F I E L D R E P O R T

823 OM91
Part 4

TECHNICAL ASSISTANCE PROGRAM FOR THE MINISTRY OF WATER RESOURCES SULTANATE OF OMAN

TASK 5: WATER MANAGEMENT
TASK 6: TECHNOLOGY DEVELOPMENT

SALT WATER INTRUSION MONITORING AND REMEDIATION
Part 4

WASH Field Report No. 353
December 1991

WATER AND SANITATION for HEALTH PROJECT

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SALT WATER INTRUSION MONITORING AND REMEDIATION

Prepared for the Omani-American Joint Commission
under WASH Tasks Nos. 254 and 255

by

Steve S. Luxton
Mitchell C. Heineman
Jonathan P. Hodgkin
Patrick T. Lang
Frederick W. Meyer
Ronald Miner
Peter N. Schwartzman
and
Dr. Kendrick C. Taylor

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ACRONYMS

ASR	aquifer storage and recovery
cm	centimeter
CSR	center sampling rotary
EC	electrical conductivity
FAO	United Nations Food and Agriculture Organization
GIS	geographic information system
GPS	ground positioning system
H.E.	His Excellency
H.H.	His Highness
H.M.	His Majesty
in	inch(es)
JICA	Japanese International Cooperation Agency
km	kilometer(s)
l	liter(s)
l/s	liters per second
L.S.	lump sum
m	meter(s)
m^2/d	square meters per day
m^3/d	cubic meters per day
m^3	cubic meters

MAF	Ministry of Agriculture and Fisheries
mcm	million cubic meters
mcm/yr	million cubic meters per year
MEW	Ministry of Electricity and Water
mm	millimeter
MM/WH	Mott MacDonald International, Limited in association with Watson Hawksley
MMP	Sir Mott MacDonald and Partners, Limited
MOC	Ministry of Communications
MOD	Ministry of Defense
MOH	Ministry of Housing
MOI	Ministry of Interior
MSS	multispectral scanner sensor
MWR	Ministry of Water Resources
NASA	National Aeronautics and Space Administration
NSA	National Survey Authority
OAJC	Omani-American Joint Commission for Economic and Technical Cooperation
pop	population
PAWR	Public Authority for Water Resources
PVC	polyvinyl chloride
R.O.	Omani Rials
SCTP	Supreme Committee for Town Planning
SFWMD	South Florida Water Management District

tm	trademark
TEM	transient electromagnetics
TM	thematic mapper sensor
TPM	team planning meeting
uS/cm	micro Siemens per centimeter
USAID	United States Agency for International Development
UTM	universal transverse mercator
WASH	Water and Sanitation for Health Project

EXECUTIVE SUMMARY

The Omani-American Joint Commission (OAJC) and the newly established Ministry of Water Resources (MWR) of the Sultanate of Oman have a common interest in the water resources of the nation. Early in 1990, OAJC requested the Water and Sanitation for Health Project (WASH) to assist the fledgling Ministry in:

- Strengthening all aspects of its operations
- Establishing a strong technical base
- Developing policy and procedures

The WASH team worked in Oman and in the United States from May through August 1991 to complete Tasks 5 and 6 of the scope of work and also work under Tasks 3 and 4 that was interrupted by the Gulf War.

Following Parts 1 and 2, which provide a general introduction and background, each of the six parts of the report on Tasks 5 and 6 covers a different area of study and contains a summary of conclusions and recommendations to which the reader can refer for a quick review.

MAJOR FINDINGS AND RECOMMENDATIONS

Part 3 ... Wadi Gauging Network Rationalization and Upgrade

More surface water gauging stations are needed in MWR's wadi gauging network to provide information on the process of groundwater recharge and the effectiveness of recharge enhancement schemes. But the expansion of the network should not delay the processing and publication of the large volume of data already in hand.

Surface water data collection is limited by various physical and practical constraints, and all users of these data would greatly benefit from an understanding of these limitations and of the methods employed by the Surface Water Department.

The department's effective relations with other agencies and private sector groups interested in surface water and floods should be cited as a model for other MWR departments.

Part 4 ... Salt Water Intrusion Monitoring and Remediation

MWR faces a serious problem of saline intrusion and upconing in the Batinah coast region. Past efforts at control have lacked a focus and a defined policy. Emphasis must now change from observation of the advancing intrusion to a detailed program designed to find a solution. This can begin with concentrated efforts to protect municipal and public water supply systems from upconing and lateral intrusion in areas where severe impacts and economic dislocations are expected.

MWR should set up a section to undertake this work urgently after reviewing and, if necessary, modifying the policy and goals recommended. Unless this is done, the saline intrusion program will continue to lack direction and purpose.

Part 5 ... Alternative Well Technologies for Use in Saline Groundwater Systems

The WASH team investigated several alternative well technologies to pump fresh water from saline aquifers. The separation of fresh water from saline groundwater is called skimming by some hydrologists. Of the methods investigated, three show the most promise in Oman:

- Conventional low-drawdown wellfields
- Scavenger wells
- Water collection galleries

Existing conventional wells with high drawdowns are prone to upconing and sea water intrusion, whereas low-drawdown wells can extract a similar amount of water without inducing salt upconing. MWR should enhance its capacity to advise others on the use of this technology.

Scavenger wells separate salt water and fresh water into two discharge streams. More work needs to be done to define their potential for specific sites in Oman.

Collection galleries may find some application in coastal areas to provide agricultural or potable water supplies. They must be operated with care and, to be most effective, should be pumped continuously at very low drawdowns.

MWR should work on these methods to provide a leadership role in their use. There are many opportunities for applying them as part of a broad regional water management strategy rather than to improve water quality in a few wells while the regional groundwater system deteriorates.

Part 6 ... Small Basin Management

The WASH team quickly discovered that the inhabitants of the upper basins and small catchments have a thorough understanding of the water resources that sustain them. Much of this knowledge has neither been recorded nor considered of any value in water resources management in these areas.

MWR should set up a Small Basins Reconnaissance Section to draw upon this knowledge in a collaborative plan for water resources development that would take the villagers' ideas into account.

Cultural, political, and human considerations are no less important than technical concerns in the planning and implementation of water related work. Although the guidelines provided relate to small basins, they can be profitably applied to many other MWR projects.

Part 7 ... Applications of Geophysics

There are several methods of geophysical exploration that could help MWR in its assessment work. However, many of these are expensive and, experience suggests, could lead to poor results unless they are properly utilized. Recommendations are offered on staff organization to develop the necessary skills and on appropriate training, equipment, and computer software.

The author of this part, Dr. Kendrick Taylor of the University of Nevada, is willing to sponsor one or more Omani students for graduate studies in the application of geophysics in Oman. The OAJC would finance these studies.

Part 8 ... Applications of Remote Sensing

Remote sensing has many useful applications but its products are expensive and MWR must be sure that they would advance its work. The range of available products, their costs, and their uses are dicussed. A pilot project to test the technology in defining water use along the Batinah coast and an incremental process that moves ahead as useful results are obtained are suggested.

Working Paper ... Discussion Paper for a Staff Orientation Document

The WASH team worked with almost the entire MWR staff from August 1990 to August 1991. Although it noted much progress in that short time, it also observed that many new staff members knew very little about Oman and its water resources and had poorly formed ideas about the nature of MWR's work. In spite of the fact that most policies and goals have been defined, the information has not yet filtered down to the rank and file of the organization. Given its rapid growth this is not surprising.

The discussion paper is an attempt to summarize important information that senior staff members should have as they begin their work. It reviews MWR's policies and approaches and explains what the Ministry is and why it was formed, what they should know about working in Oman, and how they can help the Ministry to reach the important goals ahead.

The paper is intended to fill an immediate need and should be followed by a similar document that is enlarged and refined as MWR gains knowledge and experience.

In Conclusion

To assist decision makers, the report on Tasks 5 and 6 provides the approximate capital and recurrent costs of the programs recommended. The earlier reports on Tasks 1 through 4 contain similar data.

OAJC and WASH hope that the information provided here will be useful to MWR in its important work in Oman. The OAJC staff and its managing director, H.E. Hamoud Halil al Habsi, are anxious to be of continuing support.

Chapter 1

INTRODUCTION

The implications of salt water intrusion into the groundwater underlying large parts of Oman's coastal regions are profound. Prime agricultural lands are being abandoned by farmers whose families have tended them for centuries, and important sources of potable water are threatened by advancing sea water. The situation calls for urgent and purposeful action by the Ministry of Water Resources (MWR).

Salt water intrusion is chiefly the result of overpumping that has lowered groundwater levels. The problem began in the 1960s with the introduction of engine-driven mechanical pumps and the expansion of agriculture to meet the demands of a growing population. The chief areas of concern are the Batinah and Salalah coastal plains (Figure 4-1). The Batinah plain is an arcuate alluvial plain in northeast Oman ranging in width from 10 km to 30 km and occupying about 300 km of coastline between the Gulf of Oman and the Hajar Al Gharbi mountains. It accounts for about half of Oman's agricultural activity, and the capital city of Muscat (pop. 300,000) is located there. The Salalah plain is a combined alluvial and limestone plain ranging in width from 7 km to 14 km and occupying about 100 km of coastline in the south between the Jebel Qara and the Arabian Sea. Most of Oman's beef and dairy products originate in the Salalah area. Salalah, the major city, has a population of about 77,000.

Groundwater is the principal source of water for both the Batinah and Salalah plains, where demand to satisfy agricultural and domestic requirements is growing rapidly. Desalinization, the second most important source, is five to six times more costly and is not sustainable without unlimited energy resources. Thus, the depletion of groundwater is a serious problem that must be better measured by improvements in the saline intrusion monitoring system and reversed by better management.

Chapter 2

PURPOSE AND SCOPE

The purpose of this report is to provide the MWR with a plan to monitor salt water intrusion in the Batinah and Salalah plains. It addresses the physical, informational, and institutional aspects of the present situation, and examines the existing monitoring program and the technical, institutional, budgetary, and training requirements for improvement. The plan was prepared in close cooperation with the MWR staff and provides the necessary data for evaluating and managing salt water intrusion.

It proposes the installation and monitoring of salinity transects that will provide a better understanding of the existing situation and the effects of selected interventions.

Chapter 3

SUMMARY OF CONCLUSIONS

- There is serious salt water intrusion in the Batinah and Salalah coastal plains that demand immediate action.

- The most critical areas that deserve first priority in the attention of an upgraded salt water intrusion monitoring network are:

  — the area between Seeb and Suwayq, where groundwater has dropped below sea level and agricultural production has declined primarily because of overpumping

  — the Al Khawd wellfield and dam within the Wadi Samail basin

  — an area of intensive agriculture near Sohar, which includes the Royal and Omani Sun farms and shows signs of increasing groundwater salinity

- Definition of the groundwater flow system is inadequate because of a lack of hydrostratigraphic, aquifer property, and potentiometric data.

- The present monitoring system cannot track the extent of salt water intrusion in the active flow system. Too much effort is spent on sampling shallow coastal wells that reveal little about the extent of inland intrusion and the total depth of fresh groundwater.

- A monitoring system is needed that will define water levels and saline conditions at multiple depths. This information will provide the basis for assessing the rate and direction of salt water intrusion and the effectiveness of existing and planned interventions and for predicting future action.

- The present central database is a shambles. Lithologic descriptions and well locations are often inaccurate. Water-level and groundwater salinity data stored at the district offices, particularly in critical areas such as the Batinah and Salalah plains, have yet to be transferred to the central database. There are no listings of monitoring activities and related well information in some district offices. Data have not been incorporated into usable forms such as maps, reports, and cross-sections. Quality control of data entry is inadequate.

- Institutional problems in the MWR impede the effective assessment and management of salt water intrusion. There is an absence of defined goals, central control, follow-through, and coordination.

- Poor communication between the MWR and other ministries with an interest in water resources management seriously hampers the transfer of information.

Chapter 4

RECOMMENDATIONS

- Organize, staff, and outfit a Salt Water Intrusion and Remediation Section and give the head full authority to coordinate and direct its work.

- Upgrade the salinity monitoring system by installing transects of clustered monitor wells and modifying monitor well networks and sampling frequencies.

- Review and, if necessary, modify the criteria recommended herein for selection of transect locations for discrete depth salinity monitoring, and evaluate the recommended transect locations according to finalized criteria.

- Evaluate existing information on the hydrogeology, salinity with depth, and head distributions along the selected transects. Define cluster well locations and target depths for each transect based on estimates of the leading and trailing edges of the zone of diffusion.

- Prepare a drilling contract to cover installation of the selected transects and cluster wells. Specifications will include: well design, drilling methods, borehole geophysical surveys, sampling procedures, aquifer testing, and well completion.

- Install the cluster wells along the selected transects. Collect hydrostratigraphic, salinity, and head data during drilling. Organize a library in which samples collected during well drilling can be stored for later use.

- Re-evaluate the need for sampling large numbers of dug wells to define shallow groundwater salinity. Reduce sampling density where appropriate.

- Re-evaluate the use of fully screened monitor wells for salinity profiles. The wells should be surveyed for interborehole flow. Where significant contamination of aquifers is found, the wells should be plugged, abandoned, and replaced by a set of cluster wells located a considerable distance away to avoid monitoring the effects of contamination.

- Increase the sampling frequency of time-series salinity and water-level monitor wells in areas of dynamic hydrologic conditions such as near wellfields, intervention structures, and wadi channels.

- Develop a comprehensive plan for monitoring water levels and salinity that will apply to the (modified) existing network and the recommended (salinity) transects.

- Equip wells in selected areas with data loggers and pressure transducers to record short-term fluctuations such as recharge-runoff event response, tidal efficiency, and interference drawdown. Cluster well installations should be designed to accommodate a 4-channel data logger.

- Evaluate the benefit of using the geophysical methods proposed in Part 7. Induction logging of the recommended deep PVC monitor wells and a comparison of the results with available lithologic and salinity data will define the capabilities of the induction logging method. Transient electromagnetic surveys may also be of use.

- Survey monitor well locations and elevations and consider entrusting this task to an outside surveyor with global positioning system (including vertical control) capabilities.

- Prepare and disseminate periodic reports on selected water-level and salinity data in the form of contour maps, time-series graphs, and EC-depth graphs and cross-sections.

- Investigate and report on hydrologic conditions in the areas of concern and transect locations, focusing on defining hydrostratigraphy, groundwater flow pathways, and groundwater recharge processes, and on quantifying aquifer properties and flows.

- Begin to assess and plan interventions to include: reductions in pumpage; capture of surface runoff through recharge dams; capture of coastal groundwater discharge through infiltration galleries, radial collector wells, and scavenger wells; capture of coastal wadi throughflow; relocation of pumping centers inland; conservation; and aquifer storage and recovery (ASR).

- Develop conceptual models of selected problem areas and identify additional data needed for computer modeling of the flow systems in these areas. Select an appropriate computer model such as the USGS

Sharp Model (1990) which was provided to the MWR by WASH. In areas where sufficient data exist, perform initial modeling runs.

- Perform exploratory drilling for deeper aquifers that could be useful for either additional water supply or ASR. Seismic and stratigraphic data in PDO (Petroleum Development of Oman) files should be reviewed to ascertain the total thickness of alluvium and other stratigraphic features of interest.

- Identify and contact institutional allies. Form a working group to exchange information and to address the technical and institutional aspects of interventions.

Chapter 5

EXISTING CONDITIONS

5.1 The Physical Situation

Salt water intrusion is a hydrodynamic process in which sea water moves inland along the base of an aquifer, is circulated upward through a mixing zone, and is discharged back to the sea with the seaward flow of fresh water at the top of the aquifer. The mixing zone shows a gradation between sea water and fresh water and is referred to as the zone of diffusion. Figure 4-2 is a generalized cross-section of a coastal plain showing cyclic flow of salt water and the zone of diffusion. Fresh water discharge to the sea is largely intercepted by pumping dug wells in the coastal zone.

A zone of diffusion is an indication that inland circulation of sea water is taking place. The width of the zone of diffusion is related to mechanical dispersion caused by tidal fluctuations and continuous transport of diluted sea water back to the sea by discharging fresh water. A zone of diffusion is an indication that dynamic rather than static conditions exist.

The Ghyben-Herzberg principle is commonly used to estimate the depth of the salt water interface where groundwater elevations are known. The principle states that under static conditions the depth to the interface will be 40 times the groundwater elevation (relative to mean sea level). In reality, conditions are not static and errors arise from this assumption. In most cases the salt water—fresh water interface is considerably seaward of the static position calculated by the Ghyben-Herzberg principle. For a more detailed explanation of the cyclic flow theory, see "Seawater in Coastal Aquifers" by Cooper and others (1964), and "Effect of Pulse Recharge on the Zone of Diffusion in the Biscayne Aquifer" by Kohout and Klein (1967).

Figures 4-3 and 4-4 portray the process of salt water intrusion in unconfined and stratified aquifers respectively. The zone of diffusion is simplified as a sharp interface only for illustrative purposes. In the unconfined system, the zone of diffusion is drawn inland (lateral intrusion) and upward (upconing) by pumping wells. Although lateral intrusion and upconing are sometimes discussed as separate problems, they are actually horizontal and vertical components of the same problem. Upconing most often occurs in near-coastal areas where the fresh water lens is relatively thin and wells are near the salt water interface. Lateral intrusion results from decreased inland groundwater elevations and a corresponding reduction of groundwater discharge to the sea or a rise in sea level. The relative degree of upconing and lateral intrusion caused by pumping of both coastal and inland wells depends on such factors as pumping rate, location of well screens relative to the salt water interface, and vertical and horizontal hydraulic conductivities.

Figure 4-3 illustrates the combined effects of upconing and lateral intrusion in a single unconfined aquifer as a result of the pumping of shallow coastal and deeper inland wells. This generalization also applies to systems where most of the groundwater flow occurs in an upper unconfined aquifer. There is considerable evidence for the existence of multiple stratified aquifers in the Batinah plain, but the allocation of flow between aquifers is unknown. Figure 4-4 illustrates one of many possible situations in a stratified two-aquifer system. Under pre-development conditions, the semi-confined aquifer usually receives recharge from an overlying water table aquifer along downward vertical gradients. The salt water wedge is located farther inland because of lower heads in the semi-confined aquifer. Pumping in the water table aquifer causes declining water levels and inland movement of the salt water wedge. Vertical upconing also occurs as a result of localized drawdown around the wells. Lowered heads from pumping may cause a reversal of gradient between the two aquifers and contamination of the upper aquifer by upward flowing (saltier) water. Many other scenarios can be constructed along similar lines. Investigation of groundwater conditions in the Batinah plain is likely to show some of these.

The toe of the salt water wedge is often several kilometers inland from the coast and therefore can insidiously impact existing and future inland wellfields. Salt water intrusion on the Batinah coast has been monitored by mass sampling of hundreds of dug wells (see Section 5.2), a technique that does not provide adequate data to detect the inland movement of salt water at depth. Most of these wells are screened through large intervals and may not represent actual physical conditions. Although fully screened wells were useful for reconnaissance evaluation of salinity conditions, wells that monitor discrete zones are preferred.

5.1.1 Batinah Area

The hydrology of the Batinah is characterized by floodwaters that originate in the Oman mountains and flow through wadi channels across the piedmont and coastal plain to the sea. Along the way water infiltrates to underlying gravel deposits, where it slowly moves seaward to the coastal plain as groundwater flow. The alluvium that constitutes the aquifers is highly variable in texture, but an investigation of the upper 100 m to 200 m led Gibb (1976) to define the following major components:

upper gravel—composed of clean sand and gravels occurring at shallow depths and mainly in active wadi channels

clayey gravel—composed of brown and red marly gravel and clayey sands occurring beneath the upper gravel

cemented gravel—composed of well-to-poorly cemented, white-gray gravelly marls and clay occurring beneath the clayey gravel and in older terrace deposits chiefly in the piedmont area (Figure 4-6)

The actual stratigraphy is much more complicated because the alluvium was deposited as fans of interbedded and overlapping beds of gravel, sand, and clay at the base of the mountains. Stratigraphic correlation between even closely spaced wells is therefore a problem. Most stratigraphic data obtained during drilling or through interpretation of geophysical logs are poor and lack definition. Few wells were drilled deeper than 300 m. More work needs to be done in defining the hydrogeology of the flow system (e.g., definition of aquifers, confining beds, and hydraulic properties).

Eastern Batinah

A severe salt water intrusion problem exists in the eastern Batinah (Figure 4-5). Water levels there have been declining since at least 1974 as a result of overpumping. In the coastal area between Seeb and Suwayq, a distance of about 80 km, they are below sea level and in one well (NC-2) near Barka the water level is as much as 4.5 m below sea level (Figures 4-4, 4-5, and 4-6).

The problem has been identified and described in reports by ILACO (1975), Gibb (1976), Tetratech (1978), Dale (1983), Davison (1983, 1986), Graf and others (1984), Doyel and others (1984), Davison and others (1985), Stanger (1985), AHIPL (1985), and Bhatnagar and Ravenscroft (1986). Warnings about the consequences of overpumping have been ignored over the past 15 years. MWR evaluations since 1988 have stressed the impending disaster from salt water intrusion. Recommendations by the staff in 1988 included the following:

- Declare area where water levels are below sea level a "control zone" and restrict pumping by issuing permits
- Announce that well owners in the control zone must register their wells within six months
- Coordinate information exchange with the MAF on well and land usage to estimate total pumpage in the area
- Reduce pumpage in the control zone by 20 percent to 30 percent, based on the estimate of total pumpage
- Base reductions according to a ranking of beneficial uses: drinking water, mosques, schools, hospitals, etc.
- Improve the efficiency of irrigation practices

- Allocate a designated quantity of water to licensed users, meter discharge pipes, and enforce restrictions by random visits of enforcement inspectors

- Consider any management in the control zone as a model for similar situations elsewhere

In May 1989, a staff assessment indicated major advances in salt water intrusion in shallow wells from 1982-83 to 1988 (Table 4-1). The greatest increase occurred in the coastal area seaward of the 1988 position of the 16,000 µmhos/cm EC contour, indicating that wells in an area of 33.5 sq km had become too salty for date palm irrigation. A visit to the Seeb area by the WASH team in May 1991 revealed both dead and severely stressed date palms and salt encrusted soil in the area between the dunes and the highway. Management interventions to curtail the problem were clearly necessary.

During 1984-85, MAF constructed the Al Khawd dam about 5 km south of Seeb to reduce fresh water losses to the sea and increase recharge to the unconfined aquifer in the Wadi Samail basin. Analysis of the limited available data suggests that the dam, which is the first positive step toward solving the problem of overdraft in the eastern Batinah, is having a beneficial effect.

Northern Batinah

Salt water intrusion on the northern Batinah coast is less severe and water levels for the most part show only slight long-term declines. The areas most affected by pumpage lie between Suwayq and Saham, a distance of about 70 km, but there are signs that pumpage in the Sohar area is beginning to exceed recharge. Laver (1991) described the problem at the Royal Farm (Balyat al Andhar) and concluded that intrusion began about 1983, when salinity increases were observed in 11 of the 27 wells at the Royal Farm. Thirteen of the wells were reported to have chloride concentrations exceeding the recommended limits for potable water (250 mg/l). Highly saline water was discovered in 1983 in well OB-2 at the Oman Sun Farm at a depth of 98 m, and in well OA-2 at a depth of 47 m. The WASH team found stressed and dying date palms and salt encrusted soil in the area between the Royal Farm and the coast in May 1991, but the situation was not as bad as at Seeb.

About 3.5 km south of the Royal Farm is the Hilti-Salahi recharge dam, which MAF constructed to reduce fresh water flow to the sea and increase recharge to the unconfined aquifer. The dam is about 7 km long (east-west) and impounds the combined flows of Wadis Hilti and Salahi. Another recharge dam about 23 km west-southwest of the Royal Farm in the upper reach of Wadi Jizzi was constructed for the same purpose. The effectiveness of these dams has yet to be demonstrated.

5.2 The Informational Situation

The information needed to appraise the severity and future prospect of salt water intrusion can be divided into four categories: flow system geometry and hydraulics; piezometric data; salinity data; and pumpage data. Until recently, most such data were generated during groundwater exploration and occasional water-level and salinity surveys. Regular monitoring of EC in wells started seven years ago, whereas records of water-level data typically date back between seven and 20 years. The data have been stored at several locations and in several forms and are only now being entered into a centralized database. There are no reliable estimates of pumpage.

The description of available data presented below is based on a thorough examination of the files and databases of district offices on the Batinah (Seeb and Sohar) and a cursory inspection, dictated by limitations on time, of records at the Salalah district office. Data in the central MWR office were also examined but were found to be less detailed than the data at the district offices.

Flow-System Property Data

Flow-system geometry (i.e., aquifers and confining layers) and hydraulics are essential for interpreting all other hydrologic data. As discussed earlier, the alluvial sediments that provide the Batinah's water supply form a complex aquifer system not yet well defined. The working flow-system model is continually refined as additional hydrostratigraphic and aquifer property data become available. It is not within the scope of this report to review all the sources of these data. Suffice it to say that the Batinah flow system is still imperfectly understood and not enough is known about the characteristics of even the most shallow alluvial aquifers (in which most wells are drilled) for most management and predictive purposes.

