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PROPOSED ARTIFICIAL RECHARGE STUDIES IN NORTHERN QATAR

By Joel O. Kimrey

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ABSTRACT

The aquifer system in northern Qatar is comprised of a water-table aquifer in the Rus Formation which is separated by an aquitard from a partially confined aquifer in the top of the underlying Umm er Radhuma Formation. These two aquifers, composed of limestone and dolomite of Eocene and Paleocene age, contain a fragile lens of freshwater which is heavily exploited as a source of water for agricultural irrigation. Net withdrawals are greatly in excess of total recharge, and quality of ground water is declining.

Use of desalinated seawater for artificial recharge has been proposed for the area. Artificial recharge, on a large scale, could stabilize the decline in ground-water quality while allowing increased withdrawals for irrigation. The proposal appears technically feasible. Recharge should be by injection to the Umm er Radhuma aquifer, whose average transmissivity is about 2,000 meters squared per day (as compared to an average of about 200 meters squared per day for the Rus aquifer).

Implementation of artificial recharge should be preceded by a hydrogeologic appraisal. These studies should include test drilling, conventional aquifer tests, and recharge-recovery tests at four sites in northern Qatar.

INTRODUCTION

Fresh ground water is a very limited resource in Qatar (fig. 1), an arid peninsula in the southwest part of the Arabian Gulf. However, expanding agricultural activities, particularly in northern Qatar, are highly dependent upon this limited resource for irrigation.

Background

In 1971 the Government of Qatar with technical assistance of the FAO (Food and Agricultural Organization of the United Nations), began Phase I of a long-range multiphase program of joint investigations of water resources and agricultural development. During Phase II of this joint investigation, technical consulting advice on artificial recharge was requested through the USAID (Agency for International Development) and received from the U.S. Geological Survey (Vecchioli, 1976). Phase II, completed in 1977, was followed by a third phase known as the Water Resources and Agricultural Development Project. Data collected during Phase III allowed a more refined and complex concept of the aquifer system in northern Qatar. Final results of Phase III related to hydrology were published as The Water Resources of Qatar and Their Development: Volumes I-III, Eccleston, Pike, and Harhash, 1981. In 1984, during implementation of the joint investigation's Phase III recommendations, the Government of Qatar again requested services of a hydrogeologist for advice in the area of artificial recharge.

Purpose and Scope

Both the 1976 and 1984 requests for technical advice were related to artifical recharge of aquifers in northern Qatar by injection of desalinated seawater. Specifically, the 1984 request was for assistance in developing plans for an investigation of (a) methodology for injection of the desalinated water, and (b) the optimal amounts of water that might be recharged in this manner. Subsequently, the author spent November 18 to December 16, 1984, at Doha, Qatar, gathering and assimilating information and assisting in preparation of long-range plans for augmentation of ground-water resources by means of artificial recharge. Most of this time was spent in review of existing technical reports and data related to hydrogeologic conditions, and in discussion and field reconnaissance with personnel of the Department of Agricultural and Water Research, Ministry of Industry and Agriculture, State of Qatar.

The purpose of this report is to present the author's recommendations for hydrogeologic aspects of artificial recharge experiments in northern Qatar; the Appendix contains a work plan for conducting the proposed hydrogeological appraisal. The necessary background material on hydrologic conditions in Qatar is largely from previous reports and from data files made available to the author.

Acknowledgments

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GEOLOGIC SETTING

Qatar occupies an arid peninsula of some 11,600 km^2 which extends northward into the Arabian Gulf from the main land mass of Arabia. The peninsula is about 180 km along its north-south axis, and the east-west width at its widest point is about 85 km. The surface of the peninsula is of low to moderate relief with the highest altitudes of about 100 m occurring in southern Qatar where mesa-type hills and large barchan sand dunes represent the maximum relief on an otherwise flat and eroded land surface.

The Qatar peninsula is an integral part of the Arabian peninsula and the geology of Qatar follows the detailed and well-defined stratigraphy of Saudi Arabia as presented by Powers and others (1966) (in Eccleston and others, 1981). The Qatar peninsula is underlain by a series of gently dipping to flat-lying sediments that were deposited on gradually subsiding basement rocks. The major structure of the peninsula is a broad north-south trending anticlinal arch with gentle crest and steeper marginal dips; this arch plunges to the north and south from a broad domal apex near the center of Qatar. Geologic structure along the west coast is complicated by the more tightly folded Dukhan anticline and adjacent syncline whose axes trend north-northwest to north.

Deposits of Pliocene, Miocene, and Eocene age crop out over the peninsula and are overlain locally by Quaternary deposits. The oldest strata exposed are the limestones of the Rus Formation of early Eocene age, but the most widespread outcrops are the dolomites and crystalline chalky limestones in the upper part of the overlying Dammam Formation of middle Eocene age. The Umm er Radhuma Formation of Paleocene age, directly underlies the Rus Formation throughout Qatar, but is not exposed at the surface. Mesozoic rocks have been identified during exploratory oil drilling by stratigraphic correlation with geological units in Saudi Arabia (Eccleston and Harhash, 1982).

The occurrence of fresh ground water in Qatar is restricted to the rocks of Eocene and Paleocene age, which are described below in descending order.

Dammam Formation

This formation crops out over most of the Qatar peninsula. Five members are recognized with general lithologies described below in descending order:

> The Abarug Member, composed of dolomitic limestone and marl; the Simsina Member, composed of chalky limestones, some chert and clay; the Dukhan Alveodina Limestone Member, composed of massive whitish limestone with abundant fossils and variable clay content; the Midra Shale Member, composed of yellow-brown to greenish attapulgite shale; and the Fhaihil Velates Limestone Member, composed of whitish, compact, crystalline fossiliferous limestone. Total thickness of the Damman Formation is about 50 m. The upper part tends to be well-fractured and contains vugs and solution cavities.

Rus Formation

The Rus Formation conformably underlies the Dammam Formation throughout Qatar, but crops out only in relatively small areas that are northwest of Doha, and on the Dukhan anticline in western Qatar.

The lithology of the Rus Formation consists of white to brown, chalky, dolomitic limestones; marls, clays, and shales; and gypsum and anhydrites. The beds of dolomitic limestone and evaporite tend to be massive, and the clayey beds tend to be thin and occur as intercalations. The occurrence of thick gypsum beds is mainly confined to southern Qatar, where they may comprise more than half the total thickness of the formation. In northern Qatar these evaporite beds are generally absent and the Rus is predominately composed of carbonate facies.

Thickness of the Rus ranges from less than 30 to more than 90 m. The greatest variations in thickness tend to occur in the area of the structural high in central Qatar. The formation contains abundant fractures, vugs, and solution channels, particularly in northern Qatar where the carbonate facies predominate.

Umm er Radhuma Formation

The Umm er Radhuma Formation conformably underlies the Rus Formation. Their contact is marked by an abrupt lithological change from the cream or nearly white chalky limestone of the Rus Formation above to the gray brown, dolomitic limestone of the Umm er Radhuma Formation below. The Umm er Radhuma Formation consists mainly of a thick sequence of white to gray to brownish vesicular dolomites, dolomitic limestones, and limestones. Some siliceous zones occur in form of chert and silicified limestone or dolomite. Argillaceous and gypsiferous material is believed to occur only to a minor extent and near the base of the formation in Qatar. Thickness of the Umm er Radhuma is considered more than 300 m over most of Qatar; data available for three water-exploratory boreholes indicate thickness to range from 270 to 330 m. The formation is well fractured and contains numerous solution cavities.

HYDROGEOLOGY

Rainfall over Qatar is the primary source of available freshwater. "Total average rainfall over Qatar may vary from 10 to over 200 mm in any one year but falls from individual storm events sometimes as high as 180 mm in 4-5 days (1966) have occurred. The model average annual rainfall would appear to be of the order of 75 mm in northern Qatar and slightly less in southern Qatar" (Eccleston and others, 1981, p. 5/18).

Recharge from local rainfall is the sole replenishment to the natural freshwater resource. Most recharge results from infiltration of runoff that collects in surface depressions, commonly from rainfall events of more than 10 mm.

Eccleston and others (1981, p. 10/22-10/30) describe ground water in Qatar as occurring in three aquifers: the Alat (Abarug Member in this report) aquifer; the Rus aquifer; and the Umm er Radhuma aquifer. The water table occurs in either the Dammam or Rus Formations over most of Qatar. Occurrence in the Dammam, however, is generally confined to the lower-lying coastal areas.

The Alat aquifer occurs only in southwest Qatar, and contains brackish water that is probably recharged to the west in the outcrop area of the Dammam Formation in Saudi Arabia. The Alat aquifer is not discussed further in this report.

The Rus aquifer and the Umm er Radhuma aquifer comprise a two-layer system that contains all of the fresh ground water available in Qatar. The aquifers occur in vertically adjacent geologic formations, but are hydraulically separated by intervening less permeable materials. The deeper Umm er Radhuma aquifer contains highly saline water at some depth throughout Qatar, salinity generally being lower in the top of the aquifer and increasing with depth.

