	14.8	-.03	-15.0
2	1972-73	8.2	20.8	14.1	14.7	2.8	-3.3	20.4	-.03	-17.4
2	1974-75	9.2	23.2	12.7	13.3	2.8	-3.4	22.7	-.03	-19.7
2	1976-77	10.1	25.6	11.2	11.8	2.9	-3.4	25.0	-.03	-22.0
2	1978-79	11.2	28.0	9.8	10.4	2.9	-3.5	27.8	-.03	-24.3
22		135.6	345.2	380.4	379.2	58.0	-57.4	332	-0.66	-273.2

Table 13.24 WATER BALANCE FOR CALIBRATION RUN

Notes : 1 Quantities : Mm^3 per year.

2 Recharge assumed at an annual average 26.7 Mm^3.

3 Irrigation returns. 20% of combined extractions.

4 Recharge balance. Natural recharge + irrigation returns - total abstraction.

5 Outflow. Transfer across model boundary to sea and evaporation from sabkha.

6 Overall storage coefficient 0.004

7 Balance not exact due to iteration procession.

The water balance shows quite clearly the relationship between abstraction from the lower
aquifer and displacement. There is relatively little flow from the upper aquifer to the lower and
splacement implies either the moving inland of a saline front from the sea or the upward replace-
nt of freshwater by salt water from lower in the geological sequence.

Inter-val (year)	Period (Hydro-logical (year)	Upper Aquifer							Lower Aquifer		
		Natural Recha-rge	Irriga-tion Returns	Total Abstra-ction	Recharge Balance	Outflow	Transfer (upper to lower aquifer)	Change in Storage	Total Abstra-ction	Change in Storage	Change in fresh water reserves
2	1959/61	53.4	2.2	5.4	50.5	46.1	4.5	0.0	5.6	-.06	+ 0.8
2	1961/63	53.4	4.2	10.2	47.9	45.0	4.9	-1.9	10.7	-.06	- 5.4
2	1963/65	53.4	6.1	15.0	45.3	43.4	5.2	-3.2	15.7	-.06	-10.0
2	1965/67	53.4	8.1	19.8	42.7	41.5	5.5	-4.2	20.7	-.06	-14.7
2	1967/69	53.4	10.0	24.4	40.2	39.3	5.8	-4.8	25.6	-.06	-19.5
2	1969/71	53.4	11.9	29.2	37.7	37.0	6.0	-5.3	30.4	-.06	-24.1
1	1971/72	25.3	6.6	16.2	16.5	18.0	3.4	- 4.9	17.0	-.04	-13.5
1	1972/73	8.7	7.1	17.4	-0.7	13.0	1.1	-14.9	18.2	-.07	-16.9
1	1973/74	21.6	7.6	18.6	11.6	12.9	1.6	2.8	19.3	-.02	-17.6
1	1974/75	28.9	8.0	19.7	18.3	14.1	2.5	1.6	20.5	-.01	-17.8
1	1975/76	63.9	8.5	20.8	52.7	22.6	9.6	20.5	21.7	0.1	-12.2
1	1976/77	51.8	8.9	21.9	40.0	23.2	10.2	6.6	22.8	0	-12.6
1	1977/78	13.4	9.4	23.0	1.0	15.6	4.3	- 0.1	24.0	-.14	-19.4
1	1978/79	26.7	9.8	24.1	13.7	14.9	3.8	- 5.0	25.1	-.04	-21.1
20		560.7	108.4	265.7	417.4	386.6	68.4	-18.4	277.3	-0.78	-204.0

Table 13.25 WATER BALANCE

Notes : 1 Quantities. Mm^3 per Interval (2 years : 1959-71 1 year; 1971-79)

2 Recharge 1959-1971 Estimated annual average 26.7 Mm^3
1971-1979 Based on water balance estimates

3 See Fig. 13.24 for other notes.

The computed levels in the lower aquifer for the end of the dynamic calibration period are quite low tending to zero in high abstraction nodes. It is not known whether these values are realistic as individual pressure measurements for that aquifer are not available. The corresponding water levels in the upper aquifer are 1.5 metres above sea level. These low values could be increased by reducing abstraction in the lower aquifer. The implication of increasing the transmissivity of the lower aquifer is that its thickness must increase which in term means increasing it into the saline water zone. It then follows that salt water is replacing freshwater not only laterally, as has been principally assumed, but also vertically.

13.8.6 Hydrogeological Estimates of the Water Balance

The above modelled estimates of groundwater reserves may be supplemented by others based upon measurements of aquifer parameters as detailed in Chapter 10.

For the Northern Groundwater Province the Rus and Umm er Radhuma aquifers are assessed in a linked manner for reasons already discussed. However, the gross model values and their inter dependence may be conceived as follows:-

Northern Groundwater Province

Rus Formation

Effective area (coastal belt excluded)	4000 km^2
Effective thickness	25 m
storativity	$4x10^{-4}$
Original volume in storage	40 Mm^3

NB This assumes that the average value of storativity of the depression areas of the Rus, where wells exist and test pumping has been carried out, applies overall, which should be accepted as an over estimation.

Given a storage deficit of zero for 1958 and a steady increase annually, the total for the 22 year period is assessed at 20 Mm^3, the average, 0.9 $Mm^3.yr^{-1}$ and the present rate of change is about 2 $Mm^3.yr^{-1}$. Thus it would appear that some 50% of the originally available Rus Formation storage has been removed so far. Assuming that a constant rate of deficit of 2 $Mm^3.yr^{-1}$ now applies, the remaining real original reserves of the upper aquifer alone could be depleted to zero in a further period of 40 years. However, only 50% of this storage may be extracted before mixing with saline groundwater and intrusive sea water is sufficient to contaminate the remainder beyond usability and this period therefore reduced to 20 years or by the year 2000.

The compensation for the 2 $Mm^3.yr^{-1}$ deficit may be apportioned in the ratio of 0.5 due to declining water levels and 1.5 by the upward transfer from the lower aquifer. It is likely that the rate of decline of the water levels of the upper aquifer will have reduced as the level approaches the datum level of + 4 m of the lower aquifer. The proportion of water being removed from the upper aquifer compared to the lower will also decline comparably. The closing phase of this hypothesis is where the upper aquifer no longer had a head advantage over the lower and the upper aquifer deficit is transferred entirely to the lower aquifer. That this situation has already been reached is shown by Enclosure 4 where only to the south of El Ga'iyah, in the Northern Groundwater Province, is the composite head higher than + 4 m. At this stage the decline in reserves is from the lower aquifer only with the upper acting only as conduit.

While only limited records of water levels for 1958 exist, a comparison between Figures 10.2 and 10.3 indicates that the maximum declines have occurred as expected near the centre of the freshwater body and are of the order of 7 m with diminishing declines coastward. Assuming an average decline of 3.5 m over the effective area of the Rus Formation, the reduction in reserves indicated by the falls in water level is some 5 Mm^3. That the Rus deficit is thought to amount to some 20 Mm^3 over this period indicates that 15 Mm^3 of Umm er Radhuma storage had been withdrawn via the Rus Formation after upward replacement transfer.

Umm er Radhuma Formation

Effective areas (coastal belt excluded)	4000 km^2
Average thickness of freshwater body	50 m
Storativity	$1.25x10^{-2}$
Original volume in storage	2500 Mm^3

Assuming a storage deficit of zero for 1958 and a steady annual increase, the total for the 22 year period is 220 Mm^3, the average 10 $Mm^3.yr^{-1}$ and the present rate of change in storage is about 20 $Mm^3.yr^{-1}$. Thus some 9% of the original total available volume has been removed so far without including vertical transfer to the upper aquifer. If this now takes place at 2 $Mm^3.yr^{-1}$, an average would be 1 $Mm^3.yr^{-1}$ for the 22 year period giving a total of 22 Mm^3. Thus the total decline in original reserves from the Umm er Radhuma amounts to some 242 Mm^3.

Assuming a constant rate of decline of reserves of 22 $Mm^3.yr^{-1}$ the remaining storage of 2260 Mm^3 will be depleted to zero in 100 years. Contamination, as explained above, could reduce this period to one half and thus if equilibrium between the two Formations is maintained, the life of the combined fresh water body could be of the order of 50 years to the year 2030.

Water Balance estimates for the Northern and Southern Groundwater Province and separately for the Groundwater Model Area are as follows:-

WATER BALANCE

NORTHERN GROUNDWATER PROVINCE

Mean Rainfall	50 mm. yr^{-1}
Effective Recharge area	3500 km^2
Recharge at 12% of rainfall	$21 \text{ Mm}^3. \text{ yr}^{-1}$

Steady State Conditions (pre 1955)

Rus Aquifer

• Recharge	$+ \ 21 \text{ Mm}^3. \text{ yr}^{-1}$	
• Discharge		
Transfer to Southern Groundwater Province (Sabkhas in west)	$- \ 10 \text{ Mm}^3. \text{ yr}^{-1}$	
Losses to the sea, east and north	$- \ 11 \text{ Mm}^3. \text{ yr}^{-1}$	
	$- \ 21 \text{ Mm}^3. \text{ yr}^{-1}$	BALANCED

Umm er Radhuma Aquifer

• Recharge	+ ZERO	
• Discharge		
Agricultural abstraction	- ZERO	
		BALANCED

Unbalanced Condition (1930)

Rus Aquifer

• Recharge	$+ \ 21 \text{ Mm}^3. \text{ yr}^{-1}$	
Irrigation return (at 20%)	$+ \ 7 \text{ Mm}^3. \text{ yr}^{-1}$	
	$+ \ 28 \text{ Mm}^3. \text{ yr}^{-1}$	
• Discharge		
Agricultural abstraction	$- \ 10 \text{ Mm}^3. \text{ yr}^{-1}$	
Domestic abstraction	$- \ 6 \text{ Mm}^3. \text{ yr}^{-1}$	
Transfer to sabkha evaporation	$- \ 7 \text{ Mm}^3. \text{ yr}^{-1}$	
Losses to sea (east and north)	$- \ 8 \text{ Mm}^3. \text{ yr}^{-1}$	
	$- \ 30 \text{ Mm}^3. \text{ yr}^{-1}$	
	$- \ 2 \text{ Mm}^3. \text{ yr}^{-1}$	DEFICIT

Umm er Radhuma Aquifer

• Recharge and Irrigation Returns	+ ZERO	
• Discharge		
Agricultural abstraction	$- \ 26 \text{ Mm}^3. \text{ yr}^{-1}$	
Transfer to Rus Aquifer	$- \ 2 \text{ Mm}^3. \text{ yr}^{-1}$	
	$- \ 28 \text{ Mm}^3. \text{ yr}^{-1}$	DEFICIT
	$- \ 28 \text{ Mm}^3. \text{ yr}^{-1}$	OVERALL DEFICIT

WATER BALANCE

SOUTHERN GROUNDWATER PROVINCE
(excluding the Alat Groundwater Province)

Mean Rainfall	50 mm. yr^{-1}
Effective Recharge area	8000 km^2
Recharge at 8% of rainfall	32 Mm^3. yr^{-1}

Steady State Conditions (pre 1955)

Rus Aquifer

• Recharge	+ 32 Mm^3. yr^{-1}	
Transfer from Northern Groundwater Province to sabkhas in west	+ 10 Mm^3. yr^{-1}	
	+ 42 Mm^3. yr^{-1}	
• Discharge		
Sabkha evaporation (200 km^2 active area)	- 20 Mm^3. yr^{-1}	
Losses to sea east and west	- 22 Mm^3. yr^{-1}	
	- 42 Mm^3. yr^{-1}	BALANCED

Umm er Radhuma Aquifer

• Recharge	+ ZERO	
• Discharge		
Agricultural abstraction	- ZERO	
	BALANCED	

Unbalanced Conditions (1980)

Rus Aquifer

• Recharge	+ 32 Mm^3. yr^{-1}	
Irrigation returns (at 20%)	+ 2 Mm^3. yr^{-1}	
	+ 34 Mm^3. yr^{-1}	
• Discharge		
Agricultural abstraction	- 10 Mm^3. yr^{-1}	
Domestic abstraction	- 1 Mm^3. yr^{-1}	
Losses from sabkhas (100 km^2)	- 11 Mm^3. yr^{-1}	
Losses to sea (east and west)	- 15 Mm^3. yr^{-1}	
	- 37 Mm^3. yr^{-1}	
	- 3 Mm^3. yr^{-1}	DEFICIT

Umm er Radhuma Aquifer

• Recharge and Irrigation returns	+ ZERO	
• Discharge		
Agricultural abstraction	- ZERO	
	BALANCED	

	- 3 Mm^3. yr^{-1}	OVERALL DEFICIT

WATER BALANCE

NORTHERN QATAR : MODEL AREA

Mean Rainfall	$50\ mm.\ yr^{-1}$	
Effective Recharge area	$5000\ km^2$	
Recharge at 12% of rainfall	$28\ Mm^3.\ yr^{-1}$	
Steady State Conditions (pre 1955)		
Rus Aquifer		
• Recharge	$+\ 28\ Mm^3.\ yr^{-1}$	
• Discharge		
Losses by sabkha evaporation ($100\ km^2$ active area)	$-\ 10\ Mm^3.\ yr^{-1}$	
Losses to the sea, east, west and north	$-\ 18\ Mm^3.\ yr^{-1}$	
	$-\ 28\ Mm^3.\ yr^{-1}$	BALANCED
Umm er Radhuma Aquifer		
• Recharge	+ ZERO	
• Discharge		
Agricultural Abstraction	- ZERO	
		BALANCED
Unbalanced Condition (1980)		
Rus Aquifer		
• Recharge	$+\ 28\ Mm^3.\ yr^{-1}$	
Combined Irrigation Returns (at 20%)	$+\ 9\ Mm^3.\ yr^{-1}$	
	$+\ 37\ Mm^3.\ yr^{-1}$	
• Discharge		
Agricultural abstraction	$-\ 18\ Mm^3.\ yr^{-1}$	
Domestic abstraction	$-\ 6\ Mm^3.\ yr^{-1}$	
Losses by sabkha evaporation	$-\ 7\ Mm^3.\ yr^{-1}$	
Losses to the sea (east, west and north)	$-\ 13\ Mm^3.\ yr^{-1}$	
	$-\ 44\ Mm^3.\ yr^{-1}$	
	$-\ 5\ Mm^3.\ yr^{-1}$	DEFICIT
Umm er Radhuma Aquifer		
• Recharge and Irrigation Returns	+ ZERO	
• Discharge		
Agricultural abstraction	$-\ 26\ Mm^3.\ yr^{-1}$	
	$-\ 26\ Mm^3.\ yr^{-1}$	DEFICIT
	$-\ 31\ Mm^3.\ yr^{-1}$	OVERALL DEFICIT

13.9 SALINE INTRUSION

It is difficult to calculate accurately the effect abstraction has on saline intrusion. Figure 13.5 shows schematically the relationship between freshwater and more dense saline water. For a given permeability the angle of the interface to the horizontal increases with outflow and similarly lower permeability resulting in smaller outflow, also steepens the interface angle. Thus as outflow is reduced by abstraction, for example, the saline front will advance by reducing its angle with the horizontal as well as an overall lateral migration inland. In a water table aquifer the top of the front may stay positioned at the sea coast boundary whereas in the artesian aquifer the whole front may move in.

A moving saline front has therefore been modelled and, at the 1978-1979 level of abstraction, the displacement is about 20 Mm^3 per year. If this volume is distributed over the 225 km front pertaining to the model and assuming an active thickness of 10 m, with an implied storage coefficient of 0.1 near the coast, the average rate of advance of the saline front is about 90 metres per year. Actual abstractions are concentrated locally and local rates of replacement by saline water could be much higher.

If either aquifer is unbounded in the vertical sense a freshwater lens may develop. This can be serious in terms of water development as saline water only has to displace a few metres of freshwater before appearing in the abstraction. If the aquifer is physically bounded below by an aquitard, the saline front could be allowed to advance laterally be several kilometres without adverse effect.

If abstraction is increased so as to reduce natural outflow of freshwater to zero and into deficit, the saline front will advance inland to fill the void left by the freshwater. An estimate can be made of the volume of freshwater reserved abstracted in a given period; this volume will be the difference between the total extracted and the natural recharge during the period and will be displaced by the saline front advancing, less any outflow over the interface. By assuming a given outflow rate, and from the aquifer properties an estimate can be made of the rate of advance of the saline front for a given rate of net abstraction.

For the upper aquifer, assume, over a 80 km front measured north to south, that there is an excess of abstraction over input of 5 Mm^3 per year. Let the aquifer be 20 m thick with a storage coefficient of 0.004. The average rate of advance of the saline front will be :

$$\frac{5 \times 10^6}{20 \times 80 \times 10^3 \times 0.004} = 800 \text{ m/year}$$

The maximum rate could be about 1000 m/year in areas of highest abstraction.

For the lower aquifer assume over a 80 km front measured north to south that there is n excess of abstraction over inflow of 20 Mm^3 per year. Let the aquifer be 10 m thick with hydraulic conductivity of 0.10. The average rate of advance of the saline front will be :

$$\frac{20 \times 10^6}{10 \times 80 \times 10^3 \times 0.1} = 250 \quad m/year$$

e maximum rate could be about 500 m/year.

These figures of 500 to 1000 m/year for the advance of the saline front due to current 977-79) rates of abstraction is believed to be typical in areas where the actual abstraction is taking place.

In terms of water resources development, if abstraction is less than recharge a new equilibrium situation will develop which may be acceptable. If deficit abstraction takes place there will be an replacement in the aquifer by saline water and the saline front will go on a vancing indefinitely. The rate of advance will be highest towards centres of major abstra- ction. The damage to the aquifer, in terms of rendering its reserves unsuitable, will occur slowly because the effect of over abstraction is masked by the contemporary consumption of s red freshwater. Once encroachment has occurred however it is very difficult to flush out t . salt water. If over-abstraction, beyond the limit which could be regarded as prudent, is adopted as a policy, the consequences in terms of increased saline encroachment and a permanent radation of the aquifer must be borne in mind.

Even a recommendation to reduce abstraction to the level of estimated recharge will have a erse long term consequences in terms of continuing saline replacement in the lower aquifer. e harge and irrigation returns are to the upper aquifer only which has lower transmissivities and storage coefficients. Thus the situation may be reached that the combined volumes of recharge and returns exceed the storage capacity of the upper aquifer, water levels rise and flow to the sea actually increases, fed from the declining freshwater reserves of the lower quifer.

The situation is complicated by the two layer aquifer aspect. The transfer to the lower quifer from the upper aquifer has been virtually reduced to zero by abstraction from both quifers so that the heads are everywhere very similar. This means that all the water ently being taken from the lower aquifer is being obtained by displacement of freshwater salt water.

Even if only a reasonable level of agriculture is to be pursued indefinitely in Qatar, ill have to become highly water efficient, and further supplies of freshwater for riculture, other than groundwater, will have to be found in the medium and long term.