Because there are few deep wells, there is a complete lack of hydrogeologic data to explain the geometries, properties, and roles of the multiple semiconfined and confined aquifers at depth in the Batinah. Gaining a detailed knowledge of such a complex aquifer system could be prohibitively expensive. Nevertheless, more work must be done to convert existing information on hydrogeology, transmissivity, and storage coefficients into interpretive representations such as maps, cross-sections, and fence diagrams.

Potentiometric Data

Potentiometric data are necessary to define flow paths, gradients, and changes in groundwater storage over time. Coastal areas with groundwater below sea level are early indicators of salt water intrusion. In order to interpret the potentiometric response to pumpage and recharge events, the water levels of wells in strategic locations at strategic depths must be monitored regularly.

Water-level data have been collected regularly in certain Batinah wells since the early 1970s, but most records date back only to the mid 1980s. In the eastern Batinah, water levels are measured monthly in 207 wells and records generally date back to 1982-85. In the northern Batinah, water levels are measured monthly in a network of 116 wells and most records date back to the early 1980s. Continuous water-level recorders are fitted on 20 wells in the eastern Batinah and on one well in the northern Batinah. Locations of water-level monitor wells on the Batinah are shown in Plates 1 and 2. Potentiometric surface maps have been prepared for the eastern Batinah, and for 1988 water levels in selected areas of the northern Batinah (Wadi Jizzi and the Royal Farm). Water-level data are computerized and hydrographs are maintained at each of the district offices.

Most wells have records dating back to the early 1980s. Eleven wells have the longest record, dating back to the mid 1970s. Measurements are made every few months. Survey control is available on 99 wells, but piezometric surface maps were constructed only from 1986 water-level data. Most wells are boreholes (91 percent) with depths ranging from 20 m to 350 m.

The adequacy of potentiometric data is limited by several factors. Many monitor wells (especially in the Batinah) have not been surveyed for elevation, and thus there is no relation of water levels to sea level and to measurements in surrounding wells. Interpretation of the flow system could be drastically improved by relating water levels to mean sea level and by preparing potentiometric maps. Potentiometric maps prepared at five-year intervals, although adequate for regional assessment, are not adequate for analyzing dynamic areas such as those near wellfields and active wadis. These areas should be mapped on a monthly basis and during extreme events. Additional monitor wells with continuous water-level recorders should be installed within, and adjacent to, active wellfields and wadi channels to assess drawdown, the behavior of recharge pulses, and flow between fluvial and interfluvial areas. Monitoring of deeper aquifers is generally inadequate, and, where it is done, occurs mostly in screened wells in multiple aquifers or water-bearing zones that yield average water levels. More deep monitor wells are needed to provide data at discrete depths.

Salinity Data

Groundwater salinity data have been collected since the early 1980s on the Batinah coast and since the late 1980s on the Salalah plain. Salinity is commonly expressed in terms of EC (electrical conductivity) of the water. Early mention of saline conditions can be found in various reports of exploration and water supply activities. Concern about salt water intrusion on the Batinah mounted in the mid 1970s and resulted in the contracting of several consultants to perform surveys of selected problem areas. Concern about the Salalah area probably arose later, judging from the relatively recent initiation of EC measurement.

Early surveys of salinity in the Batinah were performed by Gibb (1976) in the Wadi Bani Kharus, Wadi Semail, and Rumais areas, and by Tetratech (1978) in the Seeb area. More extensive surveys were performed by PAWR (Public Authority for Water Resources) throughout the 1980s. The surveys were designed to provide "snapshots" of salinity conditions over relatively extensive portions of the Batinah. The Batinah was divided into four survey areas and EC was measured in coastal wells within each of these areas. Shallow dug wells were the dominant well type sampled. EC measurements were taken over periods ranging from several months to almost two years, and sampling resolution was approximately one well per square kilometer. Survey areas were visited sequentially, and some have been revisited after two to three years to document change with time. Plates 1 and 2 show the locations of salinity monitor wells on the Batinah. Batinah salinity survey areas and their respective survey dates are listed below.

EXTENSIVE SALINITY SURVEYS PERFORMED BY PAWR/MWR ON THE BATINAH (1982-1988)

Area	Portion of Batinah Covered	Survey Dates
A	W. Manumah to W. Bani Ghafir	1982-83, 1985, 1988
B	W Bani Ghafir to W. Malahah	1982-84
C	W. Rusayl to W. Manumah	1984, 1986
D	Azaiba to Qurum	1985

Frequent time-series monitoring of EC in selected Batinah wells is relatively recent. Time-series data of EC generally began around 1987 on the eastern Batinah and in the early 1980s on the northern Batinah. Measurement frequencies range from a month to almost a year. Until recently, the entire network consisted of 19 wells in the eastern Batinah (Plate 1) and 34 wells in the northern Batinah (Plate 2). In the northern Batinah most wells are dug wells and in the eastern Batinah are a mixture of dug wells and boreholes. In 1991, monitoring frequency on the eastern Batinah was increased to once a month. On the northern Batinah, salinity monitoring was discontinued in the 34 dug-well network in 1989. By contrast, high-resolution salinity surveys were initiated in the Royal Farm area (in 1989) and the Al Khabourah area (in 1990). In addition, 7 transects of shallow (dug) wells set perpendicular to the coast have been monitored on a near-quarterly basis since 1989. Monitor wells in the Royal Farm area are dug wells or shallow boreholes, whereas the transect and Al Khabourah wells are predominantly dug wells. Locations of high-resolution monitor wells and transect wells are shown in Plate 4-2.

On the Batinah, definition of salinity at depth has been addressed through the installation and profiling of deep monitor wells. Wells generally are 300 m deep and many are fully screened through all saturated materials. Flow meter surveys in some wells revealed considerable flow between water-bearing zones in the borehole. Fifteen wells are regularly profiled in the eastern Batinah (soon to be increased to 22). Only one well is profiled in the northern Batinah and this will soon be retired. The frequency of salinity profile data on record is highly variable. Frequencies of several profiles per year are common, but gaps of several years are also common. Records generally extend back to the 1980s.

On the Salalah plain, aerial salinity surveys in 1985 and 1987 yielded data for EC contour maps of the entire area. Information about the types of wells and well spacing used for the survey was not reviewed during preparation of this report. Time-series EC monitoring is conducted in a network of 215 wells and 7 springs. Most (95 percent) of the wells are used for production. Boreholes account for 56 percent of the wells, most of which are less than 20 m deep. The remaining wells are hand dug. The period of time-series record is relatively short. Approximately 40 percent of the wells have records extending back as far as 1988, whereas monitoring of 60 percent of the wells began in 1991. Salinity profiling in 42 wells is performed infrequently. Profile records generally extend back to the mid 1980s, although a few wells were profiled in the 1970s. Most profile wells are 50 m to 140 m deep. Well construction is largely fully screened or open hole, and the issue of interborehole flow between aquifers has not been addressed. The locations of time-series and profile salinity monitoring wells are shown in Plate 4-3.

The groundwater salinity data suffer from poor spatial and temporal resolution. The data collected during the extensive Batinah salinity surveys provided substantial spatial resolution in two dimensions, but the lack of deep wells accounted for the failure to address salinity at depth. Data from the survey updates have not yet been reduced and published. In addition, the three-year survey interval provides insufficient temporal resolution in areas where the saline interface is likely to be most dynamic. Although the time-series salinity networks should theoretically address the dynamic nature of the saline interface, they have failed to do so to date. The sparsity of time-series monitoring in the eastern Batinah severely limits the degree of detail needed in an area of active salt water intrusion. The present network in the northern Batinah is patchy and many areas have short records, but it does suggest that higher spatial definition would yield documentation of dynamic system responses. Both time-series networks, however, suffer from a lack of detail in the vertical direction. Time-series salinity monitoring on the Salalah plain suffers from a relatively short period of record.

Salinity monitoring at various depths is needed to define the location and shape of the salt water interface. At present, there are few deep wells to define the interface, and these wells, although sufficient for reconnaissance salinity profiling, are likely to provide misleading information because of vertical flow and mixing within the borehole. Salinity measurements from discrete depths are needed without the effects of interborehole flow.

Pumpage Data

Pumpage data are needed to relate aquifer response and saline intrusion to groundwater extraction rates. This relationship can be used empirically for resource management and to calibrate models for the assessment of interventions and the prediction of future conditions. Agricultural water use has been correlated with cultivated land area (Mott-MacDonald, 1990), and similar calculations based on more accurate aerial photography are presently being made on the Batinah by the Food & Agriculture Organization (FAO) for the Ministry of Agriculture and Fisheries (MAF). Earlier estimates of cultivated areas, found in Gibb (1975), could be translated into water use by the same correlation.

Data Management

Data management varies with the district offices and the periods of collection. The district officers computerize most salinity and water-level data, which the central office has attempted to incorporate into a uniform database. Data in the district officers are stored in several software formats, which is generally not a problem as most formats are convertible. The real problem is not with entry and storage (although quality control is sometimes weak) but with summarization and reporting. At the time of the WASH visit, summary lists of the wells included in various monitoring networks (and related information) were not readily available. In addition, basic data generally remain in district office files and are not reported in any regular format. Water-level and salinity data of interest should be reported on a quarterly basis and circulated to interested parties.

An effort has been made recently to incorporate data from the regional offices into a central database, but much of the well data from the Batinah coast have not yet been entered and data from the Salalah office were reportedly still being transferred. Coordination of a central database will require the cooperation (and perhaps training) of the regional offices and will likely take years to carry out.

5.3 The Institutional Situation

MWR began erecting its institutional framework less than two years ago. Professional and technical staff are still being hired, and approaches to assessment, research, and management are still being defined. Accomplishments in managing salt water intrusion have been limited largely to monitoring the existing network. Although the staff are well qualified, progress towards developing a cohesive salt water intrusion program is impeded by the absence of central control and responsibility, coherent goals and policy, and coordination.

The institutional structure of MWR is hierarchical by design but functional chains of command need sharper definition. The duties and authority of the sections, departments, and divisions are not well defined and tend to overlap. The Saline Intrusion Section falls under the Groundwater Department, which in turn is administered by the Water Resources Assessment Division. But various other divisions also have an interest in salt water intrusion, some of them with conflicting technical bases. A common sense of direction, coherent goals and policy, and a central coordinating authority are needed for solving the salt water intrusion problem. Recommendations for a suitable institutional structure are discussed in Section 7.3

Chapter 6

ADDRESSING SALT WATER INTRUSION

6.1 Continuity Between Monitoring and Intervention

Monitoring and intervention go hand in hand in the control of salt water intrusion. To date, the response to salt water intrusion has been the monitoring of water levels and salinity in many shallow and a few deep wells, and, recently, a policy to severely restrict the drilling and deepening of wells in selected problem areas. This curtailment of groundwater development will surely help, but there are indications that the problem will continue to grow even with these restrictions. Undoubtedly, additional interventions will be needed to stop or reverse the current rate of salt water intrusion if valuable agricultural acreage is to be saved.

The choice of interventions must be based on an understanding of the hydrologic flow system, the effect of a given intervention on the flow system, and an array of engineering, social, and economic considerations. Although these considerations are a matter of feasibility, the flow system and how it will be affected can only be understood by analysis of data from a monitoring system that provides sufficient detail to evaluate the adequacy of the options under review. In addition, the monitoring system must be capable of generating data to evaluate the performance of interventions already in place. It should be clear, therefore, that there is a feedback from monitoring to intervention (i.e., assessment to management).

The criteria for the selection of monitoring sites and the physical, informational, and institutional conditions required are addressed in Section 7.1. Technical recommendations for the design, installation, and monitoring of the system are offered in Section 7.2. Interventions most suited to the Batinah and Salalah areas are discussed below.

6.2 Suitable Interventions

Interventions likely to yield the best results in the Batinah and Salalah areas are:

- Reduction in coastal groundwater discharge
- Relocation of pumping centers
- Reduction in pumping
- Aquifer storage and recovery (ASR)
- Alternative well technologies

- Recharge augmentation

Recharge dams are already the intervention of choice in several wadi basins. However, since more than one technique will be needed, salinity transects should be installed immediately to provide the data to evaluate these interventions.

Reduction in Groundwater Discharge

Groundwater losses through wadi channels at the coast should be assessed. Wadi flowthrough studies were proposed in Chapter 8 of Tasks 3 and 4 of the WASH Technical Assistance Program. Similar studies could be conducted in the lower reaches of wadis where losses are indicated by hydraulic gradients and changes in water quality. If losses are significant, steps should be taken to reduce them provided the channel can be defined. Among the possibilities would be constructing a low-level dam at the mouth by excavating and backfilling a trench with low-permeability material or by grouting a cement curtain through boreholes. The discharge could be captured by scavenger wells, shallow skimmer wells, or radial collection wells if it is sufficient.

Relocation of Pumping Centers

Pumping centers could be relocated inland near recharge augmentation structures. Regional wellfields similar to the Al Khawd wellfield could provide a safe and reliable source of supply and allow water managers to control withdrawals. A plan for abandoning irrigation wells near the coast and supplying water from inland wellfields was suggested by AHIPL (1985) in a report for MAF. This report should be updated and used as a guide for the management and development of groundwater resources.

Reduction in Pumping

In areas where water levels are below sea level, immediate steps should be taken to reduce pumping, concurrently with steps to conserve water, construct inland wellfields, and recharge augmentation structures. Reduction in pumping can be made a special condition for well permits. Voluntary reduction should be tried first, but if that should fail to bring results, penalties and impoundment of pumping equipment should be considered. A freeze on permits should be imposed immediately in areas of critical concern.

Aquifer Storage and Recovery (ASR)

A recent innovation in water management is a technique called aquifer storage and recovery. The technique involves the temporary storage of fresh water in confined aquifers usually containing brackish water for recovery during peak demand. This would apply only to areas where storage in unconfined aquifers is inadequate and the hydrogeology is suitable. In areas where recharge from impoundments exceeds the storage capacity of a shallow unconfined aquifer but a suitable confined aquifer runs below, the excess fresh water can be injected into the confined aquifer for later recovery. For a detailed discussion of the method the reader is referred to a report by Meyer (1989).

Alternative Well Technologies

Scavenger wells, galleries, radial collector and conventional wells, and skimming wells are efficient methods of extracting fresh water from aquifers with thin lenses of fresh water without inducing upward movement (upconing) of saltwater. They are discussed in detail in Part 5.

Recharge Augmentation

The U.S. Army Corps of Engineers study of 1979 recommended eight wadis as sites for recharge structures and identified four others for consideration. After further input from PAWR and Tetratech International Inc., a plan was proposed for Wadi Al Khawd. Subsequently, Stanley Consultants completed a feasibility study in December 1981. Hydroconsult followed this with a study for MAF that called for constructing recharge dams in about 25 wadi basins in the Batinah to capture runoff to the sea and provide flood protection to the coast. These are discussed in Chapter 9 of Tasks 3 and 4 of the WASH Technical Assistance Program.

Construction of the first recharge dam at Al Khawd began in March 1983 and ended in April 1985. To date, three dams at Al Khawd, Hilti-Salahi, and Jizzi have been constructed. The Ma'awil dam is almost complete, and the Taww and Rubkah dams will be completed in mid-1992. Construction of the Bani Kharus dam is expected to begin in late 1991.

Some controversy has arisen over the effectiveness of recharge dams, but the principle of capturing flows to the sea for beneficial use is sound. The downstream impact of these dams may, in some instances, exacerbate salt water intrusion. Although they will salvage most of the runoff to the sea, they will eliminate the benefits of leaching saline soils along the coast and of direct infiltration of flood waters into the coastal portions of the unconfined aquifer. If the dam is too far from the coast, it may take several months for groundwater to reach the coastal areas. Also, the peak (head) of the groundwater recharge pulse may not be strong enough to flush the salt water front seaward. Consideration should be given to these potential problems when selecting sites, and to constructing downstream dams that would permit direct infiltration of flood water in critical areas near the coast.

Chapter 7

RECOMMENDED MONITORING PROGRAM

The first step in developing a successful monitoring program is to establish goals and a policy to implement them. The recommendations offered here are not intended to be the final word but a guide to MWR in developing its own philosophy and approach. The link between monitoring and intervention in the control of salt water intrusion has been discussed earlier. It would be of little advantage for MWR to monitor an unfolding disaster unless the monitoring is part of a broader strategy for remediation.

Since budget and time constraints limit the number of problem areas that can be investigated, selection should be based on the seriousness of the problem and the feasibility of implementing effective management or interventions. Intensive monitoring systems should be installed only where the worsening of salt water intrusion will have grave economic, cultural, or social consequences.

The control of salt water intrusion is beyond the capacity of any single agency. Measures to curb it must enlist the combined efforts of other concerned ministries, political entities, and the water users themselves in recognition of the fact that this is a pressing national problem.

7.1 Locations and Requirements of the Monitoring Program

In the selection of monitoring locations, special attention should be given to:

- Municipal wellfields threatened by salt water intrusion
- Important agricultural regions where water levels are well below sea level and salt water intrusion is imminent
- Regions in which existing interventions like recharge structures can be fully tested and validated
- Regions in which a costly intervention is being planned and needs evaluation
- Regions that present an opportunity for a successful intervention because of unique cultural or political organization

The program should have a working organization capable of defining, designing, and implementing its goals and should have the following features:

- It must be directed by a single authority.

- It must not be so complex or detailed that results cannot be obtained within a reasonable time.

- It must provide an orderly decision-making process for selecting and prioritizing the areas to receive detailed studies.

- It must retain the best staff for project work so that the results obtained are highly reliable.

The technical design of the program should ensure that there is:

- Adequate three-dimensional definition of the salt water wedge and its movement over time in the selected problem areas

- Increased definition of the hydrogeology and flow system characteristics through interpretation of data gathered during drilling

- An achievable plan for installation of monitor wells and reliable monitoring equipment

- The best possible use of existing monitor wells with reliable water-quality and water-level histories

- An application of geophysical methods to examine the lateral extent of the conditions recorded by the monitoring system

- Accurate and reliable prediction of intrusion effects in the areas being monitored

- Storage of data in a computer format suitable for mapping, modeling, and statistical analysis

- A way to assess the value and applicability of the existing database for salt water intrusion monitoring

- A basis for evaluating and extending the results of simpler and more rapid surveys

No monitoring program is likely to have all these features, which should be regarded as a checklist for assigning relative weights to program elements as they emerge.

7.2 Technical Approach

The objective of the program is to determine the extent of salt water intrusion and monitor its movement. This is done by drilling to the depth of the leading and trailing edges of the zone of diffusion (ZD) along a transect lies along a groundwater flow line. The leading and trailing edges are assumed to be equal to the 1,000 and 50,000 EC surfaces, respectively, EC 1,000 being the approximate upper limit for potable water and EC 50,000 about equal to sea water. The transects will be located according to the criteria listed in Section 7.1 and will consist of four or five clusters of wells across the ZD. Each cluster will have two to four single-completion monitor wells vertically distributed in discrete zones between the base and the top of the active flow system. Their depth will be determined by a test hole drilled at each cluster location.

The first test hole in a transect should be drilled to a depth of about 300 m. at the estimated position of the toe of the salt water wedge. Thorough examination of existing data will be required to find this position. If little or no data are available, the test hole should be drilled about 5 km inland from the 2,000 EC contour most recently defined by shallow well measurements. If the first test hole intersects the ZD, the second and third should be drilled about 0.5 km inland and seaward from the first. If the first fails to intersect the ZD, the second hole should be drilled 2.5 km seaward from the first. If the second intersects the ZD, the third and fourth should be drilled about 0.5 km inland and seaward from the second. The minimum number of test holes should be three and the maximum five.

The test holes will provide information on the number and depth of water-bearing zones to be monitored. They will be gravel-packed and screened in the deepest zone with PVC casing and screen to allow for periodic induction logging to estimate EC changes in the cased-off zones between cluster well completions (see Part 7 for geophysical surveys). The practice of constructing monitor wells with screens through the entire active flow system to obtain salinity profiles should be suspended pending the determination of potential contamination of water-bearing zones by crossflow between aquifers.

The deep test holes will be drilled so that casing can be advanced as the borehole is excavated. Applicable methods, such as center-sampling rotary and casing-hammer rotary, allow collection of high-quality water samples and cuttings and the measurement of static head and approximate yield during the drilling operation. From the data obtained from the deep test holes, the remaining cluster wells can be drilled and constructed at reduced cost by the conventional rotary method. Recommended drilling procedures are discussed in Section 7.7.2.

7.2.1 Locations of Recommended Salinity Transects and Well Clusters

Based on the criteria in Section 7.1, the following wadi basins were selected for salinity transects.

- Samail—includes Al Khawd wellfields that supply Muscat and the Al Khawd recharge dam (completed 1985); overdraft along coast in northeast part of basin; salt water has intruded to within 4 m-5 km of Al Khawd wellfields

- Taww—severe overdraft along the coast; water table 4.5 m below sea level; date palms dying; saline soil; includes Taww recharge dam (under construction); extent of salt water intrusion is unknown

- Rubkhah—severe overdraft along the coast; water table below sea level; date palms dying; saline soil; includes Rubkaha recharge dam (under construction); extent of salt water intrusion is unknown

- Ma'awil—severe overdraft along the coast; water table below sea level; date palms dying; saline soil; includes Ma'awil recharge dam (recently completed); extent of salt water intrusion is unknown

- Bani Kharus—severe overdraft along the coast; water table below sea level; date palms dying; saline soil; includes Bani Kharus recharge dam (construction imminent); extent of salt water intrusion is unknown

- Hilti-Salahi—signs of overdraft; water table slightly above sea level near Sohar; date palms stressed; saline soil; Royal Farm impacted; large dairy and truck and farming area; includes Hilti-Salahi recharge dam (completed 1985); extent of salt water intrusion is unknown

- Jizzi—signs of overdraft; stressed date palms; saline soil; includes area above Jizzi recharge dam completed (1989); extent of salt water intrusion is unknown

- Hatta—signs of overdraft; includes Hatta recharge dam (proposed); extent of salt water intrusion is unknown

Wadi Samail

The Wadi Samail basin was selected as the area of most critical concern because it includes both the MEW Al Khawd wellfield, which supplies potable water to the city of Muscat, and the Al Khawd recharge dam (see Figure 4-12 for location). The dam was installed by MAF in 1985 to increase groundwater recharge and stores 12.4 million cubic meters (mcm). The wellfield was installed at about the same time, probably with the intention of capturing the increased recharge, and is composed of about 40 wells ranging in depth from 70 m to 90 m. The average pumpage of the wellfield is about 4.4 mcm/yr. The effectiveness of the dam has yet to be established, although preliminary indications are that it has improved both water levels and water quality in the wellfield.

Sufficient hydrogeologic data on the Samail basin are available from the work done by Bhatnagar and Ravenscroft (1986), whose report should serve as an example of the comprehensive salt water intrusion investigation that needs to be conducted before transect selection. The report presents salinity, water-level, and isotope data from selected wells in the Al Khawd area and only lacks an analysis of stratigraphy. Several of its recommendations on drilling methods and well completion were considered in the well construction section of this program.

The report shows that the leading edge of the ZD in the active groundwater flow system was about 6 km inland from the coast and near the northern edge of the Al Khawd wellfield in 1984-1985 (Figure 4-12). Cross-sections A-A' and B-B' show the depth and width of the ZD. The leading edge of the ZD was about 50 m. below and 0.4 km north of the wellfield pumping zone. These cross-sections clearly show that monitoring dug wells at the coast is no substitute for monitoring the leading edge of the ZD at the base of the aquifer.

EC and water-level data in the vicinity of the dam and wellfield were also used in designing the monitoring system. The 1985 water table configuration in Figure 4-12 indicates recharge below the dam by northerly trending water-level mounds along the wadi channels. Sluggish groundwater movement was indicated by water-level troughs and isotope analyses in the interfluvial areas. EC profiles in well DW-2, which is in the interfluvial area below the dam, showed the trailing edge of the ZD at a depth of about 55 m. EC profiles in well DW-1, which is east of well DW-2 and in the active wadi channel, show that the trailing edge was at a depth greater than 75 m (total well depth). The greater depth to the interface at well DW-1 is believed to be related to greater recharge in the active wadi channel.

Pumping levels and EC in the Al Khawd wellfield are recorded by MEW on a biweekly basis. Unfortunately, these records were unavailable for review, but a visit to MEW by the WASH team in June 1991 confirmed that only slight changes in salinity have occurred since 1985. The 1987 and 1988 pumpages from the Al Khawd wellfield were 3.98 mcm and 4.73 mcm, respectively. By comparison, the total flows measured at the Al Khawd gauging station about 6 km above the dam and wellfields were 13.0 mcm and 5.78 mcm, respectively. Potential recharge from runoff above Al Khawd, therefore, was sufficient to supply all the wellfield pumpage in 1987 and 1988. However, as demands increase, there will be a time when the recharge will be insufficient and the deficit will result in lowered water levels and associated salt water intrusion. It should also be noted that rainfall in the late 1980's was above average and may not reflect long-term recharge conditions.