Eccleston and others (1981) have divided the areal extent of this two-layer aquifer system into two broad hydrogeologic areas, the Northern and Southern Ground Water Provinces, as shown in figure 1. This concept of separate ground-water provinces is very important to understanding the mode of occurrence and quality of ground water throughout Qatar.

The Southern Ground Water Province, geologically, is characterized by the persistence of relatively thick evaporite beds in the Rus Formation (the "depositional sulphate facies" of Eccleston and others (1981) as noted on fig. 1). These relatively impermeable, though highly soluble, sulphate beds have persisted, in part, because of the presence of the Midra Shale Member in the overlying Dammam Formation. This overlying shale has retarded downward migration of recharge water and thus retarded dissolution of the evaporite beds in the Rus Formation to a large extent. The end result is that evaporite beds are still intact and dense, and the Rus Formation is unsaturated with ground water over some large areas. The overall permeability of the Rus

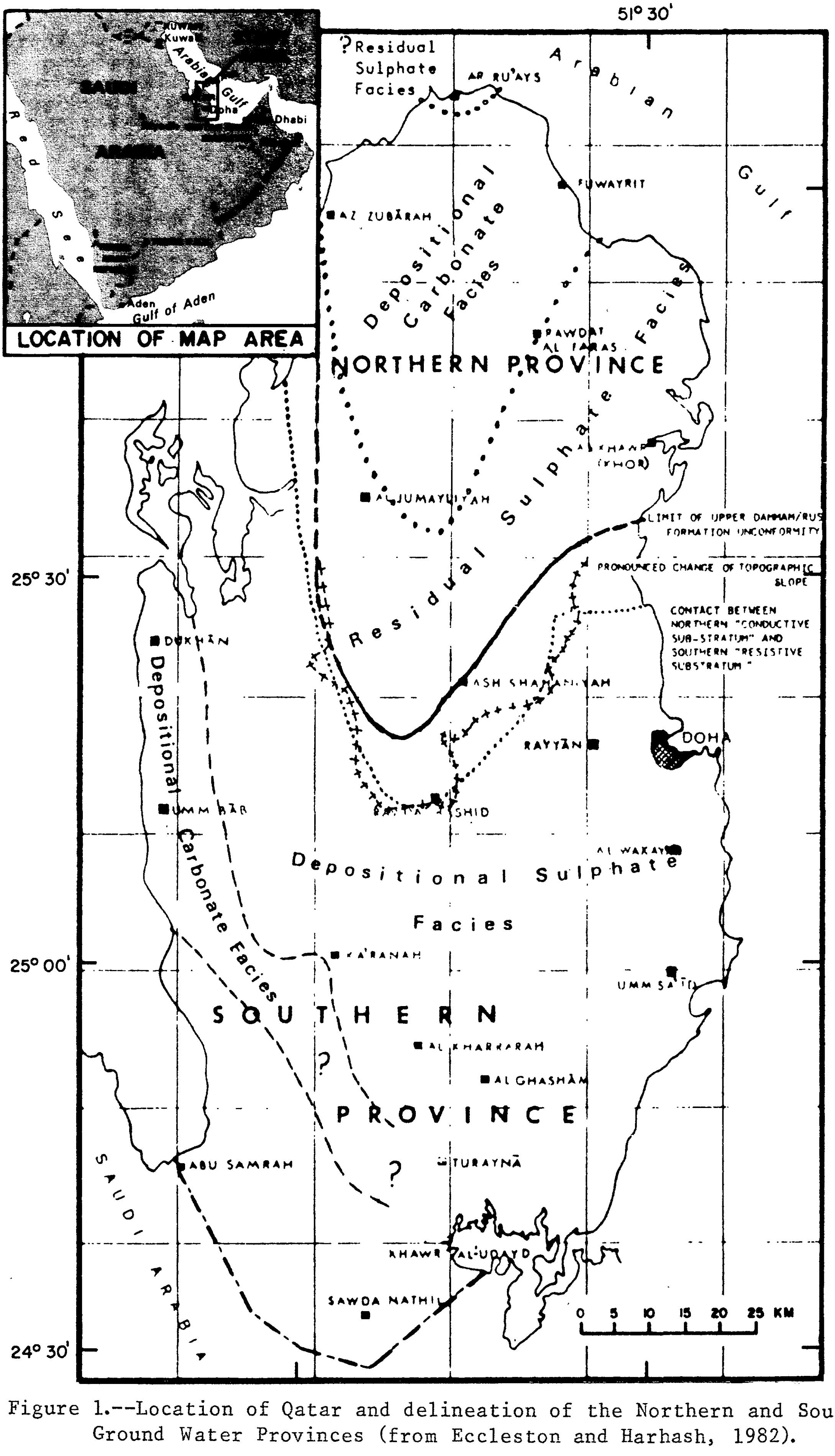

Figure 1.--Location of Qatar and delineation of the Northern and Southern Ground Water Provinces (from Eccleston and Harhash, 1982).

Formation is thus low in the Southern Ground Water Province. Where percolating meteoric waters have been able to penetrate to the Rus, some dissolution of the evaporite beds has occurred; this results in saturation of the Rus Formation in those areas, and the ground water is calcium sulphate in type. The land surface depressions that form as a result of subsurface dissolution tend to be relatively steep sided and up to 20 m in depth. Any hydraulic connection between the Rus and the underlying Umm er Radhuma aquifer is probably restricted to these areas where the land surface is depressed and the Rus Formation is saturated with ground water. Even there, it is likely poor because of the general lack of ground-water circulation in the Southern Province.

In summary, the Southern Ground Water Province is characterized by low transmissivity and the discontinuity of saturated zones in the Rus Formation; calcium sulphate type ground water; and lack of areal hydraulic connection between the Rus and the Umm er Radhuma aquifers.

The Northern Ground Water Province (fig. 1) is characterized, geologically, by the predominance of carbonate facies in the Rus Formation, with only trace or residual amounts of interbedded gypsum. "The virtual absence of gypsum is considered to be the result of non-deposition over the broad structural high at the northern end of the Qatar pericline and, also, its removal by dissolution in circulating ground water derived from recent recharge which has permitted an enhanced access to gypsum beds aided by the significant absence of lower Dammam shales in the centre of the peninsula," (Eccleston and others, 1981, p. 2/2). Note that both areas where evaporites were not deposited (the "depositional carbonate facies") and areas where they were deposited, but later removed by dissolution (the "residual sulphate facies") are included in this definition of the Northern Ground Water Province and shown in figure 1. In either case there has been, and continues to be, relatively vigorous recharge of meteoric waters and circulation of ground water in the Rus Formation. This circulation of ground water has resulted in enhanced permeability of the Rus in northern Qatar. Extensive dissolution and subsequent adjustment of land surface has produced a terrane of contrast to that of the Southern Ground Water Province. According to Eccleston and others (1981, p. 2/2) "In northern Qatar the landscape is made up of an almost contiguous series of depressions with small interval catchments ranging in area from 0.25 to 45 km^2 with irregular bodies of colluvial calcareous soils accumulated in the lower part or along major drainage courses. In general, the landscape is a deflated and subdued one where the watershed between depressions may sometimes be imperceptible. In southern, central, and western Qatar, however, the landscape is entirely different being dominated by low hills formed by outliers of the Neogene formations, barchan sand dunes and extensive areas of flat eroded limestone peneplain. Wherever depressions resulting from subsurface solution occur, however, these are invariably isolated, well defined, and with a crater-like appearance with the floor sometimes as much as 20 m below the general peneplain surface." Calcium-bicarbonate type ground water occurs in the Rus aquifer and in the top of the Umm er Radhuma aquifer in the Northern Ground Water Province. Occurrence of this relatively fresh water as a lens in the upper part of the Umm er Radhuma aquifer indicates recharge from the Rus aquifer and thus an areal hydraulic connection between the two aquifers in the Northern Ground Water Province.

Figures 2 and 3 show, respectively, ground-water levels and dissolved solids concentrations in ground water throughout Qatar in September 1971. Data for that period, when aquifer stresses were less than at present, are presented to illustrate influence of the different hydrogeologic conditions of the Northern and Southern Ground Water Provinces on occurrence of ground water. Most wells for which data are shown in south Qatar penetrate only the Rus aquifer; many wells in the Northern Ground Water Province are open to both the Rus aquifer and the underlying Umm er Radhuma aquifer. The higher water levels and head gradients in south Qatar (fig. 2) are a reflection of the lower transmissivity of the Rus aquifer. The conditions of low recharge and poor ground-water circulation are reflected in the generally poor quality of ground water in south Qatar (fig. 3). By contrast the lower water levels and head gradients, and better quality of water in north Qatar are indicative of higher transmissivities, recharge and ground-water circulation in the Northern Ground Water Province.

