FIELD REPORT

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

TASK 5: WATER MANAGEMENT
TASK 6: TECHNOLOGY DEVELOPMENT

ALTERNATIVE WELL TECHNOLOGIES FOR USE IN SALINE GROUNDWATER SYSTEMS
Part 5

WASH Field Report No. 353
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WATER AND SANITATION for HEALTH PROJECT

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Part 5

ALTERNATIVE WELL TECHNOLOGIES FOR USE IN SALINE GROUNDWATER SYSTEMS

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 upcoming 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 upcoming 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 upcoming and sea water intrusion, whereas low-drawdown wells can extract a similar amount of water without inducing salt upcoming. 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. The use of alternative well technologies for skimming fresher water from saline aquifers cannot be thought of as a remedy for regional intrusion induced by excessive abstraction. The best remedy to regional groundwater salinization due to over-use of groundwater is, simply, to reduce water use. Such actions must receive higher priority.

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 discussed. 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 rapid intrusion of sea water into the coastal areas of Oman has led to the abandonment of many conventional wells. Intrusion frequently is the result of pumping more water than recharge of the aquifer can replace, and can be curtailed and reversed only by controlling pumping or increasing recharge. Apart from overdraft, groundwater salinization can be caused by localized drawdown around concentrated pumping centers. In these instances, there are several technologies to improve the capacities of wells to produce water of better quality.

Fresh water being lighter tends to float on salt water, creating a stratification of the water quality within aquifers. Because of this, all technologies that produce fresh water do so by skimming it from the upper part of the groundwater system. Some technologies skim more efficiently than others. In aquifers where the fresh water layer is relatively thin, highly efficient skimming technologies are needed. This paper describes several of these approaches, ranging from the use of many ordinary shallow wells to the use of sophisticated scavenger/production well couples. The applicability of a particular method depends on a combination of factors, including:

- Construction cost and economic feasibility
- The hydrodynamics of the "near well" or "near intake" zone as determined by the permeabilities of the aquifer and the applied pumping stress
- The availability of fresh water moving through the aquifer (i.e., the degree of development relative to safe yield)
- The expected variation in local water levels
- The thickness of fresh water overlying salt water and the relative qualities of the two
- The desired quantity and quality of discharge
- The general position of the skimming device within the regional flow system and with respect to the position of the salt water wedge
- The degree of technological complexity and the ability of local support services to maintain the equipment

A further consideration in the selection of a particular technology is the impact of various social, political, institutional, and administrative factors, and of geographic variations. A solution that works for one region or zone may not work elsewhere.

Some aspects of water management to which the skimming technologies discussed in this paper might be applied are:

- Localized coastal groundwater collection and distribution
- Rebuilding wellfields threatened by upcoming and intrusion
- Capture of rapid throughflow in buried wadi channels with underlying salt water wedges
- Protection of inland pumping centers threatened by advancing salt water intrusion wedges and consequent reduced depths to water of unacceptable quality
- Recovery of irrigation return flows

However, skimming technologies cannot be a substitute for the efficient management of the water resources of a region. Using them in a region where water has already been overdrawn makes little sense unless the approach somehow contributes to a larger regional solution. A desperate recourse to these technologies will do no more than temporarily postpone the abandonment of a particular farm or water source while the rapid advance of sea water continues on a regional scale.

Chapter 2

PURPOSE AND SCOPE

This paper identifies and evaluates technologies for extracting the maximum amount of fresh water from aquifers containing both fresh and saline water. It discusses:

- Horizontal Collection Galleries
- Radial Collection Wells
- Conventional Shallow Drawdown Wells (Wellfields)
- Scavenger/Production Well Couples (Scavenger Wells)

The scope of work included familiarization with the terrain and hydrogeology of Oman and a review of the literature on available technologies. The report includes a brief evaluation of the various kinds of galleries and wells, and a review of their applicability in the Oman setting.

Chapter 3

CONCLUSIONS AND SUMMARY

Several technologies for skimming fresh water from saline aquifers have potential applications in Oman.

- Galleries could be used in coastal areas where the depth of the installation is about 5 m to 6 m. Although the gallery concept is simple, the hydraulics are complex. A pilot test would be advisable to determine how useful this method might be.

- Galleries could be operated by farming cooperatives in areas where saline intrusion causes upconing in wells. An institutional framework is needed for the use of galleries and technical testing.

- Radial collection wells are expensive and must be located in zones with substantial recharge to be economical. They may be suitable in highly transmissive aquifers that have recently received recharge, provided they can be combined with water storage for later use.

- Multiple shallow-draft wellfields continue to be an attractive method for skimming fresh water and limiting drawdown. The costs of these are high compared with conventional large drawdown wells, but they can be constructed and tested incrementally and adapted to most hydrogeologic conditions. MWR should gain experience with them to assist others in replacing or relocating wellfields as salt water begins to intrude.

- Opportunities for the use of scavenger well couples already exist. The costs of removing and disposing of saline water effluents from them are high. Pilot testing by MWR would determine their economic feasibility.

- Drawdowns for skimming systems should not be carried below sea level. In areas where salt has intruded, the water level in wells is close to or below sea level. Low drawdown systems will be the first to fail if regional drawdowns continue without control.

- To be effective, low drawdown skimming systems usually require water storage, which must be considered a part of future implementation of these systems.

Chapter 4

HYDROGEOLOGIC SETTING AND BACKGROUND

The gross hydrogeologic setting in Oman is discussed in Part 2 of this report and additional background is provided in Part 4, which examines the larger question of salt water intrusion.

Although skimming technologies would be of use in many places in Oman where water is stratified by quality, the regions where they are most needed and most feasible are the Batinah coast and Salalah plain. The lateral intrusion on the Batinah coast will continue to advance, bringing further difficulties with water development.

In the near-coastal zone of the Batinah region, the water table slopes upward toward the northern Oman mountains at a very low gradient. The region has widespread shallow aquifers of uncemented sands and gravels. High-permeability zones with buried wadi channels often form "shoe-string" aquifers in these areas.

In some regions of the Batinah, the water table gradient is reversed and large areas within a few kilometers of the sea have water tables below sea level. The effects of intrusion can be most readily observed in a strip about 3 km wide running parallel to the coast. Here the water level in many dug wells is only a few meters below the ground and the water table is often at sea level.

Further inland along the Batinah, the ground slopes upward at a slightly sharper gradient than the unconfined groundwater table, so that at many points along the coastal highway the depth of well water exceeds 4 m to 5 m. In a few places there is a modest head of groundwater 1 m to 2 m above sea level.

In much of the coastal zone gravel aquifers continue toward the mountains, terminating on the rocks of the piedmont that forms the upper part of the Batinah plain. Typically, these rocks can be seen as outcrops at distances of 10 km to 30 km from the shoreline.

In areas near the coast, an intruded zone of diffusion (consisting of a mixture of sea water and fresh water) extends to the top of the water table. The diffuse boundary increases in depth in the inland direction, forming a wedge beneath the overlying fresh groundwater.

