F I E L D R E P O R T

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

TASK 3: SURFACE WATER DATA COLLECTION
TASK 4: GROUNDWATER DATA COLLECTION AND MANAGEMENT

WASH Field Report No. 332
July 1991

WATER AND SANITATION for HEALTH PROJECT

Sponsored by the U.S. Agency for International Development
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WASH Field Report No. 332

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

Task 3: Surface Water Data Collection
Task 4: Groundwater Data Collection and Management

Prepared for the Omani-American
Joint Commission for Economic and Technical Cooperation
under WASH Task Nos. 229 and 230

by

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- Parts 1 & 2: Introduction and Background;
- Part 3: Wadi Gauging Network Rationalization and Upgrade;
- Part 4: Salt Water Intrusion Monitoring and Remediation;
- Part 6: Small Basin Management;
- Part 7: Geophysics;
- and Part 8: Applications.

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LIST OF ACRONYMS AND ABBREVIATIONS

B.A.	Bachelor of Arts
B.S.	Bachelor of Science
cm	centimeter
FOA	United Nations Food and Agriculture Organization
H.E.	His Excellency
H.H.	His Highness
in	inches
JICA	Japanese International Cooperation Agency
Jr.	Junior
km	kilometer
l	liters
l/s	liters per second
m	meter
m^2/d	square meters per day
m^3/d	cubic meters per day
m^3	cubic meters
M.A.	Master of Arts
MAF	Ministry of Agriculture and Fisheries
mcm/yr	million cubic meters per year
mm	millimeter
MMP	Sir Mott MacDonald and Partners, Limited
MM/WH	Mott MacDonald International, Limited in association with Watson Hawksley
MOC	Ministry of Communication
M.S.	Master of Science
MWR	Ministry of Water Resources
OAJC	Omani American Joint Commission
P.E.	Professional Engineer
PVC	polyvinyl chloride
R.O.	Omani Rials
R.P.G.	Registered Professional Geologist
Sr.	Senior
TPM	Team Planning Meeting
tm	trademark
USAID	United States Agency for International Development
uS/cm	micro Siemens per centimeter
WASH	Water and Sanitation for Health Project

EXECUTIVE SUMMARY

In response to a request for technical assistance from the Sultanate of Oman's Ministry of Water Resources (MWR), the Omani American Joint Commission (OAJC) contracted with the Water and Sanitation for Health Project (WASH) to evaluate and make recommendations on a number of water investigation and management projects under consideration by the new ministry. The WASH team worked in Oman and the United States during January, February, and March 1991 and conducted most of Tasks 3 and 4 outlined in a six-part Water Assistance Program.

This report presents evaluations and recommendations on hydrometeorological networks, drainage basin characteristics, representative basins, and aflaj flows (Task 3), and wadi throughflows and recharge alternatives (Task 4).

Major Findings and Conclusions

Key findings and conclusions are:

- The extreme climatic conditions, wide variability in rainfall, and lack of comprehensive data have made development of reliable predictive water management tools next to impossible to date. In parts of the Batinah, this has left significantly reduced groundwater pumping as the only management option. In other areas where the problem is not as acute, a better understanding of the hydrologic system and the development of management tools will help conserve limited water resources.

- The large variations in rainfall data suggest inaccurate estimates of rainfall between gauges and, in turn, that some kinds of hydrologic investigations are possible only with a very high density of rainfall gauges.

- In fact, the MWR does not need the large outlay on a dense rainfall gauging network. A network of 200 gauges for the country should be sufficient for calculation of annual and longer-term rainfall distribution for most of the areas where water management data are needed.

- Evaluation of well hydrographs in the Batinah indicate that the hydrologic processes of throughflow and/or infiltration at the mountain front are important to aquifer recharge. Quantification of the mechanisms of recharge and the development of a statistically based model will improve the management of water.

- Data on the effectiveness of major recharge dams are not available. Recharge in the basins where these dams have been constructed has not been assessed either before or after construction. Less expensive methods that might be as effective as dams have not been investigated. Recharge data may be available in the Ministry of Agriculture and Fisheries (MAF) but are not available to MWR.

- The monitoring of aflaj, an important part of the country's water resources, needs refinement and direction. Monitoring is unequal in the various districts of Oman and some valuable data are being lost.

- Relationships between rainfall and runoff have been poorly developed. The highly variable rainfall, the differences in geologic and climatic conditions, and insufficient gauges make accurate rainfall-runoff models unlikely in the near future. An examination of records for the major rainfall events of December 1989–February 1990 showed that, in the best case, the preliminary model overestimated runoff volumes by only 15 percent but underestimated flood peaks by over 200 percent. In other cases, runoff estimates were four to five times the recorded volume.

Recommendations

Key recommendations of the study team are:

- A series of surface water gauges and wells to quantify the relative rates, volumes, and timing of each recharge component should be used to measure throughflow and wadi-flood infiltration in Wadi Ahin. A statistical model should be developed from the data collected to predict water levels in the coastal plain of the Batinah one to three years in advance. This program, considered to have great promise, is estimated to cost R.O. 300,000 over five years.

- A pilot program to test alternative recharge enhancement methods, specifically wadi-flood retention structures (low "leaky dams") and infiltration pits/dry wells near the coastal highway, should be undertaken. The program is estimated to cost R.O. 600,000 over five years.

- Up to 84 more monitoring wells should be installed in seven wadis to assess the performance of existing recharge dams. The wells should be designed to monitor the hydraulic response in the first aquifer beneath the ground and should not be as widely spaced as the monitoring wells currently in use. This program is estimated to cost R.O. 425,000 over five years.

- Seventy additional automatic rain gauges should be installed during the next year at locations indicated in this report, bringing the total to about 200. This program is estimated to cost about R.O. 260,000, plus R.O. 350 per gauge per year for maintenance and operation.

- A standardized program to measure flow in aflaj, using current meters in about 400 aflaj and electronic data recording systems in 40 aflaj, should be introduced. Measurement points and data collection intervals should be uniform. An inventory of aflaj should be conducted to identify their locations, motherwells, and other pertinent features. The monitoring program is estimated to cost R.O. 150,000 over three years and the inventory is estimated to cost R.O. 415,000 over the same period.

- A program to develop a representative basin in Oman was suggested. This might answer questions about the hydrology of Oman, but it would be expensive and have more academic than practical value.

  A five-year representative basin study in three basins (Wadi Ahin, Wadi Bani Ghafir, and the basin containing Wadis Ghul, Misfah, and Bahla) is estimated to cost about R.O. 508,000.

- Studies that define basin yield and peak flows from the geometry of channels appear to be the most useful. An update of the 1977 study on channel geometry should be undertaken. It will enlarge the existing database and provide further confidence in the recurrence and magnitude of flood events for about 100 wadi gauges at an estimated cost of R.O.152,000.

Chapter 1

INTRODUCTION

1.1 Project Introduction

The Ministry of Water Resources (MWR) of the Sultanate of Oman was established in 1990 and given the formidable task of improving water management in a country where this resource is scarce and allocation is complicated by innumerable legal, political, and economic considerations. In response to a request for assistance by the MWR, made through the Omani American Joint Commission (OAJC), the Water and Sanitation for Health Project (WASH) conducted several technical studies in a series of six tasks whose underlying theme is "toward better water management." This report summarizes the results of the third and fourth tasks of the WASH assignment.

1.2 Purpose of the Project

The project was funded by the OAJC and had the following objectives:

Rain Gauging Network:

- Establish a plan for rationalizing the existing network, including its equipment and monitoring procedures
- Establish a plan for network expansion to support basin-wide management of water resources
- Establish equipment needs to upgrade and modernize the network

Drainage Basin Characteristics:

- Determine reliable correlations between basin flows and basin characteristics on the basis of similar work in other countries
- Identify basins and basin parameters for which such correlation appears feasible
- Develop an effective basin characteristics methodology

Representative Basins:

- Identify two representative basins for the establishment of detailed monitoring programs

- Establish monitoring programs for the selected basins

Salinity Transects:

- Establish programs for monitoring salinity intrusion in the Batinah and Salalah and evaluating the Salalah brackish water zone

Aflaj Flows:

- Prepare an upgrading and expansion program

- Identify equipment and personnel needs for the program

Throughflow:

- Establish an achievable program of throughflow measurement in selected basins

Recharge:

- Evaluate enhancement techniques used to date and, by reference to work done elsewhere, provide a basis for the use of other appropriate techniques

1.3 Preparation for the Assignment

The scope of work was prepared by Robert Thomas of Camp Dresser & McKee International, who interviewed numerous MWR personnel in February 1990 to identify the key areas in which the Ministry needed assistance.

At a three-day team planning meeting (TPM) in Washington, D.C., on January 7, 8, and 9, 1991, the project clients in Oman were identified and their interests in this assignment were discussed. The team reviewed the scope of work extensively, considered comments and suggestions received from United States Agency for International Development (USAID) personnel, and agreed upon a work plan, list of responsibilities and duties, schedule of implementation, and preliminary report outline.

1.4 Scope of Work

The part of the scope of work pertaining to each subtask is presented in the appropriate chapter.

1.5 Conduct of the Study

The team originally was scheduled to arrive in Oman within two weeks after the TPM, but the outbreak of the Gulf War and USAID's imposition of travel restrictions changed that. Work in salinity transects and wadi gauging, planned for January-March, had to be postponed. The salinity transect portion of the project is now planned for a later date. The wadi gauge work has been put off indefinitely. The team members began work in Oman on January 12, five days before the outbreak of the war.

While conducting the study, the team met regularly once a week with OAJC to give an account of its progress and plans and to present any problems that needed resolution. Interviews with personnel and officials of various Omani government agencies provided valuable information on the status of various projects in the country that helped in preparing this report.

The team prepared a preliminary draft of its findings in late February and early March, incorporating the comments and suggestions of key personnel in the OAJC and MWR. A presentation was made to the Ministry on March 3 and the final draft report was presented to OAJC prior to the team's departure on March 13, 1991.

1.6 Report Contents

The report has seven chapters following the Introduction (Chapter 1) and Background (Chapter 2), each presenting a subtask of the original scope of work. Hydrometeorological Network Rationalization is discussed in Chapter 3. Salinity Transects (Chapter 4) will be added at a later date. Drainage Basin Characteristics are presented in Chapter 5. Representative Basins are discussed in Chapter 6. Aflaj Monitoring is presented in Chapter 7. Wadi Throughflow is presented in Chapter 8. Groundwater Recharge Enhancement concludes the report with Chapter 9.

Chapter 2

BACKGROUND

2.1 General Background and Information

The Sultanate of Oman is highly dependent on groundwater for its domestic, agricultural, and industrial needs since precipitation averages less than 100 millimeters per year in most areas of the country. Techniques used for more than a thousand years rely on dug wells to intercept shallow groundwater that is transported through an extensive network of subsurface and above-ground aqueducts, or aflaj, to provide communities and villages with both potable water supplies and the means to support a traditional and productive agricultural base.

This system generally has been in balance, with the demand not exceeding the supply naturally replenished by rainfall. However, rapid modernization and a rising population during the last two decades have placed great pressure on the country's water resources, and the explosive growth of mechanical pumps and drilled wells to withdraw large quantities of groundwater from greater depths has compounded the problem. Some of the increased demand has been met by the construction of desalination plants. But these are capital-intensive and are expensive to operate and maintain. The pressure on groundwater resources has caused serious decreases in water levels and water supplies and the degradation of water quality in many areas, leaving many communities in decline as centers of agriculture and population.

2.2 Physiography and Regional Geology

The geology of Oman is divided into an almost featureless desert foreland in the southwest, a mountainous region in the north, and scattered narrow coastal plains. Physical features and location names are shown in Drawing No. 1. The foreland topographically and geologically is a continuation of the gently undulating shelf which extends eastward from Saudi Arabia. The mountainous region, extending from the Musandam peninsula to Sur southwest of Muscat, forms a chain distinct from the rest of the Arabian peninsula. These mountains, ranging up to 10,000 feet in elevation, contain great thicknesses of shelf carbonate rocks. The presence of extensive uplifted folds of deep sedimentary deposits and rocks formed as part of the deep oceanic crust overlying the carbonate rocks is a geologic anomaly unique to the Arabian peninsula. Late Tertiary folding and subsequent erosion have exposed these rocks to reveal the total sedimentary section as well as the metamorphic basement. The interior valleys of the mountains generally are narrow, steep-sided, and underlain with partially cemented sand and gravel. The third distinctive area is the coastal plains along the Batinah coast in the north and the Salalah coast in the south. The Batinah plain is a series of coalescing alluvial fans emanating from the wadis (valleys) along the mountain front. These fans are composed of materials ranging from silt to boulders, becoming finer graded with increasing distance from the mountain front. The alluvial materials, ranging up to 100 m or more in depth, are commonly cemented into a conglomerate.

2.3 Climate and Rainfall

Oman's climate and rainfall vary greatly. There are two seasons: winter, generally from November to April; and summer, from May to October. April and October are considered transitional months. Winter is the rainy season in the north but little rainfall occurs along the south coast. The average annual rainfall at Seeb is about 100 mm, but actual rainfall varies widely from year to year. In the years 1976-81, it varied from 3.7 to 182.6 mm. Rain can occur in the summer as a result of unsettled weather from a southwesterly airflow. Most of this rain falls on the inner side of the northern mountains. In the south rainfall coincides with this southwesterly wind of the *kharif* monsoon. Rainfall on the southern coast averages about 100 mm, increasing to some 300 mm in the mountains. On the leeward side of the mountains rainfall drops to only 50 mm per year.

2.4 Ministry of Water Resources Mandates

In November 1988, His Majesty Sultan Qaboos bin Said issued Royal Decree Number 82/88 as the basis for conserving the nation's water resources. The decree stated that "the Sultanate's water reservoir is considered as [a] public national wealth to be exploited...according to the Government's instruction," thus establishing that all groundwater and its extraction for any purpose could be regulated by the government.

In October 1989, His Majesty issued Royal Decree Number 100/89 creating the Ministry of Water Resources and appointing H.E. Khalfan bin Nasser Al Wahaibi as its acting Minister with authority to perform the tasks listed below.

- Formulate policies and regulations regarding water resources
- Monitor hydrologic systems
- Conduct surveys and perform water resources research
- Conduct hydrologic assessments
- Collect and analyze water samples
- Evaluate the potential for long-term, sustainable water resource supplies

- Establish and maintain a water resources database

- Manage and preserve the nation's water resources through long-term planning and administration

Before Royal Decree Number 100/89, water resources had been administered by various agencies and ministries—the Public Authority for Water Resources, the Ministry of Environment and Water Resources, the Ministry of Electricity and Water—none of which was dedicated to water resources assessment and management exclusively. The creation of the MWR established an entity dedicated solely to water resources, and since its inception, the Ministry has moved rapidly to fulfill its mission.

Chapter 3

HYDROMETEOROLOGICAL NETWORK RATIONALIZATION AND UPGRADE

3.1 Introduction and General Overview

The present rain gauge network operated by the MWR is largely unplanned and in need of an upgrade, which hinges on two questions:

- What is the required density of the network?
- What are the most important uses for rainfall data and what are their implications for the overall planning of the network?

The network must be suited to the weather and climate of Oman. A statistical study to obtain a preliminary idea of the network density required for various kinds of applications examined the behavior of seven closely spaced rain gauges in Musandam.

This chapter reviews the rainfall pattern, discusses the MWR's needs for rainfall data, and traces the implications of this to the rain gauge network.

The conditions and layout of the existing rain gauge system are briefly discussed for background (see Drawing No. 1). A preliminary plan for expanding the network is presented (see Drawing No. 2). The problems in the existing network are discussed and the new sites for gauges proposed.

Estimates of the cost of the project and ongoing operation are discussed and the benefits of the expansion are compared with the costs. Enhancements to rainfall data are discussed briefly at the end of the chapter. The uses and some possibilities for remote sensing are also included.

3.1.1 Scope of Work

The scope of work included the following tasks:

- Establish a plan to improve and rationalize the existing network, including its equipment and procedures
- Establish a plan for network expansion to support basin-wide management of water resources

- Establish equipment needs to upgrade the network
- Recommend a training program for Omani technicians
- Specify new equipment that the OAJC might provide

The scope of work also included a review of the MWR's existing and future needs for data and the adequacy of the present system.

Difficulties with staff travel caused by the war prevented the arrival of one member of the WASH team. By mutual agreement with MWR and OAJC, some portions of the work dealing with the rationalization of the wadi gauging network were not undertaken, and instead attention was focused on the more pressing problem of the rainfall gauging network. Work on the omitted section will be carried out within the scope of Tasks 5 and 6, unless the MWR and the OAJC opt to expand other areas of the study with the excess time and budget available.

3.2 Summary of Conclusions

- Planning for expansion of the network should include consideration of accuracy, costs, and operational aspects. Moreover, the expansion should complement the MWR's hydrological investigations.
- The existing network has equipment and layout problems and large gaps in coverage that need to be corrected.
- Several errors in earlier rainfall records can be avoided by conversion to automatic gauges and digital data input methods.
- Wide variations in the rainfall and climate of Oman give rise to unique problems in developing a network, making it very expensive to obtain accurate information about short time-scale events.
- Rainfall data analyses indicate that large errors can be expected for some kinds of rainfall data uses, given network densities that are less than ideal. Planning for the future network must take the statistical behavior of Oman's rainfall into account.
- The MWR's overall strategy for water management must enter into the design of an expanded network. Much of the most important work of the Ministry can be accomplished without extensive investments in rainfall gauging networks.

- Some studies and water resource techniques cannot be used in Oman because of the character of rainfall data and the density of network that is required for accurate information.

- The MWR should begin immediately to install 70 more rainfall gauges at various points.

- It should employ a hydrologist to augment the Surface Water Department staff during the expansion project. Gauge foundation work and gauge installation should be carried out by a construction contractor.

- The new rain gauges will cost about R.O 3,500 per site. Annual costs will be about R.O. 350.

- Satellite images can enhance the Ministry's reports on rainfall events and provide for classification of rainfall data by storm type. Economical means are available to obtain such images.

3.3 The Institutional Setting

The MWR's Surface Water Department is among the best of its units. This department really began work in 1977 before the formation of the Public Authority for Water Resources, and its first efforts were aimed at measuring the flood runoff at various points from field observations. Later, after the Public Authority for Water Resources was organized, the department embarked on a long-term plan to measure the flow from the major wadis. A new technology was developed for measuring flood stage, using staff gauges and transducers rather than mechanical apparatus.

During the past 20 years, a large number of different rain and wadi gauges for different purposes have been installed by various consultants and teams from the Japan International Cooperation Agency, the Ministry of Agriculture and Fisheries, the Ministry of Defense, and the Ministry of Communication—Civil Aviation Meteorology Office (MOC). As a result, the MWR has inherited a network with a largely unplanned spatial distribution and a variety of equipment types.