Rapid infiltration of flood water in the lower reaches of the Wadi Samail basin in 1987 caused water levels in the adjacent unconfined aquifer to rise sharply, as shown by a hydrograph of well RGS-2U located near the active channel below the dam (Figure 4-7). In April 1987, about 4.2 mcm flowed into the dam area and the flood gates were opened; about half of the flow flooded the Seeb area and ultimately reached the sea. The water level in well RGS-2U rose about 4 m as a result of the flood, but in well ADG-15, which is near the channel of Wadi Manumah about 5 km northeast of the dam, it rose only about 0.4 m. Downstream, however, water levels in wells ADG-15 and NC-2 showed an intermediate but much reduced response to the recharge and then continued in their downward trend as a result of heavy pumpage in the coastal areas between Seeb and Barka. The hydrographs (Figure 4-7) suggest that most of the recharge was confined to the active wadi channel.

In 1987, a total volume of 13.0 mcm flowed into the dam area and an estimated 6 mcm flowed to the sea (Mel Johnson, MWR, written communication, July 3, 1991). During 1988 and 1989, the dam fully contained the runoff from rainfall in the upper Samail basin. Inflows to the dam area during 1988 and 1989 were 5.8 mcm and 5.3 mcm, respectively. Most, if not all, of the flow, recharged the aquifer and seemed to have a positive effect on the nearby wellfield.

Comparison of the 1991 water levels in wells MAN-1, MAN-2, ADG-15, and WM-1 with the 1985 contours in Figure 4-12 indicates that the water levels on the western side of the basin were about 0.2 m-0.4 m lower in 1985. Water levels in the vicinity of the active wadi channel below the dam are about the same in 1991 as they were in 1985 despite the additional pumpage from the Al Khawd wellfield. Therefore, the cone of depression in the eastern part of the wellfield probably is about the same in 1991 as it was in 1985.

Hydrographs of the KWD wells and RGS wells during 1984 are shown in Figures 4-14 and 4-15. The effects of recharge from the 1987 flood and subsequent events in 1988-90 are indicated by sharp peaks. The 1988-90 recession, however, was longer than that of 1987 because the dam allowed recharge over a longer period. Comparison of the hydrograph for well KWD-1, which taps a water-bearing zone at a depth of about 330 m, with the other hydrographs seems to show that the head in the deep zone is several meters higher although head differences could, in part, result from the water density variations in the various boreholes. The water level in KWD-1 responded to the recharge events but continued to rise after the event, which suggests that recharge could have occurred by infiltration at a higher elevation. The sharp decline in the water level in late 1989 suggests that the deep zone may have responded to pumpage at the nearby Al Khawd wellfield.

The information on the Al Khawd dam and wellfield was considered in recommending the location of the transect, which should follow a line extending about 2 km north-northwest from the foot of the recharge dam. Clusters of monitor wells would be installed at depths of about 40 m, 80 m, and 150 m. The transect should also monitor the effects of the recharge dam with a cluster of wells above the dam. A test hole should be drilled in the transect to a depth of about 330 m to detect the presence of a suspected confined or semiconfined fresh water aquifer with a head several meters higher than that in the overlying aquifer.

Barka Area

The next area of critical concern is the Barka area, which includes Wadis Taww, Rubkhah, Ma'awil, and Bani Kharus (Figure 4-16). The coastal areas of the wadis are showing signs of severe overdraft. Water levels have been declining since the mid 1970s and now are as low as 4.4 m below sea level (see Well NC-2, Figure 4-17). As a result of the overdraft and lowered water levels, sea water has moved inland into the dug wells used for irrigation of date palms and for water supply. Continued use of these salty wells has caused widespread salinization of soils and reduction in agriculture. The extent of salt water intrusion at depth in the active groundwater flow system is unknown, and relocation of water supply to inland areas therefore may be impacted by upconing of salt water from below. An intervention has already been selected for these basins. MAF is constructing recharge dams in each of them to capture runoff to the sea (Figure 4-16). The dam in Ma'awil was scheduled to be completed in July 1991, the dams in Wadi Taww and Rubkhah are scheduled for completion in 1992, and the contract for construction of the dam in Wadi Bani Kharus is to be awarded in 1991. Installation of transects in these basins will help to assess the severity of the intrusion and provide a basis for determining the effects of the recharge dams.

Information on the hydrogeology and the extent of salt water intrusion in these basins is sketchy. Salinity transects in 10 wells along the coast (Figure 4-17) show the presence of sea water at depths ranging from 50 m to 90 m. Some wells show only fresh water to a depth of 100 m. All wells but one (NC-5) are screened throughout their entire depth—a design which permits interborehole flow and therefore reduces the credibility of the data. Sites for the salinity transects and cluster wells for each wadi were tentatively selected as shown in Figure 4-16. They should be reevaluated after a thorough review of the existing data before the final locations and depths are selected.

Sohar Area

The third area of critical concern is the Sohar area, which includes Wadis Hilti, Salahi, and Jizzi, and is the chief source of dairy products and vegetables in the Batinah and the site of His Majesty's Royal Farm (Bahjat Al Andhar). Water levels occasionally are lowered by pumping below sea level and there are increasing signs of overdraft. Agriculture in the area near the coast is in decline and saline soils are developing. His Majesty's dug well at the Royal Farm is now too saline for potable supply and borehole wells have become too saline for irrigating vegetables, vines, and citrus trees. Laver (1991) correctly identified the problem as salt water intrusion due to overdraft. Also included in the Sohar area are the Hilti-Salahi and Jizzi recharge dams completed in 1985 and 1989, respectively.

Information on the hydrogeology and the extent of salt water intrusion is sparse. Laver estimated the active flow system to be about 100 m thick. According to him, salinity profile data in 1983 for well OA-2 indicated the presence of sea water at a depth of 47 m, while a profile of well OB-2 located 2 km southwest of well OA-2 indicated brackish water with an EC of 6,280 µmhos/cm at a depth of 98 m. Well OA-2 is screened from 90 m-150 m but the salinity profile showed the presence of sea water in the well 20 m above the top of the screen in blank casing. The salinity profile data therefore are suspect and should be used with caution. Installation of salinity transects in this area will allow evaluation of the severity of the intrusion problem and the effects of the recharge dams. The locations of the salinity transects were selected solely according to the criteria in Section 7.2.1 and are shown in Figure 4-19. These locations are tentative and should be reevaluated by a more thorough review of existing data before final selections are made.

Shinas Area

The last area considered for a salinity transect is Wadi Hatta near Shinas (Figure 4-20). It is showing the first signs of overdraft because water levels periodically are lowered below sea level by pumping, as indicated by the hydrographs of dug wells (Figure 4-21). The configuration of the 2,000 EC for 1988 suggests that a considerable volume of groundwater is discharged to the sea at the mouth of the wadi. A recharge dam is planned but there is no immediate reason for its construction. The salinity transect would allow an early evaluation of the developing problem so that management can plan for other interventions in addition to the recharge dam.

Little is known about the extent of salt water intrusion at depth in the active groundwater flow system or about the flow system itself. Therefore, the locations of the transect and cluster wells (Figure 4-20) were selected according to the criteria in Section 7.1. Again, a thorough evaluation of the site should be made by MWR staff before final selection.

7.2.2 Well Construction

The transects of nested single-completion monitor wells (cluster wells) described in Section 7.2 should be installed so as to optimize available information and minimize costs. The first well should be the deepest, so that hydrostratigraphic, potentiometric, and salinity data can be gathered for the entire thickness at the site. This information can be used to determine the depth of the other wells.

Locations recommended in this report are for areas where sufficient data were readily available (e.g., Al Khawd fan). The deepest holes should be completed just above the level at which the water quality (chloride concentration) approaches that of sea water. An EC of about 40,000 micro-mhos would be a good index of water quality at the installation depth. The piezometer must be placed in a transmissive zone and careful judgment must be exercised during drilling and installation to ensure the best position.

The number of wells above the deepest well will depend on the thickness of sediments, the number of water-bearing zones encountered, and the position of the salt water wedge(s). Several may be needed within a single water-bearing zone to define the front of the salt water wedge (zone of diffusion).

The drilling methods suggested below will allow accurate measurements of hydraulic head and EC from discrete zones as drilling advances. Drilling should be suspended at approximately every 5 m or when significant lithology changes occur to allow measurement of piezometric head and EC. Head is best measured by driving the casing to the bottom of the excavated borehole, drilling out up to 1 m of open hole, and allowing groundwater to enter the casing until equilibrium is approached. Groundwater should be sampled by air-lifting and field-measured for EC and temperature.

Foam and mud should be avoided as much as possible because they make measurements difficult. In addition, conventional rotary methods should not be used for the deep hole because of the requirement for close resolution of down-hole data. A three-part program employing the methods described below offers the best prospects for success, given the need for formation sampling and for completing the borehole with piezometers.

- Air Rotary with Casing Hammer

This method, based on conventional air-rotary drilling, uses a casing hammer fitted to the top of the casing. As drilling proceeds, the casing is advanced by impact of the hammer and is sealed and lubricated by bariod or similar polymer clays introduced into the outer annulus of the casing created by the external upset of the drive shoe at the end of the casing string. During drilling, the borehole is under complete control and discrete sampling of the bottom-hole piezometric head, water quality, and relative yield of the water-bearing zones can be made with no danger of borehole loss. The casing hammer method combines the control and sampling resolution of percussion methods with the speed and flexibility of rotary drilling.

The penetration depth of a driven casing string is limited by sidewall friction and obstructions encountered as the casing is advanced. Because of the tight fit of the casing in the borehole and the injection of a bariod sealant, there should be little groundwater flow along the casing. Thus, EC readings of formation water ejected from the end of the borehole should be representative of water quality at the maximum extent of the bit.

Usually the casing advance is paced to match the advance of the borehole so that at no time is there any more than about 1 m between the bit and the casing shoe. Eventually the casing will be difficult to drive as friction between the borehole sidewall and the casing increases.

The depth to which it can be driven will depend on the formation materials encountered, the presence of water, the weight and impact of the casing hammer, the strength and thickness of the casing, and the available pull-back capacity of the drilling rig and jacks. In order to optimize the reach of driven casings and to ensure pull-back, the drilling contractor should be equipped with 100-ton pull-back jacks.

Drive casings must be joined by welding and they should be pre-beveled to receive welds. A casing diameter of 219.1 mm (8⅝ in.) is recommended for most installations where depth to the target completion zone is expected to be less than about 200 m. Casing wall thickness should be at least 10 mm (0.375 in.) for efficient driving. Alternatively, when deeper completions are planned, 10¾ in. API casings with a minimum wall thickness of 10 mm can be used to start the borehole. The two casings together should comfortably reach a depth of about 200 m, and a single casing should easily reach a depth of about 75 m generally and about 100 m under favorable circumstances.

- Rotary Underreaming with Air and Down-Hole Casing Hammer

Occasionally it may be necessary to continue drilling to depths greater than can be reached with the two-casing air-rotary method. A light-weight casing 168.3 mm (6⅝ in.) in diameter may be introduced into the 219.1 mm (8⅝ in.) casing and drilling proceeds with an underreaming rotary bit. One system for this application is the Odex bit and down-hole casing hammer designed by Atlas Copco. The method allows the borehole to be completely underreamed so that the casing shoe clears the borehole sidewall. The casing is advanced just behind the bit by a special down-hole casing hammer that hammers on the inside of the casing shoe or by a standard casing hammer. With the former method the wall thickness of the casing can be reduced to about 6 mm (¼ in.). Alternatively, a casing hammer can be mounted on top of the casing string, although the down-hole hammer is more efficient at moving a light casing.

Generally, it will be necessary to lift cuttings from the Odex bit with air. Piezometric head can be measured whenever there is sufficient water flowing into the end of the borehole by simply suspending drilling operations until a static condition is approached. Piezometer completions should not be made in zones that do not rapidly produce water. If they are, the observers who later use the piezometers will have to wait for long periods until the static water level recovers after the water filling the piezometer has been removed.

- Center Sampling Rotary

As an alternative to the underreaming method, boreholes can be advanced to the deepest levels by the center sampling rotary system. This reverse circulation system provides continuous formation sampling and is a fast and relatively economical method of drilling that uses a dual-wall constructed drill pipe fitted with a special bit for reverse circulation. A drilling fluid, usually air, is injected into the annulus between the two tubes and across the face of the drill bit and lifts the cuttings at high velocity through the inner tube. The bit is only slightly larger than the drilling tube so the borehole is slender and, hence, relatively stable. At each horizon, the stream of cuttings and air quickly lifts formation water to the air swivel above and EC can be accurately measured at the discharge.

Once the borehole is advanced to total depth, the sidewalls can be stabilized with a fluid if necessary and the drill string extracted. Immediately thereafter, a 5½ inch diameter pipe is run or washed down the borehole to the total depth to stabilize the borehole until the piezometer string is installed.

- Use of Conventional Rotary Methods for Piezometer Completions

In some cases a single deep borehole will provide enough stratigraphic and water quality information to allow blind installation of piezometers in closely set boreholes constructed by conventional rotary methods. Water or air foam can be circulated in unlined boreholes if they are stable enough for installation of the piezometer strings and the subsequent packing and grouting operations. Immediately after the borehole is drilled, a liner pipe is inserted to stabilize it. The formation near the end of the drilled section can be developed by inserting the drill pipes through the liner and using the liner as an eductor. Once the borehole is sufficiently clean, the piezometer string can be lowered into the liner and gravel pack can be washed down the annulus between the two pipes. Clear water can then be circulated down the annulus of the two pipes and up the inside of the piezometer string.

- Installation of Piezometers

Once casings are in place in the borehole, the piezometer string can be assembled and lowered down the borehole to the correct position inside the inner casing or liner. A fine gravel pack can be washed down the borehole and subsequently a graded plug of finer material can be introduced. Neat cement grout or bentonite clays should then be injected into the borehole on top of the plug through the annulus of the inner liner. The grouting process is continued until all the casings have been withdrawn from the borehole.

The well completion should consist of a PVC piezometer screened in a five-foot zone at the well bottom with an OD of 76 mm (3 in.) and a wall thickness sufficient to withstand overburden pressures. The screen should be strong enough to withstand the formation pressure and the hydraulic forces of the development scheme. The opening in the piezometer should be enough for it to circulate water efficiently during the installation of pack materials.

- Summary

The methods described above will yield a high percentage of successful completions. Considering the data collection required as drilling advances, they are fast and relatively inexpensive, especially where the center sampling rotary method is used with a relatively light casing system. Since drilling contractors in Oman do not yet have the capability to drill with casing hammers, nor are familiar with reverse circulation drilling methods, an international contractor will be required for the work. A training provision in the contract would enable operators from local drilling firms to be attached to the drilling crews to learn these methods.

7.2.3 Monitoring Regime

The monitoring regime to be used on particular installations will, in part, depend on experience gained as the program develops. The following are preliminary steps:

- Once clusters have been installed, observations of water levels and salinity should be made monthly for a start. Later, the frequency can be adjusted as appropriate.

- "Stale" well water must be evacuated before salinity samples are collected. As a rule of thumb, three volumes of the observation well should be pumped from the well before the sample of formation water is collected.

- An induction well log may be taken at the deepest well of a cluster to obtain a profile of the salinity at depth. The presence of several piezometers should facilitate the calibration of profiles. Vertical profiles could be obtained annually.

- Transient electromagnetic geophysical surveys can be made in carefully selected regions to extend the observations from a borehole to nearby areas or to characterize the shallow intrusion between monitoring wells.

In certain areas of interest it will be desirable to install continuous monitoring equipment. Continuous measurements of water levels may be taken by permanently installed transducers. These measurements should help to define the flow regime and the hydrogeologic response of study regions to various pumping and recharge rates.

7.2.4 Instrumentation

Instrumentation will be needed during both the drilling and the monitoring phases of the salt water intrusion program. During drilling, EC meters will be needed to measure the conductivity of air-lifted samples, and well sounders will be needed to measure static water levels as drilling proceeds. After completion, selected monitor wells will be fitted with pressure transducers and data loggers to obtain frequent measurements of water levels. Portable pumps will be needed to obtain samples from monitor wells, meters will be needed to measure the EC of these samples, and well sounders will be needed to measure water levels and periodically calibrate the data loggers.

Pressure Transducers and Data Loggers

Pressure transducers and data loggers will be needed to collect frequent water-level data for intensive studies. Outfitting all the cluster wells with pressure transducers would be prohibitively expensive. The instruments should therefore be placed on wells in selected problem areas.

Ease of programming, data collection, and transfer, as well as local servicing capability, should be considered in choosing data logging equipment. The MWR Surface Water Department has had success with several products manufactured by Omnidata International. It is currently using Datapod II and EZlogger data loggers for wadi gauging and rain gauges. This equipment is designed to be flexible and easy to program. Data are stored in solid state EPROM (Erasable Programmable Read Only Memory). The advantages of such a system are that it minimizes the risk of failure inherent in mechanical data recorders and allows the direct transfer of data to the computer database. Omnidata equipment is available and can be serviced locally. The selection of specific equipment will depend on the number of transducers to be used and the data recording interval. The Datapod II has the capability to monitor four transducers, sufficient for the number of well clusters envisioned. Each site must be enclosed to protect the data logging unit from vandalism, theft, and extreme temperatures.

Pressure transducers that compensate for variations in atmospheric pressure incorporate a strain gauge open to the atmosphere through a small breather tube in the cable. For best results, cable lengths should be specified at the time the transducers are ordered, and should be enough for submergence and to reach from the water level to the surface and from the wellhead to the data logger. Lengths of 50 m-60 m would be adequate. In addition, the transducers should be fitted with desiccant chambers to ensure that moisture does not block this small tube. They must be specified for the maximum pressures anticipated, which will depend on where they are placed and the expected variations in head. Greater data resolution is achieved by using a transducer with a lower rating. In most cases a 20 psi range should be sufficient to capture the head ranges anticipated and provide water level resolution to 1 cm. Transducer calibration must be completed in the field. A two-point calibration using a well sounder is sufficient to define water levels and will automatically compensate for the density of the water. Error due to vertical variation of density (salinity) in the well column is likely to be minimal and can be safely ignored. The sensor should be installed at least 24 hours prior to calibration to ensure that the sensor cable has had a chance to straighten out and that the sensor temperature has reached water temperature.

Every month the water level in the monitor wells should be measured with an electrical sounder and a sample should be withdrawn for EC measurement. Data from the data logger should be downloaded at this time. Although a 32 Kbyte EPROM will hold several months of data, monthly downloading and checking of data are recommended to detect any problems with the equipment. Logged data values should be checked against field calibrations. Data manipulation and analysis can also be performed every month.

Portable Pumps

Recent advances in the design of small-diameter pumps for monitor wells have made available lightweight stainless steel submersible pumps that would be optimal for obtaining salinity samples. The portable pumps can be deployed from a field vehicle equipped with a spool fitted with at least 100 m of hose and electrical cable. The pumps can be powered by a generator also attached to a field vehicle. Field enclosures around cluster wells will have to be constructed to allow access to vehicles.

Two pumps that fit the sampling requirements are manufactured by Grundfos. They are 2 in. in diameter and should be suitable for evacuating the storage volume of the recommended wells over short periods. The stainless steel construction enables them to withstand corrosive salt water environments, and their light weight makes them easily portable. Removal of the footvalves would allow the discharge tube to drain and ease the temporary installation and removal of the pump. In addition, the electrical wiring is incorporated into the flexible discharge tube, thus simplifying pump handling.

Conductivity Meters

District offices in the Batinah and Salalah currently use a variety of conductivity meters and have reported difficulties with some of the older models. Many accurate meters are now available on the market. Any robust and low-maintenance instrument with a good repair record, an accuracy of ± 1-2 percent, and a range that extends to at least 60,000 μmhos/cm would be suitable. Recently obtained meters have proved satisfactory in the Sohar district and should be considered if they meet these criteria.

Discrete Depth Sampler

A WASH team member accompanied technical staff in the Seeb district on a round of well visits to measure both water level and EC. For EC measurement, a grab sample was withdrawn from the well with an improvised sampler weighted with a rock that could contaminate the sample with soil adhering to it. A simple device that does not require weighting and allows sampling to a depth of 50 m can be constructed with locally available copper pipe, lead, and other materials (Figure 4-24).

7.2.5 Data Management

The on-site geologist should keep an accurate log containing lithologic descriptions of the materials encountered, water-level measurements, and EC measurements taken as drilling proceeds. Samples collected during drilling should be split and stored in a sample library (one sample washed, one unwashed). A detailed lithologic log should be constructed from interpretations of drilling results. Water-level and EC measurements should be used to construct pressure-depth diagrams and EC profiles to be presented in the well report alongside the lithologic logs. Logs of downhole geophysical measurements (as recommended in Section 7.2.3) should be digitized and reproduced in the well reports. Digitization of geophysical data is useful for archiving. Well construction information should be incorporated into a detailed as-built diagram that includes descriptions of all materials installed.

Data collected during regular monitoring should be maintained in both digital and hardcopy formats. Water-level data collected from pressure transducers should be used to construct hydrographs.

7.3 Institutional Approach

The Salt water Intrusion Program has as its core a number of technical activities revolving around data collection, analysis, and the design of remedial action. However, it must also progress along an institutional front to build consensus. The flowchart in Figure 4-25 emphasizes the parallel technical and institutional tracks it must follow. The development of a plan that is politically, economically, and socially acceptable to others requires collaborative management interventions.

Under the current MWR organization, the Salt Water Intrusion Program would fall under the Groundwater Department in the Directorate of Assessment. Given the scope of activities and responsibilities described below, the program may require more autonomy. Also, as much of the activity focuses on areas within the MWR districts of Seeb and Sohar, close liaison with these district offices will be necessary. Since later phases of the program will be outside the scope of the Directorate of Assessment, it might be advisable to consider relocating it within the MWR structure.

The program must begin to build links with ministries and agencies that have responsibility and interests in areas where remedial action is planned. Communication with the Supreme Committee for Town Planning, the Ministry of Agriculture and Fisheries, the Ministry of Electricity and Water, the Ministry of Housing, and others should be expanded. Although MWR is responsible for establishing regulatory policy, it must consider the interests of other agencies and water users in policy formulation.

At the regional and local levels, wilayat officials should be informed of program goals and progress. The local wali provides a valuable avenue for sharing information with water users, and this will be important if local or regional water management requires specific actions by individual citizens.

7.3.1 Mode of Organization

Organization and management of a program of this scope require careful planning and coordination at both the central and field levels. Early program activity will focus on establishing a salt water monitoring network encompassing the new salinity transects and existing monitoring facilities. This activity will consume roughly a third of the budget and a major part of the management and technical effort. The program should be structured to include four operational sections.

- Project Management
- Evaluation and Remedial Projects
- Drilling Projects
- Field Monitoring and Technical Support

Their activities and responsibilities are described below, and their structure and staffing requirements are shown in Figure 4-26.

Project Management

The project management function falls into two broad categories—overall management of the program and development of an institutional base for the planning and implementation of effective solutions. Program management will involve the administrative and technical oversight of a staff of 17. Effective solutions will require planning beyond the particulars of the required drilling and monitoring activities, and the building of a coalition capable of defining acceptable remedial action. This section should have a director and an assistant director and a support staff of two secretaries.

Evaluation and Remedial Projects

This section is the core of the program's technical activity. It is here that the detailed work of data analysis, conceptual modeling, and technical solution design will be done. Initially there will be some overlap with the work of other sections—reviewing and reconfiguring the monitoring program (overlap with "Field Monitoring and Technical Support") and preparing a detailed design for the cluster wells at the selected transect locations (overlap with "Drilling Projects"). As the program progresses, the section will be responsible for developing conceptual models of the study areas to include subsurface hydrogeological characteristics, salinity profiles, and intrusion mechanisms. As necessary, computer modeling will be used for a better understanding of the dynamics of the salt water/fresh water regime and for evaluating remedial scenarios. The section should be staffed by two professionals and three technicians.

Drilling Projects

The establishment of an effective monitoring network of lines of well clusters completed to various depths is a complex logistical and technical task. This section will be required to assist in the selection of cluster well locations, monitor and supervise drilling procedures and progress, develop lithological descriptions based on cuttings, and organize necessary logistics. It must also coordinate arrangements with the contractor to ensure that drilling is completed in a cost-effective manner, providing field oversight and making decisions regarding depths and modes of drilling. The section should have three professionals and two technicians.

Field Monitoring and Technical Support

The field monitoring and technical support section will be responsible for most of the field data collection and for geophysical surveys to gain greater understanding of the hydrostratigraphy and salinity distribution in zones without well completions. The major focus will be on assessing the existing monitoring program, designing and implementing a regular monitoring program for the cluster wells, and developing and completing specialized short-term tests as needed. In addition, the section will be responsible for overseeing borehole geophysical logging and evaluating surface geophysical methods. The section should be staffed by a professional and three technicians who will work closely with the regional offices to ensure that monitoring is carried out as specified. The technicians may be based either in the central or in the regional offices.