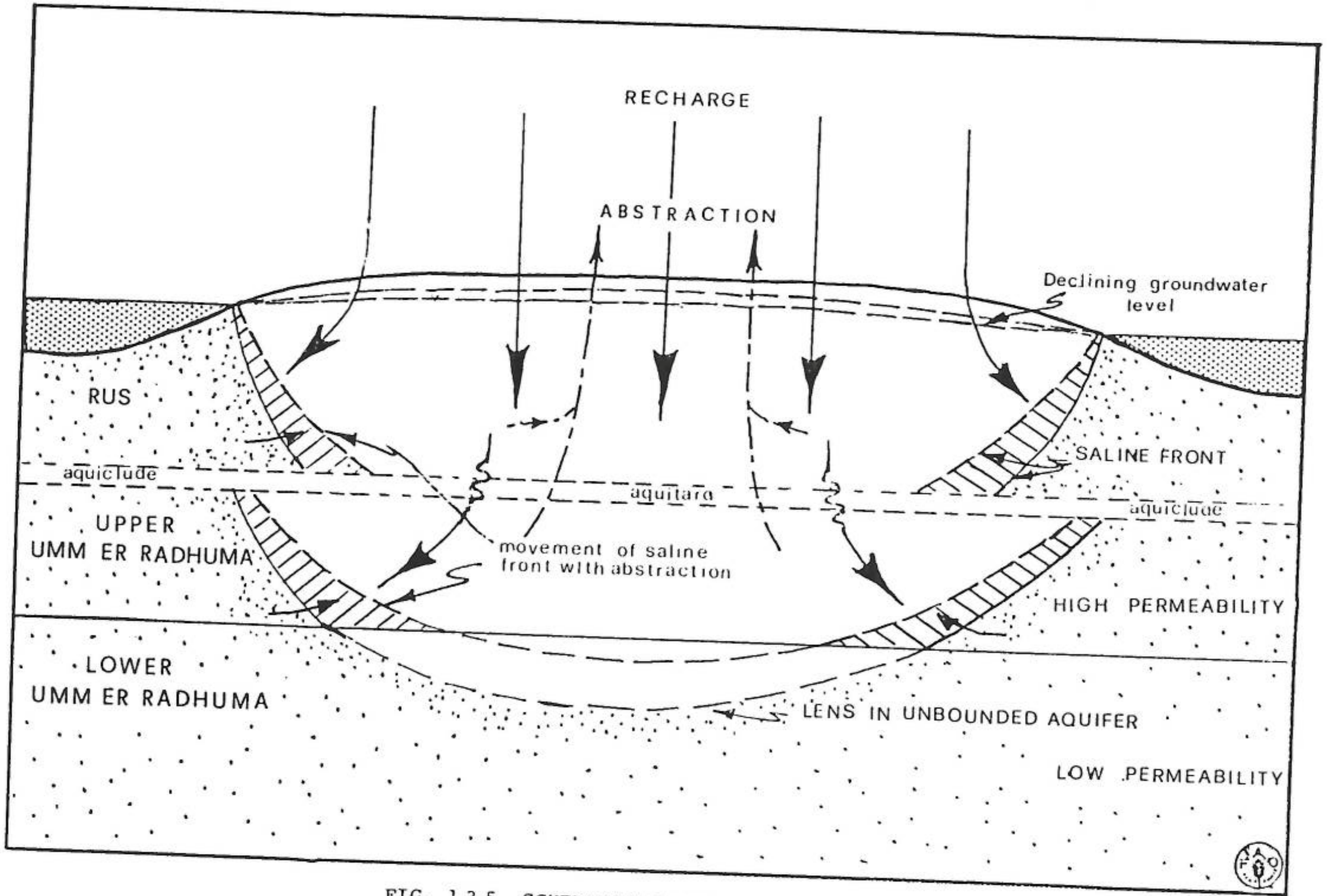


FIG. 13.5 SCHEMATIC DETAIL SHOWING SALINE INTRUSION

For the lower aquifer assume over a 80 km front measured north to south that there is an excess of abstraction over inflow of 20 Mm^3 per year. Let the aquifer be 10 m thick with a hydraulic conductivity of 0.10. The average rate of advance of the saline front will be :

$$\frac{20 \times 10^6}{10 \times 80 \times 10^3 \times 0.1} = 250 \text{ m/year}$$

The maximum rate could be about 500 m/year.

These figures of 500 to 1000 m/year for the advance of the saline front due to current (1977-79) rates of abstraction is believed to be typical in areas where the actual abstraction is taking place.

In terms of water resources development, if abstraction is less than recharge a new equilibrium situation will develop which may be acceptable. If deficit abstraction takes place there will be an replacement in the aquifer by saline water and the saline front will go on advancing indefinitely. The rate of advance will be highest towards centres of major abstraction. The damage to the aquifer, in terms of rendering its reserves unsuitable, will occur slowly because the effect of over abstraction is masked by the contemporary consumption of stored freshwater. Once encroachment has occurred however it is very difficult to flush out the salt water. If over-abstraction, beyond the limit which could be regarded as prudent, is adopted as a policy, the consequences in terms of increased saline encroachment and a permanent degradation of the aquifer must be borne in mind.

Even a recommendation to reduce abstraction to the level of estimated recharge will have adverse long term consequences in terms of continuing saline replacement in the lower aquifer. Recharge and irrigation returns are to the upper aquifer only which has lower transmissivities and storage coefficients. Thus the situation may be reached that the combined volumes of recharge and returns exceed the storage capacity of the upper aquifer, water levels rise and outflow to the sea actually increases, fed from the declining freshwater reserves of the lower aquifer.

The situation is complicated by the two layer aquifer aspect. The transfer to the lower aquifer from the upper aquifer has been virtually reduced to zero by abstraction from both aquifers so that the heads are everywhere very similar. This means that all the water currently being taken from the lower aquifer is being obtained by displacement of freshwater by salt water.

Even if only a reasonable level of agriculture is to be pursued indefinitely in Qatar, it will have to become highly water efficient, and further supplies of freshwater for agriculture, other than groundwater, will have to be found in the medium and long term.

XIV

WATER RESOURCES DEVELOPMENT

14.1 INTRODUCTION

The foregoing summary of available resources and their present levels of utilization shows that Qatar faces serious constraints in the development of water and land resources to meet agricultural, domestic and industrial demand for water and increased agricultural production to achieve even modest levels of food self-reliance. This has been brought about by the uncontrolled exploitation of the groundwater resources to a point where groundwater is being abstracted at a rate nearly twice that of replenishment from natural recharge, which is inefficiently used in the irrigation of a small cultivated area, equivalent to 0.2% of the country's soil resources. Not only are the groundwater resources being over-exploited, inefficient irrigation methods have degraded the soil through excessive salinization bringing about an estimated net loss of about 800 ha of arable soil area since 1970.

The problems of water resources and agricultural development to achieve food self-reliance cannot therefore be viewed separately for it is not simply a matter of augmenting water resources from other sources such as distilled sea water but rather one of integrating supply with optimal use in agriculture. Furthermore, the raising of irrigation efficiency in itself cannot be achieved merely by introducing improved irrigation technology but must form part of an overall agricultural and rural development programme which would include action to modify, rectify or improve the present land tenure system; provide assistance to farmers in regard to farm layout, land levelling and farm mechanization, improve capital credit and marketing facilities, introduce a pricing system and regularize the farm labour force.

Project investigations have covered both technical and organizational aspects of water and agriculture, and this work has demonstrated the technical potential that exists for a considerable increase in agricultural production with reduced amounts of water, details of which are presented in Technical Reports 1 to 4. However, many of these technical solutions will be largely nullified unless the Government mounts an intensive effort to overcome the organizational and institutional problems identified by the project and for which recommendations have also been made.

14.2 ESTIMATED FUTURE WATER AND FOOD REQUIREMENTS

14.2.1 Population Projections

The 1970-80 decade has been one of spectacular development of the basic infrastructure of the country and the large influx of population associated with this is not expected to be maintained in the future. On the assumption that the 1980 population is that which is required to maintain the present adequate infrastructure and a more modest rate of population increase of 2.8% will be maintained to the end of the century, (Agriculture Toward 2000, FAO, 1979) it is estimated that the population by that time will be approximately 437,000.

14.2.2 Water

A fundamental requirement to the future development of the State's economy and in furtherance of the aim of food self-reliance is an assured water supply. The foregoing sections of this report have provided an assessment of the country's groundwater resources, and how these have been exploited in excess of the safe yield of the aquifers for agriculture and the growth of complementary sea water distillation production to almost meet the entire domestic demand.

14.2.2.1 Domestic and Commercial Demand

The determination of future demand to meet the domestic and commercial requirements of the capital city of Doha, the industrial town of Umm Said and important rural centres and other outlying areas has posted a number of problems. Hitherto there has been considerable undertainity with regard to true per capita consumption and the full extent of losses and extent of urban garden irrigation, the actual population and thirdly the rate at which it is likely to grow over the next two decades. Project estimates and those of various other agencies involved in development planning are agreed that the total population by the year 2000 is likely to be of the order of 440,000. With an assumed consumption of 610 l day^{-1} with a peak demand rising to 910 l day^{-1} and that 5% of the population in 1980 have no access to mains water and this proportion will decline to 2% by 2000, the following table shows the total estimated domestic - commercial water demand.

Table 14/1

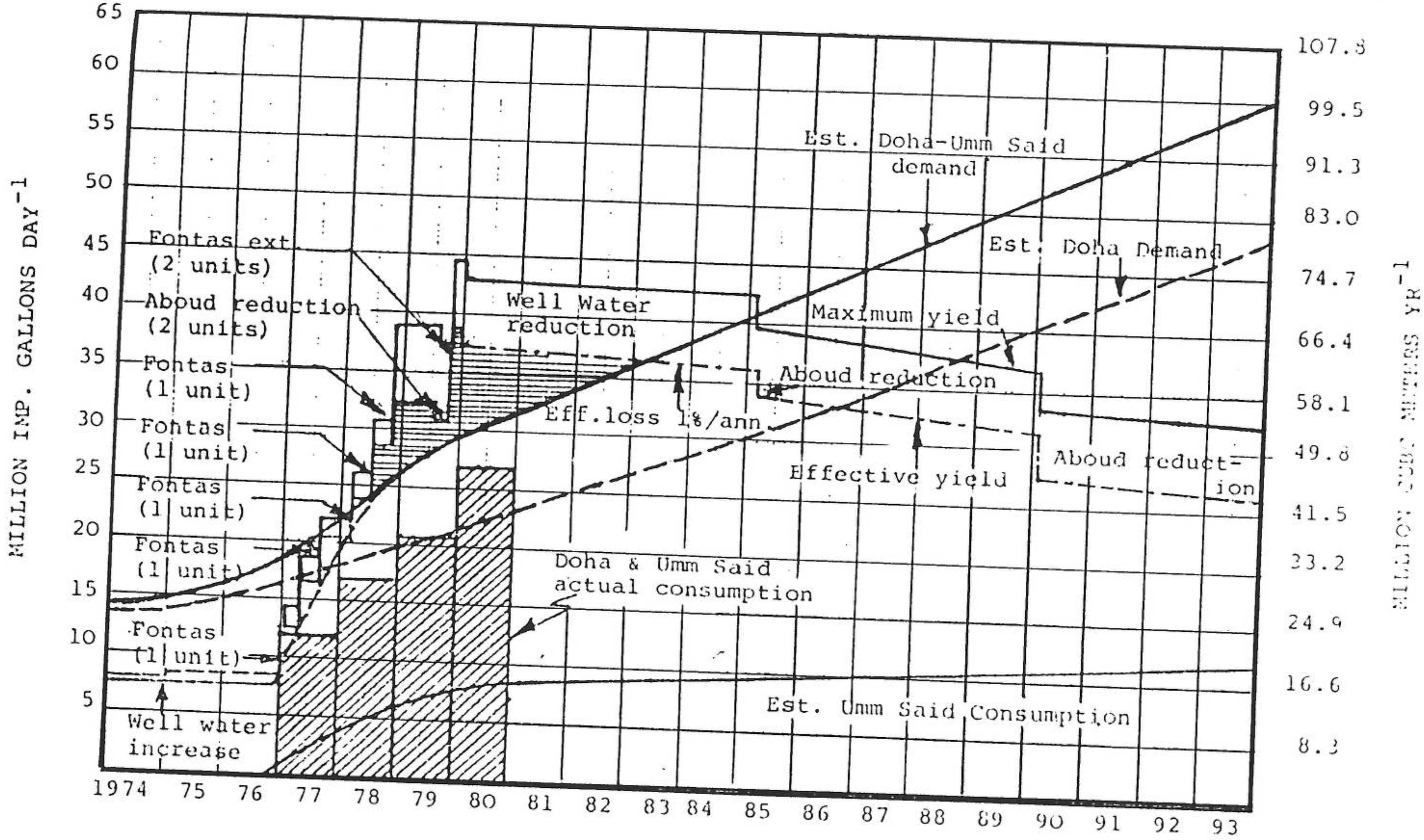
Domestic - Commercial Water Demand

1980 - 2000

m^3 day^{-1}

	1980	1990	2000
Total population	262,000	345,000	437,000
Population Served	249,000	334,600	428,250
Demand per capita			
(av.)	0.61	0.61	0.61
(peak)	0.91	0.91	0.91
Average Demand (m^3/d)	151,890	210,450	266,570
Peak Demand (m^3/d)	226,600	191,500	390,000

In 1976 ASCO, consulting engineers to the Water Department, made an estimate of future domestic and commercial demand for Doha and Umm Said. This projection is shown in Fig. 13/1 upon which is also shown the actual total gross domestic - commercial consumption for the period 1977-80. This shows that total consumption has been slightly over-estimated because the expected demand from Umm Said has not grown as rapidly as expected. The diagram remains, however, a useful planning guide for it also illustrates planned changes in distillation capacity and the phasing out of the groundwater contribution without any significant changes in plan since then. This shows the expansion of the Ras Abu Aboud plant by 2 additional units in 1978 to bring production up to 19.08 Mm^3yr^{-1} (11.5 m.g.d.) and the commissioning of new plant at Ras Abu Fontas in 1977 with an initial production of 13.27 Mm^3yr^{-1} (8 m.g.d.) rising to a maximum of 53.09 Mm^3yr^{-1} (37.5 m.g.d.) in 1980. This remains the total installed capacity and water supply after blending, the closure of northern well-fields and the two original units at Ras Abu Aboud being offset by the addition of a smaller quantity of brackish groundwater for blending purposes. Without further construction of new distillation plants and plant efficiency losses at 1% per annum, demand will exceed supply by 1983. In anticipation



ESTIMATED WATER DEMAND AND PLANNED PRODUCTION

DOHA-UMM SAID 1974-1994

(after ASCO, Qatar, 1976)

of this tenders for installation of four further 22,500 m^3day^{-1} desalinisation units were invited in early 1981 to bring the total installed capacity to 85 Mm^3yr^{-1}. In addition, invitations to consultants have been issued to prepare the planning of new power and desalinisation works at Ras Laffan in north-east Qatar as part of the overall development of the North West offshore gas field.

A comprehensive study of power and water needs to the year 2020 forms a central part of a recent study undertaken by Shell International Gas Ltd. for QGPC[1/]. In this study a population of between 351,000 and 379,000 is projected for 2000 depending upon which future development scenario is adopted. Under a static state scenario it is estimated that by 2000 distillation capacity would need to be raised to 481,000 m^3day^{-1} implying a gross per capita consumption of 1270 l day^{-1} which is considered to be very high and inconsistent with consumption planning figures adopted elsewhere under similar circumstances.

14.2.2.2 Industrial Demand

The present demand for industrial undertakings, all located in Umm Said is 5600 m^3 day^{-1} or 2.04 Mm^3 yr^{-1} and is expected to rise to double this quantity by 1985 and thereafter remain at a constant level in the absence of any large scale industrial development in that area.

14.2.2.3 Agricultural Demand

Gross extraction for irrigation and farm use amounted to 77 Mm^3 in 1980 which, after application of a 20% irrigation return factor, is equivalent to a net extraction of 61.2 Mm^3yr^{-1}. The growth of groundwater abstraction for irrigation has been considered in Chapter XII and from the water balance presented in Chapter XIII it is seen to be entirely responsible for the present state of 'mining' of groundwater in the main northern freshwater aquifer area and observed increases in total groundwater salinity noted over the period 1972-80.

In the face of this serious overdraft the safe yield of the northern aquifer and apparently uncontrolled exploitation, an Emiri decree promulgated in 1980 prohibited all further development of groundwater for agriculture and all drilling rigs in the country were impounded. With the cessation of pumping for domestic purposes and the curtailment of further well development, the deficit in the water balance of the northern recharge zone may be expected to improve in the future. However, the probable return period of annual recharge equivalent to present extraction is estimated to be once in 4 years and the aquifer would therefore remain in over-draft in the long-term. The strict enforcement of the ban on drilling is also not universally applied and a number of new wells have in fact been brought into commission more recently.

Future demand for water for agriculture will depend entirely upon which future option government may decide to pursue which may range from restricting extraction to the safe yield of the aquifer with augmenting the present yield of the aquifer and effluent supplies with considerably larger quantities of distilled sea water with the aim of achieving as high degree of food self-reliance. These various options are discussed in the following sections.

14.2.3 Food Requirements

There is considerable uncertainity in estimating food requirements two decades ahead of the present. Past projections have invariably under-estimated growth patterns and in the case of Qatar lack of an accurate population figure is one which, when used as a planning base, may lead to serious error. This is particularly relevent in the case of food requirements as these are normally projected on the basis of present per capita

---

1/ Internal Energy Supply and Demand, Qatar, Shell International Gas Ltd. 1980.

consumption. With these qualifications in mind therefore the growth of food consumption with estimated population in the years 1975 and 1979 have been studied in some detail representing a transitional phase from traditional food requirement habits to acquired tastes expected to continue into the future.

In the four-year period under consideration food consumption almost doubled from 90,000 to 198,000 tons whilst the population is estimated to have increased by 41% or at a rate of 9% per annum. This disparity is reflected in the higher per capita food consumption whereby there was 40% increase from 519 kg in 1975 to 726 kg in 1979. There is also a clear change in consumption pattern with a marked shift toward a higher consumption of meat, dairy products, processed vegetables and fruit, sugar and beverages, all consistent with the general increase in the higher per capita income associated with very considerable increase in GNP since 1973/74. Assuming that this consumption pattern will be maintained over the planning period to the end of the present century, food requirements by 2000 may therefore be of the order of :

Table 14/2

Possible Food Consumption 2000

Meat and Fish	24,000	tons
Dairy Products	21,000	"
Wheat Grain	50,000	"
Rice and Other Grain	75,000	"
Fresh Vegetables	40,000	"
Other Veg./Fruit	75,000	"
Sugar, Confectionary	9,000	"
Beverages	6,000	"
Animal Food	80,000	"
Total	380,000	tons

14.3 OPTIONS IN WATER AND AGRICULTURAL DEVELOPMENT AND PROPOSED PROJECTS

14.3.1 Introduction

With large accumulated capital reserves and committed to an energetic development programme, one aim of which is to attain self-reliance in foodstuffs, the Government of Qatar is understandably anxious to undertake a considerable horizontal expansion of agriculture. However, the work of the project has clearly identified the circumscribed natural resource environment of Qatar and the many limitations and constraints militating against such an agricultural policy. The major limitation is lack of an adequate water resource to sustain such an expansion and secondly, adverse climatic conditions which impose a severe constraint to diversified arable crop production on the limited area of arable soils.

It has been stressed earlier that neither water nor agricultural development may be regarded in isolation from each other as they are mutually dependent. Thus, as in the development of water resources, there are similarly two major development options for agriculture which are corollaries of the water resources development options, - a vertical expansion designed to stabilize the present serious groundwater overdraft and increase production on existing land through a concerted extension programme and the introduction of modern water saving techniques under close supervision, augmented by the development of new areas irrigated by sewage effluent water and selective cropping with different qualities of groundwater in the south-western region of the country, or a horizontal expansion of agriculture based on distilled sea water, groundwater and sewage effluent water.

By 2000 the total domestic/commercial and industrial demand for water will amount to approximately 105 Mm^3yr^{-1}. Similarly to meet the requirements in basic foodstuffs designed to provide self-reliance in wheat and vegetables and a certain measure of meat poultry and dairy projects to projected levels some 17,000 ha would be required to be planted to wheat and 3600 ha to vegetables with a total estimated water demand of about 250 Mm^3yr^{-1}. The overall total demand for water may therefore amount to 355 Mm^3yr^{-1} if a policy of full food self-reliance is pursued. Only 11% of this total may however be supplied from groundwater resources and future water resources development in Qatar will perforce have to be based on a large element of distilled sea water and possibly desalinised groundwater.

14.3.2 Limited Objective Agricultural Development

An analysis of the economic benefits of improved irrigation practices (Technical Note No. 13) has shown that although there is a maximum potential water saving of 15 Mm^3yr^{-1} on existing farms (2250 ha) this is nevertheless insufficient to reduce present abstraction to a safe yield level of 27 Mm^3yr^{-1} which is a corollary of any development plan. The projected increases in production on existing farms may therefore only be attained by reducing the number of productive farms or by importing additional quantities of water; either distilled sea water or effluent water. A reduction in the number of farms would, under present circumstances, be impracticable and while effluent water has certain attractive economic advantages its import into a well-populated, vegetable-growing area under private ownership poses a considerable health hazard. Without the import of desalinised water the vertical expansion option in agriculture will not therefore stabilize the present groundwater overdraft situation in northern Qatar even with the considerable investment in irrigation equipment and improving cultural practices. The development of a further 1000-1200 ha of irrigated land under irrigation by sewage effluent water and about 400 ha in south western Qatar would be the only possible course in increasing agricultural production. With this limited vertical expansion neither of the twin objectives of stabilizing the groundwater aquifer and achieving a high measure of food self-reliance will be achieved.

At the close of the previous FAO[1/] executed project in 1977, possible development scenario's were proposed and commented upon and at that time it appeared that a limited, vertical expansion option would have achieved the first objective at the level of abstraction and the area under cultivation at that time. However, since then groundwater abstraction has increased and the irrigated area expanded and this option is now no longer feasible. It must therefore be accepted by the Government of Qatar that if the twin objectives of groundwater stabilization and food self-reliance are principal policy aims, recourse to a horizontal expansion of agriculture through the conjunctive use of groundwater, sewage effluent and distilled sea water is the only means by which these objectives may be achieved.