Note, in figure 2, the extensive area in west central Qatar where ground-water levels are below sea level. This is a topographically low area, just east of the Dukhan anticline, that is associated with the very large inland sabkha (salt flats) area of Zgain al Dahth. "This approximately 100 km^2 of salt flats at or just below sea level is believed to be an important area for the natural discharge of ground water by evaporation." (Eccleston and others, 1981, p. 10/12). "An important embayment in the contour pattern stretches from the vegetive area of the sabkha near Dukhan eastward toward 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" (Eccleston and others, 1981, p. 10/14).

Figures 4 and 5, respectively, show ground-water levels and dissolved solids concentrations in ground water throughout Qatar in September 1982. These are included, for comparative purposes, to show some effects of increased aquifer stresses over the period between the 1971 and 1982 data. Note, for example, that the areas in northern Qatar that are enclosed by the 3 m water-level contour and the 1,000 mg/L dissolved solids concentrations contour are smaller for the 1982 data than for the 1971 data.

GROUND-WATER USE

Prior to the early 1960's all municipal water supplies in Qatar were from ground water. Small supplies were from local wells but the city of Doha was supplied by pipeline from a number of well fields in east-central Qatar (Eccleston and others, 1981, p. 12/1). These Government well fields are in the south-central part of the Northern Ground Water Province and withdraw

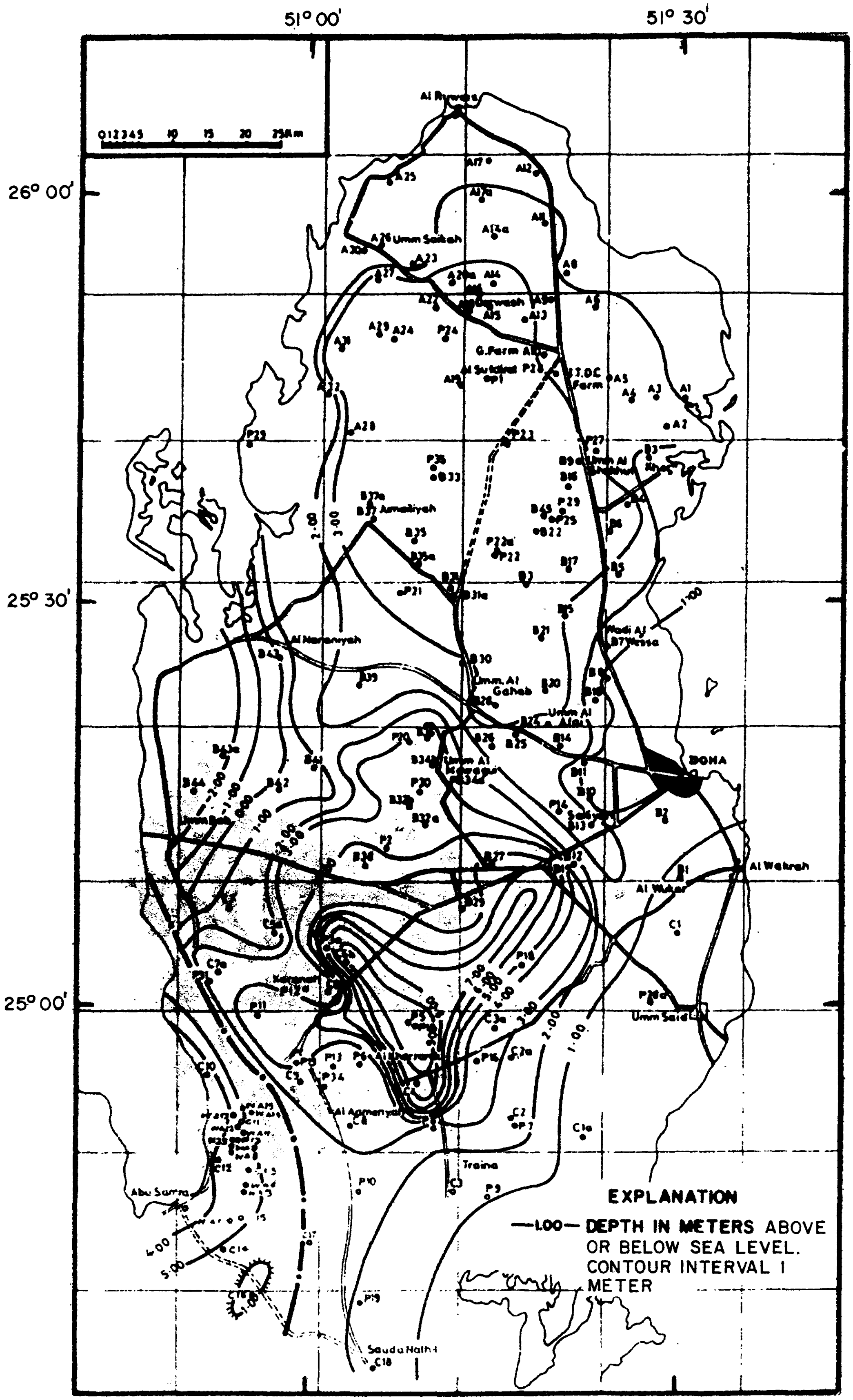

Figure 2.--Ground-water levels, September 1971 (from Harhash, 1984).

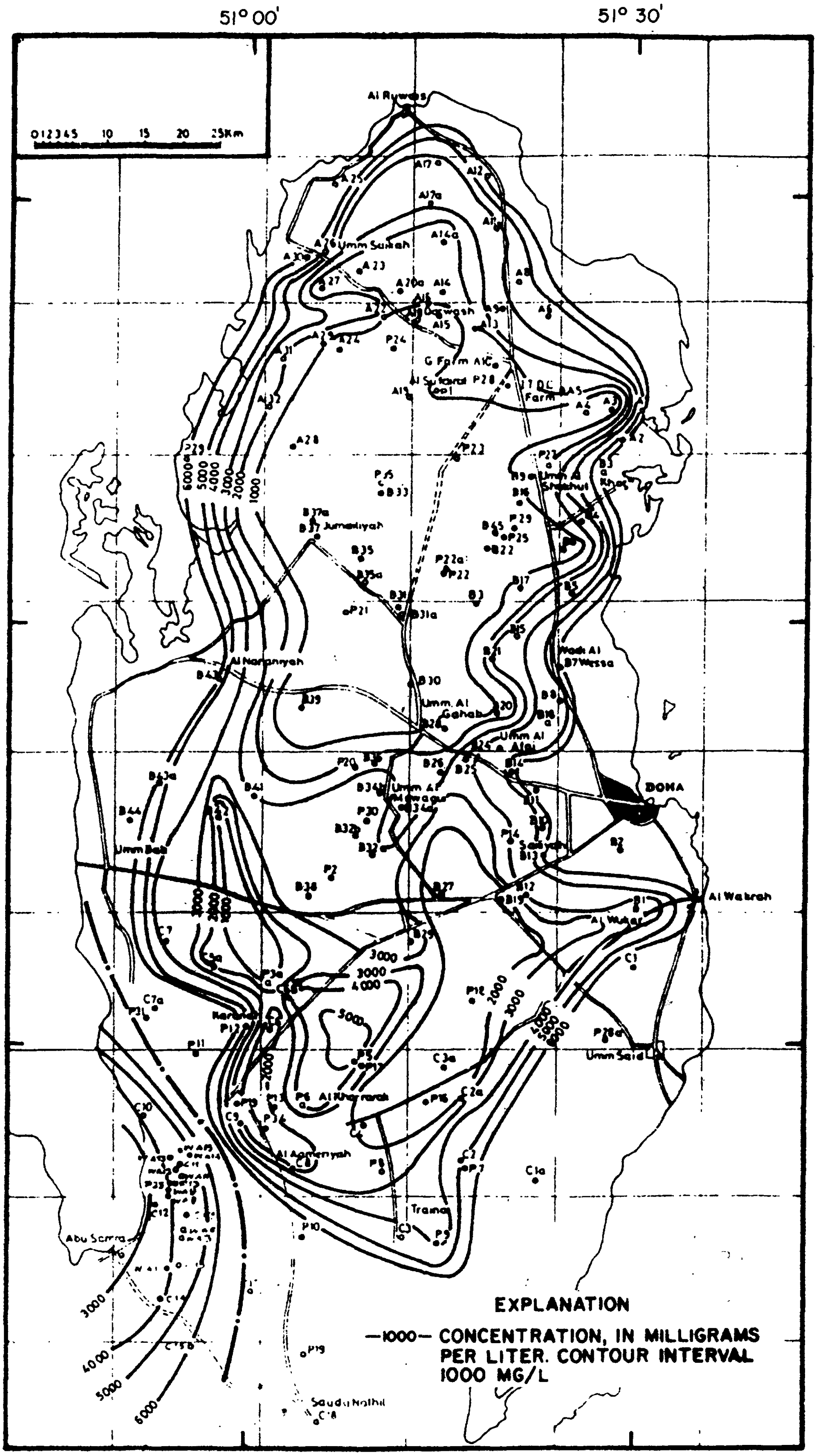

Figure 3.--Dissolved solids concentrations in ground water, September 1971 (from Harhash, 1984).