The rain gauging network is operated by the Surface Water Department's hydrometeorology section, which has the following responsibilities:

- Gauge site operations and maintenance

- Project management for network expansions

- Preliminary data processing
- Preparation of summary data reports

Closely related are the duties of the applied hydrology section:

- Planning rainfall gauging networks
- Mapping rainfall and preparing rainfall and meteorology studies
- Assessing drainage basins
- Publishing analyses
- Reviewing technical reports
- Providing information to users

In the long list of work to be done by these sections is the rationalization and upgrading of the existing rainfall gauging network. The Surface Water Department has made much headway in this respect since 1990. Many rain gauges have been replaced and some new sites have been added. For the first time, concise reports of rainfall data have been published and special reports on important rainfall events have been assembled. Careful work has been done to make the important features of these records clear, but the department is anxious to improve the accuracy and coverage of the network.

3.4 Network Planning Criteria

The future rain gauge network must meet several criteria generally agreed upon within the Ministry.

- The network should be manageable within the MWR organization.

  It should not be so large that the Surface Water Department is engrossed only in the problems of operating it and devoting much time that might be spent on other valuable tasks.

- The network should make institutional sense.

  It should be designed to optimize the collection of useful data determined in part by the MWR's main objective...better allocation and management of the water resources of Oman.

- The network should make hydrologic and statistical sense.

  Since rainfall in Oman is widely scattered and variable, not all uses of rainfall data will be fruitful. Data collection and network design should facilitate answers to specific water resource questions the country faces.

- The network should make economic sense.

  As each new gauge is deployed there is a diminishing return on the value of the data obtained. If there were no gauges in Salalah, for example, the data from the first gauge would be exceedingly valuable. On the other hand, if a large network already existed, the addition of a new gauge would be of relatively little importance. There is a point at which the costs of installing and operating a new gauge are not worth the return. The network should not be expanded beyond this point.

- The network should make operational sense.

  It should be designed for simplicity of operation and maintenance and uniformity of equipment, which will result in increased accuracy and lower costs.

- The network should make sense in the future.

  It should anticipate likely developments that will enhance the value of data to be obtained and allow better use of data now available.

- The network should be permanent.

  Expansion should take into consideration the continuing need for maintenance and the possibility that budgets may vary as they have in the past. It should be possible to operate the system when financing is substantially lower than what the MWR currently enjoys.

- The network must provide accurate results.

  System upgrades should lead to simplification and greater data reliability.

3.5 Existing Conditions

3.5.1 Existing Conditions in the Network

The MWR currently operates 135 rainfall gauges at 104 sites (31 sites have two gauges each). The distribution of these sites is shown in Drawing No. 1.

About 75 of the gauges are the continuous recording type that uses a graph paper strip chart driven by clockwork. They were installed by different organizations for a variety of projects. About 32 are Italian-made Siap rain gauges fitted with 32-day electric clocks. They are well built and a good investment. Gauges at remote sites have six-month electric clocks. Some of them are in poor condition and need replacement. There are also about 30 Akeda automatic gauges (installed by the Japan International Cooperation Agency) with three-month electric clocks and 10 American-made Leopold and Stevens gauges with 3 1/2-month mechanical clocks.

All these gauges use a tipping-bucket mechanism to detect rainfall. A small counterbalanced bucket swings back and forth on a pivot as rainfall enters the gauge. A switch is activated on each swing and the resulting signal is recorded by a pen on the graph paper chart.

The remaining gauges are mostly of the standard observer type deployed by Oman's Ministry of Defense. They rely on the diligence of an operative to make accurate daily recordings. A few totalizer gauges were formerly in use but have now been eliminated. These gauges collect the precipitation in a bottle and readings are taken at regular intervals.

The MWR has two types of monitoring stations: those that are accessible by road, and those that can be reached only by helicopter because they are deployed at elevations above 1,300 meters. The Royal Oman Police have provided the MWR with helicopter service.

In February 1991, there were eight high-altitude gauges in operation and the foundations for five more had been laid.

Most of the gauges now in operation use strip-chart recorders. The Surface Water Department has tested the Omnidata Datapod digital logger on its wadi flow gauges and has found it reasonably successful in withstanding the climate when deployed in underground standpipes. The department is considering the use of these data loggers in rain gauges, but further testing needs to be done.

3.5.2 Support for the Network within the Ministry

The MWR's Department of District Offices supervises a system of field offices primarily responsible for data collection. But these offices are understaffed and under pressure from multiple demands. In addition to collecting data, they are required to enforce regulations on well drilling and in the future are likely to spend more and more of their time on these regulatory activities. The district offices can be relied upon to support the rain gauging network operations to the extent that local problems and priorities will permit. The Surface Water Department plans to strengthen surface water operations in the district offices by assigning several of its trainees once they are technically qualified.

At present, much time is spent converting raw rainfall data from chart-type gauges into forms suitable for digital manipulation and publication. It takes about 20 man-hours to prepare each chart for database entry and subsequent report, depending upon the number of storms that have been observed during the period of record. The database currently in use is a word processing system that facilitates conversion of the data into publications. The department plans to acquire the more advanced Paradox software package that will permit geographical indexing of the various sites and enable it to provide data to other departments.

3.5.3 Quality of Existing Data

The Surface Water Department has made great strides in improving the accuracy of the data it collects. But there are several errors from the past, a legacy of the standard type of rain gauge read each day by an attendant who usually lived near the gauge. These errors in data collection are discussed below.

- Data Omissions

  These tend to occur when rainfall is heavy and the attendant has difficulty reaching the gauge. Important data on rare rainfall events were often lost in this way.

- Filled-in Data

  Some records suggest that gauge attendants who had missed a reading often entered their own figure at a later date. This is obvious from identical daily rainfalls in the records.

- Zero Entries

  Some gauge attendants have entered zero rainfall for days when no data were collected. This is evident at certain stations where rainfall is known to have occurred. Since zero readings at particular stations are possible even during widespread rainfall, such readings cannot always be assumed to be false. But inaccurate zero entries substantially degrade the value of the rainfall records.

- Incorrect Collection Time

  During periods of rainfall, all rain gauges should be read at the same time each day. Many attendants find it difficult to do this precisely when the reading time is critical. The overlap of time causes one day's record to be merged with the next and renders important data for both days inaccurate. In some cases, attendants have reported the rainfall for the day the gauge was attended when the rain actually fell the previous day.

- Transcription Errors

  Data from standard rain gauges need to be transcribed several times before they can be published. Each transcription leaves room for errors to enter the record.

- Mechanical Problems

  If the tipping buckets on gauges or intakes get filled with sand or other debris, the instrument records inaccurately.

- Record Reading and Interpretation Errors

  Errors can be made in reducing and interpreting data tracks from chart-recording gauges. This is particularly true on some of the recording gauges for the very intense convective events that are sometimes observed. Reading errors will continue to enter the record as long as data tracks are reduced by hand and until the conversion to automatic gauges and direct digital entry of data from data logger units.

3.6 Oman's Rainfall and Weather

The climate of the country is governed by the movements of the intertropical convergence zone, where winds moving northward from the equator meet air flowing southward from the Mediterranean. Because of unpredictable variations in the cycle of the convergence zone, there are distinct periods when drought follows wetter weather.

During the winter, the general flow of air from the north is driven by the mid-Asian high pressure toward a low-pressure area over the Indian Ocean. This airflow brings dry conditions and blue skies most of the time. Occasionally, however, frontal storms approach from the Mediterranean region, bringing widespread rainfall to northern Oman and hovering over the area for several days. Two or three such events may occur each year, although there are many years with no rainfall whatsoever. The rainfall from these events is of low to moderate intensity but important to the hydrology of Oman.

During the summer months the intertropical convergence zone moves northward across the Arabian peninsula, allowing moist southwesterly winds from the Indian Ocean to spill into Oman. The cool offshore ocean currents along the southern coast and upwelling of the air mass as it collides with the coast combine to bring mist and fog along a narrow coastal strip. Light rainfall often occurs on summer nights. These conditions dominate the climate at Salalah in the southern extremity of the country and are significant sources of moisture for the area.

During much of the year, but especially during the summer, southwesterly monsoon airflows can create local rainfall partly as a result of eddies and pressure disturbances arising from the convergence of northerly and southerly air masses. In some areas the terrain and orography bring localized convective rainfall that is erratic and varies from place to place. Evaporation is so high during some of these events that precipitation may never reach the ground.

Occasionally, violent tropical storms originating in the Bay of Bengal or the southeastern Arabian Sea slam into the southern coast of Oman, bringing heavy rainfall to the southern part of the country. Pedgley, who has researched the records from 1891 to 1967, has identified 28 such storms during this period.

The combination of these rain-bearing elements and high evaporation rates gives rise to a highly irregular pattern of rainfall. In convective events, one station may record heavy rainfall but another nearby may record nothing. The dynamic nature of the convergence zone over Oman and the operation of many kinds of rain-producing systems cause great variations in the temporal and spatial distribution of rainfall. These variations provide an opportunity for further study of the mechanisms and interaction of the weather systems. Meanwhile, the erratic rainfall pattern has significant implications for the design of rain gauge networks and the value of the data they produce.

3.7 The Statistical Pattern of Oman's Rainfall

Several characteristics of the rainfall in Oman affecting the design of a rain gauge network were investigated during this study and are discussed below.

Wide variations in precipitation stem partly from the fact that the mountainous terrain causes vertical movement of air. Convection, driven by rising warm air, creates small local storm cells that may bring intense localized rainfall. Evaporation, turbulence, and the interaction of the various weather systems further confound attempts to define the rainfall pattern.

One key to determining how the usefulness of the network could be enhanced is the statistical examination of expected errors in estimates and generalizations inferred from precipitation data. The study analyzed the records of seven rainfall gauges in the Musandam province, using the MWR's report "Qualitative Analysis and Presentation of Rainfall Data in Oman: Volume I: Musandam" as a database.

The Musandam rain gauges are closely spaced, many of them fewer than five kilometers apart. (A map of these locations is shown in Figure 1.) They have been observed for about 10 years. The seven stations have been operated under the supervision of a hydrologist for several years and the records are believed to be relatively accurate. Although most of the observations were made at standard rainfall stations and a number of errors were evident, the records provided an adequate database for preliminary examination of the statistical character of the rainfall in that region. (The raw data used in the analyses are shown in Table 1.)

3.7.1 Temporal Variability of Rainfall in Musandam

The trends in annual rainfall in the province between 1981 and 1988 are shown in Figure 2. The rainfall for each year is the average from four of the stations: Mehas, Simah, Ghumdah, and Khasab near Khasab.

There was a distinct dry period from late 1983 through 1986. Markedly wetter periods were observed from 1981 to 1983 and from 1986 on. Surprisingly, the average yearly rainfall during the dry period was less than ¼ of the average for the wet periods. All seven gauges traced this trend. Similar variations in annual rainfall appear in the records of the Muscat rain gauge, which has been operated since 1909.

These trends underline the fact that the amount of water available for groundwater recharge and subsequent use varies widely from year to year. Spring-source aflaj and "shoe-string" aquifers with high transmissivity may safely produce highly variable amounts of water for use in different rainfall periods. Drawdowns even from regional aquifers with large multi-year storage capacities may later need to be regulated in cycles that follow the pattern of year-to-year rainfall to protect them from the intrusion of sea water. Large aquifers in areas where intrusion of sea water is not a problem may also need active regulation on a year-to-year basis to limit drawdowns and maintain water quality.

3.7.2 Impacts of Temporal Variation in Rainfall on Network Planning

Detailed knowledge of the shifts in rainfall and the associated time-lagged effects are the building blocks of water management policy. All the rain gauges in Musandam were able to detect and quantify the substantial changes from year to year, suggesting that even a few gauges are adequate for practical purposes. A dense network is not needed. What is needed is a network that covers the areas that face or will soon face groundwater depletion or intrusion of sea water.

3.7.3 Statistical Behavior of Rainfall Observations of Different Time-Scales

To obtain a clearer understanding of the statistical behavior of rainfall, data from the seven stations were arrayed and the inter-station variations were examined for different time-scales from daily to annual observations (Table 2 and Table 3).

The shortest comparable events are daily rainfall totals. The variations among the seven rain gauges were examined using daily rainfalls for the largest storms that occurred between 1981 and 1987 (Table 1). Even for these storms, there was an average coefficient of variation of about 0.48, indicating that the average variation of the gauge readings was nearly one-half of the mean and that part of the time the variations were even larger. The monthly rainfall totals showed a coefficient of variation of 0.42 for the selected sample. Again, the variation among neighboring gauges was quite large. The annual data showed a coefficient of variation of 0.27, which although significant, does suggest that the annual totals can be more readily generalized from one station to another. All the stations closely followed the general pattern of rainfall during the several years of observation.

Variation of Rainfall of Various Time-Scales for Seven Closely Spaced Rain Gauges	
Time-Scale of Rainfall Observation	Average Coefficient of Variation
Daily Rainfall	0.48
Monthly Rainfall	0.42
Annual Rainfall	0.27

3.7.4 Impact of Time-Scale Effects on the Rain Gauge Network

The analyses show that scatter and irregularities in rainfall data tend to average out as longer observations are made. Because of the scatter, short time-scale events like daily rainfall cannot readily be generalized from one station to another or used to represent a large area without substantial error. Annual or seasonal rainfall, on the other hand, may be more accurately generalized from a point observation. If the MWR continues to have a sparse network, perhaps the most useful rainfall data will be those based on longer, rather than shorter, periods. Annual rainfall within typical Oman basins may, for example, be estimated with reasonable accuracy using only three or four rain gauges, because the variations between the gauge observations are averaged out of the record. Far more gauges must be used to achieve the same level of accuracy for short-term events.

3.7.5 Analysis of Expected Error in Areal Rainfall Estimates

Many techniques of hydrology depend on inputs of daily rainfall or rainfall for two or three days. Since rain gauges cannot be placed at every point, the rainfall at points between gauges must be interpolated. Interpolation is embedded in most of the methods for estimating event rainfall from a few gauge sites within a catchment. The analysis below investigates the scale of errors that can be expected in forming rainfall estimates from a network of the density of the Musandam group, where rain gauges are about 5 km apart.

In the calculations, the daily rainfall at various stations was recorded for 20 of the most significant rainfall events during the period of record. The most closely spaced gauges were considered in sets of three or four. The calculation of rainfall at a gauge between two or three stations was based on the rainfall observed at the adjacent gauges. Linear interpolation was used for these calculations, and the resulting formulas are shown in Tables 4, 5, 6, and 7 for four different gauges, respectively, in the central part of the group of gauges. The actual rainfall observed at the gauge is shown beside the interpolation. The difference between the observed and predicted or interpolated rainfall was calculated and the statistical parameters of the differences were computed for comparison with the average weighted distance to the adjacent gauges. The results are shown below.

Statistics of Variance Between Actual and Interpolated Rainfall for Rain Gauges in Musandam			
Rain Gauge	Weighted Distance to Adjacent Gauges	Mean Relative % Error of Estimate	Std. Deviation of Relative Error
Khasab near Khasab	4.5 km	58%	86%
Silian*	5.1 km	27%	29%
Mehas	6.1 km	58%	73%
Simah	7.4 km	71%	94%

* Three station interpolation used at Silian.

The data show that the most accurate interpolation was obtained at the Silian rain gauge, where there were three adjacent gauges at a weighted distance of only 5.1 km from the gauge for which an estimate was made. This station showed a most probable error of 27 percent, but the standard deviation of the errors indicates that about one-third of the time the deviation could be more than 29.7 percent higher than the most probable error. Analyses around the other three gauges showed larger errors in estimating interstation rainfall from adjacent stations. The magnitude of these expected errors and their standard deviations show that, for the storms and at the place under consideration, there was no prospect of forming an accurate prediction of daily rainfall for a place only 5 km away from two or three other gauges. Since areas really are only the sum of so many points in a plane, daily rainfall for an area cannot be generalized without gross errors if methods that rely on rain gauge data and interpolation are used.

Because conditions in Musandam could be unique and, hence, show higher variability than other areas, several other pairs of closely spaced rain gauges were also examined to test variations in rainfall. The large storm and the wet period of frontal storm activity that occurred in December 1989 were used for these comparisons. Data from six pairs of stations within 10 km of one another were analyzed for various daily rainfalls in the record of the storm event of December 1989 (see Table 8). The stations showed average variations from 19 percent for Daqiq and Kitnah to 52 percent for Al Zammah and Misfah. Although higher variability was expected among gauges in mountainous sites, they showed no more than the coastal gauges did. In fact, variations in all the regions were very high.

3.7.6 Impact of Variations on Network Planning

It would be incorrect to assume that similar analyses of other regions of Oman would yield similar errors and interstation variations. The Salalah region, for example, has a much different climate from Northern Oman. Many more sets of data could be tested with such analyses. Nevertheless, the results presented above illustrate some of the difficulties in estimating regional rainfall from a network of rain gauges.

Although far from conclusive, the trends also suggest that, in order to obtain estimates of precipitation over areas for various models, a network grid denser than one station every 5 km on center is desirable. Remote sensing techniques might improve the accuracy of estimates, but the results also indicate that, for the Musandam region, the minimum network density for estimates with only a 10 percent error would be 3 km, or at most 4 km on center.

This illustrates a point about rain gauge deployment. A very large number of gauges are needed to provide the basic data for models that are driven by daily or storm-based rainfall events. Typical basins in Oman range from 50 to 1,500 square kilometers. Thus, the larger basins would require more than 50 gauges to provide event-based rainfall data accurate enough for useful results. A 50-gauge network would cost about R.O. 40,000 to install and each gauge would cost about R.O.350 a year to operate and maintain. The restrictions on the MWR's budget and time would put dense networks for large portions of Oman beyond reach.

Another conclusion from the analysis is that the longer the time-base of observations, the more accurate and useful the data will be, given a constant network density. Longer time-scale observations can be applied to larger areas with reasonable accuracy, and the correlations of one area with another are likely to be strong and consistent. For many water resource investigations, annual and seasonal data are sufficient, and networks of lower density can be effective in delivering relatively accurate generalizations.

3.8 Fitting the Rain Gauge Network to the MWR's Needs

3.8.1 General

It should be obvious that the rationalization of the rain gauge network and planning for its future must be based on the MWR's diverse needs for rainfall information. However, the complexity of the hydrologic cycle and the MWR's multiple priorities do not make it simple to identify the most important uses of rainfall data and their impact on our view of the network.

3.8.2 Rainfall Data for Management of Groundwater

Many MWR officials repeated the theme the Ministry has often stressed: its most important work is finding better ways to allocate the water resources of the country. Water management will become more urgent as time passes and may include limitations on agricultural crops, water pumping, and well drilling; regulation of land use; restrictions on new wells; and a program of public information and awareness.

The Department of Water Management is formulating policies for each major basin, but much work needs to be done before a reliable database can be obtained for resource management. The legal, cultural, and institutional framework of Oman poses special problems. It is certain that those deprived of water will question the fairness and priorities of any water management policy. The Ministry now has the opportunity to prepare a credible technical justification of the measures it plans to take. Failure to do this will dim the prospects for the success of even well-planned and thoughtful management strategies.