14.3.3 Major Expansion of Agriculture to Achieve Food Self-Reliance

The possibility of using distilled sea water for irrigated agriculture in Qatar has been under consideration for some time but is present high unit cost in relation to the equivalent unit value of agricultural produce has been a major disincentive. However, within the past five years major changes in the cost and availability of world energy and food supplies have occurred, pointing towards increased shortages and costs, and the present pattern of relatively cheap, economically produced and abundant food supplies may well be replaced by other patterns by the turn of the century. At the present time 25% of the world's energy supply is consumed in producing food. In 35 years time the world's population is expected to double and the energy required for food production will have trebled. Thus, as energy supplies are expected to diminish and its cost increases, food production costs will rise accordingly and heavily subsidized food production may become increasingly necessary to assure essential supplies.

With large source of natural energy for the distillation of sea water, there exists the possibility of promoting agricultural expansion and subsidizing future food production in Qatar through the provision of high cost distilled sea water for irrigation. However, the present cost of distilled sea water by multi-stage flash distillation in Qatar is estimated to be QR 5.50 m^3 with a very substantial adverse cost/benefit ratio in terms of agricultural production. Despite this, an examination of the feasibility of a major expansion in agriculture based on desalinised water was undertaken at the request of Government and presented to the Ministry of Industry and Agriculture and subsequently in audience with H.H. The Emir of Qatar in 1980.[2/]

This study is based on a large element of distilled sea water and supplemented by fresh groundwater, treated effluent and marginal quality groundwater to produce grain, vegetable and fodder crops. These studies and proposals have been considered in three separate sections as follows :-

14.3.3.1 Northern Qatar Canal Scheme and Groundwater Stabilization

The Qatar General Petroleum Corporation (QGPC) together with Shell International Gas Ltd. (SIGL) have recently examined the various future development options based on the large scale exploitation of the considerable gas deposits of the off-shore 'North Dome'. They have, in their preliminary draft report, proposed three possible future development scenarios; (a) a static state, (b) an agricultural/light industry plan, and (c) a heavy industry plan. The agricultural/light industry scenario envisages the augmentation of existing groundwater and effluent supplies for agriculture by distilled sea water based initially on a dual purpose electric power generation/multi-flash distillation plant to be superceded by direct desalination by large scale reverse osmosis plants.

1/ FAO Terminal Report UTFN/QAT/003/QAT 1977.

2/ A Proposed Water Resources and Agricultural Development Plan : 1980-2000
Project Proposal No. 3 (J.G. Pike)

In consideration of the adverse cost/benefit factors involved in power generation and the distillation of sea water already commented upon it is not likely to be economically feasible unless such is linked to an industrial undertaking producing large quantities of additional waste heat for distillation. An alternative scenario would be to develop a liquified natural gas (LNG) plant from which sufficient process waste heat would be available to offset high direct energy costs in the distillation of up to 100 million gallons of distillate per day.

The northern Qatar canal scheme studied by the Project assumes the establishment of an electric power, LNG waste heat/distillation plant located at Ras Laffan, understood to be the optimum landing point for offshore gas which is also directly adjacent to the main agricultural development area of northern Qatar. The final capacity of the plant would be 102 m.g.p.d. (466,000 m^3 day^{-1} or 170 x $10^6 m^3$ $annum^{-1}$ or Mm^3. 1/ This water would then be pumped by pressurised pipeline over a distance of 27 km and through a static head of 35 m, requiring some 4000 HP in pumping energy, to point south west of Rawdat el Faras. At this point a storage/stilling basin/headworks structure would be constructed from whence water will be distributed by two lined gravity canals, one leading north-westward and the other southward towards Doha. This will allow irrigation water to be distributed by subsidiary gravity canals or pipelines to command a total of 15,370 ha; 7,370 to the northward and 8,000 ha to the southward. To the south-west of the main canal routes an area of higher elevation covering the north central region of Qatar and containing some 6150 ha of arable soils in separate depressions may also be irrigated by fresh groundwater. The area in question is underlain by the best quality groundwater in Qatar and may if necessary be augmented by injecting desalinised water pumped from the main canal.

It is envisaged that the water requirement to irrigate 19,600 ha of wheat and vegetables together with limited summer cropping would be met by a total supply of 150 MCM annum. However, water demand throughout the year would vary by a factor of three or more whereas the supply from the distillation plant would have to be kept constant. Storage would have to be provided and the choice lies between injecting surplus water to the lower (Umm er Radhuma) aquifer, with its high storage capacity, or surface storage. Surface storage works would be very large and expensive and as all available sites are likely to be wide and shallow depressions, evaporation loss would be about 50% of the amount stored. On the other hand, sub-surface storage by artificial recharge would be comparatively cheap but here again only about 50% of the quantity recharged may be recovered, the remainder being lost to diffusion and possibly outflow. In both cases high losses may therefore be expected to occur although in the case of artificial recharge the proportion recovered would be expected to increase with time. With these considerations in mind therefore it is proposed that of the annual production of 170 Mm^3 of distilled water, 85 Mm^3 would be utilized during the winter for surface irrigation and the remaining 85 Mm^3 recharged to the aquifer during the summer months of which 43 Mm^3 would be recovered the following winter. Thus, the 85 Mm^3 of surface water would be augmented with 43 MCM of recovered artificial recharge and 27 Mm^3 of natural groundwater, being the safe yield of the northern aquifer system. A preliminary estimate suggests that capital cost of this scheme would be of the order of $ 2,000 million.

The main canals would be designed for an initial flow of 2.82 $m^3 sec^{-1}$ and a top width of 5 m, a maximum flow depth of 1.3 m a velocity of 0.6 m sec^{-1} if a gradient of 1/7500 is to be adopted. Such a gradient would result in a head loss of 13 m over the 100 km of the south main canal terminating in the region of Rayyan at an elevation of 21 m. a.s.l. and 9 m in the north main canal over a distance of 70 km terminating in the Busayer area of north-west Qatar. At selected points along the course of the main canal (cased) wells will be sunk to Umm er Radhuma aquifer at a depth of approximately 60 m from the surface. These wells will be utilized for both recharge in the summer and extraction during the winter months.

1/ The Systems Analysis Study carried out subsequent to this proposal shows a distillate requirement ranging from 23 Mm^3 to 242 $Mm^3.yr^{-1}$ depending upon which agriculture plan is adopted (See Sec. 14.4)

This study has shown the engineering feasibility of commanding sufficient area for the irrigation of large tracts for cereal, fodder and vegetable production. However, the very high annual cost must render such a solution highly uneconomic and vulnerable. Agricultural development based upon a very high proportion of distilled sea water would be vulnerable to interuption from a variety of causes and it would be prudent to maintain a balance with other sources of water as an insurance against possible complete failure of the system. The Agricultural and Water Resources Development Plan presented in Sec. 14.4 is in recognition of this and provides a reasonable balance consistent with the achievement of a good measure of food self-reliance.

14.3.3.2 The Re-Use of Treated Sewage Effluent for Agriculture

A number of alternate sites for the development of between 1000-1600 ha of irrigated cropping with treated sewage effluent have been proposed by the project and in collaboration with the Industrial Development Technical Centre.[1] In February 1980 a semi-detailed proposal was prepared by the project[2] on the instructions of H.H. The Emir. This proposal envisaged the transfer of treated sewage effluent by pipeline to a site in the vicinity of Al-Ashara where some 1050 ha of suitable soils in a large number of scattered depressions could be developed. Later, and upon the instructions of the Deputy Minister of Industry and Agriculture an alternate site in the same area in the vicinity of Rakaiyah-Wadi Jalal was examined with the same intention and a full feasibility report prepared by the project.[3] In early 1981, a contract for the construction of the main transfer pipeline was awarded and work commenced. A final decision on which site will ultimately be developed is awaited. The merits of each site are summarised below :

(i) Al-Ashara

The Al-Ashara area is situated some 60 km west of Doha and covers a rectangular tract of undulating country astride the main Umm Bab road and to the north of the Salwa Road, is some 186 km^2 in extent. Within this area there is an aggregate of 1084 hectares of suitable soils in 310 separate depressions ranging in size from less than 1 ha to 55 ha. Its main advantages as an area of agricultural development as opposed to earlier proposals in a diversity of soil types which will allow a wide range of cropping systems such as cereals, vegetables, fodder and date palms which could, in turn, support a livestock enterprise such as a dairy, and possibly agriculturally-based light industries in the processing, drying or storage of certain crops at a site within good access to the Doha market. It is also remote from the main centres of urban and rural population and the marginal land of lithosols between depressions could be planted to trees as an alternative to future expansion.

As effluent flow will steadily increase over the next fifteen years a phased agricultural development programme would be required. Broadly it is proposed that as soon as effluent water is transferred to the Abu Nkalah lagoon a branch pipeline of some 4 km be laid to the depression to the north of Saliyah camp to develop a 50 ha, experimental farm; the second phase would come into operation as soon as water is delivered to Al-Ashara in 1983 when the flow is expected to be some 20,000 m^3/day. This will allow for the irrigation of 283 ha of grains, fodder and dates. The third phase

---

1/ A Study and Proposal for the Disposal of Effluent Water and its Use in Agriculture in Qatar. (I.D.T.C., F.A.O. Metcalf & Eddy) 1979.

2/ The Re-Use of Treated Sewage Water for Agricultural Development in the Al-Ashara Area, Project Proposal No. 2. FAO 1979.

3/ The Re-Use of Treated Sewage Water for Agricultural Development in the Rakaiyah-Wadi Jalal Area. FAO Project Technical Note No. 14, 1980.

would comprise the gradual extension in annual increments over a period of 12 years until all arable land areas within the Al-Ashara area are brought under irrigation.

The delivery system will be composed of a twin 800 mm diameter pipeline, 54.2 km long from the sewage treatment works to deliver 57,500 m^3/day at 18 hours pumping (two stage) through a total pumping head of 133 m. This is designed to deliver effluent water at suitable location which is 57 m a.s.l. and commanding the site. To cater for seasonal variations in demand it is also proposed that the Abu Nkalah site be utilized as an overflow lagoon rather than retaining the present Wadi Isameer lagoon site with its present disadvantages inherent in its location within the boundaries of Doha city. Because of diurinal fluctuations in irrigation demand on-site storage amounting to 2,760,000 m^3 would have to be provided near this point. By constructing a 2 meter high, 1 km bund a natural depression nearby may be developed for this purpose.

The proposed distribution system would be composed of two main branches leading northwards to the Wasail area and southwards to the Al-Ashara area. Distribution will be provided by pumping from the on-site storage site to a high level tank with a capacity of 13,000 m^3. This tank will maintain pressures within the distribution system when the reservior pumps are shut down. This arrangement will reduce fluctuations in the reservior pumps permitting fixed flow rates to be maintained as well as reducing pressure fluctuations and hence wear and tear.

No detailed feasibility study of agricultural development of this site has yet been carried out and an economic appraisal may only be gained in general comparison with the feasibility study carried out by the project of the alternate site at Al Rakaiyah-Wadi Jalal.

(ii) Rakaiyah-Wadi Jalal

An alternate agricultural development site has been selected at the northern end of an elevated plateau with a general surface of 65 to 75 m above sea level in the Rakaiyah-Wadi Jalal area of south central Qatar and in the vicinity of the ESD sand-washing plant. The soils are composed of extensive deposits of gravels and sands as a cropping to a range of outlier hillocks. Locally, the soils are weakly cemented but the top meter contains considerable amounts of gypsum and is more strongly cemented than the underlying sandy layer. Chemical analysis of soil samples shows a general low salinity with isolated high sulphate and chloride concentrations randomly distributed throughout the area. The land surface is gently undulating, free of vegetation, elevated above the general surface of Qatar, has a good natural drainage and has been classified as 'conditionally suitable' for agriculture. Owing to the presence of gypsum such soils would be suitable for tolerant crops such as grains and fodder but generally unsuitable for vegetable and fruit production.

Under the proposal put forward with regard to the Al-Ashara scheme it was proposed that a main pipeline would consist of twin 800 mm dia. pipeline 54.2 km in length from Al-Naijah treatment works to deliver 57,500 m^3/day at 18 hours pumping (two stage) through a total head of 133 m. In transferring effluent to the alternate site little variation of the overall route, except in the final stages, would be required. The alternate pipeline would be 16 km shorter and the total pumping energy would be reduced. However, any saving on the main pipeline would be offset by having to pump the effluent from a storage basin at an elevation of 46 m a.s.l. through a static head of 30 m to the main agricultural area.

This alternate scheme would therefore be based on a twin 800 m dia. main pipeline, 38 km in length to ultimately deliver 57,500 m^3/day to a storage basin with a full supply level of 46 m a.s.l. and located to the north of the agricultural area. From this storage basin, with a minimum capacity of 3.0 Mm^3, water would be pumped, firstly, through a 10 m head to a 100 ha first phase area and secondly, as a second and main phase, to a balancing tower at 75 m a.s.l. in the centre of the main agricultural area. From this central area water would then be distributed, under pressure, to the entire area in rotation for irrigation by sprinkler systems.

The agricultural project would be developed in five phases as the volume of treated sewage effluent increases and the corresponding crop development up to a maximum of 1000 ha would be :

Table 14.3

Phase	Period	Area	Cropping
1	1982 - 83	400	Alfalfa, wheat/barley Sorghum, Sheep
2	1985	200	Wheat/barley,sorghum
3	1990	100	Alfalfa/Sheep
4	1995	1995	Alfalfa
5	1998	200	Wheat/barley, Sorghum

The above phased programme is not the most profitable plan but is in accordance with Government policy to produce a significant amount of grain. The most profitable enterprise would be an alfalfa/sheep/sorghum one.

Capital costs of delivering water to the site are estimated at QR. 109.4 million. Since this water must be disposed of in any event these costs have not been charged to the agricultural development project. Capital costs chargeable to the agricultural development project would amount to QR. 49.0 million for water storage, pumping installation and the farm irrigation network of which QR. 38.2 million would be required for the first phase, 1982-83.

Over the development period 1982-2000 the total capital cost of all agricultural development (water supply, machinery, buildings and sheep) would amount to QR. 81.0 million.

The total capital investment would therefore be :

1.	Water Transfer	QR.	109.4	million
2.	Engineering on site	QR.	49.0	"
3.	Agricultural Development (1982-1998)	QR.	81.0	"
		QR.	239.4	"

In every year after 1986 annual gross farm sales should exceed annual operating costs by QR. 6 million increasing to QR. 12 million in 1990. At full development, expected to be reached by 1999, annual gross returns will be QR. 21 million, operating costs would be QR. 10 million and thus the annual operating profit would be QR. 11 million. Because of the high and long-life capital cost of the agricultural irrigation system, the internal rate of return of the project is expected to be 10.3%. This is below the minimum acceptable rate for investment purposes but is nevertheless highly satisfactory in the context of Qatar. Additional non-monetary benefits would be food security, feed for the expansion of the livestock industry, a model for agricultural development and the possibility of developing agriculturally-based small industries (hides, skins, wool, milling etc.). If capital construction and farm operating costs are kept at reasonable levels under experienced high-level farm management the project would be highly viable.

A detailed feasibility study of the Al-Ashara proposal was not undertaken but a tentative estimate of capital and operating costs of this scheme (revised to the end of 1980) may be compared to the proposal outlined in this report.

Table 14.4

	Rakaiyah Wadi Jalal	Al-Ashara
Water Transfer	109.4	125.0
Engineering site	49.0	54.0
Agricultural Development (1982-1998)	81.0	95.0
Cost in QR.	239.4	274.0

The total overall capital investment for the alternate site would be nearly QR. 35 million less than the Al Ashara site. Furthermore, the latter site is composed of a large number of small discrete areas of arable soil, at present well vegetated and in need of considerable development prior to irrigation. The operating costs of such a scheme are estimated to be some 10% higher compared to the alternate site where all operations may be centralized in two main blocks of land. The internal rate of return from the Al-Ashara scheme under a similar cropping enterprise as that of the Rakaiyah - Wadi Jalal alternate site would be of the order of 9%.

(iii) Possible Alternative Transfer to South Western Qatar

A major problem associated with both the foregoing sites is the lack of suitable land areas. In the Al Ashara region the extent of the sandy loam soils are limited and fragmented and in the Al Rakaiyah-Wadi Jalal area they are gypsiferous and are liable to collapse unless the irrigation water is suitably amended. In the Wadi el Araig and Abu Samrah areas of south western Qatar agricultural trials have confirmed the possibility of irrigating the undulating dune sands but here the total amount of groundwater is limited. By transfering sewage effluent water to this site a considerable expansion in agriculture would be possible under an optimized conjunctive use scheme. This alternate proposal is discussed more fully in the following section.

(c) South-western Qatar

For some years the Department of Agriculture has operated a sheep station at Abu Samrah on the Qatar-Saudi Arabian border, based on brackish groundwater of the Alat aquifer. The same aquifer supplies a limited amount of irrigation water to the agricultural experimental station at Wadi el Araig, established and operated by the project. Work at this station has demonstrated the potential for crop production in this area based on sterile sandy soils and irrigated with brackish groundwater. (See Technical Reports 1, 2 and 4). More recently the project prepared terms of reference for a feasibility study to be carried out by a firm of French consultants to the Ministry of Industry and Agriculture. At the close of the project in April 1981, the project was asked to prepare a position paper for discussion with H.H. The Emir on possible development possibilities within the area. The following paragraphs summarize these proposals.

(i) The Alat aquifer of south-west Qatar is under artesian pressure of +4 to +6 metres above sea level with a source in Saudi Arabia, an estimated annual safe yield of 2 $Mm^3\ yr^{-1}$ and a salinity which ranges from 5000 to 7500 EC with higher values in certain isolated areas, although there is some evidence to indicate that extraction from this aquifer in the Salwa/Abu Samrah area over the past 30 years has brought about marginal improvement in the quality of water. There are also some 5000 ha of sandy soils in the area, capable of yielding good crops under irrigation.

(ii) By exploiting this aquifer's full potential 'throughput' of 2 $Mm^3\ yr^{-1}$ the following three alternative schemes are possible.

Table 14.5

Enterprise	Crop	Area (ha)	Production (tons)	Capital Cost (QR)
Grain/fodder	Wheat (grain)	225	800	
	(straw)	225	800	
I	Fodder	160	4000	
	Sorghum	160	500	17.8 million
Grain/fodder/ Dates	Wheat	220	750	
	Fodder	130	3250	
II	Dates	25 (2500)	250	17.8 million
Dates III	Date palm	160 (16,000 trees)		6.7 million

(iii) With 5000 ha of available land it is clear that water is a major constraint to agricultural development. The following are the possible alternative agricultural development scenarios under a given import of sewage water of 20 Mm^3yr^{-1} by the year 2000. The cost of transporting sewage water to the site is estimated to be QR. 205 million.

Table 14.6

Enterprise	Crop	Area (ha)	Production (tons)	Capital Cost (QR)
Grains/Fodder	Wheat (grain)	1400	5000	
	(straw)	1400	5000	
I	Fodder	700	12500	
	Grain	700	2000	95 million
Grain/fodder/ Dates	Wheat	1000	3500	
	Fodder	500	12500	
II	Dates	440	4500	95 million
Grain/sheep	Wheat (grain)	600	2100	
	(straw)	600	2100	
III	Sorghum	600	2100	
	Alfalfa	400	48000	102 million

(iv) The blending of sewage water with Alat aquifer groundwater is technically feasible and would increase the salinity of mixed water by only small margin because of the small quantity of groundwater which would be available. By exploiting Alat water for mixing, only marginal increases in production would be obtained. For instance, the wheat area would be extended by 10% to 1550 ha but the additional cost of developing Alat water would increase disproportionally by 15%.

(v) The blending of groundwater with sewage water to increase the total area under production would only be worthwhile if larger amounts of groundwater were to be extracted from other aquifers, such as the Umm er Radhuma. In the Abu Samrah area the Umm er Radhuma aquifer lies at a level 180 m below ground level and contains a very substantial supply of water with a safe yield estimated to be of the order of 17 Mm^3/annum. However this water is highly saline (EC 27,000) within the immediate vicinity although at sites further inland (along the Abu Dhabi road) this reduces to 15,000. Thus any agriculture enterprise would have to designed to grow crops of different salinity tolerance levels with different combinations of water. The problem may therefore be stated as being one of optimizing a cropping programme to fit the following constraints;

1. Three different quantities of water
2. Three different qualities of water
3. Two availability modes
4. Three different crop salinity tolerances.

A computer programme was devised to assist in the design of such a development and this showed the best solution to be 19.17 Mm^3/annum of treated sewage water of a salinity of 2000 (EC); 1.3 Mm^3 of Alat groundwater of salinity of 5000 (EC); and 16.73 Mm^3 of Umm er Radhuma groundwater of a salinity of 15000 (EC) to irrigate 2100 ha under the following agricultural plan;

Table 14.7

Enterprise	Crop	Area (ha)	Production (tons)	Capital Cost (QR)
Wheat/fodder	Wheat			
Dates/Sheep	(grain)	1400	5000	
	(straw)	1400	5000	
	Sorghum			
	(fodder)	700	17500	
	(grain)	700	2000	
	Alfalfa	300	30000	
	Dates	400	4000	136 million

Under this plan the cost does not include the transfer of sewage water to the site (QR. 205 million) but does provide for storage works capable of maintaining 5 Mm^3 of live storage.