7.3.2 Staffing

The proposed staff of 17 will be headed by a Program Director who should be a hydrologist with international experience of salt water intrusion. He should also have project and administrative experience, understand the principles of water regulation, and be able to work effectively outside the MWR to develop acceptable solutions to the problems of salt water intrusion. The Assistant Director should be a hydrogeologist conversant with salt water intrusion and willing to spend much of his time collaborating with other agencies in meeting their concerns about remediation.

The head of the Evaluation and Remedial Projects Section should have a broad background in salt water intrusion hydrodynamics and remedial design and a pragmatic approach to finding solutions. Experience in project management and engineering is desirable. The head of the Drilling Projects Section must have extensive experience in managing complex drilling projects, should be familiar with all the drilling techniques to be used, and should understand drilling contracting. His skills in managing the day-to-day operation of the drilling contract are key to a successful monitoring program.

The program will require four hydrogeologists, two of whom will work closely with the senior hydrogeologist in charge of drilling and must be capable of directing on-site drilling operations. One hydrogeologist, to be assigned to the Evaluations and Remedial Projects Section, must be a competent groundwater modeler with an understanding of salt water intrusion. The fourth hydrogeologist will head the Field Monitoring and Technical Support Section. He should be skilled in data collection and acquisition and all aspects of instrumentation related to this effort, should be able to ensure quality data reduction and graphical representation, and should be sufficiently knowledgeable about geophysical methods to oversee the performance and evaluation of geophysical work.

Four senior technicians will be required. Two of these will work with the drilling inspectors examining cuttings and developing lithologic profiles. One will assist the Evaluation and Remedial Projects Section in data reduction and other tasks. The fourth will be assigned to the Field Monitoring and Technical Support Section to see that all instruments and data acquisition equipment are in working order and calibrated properly.

Three technicians will be needed to assist in field monitoring and evaluation. They should have a basic understanding of hydraulic principles but will require specialized training, much of it acquired on the job.

The secretarial needs of the program will be met by an administrative section consisting of two secretaries.

7.3.3 Training

The need for timely action and the degree of technical knowledge required to understand the flow system and design effective solutions dictate that most of the staff be experienced professionals. However, there are several areas where training may be required for MWR staff, and there may also be opportunities to educate others as part of the effort to build the partnership necessary for successful solutions.

MWR Staff

Training requirements for MWR staff fall into two broad areas—water resources management and technical training. Depending on the background and skills of the Assistant Program Director, training in the principles of coastal aquifer management and regulatory policy development could benefit the long-term goals of the program. This training would be best in overseas short courses.

Technicians must able to handle data acquisition equipment, some of it quite complex, so as to make accurate water level readings, operate the data loggers and pressure transducers, collect water samples with a portable pump, collect water and cuttings from drilling discharge, measure EC, and keep accurate field notes relating to their activities. Much of the training for these tasks will be provided on the job by senior staff members. However, depending on job requirements, a data acquisition training course may be necessary to introduce the technicians to the proper functioning and use of a specific piece of equipment. This could be a local course of a week or so or an overseas course at the manufacturer's facility.

Personnel of Other Agencies

The planning and implementation of remedial programs will be simplified if everyone involved fully understands the program, the principles of salt water intrusion, and the need for action. Short seminars at MWR, study tours of affected coastal areas, and visits to sites where remedial programs have been effective would be very instructive for officials from other ministries or agencies.

7.3.4 Scheduling

Overall program scheduling is based on the immediate need for completing a series of well clusters in transects perpendicular to the Batinah coast to improve monitoring of salt water intrusion at various depths. Drilling contracts, supervision of the drilling, and completion of the wells will drive the early phases of the program. Several drilling contracts of roughly 16 months' duration are planned during the first five years.

Existing hydrogeologic data and tentative locations for at least three transects should be evaluated thoroughly before drilling begins. Information collected during drilling may require the relocation of exploratory cluster wells in planned transects. As conceptual models of the flow system and extent of salt water intrusion are developed from drilling data, potential technical solutions will emerge.

The institutional groundwork for the implementation of remedial programs must begin at the outset with the building of a coalition to exchange information on the problems of salt water intrusion and the acceptability of technical solutions.

An implementation schedule outlining major tasks is shown in Figure 4-27.

7.4 Budget

The suggested five-year budget is R.O. 4.6 million (Table 4-2) to cover personnel, equipment, and contract drilling costs. These costs and the long-term recurrent costs are discussed below.

7.4.1 Initial Costs

The program costs, less contract amounts, are estimated at R.O. 2.8 million, of which salaries for the staff of 17 account for R.O. 2.34 million. At least three positions (Program Director and two Senior Hydrogeologists) should be filled by internationally experienced personnel. The drilling inspectors, who will supervise the critical first stages of the program, must be experienced field professionals.

Major equipment requirements include service vehicles, mobile data acquisition vehicles, and data acquisition instrumentation. Five 4x4 service vehicles and three fully equipped mobile data acquisition vehicles will be needed. Several microprocessor based data logging units, along with pressure and electrical conductivity transducers, will be used for short target studies of aquifer dynamics in critical areas. Miscellaneous field equipment, including well sounders, conductivity meters, hand-held meters, and tools, and office furniture, and computer software and peripherals will also be needed.

7.4.2 Contract Costs

Two proposed drilling contracts are expected to cost R.O. 750,000 each. Each of these will cover the drilling of eight lines of monitoring wells with five well clusters per line. An expert consultant should be engaged to draw up these contracts to ensure the efficient use of funds. Several geophysical studies to define subsurface conditions in the study area are anticipated. Although it may be possible to perform these studies in-house, equipment costs and geophysical procedures may dictate a contracting arrangement with a suitable firm.

7.4.3 Recurrent Costs

The average annual cost of over R.O. 900,000 is predicated on a five-year drilling, monitoring, and evaluation program. If the need to extend the program is diminished by its success, additional drilling may not be required. Longer term monitoring responsibilities may be assigned to the regional offices and a smaller salt water intrusion staff of about five may be able to evaluate new information and refine remedial programs.

Chapter 8

ADDITIONAL RECOMMENDATIONS

8.1 Oil Exploration Drilling and Geophysics

The WASH team discussed the possibility of using PDO's stratigraphic and seismic records to determine the thickness of alluvium in the Batinah. Dr. Gavin Graham provided maps showing the location of test wells, land-line seismic surveys, and offshore seismic surveys, and a list of references in the PDO library. Since James Laver, MWR, made the initial contact with PDO and has taken a keen interest in exploring deeper for zones that may be used for aquifer storage and recovery (ASR), it would be logical for him to provide follow-up. If the PDO information proves insufficient, a contract with a marine seismic company or a university with a research vessel should be considered for seismic profiling along the Batinah and Salalah coasts.

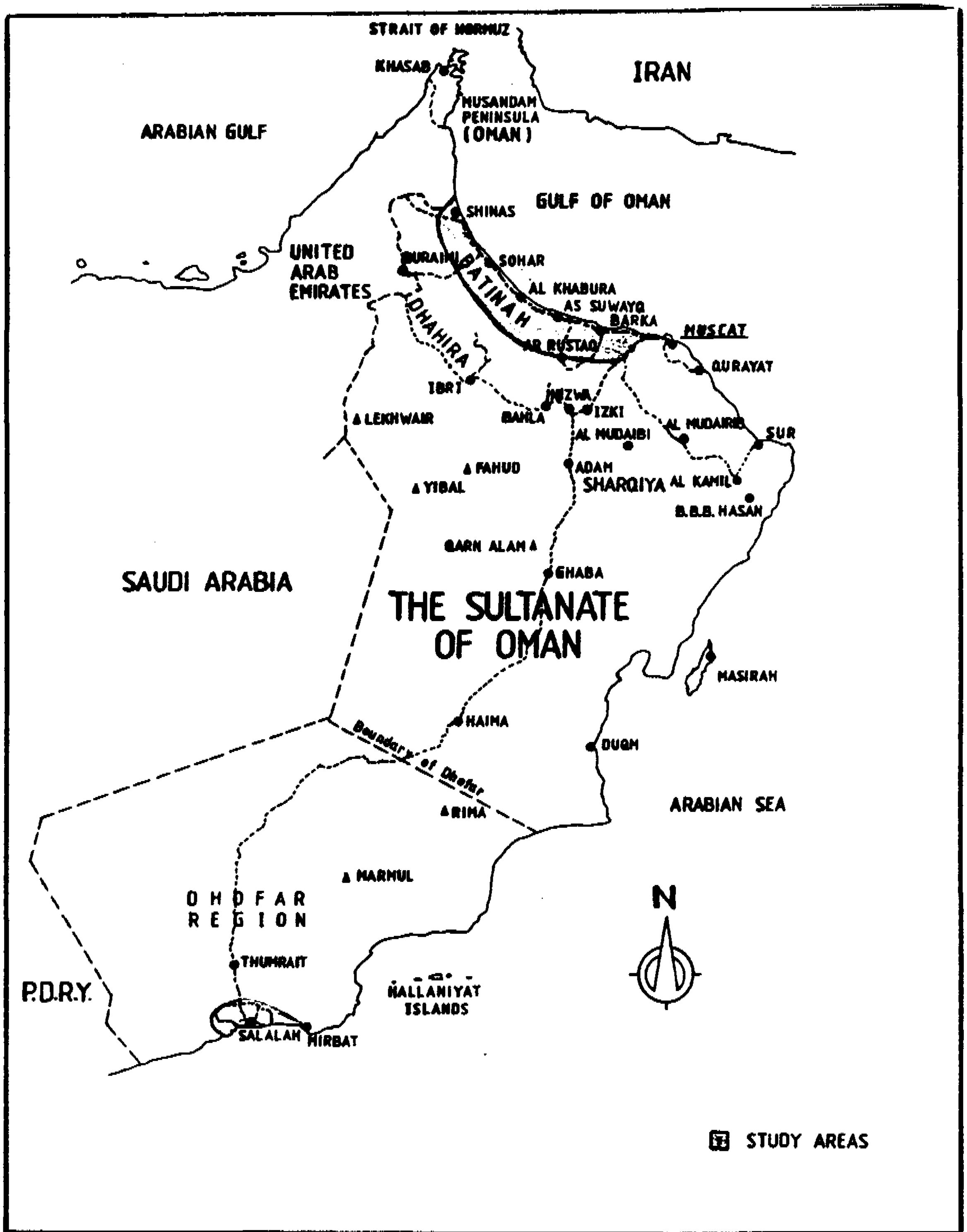
8.2 Seeking Additional Assistance

MWR is young and inexperienced in water management and needs assistance in making the transition from a data gathering and assessment agency. Several large water management districts in the United States like the South Florida Water Management District (SFWMD) in West Palm Beach could provide administrative guidance. Another option would be a short-term contract with a former water management district director to develop an organizational plan. One such person is John Wadradea, former director of the SFWMD now on the faculty of Florida Atlantic University in Boca Raton. WASH representative Fred Meyer would be pleased to provide liaison with the SFWMD and Mr. Wadradea.

8.3 Sample Library

Samples of cuttings from water and oil wells deeper than 20 m should be preserved in a library for future examination and analysis. The cost of reproducing these samples is prohibitive, and well logs do not adequately describe their lithology and the nature of the fossils that may be found in them. The library would also be a repository for cores.

Figure 4-1



PRINCIPAL AREAS OF SALT WATER INTRUSION

NOT TO SCALE

Figure 4-2

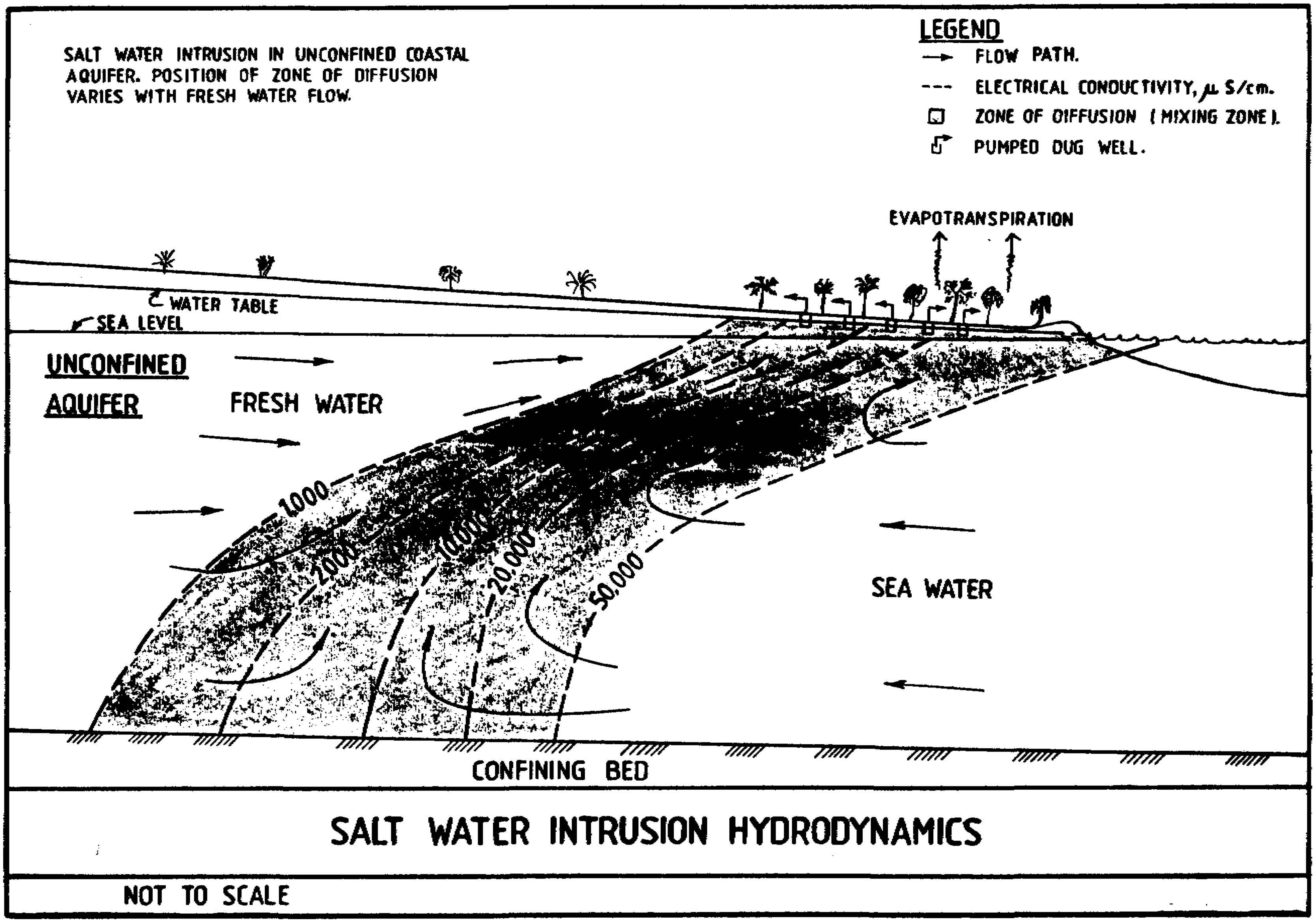
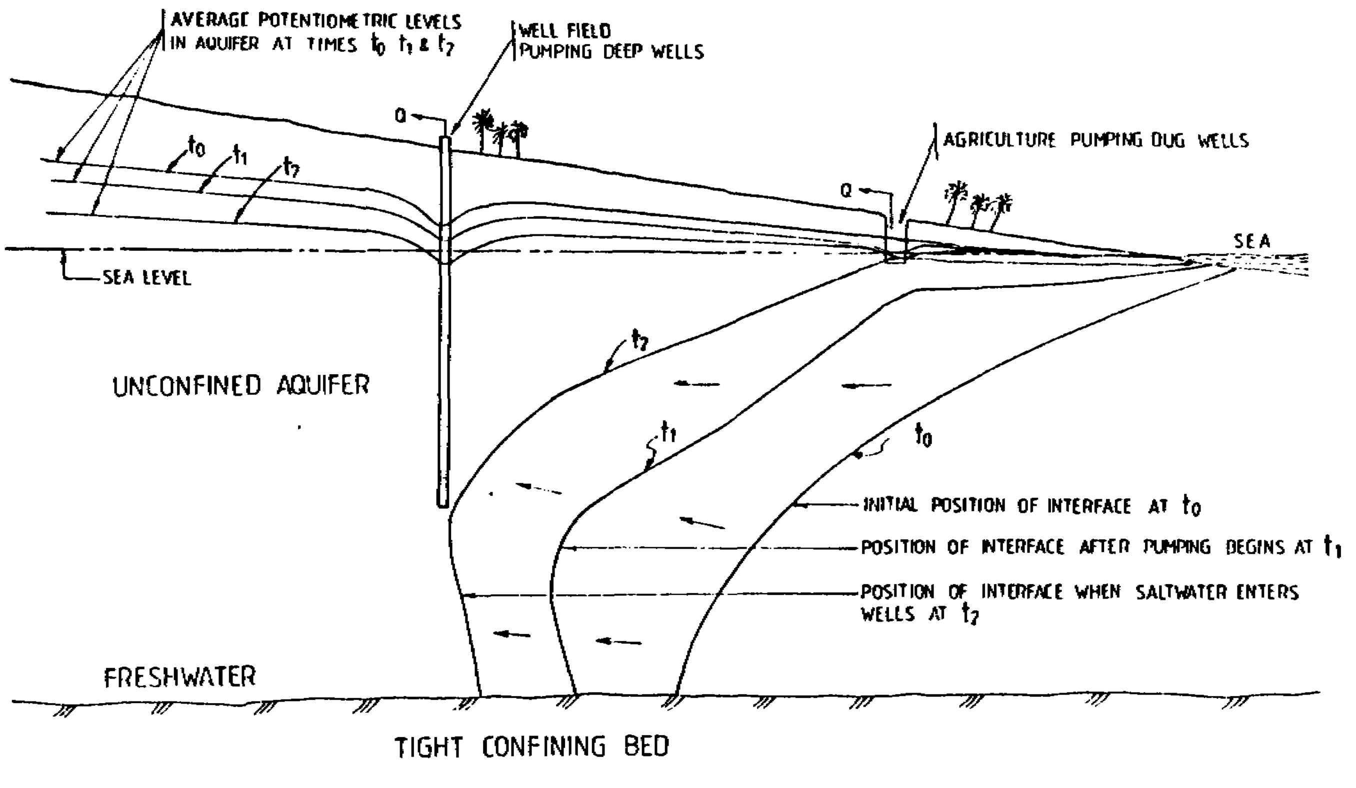
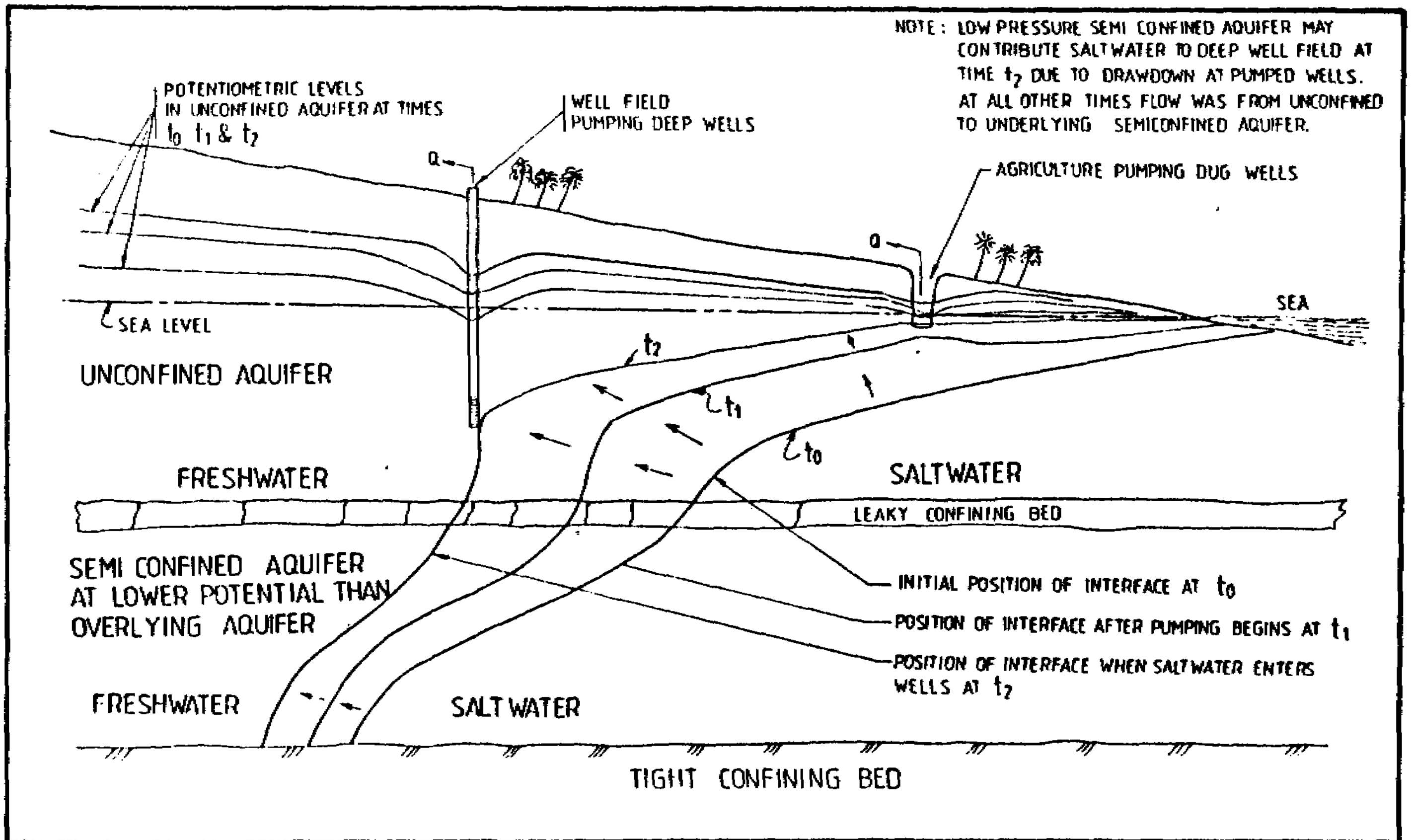

SALT WATER INTRUSION IN UNCONFINED COASTAL AQUIFER. POSITION OF ZONE OF DIFFUSION VARIES WITH FRESH WATER FLOW.
LEGEND
FLOW PATH.
ELECTRICAL CONDUCTIVITY, μ S/cm.
ZONE OF DIFFUSION (MIXING ZONE).
PUMPED DUG WELL.
EVAPOTRANSPIRATION
WATER TABLE
SEA LEVEL
UNCONFINED AQUIFER
FRESH WATER
1,000
2000
10,000
20,000
50,000
SEA WATER
CONFINING BED
SALT WATER INTRUSION HYDRODYNAMICS
NOT TO SCALE

Figure 4-3



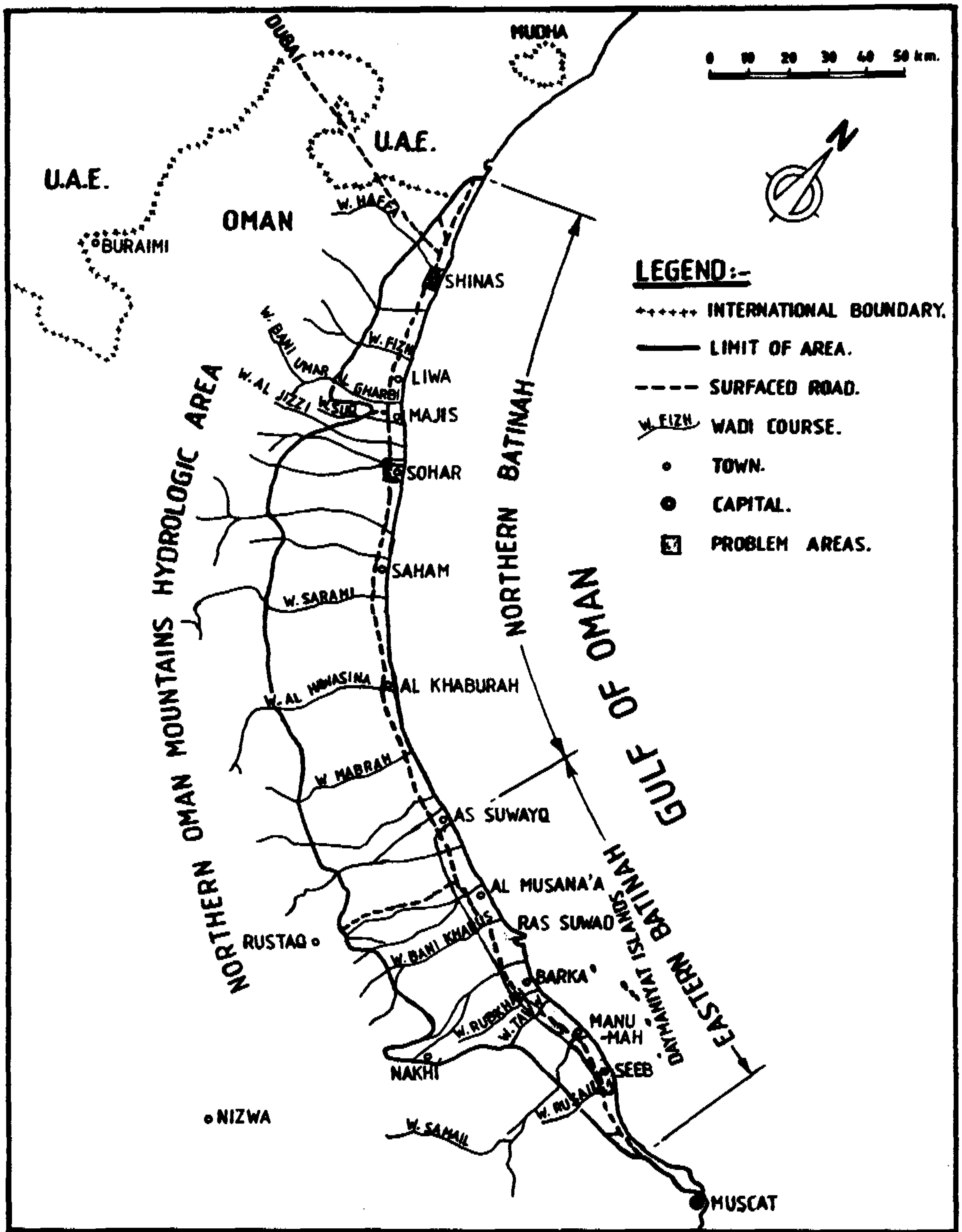
CASE 1 - SCHEMATIC CROSS SECTION OF SALTWATER-INTRUDED COASTAL AQUIFER AT VARIOUS TIMES UNCONFINED AQUIFER ONLY

Figure 4-4



CASE 2 - SCHEMATIC CROSS SECTION OF SALTWATER-INTRUDED COASTAL AQUIFERS AT VARIOUS TIMES UNCONFINED UPPER AQUIFER UNDERLAIN BY SEMICONFINED AQUIFER.