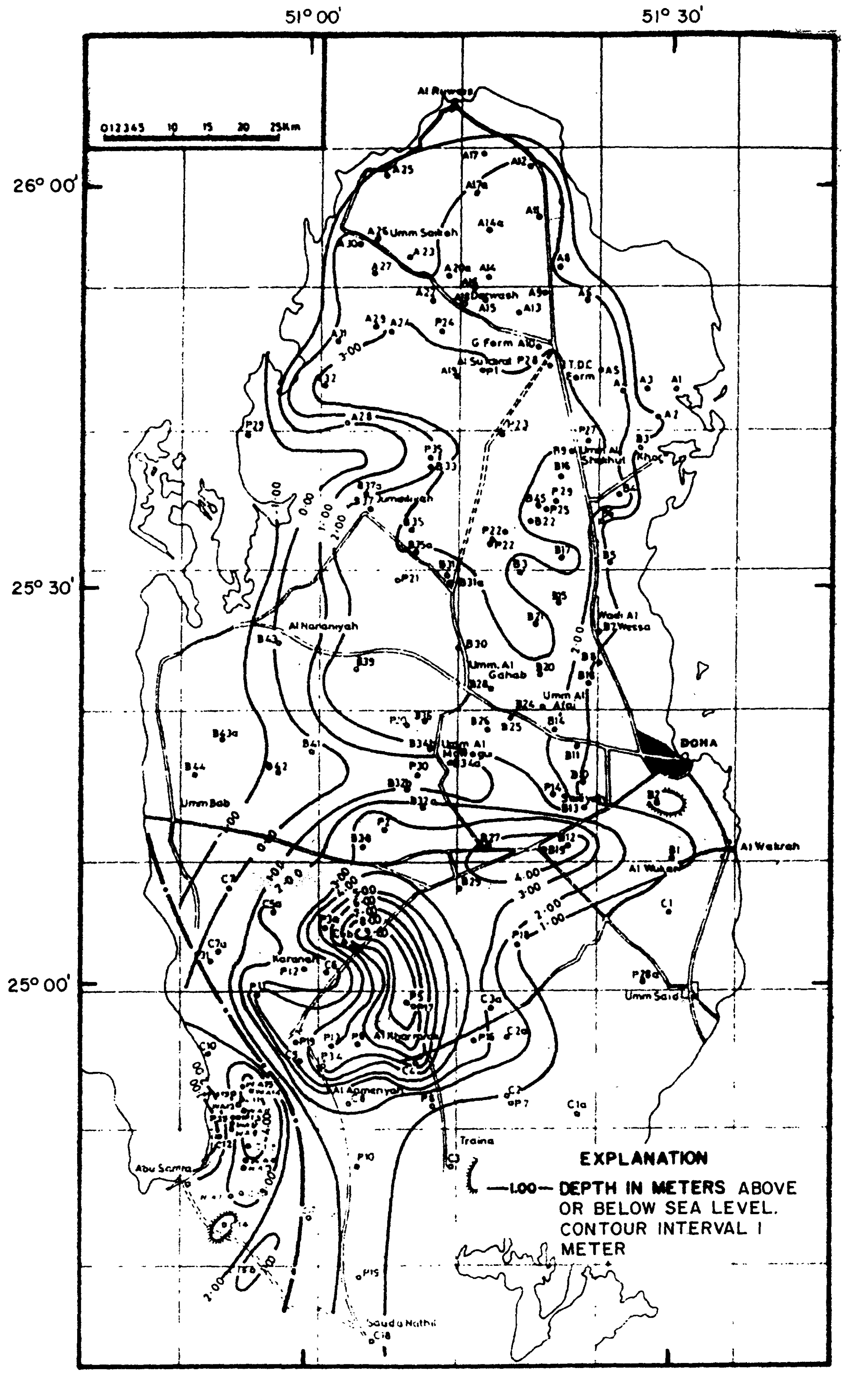

Figure 4.--Ground-water levels, September 1982 (from Harhash, 1984).

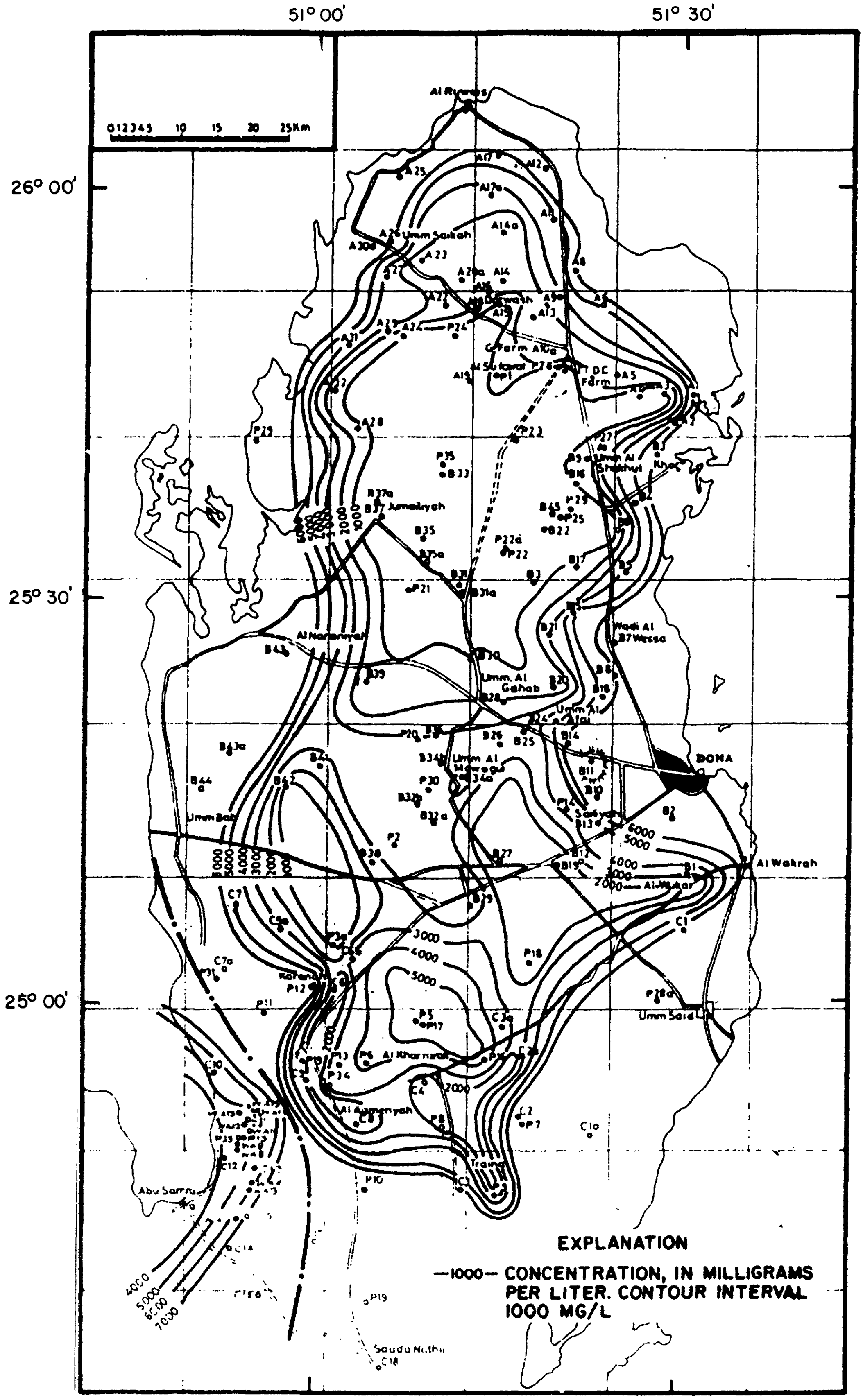

Figure 5.--Dissolved solids concentrations in ground water, September 1982 (from Harhash, 1984).

water from the Rus Formation. Beginning in 1964 water from these well fields was used to augment increasing supplies of desalinated seawater. Use of these well fields reached a peak in 1975 and 1976, then began to be reduced with the aim of phasing them out and developing brackish ground water nearer to Doha for use in blending with the desalinated seawater. Figure 6 shows the pattern of withdrawals from the Government well fields from 1964 to 1980.