14.4 A MASTER WATER RESOURCES AND AGRICULTURAL DEVELOPMENT PLAN BY SYSTEMS ANALYSIS

14.4.1 Introduction

Whilst the foregoing proposals may appear to be straightforward in technical concept and design then raises a number of complex issues and more importantly does not analyse the complicated inter-relationships of each part of the problem to every other part as well as the inter-relations among objectives and the means by which this may be achieved. The proposal is to utilize three, possibly four, sources of water of different and differing quality - fresh to brackish groundwater, distilled sea water, reclaimed treated sewage effluent water and possibly desalinised saline groundwater - to supply sufficient water of suitable quality for three main users - domestic/commercial, industrial and agricultural. The optimum apportionment of these different sources of water and their relative inter-relationships to each other for different uses is a suitable subject for a systems analysis approach in developing on overall water resources and agricultural development plan. Properly applied, a systems approach to planning not only provides those responsible for planning with a realistic optimized solution to the overall problem but should also indicate what the consequences would be by the adoption or otherwise of certain policies and alternatives. In other words, it goes beyond the simple problem-solving stage to become a much more powerful problem-identification tool. In the present stage of investigation and planning in those sectors in Qatar a total systems analysis review of the present situation is required leading to the confirmation or otherwise of ideas many of which have, to some extent, already been explored. Water is a crucial resource in Qatar and the manner it which it is developed and used will play a large part in determining the future level of national prosperity. At mid-stage in project operations therefore it was decided that a specialised approach to planning would be essential if the full benefit of the project were to be realised. This was adopted and approved which finally led to the appointment of Messrs. Halcrow-Balfour Ltd., Consulting Engineers and Environmental Planners of the United Kingdom to undertake this work in collaboration with the project in its closing stages. The consultants report comprised of 8 technical supporting documents[1] and a main summary report, was completed in mid 1981 and the following sections provide an abstract of these, sufficient for an understanding of the main findings and recommendations.

14.4.2 The Master Plan Model

In the foregoing sections of this report the factors involved in formulating a master plan for the water resources and agricultural development of Qatar have been given in some detail. These factors may be conveniently summarised under three main headings which correspond with the major inputs to any agricultural scheme : water, land and labour.

The cheapest source is groundwater. The aquifer systems are relatively complex in their structure, and water quality varies from potable to highly saline and current abstraction is much greater than the safe yield of aquifer. Increased quantities of treated sewage effluent are becoming available, but are only suitable for growing certain types of crop because of the risks of contamination. This water is available free of charge to agriculture but the associated conveyance costs make it more expensive than groundwater. Although desalinated water is of high quality and could be made available in almost unlimited quantity, and even the use of waste heat from other processes cannot mitigate the high costs of production and conveyance.

The available land resources vary from relatively good soils to sandy soils which demand good management and large quantities of water to produce even a limited range of crops. The land is divided into numerous widely-dispersed plots varying in size from under 1 ha to over 1000 ha.

1/ Halcrow-Balfour Ltd. Master Water Resources and Agricultural Development Plan. Main Report with 8 Technical S...

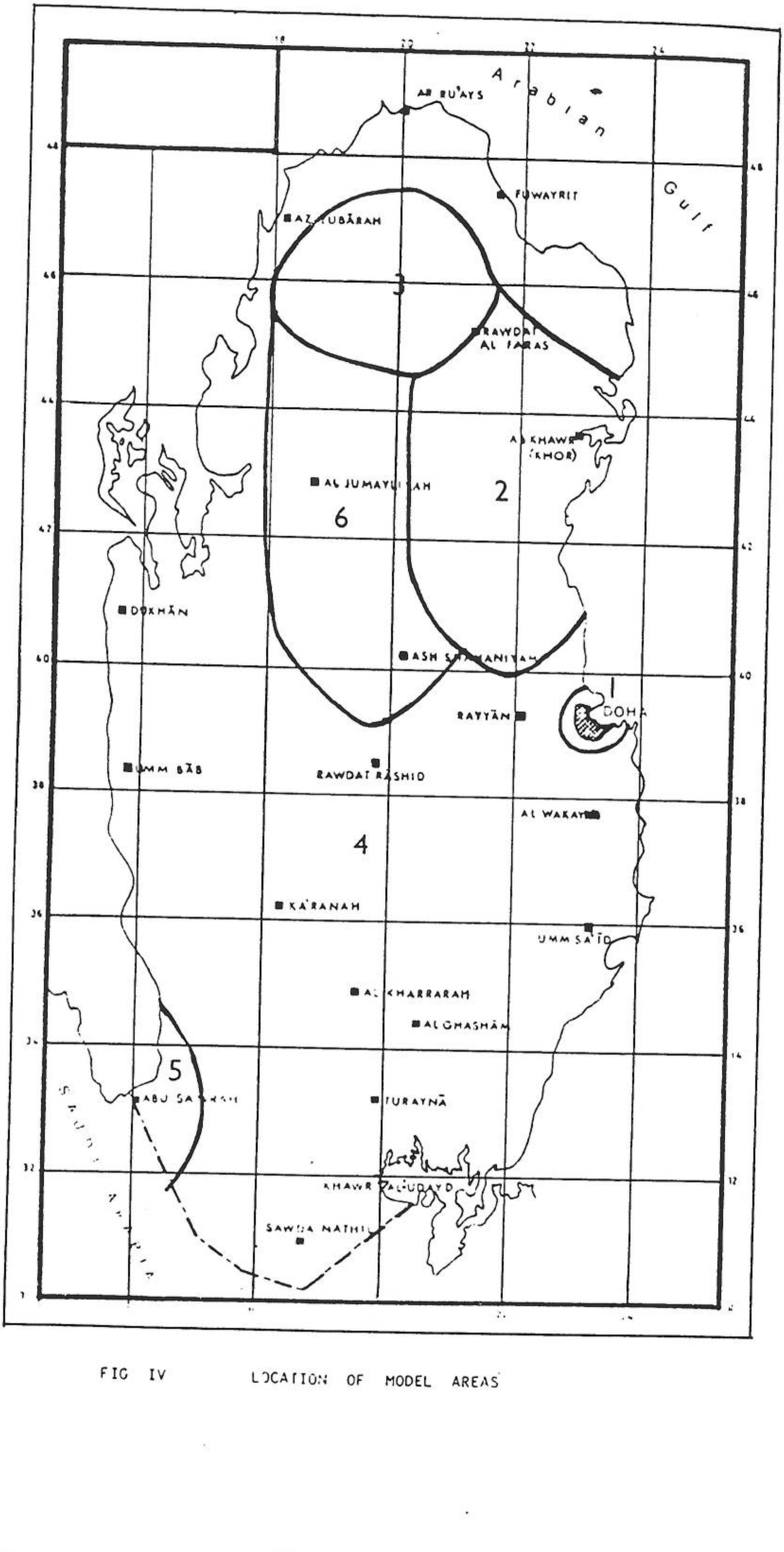
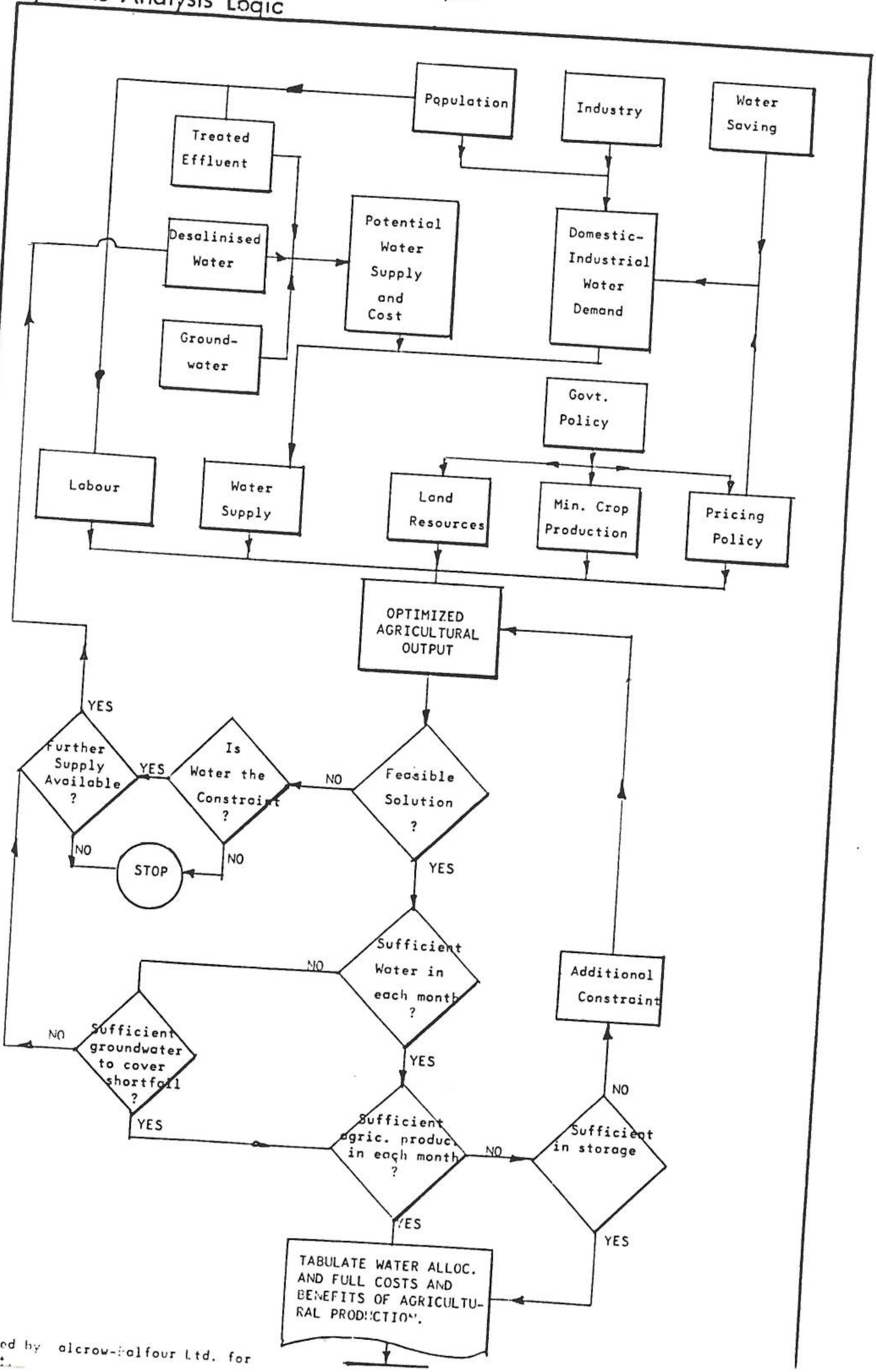


FIG IV LOCATION OF MODEL AREAS

Systems Analysis Logic



Prepared by alcrow-Balfour Ltd. for Project.

The available labour force includes a relatively high proportion of unskilled or semi-skilled workers. Many of the tenant farmers have only short-term agreements, limited capital and few incentives to diversify their farming. Managed farms similarly suffer from lack of incentives.

In a planning context, these factors must be considered together with food demands, the suitability of different crops to different areas, the compilation of cropping calendars, and the practical limitations on implementing new works and initiating unfamiliar procedures. Strong inter-relationships between these factors are readily apparent, and make the process of reaching a viable solution a tedious and time-consuming exercise by manual methods. For every realistic solution, there are many more that may ultimately prove to be impractical at a later stage of investigation. Moreover, the chances of locating a solution that satisfies a predetermined criterion of what constitues a 'best' plan are remote unless the problem is cast in an appropriate mathematical framework. In these circumstances, the advantages of employing digital computer facilities for economy in time and effort are clearly obvious. The translation of the planning problem into a form which can be examined using the computer involves the application of a group of techniques known as systems analysis.

There are basically two types of model employed in systems analysis : descriptive (simulation) models, and programming (optimisation) models. The former attempt to predict the possible future consequences in terms of output of adopting a particular configuration of system and operating that system according to a specified policy. Since the alternative policies are selected subjectively, significant strategies could inadvertantly be ignored and simulation is therefore relatively inefficient in choosing the 'best' policy according to some previously-agreed criterion. In contrast, programming techniques are particularly appropriate for deriving the policy which is optimal relative to a predetermined objective. Moreover, if all the relationships describing the system can be expressed in a linear form, a linear programming (LP) algorithm may be applied to provide the optimal solution.

A prerequisite to the application of such a systems model is the choice of a suitable objective function. Since a financial analysis of potential farm operations clearly showed that substantial capital subsidies would be required in most cases, application of conventional cost-benefit analyses was impracticable. The LP was therefore designed to allocate the available water resources so that sufficient food would be produced for the inhabitants of Qatar, either by domestic agriculture or by means of imports, at the minimum economic cost under any assumed policy. The planning period over which the LP was run began in 1980 (the base year) and ended in the year 2000.

As the resources of Qatar are not uniformly distributed, the model was based upon a division of the country into six separate regions being merely the grouping together of agricultural areas having similar characteristics as follows :

1. An artificial zone representing the port and markets of Doha, where the majority of produce is traded, within which imports can be taken into account.

2. The relatively closely-spaced parcels of good agricultural land on either side of the Doha - Ar Ru'ays road as far north as Rawdat el Faras. Most of this area is underlain by good groundwater and, if required, both treated sewage effluent from Doha and desalinated water from Ras Laffan could be conveyed to the area and distributed to farms by relatively compact conveyance systems as outlined in Sec. 14.4.3.2 (a).

3. A zone having as its axis the Rawdat el Faras - Az Zubarah road. The distribution of desalinated water to this area would be slightly cheaper than to Area 2, and conversely, the supply of treated sewage effluent would be more expensive. Otherwise, the two areas could be considered as one.

4. The potential agricultural area of central Qatar near to the Abu Samrah road intended as a site for the agricultural use of treated sewage effluent. (See Sec. 14.4.3.2 (b)).

5. The extreme south west incorporating the Government experimental farm at Wadi el Araig and the Abu Samrah sheep farm. (See Sec.14.4.3.2 (a)).

6. The remainder of northern Qatar, where cultivable land is widely spaced and hence expensive to supply by surface conveyance systems, but is underlain by the best quality groundwater in Qatar.

For each area, the basic land and groundwater resources were determined as follows.

Table 14.8

Area	Available net cultivable land (ha)			Proposed safe yield of groundwater (MCM)
	In parcels of under 30 ha	In parcels of over 30 ha	Total	
2	1570	3720	5290	5.6
3	1050	2450	3500	9.7
4	0	2210	2210	0.15
5	0	3570	3570	12.0
6	5620	3720	9340	5.7
Totals	8240	15670	23910	33.15

Notes

1. Present levels of abstractions are assumed to be reduced to or held at levels given to avoid permanent aquifer damage.

2. Comprises 2 Mm^3 of good water and 10 Mm^3 of saline.

3. Total area shown is 23,910 ha. A further 600 ha occupied by amenity farms is assumed to be unavailable for active agriculture.

Having divided Qatar into regions of different potential, all the relevant information concerning Areas 1-6 was compiled into a data bank which could be accessed by the allocation model. The data bank consisted of a series of files, each of which was created from the raw information using a suite of computer programs. The data files consisted of either 2 or 3 dimensional matrices depending upon whether the variables were fixed for the duration of the planning period or changed with time. The input files to the allocation model contained the following data .

- Land Resources
  - total available unframed land by size
  - total active farmed land by size
  - distribution of land by region
- Water Resources
  - available groundwater by region
  - available treated sewage effluent
  - potable demands
  - residual supplies for agriculture by region and quality

- Food Requirements
  - annual demands, 1980-2000
  - permissible import levels and costs

- Farm Data
  - farm types permissible in each region
  - land and water requirements of each farm type
  - water quality constraints
  - crop production levels
  - labour requirements
  - total farm costs
  - maximum creation rates for new or modified farms.

The allocation model was built around a large matrix incorporating all the relevant information. The matrix contents for each run varies, but typically involved about 50 variables and about 40 constraints. The principal contents of the matrix were :

- water quality requirements for each farm type
- total water requirements of each farm type
- supply and cost of each type of water in each year
- requirements of farm types for large plots of land
- total requirements of each farm type
- availability of land in each area in large and small plots
- food production in each category of produce for each farm type
- maximum labour requirements for each farm type
- Qatar's replaceable food requirements in each category of produce in each year
- import costs of each class of produce
- total costs of operating each type of farm
- maximum number of each type of farm in each year
- maximum volume of imports in each category in each year.

The allocation model was run to search for a set of values for the variable which enabled all the constraints to be satisfied. This solution is termed a feasible solution, but it is unlikely to be optimal, i.e. the cheapest, since there are usually many feasible solutions. Having found a feasible solution, the program then attempted to find a cheaper feasible solution. Both procedures involve an iterative technique, and the number of iterations needed to obtain the optimum solution for a single year varied from 2 or 3 to between 80 and 90.

14.4.3 Systems Model Results

The systems model as programmed was capable of handling a wide range of combination of initial assumptions to provide a comprehensive understanding of the various inter-relationships. These options were defined by the project and in collaboration with other government departments and their consultants and based upon the following basic assumptions :-

- Population
  - the population estimate discussed in Sec. 2.3.2.1 was employed for all production runs. This estimate predicts a population of 430,000 in Qatar in the year 2000. As a test of sensitivity an additional run was also made with a "conjectural" estimate of 253,000 in the year 2000.

- Potable water demands
  - Demands are a function of population growth, and included distribution losses which depend upon an assumed loss rate. For all production runs and sensitivity tests, these were assumed to decline uniformly from the estimated present level of 30 per cent to 20 per cent in the year 2000, consequent to improvements in the distribution system.

- Treated sewage effluent - The total amount of effluent is also a function of the population growth rate, but the volume passing to the treatment works depends upon the rate at which new house connections can be made. A figure of 15,000 per year was assumed throughout.

- Desalinated water - Water was assumed to be available in all cases, if required, since in practice desalinated water was only used by the model when certain solutions were specified which were constrained to employ this source.

- Land - All land not occupied by amenity farms was assumed to be available for commercial agriculture.

- Groundwater - It was assumed that it is Government policy to discontinue the practice of mining the main northern aquifers and to restrict abstraction to the safe yield. The agricultural abstractions were therefore assumed to fall to 50 per cent of their present levels by 1990 and thereafter remain at that level, giving a more reasonable rate of mining. Since control over amenity farm abstractions would present difficulties, these demands were assumed to be held at their current level of about 11 Mm^3/year and not reduced. This approach complies with a recommended major project groundwater management strategy (See 2.4 Recommendations).

- Gas and electricity - Gas and electricity prices were taken at their full economic cost in accordance with Government policy. However, the effect of assuming a zero gas price was investigated in a sensitivity test.

- Discount rates - An 8 per cent rate was selected as being the most appropriate for economic studies in Qatar. The sensitivity of the results to a change in discount rate was also tested.

The model was intended to find the most economical method of attaining the required levels of production of particular crops so that Qatar could become less dependent on imports. Although many different combinations of options are possible, there are relatively few basic alternatives. The following basic alternative policies were explored :

1. Terminate agriculture : This was essentially a control against which to measure the worth of agriculture. This option implies that commercial agricultural production is not regarded as necessary and would be actively discouraged. All traded produce would then be imported.

2. Economic optimum : For this objective, the allocation model was unrestricted, and could therefore choose which products and what quantities should be grown in Qatar to produce the economically cheapest solution.

Following this economic optimum solution, achievement of other objectives required that the model be constrained to grow additional crops which were not economic. Essentially, this approach involved making the model use more expensive water for already uneconomic crops, but the aim again was to ensure the minimum cost consistent with the defined objectives.

3. Full use of available treated sewage effluent in central Qatar.

4. Full use of treated sewage effluent in central Qatar and extensive use of desalinised water in northern and eastern areas closest to Ras Laffan which enjoy the better, more closely grouped soils.

5. As for 4 above, but also forcing the use of desalinated water elsewhere, in south-western Qatar.

These five policies permitted the various technical alternatives to be explored and understood. The remaining runs concentrated on rather more practicable aims evolved from the first five options.