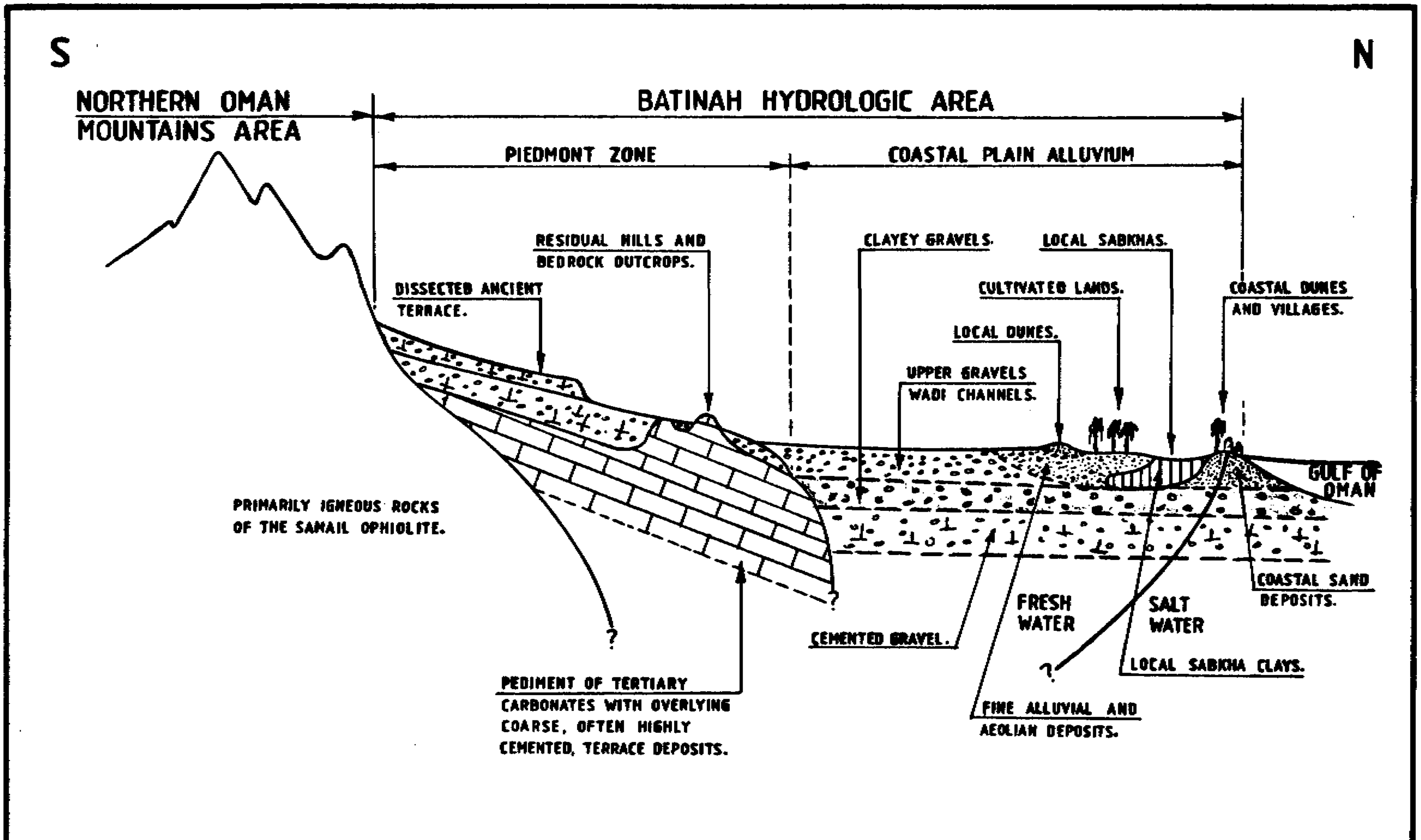
Figure 4-5



THE BATINAH AREA
(AFTER DOYEL, 1983)

NOT TO SCALE

Figure 4-6



GENERALIZED CROSS SECTION ACROSS THE BATINAH
(AFTER ILACO, 1975 AND DOYEL AND OTHERS, 1983)

NOT TO SCALE

Figure 4-7

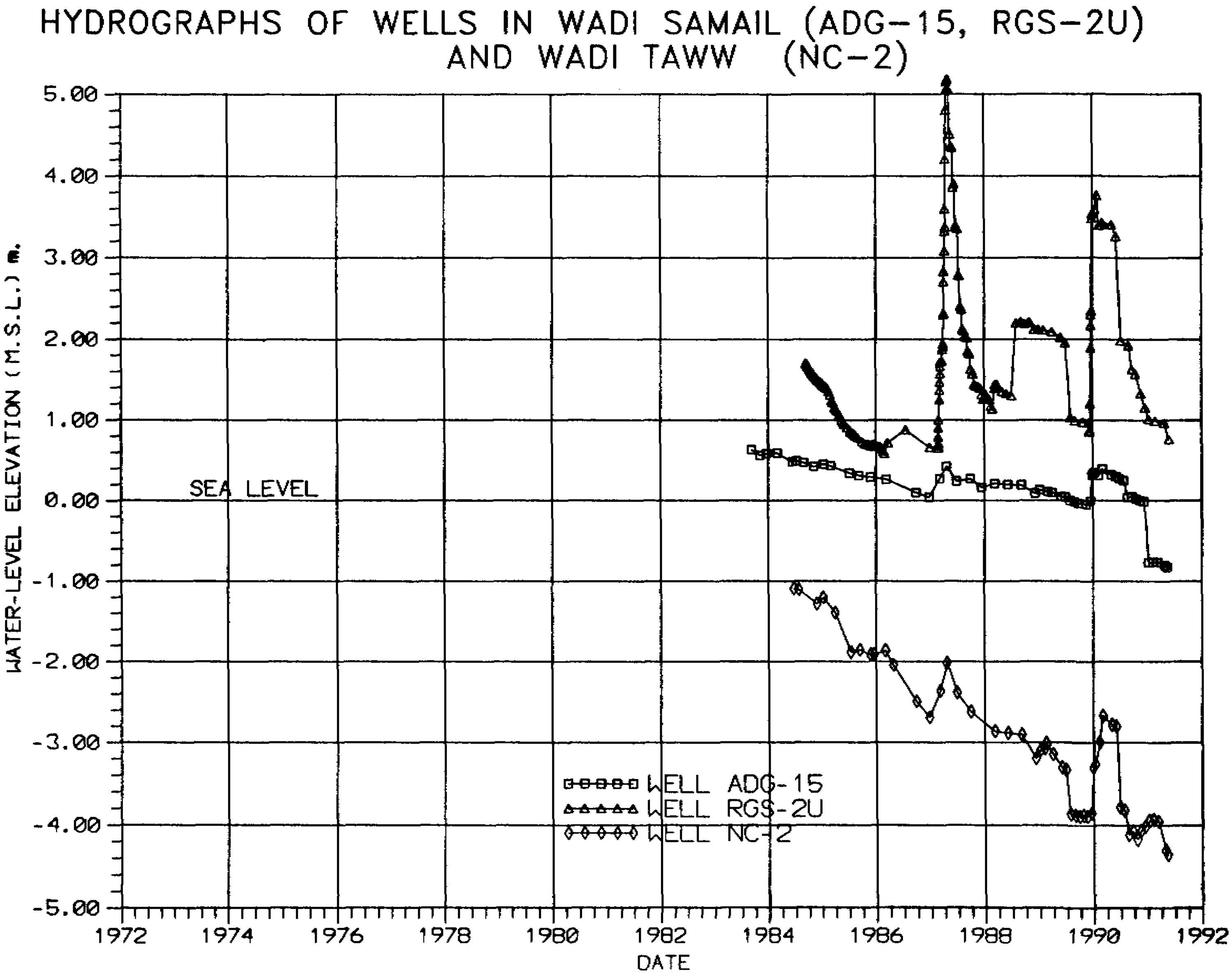

HYDROGRAPHS OF WELLS IN WADI SAMAIL (ADG-15, RGS-2U)
AND WADI TAWW (NC-2)
WATER-LEVEL ELEVATION (M.S.L.) m.
5.00
4.00
3.00
2.00
1.00
0.00
-1.00
-2.00
-3.00
-4.00
-5.00
SEA LEVEL
WELL ADG-15
WELL RGS-2U
WELL NC-2
1972
1974
1976
1978
1980
1982
1984
1986
1988
1990
1992
DATE

Figure 4-8

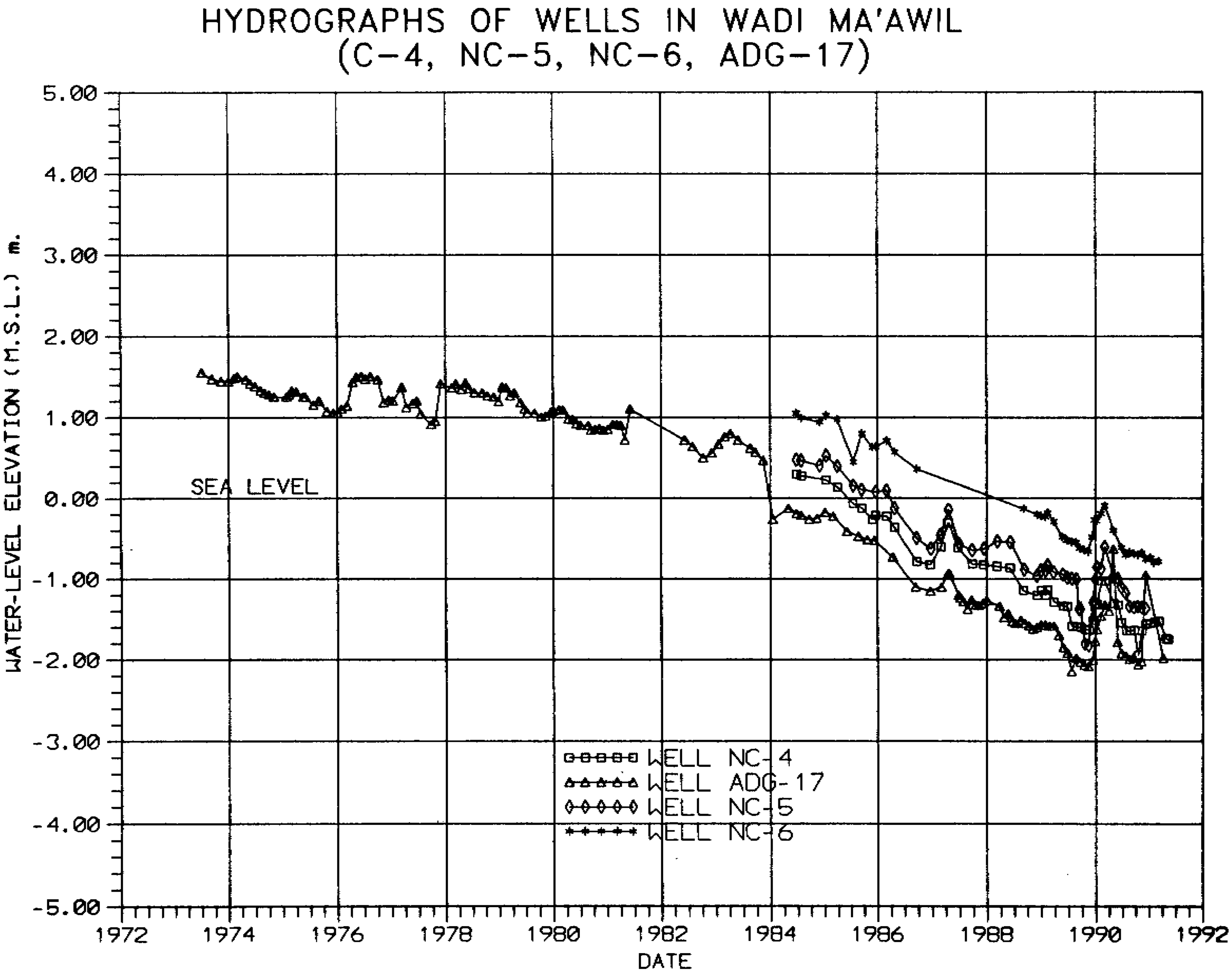

HYDROGRAPHS OF WELLS IN WADI MA'AWIL
(C-4, NC-5, NC-6, ADG-17)
WATER-LEVEL ELEVATION (M.S.L.) m.
5.00
4.00
3.00
2.00
1.00
0.00
-1.00
-2.00
-3.00
-4.00
-5.00
SEA LEVEL
WELL NC-4
WELL ADG-17
WELL NC-5
WELL NC-6
1972
1974
1976
1978
1980
1982
1984
1986
1988
1990
1992
DATE

Figure 4-9

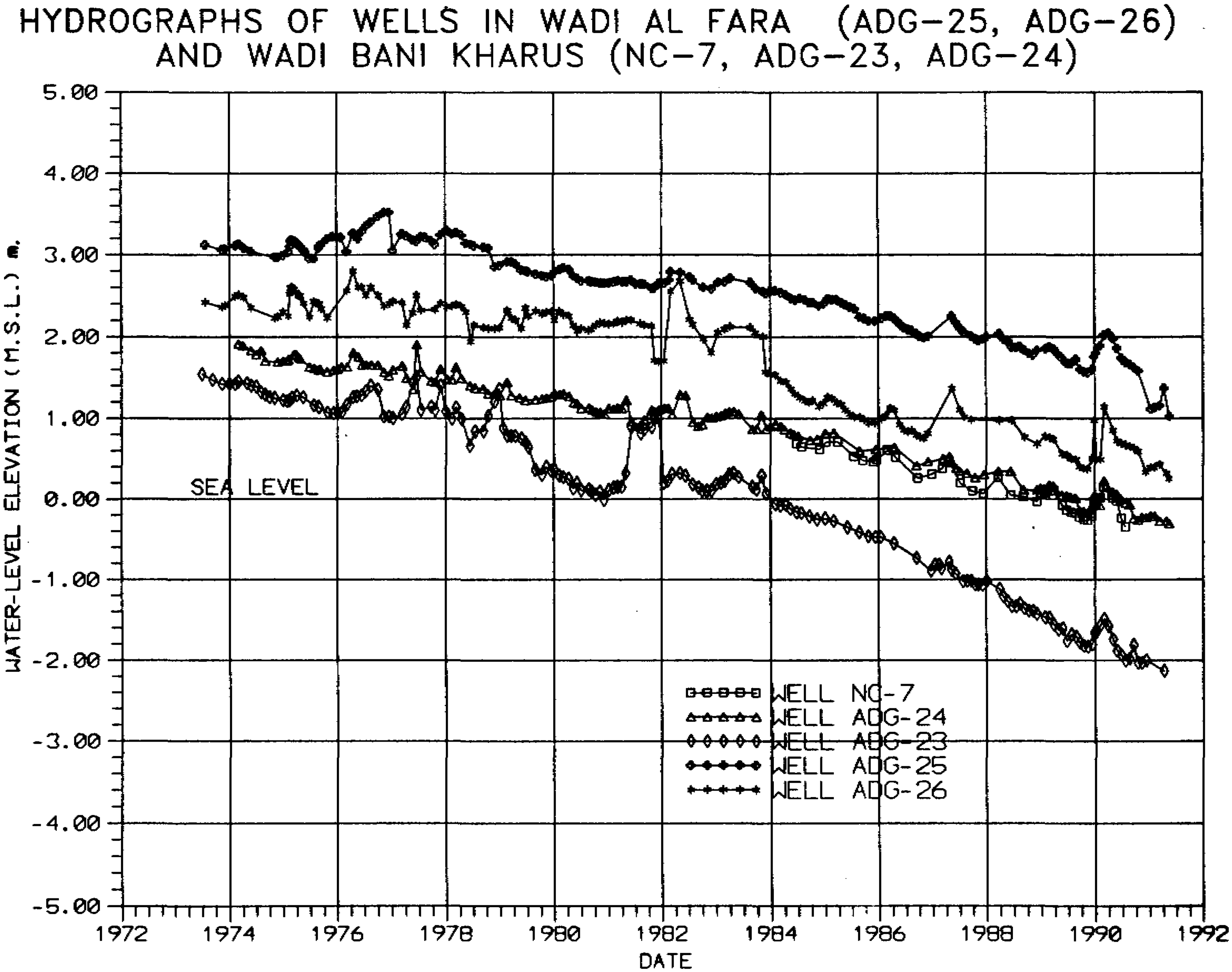
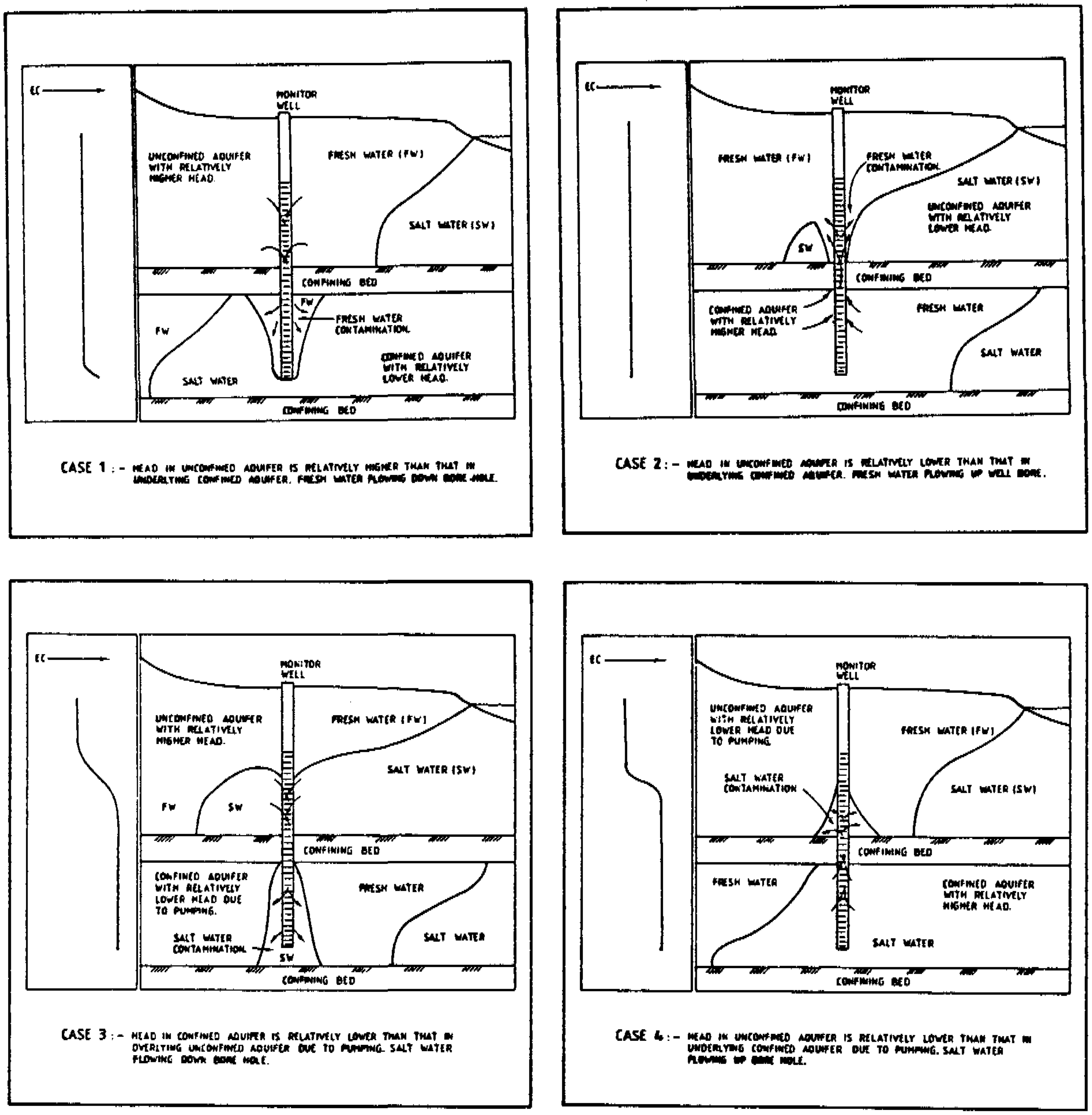

HYDROGRAPHS OF WELLS IN WADI AL FARA (ADG-25, ADG-26)
AND WADI BANI KHARUS (NC-7, ADG-23, ADG-24)
WATER-LEVEL ELEVATION (M.S.L.) m.
5.00
4.00
3.00
2.00
1.00
0.00
-1.00
-2.00
-3.00
-4.00
-5.00
SEA LEVEL
WELL NC-7
WELL ADG-24
WELL ADG-23
WELL ADG-25
WELL ADG-26
1972
1974
1976
1978
1980
1982
1984
1986
1988
1990
1992
DATE

Figure 4-10



CASE 1 :- HEAD IN UNCONFINED AQUIFER IS RELATIVELY HIGHER THAN THAT IN UNDERLYING CONFINED AQUIFER. FRESH WATER FLOWING DOWN BORE-HOLE.