Agriculture in Qatar is based almost entirely upon irrigation from ground water. The total gross extraction of ground water for irrigation purposes throughout Qatar increased from about 44 x 10^6 m^3/yr in 1972, to about 56 x 10^6 m^3/yr in 1976, to about 76 x 10^6 m^3/yr in 1980. Almost all of these withdrawals are in the Northern Ground Water Province, where it is estimated that about 20 percent of total water extracted for irrigation is returned to the aquifers by seepage (Eccleston and others, 1981, p. 12/4-12/7). Present (1984) estimates are that total gross extraction of ground water for agricultural purposes in northern Qatar is about 90 x 10^6 m^3/yr. As withdrawals for municipal supply remain at a low level, this is probably a reasonable estimate for total extraction of fresh ground water in northern Qatar.

Natural recharge to the aquifers in northern Qatar is estimated at 12 percent of the annual rainfall. The mean annual recharge is estimated at 27 x m^3/yr (Eccleston and others, 1981, p. 6/6-6/9). Thus the present (1984) gross rate of extraction (90 x 10^6 m^3/yr) is more than three times the mean annual (natural) recharge. This comparison is useful in pointing out the severity of the overdraft on the limited freshwater resources of northern Qatar. Based on 1980 water use, Eccleston and others (1981, p. 2/7) estimated that quality of ground water was deteriorating at a rate of 5 percent per year, due to both lateral and vertical saltwater encroachment. Those estimates of rate of quality decline have not been revised to reflect 1984 conditions, but the total extractions increased almost 20 percent from 1980 to 1984.

Most wells used for irrigation in northern Qatar withdraw water from both the Rus and Umm er Radhuma aquifers. These wells are, typically, about 30 cm in diameter and 60-70 m in depth. They are constructed as open holes through the Rus Formation and into the upper part of the more highly transmissive Umm er Radhuma Formation, which is separated from the Rus aquifer by an aquitard. Because these are composite wells it is not possible to apportion the total extraction to the individual aquifers. However, the transmissivity of the Umm er Radhuma is considered to be an order of magnitude greater than that of the Rus, so the greater part of total extraction may be apportioned to the Umm er Radhuma. Proportionate draft is even greater from the Umm er Radhuma when considered on a net basis of extraction versus recharge. That is, the estimated 20 percent of total extraction that returns as irrigation recharge is to the Rus aquifer. Thus, it is possible for storage in the Rus to actually be increased as part of the process of extracting and using ground water for irrigation. In addition, the natural recharge to the dual aquifer system first occurs to the Rus aquifer.

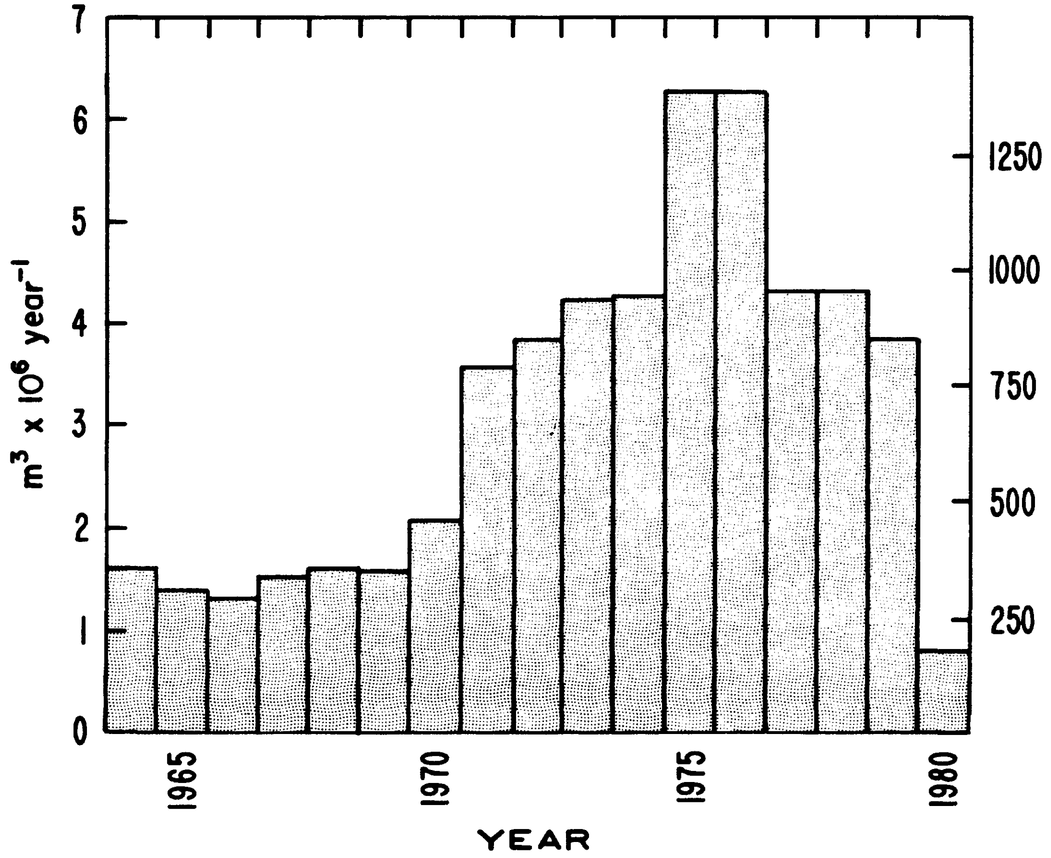

Figure 6.--Pattern of withdrawals from the Government well fields, 1964-80 (from Eccleston, Pike, and Harhash, 1981).

FEASIBILITY OF ARTIFICIAL RECHARGE

As discussed above, ground-water extractions for agriculture in northern Qatar are greatly in excess of natural recharge, and it is further estimated that the quality is deteriorating at a rate of 5 percent per year (Eccleston and others, 1981, p. 2/7). Continued extraction in excess of recharge will eventually result in depletion of the fresh ground-water resource to the point that the present level of irrigation will be impossible. Projected increases in extraction will, of course, expedite this process.

Thus, the only means to maintain even the present level of agriculture in northern Qatar is the availability of some additional source of freshwater for irrigation. In this regard, it has been proposed to use desalinated seawater to meet these demands for additional irrigation water.

The simplest scheme for use of desalinated seawater would be to make it directly available via pipeline from the desalination plant(s) to the points of necessary irrigation application. However this is the least practical scheme because volumes of available water from the desalination plant probably would not match those volumes needed for irrigation. Because need for irrigation water will vary widely (on seasonal, daily, and even hourly basis) a large storage element must be available in the distribution system because the source volume will likely be either fixed or, in any event, not adaptable to the wide fluctuations in irrigation demands. Storage of large volumes of water in the environment of northern Qatar would appear to best be done by injection into the Rus and Umm er Radhuma aquifers. These units are capable of accepting and storing large volumes of water by well-injection for recovery and use in irrigation. Vecchioli (1976), in considering this same issue, pointed out the benefits that could accrue from a properly designed and executed artificial recharge scheme, as follows:

1. Stabilization or retardation of deterioration in quality of fresh ground water now resulting from lateral encroachment of saline water from the Gulf and (or) vertical encroachment from deeper ground water.

2. Use of the freshwater aquifer as a storage reservoir to even out fluctuations in demand, seasonally and daily, by irrigation.

3. Use of the freshwater aquifer as a transmission system to distribute desalinated seawater from one or more plants to (possibly) numerous and dispersed small tracts of irrigable land where the needed water could be recovered through on-site wells.

4. Use of the freshwater aquifer as a standby reserve of potable water in event of massive failure of distillation equipment.

The advantages of artificial recharge as pointed out above are obvious and considerable. Based on the available information on hydrogeology and hydraulic properties of the aquifers in northern Qatar, artificial recharge of the aquifer(s) with desalinated seawater appears technically feasible and worthy of additional study.

Artificial recharge by use of injection wells in northern Qatar should be to the Umm er Radhuma aquifer which is separated from the overlying Rus aquifer by an aquitard. The Umm er Radhuma aquifer is a much better injection zone from a quantitative standpoint; its average transmissivity is considered an order of magnitude greater than that of the Rus aquifer (I. Harhash, oral commun., 1984). Also the majority of ground-water mining (continuing unreplaced depletion of storage) by agricultural extractions appears to be from the Umm er Radhuma, and it is thereby more vulnerable to saltwater encroachment than the Rus aquifer. According to Eccleston and others (1981, p. 2/7) "Thus, while the upper aquifer is in approximate balance between recharge, (including irrigation return), outflow, transfer to the lower aquifer and limited abstraction the lower aquifer exhibits a progressively increasing deficit and where the freshwater reserve is being irreversibly displaced laterally by saline water." The potential for saltwater encroachment to occur by upconing of mineralized water at depth also appears to be a valid concern related to mining of water from the Umm er Radhuma; this is yet another reason for emphasizing that the Umm er Radhuma aquifer should be considered as the primary potential injection zone.