The strategies with implications for the rain gauge network now being considered by the MWR—water balance modeling to predict safe yield, adaptive management of groundwater, and use of direct correlation models—are discussed below.

3.8.2.1 Water Balance Modeling to Predict Safe Yield

The water balance equation for most situations involves a bewildering array of variables, including total runoff, long- and short-term water storage in aquifers and soil, current extraction, evaporation, and rainfall. Most models operate on monthly or daily time-scales.

The trends observed in Musandam confirm that monthly or daily rainfall cannot be estimated accurately without a very dense network. Even if the MWR were willing to make the substantial financial commitment required for this, several other variables very difficult to quantify with sufficient accuracy would still be needed.

Alternative water balance models that examine only the surface flow and throughflow into percolation areas have been suggested. These models hold more promise than those that depend on monthly rainfall estimates (see Chapter 8), and eventually may prove their value in the Oman setting by defining groundwater availability in terms of annual or seasonal precipitation.

If the idea does prove to have merit, the rain gauge network will not have to be dense, because annual and seasonal totals can be predicted fairly accurately with a low-to-moderate density of gauges.

3.8.2.2 Adaptive Management of Groundwater

Adaptive management of groundwater specifies the permissible level of extraction from a basin and subsequently adjusts the draft after the effects of the previous adjustment have been determined. This does not demand a high density of rain gauging sites.

3.8.2.3 Use of Direct Correlation Models

Although aquifer parameters and over-year storage prospects may vary from place to place, it may be possible to estimate the volume of water available from upland precipitation data yielded by a network designed for that purpose. Large variations in annual rainfall would logically appear to be linked to the trends in recharge, and a few rain gauges in a particular basin, combined with correlations from a more widespread network, could provide a reasonably accurate picture of the annual and seasonal trends in rainfall over the whole basin. These data could be used in the adaptive management of groundwater to provide better approximations of the permissible interim drafts in particular areas.

3.8.3 Rainfall Data for Flood Prediction

The Surface Water Department has done excellent work in flood mapping and recognizes the need to begin flood prediction for important urban areas. The growing urbanization of Oman has highlighted the danger of flooding, which can cause serious loss of life and property. Places facing significant flood hazard include the downstream areas of Wadi Aday and Seeb Airport. A few rain gauges in the basins above these areas could be provided with telemetry systems to provide early warning of floods. Such gauges have been proposed as part of the expansion program suggested in this report.

3.8.4 Rainfall Data for Desktop Runoff Models

Engineers and design consultants have a number of drainage standards and desktop runoff prediction tools to assist them.

In the United States and elsewhere, intensity, duration, and frequency curves are used to predict runoff from rainfall data, given specific storm recurrence patterns and durations dependent on basin lag. In the United States, however, only a few rain gauge records have been reduced to data of this form. Usually these gauges are placed in important urban centers where complex drainage standards are needed. At the present stage of development in Oman there is little interest in drainage standards or regulations, and the MWR needs to focus on developing these curves for the urban areas where their first use is likely to be seen. Once the conversion to digital input has been achieved, the reduction of data to this form will be simple and inexpensive. At present the records of automatic rain gauges are being analyzed to produce intensity, duration, and frequency relationships for individual stations, partly as a training exercise for technicians to gain an understanding of the meaning and uses of rainfall records.

The Surface Water Department has developed a set of design curves relating basin area to peak runoff based on actual observations. They could be developed for smaller basins as well and might be more valuable than runoff prediction techniques that depend on duration, intensity, and frequency curves and the selection of a "design storm."

3.8.5 Rainfall Data for Recharge Enhancement Schemes

The Surface Water Department needs to make better predictions of the amount of runoff water available for infiltration. Designers of recharge structures must have runoff volume and flood recurrence data to prove the cost effectiveness of these structures and to determine the optimal sites for locating them. Unfortunately, it is difficult for rain gauges to provide this type of information in Oman. The pattern of one rainfall event cannot be used with any confidence to form generalizations about the next event. Only annual rainfall data can be relied upon to give some indication of the longer-term averages of spatial rainfall distribution. Before rain gauges are deployed, it is important to ascertain if they will provide the data needed.

3.8.6 Formatting and Analyzing Data for Ministry Use

Some useful forms and manipulations of rainfall data that might provide many of the answers the MWR seeks are:

- Estimates of annual and seasonal rainfall for various basins based on observations at several gauges in each

- Correlations of annual rainfall in adjacent basins with gauges that have the longest rainfall records

- Developing moving averages of seasonal or annual rainfall for various basins

- Developing statistics for cumulative departures from the mean and relating the cumulative rainfall at particular gauges or groups of gauges to other gauges

- Constructing maps showing the gross annual rainfall for each year of record

- Studies of orographic effects on annual or seasonal rainfall

- Studies of seasonal and annual rainfall for various physiographic regions

- Arrays of rainfall data to determine seasonal rainfall for groups of gauges in the different regions

- Studies of rainfall patterns to determine the sequences most likely to lead to recharge of groundwater aquifers, and arraying these events for subsequent use in correlation with groundwater levels at indicator wells

3.9 Recommended Network Improvements

3.9.1 Rain Gauge Network Design and Layout

The rain gauge network the MWR should install should have the following characteristics:

- The network need not be very dense if analyses are based on longer time-scale observations, which will provide the most useful data for the Ministry's water management program.

- The network should not be used to collect data about locations undergoing short time-scale events if the intent is to apply the results to other basins. The very dense network needed for this will, most likely, never be available.

- Since the collection of data for water management is the most important priority, a minimum number of rain gauges should be deployed in these areas immediately.

- The network should recognize that rainfall in the mountainous areas is more variable than in the low-lying areas and accordingly should be more dense in the mountainous areas and deployed over a range of elevations.

- All standard (observer) rain gauges should eventually be replaced by automatic recording gauges, beginning with the stations that have the poorest records.

This report proposes the addition of 70 rain gauges to the network. More can be added as planned with more precision after the network is expanded to meet new requirements. Continual and rapid expansion of the network will diminish the effort given to data analysis and reporting.

3.9.2 Area-by-Area Recommendations

Problems in the network that should be remedied before expansion takes place are discussed below by region. Recommended rain gauge deployments are shown in the Drawing No. 2, "Preliminary Plan for Future Rain Gauge Expansion Project."

- Central Batinah Region

This is a district where water management must be instituted as soon as possible. Automatic gauges should be installed between Suwaiq and Sohar for basins not currently covered by the gauging network. Gauges are also needed to provide an indication of the rainfall along the coast as well as in the piedmont and mountainous uplands, where slightly higher densities are needed. Ten rain gauges should be installed in this region as part of the expansion.

- Northern Batinah Region

The area north of Sohar near Shinas is poorly covered. Two additional gauges are needed to provide data on the rainfall in the upland area.

- Central Oman

Data for Oman's vast interior between Adam and Salalah are scarce and are needed for a better understanding of the climate and of the role of rainfall in the recharge of aquifers in the region. The gauges may help to determine whether most of the groundwater comes from upland runoff and underflow from the north. The four new gauge stations planned are at relatively accessible sites.

- Sharqiyah Region

This region is poorly covered and nine new stations have been recommended. The sites were selected to provide better coverage of basins supplying water to villages and aflaj, and to extend coverage into the southern flank of the mountains in the region.

- Buraimi Region

Although there are concentrations of gauges in the mountains east of Buraimi, there are very few in the nearby basins. Several new gauges are recommended for an area badly in need of water management.

- Capital Area (Muscat and Vicinity)

Although the capital region has enough gauges for definition of climate, there are two areas that need special attention: the Wadi Aday aquifer, an important source of water for residents of the capital that is also an area where flooding can bring loss of life and property; and the area just west of Muscat, which is among those with the most severe intrusion of sea water. Four new gauges are recommended: an automatic gauge at the historic site in Muscat, and three gauges in the areas just south of the urban centers where floodwaters concentrate. Two of these gauges—in Wadi Aday and Sayl Hatat—should be set up with real-time telemetry as a pilot project.

- Nizwa Region

A few more gauges for better definition of rainfall have been recommended for this region, where increasing use of water suggests that water management data will be needed in the near future.

- Salalah Region

More gauges must be added to the few currently operating to provide a clearer understanding of the aquifer recharge in the area; to provide information on water availability in the Nedg Region; and to track the dissipation of monsoon storms as they collide with the coast. A special station to measure moisture flux to the ground from the mists and fogs of the summer monsoon is discussed below.

- High-Altitude Gauges

Five new high-altitude stations have been sited and new gauges need to be installed on foundations already prepared.

- Other Locations

Many other locations for new gauges have been identified at sites where existing data collection with standard gauges is poor or where more data are needed.

3.10 Equipment Upgrade Recommendations

Many inaccuracies in the rainfall data records are the result of operator error or negligence. Observer rain gauges should gradually be replaced by automatic rain gauges.

The Ministry should also move completely to digital data loggers and digital data reduction techniques. Reduction of strip-chart data from the present Siap and Ikeda rain gauges is expensive and time-consuming. The overall costs are far more than the R.O.10 per hour paid to technicians when the overheads of office space and administration are added. A technician could take 20 hours or more to reduce a complicated chart, and a hydrologist could spend several hours more checking and validating the data. Moving to digital data transfer and digital data reduction could help reduce errors as well.

The Surface Water Department's success with Omnidata data loggers and the benefits of standardizing network equipment suggest that all the rain gauges should have these data loggers. Concern about their ability to withstand the 50°C temperatures often observed in the rain gauge shelters could be allayed by having a local laboratory test them for temperature and humidity tolerance. Vibration and impact testing would also be desirable. If the results prove they can function normally during a 10-day laboratory test, they should be deployed in the expanded network. Although there would be some risk in deploying them without extensive field testing, the saving in time and money by switching from strip-chart reduction would make the risk acceptable.

The department has decided eventually to replace existing rain gauges with tipping-bucket Siap rain sensors and Siap gauge housings or ones made locally. Locally made gauge shelters can be customized for local conditions, with improvements in ventilation and accessibility and a design that allows the use of both strip-chart recorders and data loggers.

One idea is for the MWR to invite two or three reputable sheet-metal workshops to construct a prototype rain gauge housing, providing them with drawings and asking for their price for the manufacture of a large quantity of the gauge housings over a six-month period. The selected prototype could be moved to the fabrication shop, bolted to the floor, and used as the quality standard thereafter.

3.11 The Network Expansion Project

3.11.1 General

Since the Surface Water Department has a number of other important tasks, some of the work of managing the network expansion should be delegated to a consultant and the installation should be entrusted to a contractor working under the consultant's supervision. The consultant should be an engineer with 5 to 10 years of experience in hydrology and project management who would work closely with the head of the hydrometeorology section.

The consultant's first task would be to establish the final sites for the gauging network, guided by the drawings in this report. Much work remains to be done in obtaining the necessary clearances and approvals for these sites.

3.11.2 Planning Gauge Deployment

The consultant should visit each district office to discuss the layout of gauges within the district and such minor adjustments as are necessary, noting any useful comments by the district chief and preparing a report on his discussions to help the Surface Water Department in planning subsequent network expansion. He should also enlist the help of the district office in obtaining access to the local Wali and other officials who may need to inspect and approve rain gauge sites. A local guide/translator should be assigned by the Surface Water Department or the district office to accompany him. The consultant should then do a reconnaissance of each recommended site and, wherever possible, enlist the services of a person living or working nearby to oversee the security of the rain gauge(s). The Ministry has found that schools, police stations, and other government offices make excellent locations for gauges. It should prepare the necessary letters and maps to obtain clearances for these sites at the Wilayats or elsewhere.

Each site finally selected should meet the following criteria:

- It should be in a position that discourages vandalism.
- It should be under the control of the property owner who, ideally, should be the person who has oversight responsibility for the gauge.
- It should not be on property where ownership is disputed.

- Since the site should be permanent, it should not be on property likely to be built upon or altered in the foreseeable future.

- Access to the site should be as easy as the coverage requirements permit.

- The site should not have encroaching structures or trees within an envelope rising at a 30-degree angle from the lip of the gauge intake.

- It should not be in an area where unusual wind patterns are caused by nearby structures or topographic features.

3.11.3 Installation of Gauges

Once a site has been confirmed, the consultant should flag it on a 1:100,000 scale road map for use by the contractor. All sites should be identified on a 1:250,000 base map for tenders for foundation laying and gauge installation by a construction company. The MWR has global positioning systems to ensure the accurate location of each site. Each site should have a stable concrete base and a protective fence before the rain gauge shelter is mounted. When this has been completed, a member of the MWR staff should visit the site to brief the gauge overseer, install and activate the datapod or chart recorder, and log the startup date.

3.11.4 Costs of the Expansion Project

The capital and the long-term maintenance and operation costs of the expansion project are summarized in Tables 9 and 10 respectively. The capital costs have two elements: the costs of project planning that precede installation and of land for some of the sites; and the costs of equipment and installation. Planning will require about four months of the consultant's time and cost about R.O. 12,000. The cost of land is difficult to estimate because some sites may be offered without charge. An allowance of R.O. 25,000 has been provided in the capital cost estimate. Eight months of consultant time for inspection and supervision of the contractor have been included in the construction costs.

About R.O. 2,100 will be spent on gauge housings, tipping bucket sensors, and data loggers for each site. The concrete foundation for each gauge should cost about R.O. 150, assuming most of the sites can be accessed by truck and provided the specifications allow the concrete to be field-mixed from rock obtained close to the site. A well-built chain link enclosure should cost about R.O. 675. Transporting the gauge to the site, assembling it, and bolting it to the foundation should cost about R.O. 60. The preliminary estimate of total project cost is R.O. 280,000, or R.O. 3,600 per site.

3.11.5 Long-term Costs

Long-term costs for the life of the installation are summarized in Table 10. They cover the replacement of inoperative or worn-out equipment, the general upkeep of the gauges, and the labor involved in reducing and checking data from the new sites. Although this labor cost is small compared with the cost of reducing data from chart-type gauges, it is included here for completeness. The MWR can expect to spend about R.O.350 per year to keep each site operational for the long term. The cost will be small during the first few years of operation and will grow as replacements and more maintenance are needed.

3.11.6 Costs Versus Benefits

The map of existing rain gauge sites shows a number of gaps in the network. Some are in areas where water management policy must be formulated. But even with the proposed expansion, the network will be far less dense than what is recommended by the World Meteorological Association for the terrain and climate of Oman (one gauge for every 250 sq.km). The value of the new data is difficult to estimate but the management of Oman's water resources should benefit greatly from this information. Another benefit will be the replacement of several standard (observer) gauges, with their potential for inaccuracies and errors that could invalidate the whole record after years of expense. The new automatic gauges will prevent this. In general, the proposed expansion should bring benefits far greater than the cost of the gauges and their continuing upkeep. The question of adding gauges to the system while maintaining a larger benefit than costs is discussed below.

3.12 Planning Future Network Expansions

The network expansion proposed in this report will provide reasonably complete coverage at minimum density. Once it is complete, the Surface Water Department will be able to determine what further expansion, if any, is required. The question of how many gauges are enough can be investigated by a number of statistical techniques, including a more rigorous application of the simple techniques described in this report. This analysis will determine the levels of accuracy required and the time-scales of the observations for various applications of the rainfall data and will be most useful in guiding the MWR's pending policy decisions on the kinds of resource investigations to focus on. The decision to undertake any resource investigation must be firmly linked to the network and its future development.

The Surface Water Department must carefully evaluate requests for special or project network installations for evidence that the additional gauges will actually produce the desired results in the context of the precipitation in Oman and the difficulties of generalizing data from a point or an event to larger areas or longer time-scales. A careful examination may indicate that some requests are based on inadequate consideration of these points.

3.13 Training Aspects

The Surface Water Department has done an excellent job in training new personnel, but the following training tasks lie ahead as the network is expanded:

- Computer Training

  Since future data inputs will be in digital format, there will be a growing need for computer-trained staff. Most technicians have had basic instruction but must be given additional training.

- Training in the Fundamentals

  Many technicians will need further training in the fundamentals of hydrology. The following topics probably need review and, perhaps, some classroom sessions:

  — The MWR's role in water resource development. Technicians could be grouped in teams to examine how their work fits into this role. The exercise could generate useful discussions about what is important and why.

  — The use and meaning of rainfall and wadi gauging measurements. This may be abstract, but some advanced technicians could offer insights to the novices.

  — The MWR's organization and brief descriptions of each department and what it does.

  — Work sessions in teams to solve some simple but practical problems. A typical problem might be how to calculate the areas of various figures and to discuss how this kind of calculation could be made on maps. Use of the planimeter could follow in the next session.

Emphasis in all training would be on encouraging technicians to exchange knowledge, so that those who master a concept can teach several others.

3.14 Other Enhancements to the Network

3.14.1 Weather Images and Remote Sensing

During the past 10 years, much has been done to enhance the data collected from the rain gauging network, in particular through the use of satellite images and radar images from ground stations. Barrett and his colleagues have described various techniques using remote sensing and "ground truth" from rain gauges to predict rainfall across wide areas. One of these techniques is scanning images of the storm for cloud height and temperature.

In Oman's peculiar conditions, rainfall at higher elevations often has evaporated before it can reach the ground at lower elevations. The satellite images in Barrett's studies provided levels of resolution too low for Oman, where variability is extreme. Although there is great potential in this work, it is still somewhat experimental and requires a highly skilled meteorological analyst.

The Surface Water Department could consider enhanced images available on modem or by satellite links as an interim step toward remote sensing. For a start it could make images of the important storms a part of its storm event data reports. General storm movement, direction, and wind speed could be added to the images in the event reports. This would have two benefits:

- The type of storm producing the rainfall could be easily identified from the images, and rainfall data could be linked to the storm type for future analyses to identify the rainfall characteristics of different weather systems and the relative importance of these systems in the rainfall hydrology of various areas.

- The image data could help in determining the importance and spread of the event in areas without gauges.

Although there would be few uses for these images and weather data at present, inspection of images and subjective analyses would introduce the ideas to the department staff and pave the way for more sophisticated methods, such as those suggested by Barrett.

3.14.2 Satellites

The European Space Agency's geostationary satellite over the equator at the Greenwich meridian can produce an image of Oman every 30 minutes and simultaneously transmit the data to ground stations. Since the satellite is fixed at about 32 degrees above the horizon in Oman, its images are oblique and not as well defined as those taken by the polar orbiting satellites. The major advantage of the geostationary satellite is that it can transmit near-real-time images of storms approaching and moving across Oman.

The National Oceanic and Atmospheric Administration of the United States and the Department of Meteorology Satellite Programs of the U.S. Air Force both maintain polar orbiting satellites. Each agency has two satellites in sun-synchronous orbits established so that the satellite goes over the same point on the earth twice each day at the same time. Thus, the two satellites transmit four images of every area on earth everyday.

The National Oceanic and Atmospheric Administration operates the NESDIS satellite, which produces infrared images at a resolution of about 7 km and visible light images at a resolution of 1 km. It can obtain data on cloud height and temperature and transmit real-time images from the NOAA offices in Washington, D.C.