Skimming technologies are primarily applicable where the fresh water layer above the salt water wedge is sufficiently thin so that, when it is pumped, localized drawdowns around the well decrease the head in both fresh and salt water zones and cause the interface (zone of diffusion) to rise towards the pumping well intake. This process, referred to as "upconing," will always occur towards the well intake in the fresh water zone. The degree to which upconing occurs in a given aquifer system depends on the pumping rate. At relatively low pumping rates, the upconed interface will not intersect the well intake and will have no effect on pumped water quality. At higher rates, slightly salty water from the zone of diffusion will be drawn into the well. Beyond a critical rate, the upconed surface will rise sufficiently to cause sea water to enter the well.

Chapter 5

SKIMMING TECHNOLOGIES AND THEIR APPLICATIONS

Four types of skimming technologies can be used where upconing is prevalent. Three of them reduce upconing by avoiding the localized drawdowns caused by individual pumping wells. They do this by distributing the pumping over a relatively large area. The fourth—the scavenger/production well couple—allows upconing to occur but captures the saltier water entering the bottom of the well and pumps it to waste. The technologies are described below.

5.1 Horizontal Collection Galleries

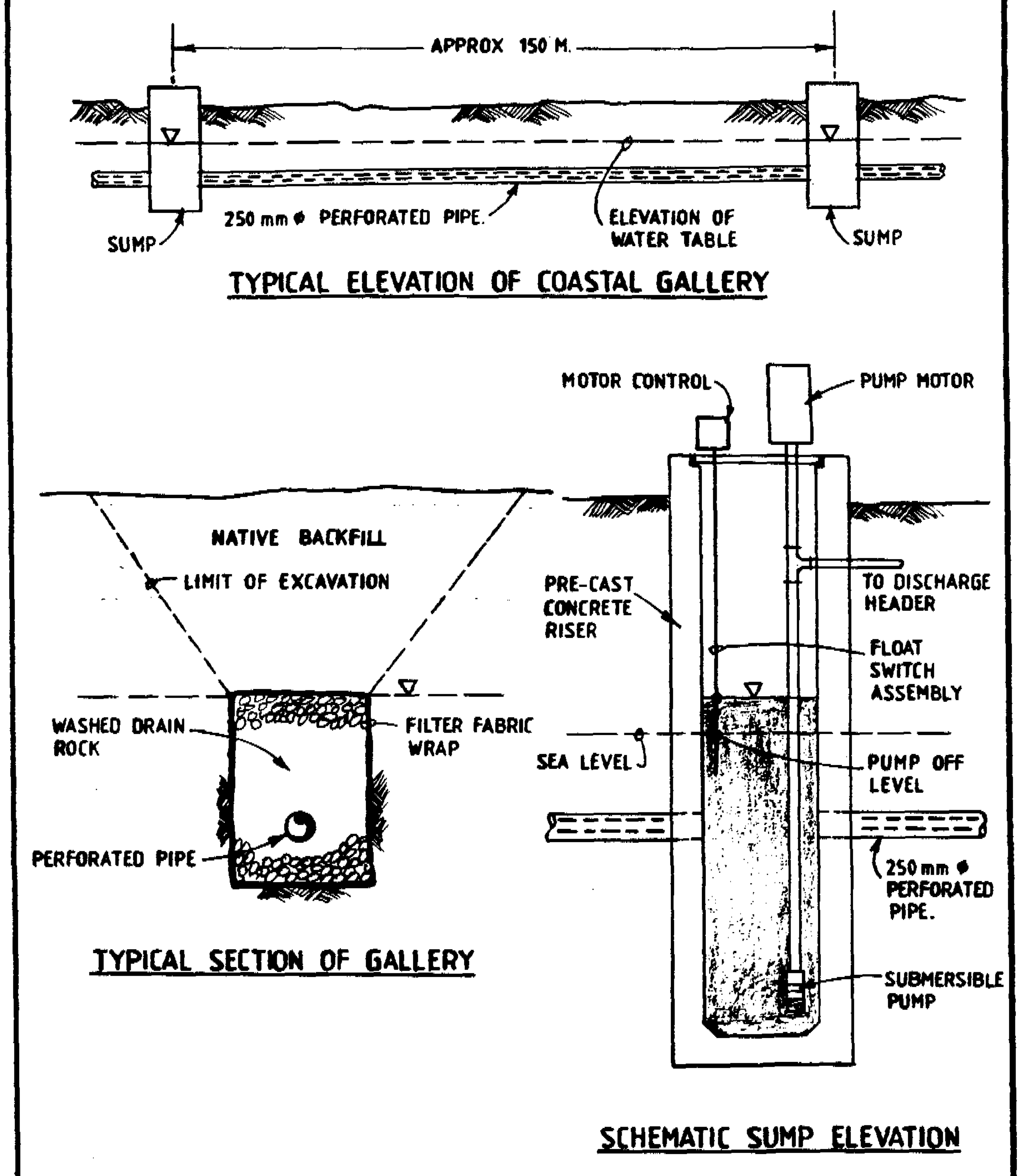
Horizontal collection galleries have been in use for thousands of years. Historically, they were constructed by tunneling. Today, however, the costs of tunneling are quite high and most galleries are excavated from the surface. Galleries rely on horizontal perforated pipes that collect groundwater by gravity flow and convey it to sumps located at intervals along the axis of the collection pipes.

A typical coastal gallery skimmer is illustrated in Figure 5-1. It consists of a blanket of washed coarse rock surrounded by a filter fabric membrane. The drain rock consists of rounded wadi gravels ranging from about 15 mm to 50 mm from which all fines have been removed by screening and washing. The membrane prevents fines from entering the gallery system. During construction, the fabric is introduced immediately after the trench is excavated and the drain rock is placed in it. After the collection pipe is installed on a controlled grade, the fabric is wrapped over the gravel pack and the gallery is backfilled. Because of the high permeability of near-coastal aquifers in Oman, most of the installation would have to be done in water-filled trenches. Dewatering the trenches during construction would be very difficult and expensive. Galleries of this nature could conceivably be built parallel to the coast to collect some of the upper fresh water that discharges to the sea.

The sumps are concrete-lined pits into which the collection pipes discharge, placed at intervals that depend upon the amount of water to be discharged and the diameter of the pipes. A 205 mm-diameter collection pipe would require a sump spacing of 100 m or more in typical applications. Suction or submersible pumps would be mounted in the sumps, and water levels could be regulated by float-level switching equipment or pumps that match the yield of the gallery.

At least three variables affect the depth at which the pipe interceptor should be installed. First, the difficulty and costs of construction go up very rapidly as the depth increases. Second, if the collection pipe is too deep, the header may collect water of high salt content since flow from deeper and saltier parts of the aquifer would have a direct route into the

Figure 5-1



DETAILS OF COASTAL GALLERY SKIMMER

NOT TO SCALE

collection pipe. Third, the collection header and trench collector will be more efficient if the drain-rock filled portion of the trench intercepts a significant portion of the layer of fresh water. If the drainage trench is exposed to a greater thickness of the aquifer, the "specific capacity" or yield of the sumps per centimeter of drawdown will be much higher than in a shallow trench exposed to only a thin portion of the aquifer. These factors need to be carefully balanced to find the optimal design.