The optimum location for artificial recharge is in the interior of northern Qatar; that is, generally within the area enclosed by the 3 m water level and 1,000 mg/L dissolved solids concentrations contours (figs. 2 and 3). This is the area where the largest reserves of freshwater now occur, and the area where agricultural extractions are presently occurring or moving toward. Concentration of artificial recharge within this area would have maximum effectiveness in maintaining (even possibly expanding) the freshwater reserves that now occur there. Another reason for concentrating recharge in inland areas is that land surface altitudes are higher; thus the unsaturated zone is thicker and there is less possibility of water logging the land by rise of the water table in response to artificial recharge. Though a significant rise in the water table (in the Rus Formation) is not anticipated in response to injection of recharge to the Umm er Radhuma aquifer, this potential factor should be considered. It is possible, for example, that the separating aquitard may not be so competent as now visualized.

The volume and rate of injection water that an aquifer will accept is dependent only upon the aquifer's capability to transmit and store water, if it is assumed that there are no attendant geochemical reactions that may change the aquifer's hydraulic characteristics. Thus, in simply planning for injection, a good knowledge of the aquifer's coefficients of storage and transmissivity (and, if applicable, its degree of hydraulic connection to adjacent zones) is sufficient. These aquifer characteristics are usually best determined by a planned program of test drilling and aquifer testing. It is then advisable to conduct actual recharge tests (to verify the aquifer's acceptance capability) prior to finalization of operational plans for injection.

Artificial recharge also involves recovery of the injected water, and usually involves a repeating cycle of injection-recovery operations. Additionally, artificial recharge usually involves injection and recovery of a higher quality water than the residual water in the injection zone. That is, a volume of high quality water is injected to displace lower quality formation water; then, at some later time, the cycle is reversed and part of the injected water is withdrawn for use. Injections are generally made when recharge water is available to be stored; and recovery is made when there is a need for use of the stored water.

Injection of a fluid of low density (desalinated water) into an aquifer that contains water of higher density (formation water in the Umm er Radhuma aquifer) results in formation of a lens, or bubble, of the lower density fluid. The fluids of different density will tend to mix in a gradational zone at the outer limits of the lens, so that the total amount of freshwater injected cannot be recovered. If water is withdrawn from the storage lens until its quality declines to some arbitrary limit (such as 1,000 mg/L dissolved solids concentration), the ratio of volume recovered to volume injected is an index of the efficiency of the recharge-recovery operation. The ratio, expressed as a percentage, is known as the "recovery efficiency." This parameter, which must be determined experimentally, is the most useful and practical indicator of the feasibility of an artificial recharge operation.

In further study of feasibility of artificial recharge in northern Qatar, experiments to determine a range of values for recovery efficiency are recommended, in addition to the more standard test-drilling and aquifer-testing procedures.

Some extensive investigations have been made of injection, storage, and recovery of surplus freshwater in central and south Florida, southeastern United States. The hydrologic characteristics of the Umm er Radhuma aquifer are similar to those of the carbonate aquifers in Florida; therefore some useful conclusions can be drawn from previous studies (Merritt and others, 1983) (Merritt, 1983). The conclusions which should apply to the proposed studies in northern Qatar include:

1. Physical processes which limit the recoverability of injected freshwater are hydrodynamic dispersion; buoyancy stratification; differences in directional permeability; and downgradient displacement by the local background flow system.

2. For a given volume of injected freshwater, the rate at which freshwater is injected (or recovered), does not appear to affect recovery efficiency. Generally, recovery efficiency will improve with increased volumes.

3. The length of time of storage does not effect recovery efficiency if (a) the regional gradient does not significantly move the stored freshwater, and (b) buoyancy stratification cannot occur under prevailing hydrogeologic conditions.

4. Partial penetration of the injection well does not appreciably affect recovery efficiency.

5. Recovery efficiency improves with repeated cycles, rapidly during initial cycles and then more slowly as a limit is approached.

6. Aquifers with water just saline enough to be unsuitable for consumptive use are optimum for freshwater injection and recovery, whereas very saline aquifers are least suitable.

7. Verification of the feasibility of cyclic injection, storage, and recovery of freshwater at specific sites can be determined only by performing actual tests. The amount of injected water that can be recovered before the withdrawn water becomes nonpotable is the prime indicator of the engineering success of the practice.

RECOMMENDED SCOPE OF ADDITIONAL STUDIES

Additional studies required prior to planning and implementation of the operational system for large-scale artificial recharge in northern Qatar are (1) a hydrogeologic appraisal, and (2) a total water-management study.

Hydrogeologic Appraisal

A hydrogeologic appraisal should investigate and document the capability of the Umm er Radhuma aquifer to receive and store injected water and the degree of efficiency with which this water may be recovered for use. Results of this appraisal will indicate the best areas for injection of recharge water; optimum methodology for injection; and total volumes that it will be practical to inject, store, and retrieve.

The available hydrogeologic understanding of northern Qatar is an excellent base for beginning additional quantitative studies and experiments related directly to use of the aquifer for storage and recovery of desalinated water. This hydrogeologic appraisal should include test drilling, geophysical logging, aquifer testing, and recharge-recovery experiments at four sites in northern Qatar. These sites should be stratigically located in each of the four quadrants of the area that is generally enclosed by the 1,000 mg/L contour of the September 1982 map of dissolved solids concentrations. The following should be done at each of the four sites:

1. A test hole should be drilled to a depth where the formation water has dissolved solids content of at least 10,000 mg/L. During drilling, continuing observations should be made of changes in lithology, salinity, water levels, and water yield of the test borehole. The percussion method of drilling should be used because it lends best to continuing collection of these data during drilling.

2. Borehole geophysical logs should include, as a minimum, caliper; electrical resistivity and spontaneous potential; borehole fluid conductivity and velocity; and natural gamma.

3. The test borehole should be converted to use as an injection well for the upper part of the Umm er Radhuma aquifer by (a) grouting the bottom of the hole with cement to seal off to a depth where salinity does not exceed a maximum of 4,000-6,000 mg/L, and (b) sealing off the Rus aquifer by installing casing to the Rus-Umm er Radhuma Formations contact.

4. Four piezometers should be installed at each site--three to moniter the Umm er Radhuma aquifer only, and one to monitor the Rus aquifer only.

5. Pumping tests of estimated 1-week duration should be made to determine the transmissivity and storage coefficients of the Umm er Radhuma aquifer, and to investigate the nature of hydraulic connection between the Rus and Umm er Radhuma aquifers.

6. A series of recharge-recovery cycle experiments should be made for an estimated total period of 90 days at each site. For planning purposes it is suggested that each cycle be about 2 weeks in length (about 1 week of injection followed by withdrawal until the appropriate level of dissolved solids content is reached). This would allow collecting data over a total of six complete recharge-recovery cycles at each site.

Some additional comments in regard to accomplishing the above work items are:

1. The source of injection water for the recharge experiments might, of necessity, have to be from wells in the Rus aquifer, because desalinated water may not be available at sites that are selected for the experiments. In this regard, some of the existing well fields in the Rus aquifer could be used as experimental sites; or new wells in the Rus aquifer might be drilled for sites that may be selected in other areas. In either event care should be taken that composite wells in the Rus and Umm er Radhuma aquifers are not present in enough proximity to interfere with hydraulic tests at the experimental sites.

2. It should be noted that geochemical reactions in the Umm er Radhuma aquifer may be different in response to injection of water from the Rus aquifer, than to injection of desalinated seawater. However, it is considered unlikely that these reactions would have any significant effect on the hydraulic characteristics of the Umm er Radhuma aquifer.

3. It is arbitrarily assumed that the contrast in dissolved solids concentration of the recharge water used and the residual water in the injection zone should not exceed about 2,000 mg/L. In most areas likely to be selected as experimental sites, dissolved solids concentration of ground water in the upper part of the Umm er Radhuma aquifer is likely to approach 2,000 mg/L and that in the Rus aquifer to be less than 1,000 mg/L. So the assumed range of contrast in dissolved solids concentration should prevail, whether the source of recharge water is the Rus aquifer or desalinated seawater. However, a minimum thickness of injection zone is suggested as 5-10 m, depending on concentration and vertical distribution of dissolved solids concentration in the upper part of the Umm er Radhuma aquifer. Hence, at some sites, it may be necessary to inject to a zone where the resident total solids are on the order of 4,000-6,000 mg/L (which is thus used as the limit in item 3 above).