The Air Force DMSP satellite has a Special Sensor Microwave Imager that can be used to estimate rainfall through direct measurements using an echo technique. Data from this satellite are available from WETNET and the informational network operated by NASA. Data are about a week old, although it may be possible to obtain real-time information. Dr. Ron Scofield of the NESDIS information processing department is perhaps the most authoritative source of information on the capabilities of the system, which has been used around the globe for rainfall prediction.

By April 1991, the European Space Agency will be licensing its Meteorological Data Distribution system linked with Meteorsat. The new system will provide much improved images of Oman, with an image obtainable every hour.

3.14.3 Sources of Processed Weather Information

At least two specialized firms in the United States regularly purchase data from various satellites and radar stations and process them into images. WSI Corporation of Billerica, Massachusetts (phone 508 670 5000) produces a number of weather maps and images from satellite data to interpret cloud height and temperature and has elaborate computer models to enhance the images and fill in areas where information is sparse. The firm creates a series of digital overlays and transmits the data to communications centers around the world. WSI's most important business is the production of weather maps or weather forecasting maps, but it can also produce a fairly good, but oblique, image of cloud cover over Oman resolved to 12 levels of cloud height. Users of the system may obtain a patented software to operate on the digital image data and transform it into images that can be plotted on paper, displayed on the computer screen, or compressed by special software for storage. Each file requires about 1 to 2 megabytes of disk space for storage. The user may select the type of image or map required and build it up at the computer screen.

Alden International of Westboro, Massachusetts produces similar products, using images from the polar orbiting Tyros Satellites and the European Space Agency's Meteorsat, and can provide three images of Oman each day. Alden International will soon be linked to the

European Space Agency's Meteorological Data Distribution system and within a few months enhanced data for Oman should be available.

3.14.4 Ground Moisture Flux Measurement

The summer monsoons bring fog and mist to southern Oman, covering the ground and vegetation with moisture in the morning. Some of this moisture is absorbed by the soil and may be an important element of the hydrologic cycle in the southern region. Rain gauges can provide no indication of the quantity of water taken up by the soil during the monsoon season.

A new instrument, called the particulate volume monitor, may be able to measure the moisture flux to the ground with some accuracy. It passes a laser beam through fog-laden air and measures the light scattered by the small droplets of moisture to estimate moisture content.

Typically, the instrument has been used to measure moisture density in the air but can be modified to measure the direction and flux of moisture. In one application, it was placed over the forest canopy to measure moisture flux in a forest region. The instrument measures and records the moisture content of the air passing a point with the help of a wind vector analyzer that integrates the moisture density with the net movement of air and provides an estimate of the flux.

It is doubtful whether the instrument can be used successfully to measure surface moisture, which may be largely the result of condensation rather than the flux of fog droplets. The boundary layers near the ground and the influence of plants and even minuscule projections above the ground may have important local effects. It is doubtful whether any vector analyzer could be accurate enough to resolve the relatively minor flux of air into the ground observed during cycles of temperature and barometric pressure, amidst the normal turbulent air movements near the surface and the more laminar flows of air at the surface boundary layer.

Perhaps the use of weighing lysimeters is more appropriate for measuring actual flux of ground moisture. More information about the devices can be obtained from Gerber Scientific in the United States.

Chapter 4

SALINITY TRANSECTS

See Part 4, Chapter 6, "Salt Water Intrusion, Monitoring, and Remediation," Task 5 and 6, in WASH Field Report No. 353.

NOTE: This topic was originally to have been treated under Tasks 3 and 4 but was rescheduled, because of the Gulf War, under Tasks 5 and 6.

Chapter 5

DRAINAGE BASIN CHARACTERISTICS

5.1 Introduction

5.1.1 General

The use of drainage basin characteristics to predict annual and seasonal flows in areas of minor topographic relief served by perennial streams has proved more satisfactory than in arid regions with major mountain systems. The sporadic nature of the storms that visit rainfall upon the latter makes runoff predictions difficult. It is possible that with a rain gauge network of adequate density the shapes of flood flow hydrographs generated in gauged basins can be related to such physical parameters as drainage area, main channel slope and length, mean basin elevation, and drainage density, provided sufficient information can be obtained on soil and rock coverage, basin permeability, flow attenuation in channels, and other geomorphological characteristics. Flood flow frequency analysis can be used not only for the hydrologic design of dams, bridges, spillways, and culverts, but also to predict long-term average flow for improved water management techniques.

5.1.2 Scope of Work

The scope of work for the drainage basin characteristics section covered these tasks:

- Visit areas in northern and southern Oman, primarily along the Batinah and Interior regions of the Jebal range in the north and the Jebal Qara and Salalah plain in the south, to become familiar with the terrain and basin characteristics.

- Review records of flood hydrographs from gauged basins to correlate basin characteristics (slope, shape, aspect, channel density, channel length, etc.) with flood hydrograph shapes.

- Evaluate the feasibility of relating basin characteristics to flood hydrographs and applying the correlations to ungauged basins to predict catchment yield, considering the conditions in Oman and similar work done in the southwestern U.S. and other arid mountainous locations.

- Prepare a plan to relate wadi basin characteristics to flood flows and surface water yields and to apply those correlations to the prediction of catchment yield in ungauged basins.

5.1.3 Background

The U.S. Geological Survey has greatly expanded its database during the past two decades, enabling special studies to be undertaken that estimate streamflow characteristics of selected ungauged sites based on a comparison of drainage basin characteristics of gauged and ungauged sites. One method for estimating monthly streamflow characteristics at ungauged sites uses multiple-regression equations that relate the monthly streamflow characteristics at gauged sites to various basin and climatic variables. The method has been used in Montana to estimate monthly streamflow characteristics of perennial streams. Another method that has been used in Montana, Colorado, New Mexico, and Kansas relates monthly streamflow characteristics to selected channel geometry parameters, particularly channel width. A third method requires 12 monthly streamflow measurements at the ungauged site and hence is valid only for perennial streams.

The wadi channels in Oman are composed of silts, sands, gravels, and cobbles with varying degrees of permeability. They are visited by infrequent rains that can produce major floods in 10 to 30 minutes of intense rainfall, since much of the rain falls on impervious surfaces such as the mountains or naturally cemented channels. Because these channels can receive or lose water as a result of local geological features such as braided or sand channels, the methods that are reasonably successful for perennial streams do not always work as well in arid regions. This study examines certain catchment areas for drainage basin characteristics that might bear a relationship to rainfall-recharge-runoff values derived from the existing database.

5.2 Summary and Conclusions

The summary and conclusions relating to the feasibility of using drainage basin characteristics to develop flood flow hydrographs and estimate total flow volumes for ungauged basins in Oman are listed below.

- The use of drainage basin characteristics to correlate flow data in arid regions has not been too successful because of the ephemeral flows generated by sporadic and often isolated storms.

- The two most significant variables are the distribution of rainfall over the catchments and subcatchments, and the permeability of the various types of rocks and soils found in each catchment, especially the wadi sands and gravels and adjacent alluvium.

- Analyses of a series of storm events over three different drainage basins from December 1989 to February 1990 showed the existing rain gauge network (with average coverage of 200-250 sq.km per rain gauge) was not dense enough to adequately define the extent, intensity, and duration of the rainfall, and therefore probably estimated greater rainfall than actually occurred.

- Attempts to generate synthetic hydrographs based on runoff patterns deduced from rainfall data from existing gauges produced wide-ranging results, with peak flow usually less and total flow volume usually more than recorded, sometimes by a factor of 3 or 4, once again suggesting rainfall patterns of great variation with only partial coverage of the basin.

- Studies of the Wadi Ghul-Wadi Misfah-Wadi Bahla basin showed not only that the density of rain gauges is not sufficient, but that the two existing wadi flow gauges are not adequate to portray the sources of incremental flows in the basin.

- Studies show that the more mountainous the terrain and arid the region, the more variable the rainfall patterns tend to be. Recommended densities are 60-100 sq.km per rain gauge—to keep the range of error within 10-15 percent—and 100-120 sq.km per wadi flow gauge.

- The program to update the 1977 report on channel geometry techniques for estimating wadi flows should include data for 80 new wadi flow gauges. Flood frequency relations and estimates of mean annual flow should be developed for each gauged site, and ungauged sites should be analyzed subsequently. A three-year update program would cost about R.O.152,000.

- An alternative to this program would be to set up approximately 15 new wadi gauge stations, some of them in the upper piedmont of the Batinah area, to quantify the total surface water flow available for recharge. These stations would cost about R.O.90,000.

5.3 Physiographic Regions of Oman

5.3.1 The Batinah

The Batinah begins just east of Seeb Airport, widening from less than 10 km to 30 km at Barka and maintaining this width for about 50 km northward to Suwayq, then narrowing beyond. It consists of two zones paralleling the coast: a piedmont zone that extends from the base of the mountains to the sea and terminates in a series of stream terraces, and a coastal plain between the piedmont zone and the sea that contains the alluvial deposits of the wadi channels, the fertile soils used for agriculture, and the coastal dunes. The piedmont zone comprises about 56 percent of the Batinah and the coast plain the rest. The climate is arid. The winter months from November to April are characterized by widespread and sometimes heavy rainfall when the northwest airflow is interrupted by disturbances from the north. In summer, the southwest airstream brings frequent rainfall to the northern mountains, but this rarely reaches the Batinah. Although there are no perennial flows in this region, the wadi channels carry surface water during periods of heavy rainfall and many of the streams originating in the mountains flow for some time after rainfall, particularly in the downstream reaches of the piedmont zone.

5.3.2 The Interior

The eastern side of the northern mountains extends to the Batinah; the western and southern sides overlook many alluvial fans and the piedmont zone of the interior desert. These mountains generally rise above 1,500 meters, and the Jabal Akhdar section between Rustaq, Al Hamra, and Sayq has elevations close to 3,000 meters. They are composed mostly of barren bedrock and receive much of the rainfall that recharges the low-relief alluvial plains of the Batinah and the interior desert. Much of the sediment deposited in the broad alluvial fans comes from the erosion of these mountains.

The northern mountains greatly affect the amount of rainfall that becomes available as fresh water in this part of the country. The moisture intercepted at the higher elevations enters fractures and joints in the rock and reappears at lower elevations as springs that feed the major falaj systems serving the piedmont and higher inhabited areas. Much of the rain that falls in the mountains is from short intense storms and quickly becomes runoff.

5.3.3 The Salalah Plain

The Salalah plain is a flat southern coastal plain of about 800 sq.km along the Arabian Sea. Its groundwater system is recharged by the Jabal Al Qara, a mountainous divide to the north. The Salalah area receives an average annual precipitation of 100 mm, about 75 percent of this occurring during the monsoon months of June, July, and August. It has much natural vegetation and significant agricultural development, sustained by groundwater from numerous springs and wells. The springs also serve major falaj systems. Surface-water runoff is infrequent, sometimes occurring during or after monsoons and sometimes associated with cyclonic-type events, and has played a negligible role in the water supply. Records of surface flow volumes are sparse, and only a few flows have been measured.

5.4 Review of Rainfall/Runoff and Catchment Area Yields

5.4.1 Rainfall During Storm Periods

This study focused on the three months from December 1989 to February 1990, when most of northern Oman experienced above average rainfall and rain and wadi flow gauges were full; hence, more records were available for correlation studies. The records (Ministry of Water Resources, 1990) show that in December 1989 rainfall in the north Batinah ranged from 44 mm to 113 mm, averaging 71 mm for 12 stations, and was four to eight times the average. In the south Batinah, rainfall ranged from 15 mm to 144 mm, averaging 63 mm for 21 stations, and was four to nine times the average. In the interior, rainfall ranged from 5 mm to 63 mm, averaging 38 mm for six stations, and was five to nine times the average. In the Salalah area, rainfall was much less, ranging from 3 mm to 49 mm and averaging 18 mm for four stations.

For the three-month period, rainfall in the north Batinah ranged from 112 mm to 224 mm, averaging 179 mm for 13 stations, or 1.8 times higher than the yearly average. In the south Batinah, rainfall ranged from 66 mm to 235 mm, averaging 156 mm for 22 stations, or 1.5 times higher than the yearly average. In the interior, the total ranged from 72 mm to 241 mm, averaging 167 mm for 10 stations, or 1.2 times higher than the yearly average. In the Salalah area, rainfall was again much less, ranging from 8 mm to 58 mm and averaging 30 mm for four stations.

5.4.2 Flow Data from Wadi Gauge Monitoring

The above-normal rainfall from December 1989 to February 1990 resulted in higher than normal wadi flows in those areas that received the most rainfall, and heavy wadi flows during December along the Batinah from Muscat to Shinas. Most of the wadi flows during January were also in the Batinah, while February wadi flows were widespread in northern Oman, with the largest flows recorded in the interior and Sharqiyah regions. The largest volume recorded in December was 8.782 million cubic meters (mcm) at Wadi Bani Ghafir near Falaj as Saidi, near the foothills of the jebals in the Batinah; the largest volume recorded in January was 3.467 mcm in Wadi Fizh near Sabakh in the north Batinah. In February, a volume of 13.01 mcm was recorded at Wadi Ahin near Hayl, also in the north Batinah. Flow data for the three-month period for selected stations near the foothills of the jebals in the Batinah and the interior are given in Table 11 in mcm as well as in runoff—the depth in millimeters the runoff would reach if spread uniformly over the catchment. Runoff depths varied from a low of 5.57 mm at Wadi Al Khawd to a high of 50.2 mm at Wadi Tanuf. There is a definite relationship between size of drainage area and total runoff, as depicted in Figure 3. The smaller watersheds are usually higher and have steeper slopes covered by more impervious rock surfaces, whereas the larger watersheds have longer and wider wadi channels with more permeable strata that accommodate more recharge and leave less flow for surface discharge. Rainfall data for eight of the selected wadis in Table 11 have been averaged for each basin and the three-month rainfall is compared with the total runoff and shown in Table 12. Figure 4 shows the relationship between size of drainage area and the ratio of runoff to rainfall for the three-month period; as in Figure 3, the smaller the watershed, the greater the rainfall that can be expected to approach as runoff.

The flow data for the analysis included flood hydrographs tabulated and plotted by the MWR, often with peak flow and calculated storm volumes given. The Surface Water Department's April 1990 report estimated that the total surface flow reaching the Batinah's coastal plain during the three-month period was 75 mcm and that about 75 percent of this was lost to the ocean. A similar estimate of surface flow from the foothills to the upper Batinah would provide a comparison of the differences. The plotted flood hydrographs matched with rainfall data yielded response times, rainfall intensities, and durations necessary to produce surface flows in the wadis. The hydrograph shapes also gave an idea of the part of the upstream catchment that might have produced surface flow for a particular storm event.

5.4.3 Flood Hydrograph Shapes Related to Rainfall Patterns

Small drainage basins probably yield the most meaningful relationship of hydrograph shapes and runoff volumes to rainfall records, even if only one rainfall gauge furnishes data. This is because of more even rainfall distribution in small basins, provided the topographic relief or orographic features do not alter this. The uniformity also makes predictions of runoff more reliable. Figure 5 depicts rainfall and flood hydrographs for Wadi Misfah at Al Hamra for two events, on December 8, 1989 and February 8, 1990. The first produced a peak flow of 21.0 cm after a total rainfall of 9.6 mm in about 90 minutes; the second resulted in a peak flow of 24.4 cm after a total rainfall of 7.8 mm in two downpours about three hours apart. The December 8 event produced a total runoff of 180,472 cm, which is 3.08 mm spread evenly over the catchment. The February 8 event produced a total runoff of 212,107 cm, which is 3.62 mm spread evenly over the basin. The runoff-to-rainfall ratio was 32.1 percent for the first and 46.4 percent for the second event. At first glance, this suggests a greater runoff from less rainfall. As it happened, a rainfall of 13.4 mm over four hours occurred on February 7 and probably affected the baseflow or groundwater level for the February 8 event. A good example of why large basins will often produce results having little value is given in Figure 6, which depicts the rainfall and flood hydrograph for Wadi Bahla at Bahla for the February 7, 1990 event. Wadi Bahla has a catchment more than 10 times that of Wadi Misfah, which is included in the Wadi Bahla catchment. The February 7 event produced a peak flow of only 21.1 cm and a total runoff of only 164,358 cm, which is only 0.27 mm spread evenly over the catchment. If it is assumed that the average rainfall for the catchment is the average of the Al Hamra and Bahla gauges, then the runoff-to-rainfall ratio is a minuscule 1.8 percent, which is highly unlikely. In all probability the basin-wide average rainfall must have been less than 14.9 mm, suggesting that not all of the subcatchments received comparable rain.

These are some of the deductions that can be made by analyzing particular storm events from rainfall and wadi flow gauge data. The need for greater coverage density is discussed later.

5.5 Review of Flow Hydrographs and Drainage Basin Characteristics

5.5.1 Basin Characteristics Method

The basin characteristics method has been used by the U.S. Geological Survey in several areas of Montana (Parrett, Johnson, and Hull, 1989) to estimate flood and stream flows for ungauged perennial streams. The method uses multiple regression equations that relate streamflow characteristics at gauged sites to various measured basin and climatic variables to generate flow data for certain ungauged sites. The variables are drainage area, basin perimeter, basin slope, main channel length, mean annual precipitation, main basin elevation, maximum basin relief, and percentage of basin above a particular elevation. The analysis uses a computerized procedure that yields a nonlinear regression equation in the following form :

$$\log Q = \log a + b1 \log B + b2 \log C + \ldots bn \log N,$$

where

Q	(response variable) is the desired monthly streamflow in cubic feet per second (monthly mean streamflow exceeded 90, 80, 50, or 20 percent of the time for all years of record, or mean monthly streamflow),
a	is the multiple regression constant,
b1, b2 .. bn	are the regression coefficients, and
B, C, ... N	are values of the significant basin or climatic characteristics (explanatory variables).

The basin characteristics equations thus derived are generally more reliable for estimating higher-flow than lower-flow monthly characteristics. The study concluded that regression equations based on drainage basin and climatic characteristics are not applicable to streams that receive or lose water as a result of localized geologic factors. Certainly, the wadi channels in Oman, with their varying capacity to recharge aquifers below, make the applicability of this method open to question.

5.5.2 Channel Width Method

The channel width method has been used by the U.S. Geological Survey in several western states[1] to estimate monthly streamflow characteristics and to a limited degree in Oman and Saudi Arabia. This method also uses a regression analysis relating streamflow characteristics to such channel width features as active channel width and bankfull width, with active channel width more significant. The active channel width has been described by Osterkamp and Hedman (1977) as "...a short-term geomorphic feature subject to change by prevailing discharges. The upper limit is defined by a break in the relatively steep bank slope of the active channel to a more gently sloping surface beyond the channel edge. The break in slope normally coincides with the lower limit of permanent vegetation...". Some studies have included mean depth in the analysis, and although this may narrow the range of 95 percent confidence limits, mean depth is not considered statistically significant at the 1 percent level. The equation takes the form:

$$\log Q = \log a + b \log W_{AC}.$$

where

Q	is a monthly streamflow characteristic as previously defined,
a	is the regression constant,
b	is the regression coefficient, and
W_{AC}	is the active channel width.