6. Maximum degree of self-sufficiency in all produce which could be grown in Qatar.

7. Maximum degree of self-sufficiency in all produce which could be grown in Qatar except for mutton and cereals.

8. Maximum degree of self-sufficiency in cereals alone, with other produce grown only where economically viable.

The computer runs 1-8 described above demonstrated that large changes to many of the imposed conditions could be made without affecting the ranking of the preferred crops. Small changes, such as variations in irrigation efficiency or operating costs on different soil types clearly did not affect the basic selections. Sensitivity analyses were therefore confined to examining the effects of major changes in the basic assumptions amenable to such variations. These analyses included :

i. investigating the effects of treating natural gas as a free gift rather than allowing an equivalent market price. The change directly affects the cost of producing electricity, and therefore reduces the cost of desalinating water, pumping water and general power costs on the farm. These studies were amalgamated into run 9.

ii. investigating the effects of a much lower population growth rate, taken as the "conjectural" estimate discussed earlier. This change affects the demands for food and potable water, as well as reducing the amount of TSE available. These studies were carried out in run 10.

iii. investigating the effects of adopting alternative interest rates. Whereas the selected rate of 8 per cent was considered appropriate to an economic study in Qatar, a somewhat higher financial return would be sought on any commercial venture. The general application of higher rates than 8 per cent was therefore studied in run 11.

iv. removing the constraint that treated sewage effluent would only be available in the designated area in central Qatar. The results obtained from several runs suggested that TSE could be more productively employed in northern Qatar, and run 12 was designated to explore the consequences of effluent being taken to alternative sites.

The output given by the model may be divided into two parts : technical, of major interest in verifying that the model has worked correctly; and the main results. The principal items included in the latter were :

- amounts of local produce to be grown;
- total demands for each source of water;
- total annual cost, showing principal allocations; and
- total land used for agriculture.

Table 25 presents these results for each of the eight policies for the year 2000. Because of the changing conditions for each run, and the interactions of varying demands, any interpolations or extrapolations should only be made with care. The results of the four sensitivity runs have not been reproduced in tabular form since the overall results were of more significance than the details of the individual variables in each solution.

Table 14.9

SUMMARY OF POSSIBLE ALTERNATIVE AGRICULTURAL AND WATER RESOURCES DEVELOPMENT OPTIONS BY SYSTEMS ANALYSIS

Parameter	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8
Local produce (tonnes)								
Milk	–	–	5,600	5,600	5,600	5,600	5,600	–
Beef	–	–	240	240	240	240	240	–
Mutton	–	150	660	750	2,400	4,500	300	–
Cereals	–	–	–	18,000	23,000	23,000	–	23,000
Dates	–	–	–	–	3,300	3,700	3,700	–
Winter vegetables	–	18,000	18,000	18,000	18,000	18,000	18,000	–
Summer vegetables	–	8,100	8,100	8,100	8,100	8,100	8,100	–
Fruit	–	–	–	–	1,700	3,700	3,700	–
Cucumbers	–	–	–	–	–	650	650	–
Water used (MCM)								
Groundwater	–	19	19	21	29	29	23	24
Treated Sewage Effluent	–	–	35	35	35	35	11	20
Desalinated Water	–	–	–	50	142	242	35	23
Total	–	19	54	106	206	306	69	67
Economic Costs (QR million)								
Farm costs	–	40	80	160	250	350	90	95
Water costs	–	5	35	350	940	1,580	230	165
Imports	230	140	115	95	50	–	90	215
Total	230	185	230	605	1,240	1,940	410	475
Area farmed (ha)	–	1,900	2,900	9,100	13,800	17,600	4,800	7,700

14.4.4 Results Of The Analysis

Table 14.9 summarises the expected agricultural production, water and land requirements and the economic cost of each of the eight possible development options examined. Option 1 assumes that all agriculture will cease by 1985 and was made in order to test the economic cost, although essentially this is a control against which the other options may be evaluated. The seven other options 2 to 8 show an overlapping progression starting with the economic solution (2) based upon groundwater alone and thereafter supplementing this economic source with moderate-cost treated sewage effluent (upon which certain constraints in its utilization have been set) and increasing volumes of distilled water being brought in to finally achieve self-sufficiency in replaceable food demands (option 6). The remaining two additional options are variations on the self-sufficiency option no. 6.

The following are the salient conclusions arising from the analysis :

- Winter and summer vegetables irrigated by groundwater are the only crops that may be economically grown in Qatar : all other crops are cheaper to import. The total economic cost of meeting this policy would amount to QR 186 million in the year 2000, some 20 per cent less than the cost in the same year if everything were to be imported. This suggests that there is real benefit to Qatar from growing vegetables.

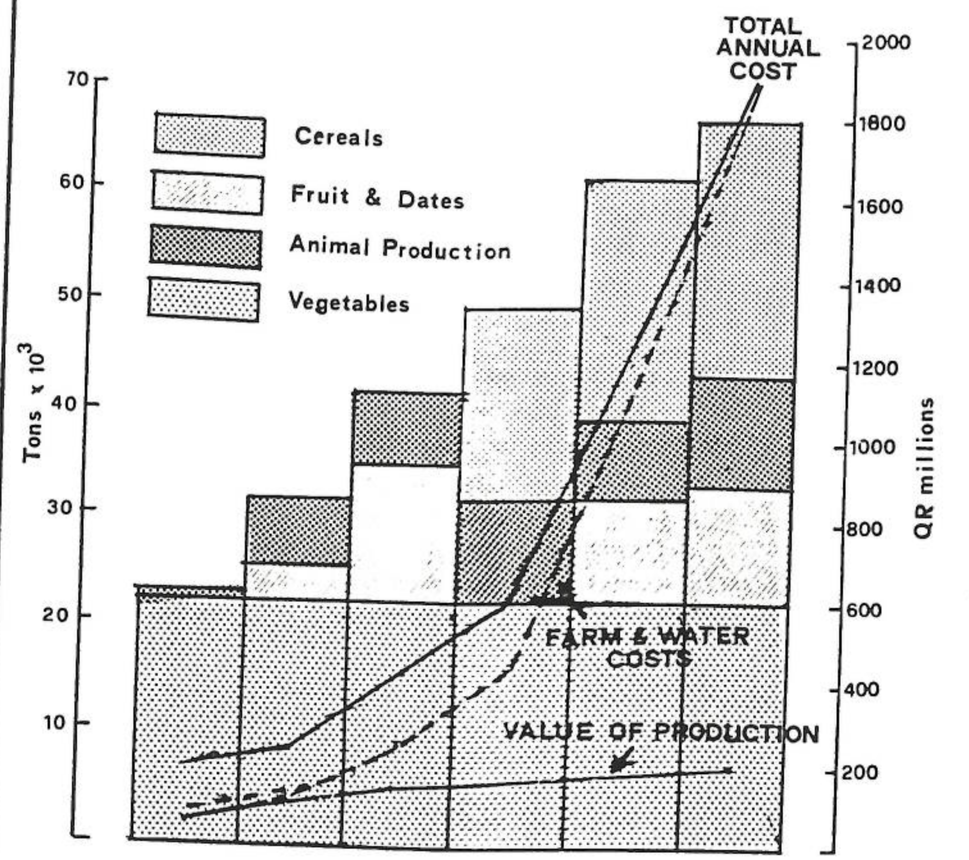
- It was demonstrated (Option 3) that with treated sewage effluent transferred to central Qatar as planned at present, the maximum amount of milk and beef could be produced. Such an enterprise would not however require the entire expected quantity of effluent by 2000 and it would be necessary to develop sub-economic sheep farming in the same area.

- The first five options clearly established that cereal and sheep rearing enterprises are highly uneconomic because of the heavy water demand and high farm costs for relatively low output. By including these two enterprises not only do the water costs increase dramatically by having to utilize high cost distilled water but also because farming costs alone still outweigh the value of production.

- Once the use of distilled sea water becomes necessary, the production costs of any crop rise dramatically (See Fig. 14.3). This also has the effect of highlighting the diseconomies inherent in developing agriculture in Qatar beyond the present water resource limits. For instance, the total economic cost of Option 3 based on groundwater and treated sewage effluent is QR. 230 million whereas by introducing even a modest quantity of distilled water (35 MCM in Option 7) causes the water costs to increase by a factor of 6.5 from QR 35 million to QR 230 million and the overall costs to QR 410 million. In this particular case the benefits which accrue amount to an additional 8000 tonnes of dates, fruit and cucumber for an additional cost of QR 180 million per year. When cereals and sheep rearing are included in the Option (Option 6) the costs rise at an accelerated rate and the total cost rises to QR 1940 million, ten times greater than the economic optimum (Option 2).

- In Option 7 cereals and sheep-rearing were excluded for the reasons given above and because of this not all the available treated sewage effluent would therefore be required at the proposed development site in central Qatar. A cheaper overall solution could, however, be realised if some of this water were to be made available in northern Qatar. In an alternate option (12) it was shown that if the unused balance of treated sewage water was not restricted to central Qatar and allocated to the main farming areas of northern Qatar, the demand for distilled seawater was reduced by 27 MCM in 2000 with a saving of QR 140 million, per year. This conclusion draws attention to the high value of treated sewage effluent in comparison with other sources of water in future agricultural development. (This alternate, however economically attractive, is unlikely to be realised in view of Governments prevailing policy of not allowing the use of treated sewage effluent in the main populated farming districts of northern Qatar).

The sensitivity test showed that variations in either the interest rate or, the population estimates, or whether or not gas was regarded as a free good did not affect significantly the preferred order of crops and their economic viability. In one parameter, however, the results were significantly affected by changing the estimated population for the year 2000 to a "conjectural" one of 253,000 in the same year. This had the effect of reducing the economic cost of meeting the country's food demands and the annual costs are only 50 per cent greater than at present. The "conjectural" population estimate was taken at 60 per cent of the assumed estimate, illustrating that the marginal cost of feeding an additional inhabitant under those policies is greater than the average cost. This results, once again, from the high cost of desalinised water being required to produce his fruit and vegetables if abstraction of groundwater is to be maintained at the safe yield of the aquifer. The total cost of water for both agricultural and domestic demand by 2000, even in this case, would be QR. 325 yr^{-1}.



OPTION	2	3	7	4	5	6	
WATER DEMAND MCM YR^{-1}	19	19	23	21	29	29	Groundwater
	–	35	11	35	35	35	Treated Sewage Effluent
	–	–	35	50	142	242	Distilled Sea Water
	19	54	69	106	206	306	TOTAL

FIG I: Summary of Possible Options in Increasing Order of Water Demand

14.4.5 Policy Options

The eight options examined fall into two distinct groups. The first group composed of Options 2 and 3 have in effect maximised production with respect to available water resources at minimal cost and in accordance with all constraints and variables. Options 4, 5 and 6 on the other hand are the result of progressively supplementing the total water requirement with increasing amounts of distilled water to achieve full self-sufficiency in replaceable food demand by the year 2000 (Option 6). These latter options may be regarded as maximising production with regard to the location, distribution and extent of arable land with the water constraint partially relaxed. The remaining two Options, 7 and 8 are variations on Option 6 where in Option 7 highly uneconomic enterprises (cereals and sheep rearing) were excluded from the maximised solution and in Option 8 cereals precluded the economic production of all other crops.

After consideration of the allocation model results, the Consultants (Halcrow-Balfour Ltd) identified four basic policies, the choice essentially depending upon the level of agriculture desired by Government. The four policies are :

I : concentrate on growing the economic crops of vegetables to the exclusion of all other non-economic crops, based on Option 2.

II : as in Policy I, but using all available treated sewage effluent in central Qatar as planned and growing the appropriate traditional crops, based on Option 3.

III : increasing production by the provision of distilled sea water to enable Qatar to raise its levels of production to the maximum practicable in all crops except cereals and mutton, based on Option 7.

IV : as Policy III, but based on Option 6 including cereals and mutton to achieve the highest degree of self-sufficiency to the full extent of available arable land resources.

In forming a development plan based on any one of the foregoing four policy options it is clear that there are only two apparent choices : These are Policy II and IV and correspond in principle to the development options previously recommended for Government's consideration by FAO in 1977; a 'vertical' or a 'horizontal' expansion in agriculture. The crux of the matter was then seen to be a choice between whether or not high cost distilled water should be used for agriculture. Considered in a systems context, however, the choice is not as clear-cut as this earlier recommendation nor the various policy options shown in Table 14.9 might suggest.

14.4.5.1 Maximum Expansion of Agriculture

The horizontal expansion option, as represented by Policy Option IV, has maximised production to available land and productive resources, with the limited water resource augmented to a considerable degree by distilled sea water. To meet the set targets, including cereals and mutton, the demand for land and water rise dramatically, while a total of nearly 4,000 agricultural workers would be required by the year 2000. Approximately 80 Mm^3yr^{-1} of expensive distilled water would be required by 1990, rising to 240 Mm^3yr^{-1} by the year 2000.

The expected value of agricultural production in 2000 is estimated at QR 204 million, a three fold increase over present levels of production. However, as Fig. 14.3 shows the escalation of costs is phenomenal, rising to a annual cost of QR 1940 by the year 2000, equivalent to about 12 per cent of estimated 1980 GNP at 1980 prices while the value of agricultural production would be equal to 1.3 per cent. This indicates a negative cost/benefit ratio of approximately 10. The diminishing returns from agricultural development based on high cost distilled water are particularly evident when it is recalled that this investment will only fulfill about 20% of Qatars estimated food need by the year 2000. The agricultural sector at this level of output and costs would be obtaining a dispropor-tionately large share of GNP in relation to its contribution.

In addition to these overwhelming economic arguments against the use of large amounts of distilled sea water for agriculture, as pointed out earlier, it would be imprudent to base 80% of the country's agricultural economy upon a source of irrigation water which is vulnerable to interruption from a variety of causes.

14.4.5.2 A Limited Expansion of Agriculture

Policy Option II represents the possible maximum production based on the safe yield of the groundwater aquifer and the expected volume of treated sewage effluent by the year 2000. In addition to economic vegetable targets being achieved those of beef and milk are also met. In this solution a constraint was set whereby all treated sewage water was to be utilized and confined to the central regions of Qatar. This has had the effect of introducing uneconomic sheep-rearing in this area to be set against the cost of dumping it if it were not used.

This policy would double the value of agricultural production realised in 1980 at similar prices and the annual cost would be QR 40 million higher in the year 2000 compared to the economic optimum. Total annual costs in the year 2000 for all elements including the remaining imports required is less than 2 per cent of estimated GNP in 1980 prices and the total value of agricultural production would be less than 1 per cent.

This solution is an optimum one whereby costs are minimised and although it represents only a small proportion of Qatars total expected food imports, it provides the basis for a practical agricultural development plan within reasonable limits of subsidy and the country's capacity. However, by subjecting the whole question of agricultural and water resources development to a systems analysis study whereby the various inter-relationships of each part of the problem to every other part as well as the relationship to each other are examined, it is clear that this solution would not provide for an acceptable develop-ment strategy.

Under such a policy the use of treated sewage water being constrained to central Qatar, will have the effect of developing this area preferentially to the detriment of higher value vegetable and orchard enterprises in northern Qatar where farms would have to close in order to redress the present abstraction/recharge imbalance. This would bring about a radical alteration to existing farming patterns and is one which would not find favour with present landowners in northern Qatar. But in any event, even if the present high rates of abstraction are maintained and not brought back into equilibrium with average recharge, increasing groundwater salinity will force the abandonment of almost all present vegetable farming in northern Qatar within 20 years. This would effectively bring about a shift away from economic vegetable production to increasingly uneconomic fodder production based on treated sewage water and increasingly saline water.

To preserve the preferred pattern of improving existing vegetable/orchard farms in northern Qatar, concentrate animal production on treated sewage effluent in central Qatar and reduce the abstraction of groundwater to the safe yield, any future strategy must therefore be based on providing a limited additional source of water in northern Qatar. This can be provided by either the unused balance of treated sewage effluent or distilled sea water. As there would be a serious social objections to the utilization of the former for vegetable production recourse would have to be made to distilled sea water. With this strategy in mind Policy III (based on Option 7) was developed by the Consultants as the most suitable alternative policy and upon which viable agricultural and water resources development plan could be based.

Under this Policy only 11 Mm^3yr^{-1} of the 35 Mm^3yr^{-1} of treated sewage eff...
be requi...

excluded. Additionally, 35 Mm^3yr^{-1} of distilled water would be required in north-eastern Qatar to replace reduced groundwater abstraction which would be necessary to return the aquifer to equilibrium.

Under this policy total annual costs, including the balance of imports rises to QR. 410 million; slightly less than double the equivalent costs under Policy II, and as pointed out earlier, water costs are increased by 75%. The incremental value of production for this very large increase in cost is QR 18 million worth of dates, fruit and cucumber representing only 15% of the total value of production. The additional cost should not, however, be compared with increased production for this represents in reality the cost of stabilizing the northern groundwater aquifer. The QR 200 million additional water costs may also be regarded as an annual subsidy cost to farmers in northern Qatar who would expect to be supplied from an alternate source as compensation for reduced groundwater abstractions.

As pointed out in Sec. 3.3, if all unused treated sewage effluent were permitted to be introduced into northern Qatar and substituted for high cost distilled water, the annual cost saving would amount to QR 140 million. This potential saving of up to 70% in cost should stimulate consideration of the possiblity of strictly controlled usage in the area despite present objections based on principle only.

As an alternate solution, not considered in the Master Plan, is the possibility of the artificial recharge of the unused balance of treated sewage water if direct usage is rejected. Detailed knowledge of the aquifer systems of Qatar suggest that such a solution would be feasible but the percentage recover remains uncertain without further investigation.

14.4.6 A Proposed Agricultural and Water Resources Development Plan

14.4.6.1 Introduction

The proposed agricultural development plan proposal assumes that the Government of Qatar will first select their required level of agricultural activity and that the development of water resources will then be organised to satisfy the overall water demands of the country. In accordance with this approach, the proposed Agricultural Development Plan is presented first followed by an associated Water Resources Development Plan designed to meet these needs. The proposed Agricultural Development Plan is a practical interpretation of Policy III and fully discussed in the foregoing section. This Policy involves raising the levels of agricultural production of all suitable crops except cereals and mutton to the level at which the greatest practicable amount of imports have been replaced. The production of both cereals and mutton a large scale requires very large quantities of desalinated water at considerable cost, and even if this water cost is ignored, these foodstuffs can only be produced in Qatar at several times the imported cost. Table 14.2 summarised expected production, water requirement, costs and value of the plan.

14.4.5.2 The Agricultural Development Plan

(i) Traditional Mixed Farming Development

This sector would continue to provide the bulk of local vegetables, fruit and dates as well as some mutton. Using the three farm types, vegetable, vegetable/orchard/forage and orchard/forage (See Sec. 2.2.2.4) with average areas of 18, 19 and 10 ha respectively, about 250 productive farms would be required. These farms should be encouraged to adopt new techniques and to invest in new equipment to save water and to increase yields and cropping intensity.

The increase in the area of fruit would need to be relatively greater than the growth in the area of vegetables and could be established on land currently followed. Fruit production could be increased from existing trees and new plantations, but prices are low and the high cost of labour discourages production by landowners who are not greatly interested in producing for the market. Financial incentives, access to credit and increased security of tenure should be used to encourage fruit production from tenanted farmers, although some direct Government investment would also be necessary in view of the delay between planning and full production (at least 5 years).

The proposed expansion in vegetables and fruit cannot be achieved using ground-water only as availability is limited. Vegetable and fruit farms using water saving and improved production technologies should be developed in northern Qatar as close as possible to the proposed desalination plant at Ras Laffan, so minimising the cost of the reticulation system. About 30 MCM of desalinated water would be required in 1990 and 35 MCM in the year 2000 for the production of vegetables, fruit and dates.

The quality, grading and packaging of domestically produced vegetables and fruit particularly tomatoes would need to be improved for them to be competitive with imports. Care would be needed to avoid stimulating production at a rate faster than the market could absorb the extra foodstuff, which would lead to falling prices and ultimately defeat the objective of raising output.

(ii) Milk and Beef Production

Assuming the Qatar Dairy Company continues to produce 1,450 tonnes of milk per year from 380 cows, approximately 1,430 cows would be required to produce 5,600 tonnes of milk by 2000. The Qatar Dairy Company is currently considering plans for increasing milk production which would need to be taken into account prior to embarking on the expansion of milk production. The Qatar Dairy Company has the infrastructure and dairy management expertise, and its production costs per unit of milk would probably be less than those of completely new ventures. Therefore, encouraging its expansion up to the levels required would be preferable. Assuming all additional milk output is produced from new farms using treated sewage effluent in central Qatar, the milk production strategy could be as follows :-

- establish a 90 cow pilot farm ready for production in 1985;
- double up the above 90 cow unit to 180 in 1990 and develop one new 180 cow unit;
- develop two further 150 cow units in 1995; and
- develop two further 195 cow units in the year 2000.

At present, the Qatar Dairy Company feeds a high proportion of imported concentrates and the minimum of alfalfa because this is a cheaper policy than producing larger quantities of alfalfa. If the costs of supplying irrigation water were set too high, any new private dairy enterprise would do likewise and merely import cattle feed, thereby partially defeating the objective of increasing self-sufficiency.