The gallery system can skim large quantities of water with very small drawdowns. Trench depth limitations imposed by the construction process restrict gallery positions to within 1 km of the coast in Oman. In these positions, the galleries would be required to operate within a very narrow drawdown range running from the original phreatic surface down to slightly above sea level. In the near-coast region this range may be only a few centimeters. Thus, there is a benefit in producing a system with a high specific capacity.

Typically, sumps need to be placed well below the water table to provide sufficient water storage to protect the pumping equipment and to provide equalization. The sumps can be constructed of precast sewer manhole risers placed in a water-filled pit and backfilled without attempting to dewater the excavation.

Costs and Economic Considerations

The capital costs of galleries depend on the following factors:

- Depth of the collection trench
- Depth below water of the collection pipe
- Type of material being excavated
- Haul distance to sources of drain rock
- Presence of heaving sands

Because of limitations on the reach of excavating equipment and the extreme difficulty of excavating below the water table in sands and loose gravels, infiltration galleries cannot be placed deeper than about 7 m to 8 m below the surface. Costs go up rapidly as depth increases much beyond 5 m to 6 m, which should be considered the operational limit.

Large quantities of drain rock must usually be imported to improve the hydraulic efficiency of the ditch in collecting and conveying water to the sumps. The rock provides a low permeability route for water and ensures that the ditch will capture the intercepted groundwater flow. The cost of this gravel will depend on the distance to quarrying sites where wadi gravels can be screened and washed.

The typical installation would have a trenching depth of 5.6 m and work would continue to a depth 2 m below the water table. The collection pipe would be installed at about 5.2 m below the surface. These dimensions are appropriate for near-coast galleries.

A construction cost analysis (Table 5-1) indicates that a simple ditch and gallery collector without discharge pipes or pumps would cost on the order of R.O. 100 per m when sumps are placed every 150 m along the gallery. If the collection trench were deepened to a depth of 6.6 m, costs would quickly rise to over R.O. 200 per running meter. Water transmission pipes, pumps, electrical power distribution, land acquisition, access roads, and water storage facilities could easily add another R.O. 50 to R.O. 100 per meter. Assuming a 30-year life, about R.O. 7,000 to R.O. 10,000 would be spent each year to maintain and operate each kilometer of the system.

5.2 Radial Collection Wells

A modification of the collection gallery principle was introduced by Ranney in 1933. The radial collection well is essentially an array of horizontal collection galleries emanating from a central caisson. The first such system was installed at London, England in the same year. Since its introduction hundreds of the wells have been installed around the world.

Radial collection wells can be installed at significant depths below the water table. In areas where saline water underlies a zone of fresh water, they will distribute drawdown over a large area to produce large yields without causing upconing. They need penetrate only a few meters into the saturated part of the formation.

The design of a typical radial collection well is shown in Figure 5-2. A concrete caisson is lowered into the ground by excavating the earth under the caisson from within, usually with a specialized clamshell bucket. Once the caisson is below the water table, the bottom is sealed with concrete and the water is pumped out of it.

The radial collection pipes, or laterals, are generally made of stainless steel slotted screens terminating in well points, and are jacked from the inside of the caisson into the water-bearing formation. The system must be strong enough to withstand axial loading from the jacking process. In many applications the wells are used to induce infiltration through sand deposits under or near surface water bodies. In the near-coastal zone in Oman's Batinah coast, the system could be completed in water-bearing sands and radial collection pipes could be pushed and washed into the formation. Under optimal conditions, laterals can be installed to distances of 80 m.

Table 5-1

Cost Estimate for Coastal Gallery Construction

ASSUMPTIONS

Total depth of gallery trench = 5.6 meters. Trench is terminated 2 meters below water table. 8" (250 mm) diameter slotted C-900 PVC is to be used for the collection header. Sumps at 150 meter intervals.

PRODUCTION RATE:

30 meters per 10 hour day for trench. One sump per work week.

CREW REQUIREMENTS	Qty.	Unit Rate (R.O.)	Day Rate (R.O.)	Total (R.O.)
Crew Chief	1	65	65	
Heavy Equipment Operators	3	55	165	
Pipe layers/labor	2	40	80	
Carpenters/steel tiers	2	50	100	
Carpenter Assist./labor	2	40	80	
			Sub-Total	490

EQUIPMENT REQUIREMENTS	Day Rate (R.O.)	Total (R.O.)
Truck crawler backhoe, 1 1/2 CM capacity	475	
Loader, 4-way bucket	290	
Backhoe, 200 HP 1/2 CM capacity	200	
Pumps, cofferdams and shoring	100	
Light boom crane and concrete bucket	180	
	Sub-Total	1,250

Table 5-1 (continued)

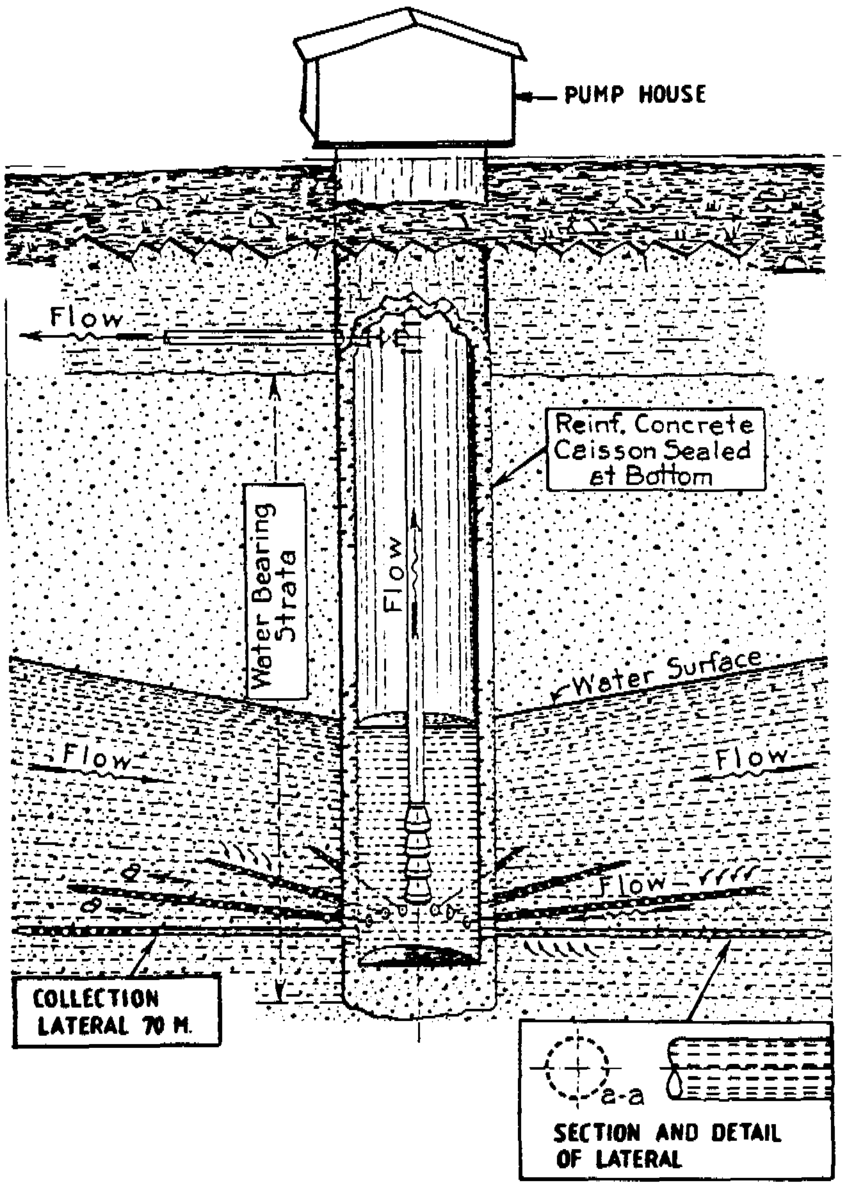
MATERIALS & SUBCONTRACTS		Day Rate (R.O.)	Total (R.O)
Layout survey		30	
Inspection work		75	
Washed coarse gravel	RO.2.5/M^3 x 30M x 2.8 M^3/M	210	
Filter fabric	7 M^2/M x 30 x 0.4 RO/M^2	84	
Pipe C-900 slotted	RO.4.2/M x 30 M	125	
Concrete, structural) includes forms, etc.)	15 M^3/week/6 days x 125 RO/M^3.	312	
Contingencies, Risks		50	
		Sub-Total	890