The study concluded that regression equations based on channel width are generally not applicable where bedrock is exposed in the channel or on braided or sand-channel streams as in Oman.

5.5.3 Unit Hydrographs

The unit hydrograph is a natural or synthetic hydrograph of one inch of direct runoff from the drainage area (U.S. Department of Agriculture, 1971). It is based on an estimation of the runoff from rainfall as well as a determination of paths of flow, travel time, lag, and time of concentration, which are influenced by such drainage basin characteristics as topography, stream density and length, degree of imperviousness based on soil types, and degree of development and basin slope. The runoff is also based on basin imperviousness as well as on rainfall duration and intensity that produce a precipitation excess. This excess is most difficult to estimate in arid climates because of the wide range of permeability in the stream or wadi channels as well as the permeability and porosity of rock types like those that pervade the upper reaches of most wadis in Oman. Further, the variability of rainfall in

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[1]Montana, Colorado, New Mexico, and Nevada

Oman also makes rainfall estimates questionable on all but the smallest catchments. Herein may lie the practicality of this method. By dividing a catchment into a number of subcatchments, not only can basin characteristics be determined for each subcatchment, but the likelihood of more uniform rainfall increases substantially with the smaller subcatchment. Unit hydrographs for each subcatchment can be adjusted to reflect the expected runoff from particular rainfall events, and the hydrographs can then be combined and routed for comparison with the record from a wadi flow gauge on the major wadi. This technique, combined with the two methods just described, could provide the needed comparisons to enhance confidence in the analyses.

5.5.4 Flood Hydrograph Shapes and Correlations

Hydrographs for a number of wadis along the foothills of the Batinah and in the Interior show some distinctive characteristics. The hydrograph is an integration of the physical characteristics of the drainage basin (which control the lag times between rainfall and runoff) and the intensity, duration, and extent of the rainfall events that produce runoff. The magnitude of the flood in the main stream or wadi is determined by the size, orientation, and movement of the storm relative to the various subcatchments. There is no general relationship between flood magnitude and the catchment area in arid zones, except for small basins. The peak flow rates generated by high-intensity rainfall may occur within 10-15 minutes of the start of a rise in discharge, particularly if there has been antecedent rainfall within a 3-6 hour period. When a flood produces more than one peak, the highest usually occurs within 2-3 hours of the start of a rise, and the earlier peaks can be due to wide variations in lag time in the various subcatchments as well as the randomly distributed multi-cell convective rainfall occurrences and the runoff response at the point of observation. Sometimes near-translatory flood wave types develop and are propagated downstream with a velocity greater than the original flood peak, causing a "wave-train" to form and producing a hydrograph with a series of sharp rises before the highest peak.

In arid regions, flood peaks and flow volumes usually diminish with their passage downstream as flows infiltrate into the channel bed and spill over the bank. As the groundwater level below the alluvial channel rises during a flood, recharge by infiltration and percolation decreases, and the recharge amount is controlled by the limited volume of storage available beneath the bed. Where groundwater levels are too low to affect infiltration, recharge amounts are a function of the availability of floodwater. Flow-duration and flow-volume curves generally are very steep, with a significant proportion of the total flow occurring at high discharge rates. No reliable general relationships can be derived between seasonal or annual runoff and rainfall, except with abnormally high precipitation events (November 1989—February 1990), which show a diminishing ratio of runoff to rainfall as drainage area increases (see Figure 4).

5.5.5 Definition of Drainage Basin Characteristics

The physical characteristics of a drainage basin are defined as follows:

- Drainage Area: the area that contributes flow to the point in question during a runoff-producing event.
- Basin Perimeter: the length in kilometers of the drainage basin outline.
- Mean Basin Elevation: the average elevation of the drainage basin, usually determined by averaging the elevations from a grid placed on a map of the drainage area. The area above a given elevation is sometimes expressed in percentage of total drainage area.
- Main Channel Length and Slope: the length of the main channel in kilometers, and the difference in elevation between the high and low points divided by channel length.
- Basin Slope: the length of all contours within a drainage basin multiplied by the contour interval and divided by the drainage area.
- Drainage Density: the length of all drainage channels or wadis divided by the drainage area.
- Basin Coverage: the area within a drainage basin covered by rock; also the total length and area of alluvium in wadis.
- Circularity Ratio: the drainage area divided by the area of a circle with the same basin perimeter.
- Maximum Basin Relief: the elevation of the stream or wadi at the basin outlet subtracted from the maximum elevation of the drainage basin.

The study has ranked the following characteristics on an ascending scale of 1 to 10 and suggests that a ranking below 6 merit no further consideration:

Ranking	Characteristic
10	Drainage Area
9	Main Channel Length and Slope
9	Basin Coverage
8	Basin Slope
7	Mean Basin Elevation
7	Drainage Density
6	Basin Perimeter
5	Maximum Basin Relief
4	Circularity Ratio

A review of other studies shows the most significant variable in almost all instances to be main-channel length, which bears a distinct relationship to drainage area. The key to developing meaningful data in arid regions is a reliable estimate of the permeability of the catchment. This is a function not only of impervious rock formations, but also of the area occupied by wadi sands and gravels and adjacent alluvial deposits. The slope of the basin completes the four most important drainage basin characteristics.

5.6 Feasibility of Relating Drainage Basin Characteristics to Flood Hydrographs

5.6.1 Problems in Arid Zone Hydrology

The arid zone basins in Oman are characterized by ephemeral flows generated mostly by sporadic and often isolated storms. Because of the difficulties of correlating runoff within a basin, not to mention adjacent or similar basins, it is important to establish a network of gauging locations that can provide data from a number of unrelated sampling points should it not be possible to develop a general knowledge of spatial runoff. Representative basins must be small subcatchments if an understanding of the rainfall-runoff processes is to be followed by realistic flow estimates and hydrograph data. In some basins, it might be preferable to obtain runoff data from a larger catchment than to subdivide the basin for detailed data gathering. The periodic measurement of natural spring flows should aid in understanding the hydrologic activity of some agents, including confined aquifers that produce artesian flow. The measurement of aflaj flows also should improve the general understanding of the hydrology of certain areas.

5.6.2 Preliminary Approach—Development of Correlations for Gauged Basins

Studies based on basin characteristics for perennial streams and channel width techniques for both perennial and ephemeral streams suggest that a technique embodying characteristics significant to the hydrology of arid region streams might have the potential for relating rainfall to runoff for particular events. The two most significant variables are the distribution of rainfall over the catchment or subcatchments and the permeability of the prevailing rocks and soils, especially the alluvium. The present rain gauge network in Oman is not dense enough to ascertain average rainfall for a catchment having a wadi flow gauge at the outlet from the mountains, let alone rainfall for the subcatchments necessary to focus on small basins. Determining the permeability of each catchment or subcatchment would take detailed studies of specific events over a 3-5 year period with adequate rain gauge density.

Since seven weeks in Oman were not enough for a detailed evaluation, the study team selected the unit hydrograph method. Each catchment was divided into subcatchments, whose characteristics (such as time of concentration, lag time, time to peak, and time of base) were determined using SCS methods. The unit hydrographs for each subcatchment were then combined to produce a unit hydrograph for the catchment. The test for this approach consisted of taking a rainfall event for which there was a wadi flow hydrograph and utilizing the available rainfall records to determine rainfall distribution over the various subcatchments. The excess rainfall (that assumed to produce runoff) was determined by considering only rain that fell at a rate of more than 0.03 inch in 5 minutes (Arteaga and Rantz, 1973). Admittedly, this approach did not factor in the impact of antecedent precipitation, which probably did affect some storms. A pilot program as part of a representative basin study could develop a range of values for each catchment as well as a relationship between average rainfall intensity and basinwide water loss. The team recognized that the paucity of dependable rainfall data, together with the assumptions made to quantify the rainfall that might appear as runoff, could produce results very dissimilar from the actual flow hydrographs. It was also realized that the general shape of the unit hydrograph would cause peak flow rates to be underestimated and the total flow volume obtained by the unit hydrograph method to exceed the record, largely because the variable intensity and coverage of the storm reduced rainfall intensities averaged for the whole catchment.

Basin characteristics and storm hydrographs were prepared for the following catchments: Wadi Ahin, Wadi Bani Ghafir, and Wadi Ghul-Wadi Misfah-Wadi Bahla.

Wadi Ahin—The Wadi Ahin catchment has its source on the northeast side of the northern end of Jabal Akhdar in mountains ranging up to 3,000 m in elevation. The catchment is somewhat circular and has a drainage area of 765 sq.km near Hayl (elev. 250 m) where it enters the piedmont of the coastal plain, flows about 35 km to a point 20 km southeast of Sohar, and meets the Gulf of Oman. The catchment has four rain gauge stations and one wadi flow gauge station near Hayl. This analysis used data from Al Qufays, Al Wuqbah, and Hayl Ashkiriyan, the only stations for which data were available for the storm period. The catchment was divided into six subcatchments whose drainage areas ranged from 112 to 148 sq.km. These are shown in Figure 7, which also shows the locations of existing rain gauge and wadi flow gauge stations. Since each of the three rain gauges covered an average of 225 sq.km, sophisticated techniques were not used to estimate rainfall in each subcatchment. Instead, data were applied as follows:

Rain Gauge	Subcatchment
Al Wuqbah	A-5 and A-6
Al Qufays	A-1 and A-2
Hayl Ashkiriyan	A-3 and A-4

Data analyzed for the storms on December 7-8, 1989 and February 7-8, 1990 are given in Table 13. According to MWR data, the February storm resulted in a peak flow of 178 cm and a total flow of 2.39 mcm at the wadi flow gauge near Hayl.

The synthetic hydrograph analysis produced a peak flow of 102 cm and a total flow of 2.81 mcm, using rainfall excess above a rate of 1.2 mm (0.03 inches) per 5-minute increment. Whereas the calculated peak flow was only 57 percent of the actual, the calculated total flow was only 17.8 percent greater than that reported by the MWR. The December storm was less in magnitude, with a peak flow of 73 cm and a total flow of 584,570 cu.m at the Hayl gauge. The synthetic hydrograph analysis, however, produced a peak flow of 136 cm and a total flow of 3.31 mcm, using rainfall excess above a rate of 1.2 mm (0.03 inches) per 5-minute increment. The calculated peak flow was 86 percent greater than reported, while the calculated total flow was nearly seven times that reported by the MWR. A subsequent sensitivity analysis made for both storms showed that by increasing the rainfall excess value to 1.6 mm (0.04 inches) per 5-minute interval, the synthetic hydrograph volume for the February 1990 storm decreased to 1.63 mcm (68 percent of that reported by the MWR); whereas for the December 1989 storm it decreased to 5.6 times, while increasing the rainfall excess to 2.0 mm (0.05 inches) per 5-minute increment reduced the total flow to only 4.2 times that reported by the MWR. The hydrographs for the February 1990 storm are shown in Figure 8. Clearly, the analysis of the December 1989 storm suggests that rainfall data deduced from the gauges yielded greater amounts than prevailed over the various subcatchments, thus increasing estimated runoff volumes. This is an excellent illustration of the importance of an adequate density of rain gauge stations if data are to have any degree of reliability.

Wadi Bani Ghafir—The Wadi Bani Ghafir catchment has its source in the Al Hajar Al Gharbi portion of Jabal Akhdar in mountains that also range up to 3,000 m in elevation. The catchment has a drainage area of 617 sq.km near Houqain (elev. 250 m) where it enters the piedmont of the coastal plain and flows about 34 km to enter the Gulf of Oman at Suwayq. There are four rain gauge stations, three within the catchment and one on the watershed divide at Jabal Shams (high-altitude gauge), and a wadi flow gauge station near Falaj as Saidi. Rainfall data for this analysis came from Daba, Yiqa, and Houqain. The catchment was divided into four subcatchments ranging from 110 to 186 sq.km. The catchment and four subcatchments are shown in Figure 9 with the locations of rain gauge and wadi flow gauge stations. Here again, since each rain gauge covered an average of 205 sq.km, such techniques as the Thiessen polygon were not used to estimate the rainfall in each subcatchment. Instead, the data were applied as follows:

Rain Gauge	Subcatchment
Daba	BG-1
Yiqa	BG-2 and BG-3
Houqain	BG-4

The storms analyzed were those of February 7 and February 22, 1990 and the one on December 17, 1989. Rain gauge data are given in Table 14. MWR data for the December storm showed a peak flow of 95.8 cm and a total flow of 1.58 mcm at the wadi flow gauge near Falaj as Saidi. The synthetic hydrograph analysis produced a peak flow of 184.3 cm and a total flow of 4.35 mcm, using rainfall excess above a rate of 1.2mm (0.03 inches) per 5-minute increment. The calculated peak flow was nearly double and the calculated total flow nearly 2.8 times that reported by the MWR. A subsequent sensitivity analysis showed that by increasing the rainfall excess to 1.6 mm (0.04 inches) per 5-minute interval, the synthetic hydrograph's total flow decreased to 3.26 mcm, about double that reported, while the peak flow decreased to 158.6 cm, about 1.6 times that recorded. The February 7 storm was unusual in that only the most downstream of the four subcatchments (BG-4) had rainfall of sufficient duration and intensity (Houqain) to produce an excess. Because the subcatchment has a significant calculated lag time, the synthetic hydrograph for this storm differs sharply from data recorded by the MWR, as shown in Figure 10. Actual rainfall was less and occurred on portions of the catchment with smaller lag times. It is worth noting that the synthetic hydrograph was based on a rainfall excess above a rate of 1.2 mm (0.03 inches) per 5-minute increment, and thereby produced a calculated flow of 1.52 mcm, or about 50 percent greater than that recorded by the MWR. Adjusting the rainfall excess to 1.6 mm (0.04 inches) per 5-minute interval reduces the total calculated flow to 1.00 mcm, or 96 percent of the 1.04 mcm recorded.

The February 22 storm resulted in heavier rainfall, bringing sufficient excess to produce runoff in three of the four subcatchments; only the subcatchment farthest upstream (BG-1) contributed no runoff. The synthetic hydrograph analysis (Figure 11) for this storm produced a peak flow of 232 cm, nearly double the 128 cm peak reported by the MWR, and a total flow of 6.67 mcm, nearly 3.7 times the volume reported by the MWR. By increasing the rainfall excess from 1.2 mm (0.03 inches) to 1.6 mm (0.04 inches) per 5-minute increment, the peak flow was reduced to 146 cm (114 percent of the actual) and the total flow to 3.91 mcm, about 2.15 times the actual. These comparisons confirm that the present rain gauge density in the Bani Ghafir basin is not sufficient to define coverage and intensity of rainfall for synthetic hydrograph generation.

<u>Wadi Ghul—Wadi Misfah—Wadi Bahla</u>—This catchment was analyzed for the Interior because of the number of rain gauges and wadi flow gauges existing and soon to be augmented. The northern part of this catchment begins in the Al Hajar Al Gharbi section of the Jabal Akhdar mountains at elevations up to 300 m. The northwestern part drains into Wadi Ghul, which joins Wadi Misfah at Al Hamra to form Wadi Bahla, and flows south to

Bahla and on to Bani Shukayl. The catchment has a drainage area of 611.5 sq.km at Bahla, which increases at Bani Shukayl where it is joined by Wadi Sayfam. The MWR has three rain gauge and two wadi flow gauge stations but the completion of a recharge dam on Wadi Ghul in 1989 by the MAF and another now under construction on Wadi Bahla should soon make available data from two more rain gauges and two more wadi flow gauges (one of each per dam). Rainfall data for the analyses were from Misfah and Bahla and the high-altitude gauge at Jabal Shams. The wadi flow gauge stations providing data were Wadi Misfah at Al Hamra and Wadi Bahla at Bahla. The catchment was divided into five subcatchments: Wadi Misfah, Wadi Ghul at the MAF dam, downstream from the confluence of Wadi Misfah and Wadi Al Hamra, Wadi Bahla at the MAF dam under construction, and Wadi Bahla at the present wadi flow gauge. The five subcatchments have drainage areas ranging from 58 to 173 sq.km. Figure 9 shows the catchment and subcatchments and the locations of existing rain gauge and wadi flow gauge stations as well as those to be operated by the MAF at the two recharge dams. The average coverage per rain gauge is 204 sq.km, virtually the same as for Wadi Bani Ghafir. Once the two rain gauges at the dams are working, coverage per gauge would diminish to about 122 sq.km.

For the analyses, rain gauge data were applied as follows:

Rain Gauge	Subcatchment
Jabal Shams	G-1 (average with Misfah)
Misfah	G-1 (average with Jabal Shams)
"	G-2
"	M-1
"	B-1 (average with Bahla)
Bahla	B-2

The Wadi Misfah catchment (58.6 sq.km) is ideal for small basin analysis because it has both a rain gauge and a wadi flow gauge. The three storms analyzed were those of December 8, 1989, February 8, 1990, and February 25 and 26, 1990. The Wadi Bahla catchment gave quite variable results, which is not surprising when the variations in basin characteristics are considered. Rain gauge data are given in Table 15.

The storm of December 8 produced a peak flow of 21.0 cm and a total flow of 180,472 cu.m at the flow gauge on Wadi Misfah at Al Hamra. The synthetic hydrograph produced a peak flow of 23.9 cm and a total flow of 145,722 cu.m, about 80 percent of the flow reported by the MWR. The hydrograph used rainfall excess above a rate of 1.2 mm (0.03 inches) per 5-minute increment; it is shown in Figure 12. The wadi flow for this storm was the result of 9.6 mm of rain that fell between 1300 and 1430 hours.

The storm of February 8-9 produced a peak flow of 22.5 cm and a total flow of 212,110 cu.m at the Wadi Misfah flow gauge. Attempts to generate a synthetic hydrograph proved unsuccessful since the rainfall data showed a total of 9.0 mm at 1000 hours, more than four hours before the peak flow occurred. A total of 3.8 mm between 1400 and 1430 hours could not have been sufficient to cause the peak.

The storm of February 25-26 produced a peak flow of 27.2 cm and a total flow of 798,320 cu.m at the Wadi Misfah gauge for February 25-28, about 3.7 times the February 8-9 flood. This storm had two other peaks: one of 8.4 cm one hour before, and the other of 15.8 cm nearly three hours after, the main peak. The records showed three distinct periods of rainfall: 12.4 mm between 2150 and 2235 on February 25, 4.6 mm between 2345 and 0045 on February 26, and 13.8 mm between 0220 and 0350 on February 26. Although the three periods seemed to bear a relationship to the three peaks, time did not permit an in-depth analysis.