PROPOSED AGRICULTURAL AND WATER RESOURCES DEVELOPMENT PLAN (2000)

1. Production

Product	Replace-able imports (tons)	Local Pro-duction (tons)	Cul-tivated area (ha)	Labour (no)
Milk	5628	5628		
Beef	235	235	370	200
Mutton	3883	300		
Cereals	23034	-		
Dates	3650	3300		
Vegetables (W)	18270	18270	4401	1900
Vegetables (S)	8070	8070		
Fruit	3650	3700		
Cucumber	650	650	13	100
Total	67070	40,153	4784	2200

2. Water Requirements (MCM)

	Agriculture	Domestic
Groundwater	23.5	-
Treated Sewage Effluent	10.5	-
Distilled Water	35.2	105
Total	69.2	105

3. Cost (QR millions)

	Agriculture	Domestic
Farming Costs	92.2	-
Water Costs	229.5	618
Food Imports	89.5	-
Total	411.1	618

4. Value

Total value of production (QR million)	115.4
Total value of production (% of 1980 GNP)	0.7
Total % increase in value of agricultural production over 1980.	139

(iii) Protected Agriculture

Off-season cucumber production from coolhouses located in central Qatar and using good quality groundwater should be developed from the existing 0.t ha of Ministry of Industry and Agriculture and IDTC coolhouses so that in 1990 there would be 1.65 ha of coolhouses plus 1.65 ha of adjacent outdoor vegetables. This development would rise to 6.5 ha of coolhouses and 6.5 ha of outdoor vegetables by the year 2000.

Each one hectare of coolhouses would produce 100 tonnes of off-season cucumber and could also supplement vegetable production during other periods.

(iv) Abu Samrah Sheep Farm

Domestic mutton production has been shown to be very uneconomic. However, as the Abu Samrah sheep farm is a sunk cost, the Government should rehabilitate its drainage and irrigation systems and continue to utilise existing groundwater resources. The farm's original objective of producing improved breeding stock for distribution to the traditional sector should be the main aim.

14.4.5.3 The Water Resources Development Plan

(i) Annual Demands

Under the proposed Agricultural Plan, the demand for water for productive agriculture rises from 53 Mm^3 in 1980 to about 69 Mm^3 in the year 2000, which should be added to demands from other sectors. However, not all of the demands need to be considered directly in preparing an overall plan. Industrial and other consumers with their own desalination plants may be excluded. The specific requirements in Doha for landscaping (0.7 Mm^3 in 1980) may in future be met by the development of the freshwater dome building up under the city, (See Section 13.2.1 (a)). The remaining demands are for productive agriculture, amenity farms, central potable supplies and isolated domestic supplies not drawn from agricultural wells. These isolated supplies amount to about 0.8 Mm^3 and may be expected to continue at a similar level. The demands from each of the three remaining sectors rise from 124 Mm^3 in 1980 to 196 Mm^3 in the year 2000.

The most practical large source of desalination water in Qatar would be multi-stage stage flash distillation associated with waste heat from thermal power stations or industrial processes. The installations at Ras Abu Fontas and Ras Abu Aboud could produce about 64 MCM at present at a load factor of 75 per cent. This capacity will rise to 88 MCM when the installation of four new units and ancilliaries is completed in the next 2-3 years. No further extension to either plant is planned, and future desalination facilities are proposed at Ras Laffan. The results obtained from this Study confirm that there are no cheaper or more reliable sources of water and that any deficit in Qatar's supplies should be made good by increased capacity at Ras Laffan.

Under the suggested Water Resources Development Plan, the dependence of productive agriculture upon groundwater would be reduced in order to curtail the over-abstraction in the north to restore equilibrium with recharge. This would involve :

1. continuing abstractions at their present level unitl 1985; then
2. reducing the level of net abstraction progressively to 27 Mm^3/year in 1990; and
3. continuing thereafter at the lower abstraction rate.

Under this operating rule, the overall net abstraction rate for the next 30 years would be equivalent to the safe yield of 33 Mm^3.

The quantity of distilled sea water required would however, be considerably reduced if treated sewage water could either be made available in the north east of Qatar or if the quality constraints could be relaxed. Neither of these changes has been incorporated into the Water Resources Development Plan, and so Ras Laffan would be called upon to produce about 29 MCM in 1990 rising to 45 Mm^3 in the year 2000. Although in theory there would be some spare capacity at Ras Abu Aboud and Ras Abu Fontas in 1990, the construction of a special distribution system would not be practicable for such a short period, and all the agricultural demands have been assumed to be met from Ras Laffan.

(ii) Monthly Variations in Water Demand

The total annual water demand figures derived in the foregoing show a considerable encouraged, groundwater abstractions could be regulated to reduce the peak demands on other sources, particularly desalination. Under the suggested Plan, distilled sea water for agriculture is proposed for irrigation in northern Qatar, close to the Ras Laffan site. The allocation model indicated which farm types should be located in which areas, and on combining these results with the overall monthly irrigation demands for each farm type, the monthly agricultural water requirements were obtained. After subtracting the groundwater supply in a suitable temporal pattern, the agricultural demand for desalinated water was found to range from 1.7 to 2.7 Mm^3/month in 1990, and from 2.1 to 3.3 Mm^3/month in 2000. Combining agricultural demand with the potable demand the total pattern of demand for desalinated water is arrived at.

The conclusions of the analysis of annual and monthly water requirements were :

1. The installed desalination capacity at Ras Laffan will need to rise to 33 Mm^3 by 1990 and 57 Mm^3 by 2000, representing 4 units and 7 units respectively of the size currently installed at Ras Abu Fontas and proposed for Ras Laffan;

2. The load factors for Ras Laffan are adequately high yet retain sufficient margins to allow for maintenance; and

3. The demands for water are sufficiently well matched to the supply to avoid the need for very large storage reservoirs.

As a corollary to point (3) above, the earlier proposal that aquifer storage by injection should be provided to minimise fluctuations in demand is therefore seen to be unnecessary. Further investigation of this proposal has not therefore been pursued.

BIBLIOGRAPHY

ALMOJIL (1963) "Report on Drilling Programme, Qatar", 1963 Unpublished Report to Govt. of Qatar

Berstein, L. (1974) "Crop Growth and Salinity" Chap 3 in Van Schiltgaards, Agronomy 17. Am Soc. Agro. Madison, Wisconsin

Bloom, A.L. et al (1974) "Quaternary sea level fluctuations on a tectonic coast : new $^{230}Th/^{234}U$ dates from the Huon peninsula, New Guinea Quat. Res. 4. 185-205

BRGM (1976) "Wasia Study" Unpublished report to Ministry of Water and Agriculture, Saudi Arabia.

BRGM (1977) "Al Hasa Study" Unpublished report to Ministry of Water and Agriculture, Saudi Arabia.

Bramkamp., R.A. (1946) See Powers et al, 1961

Brooks, C.E.P. (1923) "Variations in the level of the Central Arican lakes Victoria and Albert", Geophys. Mem. 20, 1923

Brunsden, D., Doomkamp J.C. Jones, D.K.C. (1979) The Bahrain Surface Materials Resources Survey. Geogr. jour vol 145(1)

Burdon, D.M. (1967) "Water Resources of Qatar for Municipal and Agricultural Use" FAO Report MR 65852, Rome.

Businger, J.A. (1959) "Some remarks on Penman's Equation for evapotranspiration". Neth. Jour. Agric Sc., 4

Cavalier, C., Al Salatt, Y. Heuze (1970) "Geological Description of the Qatar Peninsula", Bureau of recharches geologiques et minieres, Paris.

Clark, L. (1977) "The Analysis and Planning of Step Dreawdown Tests." Q.Jl. Engng. Geol. Vol 10 No. 2 125-144

Clark, L. (1978) Discussion on "The Analysis and Planning of Step Drawdown Tests" Q.J. Engng Geol. Vol 11 No. 2 203-4

Cooper, H.H. and Jacob, C.E. (1946) "A Generalised Graphical Method for Evaluating Formation Constraints and Summarising Well Field History." Am. Geophys. Union Trans. Vol 27 : 526-534

Craig, H. (1961) Standard for reporting concentrations of deuterium and O^{18} in actual waters. Science, 133, 1823-1834.

Chidley, T.R.E. (1981) "A Mathematical Model of the Northern Groundwater Aquifer System of Qatar" FAO Project Technical Note No. 15 (NS) Doha, Qatar.

Cochrane N.J. (1957) "Lake Nyasa and River Shire" Proc. Inst. Civil Engrs, London 8

Darcy, H. 1856 — Les fontaines publiques de la ville de Dyon. V. Dalmont, Paris

Dastane N.G.; Al-Faihani M. (1980) — 'Irrigation Practices'. FAO Project Technical Report No.4 Doha, Qatar.

Dickson, H.R.P. (1956) — "Kuwait and her neighbours" Allen & Unwin, London p. 595.

Dincer, T.A., Al-Mugrin & Zimmerman U. (1974) — "Study of the Infiltration and Recharge through the sand dunes in arid zones with special reference to the stable isotopes and thermonuclear tritium". <u>J. Hydrology</u>, 23

Dixey, F. (1924) — "Lake Level in Relation to Rainfall and Sunspots". <u>Nature</u>, 114

Doorenbos, G., Pruit, W., (1975) — "Crop Water Requirements". FAO Irrigation and Drainage Paper No. 24, Rome.

Dupuit, J. 1863 — Etudes théoretiques et pratiques sur le mouvement des eaux dams les canaux découverts et à travers les terrains perméables. 2 evie edition; Dunot, Paris

Eden, R.N. and Hazel, C.P. 1973 — Computer and Graphical Analysis of Variable Discharge Pumping Tests of Wells. <u>Civil Eng. Trans. Inst. Eng. Austr.</u> 5-10

Edmunds, W.M. and Walton N.R.G. (1980) — Assessment of recharge to aquifers. <u>Hyd. Sc. Bull 25</u>, 3, 9.

Evans G. Schmidt V., (1969) Bush P. and Nelson H. — Stratigraphy and geologic history of the Sabkha, Abu Dhabi, Persian Gulf. <u>Sedimentology</u>, 12, 145-9

Fisher, R.A., Tippett, L.M.C. (1928) — "Limiting forms of the frequency distribution of the smallest and largest member of a sample". <u>Proc. Cambridge Phil. Soc.</u>, 24

FAO (1974) — "Qatar - Water Resources and Use" AGL : DP/QAT/501 Technical Report No. 2, Rome.

FAO (1979) — "Survey and Evaluation of Available Data on Shared Water Resources in the Gulf States and the Arabian Peninsula" FAO Rome.

FAO (1977) — "Water Resources of Qatar and their Development" Integrated Water and Land Use Project UNDP/FAO. Technical Report No. 1.

GDC/MAW (1980) — Umm er Radhuma Study Groundwater Development Consultants (International) Ltd for Ministry of Agriculture and Water. Kingdom of Saudi Arabia.

GDC/MAW (1980) — Umm er Radhuma Study - Bahrain Assignment. Groundwater Development Consultants (International) Ltd for Ministry of Agriculture and Water. Kingdom of Saudi Arabia.

Gemmell, B.A.P. (1977) "Observations of Rainfall, Run-off and Infiltration in Qatar, 1976". FAO Project working paper.

Gumbel, E.J. (1941) "Probability interpretation of the observed return period of floods". Trans Am. Geophys. Union, 2.

Hadi-el, H. (1975) "Results of 1975 Drilling Programme, Qatar" FAO Project Technical Note No. 35, Doha, Qatar.

Harhash, I. (1975) "Artificial Recharge Wells in Northern Qatar". FAO Project Technical Note No. 36, Doha, Qatar.

Hem, J.D. (1970) Study and Interpretation of the chemical characteristics of National Water. USGS Water Supply Paper, 1473.

Henry & Brown (1935) ARAMCO Report (unpublished)

Howard, K.W.F. (1979) Hydrochemical studies related to groundwater flow and saline encroachment in the chalk aquifer of north-east Lincolnshire and south Humberside. Ph.D. Thesis, Univ. of Bermingham,268.

Howard, K.W.F. and Lloyd, J.W. (1978) Iodide enrichment in the groundwaters of the chalk aquifer, Lincolnshire, England. Int. Symp. Hydrochemistry of mineralised waters, Int. Assoc. Hydrologists, Poland.

Huber, C. (1891) "Journal d un voyage en Arabia", Paris. P. 121 and 773.

IDTC (1979) "Conductivity Report : Qatar Peninsula" by Geoterrex Ltd., Canada.

IDTC (1980) "Qatar Geological Map and Exploratory Booklet. Seltrust Engineering Ltd. Govt of Qatar.

ITALCONSULT (1969) "Water and Agricultural Studies in Area IV" Ministry of Agriculture and Water, Saudi Arabia.

ITALCONSULT (1971) "Water and Agricultural Studies in Bahrain" Ministry of Agriculture and Water, Govt. of Bahrain, 2 Vols.

Jacob, C.E. 1946 Drawdown test to determine effective radius of artesian well. Proc. Am. Soc. Civ. Engrs. 72 629-46

Johnson, S.J. et al (1972) "Oxygen isotope profiles through the Antartic and Greenland ice sheets. Nature 235 : 429-434

Johnstone, N.E. and Stern, S.R. (1972) "Technical Report on the Hydrogeology of Qatar" FAO Project Working Paper 1972.

Johnstone, T.M. and Wilkinson, J.C. (1960) "Some geographical aspects of Qatar" Geogr. J., London 126 p. 442-450

Logan, J. 1964 Estimating transmissibility from routine production tests of waterwells. Groundwater, Vol. 2. No.1. 35-37

Le Grand Adsco (1959) "The Freshwater Resources of Northern Qatar". Mineographed report to Government of Qatar.

Lloyd, J.W., Eccleston, B.L. and Pike, J.G. (1981) "The Hydrochemistry of the Groundwaters of Qatar" FAO Project Technical Note No. 14 (NS) Doha, Qatar

Maas, E.V. and Hoffman. G. (1977) Crop salt tolerance - Current Assessment. J. Irrig and Drainage Div. ASCE 103 (IR2) 115-134

Mather, J.D. Development of the groundwater resources of small limestone islands. Q.Jl. Engng. Geol. Vol 8 No. 2 141-50

Milliman J.D., Emery, K.O. (1958) Sea levels during the past 35,000 years, Science, 162, 1121-3.

Mitra, A.K. (1976) "An Analysis of the cost of lifting groundwater on private farming units in Qatar". FAO Project Technical Note No. 37, Doha, Qatar.

McCulloch, J.S.G. (1961) "Evaporation Pans in East and Central Africa". Proc. Inter. African Hydr. Conf. CCTA Pub 16.

McClure, H.A. (1976) "Radiocarbon chronology of late Quaternary lakes in the Arabian Desert", Nature vol. 263 p. 755

Musil, A. (1926) "Manners and Customs of the Rwala Rural Bedouins" in Encyclopedia d'Islam, (New York) p. 679.

Naimi, Al (1965) "The Groundwater of Northern Saudi Arabia". Proc. 5th Arab Petroleum Cong.

Obied, M. (1975) "A study of the Natural Vegetation of Qatar. FAO : AGO QAT/74/007, Rome.

Parker, D.H., Pike, J.G. (1976) "Groundwater Resources of Qatar and their Development" FAO Project Technical Note No. 34, Doha, Qatar.

Payne, B.R. (1981) Report on Environmental Isotope Data - Qatar. IAEA, February.

Pearson F.J. and Hanshaw N.V. (1970) C^{14} evidence for the origin of arid region groundwater, NE province, Kenya, IAEA.

Philby, H. St. J.B., (1922) "Heart of Arabia" Constable, London P. 319.

Philip, J.R. (1959) "The theory of local advection" J. Meteorology 16.

Pike, J.G. (1959) "The sunspot/Lake level theory and the control of Lake Nyasa". Jour. Inst. Water Engrs., London 19.

Pike, J.G. (1971) "The evaporation of groundwater from coastal playas in the Arabian Gulf". Jour. Hydrology, 11.

Pike, J.G., Harhash, I., and Gemmell, B.A.P. (1975) "Rainfall and Recharge over Qatar" FAO Project Technical Note No. 24, Doha, Qatar.

Pike J.G. (1978) "The Agro-climatology of Qatar". FAO Project Technical Note No. 1 (N.S.) Doha.

Pike, J.G. (1980) "Water Resources and Agriculture in Qatar" Arabian Studies, Vol. V. Centre for M.E. Studies, Cambridge University, 1980.

Pilgrim, G.E. (1908) "The geology of the Persian Gulf and adjoining portions of Persia and Arabia Mem Geol. Surv. India XXXIV, 4.

Powers, R.W., Ramirez, I.F. Redmond, C.D. and Elberg, E.L. (1966) "Geology of the Arabian Peninsula" US Geological Survey Professional Paper No. 5600, Washington.

Raikes, R.L. (1967) "Field Archaeology in Saudi Arabia" East and West Vol 17, ISMEO, Rome.

Reardon, E.J. and Fritz, P. (1977) Computer modelling of groundwater C^{13} and C^{14} isotope compositions. J. Hydro. 36, 201-224

Richards, L.A. (ed) (1954) Diagnosis and improvement of saline and alkali soils. U.S. Dept. of Agriculture Handbook 60.

Rorabaugh, M.I. 1953 Graphical and theoretical analysis of step drawdown tests of artesian wells. Proc. Am. Soc. Civ. Engrs. 79. Separate No. 362 1-23.

Sander N.J. (1962) Apercu, paléontologique et stratigraphique de paléogene en Arabic Séoudite orientale : Rev. de Micro-paléontologic, v.5, no. 1, p. 3-40.

Sarahead, A., and Kishiel, H. (1970) "Computer modelling of random thunderstorms and run-off in an arid climate". Proc. IASH Conference, Tucson, UNESCO

Shackleton, N.J., and Opdyke, N.P. (1973) Oxygen isotope and paleomagnetic stratigraphy of Equitorial Pacific Core v̇ 28 - 238 : Oxygen isotope temperatures and ice volumes on a 10^5 year and 10^6 year scale.

Shainberg, I, and J.D. Oster (1978) "Quality of Irrigation Water", I.I.I.C. pub No. 2, Ottawa, Canada.

Shonse, P., Jury W.A., and Stolzy, L.H. (1980) "Use of Determistic and Empincal Models to Predict Potential Evapotranspiration in an Advecture Environment". Agron. Jour. Vol. 72 p. 994.

Siegenthaier, U. (1971) O^{18}, Deuterium and Tritium in Wassenkreislanf. Ph.D. Thesis, Bern. 109.

Smout, A.H. (1954) "Lower Tertiary Foraminifera of the Qatar Peninsula" London, Jerrold and Sons Ltd 96 p.

Smout, A.H. (1954) "Lower Tertiary Foraminifera of the Qatar Peninsula" British Museum (Natural History) London.

SOGREAH (1966) "Report on Increasing groundwater supplies for the city of Doha, Qatar". Unpublished Report Water Dept., Govt. of Qatar.

Steineke, Max and Bramkamp, R.A. (1942a) "Mesozoic rocks of eastern Saudi Arabia (abs)". Am. Assoc. Petroleum Geologists Bull., v. 36, no. 5, p. 909.

Sugden, W. (1956) QPC Report (unpublished).

Tanner, C.B. and Pelton, W.L. (1960) "Potential evapotranspiration estimates by the approximate energy balance method of Penman". Journ. Geophy. Res., 65.

Thiem, G. 1906 Hydrologische Methoden. Gebhardt, Leipzig.

Thies, C.V. 1935 The Relation between the Lowering of the Piezometric Surface and the Rate and Duration of Discharge of a Well using Groundwater Storage. Am. Geophys. Union Trans. Vol 16 : 519-524

Thralls, H.W. and Hasson R.C. (1956) "Geology and oil resources of eastern Saudi Arabia". Internat. Geol. Cong., 20th, Mexico, Symposium Sobre Yacimentos de Petroloco y Gas, V.2, p. 9-32.

Van Bavel C.H.M. (1966) "Potential Evaporation : The Combination Concept and its Experimental Verification". Jour. Water Resources Res. 2.

Vita Finzi, C. (1978) 'Environmental History' chap. in Qatar Archaeological Report (1973) ed Beatrice de Cardi, Oxford Univ. Press.

Wigley, T.M.L. (1976) Effect of mineral precipitation on isotopic composition and C^{14} dating of groundwater. Nature Vol. 263.

Wigley, T.M.L. and Plummer L.N. (1976) Mixing of carbonate waters, Geochim. cosochim. Acta, 40 989-995.

Williamson, Ṫ.R. and Pomeyrol, H. (1938) "Geology of the Qatar Peninsula" (QPC Report GR 97) App. I. "Note on the Water Resources of the Qatar Peninsula".