COST OF OVERALL DAILY OPERATION R.O. 2,630

Daily Operation Costs	R.O. 2,630
Other O/H & Profit @ 20%	500
Total Daily Cost	3,130
Total Daily Production	30 Meters/Day
Total Cost Per Meter	" 105
Total Cost Per Kilometer	" 105,000

Production rate at a total depth of 6.6 meters falls to 15 meters/day. Thus total cost per meter rises to R.O. 200/meter or about R.O. 200,000 per kilometer.

Figure 5-2



SCHEMATIC DIAGRAM OF RADIAL COLLECTOR WELL

NOT TO SCALE

In regions more distant from the shore where gravels tend to prevail, installation of the collection laterals would require the use of specialized rotary drilling rigs that allow the insertion of a liner that can be extracted from the borehole after the lateral is in place (Wright & Herbert, 1985). A caisson at least 3 m in diameter is needed to accommodate the drilling equipment; many are 4 m or more in diameter.

The collectors can be completed in the typical radial pattern or in a linear pattern much like that for an infiltration gallery. The choice depends upon the prevailing direction of groundwater flow and on the area of intake needed to produce the amount of water the formation will yield at the limited drawdowns required to prevent upconing.

Some of the advantages of radial collection wells are as follows:

- Installation is economical to depths of about 50 m, much deeper than gallery collectors can go.

- Because of low intake velocities, the wells require less maintenance than conventional wells.

- The large effective radius of the wells makes them far more efficient than conventional wells. Little of the observed drawdown in a radial well arises from losses in the near-well area.

- The caisson design allows the centralization of pumping and electrical equipment, provides equalization storage, and offers simplicity of operation.

But these disadvantages must also be considered:

- The capital costs of installation are higher than for conventional wells. When used with limited drawdowns, the wells must be able to produce enough water to justify the additional costs.

- The wells are more difficult to develop than conventional wells.

Costs and Economic Considerations

At present there are no radial wells operating in Oman and there is no local experience in construction. Based on construction costs in other parts of the world, the installation of a 4 m-diameter caisson at a depth of 20 m to 30 m should cost about R.O. 5,000 per m, and of each 205 mm (8-inch) lateral collection pipe should cost about R.O. 900 per m. (Cost data derived from information provided by Ranney Well Systems, U.S.A.).

A typical radial well would consist of four laterals each 70 m long and a caisson at a depth of 25 m, and would cost about R.O. 375,000. Risers, pumps, and electrical equipment would add R.O. 50,000.

Because of the large capital investment, a preliminary hydrogeologic investigation would be necessary to ascertain the capacity of the system and the aquifer response at each site. This would mean drilling and pumping tests in addition to analysis and reporting and would cost about R.O. 75,000 per site. Thus, a typical radial collection well ready for service would cost about R.O. 500,000, or $1.3 million.

5.3 Conventional Shallow Drawdown Wells

Multiple shallow wells may serve the same purpose as radial collection wells and galleries in that a maximum drawdown constrains the yield of the system. The wells can be installed in a line to function like a gallery or can be dispersed over a specified area. Well spacing and design would be based on hydraulic analysis, and wells would pump at relatively low rates to discharge water into a collection header for storage and use. Existing dug wells could be employed.

Multiple shallow wells can be used where a thin fresh water zone overlies salt water. Conventional well-drilling techniques impose no limitations on installation depths, formation characteristics, and hydrologic conditions. Each well is tested to determine the allowable pumping rate, and would need a separate pump, mechanical equipment, and electrical feeders and controls.

Multiple shallow wells cause a limited drawdown, and little temporary storage is created by a recovering cone of depression in unconfined systems. Thus, these systems should be pumped continuously rather than intermittently for maximum efficiency, and should be combined with water storage facilities to maintain pumping during periods of low system demand.

To design such a system, the maximum allowable drawdown must be based on the depth and thickness of the zone of diffusion, which, theoretically, would rise uniformly without upconing by drawing down the aquifer. The degree to which the zone of diffusion is permitted to rise would depend upon the salinity tolerated at the depth of the well intakes and could be determined by hydraulic analysis. But given the limited understanding of the flow system, it would be preferable to determine this from field tests.

Optimal well spacing to achieve a uniform drawdown would vary with aquifer permeability and could be determined by constructing and testing the wells one by one. Completion depths would depend on the nature of the formations encountered and would be the least depth necessary to produce a reasonable yield of water.

The advantages of multiple shallow wells are:

- Ease and low cost of installation
- Adaptability to a variety of hydrogeologic conditions
- Possibility of incremental construction and testing

The disadvantages are:

- Large outlays on pipelines, electrical feeders, roads, and control systems since water collection is dispersed and requires many small pumps and electrical controls
- Difficulty and expense of operations and control
- Need for testing and tuning of many wells for optimal operation

Costs and Economic Considerations

The analysis in Table 5-2 shows that a 1 km line of 14 wells spaced at intervals of 75 m and completed at depths of 20 m would cost R.O. 39,000 to install. Low-yield pumps, wellhead assemblies, risers, and control valves would add approximately R.O. 38,000, allowing R.O. 10,000 for electrical feeders. Other costs would be R.O. 20,000 to cover hydrogeologic analyses, engineering, and supervision of the work. Thus, the total costs of a typical line of wells would be about R.O. 100,000 using the assumptions made here. This would not include the costs of the collection header or water transmission pipelines that are higher for dispersed collection systems.

5.4 Scavenger/Production Well Couples

Scavenger/production well couples, or scavenger wells, are used to maximize the extraction of fresh water from aquifers where conventional wells pump water of unacceptable salinity.