The storm of February 25-26 produced major flows at the Wadi Bahla flow gauge at Bahla, with the MWR reporting a peak flow of 164 cm and a total flow of 1.74 mcm for the 17-hour period from 2300 on February 25 to 1600 on February 26. The rainfall was lightest at Jabal Shams (14.8 mm), increasing toward Misfah (35.0 mm), and reaching a maximum in 10 hours at Bahla (54.7 mm). The synthetic hydrograph analysis produced a peak flow of 273 cm and a total flow of 8.67 mcm, using rainfall excess above a rate of 1.2 mm (0.03 inches) per 5-minute increment. By increasing the rainfall excess from 1.2 mm (0.03 inches) to 1.6 mm (0.04 inches) per 5-minute increment, the peak flow was reduced to 238 cm (145 percent of the actual) and the total flow to 7.50 mcm, about 4.25 times the actual. The hydrograph for this storm is presented in Figure 13. Again, the data point out not only that the density of rain gauge stations in the Wadi Ghul—Wadi Misfah—Wadi Bahla basin is not sufficient to adequately define rainfall coverage and intensity, but that the two wadi flow gauges are not adequate to measure the sources of incremental flows in this basin. The generation of meaningful synthetic hydrographs will require an expansion of both rain gauge and wadi flow gauge networks.

Wadi Sahalnawt—This catchment was considered for study for the Southern (Dhofar) Region because of its significance to the Salalah area, as well as for rain gauge coverage and coverage of a wadi flow gauge about 8 km north of Salalah. The source of this catchment is in Jabal Al Qara about 25 km north of Salalah in mountains ranging from 850 to 880 m in elevation. The catchment is fan-shaped, with three major wadis joining to form Wadi Ruvihawt, which then joins Wadi Thaydawt and Wadi Sahalnawt. The catchment has a drainage area of 138.4 sq.km at the wadi flow gauge station; the MAF is constructing a recharge dam on Wadi Sahalnawt. There were four rain gauges in this catchment in addition to the long-term records at Salalah. However, at present rain gauge data are available only from one of them, Qaroon Haritti. After a field reconnaissance and discussions with the MWR's Southern District office, it was decided that the records at Salalah were the best indicator of the hydrologic response of the area to long-term rainfall effects.

5.6.3 Data Requirements to Develop Correlations for Ungauged Basins

The discussion of the preliminary approach confirms the inadequate density of the existing rain gauge and wadi flow gauge networks. The actual hydrographs show very flashy peaks, with rapid rises in 10-30 minutes and fairly quick recessions. It was recognized that the unit hydrograph technique would generate a hydrograph reflecting runoff from the entire catchment. But the slimness of the actual storm hydrograph shows that it measured only that portion of the catchment producing runoff at a rate equal to the assumed rate of rainfall excess. The rain gauge density required for this analysis is considerably greater than that of the network now in place or planned for the next 5 to 10 years. Other studies show that rainfall patterns tend to be less variable in less arid and generally less mountainous terrain. A study of an 840 sq.km experimental catchment in the Japanese foothills (Kawabata, 1960, cited in Stanger, 1985) suggested the following relationship for rain gauge density:

Area per station in sq.km	280	140	90	70	50	3
Percentage error	25	18	13	10	6	3

The need to keep the percentage error in the 10-15 percent range suggests a rain gauge density in Oman of 60 to 100 sq.km per gauge.

The wadi flow gauge density required for the proposed analysis is also considerably greater than that of the present network. A density of 100 to 120 sq.km per gauge is suggested to enable determination of flow patterns in each subcatchment.

Probably the most difficult variable to define is permeability, which is a function of the type of soil or rock in each subcatchment and also varies during the storm period. The rocks in the upper elevations of each catchment contain joints, fissures, and solution channels that provide paths along which rainfall can travel or be stored, thus reducing its contribution to runoff. The sands and gravels and cobbles in the wadi channels, as well as the alluvium below and adjacent to the channels, significantly reduce runoff potential. Therefore, during intense storms, only source areas of the catchment contribute runoff. The remaining areas permit infiltration at rates that exceed the maximum rainfall intensities experienced. The delineation of these areas and the determination of runoff coefficients for the source areas would require data from the existing 1:100,000 scale maps, supplemented by field trips to confirm the noncontributory areas by observing them during storms. Field inspections would also reveal whether an increase in source area resulted from an increase in total precipitation. Delineation of source areas and a proper understanding of how they function during certain types of storms will go far in determining their potential runoff contribution. These are most necessary for developing acceptable synthetic hydrographs.

5.6.4 Flood Frequency Data Using Channel-Width Method for Relative Results

One of the moderately successful methods of estimating the effects of perennial and ephemeral storms on monthly streamflow in the U.S. is the channel-width method. This method uses multiple regression equations developed from measured channel widths rather than measured basin characteristics in a gauged area. Although the application of this method requires training and experience, the regression analysis yields prompt results once the field work has been completed.

This method was first used in Oman more than 13 years ago (Johnson, 1977) to determine peak rates of runoff and flow volumes in selected wadi channels flowing across the Batinah so that the data could then be applied to develop flow relations for wadis with similar basin characteristics. Channel-geometry techniques were used to estimate flood-frequency relationships and mean annual runoff at six sites. Stage-discharge relationships were developed at four gauged sites, using indirect measurements of flow. The study concluded that "there are definable relationships between channel geometry and wadi flow in the mountain area above the coastal plain, but stream-flow records at gauged sites would be needed to substantiate or correct the assumed relationships." At the time of the report, there were 19 wadi gauge stations that had been in operation for only two or three years, and stage-discharge relationships had not yet been established at most of them. By 1984, the number of stations had increased to 53 (35 were continuous record stations). Today there are 120.

An updating of the report with a confirmation or adjustment of flood frequency and mean annual flow data would be far easier than trying another technique such as basin characteristics. Furthermore, regression equations could be developed for most of the nearly 100 wadi gauge stations established since 1977. Studies conducted in Montana and New Mexico show that when two or more methods are used to make flow estimates at ungauged sites, the standard error of the estimate decreases according to the number of methods used. Certainly, a program to establish flood-frequency relationships and estimated mean annual runoff by channel geometry at the gauging sites added since 1973, coupled with a program that might use drainage basin characteristics, would produce more reliable estimates for a given station.

5.7 Recommendations

5.7.1 Channel-Geometry Program—Wadi Flows

The channel-geometry program has been scheduled for a three-year period, with updating of data from the original 19 wadi gauge stations to occur during the first six months. The program would review channel characteristics for the 19 sites, confirm flood-frequency relations for 10 of them, and develop new estimates of mean annual flow for all.

The program for the newer 80 gauges would cover the identification of channel characteristics in the field, followed by an office review and development of regression equations. These would be applied to develop flood-frequency relationships, and estimates of mean annual flow first at gauged sites and then at ungauged sites. The results would be discussed in a summary report.

5.7.2 Expectations of the Program

Experience has shown that channel geometry is one of the more successful methods for estimating monthly and annual flows. Regression equations developed from channel width measured in the field calculate the ranges of flow for each stream or wadi and determine flood-frequency relationships (important for the design of dams, bridges, highways, and culverts). Mean annual flow data can be compared with records at gauged sites to estimate mean annual flow for ungauged sites. Channel geometry yields the most information for the least cost among all the methods studied and is recommended for this reason.

5.7.3 Alternatives to the Program

Alternatives, such as the addition of a large number of new stations, should be considered only as supplements. As presently envisaged, the program would provide basic flow and flood data from approximately 100 stations at about the same cost as setting up 25 new stations. Operation and maintenance of these 25 stations would add another 20 percent. There are 15 locations (six each in the Batinah and Interior and three southeast of Muscat) where the installation of gauges would expand the present database. These should be kept in mind as supplements.

5.8 Implementation

5.8.1 Personnel

The program will require four part- or full-time qualified staff: a senior hydrologist devoting 20 to 25 percent of his time, a staff hydrologist devoting 65 to 70 percent of his time, and one engineer and one technician working full time. The senior hydrologist will manage the project and at the outset spend most of his time in the field. He will also be responsible for the technical review process.

5.8.2 Schedule

The schedule for the update of the first 19 stations and for the 80 new stations is shown in Figure 14. Should the MWR wish to compress the program into two years, it would have to add one full-time engineer, make the staff hydrologist full time, and increase the commitment of the senior hydrologist to 30 to 40 percent of his time.

5.8.3 Costs

The costs of a three-year program are given in Table 16. There would be no need to extend the program beyond this. Should the MWR wish to increase the number of stations, the unit cost would be about R.O.1,500.

Chapter 6

REPRESENTATIVE BASINS

6.1 Introduction

6.1.1 General

The complexity of the hydrologic cycle governing the many wadi basins in northern Oman requires not only adequate monitoring systems to report rainfall and runoff, but data relating flood flows to groundwater recharge and data on groundwater movement through the basins. Dividing a catchment into subcatchments facilitates an understanding of the hydrologic response in a smaller area whose characteristics can then be applied to the study of similar subcatchments. Monitoring systems provide flow prediction data for estimating recharge as well as data on flood frequency and total yield from a methodology based on basin characteristics.

6.1.2 Scope of Work

The scope of work for the representative basins section of this assignment covered the following tasks:

- Visit the Northern Oman, Batinah, and Interior Regions to become familiar with hydrologic conditions.

- Review available data on wadi basins and recommend two as representative basins for concentrated study.

- Once the MWR has accepted this recommendation:

  — Assist with preparing a basin monitoring program and selecting monitoring sites for rainfall, wadi flow, groundwater levels and movement, meteorological parameters, soil moisture, sediment, and bedload movement

  — Recommend equipment and assist with a plan for procurement

  — Estimate personnel needs and assist in preparing a training program consistent with the training plan prepared under Task 4

- Ensure coordination with the activities relating to monitoring network expansion, studies of basin characteristics, and throughflow measurements

6.1.3 Background

Surface water runoff in arid zones occurs sporadically, generally in short isolated periods. Sustained flow is very rare. In Oman, a notable exception is Wadi Dayqah at Mazara, which had an average annual flow of 63.10 mcm from its 1,689 sq.km drainage area for the period 1978 to 1984. In arid zones, flood peaks tend to diminish with movement downstream as infiltration into the channel bed and adjacent alluvium takes place. This transmission loss is the single most important recharge mechanism for the alluvial aquifers so common in arid zones. The absorption capacity of a channel bed is determined by the nature of its surface, while the flow width of an alluvial channel during a flood varies with the rate of discharge and the sediment load. The magnitude of a flood in a drainage system is determined by the extent and movement of the storm and the intensity and duration of the rainfall it brings to the subcatchments. In contrast to the experience in temperate zones, arid zones provide no relationship between the magnitude of an event and its effect on a catchment area, except when this is a small basin. Herein lies the key to the use of representative basins; they must be small if meaningful relationships between rainfall and runoff are to be discovered.

6.2 Summary and Conclusions

The summary and conclusions relating to the selection of two wadi basins for more detailed study are:

- Representative basins must be kept small for a proper understanding of the rainfall-runoff relationship from which meaningful synthetic hydrographs can be generated.

- Candidate basins should have monitoring facilities, a database under development, and a flow gauge where the wadi enters the upper piedmont, in the case of the Batinah, or at the lower limit of the main wadi, as well as a smaller gauged catchment within the basin.

- The Wadi Ahin and Wadi Bani Ghafir basins are prime candidates for the Batinah, with Wadi Ahin also appropriate for a potential throughflow study. The Wadi Ghul-Wadi Misfah-Wadi Bahla basins are prime candidates for the Interior.

- Two or three candidate basins should be considered for a representative basin pilot program under which new rainfall and wadi flow gauges will provide data to be used with basin characteristics for a hydrologic model developed through regression analysis. The model would be used to estimate mean annual flows for gauged sites initially, then for ungauged sites. The results would be compared with those from the channel-geometry report completed earlier.

- Should the proposed pilot program prove successful, the small basin characteristics could be applied to the study of similar basins in the Batinah and to determining the efficiency of recharge occurring in the region.

- Should the proposed pilot program prove unsuccessful, it should be terminated at the end of five years and other alternatives considered. The estimated cost of the five-year program is R.O.508,000.

- A suitable alternative to this program would be the installation of at least one flow gauge for each wadi as it emerges onto the upper piedmont of the Batinah. This would enable determination of total flow entering the Batinah by using a combination of gauged flows and unit discharges for ungauged areas.

- The schedule has been designed for a study of three basins. A study of two would be cheaper, but the five-year duration of the program should not be changed.

6.3 Background—Representative Basin Candidates

6.3.1 Types and Locations of Catchments in Oman

The Batinah is an area of major concern because its groundwater resources are being tapped at an increasing rate to provide irrigation in the coastal plain used for agriculture. The Batinah slopes gently from the upper piedmont to the sea. The runoff from its wadis as they leave the mountains infiltrates its permeable sands, gravels, and alluvium and is greatly diminished when it reaches the coastal plain. The importance of the alluvial deposits along the Batinah cannot be underestimated, since wells driven into them are the primary source of water supply. Although there are no perennial streams, many of the wadis have been observed to flow for an extended period in the downstream reaches of the piedmont zone, suggesting a significant groundwater contribution. Flood flows are greatly attenuated as they make their way across the Batinah and toward the sea, flowing through distributories as they recharge the groundwater system. The more frequent low-intensity storms seldom discharge flows to the sea as the infrequent major flood events do. A representative basin along the Batinah would not only provide better definition of surface flows leaving the mountains but better understanding of the surface water-groundwater relationship in the recharge areas of the piedmont.

A second area for a representative basin is to the south and west of the northern mountains. Sometimes referred to as the Bajada, it is a broad sloping plain that varies in elevation from 400 m near the mountains to less than 100 m at its southern edge. It is a transitional zone between the mountains and the central plateau, and receives, stores, and transmits surface runoff. Runoff associated with storm events occurs mainly along the major wadi channels extending from the mountains. A single large storm like that of February 25-26, 1990 can cause a flood of such magnitude that some of it will reach the southerly limits of the Bajada. Such flows seldom last more than a few hours, since most of the runoff permeates the alluvium below and adjacent to the wadi beds. When recharge does occur along the wadi channels, much of this water is lost to the interior as it is conveyed by Wadi Halfayn to the Gulf of Masia and the Huqf depression. This is similar to the excess flows of the Batinah, which are discharged into the sea. The capture of these flows for domestic or agricultural use before they recharge uninhabited territory would improve the management of water resources.

6.3.2 Determination of Criteria for Representative Basin Selection

The selection of representative basins must focus on surface water details. Certainly those basins that have monitoring facilities and a database under development are prime candidates, and among them the basins with a rain gauge density of at least one per 250 sq.km are preferred, particularly if the records are dependable and the station has been in service more than five years. Equally important is a wadi flow gauge that has operated as long, provided it is located where the wadi enters the upper piedmont in the case of the Batinah. The second criterion would be a basin that had a wadi flow gauge at its lower limit and a smaller catchment with its own gauge so that past records of flow could be prepared. The third criterion would be a basin with significant potential for recharging the groundwater system, particularly if this occurs where the wadi enters the upper piedmont in the case of the Batinah. This could be linked to a throughflow analysis of both surface water and groundwater hydrology.

6.4 Suggested Representative Basins

6.4.1 Wadi Ahin

The Wadi Ahin basin has three rain gauge stations, and a fourth (Haybi) could possibly be reestablished. The wadi flow gauge at Hayl is located where this wadi enters the upper piedmont at an elevation of approximately 250 m then drops about 170 m in 26 km, an average gradient of 6.5 per 1000, as it travels the 35 km to the Gulf of Oman. The addition of three rain gauges and six wadi flow gauges would provide rain gauge coverage of one per 128 sq.km and wadi flow gauge coverage of one per 110 sq.km.

The rain gauge locations would be:

Existing	Proposed
Al Wuqbah	8 km east of Maydah
Al Qufays	Haybi or Hajz
Hayl Ashkiriyan	6 km northwest of Ghuzayfah

They are shown in Figure 7. The program will provide at least one rain gauge and one wadi flow gauge for each of the six proposed subcatchments. As will be discussed in a later chapter, Wadi Ahin would also serve the wadi throughflow study of this basin.

6.4.2 Wadi Bani Ghafir

The Wadi Bani Ghafir basin has three rain gauge stations, one a high-altitude station on the divide (Jabal Shams). There are prospects of a second high-altitude station (foundation complete) about 7.5 km southwest of Maydan. The wadi flow gauge at Falaj as Saidi is also located just downstream from where the wadi enters the upper piedmont at an elevation of approximately 250 m then drops about 220 m in 22 km, an average gradient of 10 per 1000, as it travels the 34 km to the sea. The addition of four rainfall and four wadi flow gauges would provide rain gauge coverage of one per 70 sq.km (assuming two existing high-altitude gauges) and wadi flow gauge coverage of one per 123 sq.km. The rain gauge locations would be:

Existing	Proposed
Daba	Sa'ab
Yiqa	Ghafdi
Houqain	2 km west of Nazwah
Jabal Shams*	11 km south of Maydan*
7.5 km southwest of Maydan* (U.C.)	

* High-altitude gauges

They are shown in Figure 9. The program will provide at least one rain gauge and one wadi flow gauge for each of the four proposed subcatchments. The suitability of this basin is enhanced by its accessibility and the presence of a wadi flow gauge at Al Madinak (about 11 km upstream from the present gauge) that dates back to October 1974.

6.4.3 Wadi Ghul-Wadi Misfah-Wadi Bahla

The Wadi Ghul-Wadi Misfah basins form the Wadi Bahla just downstream from their confluence near Al Hamra. The Wadi Misfah basin has one rain gauge and one wadi flow gauge for its 58.6 sq.km drainage area, while only one rain gauge (Al Hamra) exists in the Wadi Ghul basin. The recharge dam on Wadi Ghul, constructed by the MAF in 1989, should also have rain gauge and wadi flow gauge records. Wadi Bahla has a rain gauge and a wadi flow gauge at Bahla. There is a second recharge dam under construction by the MAF about 4 km upstream from Bahla that should also provide rainfall and wadi flow data in due time. Downstream from the wadi flow gauge at Bahla, Wadi Bahla falls 50 m in 17 km, an average gradient of 3 per 1000, as it makes its way south to its confluence with Wadi Sayfam. One rainfall and two wadi flow gauges should be added in the Wadi Misfah basin to better define the origin of flows. The Wadi Ghul basin should have two new rain gauges and three new wadi flow gauges, and the Wadi Bahla basin should have two new rain gauges and two new wadi flow gauges. This would provide rain gauge coverage of one per 70 sq.km (counting the Jabal Shams high-altitude gauge), and wadi flow gauge coverage of one per 70 sq.km. The rain gauge locations would be:

Existing	Proposed
Misfah	Subayb
Bahla	Ghul
Jabal Shams*	Al Hamra
	Bilad Sayt
	Hayl Juwari

* High-altitude gauges

They are shown in Figure 9. The program will provide at least one rain gauge and one wadi flow gauge for each of the five proposed subcatchments. The suitability of this basin is enhanced by its accessibility, the presence of the Wadi Bahla flow gauge dating back to May 1974, and southerly drainage to the interior region.

6.5 Recommendations

6.5.1 Pilot Program

A five-year pilot program for the study of the representative basins described has been designed for three basins and would include the installation of additional rainfall and wadi flow gauges. The characteristics of the subcatchments would be examined in the field and in the office, and a hydrologic model would be developed through regression analyses. After a successful testing of the model, it would be used for estimates of mean annual flow, first for gauged sites (to permit corroboration), then for ungauged sites. The findings of the program would be compared with those derived two to three years earlier under the channel-geometry project, and the results discussed in a summary report.