Willis R.P. (1967) "Geology of Arabian Peninsula - Bahrain" USGS Prof. Paper 560 E. U.S. Govt Print Office Washington 4. pp.

Yurtsevor Y. and Payne B.R. Application of environmental isotopes to groundwater investigations in Qatar IAEA, Neuterberg, Germany.

Yaron, B., Shimshi, D., and Shalhevet, J. (1973) Patterns of salt distribution under trickle irrigation Ecological Studies 4 : 389-394, Springer Verlag, Berlin

Zöll, G., Saad, S., and Al-Sayari (1978) Quaternary Period in Saudi Arabia. Springer Verlag, Wien, N.Y.

Harhash, I. (1979) Report on Wadi Al-Aurage Drilling Programme in the Artesian Aquifer. Project Technical Note No.44.

Harhash, I. (1980) Rainfall-Run-off-Recharge Evaluation Qatar 1972/79. Project Technical Note No.7(New Series)

ANNEXURE

Groundwater Model Programs

ANNEXURE

GROUNDWATER MODEL PROGRAMS

1. Introduction

The groundwater programs described in this Appendix solve a two-layer groundwater model that has been applied in Qatar. It was written in the programming language BASIC for a Hewlett-Packard 9830B micro-computer but which was subsequently transferred and modified to the Apple II for the purposes of the master planning study by Halcrow-Balfour.

The available groundwater modelling programs consist of both lumped parameter and distributed parameter (finite difference) models. The former group comprise three programs : STSTGW, FRK2TRC and FRK3TRC. The steady state groundwater model program STSTGW was used to calibrate three empirical factors in the lumped groundwater model, and was unchanged from the original HP version. For completeness, a brief description of this program is presented in Section 2 together with full operating instructions. Programs FRK2TRC and FRK3TRC were updated versions of program RK2TRC, which was the original lumped parameter groundwater model. These programs, which are built around a standard Hewlett-Packard program for the solution of differential equations, are described in Sections 3 and 4 respectively.

The distributed parameter model was tabelled program HWWMD7. The data files associated with this program HWPM20 (aquifer parameters), HWRE06 (steady state recharge matrix) and HWRE10 (pumping matrix). A modified version of HHWMD7 was mounted on the Apple II in which :

- the formula expressing the gross pumping as a function of number of years since 1957 was changed in order to take account of the large increase in rate of pumping after 1978; (See Chap. XII para 12.1).

- irrigation return flow was reduced from 25 to 20 per cent of total gross abstraction; and

- the units in which recharge and flows were printed out were changed to MCM per one or two-year period from m^3/day.

In addition to HHWMD7, which was used to model the piezometric levels in the northern aquifer system over the period from 1958 to 1979, three further versions of the program were developed on the Apple II to forecast the effect on the aquifer of different abs r action policies. The first of these forecasting programs, GWMDPROD1, assumes that the 1979 spatial distribution of abstractions remains unchanged. In the second, GWMDPROD2, the effect of an entirely new abstraction policy can be tested. The third, GWMDPROD3, assumes the same basic abstraction pattern as GWMDPROD1, but allows the user to specify additional abstractions at specified nodes of the model. Full descriptions and operating instructions for these programs are presented in Sections 5 to 7 respectively. A further utility program, UDRAF, was developed to update the random access files which contain the input data for the distributed parameter groundwater models.

2 PROGRAMME HHWMD7

2.1 Purpose and Data Requirements

The program uses four sets of data, three of which have to be created previously. It assumes a constant rate of recharge to the upper aquifer and a steady increase of total abstraction with time which is built into the program.

Aquifer parameters are the transmissivity and storage coefficients for each aquifer. They may be stored as absolute or relative values since they are converted to actual units at run time. One value is given for each parameter on a 15 x 9 grid of points. The sea is simulated by assigning very high T values to nodes which are to be excluded from the model. The arrays are stored in the order : upper aquifer transmissivity; upper aquifer storage coefficient; lower aquifer transmissivity; lower aquifer storage coefficient. Final calculated values are on the file FHWPM24.

The recharge and pumping data are given on a separate file as three arrays of data, 15 x 9. The first array contains the steady state recharge to the upper aquifer; the second array the proportion of the total pumping in each node to come from the upper aquifer, with allowances made for whether water is totally removed from the area or partly returned as irrigation water, (20% of abstraction from each aquifer is returned as irrigation return); the third array contains for each node the proportion of total pumping to come from the combined upper and lower aquifers. This latter amount is split at run time. These data are recorded under the title TRECH2O. Initial values may be assigned for each aquifer or all assigned to a constant in a new file created at run time. At the end of a run the initial file will contain the most recent values of the water levels.

2.2 Description

At run time, after creating the main data arrays in FRECH21 or FRECH07 and FHWPM24, a number of other parameters are assigned. These are :-

(1) Time step for integration in days (usually 365 or 730) 365 for steady state runs.

(2) Relaxation factor (0.8 to 1.5) normally 1.5.

(3) Conversion coefficient for aquifer transmissivity in upper aquifer, which under this calibration, is 170. This converts the figure in the first array of the file FHWPM24 to transmissivity in m^2/day.

(4) Conversion coefficient for storage coefficient in upper aquifer, calibrated value 0.004. This converts the figures in the second array on the file FHWPM24 to storage coefficient. For steady state runs set this parameter to zero.

(5) Conversion coefficient for recharge in upper aquifer, normally 180. This factor converts the values in the first array on file FRECH2O to recharge in cubic metres per day. The original values are in cm of effective rainfall.

(6) Same as (3) for lower aquifer, calibrated value 3000.

(7) Same as (4) for lower aquifer, calibrated value 0.0001.

(8) Global factor for permeability between aquifers normally 0.00005. This value varies from place to place and is set as a multiply of the given value in the program.

(9) Initial head in upper aquifer, normally 0. This value is used on setting up a new file of head data.

(10) Same as (9) for lower aquifer, normally 4.

(11) Proportion of combined aquifer abstraction from upper aquifer, calibrated value 0.3.

The utility program UDRAF is given which enables the main data arrays to be edited and copied. Any individual element can be changed and the program is self documenting.

When a run ends the water levels are saved on the IN VALUES file. These values can be used as the initial values for a continuation run. The file FHHINO5 contains the calibrated water levels for the end of 1979. To investigate a proposed development one makes a copy of FHHINO5 using UDRAF and then uses this copy in running the groundwater model as initial values for the run.

3 Program STSTGW

3.1 Purpose

The steady state groundwater model program STSTGW is employed to calibrate three empirical factors which are contained in the lumped parameter groundwater model. In this model, the outflows from both the upper and lower aquifers and the flow between the two aquifers are assumed to be proportional to differences in governing head. The empirical factors appear as the proportionality constants in each equation, and are defined by the product of a permeability and a flow area divided by the distance over which the head difference is applicable (see Chidley, 1979; pp. 7-11).

3.2 Description

The program first asks the user to specify the details of the steady state pumping regime, the natural recharge and the boundary head in the lower aquifer. STSTGW then computes the following information for a range of values of the three empirical factors :

1. the head in the upper aquifer (Y);
2. the head in the lower aquifer (Y2);
3. the rate of flow from the upper aquifer to the sea (Q1);
4. the rate of outflow from the lower aquifer (Q2);
5. the rate of flow from the upper to the lower aquifer (Q3); and
6. the sum of Q1, Q2 and Q3 (Q).

The output table provides the basis for selecting the values of the three empirical factors which reproduce most closely the assumed steady state characteristics of the northern aquifer system.

3.3 Operating instructions

Run STSTGW. The following requests are made by program :

"INPUT Y3 - BOUNDARY HEAD IN LOWER AQUIFER"
Type in the required value (m).

"INPUT P - LEVEL OF PUMPING IN THE STEADY STATE"
Type in the value (MCM/year).

"INPUT A - PROPN. OF COMBINED PUMPING FROM UPPER AQUIFER"

"INPUT B - PROPN. OF TOTAL PUMPING COMING FROM COMBINED PUMPING"

When all these values are input, the program calculates the information listed in Section (A.2.2) and prints out the results.

4 Program FRK2TRC

4.1 Purpose

This program calculates the head in the upper and lower aquifers of the northern groundwater area at the end of each one or two-yearly interval over the period 1958-1980. Additional information concerning the volume of water abstracted and flows into and out of the two aquifers is also specified.

Unlike the program HHWMD7, the calculations are made in 'lumped' terms; no detailed information is required on the formation constants for individual nodes of the grid. However, given the same input, the two programs should produce approximately the same output.

The program FRK2TRC is simply an application of the standard Hewlett-Packard program for solving differential equations using second-order Runge Kutta integrations.

4.2 Description

FRK2TRC first asks the user to input a considerable amount of information concerning the overall characteristics of the two aquifers. This information includes the three empirical factors calculated using STSTGW as described in Section (A.2). Other information required for input to STSTGW must also be specified for FRK2TRC, such as the boundary head in the lower aquifer and the proportion of pumping from each of the two aquifers. Also needed is the number of years for which the output is required, and the size of the time interval.

The level of gross abstraction in each year (P9) is calculated using the following formula (line 1080) :

$$P9 = 1.06(3 + 2.5X - 0.0075X^2)$$

where X = years since 1958.

Two differential equations are formulated, one for each aquifer. The equation for the upper aquifer (lines 1110-1120) is :

$$H3 = [RE + (0.2).P9 - P9.(1-B9) - A9.P9.B9 - (K1 + K3).Y + K3.H2] / (A8.S9)$$

where H3 = the increase in head during the year (m);

RE = the steady state recharge (MCM);

B9 = the proportion of total pumping from combined pumping;

A9 = the proportion of combined pumping (upper aquifer);

K1 = the empirical factor for the upper aquifer;

K3 = the inter-aquifer empirical factor;

Y = the head in the upper aquifer (m);

H2 = the increase in head in the lower aquifer during the year (m);

A8 = the area of the aquifer (km^2);

and S9 = the storage coefficient of the upper aquifer.

The equivalent equation for the lower aquifer is (lines 1090-1100) :

$$H2 = (K3.Y + K2.Y3 - (1-A9).B9.P9)/(K3+K2)$$

where K2 = the impirical factor for the lower aquifer; and

Y3 = the boundary head in the lower aquifer (m).

These formulae are similar to those developed earlier in HHWM7. There are, however, two differences : firstly, the abstraction variable, P9, is gross in program FRK2TRC, but net originally, which has involved small adjustments to the formulae; and secondly, the irrigation return has been reduced from 25 to 20 per cent.

The differential equations are solved using the Runge Kutta method, as noted above. The results are printed, and the calculations repeated for the following year. When the final year has been completed, the program terminates.

4.3 Operating instructions

Run the program. The following requests for information are made :

"INPUT RE - RECHARGE IN MCM/YEAR"

Type in the steady state recharge in each year.

"INPUT K1 - UPPER AQUIFER COEFFICIENT"

"INPUT K2 - LOWER AQUIFER COEFFICIENT"

"INPUT K3 - INTER AQUIFER COEFFICIENT"

These are the empirical factors selected by inspection of the output from STSTGW.

"INPUT A9 - PROPN OF COMBINED PUMPING FROM UPPER AQUIFER"

"INPUT B9 - PROPN OF TOTAL PUMPING COMING FROM COMBINED PUMING"

"INPUT A8 - AREA OF AQUIFER IN SQ. KM."

"INPUT S9 - STORAGE COEFFICIENT OF UPPER AQUIFER"

"INPUT Y3 - BOUNDARY HEAD IN LOWER AQUIFER"

"INPUT INITIAL YEAR FOR WHICH OUTPUT REQUIRED - 1958 = 0, 1959 = 1, ETC"

"INPUT WATER LEVEL IN UPPER AQUIFER IN THIS INITIAL YEAR"

"INPUT NUMBER OF YEARS FOR WHICH OUTPUT IS REQUIRED"

"INPUT REQUIRED INTEGRATION STEP SIZE"

"INPUT YEARLY INTERVAL AT WHICH OUTPUT IS REQUIRED"

Recommended values for all the aquifer parameters were given in Chapter XIV. The initial water level in the upper aquifer must be compatible with the inflows and outflows at that time. This head can be estimated using the following formula :

Initial water level = (RE - 1.5 + K3.Y3)/(K1 + K3)

5 Program FRK3TRC

5.1 Purpose

This program is the 'lumped equivalent to program GWMDPROD1, and forecasts the level of water in the upper and lower aquifers from 1980 to the year 2000, as a result of different pumping policies. The level of abstraction can be reduced to a proportion of its 1980 level by any date specified during the modelled time period.

5.2 Description

The program is almost identical to program FRK2TRC. The only difference concerns the level of pumping in each year. In the original, this figure was calculated by means of a formula which is quoted in Section (4.2). In the case of FRK3TRC, the user is requested to specify the level of pumping in the base year (1980), the target reduction, and the year at which this target is to be reached.

The program assumes that the level of abstraction falls linearly between the two years, and remains constant thereafter (lines 1080-1083).

5.3 Operating instructions

The instructions are the same as for FRK2TRC, except that three additional requests are made :

"ENTER 1980 ABSTRACTION"
Type in the gross abstraction in that year, in MCM.
"TARGET REDUCTION IN ABSTRACTION, % OF ORIGINAL"
Type in the number of years which is to be taken for the target reduction to be reached.

6 Program GWMDPROD1

6.1 Purpose

Program GWMDPROD1 forecasts the head of water in the upper and lower aquifers in the northern groundwater area. The forecast is provided for each node on a grid covering the modelled area, for the end of each one or two-year period between the years 1980 and 2000. Additional information is supplied for each of the two aquifers taken as a whole, such as the net recharge, the inflow and the change in storage over the time period.

When producing these forecasts, the program assumes that the spatial distribution of abstractions from the aquifers in 1978 is not changed. However, the effect of a reduction in the total volume of water abstracted from the aquifers can be tested. The user specifies the percentage of the 1980 level to which it is assumed that the abstractions will fall, and the date by which this target will be achieved. After this date, the volume of water abstracted is assumed to continue at the reduced level.

6.2 Description

GWMDPROD1 first reads details of nodes through which there is an outflow to the sea. The information is obtained from data statements and stored in the array D. This array is used when calculating the volume of water passing between the two layers and the sea in lines 2670-2700.

The program now asks the user to specify the names of the three input files. The first contains the aquifer parameters, i.e. the transmissivity and storage coefficients for each aquifer. The second contains the recharge parameters, and the third, the input values of the heads of water in the upper and lower aquifers in the base year. Details of the contents of these three files are given in Chap. XIIV (Tables B.16 to B.22).

When the information has been read from each of the files and stored in arrays in core, the program requests the user to type in at the keyboard of the micro-computer more data required for the calculations (lines 689-702). These data include additional information concerning the characteristics of the aquifers, such as the initial head in both, and the assumptions to be tested in the run concerning the level to which the total abstractions will fall, and the date at which the new level is achieved.

Conversion coefficients are now applied to the information stored in many of the arrays in order to alter the units in which the information is held (lines 720-990). For example, the recharge at each node is converted from mm/year to m^3/day.

Two arrays are now printed by the program. The first is the transmissivity in the upper layer at each node of the grid (in m^2/day). The second is the storage coefficient in the upper layer at each node. The permeability between the two layers at each node is now defined (line 1180-1240). For any one node, the permeability is either kept at zero (the initial value), or set at the global value as specified by the user. At certain nodes, a factor is applied to this global value. The heads on the boundary of the grid are generally assumed to be zero, i.e. at sea level. Adjustments to this level at certain nodes are now made to incorporate the effect of local conditions.

The loop within which the calculations are carried out for each one or two-year period is now entered for the first time (line 1360). The total gross abstraction during this time period is calculated according to the criteria specified by the user, printed and converted from MCM/year to m^3/day for use in the subsequent calculations.

The contents of three arrays are now calculated (lines 1460-1520). The first, E, contains net abstraction from each node due to upper aquifer pumping. The array W contains net pumping from the upper aquifer, resulting from both upper and combined aquifer pumping. The array R contains net recharge at each node (total recharge minus pumping), excluding that from lower aquifer pumping.

Two combined totals for the whole model area (excluding the boundary), are now calculated by summing over individual nodes. The first is net pumping from the upper aquifer, summed over array W; the second is the steady state recharge to the upper aquifer, summed over array A. The results are then printed.

The contents of the two arrays used in the above calculations are now modified (lines 1610-1630, and 1680-1710). Recharge resulting from pumping from the lower aquifer is added into the array R; and the array E is set equal to net recharge to the lower aquifer at each node (the negative of net abstraction).

The first solution of the finite difference equations is now made, firstly for the upper aquifer (lines 1800-1990), and then for the lower aquifer (line 2000-2160). The theory behind these calculations is fully described in Chidley (1981; pp. 27-29). The output from the equations is the head at each node in both aquifers. The results are written into the data file containing the input values on disk.

These computed heads are now compared with those from the previous iteration (or the input values in the case of the first iteration). If they differ by less than a certain specified amount the solution is assumed to have been obtained. Otherwise, the program returns to line 1730, and a further iteration is carried out.

When the solution has been found (or after 50 iterations have been carried out), a number of the nodal values are aggregated to give overall results for the time period in question. These results include the change in storage in the two aquifers, the net recharge to the two aquifers and the flow from the upper to the lower aquifer (lines 2440-2550).

The main results from the calculations, namely the heads at each node in both aquifers, are now printed. The net inflow to the upper and lower aquifers from the sea is calculated, (lines 2660-2710). The aggregate statistics, computed as described above, are now printed out. The units in which the figures were calculated are changed in most cases from m^3/day to MCM/time period.

The output of these summaries marks the end of the loop within which the calculations are carried out for each time period. The next time period for which the results are required is now taken, and the process repeated. Alternatively, if the final time period has been reached, the program terminates.

6.3 Operating instructions

Copy the random access file FHHINO5 to another named file (with a block length of 1500) using program UDRAF (see Section (A.8)). This file contains the heads in the upper and lower aquifer at each point in the grid at the end of 1979. Run GWMDPROD1.

The program makes the following requests :

"AQUIFER PARAMETERS"

Input the name of the file containing the required aquifer parameters. The current version of this file is FHWPM24.

"NET RECHARGE"

Input the name of the file containing the required recharge parameters. The appropriate file for use with GWMDPROD1 is RECH21.

"INPUT VALUES"

Type in the name of the file containing the input values, i.e. the copy of file FHHINO5, as indicated above.

Program GWMDPROD1 then requests the user to type in the required values of conversion coefficients and certain characteristics of the two aquifers. These are the same for any run of the grid model, and the recommended values are given in the operating instructions to HHWMD7 presented by Chidley (1981).

The program continues with the following requests :

"IRRIGATION RETURN FLOW - FACTOR 1 FOR 100% USAGE NIL RETURN"

The value currently recommended is 0.8, for 20 per cent irrigation return flow.

"1980 TOTAL ABSTRACTION MCM/YEAR (60 + OR -5)"

Type in the assumed total abstraction in 1980 within the range 55-65 MCM.

"TIME PERIOD TO ACHIEVE REDUCED ABSTRACTION"

Type in the required time period less than or equal to the 20 years over which the model is being run.

"REDUCED ABSTRACTION AS PERCENTAGE OF TOTAL 1980 ABSTRACTION"

The typical figure to test is one within the range 25-75 per cent.

The program then continues with no further input required from the user until all the results have been printed for the time period specified.

7 Program GWMDPROD2

7.1 Purpose

Program GMWDPROD2 is similar to GWMDPROD1, and forecasts the heads at each node in the upper and lower aquifer of the northern groundwater area. However, program GWMDPROD1 assumes that the spatial distribution of abstractions from the two aquifers remains the same as in 1978, but GWMDPROD2 can test an entirely new abstraction plan. In addition, GWMDPROD1 can allow for the effect of a reduction in the total volume of abstractions over a specified time period, but this option is not available in GWMDPROD2.

7.2 Description

The methodology of program GWMDPROD2 is the same as that of GWMDPROD1, the only difference being that in the latter, the recharge parameters file contains the proportion of the abstraction from the upper aquifer alone at each node. Similarly, the file giving the parameters for pumping from the combined aquifers contains proportions and not absolute values. Subsequently, the user specifies the total volume of water pumped (in 1980), and the two are multiplied to give the pumping from each node. However, in GWMDPROD2, the total volume of water pumped from each node is specified in the recharge file, not the proportions. The spatial distribution of the pumping at the level specified is assumed to remain constant over time.

7.3 Operating instructions

The basic abstraction file is FRECHO8, which contains three matrices. The first is the natural recharge at each node, and the other two are blank. This file is copied to another named file using the program UDRAF. When copying, the first matrix is left unaltered. The second matrix is completed with the volume of water assumed to be abstracted from each node from the upper aquifer alone (in 10^3m^3 per year). In addition, the third matrix is filled with the water abstracted from each node by means of combined aquifer pumping.