Conventional wells often fail in coastal areas, either because they are located in both fresh and salty zones, or because localized drawdown due to pumping and the dynamics of flow in the near-well zone causes upcoming of salty water into the thin fresh water lens. Scavenger wells allow selective pumping of fresh water by intercepting the salty water with a scavenger intake before it can reach the production intake. The salty water is then pumped to waste. The principle is illustrated in Figure 5-3.

Table 5-2

Construction Cost Estimate for Conventional Shallow Drawdown Wells

ASSUMPTIONS

205 mm (8-inch) diameter wells are required at intervals of 75 meters. 14 wells are required for 1 kilometer line of wells. Depth of wells is about 20 meters. 5 meters of well screen is provided per well.

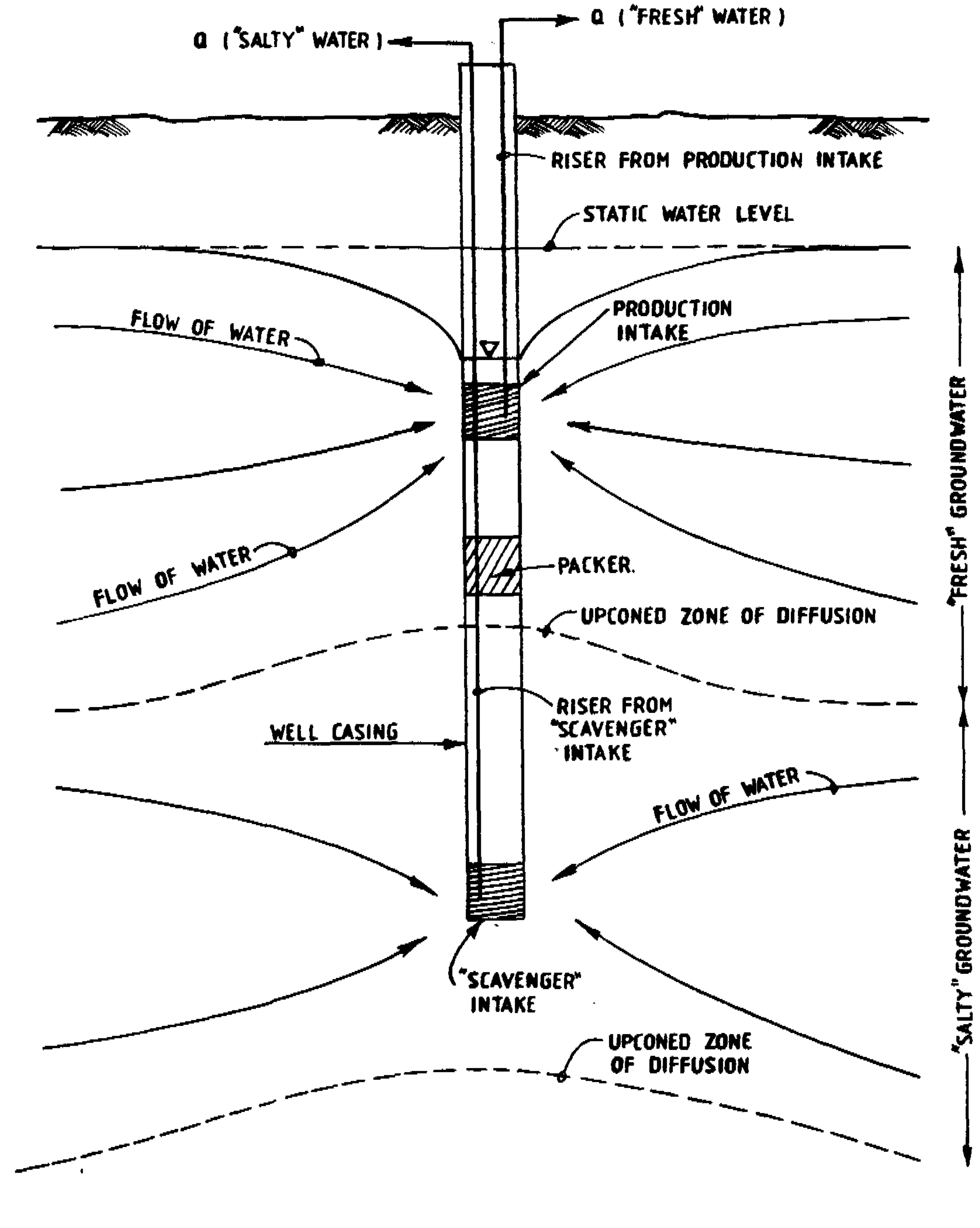
DRILLING AND CONSTRUCTION COST

	Item	Qty.	Unit	Unit Price (R.O.)	Amount (R.O.)
1.	Mobilise to site of work	1	L.S.	400	400
2.	Surface Casing	4	M.	30	120
3.	Drilling and test 12 1/4" borehole	18	M.	31	558
4.	Provide and install stainless well screen and casing	20	M.	24	480
5.	Develop well	4	Hrs.	25	100
6.	Conduct pumping test	1	L.S.	400	400
7.	Well head assembly	1	L.S.	200	200
8.	Misc contingencies		L.S.	500	500
	TOTAL COST OF TYPICAL 100 M WELL				R.O. 2,758
	PRICE PER METER				R.O. 138
	TOTAL COAST OF 14 WELLS READY FOR WELL PUMPS				R.O. 39,000

PUMPS, MECHANICAL EQUIPMENT & ELECTRICAL FEEDERS

	Item	Qty.	Unit R.O.	Unit Price (R.O.)	Amount (R.O.)
1.	Well pumps and risers	14	Each	1,000	14,000
2.	Well-head mechanical	14	L.S.	200	2,800
3.	Electrical feeders	1	Allowance	10,000	10,000
4.	Control and telementry system		L.S.	6,000	6,000
5.	Misc. related work		L.S.	5,000	5,000
	TOTAL OF PUMPS, ELECTRICAL & MECHANICAL . . .				R.O. 38,000

Figure 5-3



SCAVENGER / PRODUCTION WELL PRINCIPLE

NOT TO SCALE

Water enters the well from both salt water and fresh water zones in the aquifer, and the degree of upconing and thus the salinity of the effluent depends mostly on the pumping rate. The rate at which salt enters the two intakes is roughly equal to the rate at which it would be discharged by a conventional well pumping at the same rate as the scavenger well couple. This mass balance may be affected by variations in the construction of conventional and scavenger wells, but the concept is valid for wells of similar design. The total salinity is divided between the two intakes. Maximum production of low-salinity water is achieved by adjusting the depths of the production and scavenger intakes and balancing the pumping rates at the two intakes.

Scavenger wells can be installed in two ways: two wells can be completed at different depths, or two intakes can be provided on the same well casing, one in the relatively fresh water above and one in the underlying saline water. (Figure 5-4). In either case, the intake of the production well is placed in the fresh water zone as far as possible from the salt water interface, and the intake of the scavenger well is placed within the salt water zone.