6.5.2 Expectations of the Program

One of the keys to better management is a quantification of surface and groundwater resources. The volume of recharge in the Batinah during a flood event can be estimated from a comparison of flow volume at the mountain front with flow at the coastal highway. This in turn will provide a measure of the unused recharge capacity and suggest techniques for greater use of it.

If the pilot program proves successful, it should offer a better understanding of the surface and groundwater hydrology of the Wadi Ahin and Wadi Bani Ghafir basins that can then be applied to similar basins along the Batinah. This will enable a determination of the efficiency of the recharge along the Batinah and an appropriate method to improve it.

If the pilot is unsuccessful, it could be terminated at the end of five years and other alternatives considered.

6.5.3 Alternatives to the Program

Alternatives to the pilot program would include the installation of at least one flow gauge for each wadi where it enters the upper piedmont of the Batinah. This will enable determination of total flow entering the upper piedmont through a combination of gauged flows and unit discharges for any ungauged areas between the measured points. If the pilot program does not prove successful, the wadi flow gauges should not be removed from the subcatchments and records should continue to be maintained until a suitable method of analysis is found.

6.6 Implementation

6.6.1 Personnel

The pilot program will require a senior hydrologist, staff hydrologist, two engineers, and two technicians. The senior hydrologist will have to devote approximately 25 percent of his time to the project. The staff hydrologist and the engineers and technicians will be involved full time in almost all aspects of the project, with the staff hydrologist concentrating on office tasks. The senior hydrologist will manage the project and be responsible for the technical review process.

6.6.2 Schedule

The schedule for the pilot program with three representative basins is shown in Figure 15. Should the MWR wish to proceed with only two representative basins, the schedule could be modified but its five-year duration should not be changed.

6.6.3 Costs

The costs of the pilot program for five years are given in Table 17. An extension beyond this would be at a greatly reduced rate. A similar five-year program for other representative basins would average R.O.150,000—175,000 per basin, depending on existing rain gauge and wadi gauge coverage and the need for supplemental monitoring.

Chapter 7

AFLAJ FLOW MONITORING PROGRAM

7.1 Introduction

This chapter assesses the MWR's aflaj monitoring program and explains why aflaj flows need to be measured. It examines existing problems and recommends improvements and the basis of a network strategy.

The chapter has six sections following this introduction and a summary of conclusions: background on aflaj and flow monitoring; field work conducted during the study; the existing MWR aflaj flow monitoring program; recommendations for upgrading and expanding the program; the logistics involved; and implementation costs and scheduling.

7.2 Summary of Conclusions

- The MWR should review the existing aflaj monitoring network and assign each falaj a priority in terms of the information it will provide. The program should then be adjusted accordingly.

- The Surface Water Department should continue to evaluate aflaj monitoring stations in each district and relocate them when necessary.

- Aflaj discharge should be measured with a rotating current meter whenever possible.

- Staff gauges should be installed at aflaj monitoring stations and the flow should be rated. Stage should become one of the primary forms of routine discharge measurement.

- Datalogger-type water level recorders should be installed at selected aflaj to continuously monitor the discharge rate.

- The MWR should conduct a comprehensive inventory to identify each falaj, accurately locate the motherwell and all contributing sources, map the conveyance and distributory channels, and estimate the area of land cultivated.

- The inventory team should be responsible for identifying the most appropriate flow monitoring station, and measuring the discharge, at each falaj. It should recommend improvements for flow monitoring at each station and measure the conductivity of water in each falaj to indicate water quality.

7.3 Background

7.3.1 Aflaj in Oman

Water in Oman traditionally has been supplied by shallow dug wells or aflaj (singular = falaj), which still provide much of the water for agriculture. The Ministry of Agriculture and Fisheries (MAF) estimates that there are more than 4,000 in operation (JICA, 1990).

Falaj systems convey water from an upland source to downstream users through open and closed conduit sections. They are financed, constructed, and maintained cooperatively, and water rights are generally hereditary.

There are three types of aflaj: *ghayl*, *daudi*, and *ayn*. *Ghayl* aflaj are found in the mountainous areas and generally are supplied by the diversion of surface water baseflow from the wadi channel. They are usually constructed as either open or "cut and cover" channels, and their rate of flow tends to be highly variable and often seasonal.

A *daudi* falaj consists of a subterranean tunnel driven upstream at a gradient less than the land surface to intercept either a buried spring or the water table. The main source of this type of falaj is the motherwell, or *umm*, although other parts of the falaj may also contribute to the total flow. *Daudi* aflaj are generally constructed to intersect either surface or buried wadi channels where the alluvial gravels are relatively transmissive and aquifer yields are highest. The discharge rate of a *daudi* falaj tends to be less variable than that of the *ghayl* type; variations correspond with fluctuations of the water table. A sketch of a typical *daudi* falaj is presented in Figure 16.

Ayn aflaj tap springs issuing from the bedrock and are very reliable sources of water. In Salalah, all of the aflaj observed convey water from springs along the mountain front to large agricultural areas on the alluvial plain.

7.3.2 Monitoring of Aflaj

In 1979, the Public Authority for Water Resources (PAWR) was set up as a data-gathering institution. Since 1985, several other institutional arrangements for water resources have been established and changed. In October 1989, the Ministry of Water Resources (MWR) was established to take over the technical resources of the PAWR and given a mandate to manage the country's water resources.

The MWR has continued the aflaj monitoring program established by the PAWR in the early 1980s for flow discharge, temperature, and conductivity. Periodically samples are collected for water quality analysis.

The number of aflaj monitored in each region, shown below, reflects the importance of the falaj as a means of water supply in that area.

Region	Total No. Aflaj Monitored
Capital	13
Batinah	14
Interior	107
Sharqiyah	181
Southern	9

The MWR has subdivided the country into 10 districts, each with a headquarters office staffed by experienced personnel. Figure 17 shows the boundaries of each district and the office location.

7.4 Field Reconnaissance

Sixty monitoring sites in seven districts in the north and south were visited to observe aflaj flow measurement procedures, assess the placement of monitoring stations, interview district personnel, and observe field work to improve the aflaj flow monitoring program. In only two districts were measurements being made at the time of the visit.

7.5 MWR Aflaj Monitoring Program

7.5.1 Program Objectives

The primary objective of the monitoring program is to collect accurate flow data for the assessment and management of water resources. Some of the uses of information listed by MWR managers were:

- Provides a general indication of regional groundwater conditions
- Facilitates decisions on permitting of wells to supplement aflaj discharge and/or to extend aflaj

- Provides data for hydrographs to forecast water availability and thereby strengthen the joint management of wells and aflaj in an area

- Enables estimates of recharge

- Fills gaps in the regional hydrological data network

When even the most accurate data are available, however, questions remain as to how representative the numbers may be and whether they reflect the actual condition of the aquifer or merely the structural pattern of the falaj. Tunnel collapse, siltation, and channel losses are common, and each will affect the discharge from a falaj. In some instances, the flow measured along a falaj may not be the amount of water actually coming out of the falaj or even what is being used downstream. There may be diversions of water from the falaj, or wells supplementing the falaj flow, both upstream and downstream from the monitoring point. Nevertheless, aflaj flow data cannot be overlooked as an important source of information.

7.5.2 Monitoring Stations

Most of the MWR's aflaj monitoring stations were selected many years ago by hydrogeologists working for the PAWR. They are poorly marked as a consequence of weathering and in many cases could be replaced, especially since a number of aflaj have recently been reconstructed.

Under ideal conditions, a monitoring station should be located as close to the first emergence of the falaj above ground or as near to its source as possible. This will provide a truer measurement of the total discharge by minimizing both water loss and flow disturbance along the channel. However, many factors have made the selection of such sites difficult if not impossible.

In many instances, the first accessible point along a falaj, called a *shriya*, is used primarily by women for collecting drinking water or bathing. Men seldom visit the *shriya*, so out of respect for local customs a section further downstream is selected for the monitoring station. In other cases, the upper reaches of the falaj are irregular, with bends in the channel or an unstable scoured or rocky bottom. Under these circumstances the monitoring station generally has been located further downstream, although it is apparent that channel stability often has been disregarded in the selection process.

Since a falaj provides people with water for many uses, interruptions in the flow are common. Water losses at upstream diversions and water collected for bathing, drinking, or washing clothes often account for these. Backwater conditions may also occur at points along a falaj as irrigation water is ponded for diversion to local gardens. In the southern district near Salalah, the flow of water through the natural spring channel is often disrupted by swimming holes created by local residents who dam the channel with rocks.

7.5.3 Measurement Techniques

Monitoring requires considerable time and manpower. Monitoring locations are often dispersed, and direct measurements generally require the attention of at least two field personnel.

Although measurement methods vary, they all operate on the basic premise that the discharge or rate of flow (Q) is the product of the cross-sectional area of flowing water (A) and its velocity (V), or simply $Q = VA$. Since the cross-sectional area can be calculated from the channel dimensions and depth of flowing water, only the velocity has to be detennined with accuracy.

Float Method

A popular measurement technique used by the PAWR was the float method. A matchstick or chip of wood is floated on the water and timed over a measured reach. This is repeated a number of times to determine the average surface velocity. A correction factor of 0.9 is then applied to obtain the mean flow velocity (V). The cross-sectional area (A) is determined by the product of a single depth measurement at the monitoring section and the channel width. The discharge rate is then calculated using the relationship $Q = VA$.

Although the float method is virtually cost free, it provides only an approximation of velocity, and thereby discharge, and should be used only when a more precise method is not available. Long, straight, and uniform channels are required for float measurements, and the velocity of a floating object can be easily influenced by external factors such as wind speed and direction. To assume the channel of flow is uniform introduces an almost certain margin of error.

The float method is still used by MWR regional offices, sometimes because the depth of water is not sufficient to accommodate another technique, but often because it is quick and easy or a current meter is not available.

Current Meter

The velocity of flow can also be measured with a rotating current meter, which has a horizontal wheel to which six small cone-shaped cups are attached. As the wheel turns in the current, an electrical contact is made with each revolution. The number of contacts is counted over a selected interval, generally between 30 and 60 seconds, and the velocity is determined by a calibration curve that relates revolutions per second to flow velocity.

The current meter is mounted on a graduated wading rod. Since flow velocity in a falaj will vary from side to side, a measuring tape is stretched across the falaj and the channel is subdivided into segments approximately 10cm in width. The depth of water is measured at the midpoint of each segment. The meter is set to 0.6 of the depth, where studies show the velocity is close to the average, and the current velocity is measured. The discharge for each segment is then calculated by multiplying water depth by segment width by average velocity. The sum of these discharges gives the total discharge at the monitoring station.

Although current meters generally operate with a high degree of precision, errors may occur because of turbulent flow or the oblique angle at which the current strikes the meter. A number of other factors may also affect the accuracy of measurement. However, attentive use and proper maintenance of the equipment can minimize error.

The MWR has at least one current meter in each regional office. Districts monitoring only a small number of aflaj use the current meter almost exclusively. In other districts, there are not enough current meters and the float method is still used.

Stage-Discharge Method

This method is based on the relationship between the elevation of the water level above an arbitrary datum, called stage, and the discharge rate. A calibrated staff gauge extending upward from the point of zero flow is mounted along the wall of the falaj channel. The discharge rate is measured by direct methods and the stage recorded for several heights. Stage versus discharge is then plotted to produce a rating curve for the monitoring station. Discharge rates are determined periodically by reading the stage from the staff gauge and referring it to the rating curve, or by continuously monitoring the stage with an automated water level recorder.

Monitoring of flow in aflaj can be performed rather effectively and accurately using the stage-discharge relationship. Measurements can be made relatively quickly, and it is a cost-effective approach when covering large areas. The primary considerations when selecting a location for stage-discharge monitoring are that the channel geometry must be stable and the station should not be affected by backwater conditions or tributary flow. At a number of aflaj in the Interior, where flow is determined by either a current meter or the float method, the vertical distance from a fixed reference point to the water surface is also recorded as a measurement of stage.

The MWR has recognized the importance of establishing stage-discharge relationships as a method of monitoring aflaj discharge and is integrating this technique into the program.

Other Methods

Several other methods have been used to measure the discharge of a falaj. One is the slope-area method, which relates the rate of flow to the slope of the water surface, the cross-sectional area of flowing water, and the roughness of the channel. Another uses specially designed temporary weirs or flumes to measure the rate of flow. These methods generally have been employed in rating flow channels or in special studies rather than for routine monitoring.

7.5.4 Flow Hydrographs

The MWR's records of aflaj flow data go back to the late 1970s and early 1980s. Data for each falaj monitored are plotted as a hydrograph that shows the changes in flow over time and often the effect of pumping from wells. Figure 18 shows a typical hydrograph. Despite the questionable accuracy of some measurements, the long-term trends and fluctuations are evident.

Aflaj hydrographs are also important in showing the response of source areas to hydrometeorological events, and could be used for predictions that improve the management of water resource in areas served by aflaj. Figure 19 shows the long-term responses of a number of aflaj along the Batinah to periods of heavy rainfall.

7.5.5 Improvements

The MWR is emphasizing the use of rotating current meters to replace the float method for routine monitoring and is instructing field technicians in the proper application and care of the instrument. In addition, the Surface Water Department is evaluating the sites of monitoring stations and relocating them when warranted.

Recognizing the stage-discharge relationship as an effective means of monitoring flow, the Department has begun to rate the flow at each falaj. The shape and elevation of the falaj channel and the slope of the water surface are noted, and the discharge is measured with a current meter. Data are then used to compute discharge by the slope-area method as a means of comparison with the direct flow measurement and to develop a rating curve for the falaj. Staff gauges eventually will be installed and stage will be the primary measurement of discharge.

The Surface Water Department is also preparing rating curves based on historical flow data. Data from each monitoring station are plotted as a depth of water versus discharge graph. If the data are consistent across the graph, a best-fit curve is drawn through the points. If the monitoring station is suitably located, rating curves will identify inaccurate data, which can be either adjusted to fit the rating or eliminated from the record.

Two examples of typical rating curves are presented in Figures 20 and 21. In Figure 20 data appear to be relatively accurate and a best-fit curve can be drawn. In Figure 21, on the other hand, the points are scattered and no reliable depth-discharge relationship can be established. This could indicate, among other things, that the measuring point was not fixed along the falaj, the channel geometry varied between measurements, backwater or turbulent conditions existed at the time of measurement, the monitoring observer(s) were not attentive, or there were mistakes in the discharge calculations.

7.6 Recommendations to Upgrade and Expand the MWR Aflaj Monitoring Program

7.6.1 Monitoring Stations

The MWR should continue to select more appropriate sites for monitoring stations when necessary. Since the aflaj are frequently repaired, altered, or reconstructed, the flow condition at the monitoring station, and upstream and downstream from it, should be visually noted and recorded in the field log as part of the standard monitoring visit. It would be advisable periodically to confer with the *wakil*, who is the administrator of a falaj and deals with the falaj property, repairs, and records of water division, concerning changes in the flow or activities that may have affected the falaj since the last monitoring visit.

The measured section at each station should be well marked to ensure that measurements are taken from the same point each time. Algal growth should routinely be scraped from the channel, both at the monitoring station and immediately upstream and downstream from it, to improve the flow through the measuring section.

In some cases, it may be necessary to reconstruct a segment of the falaj as a measuring section of uniform dimension. The segment should be constructed of smooth finished concrete, and the walls should be straight, plumb, and square with the channel base. It would be wise to coordinate the construction with the MAF's regular aflaj reconstruction program. Nearly 1,600 will be reconstructed over the next ten years, and 800 of these repaired over the next five years (JICA, 1990).

7.6.2 Standard Field Measurement

Current meters should be used whenever there is enough water in the falaj. When using a current meter, flow measurements should be taken from a fixed location along the falaj and the discharge along the measured section should be recorded at frequent intervals. A check with the float method during each monitoring visit might help to identify errors in the current meter measurements.

The Surface Water Department should continue to establish reliable stage-discharge relationships with the exclusive use of current meters. This method takes only 15-20 minutes more than the float measurement, which is a small cost to pay for greater accuracy.

Staff gauges should be installed wherever appropriate not only to improve the accuracy of data but to reduce the effort of monitoring. At stations that have been rated, direct measurements with a current meter need to be taken only periodically, usually at intervals of three to four months.

7.6.3 Continuous Monitoring

Continuous monitoring will refine the flow data collected from monitoring stations that have been successfully rated. Automated recorders along well-established aflaj serving large agricultural communities will improve the tracking and understanding of flow variations in response to local hydrometeorological events, and will provide data for flow hydrographs useful for predictions that can improve water resource management.

Continuous monitoring would also be advantageous in settling disputes that hinge on suspected interference from the pumping of wells. A hydrograph based on continuously recorded data would document daily changes in flow over an extended period and these, compared with the daily pumping schedule of the wells, would clearly determine the impact.

Continuous monitoring would help in special studies of aquifer throughflow and in recharge enhancement studies where flow data can be related to rainfall, runoff, and well hydrographs to explain regional hydrological conditions more clearly.

A qualified consulting firm could supervise construction of all continuous monitoring gauge stations, suitably protected from intruders. A diagram of a gauge installation is shown in Figure 22. It would have to be adapted to the physical conditions of each site. A temporary monitoring station could also be designed to allow a continuous recorder to be moved from one location to another.

7.6.4 Network Rationalization

The existing aflaj monitoring network seems to have been set up at random merely to collect, record, and then file away data. That might have met the requirements of the time. Today, however, the MWR must rely on flow monitoring for the data it needs for effective water resource management. But manpower and budgetary limitations necessitate a careful selection, so that only those aflaj that provide the most valuable information are included in the monitoring network.

Of the three types of aflaj, the *ayn*, which taps springs issuing from the bedrock, probably provides the best data since it permits measurement of direct groundwater discharge. The next best for data is the subterranean *daudi* type of falaj, whose discharge, although influenced by the structural integrity of the falaj, responds to fluctuation in the water table since its source is groundwater. *Ghayl* aflaj provide the least valuable data since they divert only a portion of the flow from a wadi, and discharge can be easily affected by the height of the diversion.

Some important considerations in selecting aflaj for monitoring are:

- *They should be well established*

  Well-established aflaj serving large communities can provide data of use in the joint management of wells and aflaj.

- *They should serve large agricultural areas*

  Aflaj serving large agricultural areas supply water for an important sector of the economy.

- *They should be the primary water supply*

  In villages where the water supply is not supplemented by wells, the aflaj are the lifeline of the people. The MWR eventually will receive requests for permits to install wells or extend the aflaj, and it would be useful to have historical flow data on which to base the permitting decisions.

- *They should be in areas of dispute*

  Monitoring aflaj in areas where there are disputes over the interference of flow by wells or another falaj would help adjudication.

- *They should be distributed regionally*

  Aflaj selected for monitoring should provide coverage in both the upper and lower catchment areas as a means of comparing interbasin responses to local hydrometeorological events.