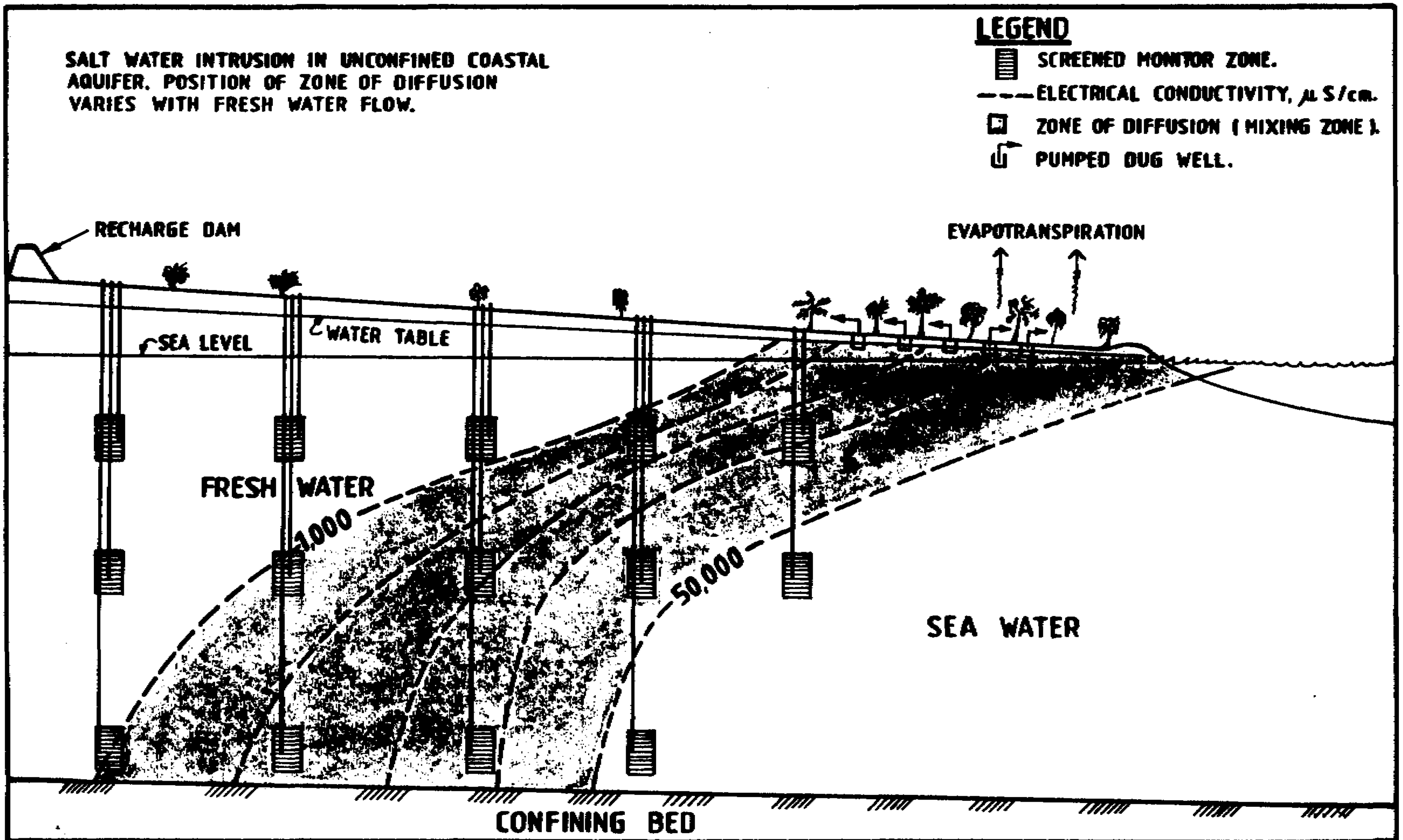
CASE 2 :- HEAD IN UNCONFINED AQUIFER IS RELATIVELY LOWER THAN THAT IN UNDERLYING CONFINED AQUIFER. FRESH WATER FLOWING UP WELL BORE.

CASE 3 :- HEAD IN CONFINED AQUIFER IS RELATIVELY LOWER THAN THAT IN OVERLYING UNCONFINED AQUIFER DUE TO PUMPING. SALT WATER FLOWING DOWN BORE HOLE.

CASE 4 :- HEAD IN UNCONFINED AQUIFER IS RELATIVELY LOWER THAN THAT IN UNDERLYING CONFINED AQUIFER DUE TO PUMPING. SALT WATER FLOWING UP BORE HOLE.

VARIOUS ILLUSTRATIONS OF INTRA BORE HOLE FLOW	
NOT TO SCALE	FIG. 4-10

Figure 4-11



SCHEMATIC OF CLUSTER WELLS ALONG SALINITY TRANSECT

NOT TO SCALE

Figure 4-12

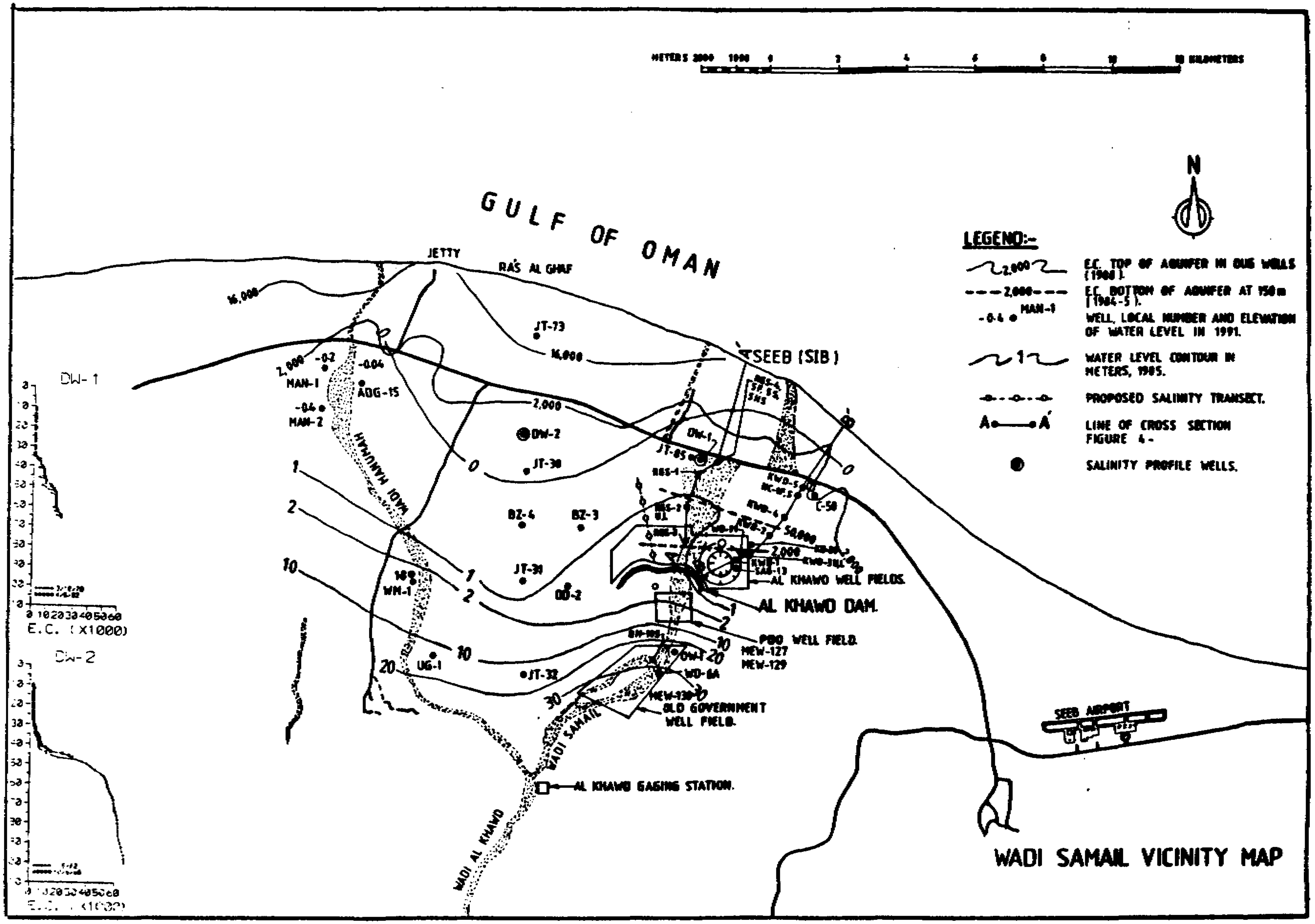
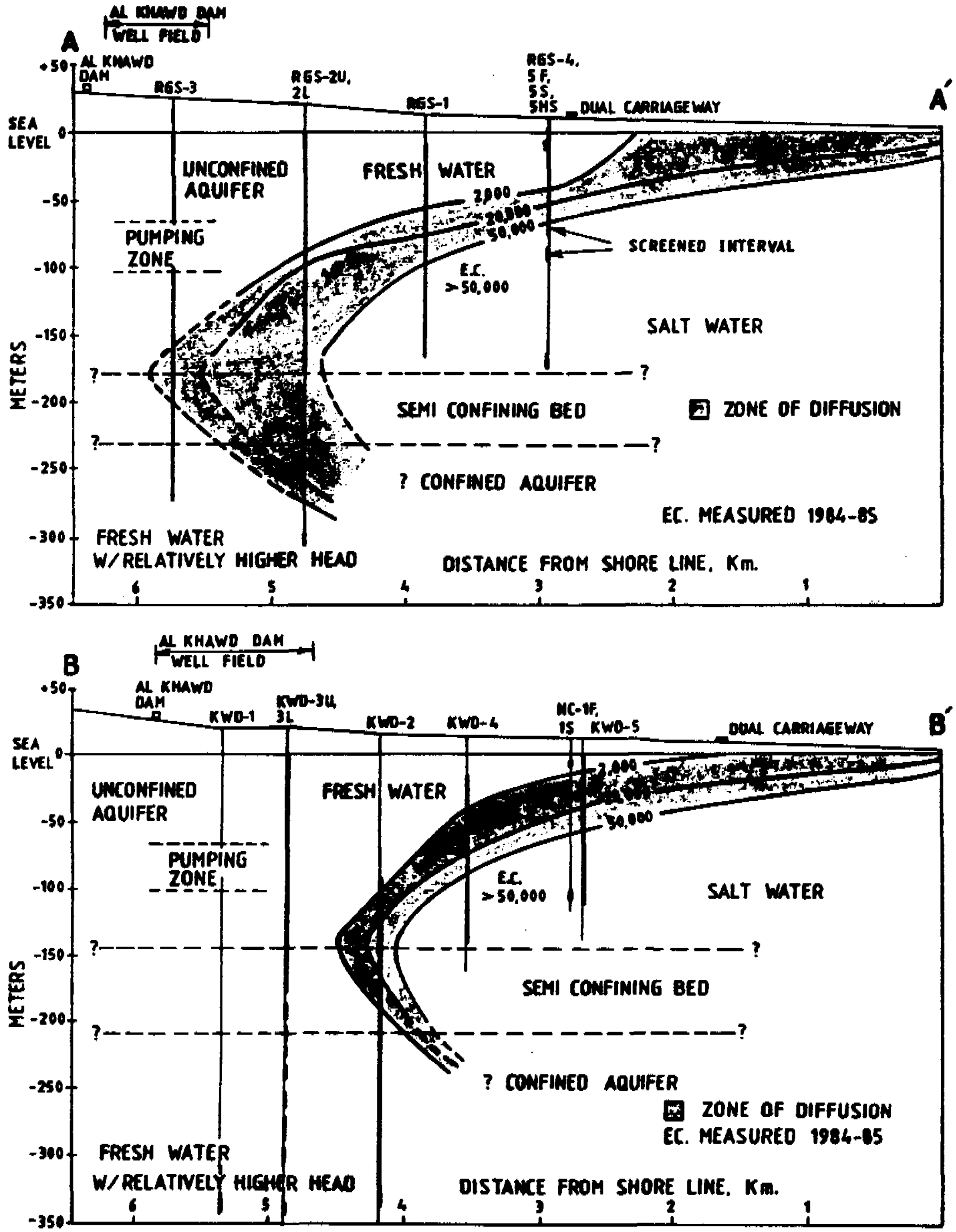

GULF OF OMAN
JETTY
RAS AL GHAF
TSEEB (SIB)
LEGEND:-
E.C. TOP OF AQUIFER IN DUG WELLS
E.C. BOTTOM OF AQUIFER AT 150 m
WELL, LOCAL NUMBER AND ELEVATION OF WATER LEVEL IN 1991.
WATER LEVEL CONTOUR IN METERS, 1985.
PROPOSED SALINITY TRANSECT.
LINE OF CROSS SECTION FIGURE 4-
SALINITY PROFILE WELLS.
N
DW-1
DW-2
E.C. (X1000)
MAN-1
MAN-2
ADG-15
JT-73
JT-30
JT-31
JT-32
BZ-4
BZ-3
WM-1
UG-1
WADI MAWAWAH
AL KHAWD WELL FIELDS
AL KHAWD DAM
PDO WELL FIELD
MEW-127
MEW-129
WD-6A
OLD GOVERNMENT WELL FIELD
WADI SAMAIL
WADI AL KHAWD
AL KHAWD GAGING STATION
SEEB AIRPORT
C-50
WADI SAMAIL VICINITY MAP

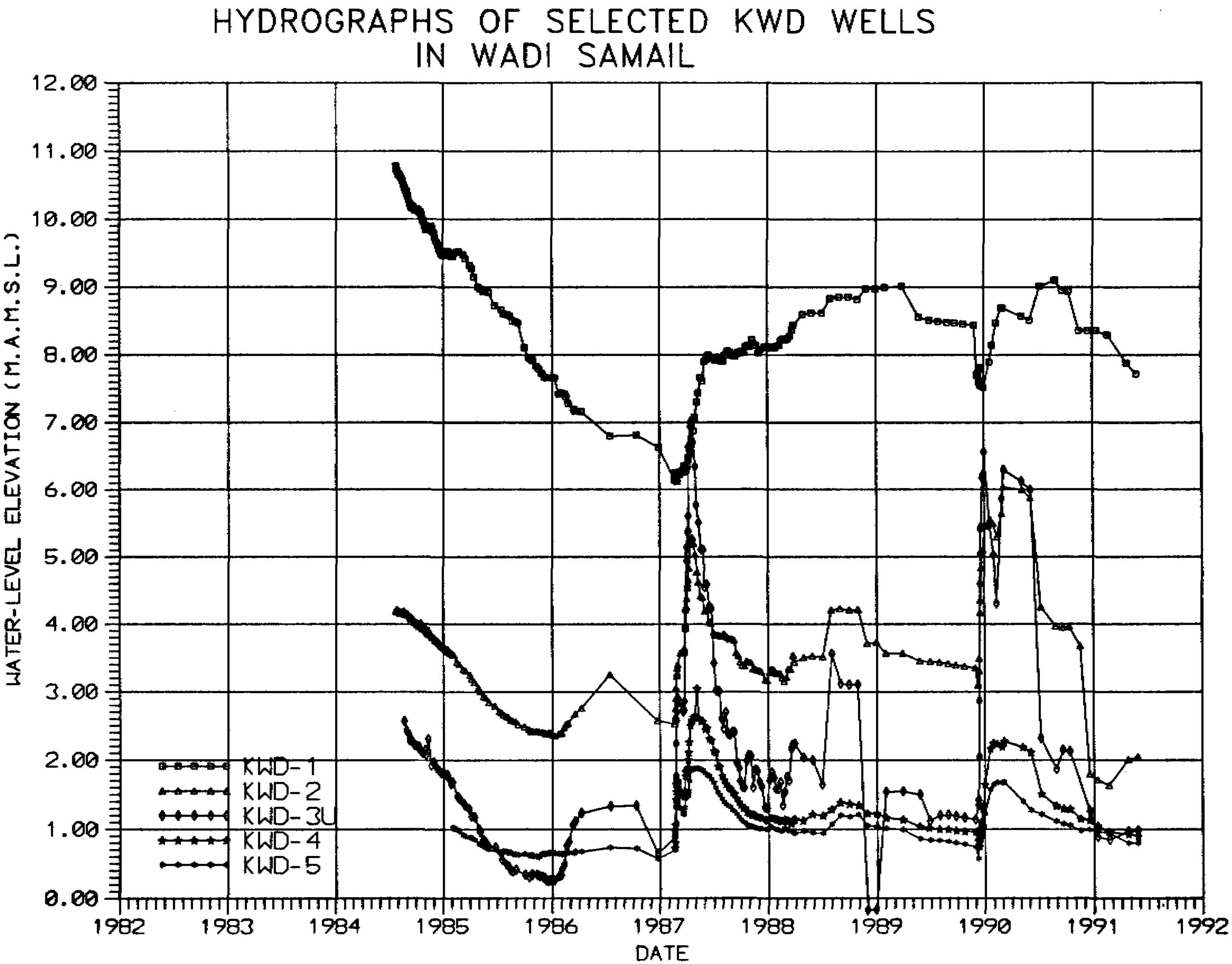
Figure 4-13



CROSS SECTIONS WADI SAMAIL AREA
AFTER BHATNAGAR AND RAVENSCROFT, 1986

NOT TO SCALE

Figure 4-14



HYDROGRAPHS OF SELECTED KWD WELLS
IN WADI SAMAIL
WATER-LEVEL ELEVATION (M.A.M.S.L.)
12.00
11.00
10.00
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
DATE
KWD-1
KWD-2
KWD-3U
KWD-4
KWD-5

Figure 4-15

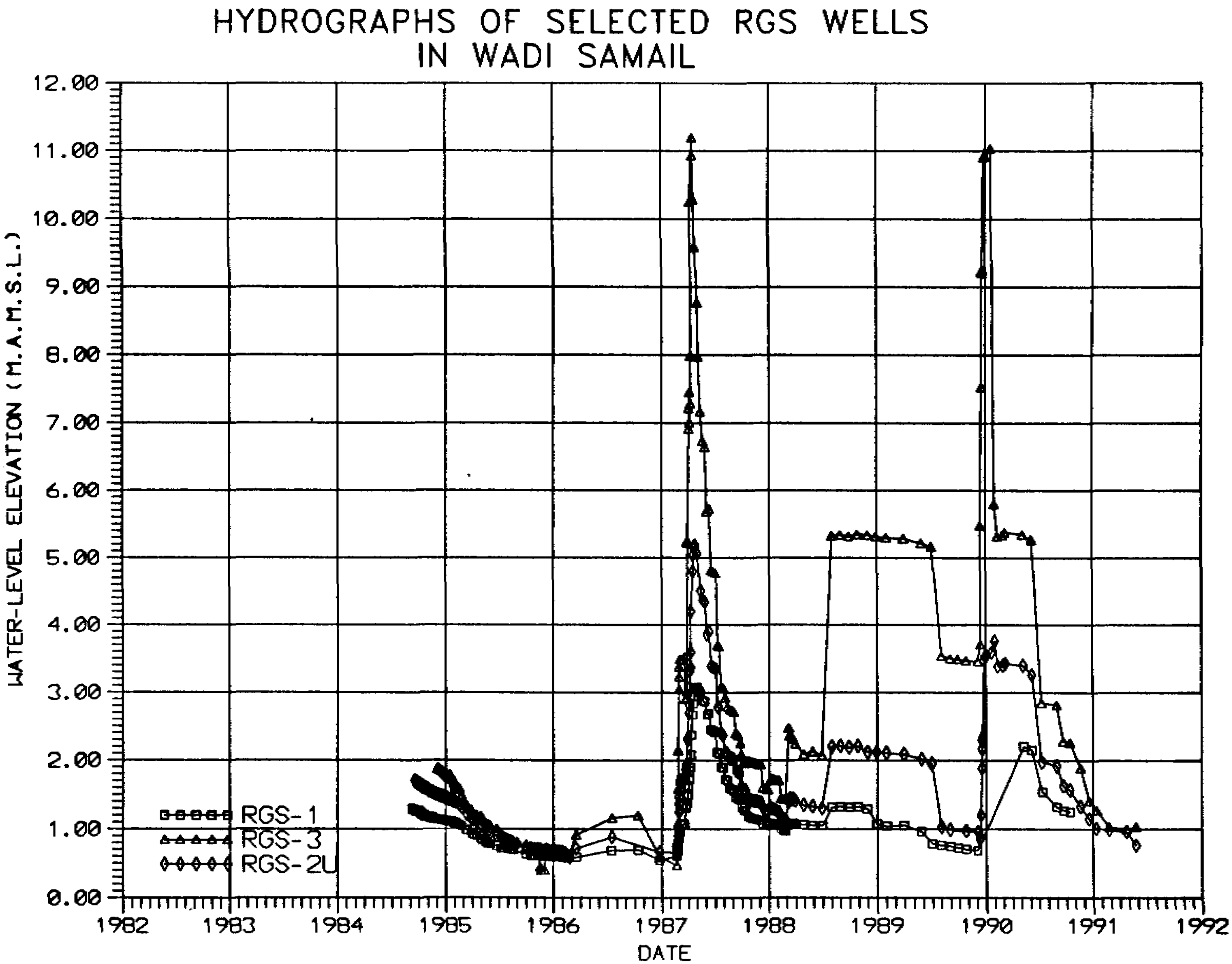
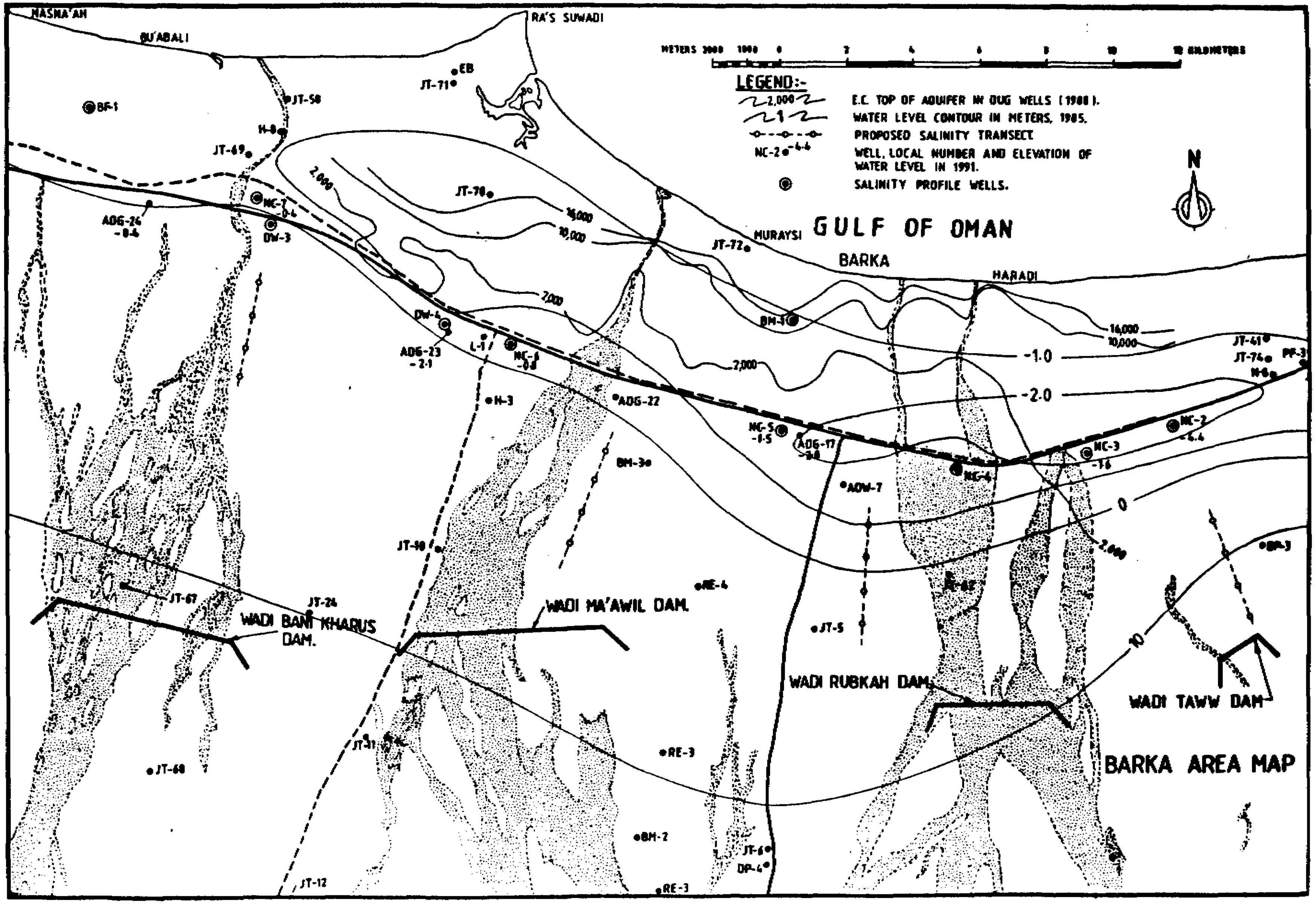
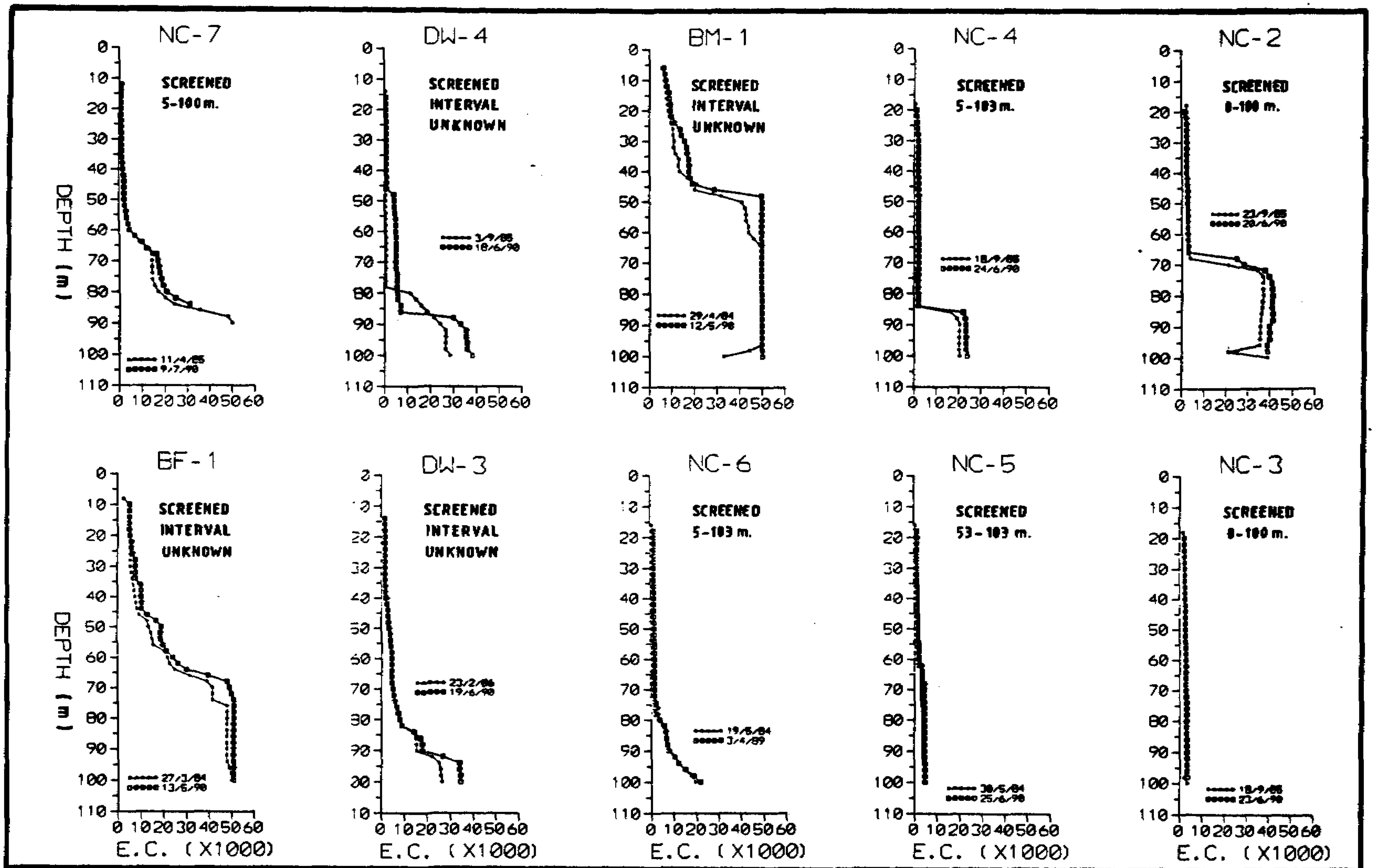