4. Rates of injection for the recharge experiments may be dependent upon quantity of water available for injection, and the hydraulic characteristics of the injection zone. Thus, rates of injection cannot be selected until information on these two factors becomes available. Assuming availability of injection water, it is recommended that injection rates not cause more than 10 m of head buildup in the injection well. The maximum recommended injection rate (Ri) may thus be expressed in terms of the specific capacity (Cs) of the injection well as:

$$Ri = \Delta h.Cs \leq 10.Cs$$

Successful completion of all work items above will require a 2-year period of investigation and the full-time assignments of two hydrogeologists (or ground-water hydrologists). Estimated costs for the hydrogeologic appraisal are:

1. Testhole Drilling:	
(4 holes, 30 cm diameter) (200 m/hole) at QR. 900/meter	720,000
2. Geophysical Logging:	
(4 holes) at QR. 8,000/hole	32,000
3. Converting Boreholes:	
(a) Casing - (4 holes) (50 m/hole) at QR. 300/meter	60,000
(b) Grouting - (4 holes) (140 m/hole) at QR. 50/meter	28,000
4. Piezometers:	
(4 holes, 15 cm diameter) (40 m/hole) at QR. 600/meter	96,000
5. Piezometers:	
(12 holes, 15 cm diameter) (60 m/hole) at QR. 600/meter	432,000
6. Aquifer Tests:	
(4 wells) (7 days/well) at QR. 4,500/day	126,000
7. Recharge-Recovery Tests:	
(4 wells) (90 days/well) at QR. 4,800/day	1,728,000
8. Project Hydrologists:	
(2) (24 months) at QR. 30,000/month	1,440,000
Subtotal	4,662,000
Contingency allowance (15 percent)	700,000
Total	5,362,000

Management Appraisal

In 1980 total freshwater use in Qatar was about 107 x 10^6 m^3, of which about 58 percent was the net fresh ground water used for irrigation and 41 percent was desalinated seawater used for public water supply. Since 1964 the percentage of total freshwater used for domestic consumption has increased more rapidly than that used for agriculture, but both elements have experienced steady growth (Eccleston and others, 1981, table 12.4, p. 12/8). Other elements of total water use reported for 1980 were 3.3 x 10^6 m^3 of brackish ground water used for blending, and 1.6 x 10^6 m^3 of treated sewage effluent (renovated wastewater) for irrigation of trees and public landscape projects. Use of renovated wastewater is a relatively new and growing element in total water use.

Thus, total water use in Qatar has grown rapidly over the past 20 years, and promises to continue to grow and become more complex. Large scale artificial recharge by use of desalinated seawater, if implemented, will add another significant element. Hence, a management study is recommended concurrent with the hydrogeologic appraisal. Specifically, this management appraisal should:

1. Consider all the factors related to planning and implementation of artificial recharge in northern Qatar. This appraisal should integrate results of the hydrogeologic appraisal with other pertinent engineering factors to include availability of water for recharge; distribution of water from the desalination plant(s) to irrigation areas; and various combinations of aquifer storage-distribution through artificial recharge, or alternately, some integrated combination of surface and aquifer storage. Costs of implementation should then be developed.

2. Consider all other aspects of water use, as well, and prepare a total integrated plan for future management of water resources in Qatar. This water management plan should include recommendations for an organizational structure to administer the plan and apportion and regulate use of water for all purposes.

CONCLUSIONS AND RECOMMENDATIONS

1. Ground-water extractions for agriculture in northern Qatar are greatly in excess of natural recharge. It was estimated, in 1980, that quality of ground water (in terms of dissolved solids) was declining at a rate of 5 percent per year. Extractions for irrigation have increased by almost 20 percent from 1980 to 1984.

2. Most water for irrigation is withdrawn from wells that are open to both the Rus and Umm er Radhuma aquifers, which are separated by an aquitard. The majority of net extraction is from the more highly transmissive Umm er Radhuma aquifer, which contains saline water at some depth. The Rus aquifer may essentially be in equilibrium between extraction and recharge from irrigation return water.

3. The only means of indefinitely maintaining even the present level of agriculture is the availability of some additional source of freshwater for irrigation. Use of desalinated seawater for artificial recharge on a large scale has been proposed. This scheme appears feasible from present knowledge. Artificial recharge would offer the advantages of stabilization or retardation of deterioration in quality of ground water; aquifer storage and transmission of desalinated seawater; and maintenance of a standby supply of potable water.

4. Artificial recharge should be by injection to the upper part of the Umm er Radhuma aquifer. A hydrogeologic appraisal should investigate and document the capability of the Umm er Radhuma aquifer to receive and store injected water, and the degree of efficiency with which this water may be recovered for use. Results will indicate the best areas for injection of recharge water; the optimum methodology for injection; and the total volume that it will be practical to inject, store, and recover. Total costs of the hydrogeologic appraisal are estimated to be QR. 5,362,000.

5. A management appraisal should be made concurrent with the hydrogeologic appraisal. The management appraisal should develop plans and costs for implementation of artificial recharge; it should also consider all other aspects of water use in Qatar and prepare an integrated plan for future management of water resources. The integrated plan should recommend an organizational structure to administer the plan and to apportion and regulate use of water for all purposes.

6. Proposals for the management appraisal should be solicited from international water-resources engineering firms who have the resources to provide all technical expertise required. The hydrogeologic appraisal may be handled by personnel of the Government of Qatar, or alternately, may be included in the contract for the management appraisal.

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APPENDIX

Work Plan for the Hydrogeologic Appraisal

This appendix is prepared to furnish more details for conducting the hydrogeologic appraisal. It is intended mainly to be used as a guideline, assuming that the appraisal is made by personnel of the Government of Qatar. The work plan should be used in close conjunction with the main text of this report.

The purposes of this hydrogeologic appraisal are:

1. To investigate and document the capability of the Umm er Radhuma aquifer to receive and store injected water, and the degree of efficiency with which it may be recovered for use, and;

2. to interpret these results of investigation in terms of best areas for injection of recharge; the optimum methodology (rates, length of cycles, etc.) for injection and recovery; and the total volumes that it is practical to inject, store, and retrieve.

Successful completion of this hydrogeologic appraisal will require a 2-year period of field investigations and the full-time services of two hydrogeologists, or ground-water hydrologists. One of these project hydrologists should have at least 5 years experience in areal ground-water investigations, and a significant part of this experience should be in the quantitative aspects of hydrology of carbonate aquifers. The other project hydrologist may be a less experienced individual, but should have a minimum of 2 years of experience in ground-water investigations. These project hydrologists will require full logistics support for their office and field activities (i.e., supplies, vehicles, field assistance, etc.) throughout the entire period of investigation.

The project hydrologists will also require the continuing availability, in advisory capacity, of a consultant in the area of artificial recharge, and periodic assignment of specialists in the areas of hydraulics and geochemistry of carbonate aquifers. These advisors and specialists may be senior technical personnel of the Government of Qatar; or they may be consultants on loan from other agencies, as appropriate. Hereinafter, they are referred to as project advisors.

It is suggested that the project hydrologists be available for a 3-month period prior to beginning the 2-year period of field investigations. This will allow them to accomplish some necessary preliminary work in both office and field and become thoroughly familiar with the project area. The preliminary work should include the organization of a data base for use during the investigation. A large amount of good background data (well records; ground water with withdrawals, levels, and quality; etc.) are available in the files of the Department of Agricultural and Water Research and other agencies of the Government of Qatar. Then data should be examined by the project hydrologists, and selectively screened into a working data base for the 2-year investigation. Consideration should be given to computerization of the data base at this time. Contracts for test drilling, well logging, and aquifer testing will also need to be prepared. Preliminary work in the field may include collection of new data from specific capacity tests and, possibly, some more rigorous aquifer tests by use of existing wells and well fields.

Successful completion of the project should include preparation of a report to (1) document results of all field tests and experiments, and (2) draw final conclusions and recommendations. Early in the investigation the project hydrologists should plan the final report and prepare a working outline. Work on the report should then proceed during the investigation as progress is made and results become available.

When supplied with support in the areas of logistics and technical advice and support, the project hydrologists should have responsibility for carrying out all aspects of project work. The senior project hydrologist should be designated as project chief, and have the first-line responsibility over day-to-day activities.

The hydrogeologic appraisal will include test drilling; geophysical logging; aquifer testing; and recharge-recovery experiments at four sites in northern Qatar. These sites should be strategically located in each of the four quadrants of the general area that is enclosed by the 1,000 mg/L contour of the September 1982 map of dissolved solids concentrations.

Sites will be selected by the project advisors. Criteria to be used for selection are, in order of priority:

1. A source[1/] of water, from the Rus aquifer, for injection. Dissolved solids concentration should be less than 1,000 mg/L. Quantities available should be at least 5 L/s, and greater quantities are suggested if available.

2. An area where the potentiometric surface of the Umm er Radhuma aquifer is not affected by pumpage. If this is not possible, then choice will be made on basis of the least affected areas that are available.

3. A generally central location within the quadrant.

[1/] NOTE: The source of water may be from existing well fields in the Rus aquifer, if the other criteria are met for the site. If not, new wells in the Rus aquifer will have to be drilled to furnish the source of injection water.

The remainder of this work plan is developed around the six blocks of activity, or "work elements," that must be accomplished for successful completion of this hydrogeologic appraisal. These work elements are discussed below, in general chronological order, as they should be accomplished at each site. Then, an overall timeline is included at end of discussion.

I. A test hole should be drilled to depth where the formation water has dissolved solids content of at least 10,000 mg/L. During drilling, continuing observations should be made of the changes in lithology; salinity; water levels; and water yield of the borehole. The percussion method of drilling should be used because it lends best to continuing collection of these data during drilling.