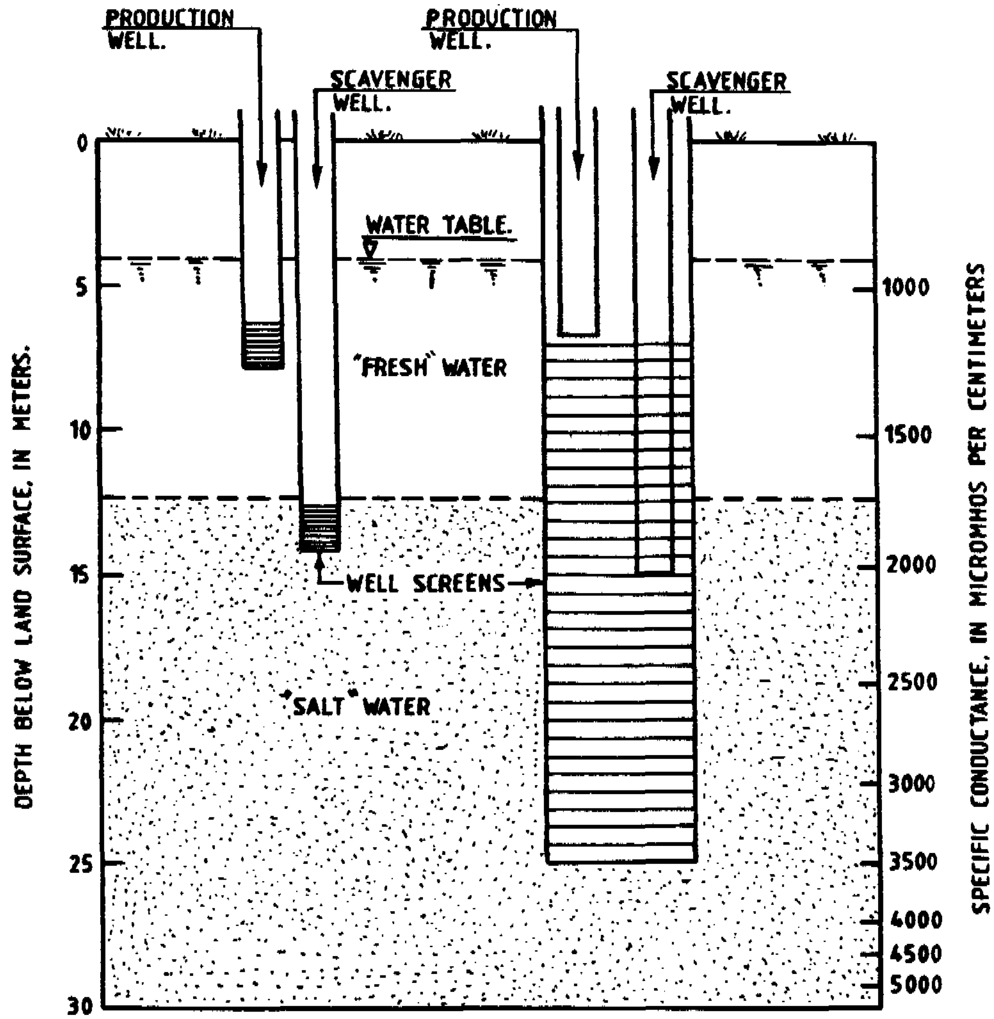
Alternatively, a scavenger well can be a fully screened well with packers and plugs placed between the pump intakes. Although separate wells and screened intake zones are more efficient, fully screened existing wells offer a cost-effective solution.

Because the determination of optimal pumping rates and screen or intake depths is not easy, the scavenger well technique has not been applied extensively. Where it has been successful, intake depths and pumping rates have usually been determined by trial and error. Long (1965) describes the optimization of a conventional well converted to a well couple, using packers to isolate pumping zones. Zack (1984, 1988) designed a method of hydraulic analysis to eliminate trial and error based on experimentation in a well penetrating the thin fresh water lens in coastal Puerto Rico. However, it assumes regional stability in the stratification of saline and fresh water, and might not be reliable for wells of large discharge or for wells that operate for long periods.

Scavenger/production well couples can be constructed in the same way as conventional wells. Where a single installation houses both production and scavenger wells, isolation of the production and scavenger intakes (e.g., by using packers) is optional. Where two separate wells are employed, the deeper well can be drilled first, salinity conditions defined as drilling proceeds, and the aquifer tested to find a completion zone for the production well.

Scavenger/production well couple technology can be applied wherever a thin fresh water zone overlies salty groundwater. It can be used in coastal areas where groundwater is relatively shallow and further inland where it is deeper and sediments are partly cemented. It is also suitable in buried wadi channels to capture throughflow where fresh water overlies salt water tongues. Because conventional well-drilling techniques are used, variations in installation depths, formation characteristics, and hydrologic conditions do not pose a problem.

Figure 5-4



SCHEMATIC DIAGRAM OF SCAVENGER-PRODUCTION WELL COUPLES PLACED DIRECTLY WITHIN THE AQUIFER AND WITHIN A LARGER WELL, SCREENED IN BOTH FRESH AND SALINE WATER.

NOT TO SCALE

The main advantages of the technology are:

- Scavenger wells are easily installed under a variety of hydrogeologic conditions.

- The scavenging system allows more water to be pumped because more drawdown can be applied than with conventional wells that skim water by limiting drawdown.

- Various hydrologic conditions (water levels and depth to the interface) can be accommodated by adjusting intake depths and pumping rates.

The major disadvantages are:

- The costs of drilling, equipping, and maintaining the duplex well system are high.

- Pumping two wells and moving the salty water to a point of discharge consumes more energy.

- Adjusting and tuning the well system requires special expertise.

- Disposing of salty water from the scavenger well to waste can be expensive and difficult.

An initial investment in analysis and testing at the point of installation will be necessary because the technology is new and unfamiliar. To arrive at optimal pumping rates, it would be wise to use variable speed pumps.

Costs and Economic Considerations

Table 5-3 provides a detailed cost estimate for a typical scavenger/production well shown in Figure 5-5. It could be placed about 1,500 m from the sea along the Batinah coast in an area beginning to experience saline intrusion. It would be about 38 m deep in a single casing 330 mm (13⅜ in) in diameter. It would produce about 4 l/s (50 gal/min) of fresh water.

The relatively shallow well can be constructed for about R.O. 7,500, or about R.O. 200 per meter of depth, compared with about R.O. 80 for a conventional well. Pumps, specialized mechanical equipment for variable speed operation, and electrical controls would add about R.O. 6,050. Technical work to balance the production and tune the well would cost about R.O. 2,000, but the pipeline and related work to convey the salty water for discharge in the near-shore zone would cost R.O. 14,000. Clearly, the disposal of the salt-laden effluents is the most expensive element of the system. This cost can be reduced to some degree by the use of pipelines or open channels that serve a number of installations.

Table 5-3

Cost Estimate for Typical Scavenger/Production Well

ASSUMPTIONS

Cost estimate assumes that scavenger will be used to produce water in an area where salt water begins to appear at a depth of 20 to 30 meters. The well would have sufficient capacity to produce 3 to 4 liters per second (50 gallons per minute). Static water lies at 8 meters below the surface and total depth of the well is about 35 meters. The estimate also assumes the stratigraphy and salinity distribution are known. Finally the estimate assumes that a single casing with two variable speed line shaft pumps will be used. Please refer to figure 5.5 for details of the typical well priced here.