HYDROGRAPHS OF SELECTED RGS WELLS
IN WADI SAMAIL
WATER-LEVEL ELEVATION (M.A.M.S.L.)
12.00
11.00
10.00
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
DATE
RGS-1
RGS-3
RGS-2U

Figure 4-16



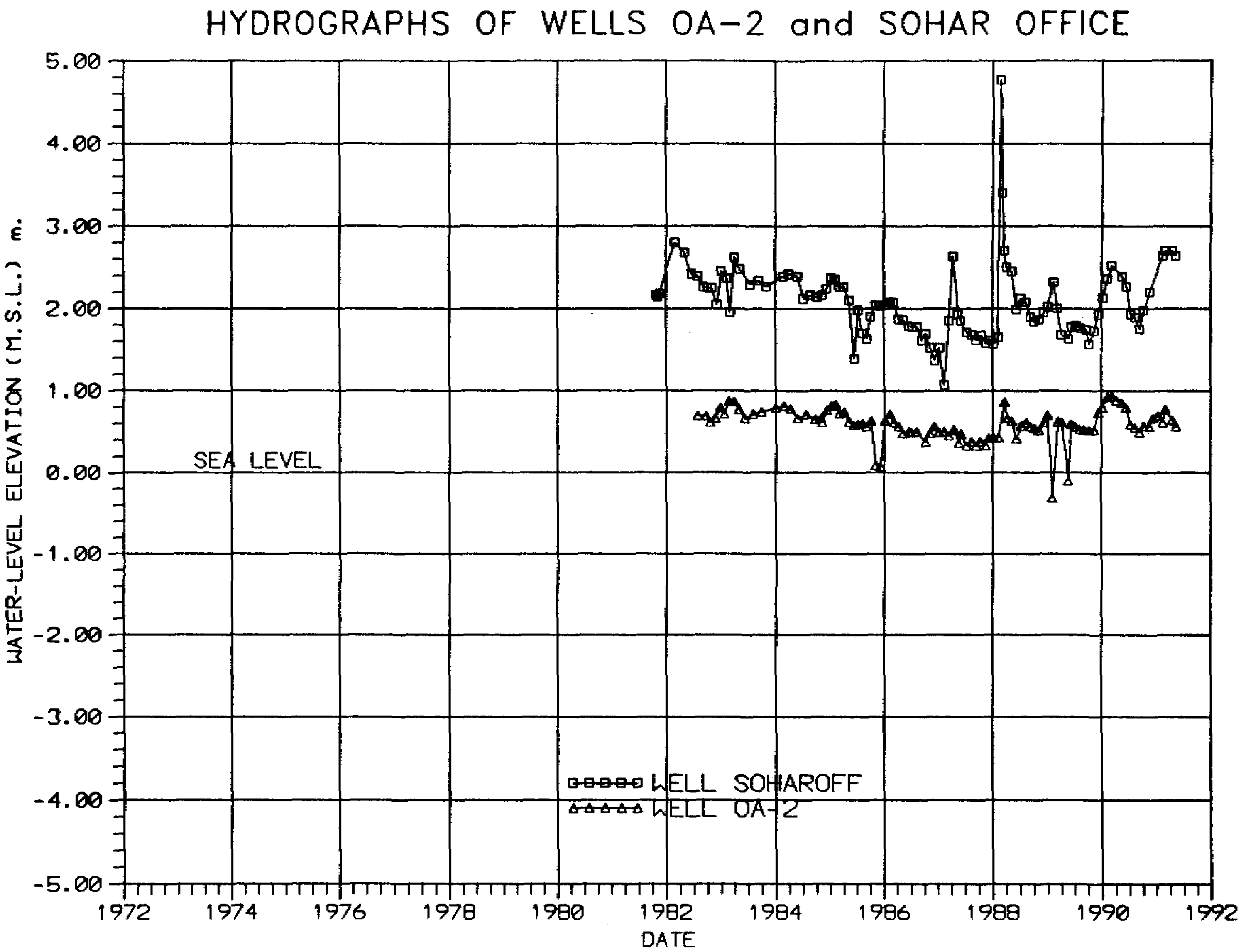
RA'S SUWADI
LEGEND:-
E.C. TOP OF AQUIFER IN DUG WELLS (1980).
WATER LEVEL CONTOUR IN METERS, 1985.
PROPOSED SALINITY TRANSECT.
WELL, LOCAL NUMBER AND ELEVATION OF WATER LEVEL IN 1991.
SALINITY PROFILE WELLS.
N
GULF OF OMAN
MURAYSI
BARKA
HARADI
WADI BANI KHARUS DAM.
WADI MA'AWIL DAM.
WADI RUBKAH DAM
WADI TAWW DAM
BARKA AREA MAP

Figure 4-17



SALINITY PROFILES IN THE BARKA AREA

Figure 4-18



HYDROGRAPHS OF WELLS OA-2 and SOHAR OFFICE
WATER-LEVEL ELEVATION (M.S.L.) m.
5.00
4.00
3.00
2.00
1.00
0.00
-1.00
-2.00
-3.00
-4.00
-5.00
SEA LEVEL
WELL SOHAROFF
WELL OA-2
1972
1974
1976
1978
1980
1982
1984
1986
1988
1990
1992
DATE

Figure 4-19

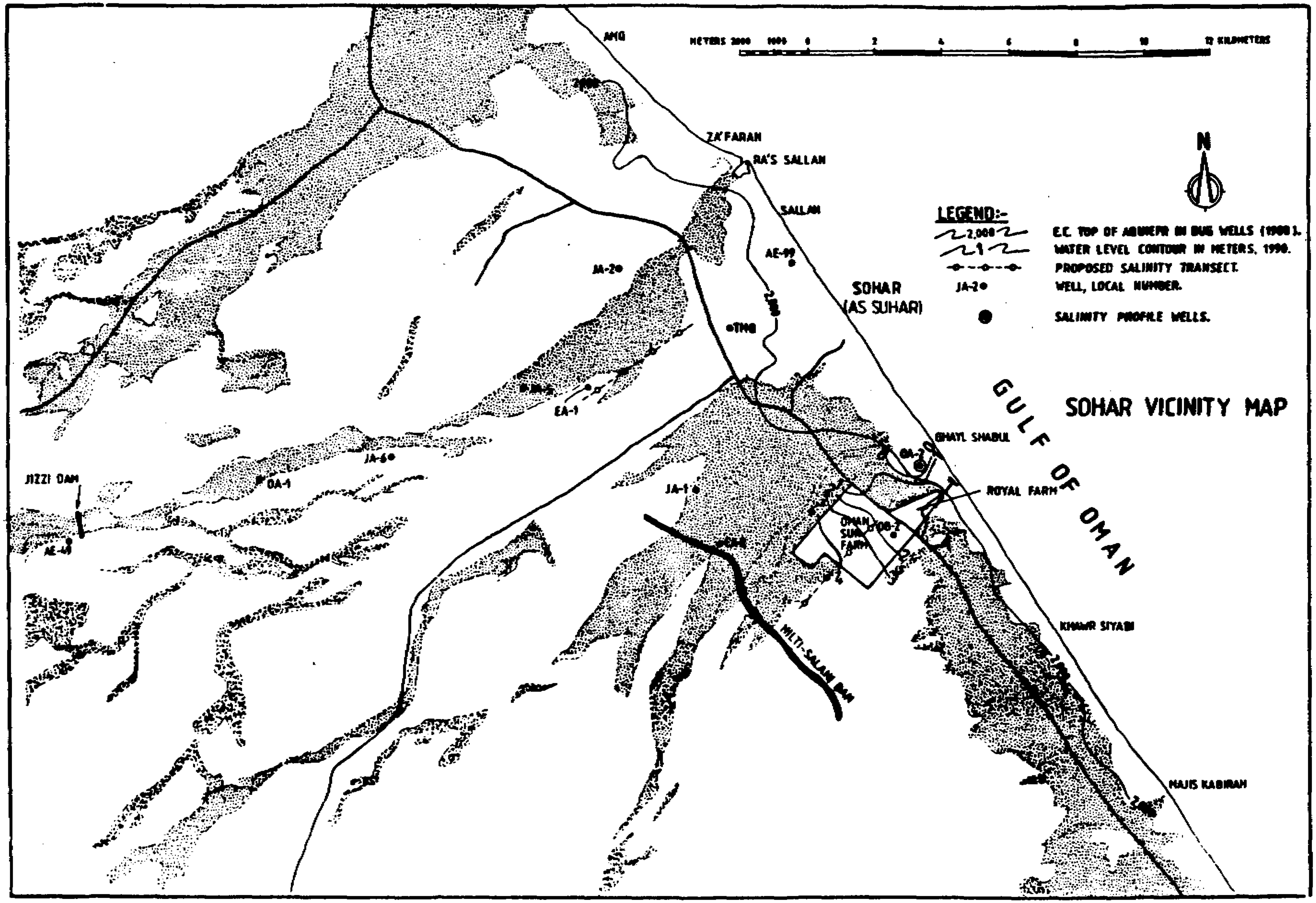

METERS 2000 1000 0 2 4 6 8 10 12 KILOMETERS
N
Z'AFARAN
RA'S SALLAN
SALLAN
LEGEND:-
2,000
E.C. TOP OF
WATER LEVEL CONTOUR IN METERS,
PROPOSED SALINITY TRANSECT.
JA-2
WELL, LOCAL NUMBER.
SALINITY PROFILE WELLS.
SOHAR
(AS SUHAR)
GULF OF OMAN
SOHAR VICINITY MAP
JA-2
AE-99
TMG
EA-1
JA-6
OA-4
JIZZI DAM
AE-48
JA-1
GHAYL SHABUL
ROYAL FARM
MILTI-SALAM DAM
KHAWR SIYABI
MAJIS KABIRAH

Figure 4-20

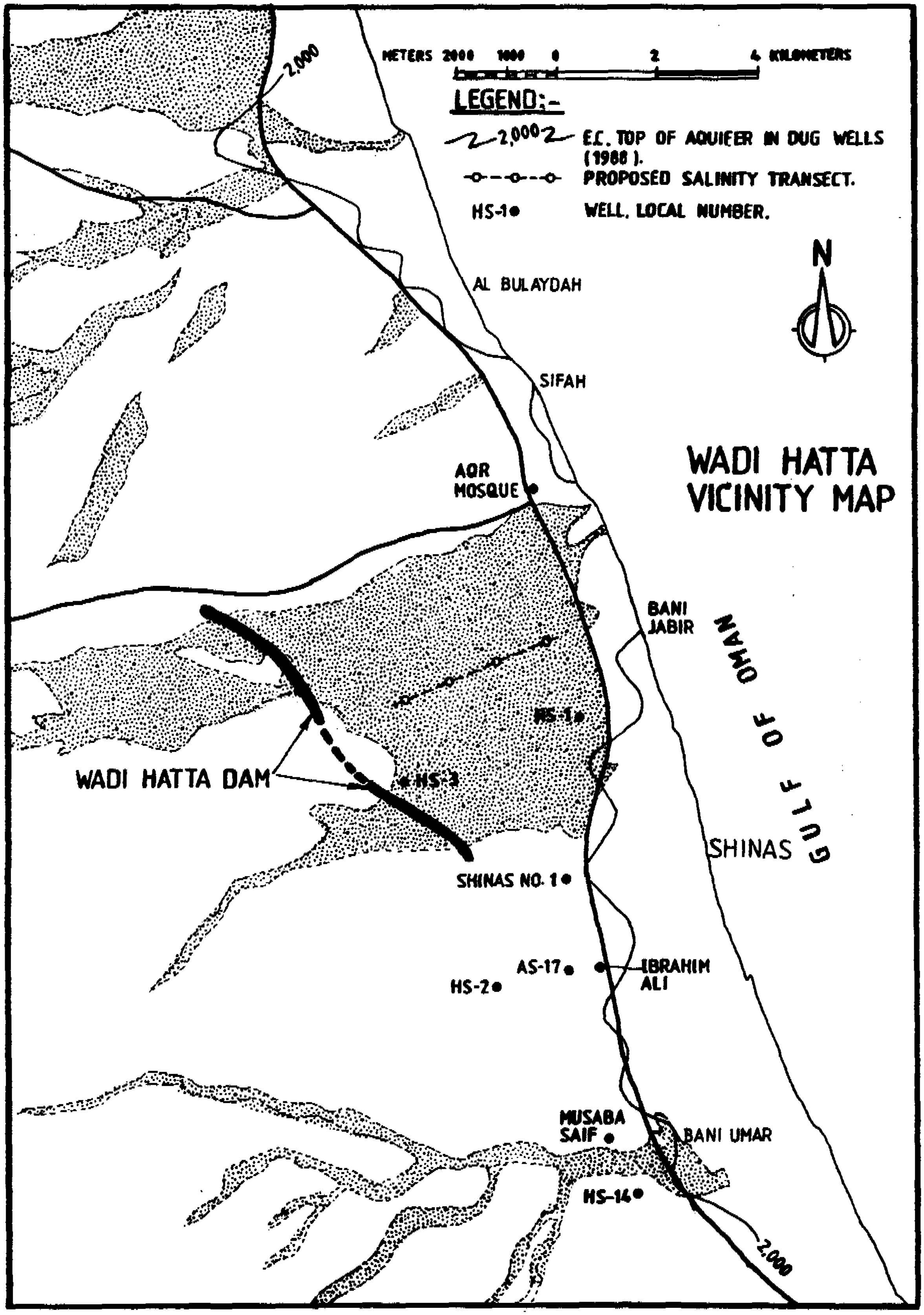

METERS 2000 1000 0 2 4 KILOMETERS
LEGEND:-
2,000 E.C. TOP OF AQUIFER IN DUG WELLS (1988).
PROPOSED SALINITY TRANSECT.
HS-1 WELL, LOCAL NUMBER.
N
WADI HATTA VICINITY MAP
2,000
AL BULAYDAH
SIFAH
AQR MOSQUE
BANI JABIR
GULF OF OMAN
HS-1
WADI HATTA DAM
HS-3
SHINAS
SHINAS NO. 1
AS-17
IBRAHIM ALI
HS-2
MUSABA SAIF
BANI UMAR
HS-14
2,000

Figure 4-21

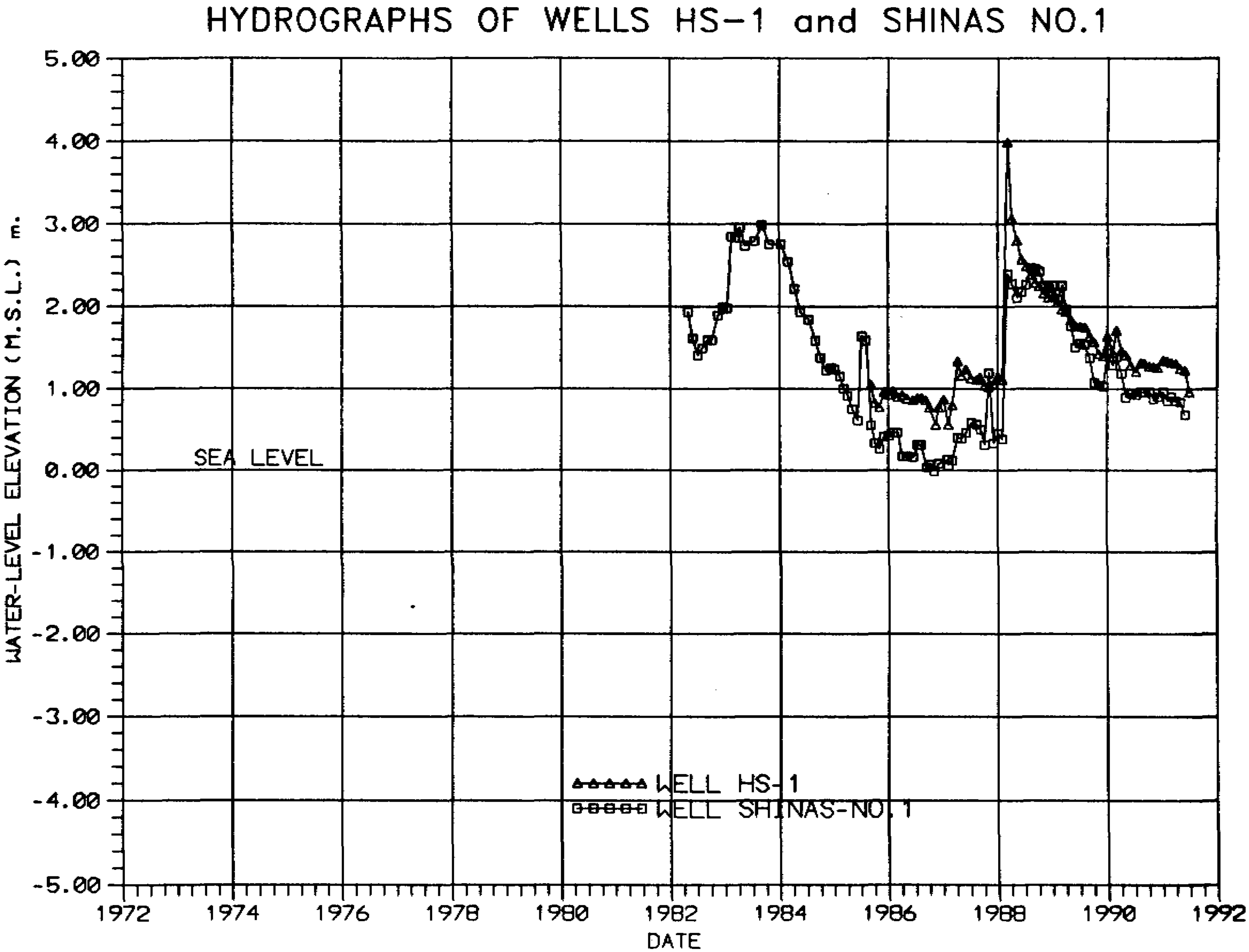
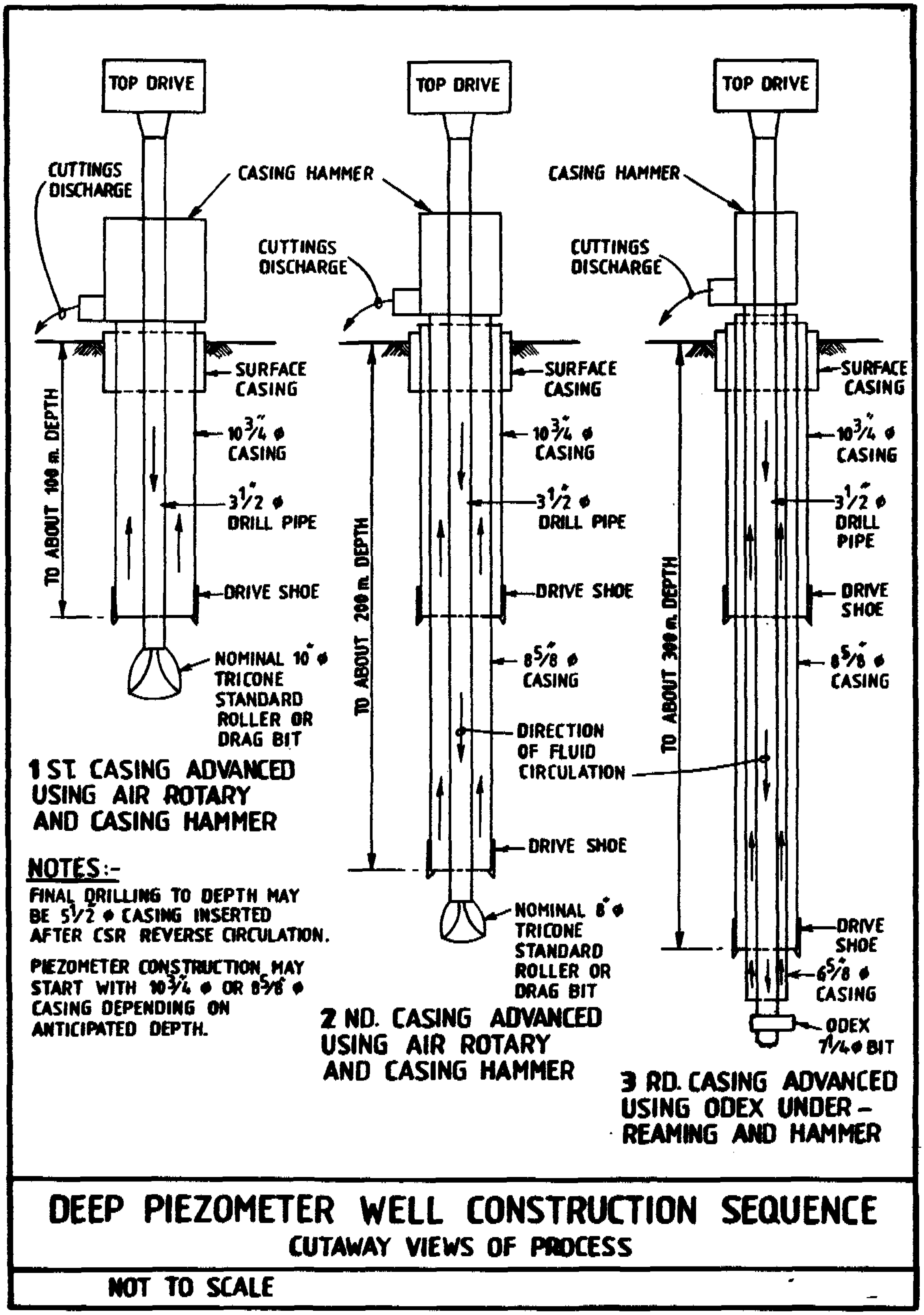
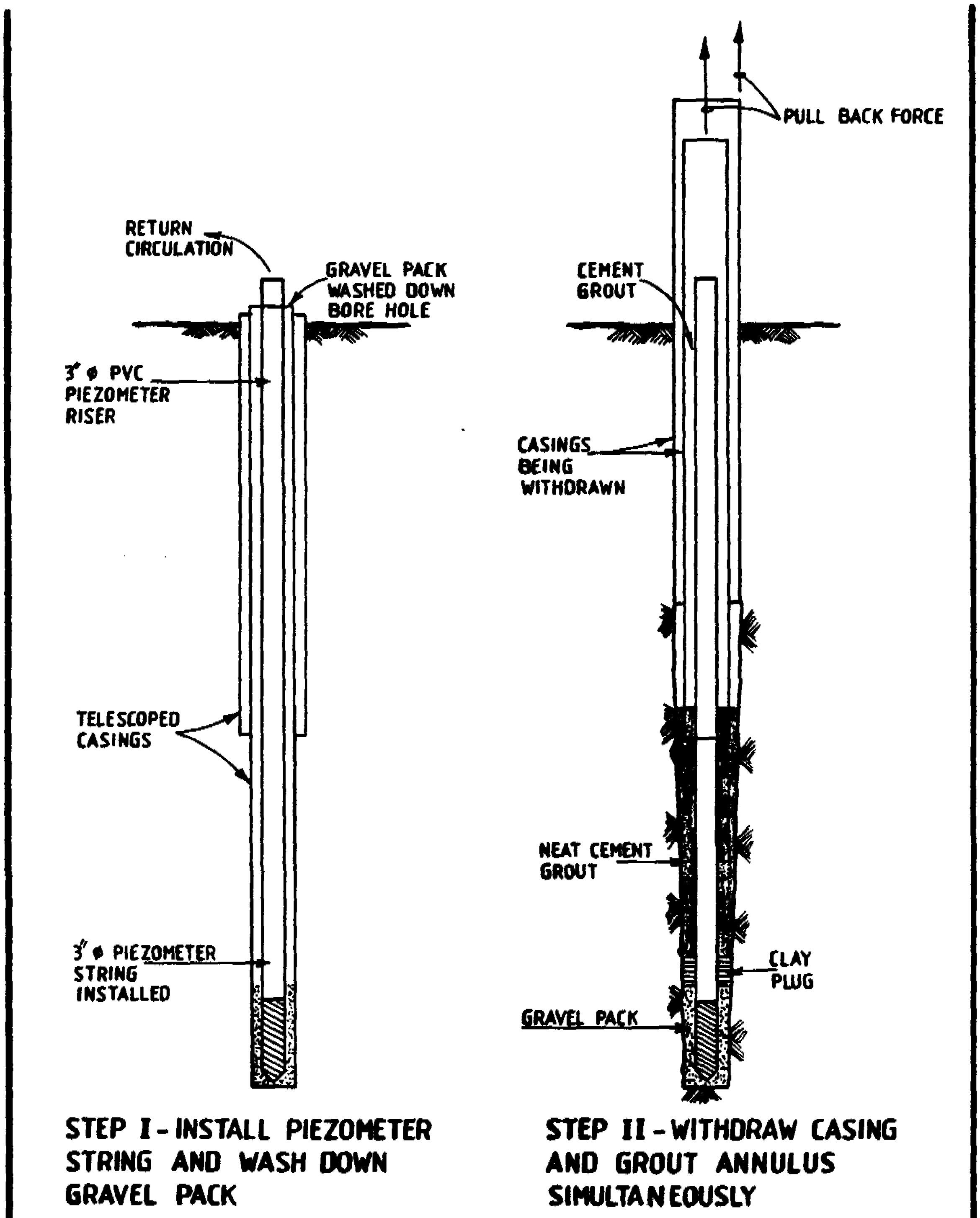