The drilling should be done by qualified contractors, with percussion drilling equipment that is readily capable of drilling and obtaining lithologic and water samples to total depth of 200 m. The project hydrologists should assist in preparing the technical specifications and descriptions for the drilling (as well as all other) contracts.

Major duties of the project hydrologists during test drilling will be to continually monitor and collect samples during all aspects of the drilling operations, and to maintain complete logs of lithology, to include notes on changes in drilling conditions; changes in water levels and quality; and any other pertinent details related to the drilling operation. The water-quality parameters to be measured during drilling are specific conductance and temperature. Each test hole should be drilled to total depth of 200 m to allow maximum correlation between holes (dissolved solids are expected to be in excess of 10,000 mg/L at this depth). At bottom of each test hole, a composite water sample should be collected for laboratory analyses of major ions and other parameters as appropriate.

Equipment needed during test drilling are the common tools for observing test drilling and water quality. It is important that the conductance meter used be maintained in accurate calibration.

II. Borehole geophysical logs should be obtained for the completed test borehole to include, as a minimum: caliper; electrical resistivity and spontaneous potential; borehole fluid conductivity and velocity; and natural gamma.

The geophysical logging should be done by qualified contractor. The logs should be made on an open borehole containing the native formation water. The project hydrologist should observe all geophysical logging operations and, as appropriate, incorporate notes on logging conditions into their records of test drilling observations.

Upon completion of geophysical logging all data and results should be reviewed and the project hydrologist (with assistance, as necessary, from the project advisors) will select the section of borehole to be used for aquifer testing. The drilling contractor will then convert each of the four test boreholes to test wells, as stipulated below.

III. *The test borehole should be converted to use as an aquifer and recharge-recovery test well for the upper part of the Umm er Radhuma aquifer by (a) grouting the bottom part of the borehole with cement to seal off to a depth where the salinity does not exceed a maximum of 4,000-6,000 mg/L, and (b) sealing off the Rus aquifer by installing casing to the Rus-Umm er Radhuma Formations contact. A minimum of 5 m thickness is suggested for the aquifer test-injection zone, if possible to achieve without exceeding a residual dissolved solids content of 4,000-6,000 mg/L in the Umm er Radhuma aquifer.*

Major duties of the project hydrologists during this period are to observe construction and ensure that the selected section of borehole is isolated as the test-injection zone.

IV. *Four piezometers should be installed at each site--three to monitor the Umm er Radhuma aquifer only, and one to monitor the Rus aquifer only.*

The project hydrologists should select spacing and depth of these piezometers, based on results of drilling and geophysical logging, and observe their construction to ensure its being done properly.

The three Umm er Radhuma piezometers at each site should (1) have the Rus aquifer sealed off by installation of casing to the Rus-Umm er Radhuma Formations contact, and (2) be open to the upper 5 m of the Umm er Radhuma aquifer. Radial spacing of the three piezometers at each site is suggested as about 30, 100, and 300 m from the test injection well.

The single Rus aquifer piezometer at each site should be open to most of the saturated thickness of the Rus, but should *not* penetrate below the top of the aquitard that separates the Rus aquifer from the Umm er Radhuma aquifer. The Rus aqifer piezometer should be a radial distance of 30 m, or less, from the test-injection well, but should be on the opposite side from the closest Umm er Radhuma well.

V. *Pumping tests of estimated 1-week duration should be made to determine the transmissivity and storage coefficients of the Umm er Radhuma aquifer, and to investigate the nature of hydraulic connection between the Rus and Umm er Radhuma aquifers.*

Responsibility of the project hydrologists during aquifer tests is to coordinate all data collection, as well as to personally collect data. The test-injection well at each site should be pumped at a constant rate for a 7-day period; and water level changes should be recorded for the pumped well and the four piezometers. The pumped rate should be a minimum of 10-15 L/s, though considerably higher rates are suggested if possible. Water level changes should be collected from continuous recorders installed on, as a minimum, the Rus aquifer and the nearest Umm er Radhuma aquifer piezometer at each site.

These recorder records should also have been maintained for at least a week prior to beginning a test. At end of pumping, water-level recoveries should be measured in all wells until equilibrium under non-pumping conditions is approached.

The project hydrologists should analyze all drawdown and recovery water-level data from the aquifer tests in consultation with the project advisors. In analysis, it is particularly important to obtain (1) representative values for transmissivity of the injection zone in the Umm er Radhuma, and (2) an indication of the degree of hydraulic connection between the Rus and Umm er Radhuma aquifers. For these reasons it is very important that casing be properly seated (in the test well and Umm er Radhuma piezometers) so that interaquifer pressure transmission does not occur through improperly sealed boreholes.

Quality of ground water should be monitored throughout the aquifer test(s). This may consist of collecting water samples for laboratory analyses of major ions at beginning and end of the test, and monitoring of specific conductance during the test. Disposal of water pumped during aquifer tests may be a problem, because there will likely be no surface drainage available to convey water from the test site. Portable discharge pipe should be used to convey water as far as practical away from the site, where it will probably accumulate in a shallow depression and begin seeping back into the Rus aquifer. This factor should be considered in analyses of test data, because it could result in rise of water levels in the Rus aquifer during aquifer testing.

Equipment needed during aquifer tests are those standard tools for measuring water levels and field quality of ground water. Water levels should be measured by use of a wetted, steel tape rather than electric tape, and (as discussed above) continuous water level recorders should be installed on at least two of the piezometers. The project hydrologists will need assistance of several additional personnel during aquifer tests in order to continually man the site and collect data over a week-long period.

VI. A series of recharge-recovery cycle experiments should be made for an estimated total period of 90 days at each site. For planning purposes it is suggested that each cycle be about 2 weeks in length (about 1 week of injection followed by withdrawal until the appropriate level of dissolved solids concentration is reached). This would allow collecting data over a total of six complete recharge-recovery cycles at each site.

Responsibility of the project hydrologists during recharge-recovery experiments is to coordinate all data collection as well as to personally collect data. The experiments at each site are estimated to require 90 days, and data collection will be similar to that for the conventional aquifer tests. Thus the same types and numbers of equipment and additional personnel are needed, as for the aquifer tests.

The recharge-recovery experiments will involve injection of fresh water, with attendant monitoring of water levels in the injection well (and in all piezometers)--followed immediately by withdrawal, with attendant monitoring of head changes and water quality until dissolved solids concentration of the recovered water reaches an arbitrary limit of 1,000 mg/L. The recovery efficiency for the completed cycle may then be computed, and subsequent cycles are then conducted.

The purpose of these recharge-recovery experiments is to obtain understanding of the recharge efficiency (or range of values for recharge efficiency) that may be achieved with the Umm er Radhuma aquifer in northern Qatar. There are no rigidly established procedures for conducting these field tests. The following recommendations derive from a combination of results of investigation in central and south Florida and the author's observation of hydrogeologic conditions in northern Qatar:

> The source of water for the injection experiments will be from wells in the Rus aquifer, either existing wells in one of the Government well fields, or new wells drilled specifically as a source of water for the experiments. The Rus aquifer source should be capable of maintaining a minimum injection rate of 5 L/s, though higher rates are recommended if available from the Rus at each site. (NOTE: Assuming availability of injection water, it is recommended that injection rates not cause more than 10 m of head buildup in the injection well).
>
> Six complete recharge-recovery cycles are suggested for the first experiment site. For the first cycle, water should be injected for about 1 week and then recovered at the same rate until the dissolved solids concentration reaches 1,000 mg/L. Rates and times may then be varied to some degree during the remaining five cycles, at discretion of the project hydrologists and advisors.
>
> Following completion of experiments at the first site, it is important that all project advisors be consulted in analyses of the data and planning of the subsequent experiments. Until that time, however, it is premature to plan the sequence and duration of recharge-recovery experiments at the remaining three sites. It is possible, for example, that results of the first experiment may indicate the need for longer-term experiments at one (or two) of the remaining three sites rather than the 6-cycle 90-day tests that have been used for planning purposes.

The project advisors will again need to be consulted during the final months of the 2-year period of field study (that is, at or near the end of the recharge-recovery experiments). At that time the project hydrologists should have a working draft report of their documentations of all field work results. Then the project hydrologists and advisors will jointly make final conclusions and recommendations.

A general timetable for the hydrogeologic appraisal is included below:

		1st year field work				2nd year field work			
Review of all available data; organization of data bases and references; preliminary collection of selected field data; preparation of contracts.	X	X							
Test drilling; test and piezometer well construction.		X	X						
Conventional aquifer tests.				X					
First 90-day recharge-recovery tests.					X				
Consult all project advisors.						X			
Remaining (2-3) recharge-recovery tests.						X	X	X	X
Consult all project advisors; finalize documentary report; conclusions, and recommendations.									X