Run program GWMDPROD2. The files of aquifer parameters and the input values are same as for GWMDPROD1.

The information which the user is required to type in at the keyboard is also the same as for the first program, except that the option to reduce total abstraction in base year to a proportion of this amount over time is not available in GWMDPROD2.

8 Program GWMDPROD3

8.1 Purpose

This program is the third of the series designed to forecast the impact on the northern aquifer of different abstraction policies up to the year 2000. GWMDPROD3 expects the same basic pattern of abstraction as GWMDPROD1, which can be reduced to a percentage of the 1980 level in the same way. However, in the case of GWMDPROD3, the user can test the effect of additional abstractions at selected nodes on the grid. The volume of water abstracted from these is assumed to remain constant over time.

8.2 Description

GWMDPROD3 first requests the user to specify the number of nodes at which new abstractions will take place. The program then takes each node in turn, and requests that the volume of water abstracted be typed in. The volume, corrected to m^3/day, is stored in the location appropriate to the node in question in array NP.

The program then proceeds to ask the user to specify the names of the input files in the same way as GWMDPROD1. The file containing the recharge matrices should be the same as that input to GWMDPROD1, i.e. the 1978 proportions, not total volumes.

GWMDPROD3 continues in exactly the same manner as GWMDPROD1. The only differences are caused by the need to add the effects of the new pumping into the appropriate arrays. For example, the total net recharge, held in array R, is less at those nodes at which additional pumping is assumed to be taking place (line 1500). The contents of array E, in which net recharge to the lower aquifer at each node is held, will be different for the same reason (line 1700).

8.3 Operating instructions

Produce a copy of the input data file, as for GWMDPROD1. Run GWMDPROD3.

The program then makes the following requests :

"NUMBER OF NEW ABSTRACTIONS"

Type in the number of nodes on the grid at which new abstractions are assumed to take place. The following request will appear for each new abstraction :

"ROW, COLUMN, QUANTITY (MCM/YEAR)"

Type in the row and column number of the node, and the quantity of water assumed to be abstracted each year (in MCM).

The program then requests :

"AQUIFER PARAMETERS",

and continues in an identical manner to GWMDPROD1. The input files are the same.

9 Program UDRAF

9.1 Purpose

This program updates the random access data files which are used for input to the groundwater model programs. UDRAF can also be employed to create a copy of file, with a different name, by running the program and specifying no changes.

9.2 Description

The program first asks the user to specify the name and location of the input file and the output file. The user is then asked to give the block size, the dimensions of the matrices and the number of blocks. The file is then read into core, block by block. As each block is read, the user is requested to type in all the changes required. When all the changes have been completed, the converted block is copied to the output file and the next block read in.

Finally, the input and output files are closed, and the user is asked if he wishes to update another file. If he does, then the process is repeated; otherwise the run is terminated.

9.3 Operating instructions

Mount the disk containing the input file and that which is to carry the output file. Run the program. Specify the name and location of the input and output files, as requested by the program. The program continues with the following requests :

"BLOCK SIZE"

Type in the length of each record on the file, in bytes.

Recharge parameters file	-	1000 bytes
Aquifer parameters file	-	1000 bytes
Input values file	-	1500 bytes

"DIMENSIONS OF MATRICES - ROW FIRST"

Type in the dimensions of the matrix held in each block.

"DO MATRICES HAVE A NUMERIC HEADER? E.G. THE YEAR ? - Y OR N "

Generally "N"

"NUMBER OF BLOCKS"

Recharge parameters file	-	3 blocks
Aquifer parameter file	-	4 blocks
Input values file	-	2 blocks

The program then reads the first block into core. The following message appears :

"BLOCK 1 ANY CHANGES ? - Y OR N"

If the answer is "N" then this block is copied to the output file and the next block read in. If the answer is "Y", the following message appears :

"WHICH ELEMENT OF THE MATRIX DO YOU WISH TO CHANGE ? - ROW FIRST"

Type in the row and column number of the element in the matrix to be changed, separated by a comma.

"OLD VALUE WAS XXXX"

"NEW VALUE IS"

Type in the new value.

"MORE CHANGES - Y OR N"

If the answer is "Y" the message requesting that the element of the matrix to which the change is requied appears on the VDU again. If the answer is "N", the block is copied to the output file and the next block read in. This procedure continues until every block on the file has been processed.

The program then makes the following request :

"DO YOU WISH TO UPDATE ANOTHER FILE - Y OR N"

If the answer is "Y", the name and location of the new input and output files are requested. The following message then appears :

"ARE ALL THE FILE CHARACTERISTICS THE SAME AS BEFORE ? - Y OR N"

If the answer is "Y", then none of the first five prompts above are displayed; the details of the matrices are assumed to be the same. The program then continues in the same manner as before.

Annex 12

GROUNDWATER MODEL PROGRAM

(HHWMD 7)

```
:?""
]LIST
10  REM  HHWMD7
20  REM  2LAYER BOUNDARY HEAD FIXED SOUTH END BOTH AQUIFERS
25  HTAB 28: PRINT "31-JULY-79": PRINT
30  REM  SAVED UNDER HGWMD SERIES CALIBRATION MODEL
40  REM  VERTICAL PERMEABILITY AT SELECTED NODES
50  REM  INCLUDES WATER BALANCE FOR MODEL AREA APPROXIMATE ONLY
60  DIM D(2,42),N(18)
70  DIM Y,II,LI,JI,NI,MI
80  DIM T(135),S(135),R(135),C(135),Q(135),E(135),P(135)
90  DIM F(135),B(135),X(135),H(135)
100  DIM A(135),Y(135),Z(135),W(135)
110  DIM NULL$(8).
120 NULL$(3) = "   "
130 NULL$(8) = "        "
140 DD$ = ""
150  FOR J = 1 TO 42
160  FOR I = 1 TO 2
170  READ D(I,J)
180  NEXT I
190  NEXT J
195  PRINT DD$,"OPEN GWMRD"
196  PRINT DD$;"PR# 1"
200  PRINT "AQUIFER PARMS?";
210  INPUT GA$
220  PRINT DD$;"OPEN ",GA$,",L1000"
230  PRINT "NET RECH?";
240  INPUT GB$
250  PRINT DD$;"OPEN ",GB$;",L1000"
260  PRINT DD$;"READ ";GB$,",R1"
270  FOR I = 1 TO 135
280  INPUT A(I)
290  NEXT I
295  PRINT DD$;"READ ";GB$,",R2"
300  FOR I = 1 TO 135
310  INPUT Y(I)
320  NEXT I
325  PRINT DD$;"READ ",GB$;",R3"
330  FOR I = 1 TO 135
340  INPUT Z(I)
350  NEXT I
360  PRINT DD$,"CLOSE ";GB$
370  PRINT DD$;"READ ",GA$;",R1"
380  FOR I = 1 TO 135
390  INPUT T(I)
400  NEXT I
```

```
405  PRINT DD$,"READ ",GA$,",R2"
410  FOR I = 1 TO 135
420  INPUT S(I)
430  NEXT I
435  PRINT DD$,"READ ";GA$,",R3"
440  FOR I = 1 TO 135
450  INPUT C(I)
460  NEXT I
465  PRINT DD$;"READ ";GA$;",R4"
470  FOR I = 1 TO 135
480  INPUT Q(I)
490  NEXT I
500  PRINT DD$;"CLOSE ";GA$
510  PRINT "IN VALUES?";
520  INPUT GC$
530  PRINT DD$,"OPEN ";GC$;",L1500"
540  PRINT "DOES THIS FILE CURRENTLY EXIST-YES OR NO",
550  INPUT A$
560  IF A$ = "YES" GOTO 590
570 N3 = 0
580  GOTO 689
590 N3 = 1
600  PRINT DD$,"READ ";GC$;",R1"
610  FOR I = 1 TO 135
620  INPUT H(I)
630  NEXT I
635  PRINT DD$;"READ ";GC$,",R2"
640  FOR I = 1 TO 135
650  INPUT B(I)
660  NEXT I
670  PRINT DD$;"CLOSE ";GC$
680  PRINT DD$;"IN# 0"
689  INPUT "INPUT INITIAL TIME STEP FOR INTEGRATION, IN DAYS",D3
690  INPUT "RELAXATION FACTOR IN CALCULATION OF SIMULTANEOUS EQUATIONS (0.8-1.5)";Y
691  INPUT "CONV. COEF. FOR TRANSMISSIBILITIES INTO UNITS OF M^3/DAY (UPPER AQUIFER)";T9
692  INPUT "CONV. FACTOR FOR STORAGE COEF. (UPPER AQUIFER)";S9
693  INPUT "CONV. FACTOR FOR RECHARGE INTO UNITS OF M^3/DAY";R9
694  INPUT "CONV. COEF. FOR TRANSMISSIBILITIES (LOWER AQUIFER)";C9
695  INPUT "CONV. FACTOR FOR STORAGE COEF. (LOWER AQUIFER)",Q9
696  INPUT "GLOBAL FACTOR FOR PERMEABILITY BETWEEN AQUIFERS",F9
697  INPUT "INITIAL HEAD IN UPPER AQUIFER",X9
698  INPUT "INITIAL HEAD IN LOWER AQUIFER";F9
699  INPUT "PROPN. OF COMBINED AQUIFER PUMPING FROM UPPER AQUIFER";A9
703 D2 = 7500
704 I1 = 1:I2 = 15
705 J1 = 1:J2 = 9
707 E9 = 0
710 D9 = 0
```

```
720  FOR I = 1 TO 135
730 Z(I) = 1 * Z(I)
740 T(I) = T9 * T(I)
750 S(I) = S9 * S(I)
760 A(I) = R9 * A(I)
770 C(I) = C9 * C(I)
780 Q(I) = Q9 * Q(I)
790 X(I) = 1
800 X(I) = X9 * X(I)
810 F(I) = 1
820 F(I) = F9 * F(I)
830  IF N3 = 1 THEN 860
840 B(I) = F(I)
850 H(I) = X(I)
860 F(I) = B(I)
870 X(I) = H(I)
880 P(I) = 0
990  NEXT I
1010  PRINT "";
1020  PRINT "TRANSMISSIBILITY UPPER AQUIFER"
1030  FOR I = 1 TO 15
1040  PRINT I
1050  FOR J = 1 TO 9
1060  PRINT T((I - 1) * 9 + J);NULL$(3),
1070  NEXT J
1080  PRINT NULL$(3)
1090  NEXT I
1100  PRINT "STORAGE COEF IN UPPER AQUIFER"
1110  FOR I = 1 TO 15
1120  PRINT I
1130  FOR J = 1 TO 9
1140  PRINT S((I - 1) * 9 + J);NULL$(3);
1150  NEXT J
1160  PRINT NULL$(3)
1170  NEXT I
1180 P(1) = P9:P(2) = P9:P(9) = P9:P(10) = P9:P(11) = P9:P(12) = P9.P(17) = P9:P(18) = P9:P(20) = P9:P(21)
1190 P(24) = P9:P(25) = P9:P(26) = P9.P(30) = P9.P(31) = P9:P(33) = P9:P(32) = P9:P(39) = P9:P(40) = P9
1200 P(41) = P9:P(49) = P9
1210 P(16) = P9 * 0.5:P(22) = P9 * 0.5:P(23) = P9 * 0.5.P(27) = P9 * 0.5:P(29) = P9 * 0.5:P(34) = P9 * 0.5:
1220 P(42) = 0.75 * P9
1230 P(22) = 2 * P9:P(23) = 2 * P9.P(24) = 2 * P9
1240 P(41) = 0.05 * P9:P(42) = 0.05 * P9:P(48) = 0.05 * P9:P(49) = 0.05 * P9
1250 H(100) =  - 2:H(109) =  - 2:H(127) =  - 2
1260 H(118) =  - 4
1270 H(129) = 3:H(130) = 3
1280 H(131) = 3.5
1290 H(132) = 4
1300 H(133) = 1
1310 H(134) = 0.2
1320 B(18) = 1:B(27) = 1
1330  REM  SET BOUNDARY HEADS ON SOUTH EDGE OF UPPER AQUIFER
1340  REM  SET BOUNDARY HEADS ON LOWER AQUIFER SOUTH BOUNDARY
```

```
1350  PRINT DD$;"PR# 0"
1360  FOR M = 1 TO 11
1370  PRINT M
1380 D1 = D2 * D2
1390 D = D1 / D3
1400 T1 = (D9 + D3 / 2) / 365
1410 P = (3 + (2.5 - .0075 * T1) * T1) * 2739.7 * 1.06
1420 I3 = I1 + 1
1430 I4 = I2 - 1
1440 J3 = J1 + 1
1450  REM  COMPUTE ABSTRACTION
1460  FOR I = 1 TO 135
1470 R(I) = (0.80 * P) * Y(I)
1480 R(I) = A(I) - R(I)
1490 E(I) = (A9 * P) * Z(I) * 0.8
1500 R(I) = R(I) - E(I)
1510 W(I) = A(I) - R(I)
1520  NEXT I
1530 Z8 = 0:Z9 = 0
1540  FOR I = 2 TO 14
1550  FOR J = 2 TO 8
1560 N = (I - 1) * 9 + J
1565  IF N = 11 OR N = 12 OR N = 16 OR N = 17 OR N = 20 OR N = 26 OR N = 29 OR N = 35 OR N = 89 THEN 1590
1570 Z8 = Z8 + A(N)
1580 Z9 = Z9 + W(N)
1590  NEXT J
1600  NEXT I
1610  FOR I = 1 TO 135
1620 E(I) = (0.2 * (1 - A9) * P) * Z(I)
1630  NEXT I
1640  PRINT DD$;"PR# 1"
1650  PRINT "";
1660  PRINT "PUMPING FROM UPPER AQUIFER PER TIME PERIOD (MCM) ";Z9 * .000001 * D3
1670  PRINT "RECHARGE TO UPPER AQUIFER AREA MCM PER TIME PERIOD ";Z8 * .000001 * D3
1680  FOR I = 1 TO 135
1690 R(I) = R(I) + E(I)
1700 E(I) = ( - 1 * (1 - A9) * P) * Z(I)
1710  NEXT I
1720 J4 = J2 - 1
1730  FOR L = 1 TO 50
1740  PRINT DD$;"PR# 0"
1750  PRINT "L";L
1760 U = 0
```

```
1770  FOR I = I3 TO I4
1780  FOR J = J3 TO J4
1790 N = (I - 1) * J2 + J
1800  REM  UPPER AQUIFER
1810 T7 = T(N)
1820 N1 = N - J2
1830 N2 = N - 1
1840 N3 = N + J2
1850 N4 = N + 1
1860 T1 = 0.5 * (T7 + T(N1))
1870 T2 = 0.5 * (T7 + T(N2))
1880 T3 = 0.5 * (T7 + T(N3))
1890 T4 = 0.5 * (T7 + T(N4))
1900 T5 = T1 + T2 + T3 + T4
1910 Z = T1 * H(N1) + T2 * H(N2) + T3 * H(N3) + T4 * H(N4)
1920 Z1 = D1 * P(N)
1930 Z2 = D * S(N)
1940 Z = Z + R(N) + X(N) * Z2 + B(N) * Z1
1950 T5 = T5 + Z1 + Z2
1960 Z = Z / T5
1970 V = Z - H(N)
1980 U = U + V * V
1990 H(N) = H(N) + Y * V
2000  REM  LOWER AQUIFER
2010 T7 = C(N)
2015 T1 = 0.5 * (T7 + C(N1))
2020 T2 = 0.5 * (T7 + C(N2))
2030 T3 = 0.5 * (T7 + C(N3))
2040 T4 = 0.5 * (T7 + C(N4))
2050 T5 = T1 + T2 + T3 + T4
2060 Z = T1 * B(N1) + T2 * B(N2) + T3 * B(N3) + T4 * B(N4)
2070 Z1 = D1 * P(N)
2080 Z2 = D * Q(N)
2090 Z = Z + E(N) + Z2 * F(N) + Z1 * H(N)
2100 T5 = T5 + Z1 + Z2
2110 Z = Z / T5
2120 V = Z - B(N)
2130 U = U + V * V
2140 B(N) = B(N) + Y * V
2150  NEXT J
2160  NEXT I
2170  PRINT "U";U
2180  PRINT DD$;"OPEN ";GC$;",L1500"
2190  PRINT DD$;"WRITE ";GC$;",R1"
2200  FOR I = 1 TO 135
2210  PRINT H(I)
2220  NEXT I
2225  PRINT DD$;"WRITE ";GC$;",R2"
```

```
2230  FOR I = 1 TO 135
2240  PRINT B(I)
2250  NEXT I
2260  PRINT DD$;"CLOSE ";GC$
2380  IF U < 0.01 THEN 2400
2390  NEXT L
2400 D9 = D9 + D3
2410  PRINT DD$;"PR# 0"
2420  PRINT "TIME",D9;"DAYS"
2430 E8 = 0:R8 = 0
2435 S8 = 0:S7 = 0:Q8 = 0
2440  FOR I = I3 TO I4
2450  FOR J = J3 TO J4
2460 N = (I - 1) * J2 + J
2465  IF N = 11 OR N = 12 OR N = 16 OR N = 17 OR N = 20 OR N = 26 OR N = 29 OR N = 35 OR N = 89 THEN 2490
2470 E8 = E8 + E(N)
2475 S8 = S8 + (H(N) - X(N)) * S(N)
2476 S7 = S7 + (B(N) - F(N)) * Q(N)
2477 Q8 = Q8 + P(N) * (H(N) - B(N))
2480 R8 = R8 + R(N)
2490  NEXT J
2500  NEXT I
2520  PRINT DD$;"PR# 1"
2530  PRINT "",
2540  FOR I = 1 TO I2
2550  PRINT "H ROW";I;NULL$(3);
2560 N1 = (I - 1) * J2 + 1
2570 N2 = (N1 + J2 - 1)
2580  FOR N3 = N1 TO N2
2590  PRINT H(N3);NULL$(3);
2620  NEXT N3
2630  PRINT NULL$(3)
2640  NEXT I
2650 Q7 = 0:Q6 = 0
2660  FOR J = 1 TO 42
2670 K1 = D(1,J)
2680 K2 = D(2,J)
2690 Q7 = Q7 + ((H(K1) - H(K2)) * (T(K1) + T(K2)) / 2)
2700 Q6 = Q6 + ((B(K1) - B(K2)) * (C(K1) + C(K2)) / 2)
2710  NEXT J
2720  FOR I = 1 TO 135
2730 X(I) = H(I)
2740 F(I) = B(I)
2750  NEXT I
2760 D3 = D3
2770  PRINT NULL$(3)
2780  FOR I = 1 TO I2
2790  PRINT "B ROW";I;NULL$(3);
2800 N1 = (I - 1) * J2 + 1
2810 N2 = N1 + J2 - 1
2820  FOR N3 = N1 TO N2
2830  PRINT B(N3),NULL$(3);
2850  NEXT N3
2860  PRINT NULL$(3)
2870  NEXT I
```

```
2880 S8 = S8 * 7.5 * 7.5
2890 S7 = S7 * 7.5 * 7.5
2900 Q8 = Q8 * 7.5 * 7.5 * D3
2902 R8 = R8 * 1.0E - 6 * D3
2903 E8 = E8 * 1.0E - 6 * D3
2904 Q7 = Q7 * 1.0E - 6 * D3
2905 Q6 = Q6 * 1.0E - 6 * D3
2910  FOR I = 1 TO 135
2920 F(I) = B(I)
2930  NEXT I
2940  PRINT "NET RECHARGE TO UPPER ";R8;"MCM/TIME PERIOD"
2950  PRINT "NET RECHARGE TO LOWER ";E8;"MCM/TIME PERIOD"
2960  PRINT "FLOW FROM UPPER TO LOWER ";Q8;"MCM/TIME PERIOD"
2970  PRINT "CHANGE IN STORAGE UPPER ";S8;"MCM"
2980  PRINT "CHANGE IN STORAGE LOWER ";S7;"MCM"
2990  PRINT "INFLOW TO UPPER ";Q7;"MCM/TIME PERIOD"
3000  PRINT "INFLOW TO LOWER ";Q6;"MCM/TIME PERIOD"
3010  NEXT M
3015  PRINT DD$;"CLOSE GWMRD"
3020  DATA   12,13,4,13,5,14,6,15,16,15,16,25,26,25,35,34,35,44
3030  DATA  45,44,54,53,63,62,72,71,81,80,89,80,89,88,89,98
3040  DATA   99,98,108,107,117,116                    ,126,125,134,125,133,124,132,123,131,122
3050  DATA  130,121,129,120,109,110,100,101,91,92,82,83,73,74,64,65,55,56
3060  DATA  46,47,37,38,29,38,29,30,20,21,12,21,118,119,128,119
3070  END
```