DRILLING AND CONSTRUCTION COSTS

Item	Qty.	Unit	Unit Price (R.O.)	Amount (R.O.)
1. Mobilise to site	1	L.S.	700	700
2. Spud surface casing borehole	8	Meter	50	400
3. Provide and install 16" surface casing	8	Meter	40	320
4. Drill borehole to receive 13 3/8" casing	30	Meter	48	1,440
5. Build up casing and well screens and install	40	Meter	62	2,480
6. Develop both screened zones	16	Hrs.	25	400
7. Conduct 24 hours of pumping tests	25	Hrs.	33	825
8. Cap and complete well head, install surface seal	1	L.S.	350	350
9. Misc. Contingency (Packers, etc.)	1	L.S.	600	600
SUB-TOTAL CONSTRUCTION COST:			R.O.	7,500

WELL HARDWARE PUMPS AND RELATED WORK

Item	Qty.	Unit	Unit Price (R.O.)	Amount (R.O.)
1. Provide 60 m. head by 4 liters/sec. pump and 4 HP variable speed motors.	2	Each	1,025	2,050
2. Provide and install 3" line shaft riser columns.	45	M.	40	1,800
3. Well head mechanical assembly & control valves.	1	L.S.	950	950
4. Electrical controls, switchgear.	1	L.S.	750	750
5. Electrical power entrance panel and feeders.	1	Allowance	500	500
SUB-TOTAL HARDWARE & PUMPS			R.O.	6,050

Table 5-3 (continued)

START-UP TESTING AND SYSTEM TUNING

Item	Qty.	Unit	Unit Price (R.O.)	Amount (R.O.)
1. Various pumping tests at variable rates.	16	Hrs.	100	1,600
2. Develop operation manual	1	L.S.	400	400

SUB-TOTAL WELL TUNING = R.O. 2,000

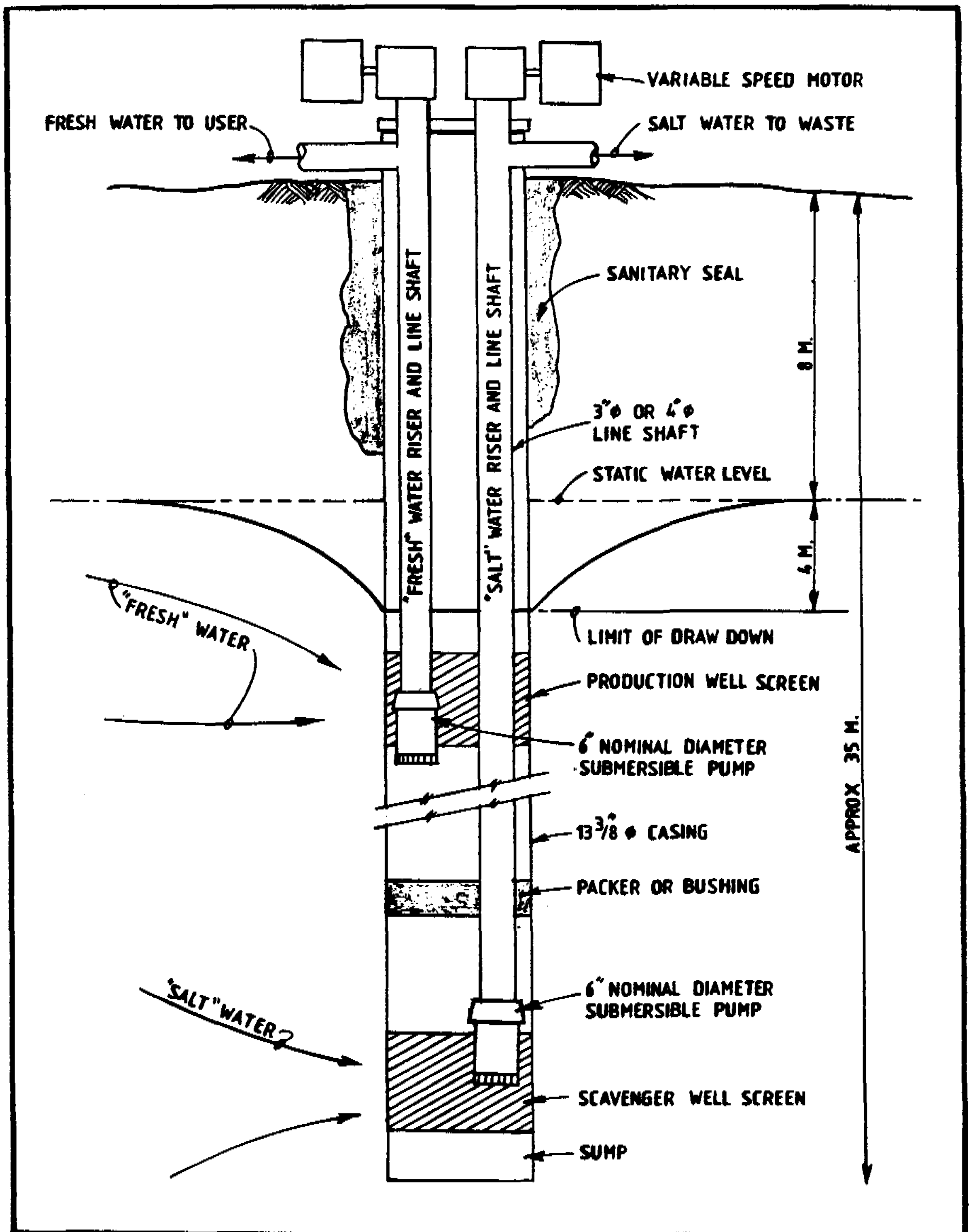
SALT WATER DISPOSAL

Item	Qty.	Unit	Unit Price (R.O.)	Amount (R.O.)
1. 4" diameter pressure pipe to shoreline 0.8 meter depth. PVC, H&S	1400	M	9	12,600
2. Misc. work and materials related to pipeline	1	L.S.	1,500	1,500

SUB-TOTAL SALT WATER DISPOSAL R.O. 14,000

APPROXIMATE TOTAL COST FOR SCAVENGER SYSTEM R.O. 29,500

Figure 5-5



TYPICAL SCHEMATIC SCAVENGER/PRODUCTION WELL COUPLE

NOT TO SCALE

Chapter 6

APPLICATIONS IN OMAN

The control of salt water intrusion is essentially a regional problem. Aquifers can be exploited only at a finite rate, and pumping at any point ultimately will affect the aquifer as a whole. These technologies undoubtedly can provide local and temporary supplies of fresh water, but only at the expense of the overall deterioration of the groundwater system. Thus, they should not be used except as part of a broader plan to manage the resources of an entire area.

When the economics of short- versus long-term gain are carefully considered, saline intrusion may be permissible up to a certain distance inland. Skimming technologies might be employed to pump the remaining storage of an aquifer or collect the portion of groundwater that would otherwise be lost to the sea.