HYDROGRAPHS OF WELLS HS-1 and SHINAS NO.1
WATER-LEVEL ELEVATION (M.S.L.) m.
5.00
4.00
3.00
2.00
1.00
0.00
-1.00
-2.00
-3.00
-4.00
-5.00
SEA LEVEL
WELL HS-1
WELL SHINAS-NO.1
1972
1974
1976
1978
1980
1982
1984
1986
1988
1990
1992
DATE

Figure 4-22



TOP DRIVE
CUTTINGS DISCHARGE
CASING HAMMER
SURFACE CASING
10 3/4" ⌀ CASING
3 1/2" ⌀ DRILL PIPE
DRIVE SHOE
TO ABOUT 100 m. DEPTH
NOMINAL 10" ⌀ TRICONE STANDARD ROLLER OR DRAG BIT
1 ST. CASING ADVANCED USING AIR ROTARY AND CASING HAMMER
NOTES:-
FINAL DRILLING TO DEPTH MAY BE 5 1/2 ⌀ CASING INSERTED AFTER CSR REVERSE CIRCULATION.
PIEZOMETER CONSTRUCTION MAY START WITH 10 3/4 ⌀ OR 8 5/8 ⌀ CASING DEPENDING ON ANTICIPATED DEPTH.
TOP DRIVE
CASING HAMMER
CUTTINGS DISCHARGE
SURFACE CASING
10 3/4" ⌀ CASING
3 1/2" ⌀ DRILL PIPE
DRIVE SHOE
8 5/8" ⌀ CASING
TO ABOUT 200 m. DEPTH
DIRECTION OF FLUID CIRCULATION
DRIVE SHOE
NOMINAL 8" ⌀ TRICONE STANDARD ROLLER OR DRAG BIT
2 ND. CASING ADVANCED USING AIR ROTARY AND CASING HAMMER
TOP DRIVE
CASING HAMMER
CUTTINGS DISCHARGE
SURFACE CASING
10 3/4" ⌀ CASING
3 1/2" ⌀ DRILL PIPE
DRIVE SHOE
8 5/8" ⌀ CASING
TO ABOUT 300 m. DEPTH
DRIVE SHOE
6 5/8" ⌀ CASING
ODEX 7 1/4 ⌀ BIT
3 RD. CASING ADVANCED USING ODEX UNDER-REAMING AND HAMMER
DEEP PIEZOMETER WELL CONSTRUCTION SEQUENCE
CUTAWAY VIEWS OF PROCESS
NOT TO SCALE

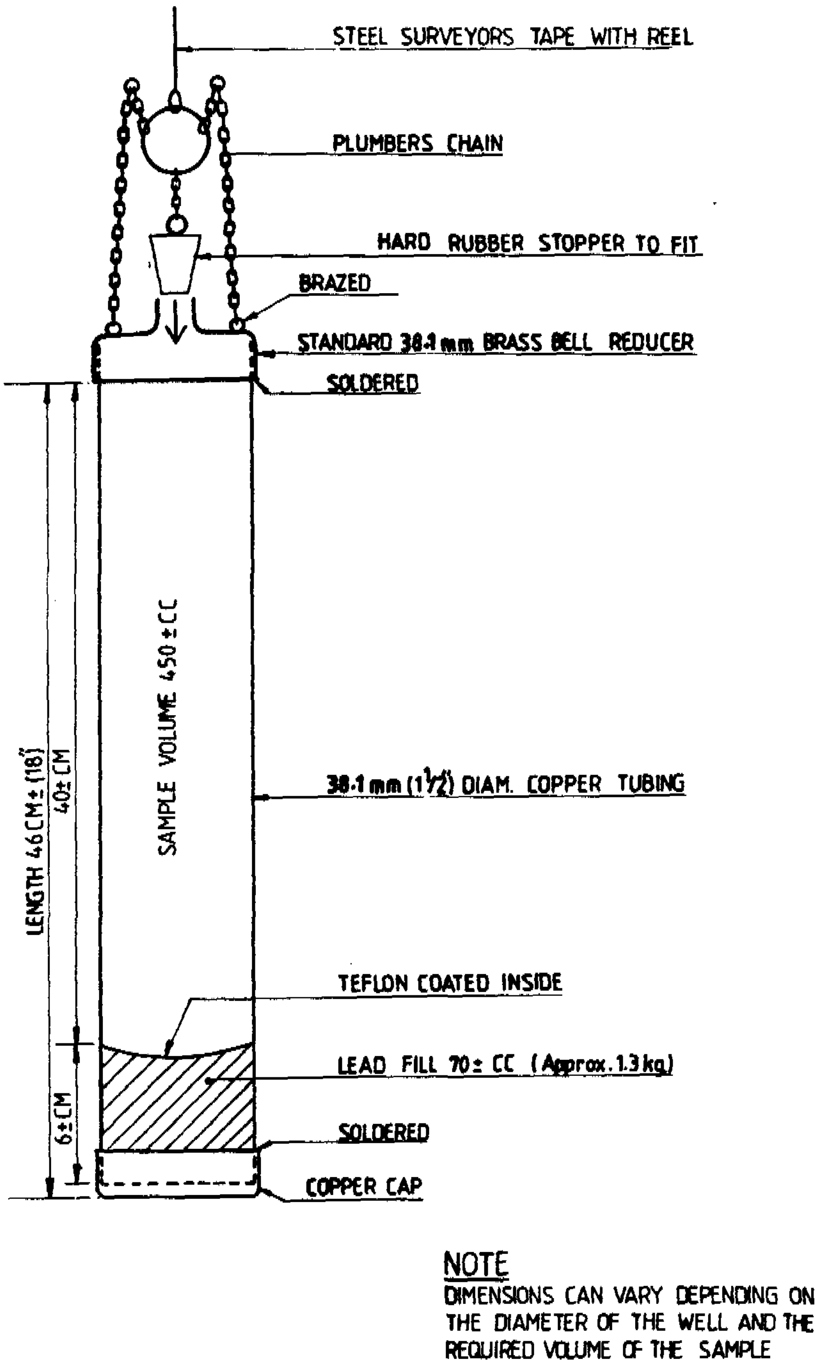
Figure 4-23



DEEP PIEZOMETER COMPLETION SEQUENCE

NOT TO SCALE

Figure 4-24



SIMPLE WELL WATER SAMPLER
(SHOP DRAWING)

NOT TO SCALE

Figure 4-25

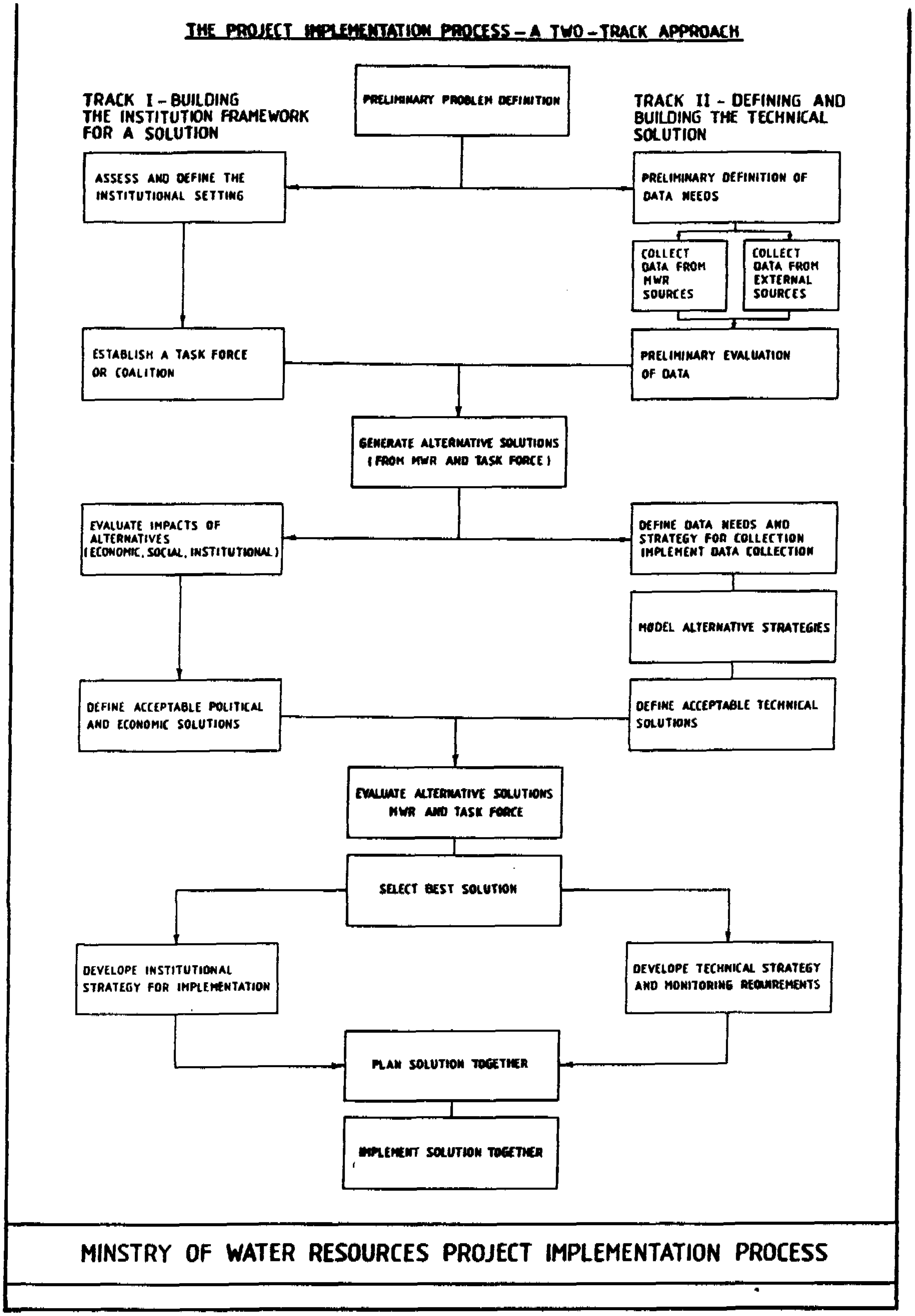
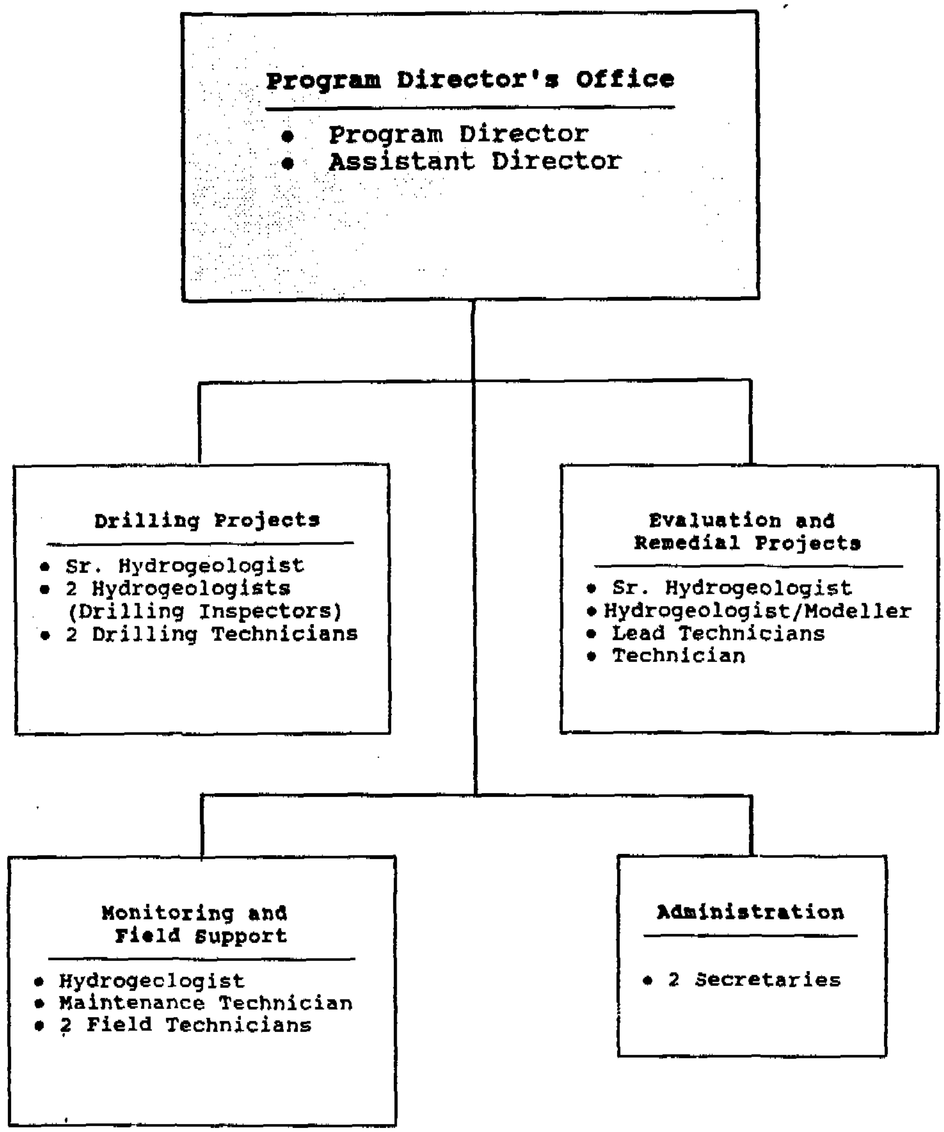

THE PROJECT IMPLEMENTATION PROCESS – A TWO-TRACK APPROACH
TRACK I – BUILDING THE INSTITUTION FRAMEWORK FOR A SOLUTION
PRELIMINARY PROBLEM DEFINITION
TRACK II – DEFINING AND BUILDING THE TECHNICAL SOLUTION
ASSESS AND DEFINE THE INSTITUTIONAL SETTING
PRELIMINARY DEFINITION OF DATA NEEDS
COLLECT DATA FROM MWR SOURCES
COLLECT DATA FROM EXTERNAL SOURCES
ESTABLISH A TASK FORCE OR COALITION
PRELIMINARY EVALUATION OF DATA
GENERATE ALTERNATIVE SOLUTIONS (FROM MWR AND TASK FORCE)
EVALUATE IMPACTS OF ALTERNATIVES (ECONOMIC, SOCIAL, INSTITUTIONAL)
DEFINE DATA NEEDS AND STRATEGY FOR COLLECTION IMPLEMENT DATA COLLECTION
MODEL ALTERNATIVE STRATEGIES
DEFINE ACCEPTABLE POLITICAL AND ECONOMIC SOLUTIONS
DEFINE ACCEPTABLE TECHNICAL SOLUTIONS
EVALUATE ALTERNATIVE SOLUTIONS MWR AND TASK FORCE
SELECT BEST SOLUTION
DEVELOPE INSTITUTIONAL STRATEGY FOR IMPLEMENTATION
DEVELOPE TECHNICAL STRATEGY AND MONITORING REQUIREMENTS
PLAN SOLUTION TOGETHER
IMPLEMENT SOLUTION TOGETHER
MINSTRY OF WATER RESOURCES PROJECT IMPLEMENTATION PROCESS

Figure 4-26



PROPOSED STRUCTURE OF SALT WATER INTRUSION PROGRAM

NOT TO SCALE

Figure 4-27

Illustrative Schedule for Program Implementation

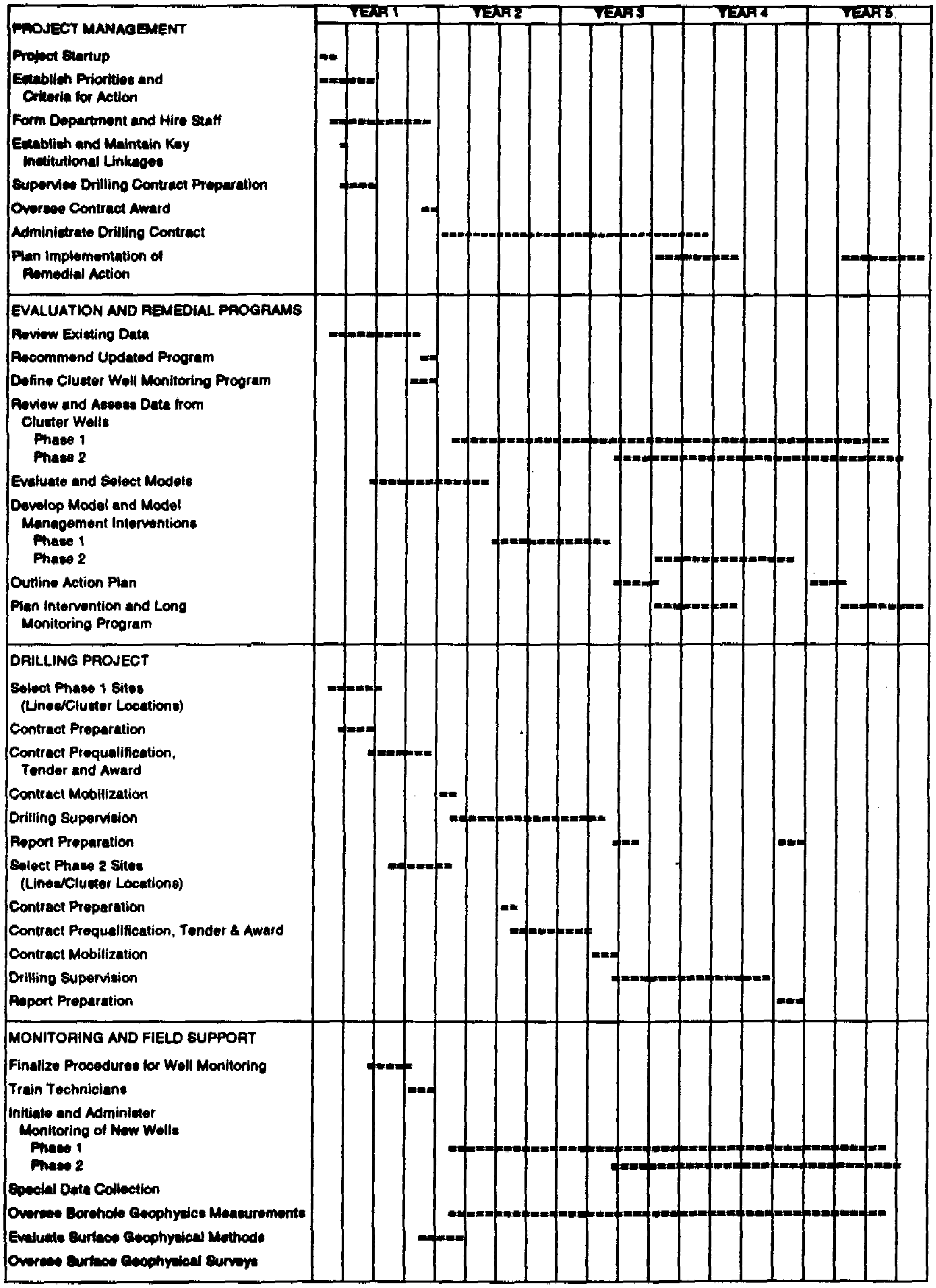


Table 4-1

Change in Size of Areas Affected by Seawater Intrusion in Shallow Wells
in the Eastern Batinah (Wadi Manumah to Suwayz) 1982/3 to 1988.

Salinity expressed in terms of electric conductivity (EC)

Locality	Increase in area (sq km) >16K µmhos	Equivalent move inland (m)	Increase in area(sq km) >10K µmhos	Equivalent move inland (m)	Increase in area(sq km) >6K µmhos	Equivalent move inland (m)
Manumah	3.4	680	1.4	280	1.95	390
Rumais	4.7	465	4.9	485	3.5	347
Barka	4.5	429	3.5	333	1.75	167
Suwadi	10.48	974	1.885	175	0.085	8
Bani Kharus	9.18	900	3.215	315	2.08	204
Masna'ah/Wudam	2.741	253	.27	25	(-3.19)	(-297)
Al Bid'ah	(-1.445)	(-135)	1.68	157	1.44	135
Suwayq	0.01	2.4	.555	1.32	0.7	166
Total	33.545	465	17.405	241	8.315	115

Source: written communication from Geofrey Wright Seeb office to H.E. Deputy Chairman PAWR
May 28, 1989

Table 4-2

Projected Cost Schedule for Salt Water Intrusion Program

	Number of Units	Unit Cost (R.O.)	Annual Cost (R.O.)	Extended 5-Year Cost (R.O.)
LABOR				
Project Director	1	48,000	48,000	240,000
Assist.Director	1	14,000	14,000	70,000
Sr. Hydrogeologist				
Drilling supervision	1	38,000	38,000	190,000
Saline intrusion	1	38,000	38,000	190,000
Hydrogeologist				
Hydrogeologist (Drilling Inspectors)	2	35,000	70,000	350,000
Field monitoring	1	35,000	35,000	175,000
Modelling	1	35,000	35,000	175,000
Sr. Technician				
Drilling	2	30,000	60,000	300,000
Modelling	1	12,000	12,000	60,000
Instrumentation	1	12,000	12,000	60,000
Technicians	3	6,000	18,000	90,000
Secretarial	2	5,000	10,000	50,000
Total Labor	17		390,000	1,950,000
EQUIPMENT				
Vehicles (4x4)	5	15,000	75,000	75,000
Mobile Data Aquisition				
Vehicles	3	35,000	105,000	105,000
Basic outfitting	2	35,000	70,000	70,000
Basic+Borehole logging	1	20,000	20,000	20,000
Data aquisition	LS	75,000	75,000	75,000
Misc. field equipment	LS	10,000	10,000	10,000
Office Furniture	LS	20,000	20,000	20,000
Computers and peripherals	LS	15,000	15,000	15,000
Total Equipment			390,000	390,000
CONTRACTS				
Drilling Contract Prep.	1	10,000	10,000	10,000
Drilling Contract	2	750,000	1,500,000	1,500,000
Geophysical Surveys	as needed	15,000	15,000	15,000
Total Contracts			1,525,000	1,525,000
Subtotal				3,865,000
Contingency (20%)				773,000
TOTAL PROJECT COST				4,638,000