Skimming large quantities of water for long periods will change the hydrologic conditions in the thin fresh water zones along the coast and slightly inland. As salt water intrusion advances because of overdraft, the salt water wedge and the area of thin fresh water zones will move inland, and water levels will continue to fall. Low-drawdown devices and skimmers may later fail because of the conditions they impose on the groundwater system.

Skimming technologies relying on limited drawdown work most efficiently with continuous pumping. Conventional wells may provide a recovering cone of depression for groundwater to enter between periods of intermittent pumping. Low-drawdown devices do not have this advantage and pump at much lower instantaneous rates. Thus, pumping should be continuous for best advantage. For skimming to be most effective water storage must be provided, unless water use can be restricted to moderate rates at all times. Since storage and pumping are expensive, it may be necessary to organize falaj-type management of water and extend the hours of use as an alternative to building storage.

Application of Collection Galleries

The horizontal collection gallery cannot be used where the water table is deeper than about 5 m and thus would be suitable only within 1 km of the shore along the Batinah coast. Useful drawdowns should be bounded by sea level and are likely to be very small, limiting the potential yield of the galleries. Galleries should not be used where groundwater levels are rapidly declining to sea level, a condition unfortunately true in much of the near-shore region in the Batinah.

In spite of these constraints, there are regions along the Batinah coast where the gallery skimmer could be successfully employed. A pilot program could be established to test an installation that might be entrusted to a group of farmers who would learn to control it. They could form a cooperative to use the water continuously and later build their own water storage to optimize the use of the gallery. A full-scale test and a parallel effort to develop and strengthen a cooperative to operate the gallery would be beneficial.

Application of Radial Collection Wells

Radial collection wells are expensive because of the complicated process to install the caisson and laterals. They are so efficient that they can rapidly dewater a region that does not receive sufficient recharge. Conventional wells reduce this risk by allowing a progressive development of the aquifer.

Radial collection wells should be considered after a careful investigation of the available recharge to an aquifer, and should be located only where there is a large and reliable throughflow originating in a recharge zone. To prevent regional drawdowns from leaving the collection laterals high and dry, the wells probably should not be used in zones where pumping is uncontrolled and water levels are rapidly declining. Although few places in Oman seem to meet these siting criteria, radial wells might be successfully employed below recharge enhancement structures to rapidly capture receding mounds of throughflow that are sometimes underlain by transient wedges of saline intrusion. Alternatively, the wells could be placed in the lowest reaches of wadis known to be carrying large volumes of water to the sea.

High-capacity radial collection wells rapidly capture large volumes of water. Thus, water storage is required for their use. This might take the form of upland aquifers where wellfields are installed or conventional irrigation reservoirs constructed to make the best use of seasonal discharges.

Application of Conventional Shallow Drawdown Wells (Wellfields)

Multiple conventional low-drawdown wells can be installed over Oman's range of hydrogeologic conditions. The constraints of this technology are largely economical. For example, to achieve a uniform drawdown in areas where the fresh water zone is very thin and where drawdowns are limited to a fraction of a meter, well spacing would have to be very close indeed. Well yields could be improved somewhat by intermittent operation at drawdowns slightly below sea level so that the effect did not aggravate saline upconing.

In most of the near-coast areas, drafts per well are likely to be limited to a fraction of a liter per second, and wells would be spaced 10 m or 20 m rather than hundreds of meters apart. Thus, costs for wellfields of this type would be greater than for conventional wells with more drawdown.

In upland areas of the Batinah and the Salalah plain, the technology would be more economical because more drawdown is available and well spacings can be wider. Many existing wellfields in the Batinah coastal region need to be converted to multiple-well shallow drawdown installations.

Application of Scavenger Wells

Scavenger/production well couples can be installed under almost all the hydrogeologic conditions encountered in Oman. The technique is applicable both in coastal areas with very thin fresh water zones and further inland where the fresh water is thicker but the aquifer is pumped at a higher rate. The principal constraints are the extra costs of constructing two wells or one large well and operating two pumps. The major difficulty with the scavenger system is the disposal of salt water and the lack of experience in designing, constructing, and operating wells of this type.

The disposal problem can be overcome in part by constructing combined drainage utilities that may serve a number of wells. The quality of saline effluent is likely to vary according to the use of the parallel fresh water discharge, the location, the details of well construction, and the operational mode. Some of the effluent could perhaps be used; work needs to be done to identify appropriate uses.

Chapter 7

CONCLUSIONS

Skimming technologies and alternative wells can be employed in Oman. Galleries may find some applications in near-coastal regions where groundwater levels still remain above sea level and the depth of the unconfined water table is less than 4 m to 5 m. Although galleries appear to be simple, the hydraulics that govern them are complex and it is difficult to design an effective gallery or predict yields without full-scale testing. Technical limitations to the application of galleries can most likely be overcome.

The most difficult obstacle is to integrate systems like this into the social, agricultural, cultural, and economic patterns of the country. Preliminary testing and later full-scale testing of a one-half kilometer system would provide a model for future actions and simultaneously assess the technical feasibility of the system.

Radial collection wells will probably find limited use in Oman, but because of their large yields they can be important. Ideal sites need to be found as a first step, but methods to store and later recover water for use must be developed in parallel with the advancement of these systems.

Conventional shallow drawdown wells can be used in many places in Oman and might be the answer to the increasing national problem of saline intrusion. MWR should begin to assess the existing wellfields in saline zones and to plan to use this technology as a way of increasing its stake in preserving the country's water supply and strengthening cooperation with all institutions that operate water wells for the public. Within one or two decades it will be necessary for many utilities to relocate water supply wells or revert to skimming. By that time MWR should be the national authority on shallow drawdown wells.

Scavenger wells could be used for skimming fresher water in several areas where intrusion is present. MWR should begin increasing its expertise in this technology through a pilot project, for which the Royal Goat Farm in Sohar is a good location. However, scavenger wells are likely to be used as a local and temporary remedy for a problem that really needs a long-term and large-scale solution. Use of skimming technologies and alternative wells should be carefully regulated by MWR. Technologies to extract fresher water from intruded aquifers should be a part of a regional program to make the best use of water resources.

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WASH Operation Center
1611 N. Kent St., Room 1001
Arlington, Virginia 22209-2111 USA

Telephone (703) 243-8200
Telex No. WUI 64552
Cable Address: WASHAID
FAX No. (703) 243-9004

19 October 1992

TAS 229 and 230

Dear Colleague:

On behalf of the WASH Project, I am pleased to provide you with WASH field report number 332, *Task 3: Surface Water Data Collection and Task 4: Groundwater Data Collection and Management*, by Steve Luxton, Charles Fuller, John Kent Kane II, Ralph E. Preble, and Mark Utting. This report was produced under WASH Tasks 229 and 230 as part of a Technical Assistance Program For the Ministry of Water Resources, Sultanate of Oman. The overall objectives of the technical assistance were to assist the Ministry of Water Resources to: 1) strengthen all aspects of its operations, 2) establish a strong technical base, and 3) develop policy and procedures.

If you have any questions or comments about the findings or recommendations contained in this report, we will be happy to discuss them. Please contact Phil Roark at the WASH Operations Center. Please let us know if you would like additional copies.

Sincerely,

J. Ellis Turner
WASH Project Director