- *They should fill data gaps*

  Aflaj should be selected according to source location to fill identified gaps in the regional hydrological data network.

Monitoring is also important to isolate the effect of one falaj on another. In some cases, the source of a downgradient falaj may actually be irrigation water that percolates to the water table beneath a cultivated area. Here, only the upgradient falaj needs to be monitored to detect changes that will occur throughout the system. However, water quality should be monitored at both aflaj to assess the deterioration as the water moves downgradient.

7.6.5 Aflaj Inventory

An inventory of aflaj in the country should be conducted by three expatriate hydrologists to be engaged by the Ministry for three years. Each hydrologist will be assigned an Omani technician from the MWR district in which he is working. The technician should be knowledgeable about the district's monitoring network, have a personal interest in the project, and be willing to work long hours in the field. Technicians will assist the hydrologists in data collection and will act as local go-betweens.

The inventory teams will be provided with maps and aerial photographs of each area to help them accurately locate the motherwell and all contributing wells and channels of each falaj. All motherwells should be properly marked. Since there are reports that aflaj names and motherwell locations have been deliberately misidentified by local villagers, the inventory should be coordinated with a representative from the wilayat's Wali Office, the local sheikh, and the falaj wakil.

All conveyance channels and distributaries should be mapped and an estimate of the cultivated area made. The most suitable discharge monitoring location should be identified and marked, the discharge of the falaj should be measured, and the electroconductivity of the water should be determined as an indicator of water quality. The inventory teams should recommend appropriate monitoring techniques for the stations and any other measures to improve the operation of the aflaj. An inventory form that has been used in the Seeb district is shown in Figure 23 and may serve as a guide.

The inventory could be the first phase of a thorough investigation of aflaj operations. The second phase could examine the water rights and ownership of each falaj and the effects they have.

7.7 Logistics

7.7.1 Staffing

Aflaj Monitoring Upgrade

The number of technicians in each district has increased substantially over the last two years and should be sufficient for an upgraded and expanded monitoring network. In addition, the

Surface Water Department intends to assign some of its personnel to each district permanently. These could include a surface water hydrologist and one or two field technicians, who would be responsible for the servicing of rain and wadi gauges and data collection and would train district personnel in proper field measurement techniques.

Aflaj Inventory

The inventory will require three surface water hydrologists with five or more years of experience in streamflow gauging, data interpretation, mapping, and land surveying. They should have an M.S. degree or equivalent in civil engineering with an emphasis in surface water hydrology, a strong interest in field operations, and a willingness to travel and work long hours. They will be expected to train other personnel in field measurement techniques, and should be fluent in English and preferably in Arabic as well.

7.7.2 Equipment

The Surface Water Department is preparing a tender for the purchase of 50 sets of pygmy-type rotating current meters designed to measure the flow of water at low velocities and shallow depths. The meters are manufactured by Scientific Instruments, Inc. and cost approximately R.O.350 each. They come with top-setting wadi rods, headsets for audible tracking, and digital counters and should be adequate for aflaj flow monitoring.

For stage measurement, Leupold & Stevens, Inc. manufactures porcelain enameled iron staff gauges that are easy to read and resist rust discoloration. Metric gauges are available in 1-meter sections divided into centimeters with each decimeter numbered. The cost per section is approximately R.O.15.

For continuous monitoring, the Omnidata Datapod II datalogger recorder equipped with a Druck pressure transducer and a 5-meter length cable would be appropriate. These units are in use at many wadi gauging stations, and personnel are familiar with them. Changes in water level are transmitted via the pressure transducer to the datalogger where they are stored on a computer chip. The datalogger can be programmed to scan and record at various intervals, and intervals can be automatically changed with change in stage. Data are retrieved by removing the computer chip and downloading it onto a computer using a data reader. Data recorders equipped with pressure transducers and two data storage modules cost about R.O.1,600 each. Data readers cost approximately R.O.500 each.

The inventory team will require various types of equipment. Magellan Systems Corporation manufactures Global Positioning System NAV 1000 PRO receivers that give accurate latitude/longitude positions, and at times altitude, by keying in on the position of three or four satellites. The GPS system, operated by the United States government, is still in the developmental phase. The MWR is using the receivers in its district offices with great success. The inventory team would use them to locate motherwells and establish flow monitoring sites. The receivers cost about R.O.1,650 each, and kits permitting operation from a vehicle cost approximately R.O.200 more each. Each team member will require a rotating current meter, a water conductivity probe, and a Brunton compass or the equivalent. The Ministry uses several types of conductivity probes and should select one that is accurate yet stabilizes quickly for the inventory.

7.7.3 Training

The Surface Water Department should continue training field technicians to reinforce the importance of accurate field measurements. The inventory team should also provide hands-on instruction.

This field training should be supplemented by technical meetings, seminars, and training sessions at the MWR for technicians from each district, providing the opportunity for an exchange of experiences and observations. Guest speakers on topics relevant to the monitoring program would be an additional asset.

7.8 Implementation

7.8.1 Costs

The budget is based on the assumption that the monitoring network will be expanded to approximately 400 monitoring sites, of which 90 percent will be equipped with staff gauges. Ten percent of gauged sites will be monitored continuously. An estimated 10 percent of the aflaj in the network will require partial reconstruction of the channel for an acceptable measuring section. Estimated costs of the upgrade are shown in Table 18.

The inventory has been projected to take three years, assuming a total of 4,000 aflaj and a quota of two per day for each hydrologist. An annual vacation of 45 days for each hydrologist has been included in labor costs. Estimated costs of the inventory and of the total project are shown in Table 19.

7.8.2 Schedule

In support of the Surface Water Department's efforts to improve the accuracy of the data collected, the MWR should acquire monitoring equipment immediately. District managers should examine the monitoring network to determine which aflaj should be included in the program. Thereafter field work should begin as soon as possible. The inventory team should keep district offices informed of the progress of work and offer recommendations for upgrading the network.

Chapter 8

WADI THROUGHFLOW

8.1 Introduction

8.1.1 General

This chapter examines the concept of wadi throughflow and its role as part of the groundwater resources in the Batinah, outlines a program to verify and quantify it, considers possible management tools, and presents an estimate of project costs.

Wadi throughflow is the groundwater flowing through the alluvium under a wadi, typically within buried channels of older wadis covered by more recent sediments but also within fractured zones in cemented alluvium under the wadi. A schematic diagram of wadi throughflow is shown in Figure 24.

This report considers wadi throughflow as it exits at the mountain front and enters the piedmont region of the Batinah. Drawing No. 2 shows the general project area, but this report also uses information from other parts of the country to explain throughflow in the Batinah.

Although many workers believe throughflow is important to the water resources of the Batinah, none has attempted to quantify or verify it. Yet, with the exploitation of the Batinah's resources during the past few years, an understanding of the role of throughflow in aquifer recharge becomes necessary. It is also important to develop tools to manage throughflow in the Batinah to its full capacity.

This chapter is divided into six sections following this introduction: the major conclusions and findings; the evolution of the throughflow concept; a review of two throughflow projects in the Interior; the selection of throughflow project sites; recommendations for a throughflow investigation project; and details of implementation.

8.1.2 Scope of Work

The scope of work for wadi throughflow evaluation covered these tasks:

- Visit potential wadi throughflow measurement sites to determine the resources required to perform measurements.

- Review available well logs, results of aquifer tests, appropriate analytical methods for interpreting aquifer tests in cemented alluvium, groundwater hydrographs, geologic maps, and surface water flows.

- Prepare recommendations for a wadi throughflow program that includes throughflow measurement sites and an implementation plan to cover staffing, equipment and assistance needs, and cost estimates.

- Coordinate the recommendations with other teams and team members.

8.2 Summary of Conclusions

- Several studies have suggested throughflow as a major recharge component for aquifers along the Batinah coast. Three recharge mechanisms have been proposed: throughflow, wadi-flood infiltration, and direct infiltration of precipitation (Figure 25). No definite conclusions have been made regarding the importance of throughflow.

- Well and rainfall hydrographs for the Batinah and other areas show that rises in the water level from recharge become smaller and occur later as distance from the mountains increases (Figure 26). The data suggest that a hydraulic process or processes occurring at or near the mountain front may be responsible for this behavior.

- Existing throughflow quantification projects in the Interior at Wadi Fida and Wadi Halfayn are reviewed. These projects quantify throughflow using a series of wells placed across the buried channel-aquifer underlying the wadi (Figures 27, 28, and 29). Pump testing of the aquifer and measurement of hydraulic gradient are used to calculate the rate of throughflow.

- This report expands the throughflow project to one that also quantifies the wadi-flood infiltration in the area below the mountain front, assesses the aquifer response during recharge, and leads to the development of a statistical model that predicts water level behavior in the Batinah one to three years in advance.

- Six basins were selected on the basis of hydrologic and geological data from the Batinah (Table 20), and a field reconnaissance of each was conducted (Figures 30 through 34). In a ranking of the six basins

(Table 21), Wadi Ahin emerged as the preferred location for the expanded throughflow assessment because of the high probability of its having significant throughflow and the ease of throughflow measurement.

- The ideal setting for a throughflow project (Figure 35) has a high probability of generating throughflow because of a high percentage of mantle sequence ophilite bedrock and high levels of baseflow. It also allows for easy measurement of baseflow with a surface water gauge situated on gabbroic bedrock, and is situated downstream where throughflow and infiltrated wadi-flood water can be measured with a combination of surface flow gauges and throughflow wells.

- The Wadi Ahin throughflow project includes construction of a surface water gauge and weir at Hayl, a series of 25+ wells 10 km down-wadi where the last outcrops of Hawasina siltstone and shale crop out, and four to six wells spaced 5 km apart in a line toward the coast.

- The recommended initial installation will cost about R.O. 199,000 (Tables 22 through 25). Ongoing costs for the five-year project are estimated at R.O. 22,000 per year, making a total cost of R.O. 309,000.

8.3 Development of the Throughflow Project Concept

The concept of throughflow in the Batinah has evolved with a better understanding of the hydrogeology of Oman. This section reviews the concept, several projects that have suggested its importance, and the benefits of undertaking a throughflow study in the Batinah.

8.3.1 Original Throughflow Concept

Throughflow was originally conceived as a mechanism that transferred groundwater from mountain basins to lowland aquifers through narrow bedrock gaps at the front of the mountains (Davidson, 1991, and Kaczmarek, 1991a). Measuring it would quantify one part of a basin's water budget. If throughflow was large (and possibly the major source of recharge), quantification would provide an upper value to indicate maximum permissible basin withdrawals.

The Batinah is one of the few places in Oman with a relatively large groundwater reservoir. Yet despite the relatively large storage capacity of the Batinah's aquifers, little is known about their rate or mechanism of recharge.

Three mechanisms, shown schematically in Figure 25, have been suggested:

- Groundwater discharge from mountain basins via wadi throughflow at the mountain front
- Infiltration of surface water in wadi beds and over-bank areas during major flood events
- Direct precipitation on the areas overlying the aquifers in the coastal plain

Understanding the relative importance of each is critical to managing groundwater in the Batinah. For example, if throughflow is significant, it may be possible to develop a mathematical relationship between throughflow at mountain front gaps and water levels in the lower parts of the basin and to forecast water level trends in the lower basin one to three years in advance. In addition, it would indicate the need to manage the upper (mountain) and lower (Batinah) basins as one system.

Three projects or studies suggesting the potential importance of each of these mechanisms are discussed below.

8.3.1.1 Throughflow at Buraimi

A water supply project in the Buraimi area demonstrated the major contribution of throughflow to the recharge of the groundwater system (Kaczmarek, 1988). A series of pumping tests, water level studies, and hydrogeological assessments indicated that a source other than direct recharge of the alluvial aquifer was needed to explain the volume of water in the well system in the "X-11 gap" area near Buraimi. Recharge through direct infiltration of periodic flood water was insufficient of itself.

The study indicated that slow discharge from mantle ophilite[2] bedrock supplied much of the recharge to the alluvial aquifer. This recharge originated as precipitation on mountain uplands that infiltrated into the fractures in the rock, flowed downward as groundwater, and discharged into the wadi alluvium. The slow draining of mantle ophilite bedrock provided the

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[2]Mantle ophiolite refers to rocks originating many tens of kilometers below the earth's surface that were thrust to the surface during a collision of major crustal blocks through the geologic process of "plate tectonics." Mantle ophiolite rocks are well fractured and weathered. Water infiltrates at the surface and flows within the fractures as groundwater. Stanger (1985, page 184) states that water flows slowly through these fractures that are "ubiquitous, at least in the near surface environment (i.e. < tens to hundreds of meters deep)."

source of groundwater needed to explain the yield of the basin above what could be supplied by direct recharge to the limited alluvium.

Groundwater originating in the mantle ophilite rock flows within the alluvium through gaps in the bedrock near the mountain front. A series of hydrologic tests and measurements in the "X-11 gap" quantified the rate of this throughflow and concluded that throughflow could be a significant component of the groundwater system in interior basins.

8.3.1.2 Mott MacDonald Recharge Study

A report by Sir Mott MacDonald and Partners (1989) concluded that throughflow was not a significant component of recharge in the Barka-Rumais area of the Batinah and credited direct infiltration of precipitation as the major source of recharge in the Batinah. This conclusion was based on a computer model but not verified by direct measurement.

The model, part of a feasibility study for proposed recharge dams in the area, covered terrain from the mountain front to the sea. Through the use of their model, they concluded that throughflow from mountain basins was 3.8 mcm/year, and that rainfall and flood infiltration contributed 16.6 mcm/year and 5.6 mcm/year, respectively, to recharge (page 10-27). In other words, throughflow contributed only 15 percent.

In modeling, several variables, such as recharge rates, are adjusted to replicate known hydraulic conditions. The model then is said to be "calibrated" and the values used in the calibration are assumed to be "correct." However, it is possible that an entirely different set of values could also replicate a previous hydraulic situation and appear to be "correct." This possibility—of different values being correct—is suggested by isotope data, to which the report refers in Chapter 8 (page 8-3): "...the groundwater plots [for isotope data] indicate that it is primarily high-altitude rainfall that provides recharge to the coastal plain aquifer."

High-altitude rainfall (rain originally falling in the mountains) could recharge the Batinah only through throughflow and/or infiltration of wadi floods originating in the mountain basins. Only low-altitude rainfall, which is not mentioned, could recharge it through direct infiltration of precipitation. The proportional contributions of the three types of recharge indicated by the model seem to be contradicted by the isotope data.

8.3.1.3 Rendell Memo

A memo by Rendell (1991) describes a correlation between water levels near the mountain front and near the coast in the southern Batinah. Increases in water levels, apparently from groundwater recharge, occur sooner and at greater magnitude near the mountains than closer to the coast. This relationship is shown in Figure 26. The 8-meter rise observed in well JT-12 around November 1984 is attenuated and delayed in wells JT-11, JT-68, JT-67, and JT-24 further downgradient. Well JT-57 even closer to the coast shows no measurable recharge rise. Rendell reports a time lag of two to three years between years of heavy rainfall/recharge and rising water levels in wells away from the mountains. Laver (1991a) reports a similar response in Wadi Hilti in the Sohar area of the Batinah, as does Kaczmarek (1991b) in the Interior at Wadi Shawan. These responses in different areas suggest a common mechanism. Rendell calculates a "recharge wave" travel time of about 10 m per day and by upstream projection of this rate concludes that the "recharge wave" originated at or near the point where the wadi exits the mountains onto the Batinah plain.

Several mechanisms could produce this effect:

- Throughflow originating as discharge from the ophilite bedrock
- Infiltration of flood waters as the wadi exits the mountains
- Slow infiltration and downward flow of flood waters through the alluvium

Rendell's simple computer model was inconclusive and did not indicate which mechanism was more likely, although water quality data for wells JT-57 and JT-67 suggested that the recharge wave could have resulted from the displacement of water downgradient. The memo concludes that more work should be done to isolate the recharge mechanism, but calls attention to a process significant to recharge that occurs where the wadi exits the mountain front. This point corresponds to the gap in bedrock where surface water infiltrates the wadi bed and enters the groundwater system, and/or where throughflow from mountain basins discharges in the Batinah. A better understanding of hydraulic behavior at the mountain front would explain the time lag and attenuation of recharge responses downgradient.

8.3.2 Need for Water Management in the Batinah

Salt water intrusion is present in many parts of the Batinah, suggesting that groundwater is being overdrawn. Several studies support this deduction but a systematic investigation has not been conducted to date. A reliable tool to predict conditions in the Batinah as a means to sound water management is needed. Data limitations and a poor understanding of the flow system make it unlikely that a reliable physically based water balance or computer model can be developed in the near future. Meanwhile problems such as saltwater intrusion could become much worse.

If, however, a mathematical relationship between flow at the mountain gap and water levels nearer the coast can be established, it might be possible to develop a statistically based model to forecast increases and deficiencies in groundwater in the lower areas of the Batinah one to three years in advance with data obtained at the mountain front. An understanding of recharge mechanisms and flow paths at the mountain front would help in developing this model.

8.3.3 Revised Role of the Throughflow Project

The throughflow assessment project has expanded beyond the original purpose of quantifying one component of the water budget to include:

- Better understanding of recharge in the Batinah
- Input for future physically based groundwater management models
- Data for a statistically based model to be developed over the short term
- Validation of managing the upper and lower areas of the basins as a single groundwater system

A throughflow project with two or more surface water gauges could quantify the infiltration of wadi floods. A better understanding of the location, volume, and timing of throughflow is needed for a physically based management model and a statistically based predictive model. A throughflow project would define the relative importance of water use in mountain basins and establish whether these basins need to be managed separately from the basins downstream. It would quantify the baseflow discharge from these basins and indicate the degree of hydrologic connection to the coastal basins.

8.4 Review of Existing MWR Throughflow Projects in Oman

The study team visited two throughflow assessment projects in the interior of Oman. The initial conclusions and lessons learned from these visits are discussed below.

8.4.1 Wadi Dank/Wadi Fida

The project in the Wadi Dank/Wadi Fida system near Yanqul is trying to quantify the groundwater leaving Wadi Dank underground. Flow through the wadi is considered to be the "baseflow" to the area below the mountain front. Throughflows may be integrated to provide an approximation of the minimum input to the areas west of the basin. Pumping rates equal to this throughflow are proposed.

A string of wells placed between bedrock outcrops on either side of the valley across Wadi Yanqul (a tributary of Wadi Fida) and within the narrow confines of Wadi Fida have revealed a buried channel 10 to 20 m below the surface.

The aquifer consists of fractures, revealed by down-hole video cameras, in highly cemented alluvium. Similar materials were found in the upper portions of the wadi system. The wadi has cut into terraces of the cemented alluvium, exposing major fractures in zones up to 2 m thick, with spacings of 5 cm to 25 cm between fractures. The non-aquifer materials are similar to those of the aquifers but without fractures. These aquicludes are also exposed in the incised terraces of the upper wadi.

The aquifer is confined and overlaid by hard cemented gravel. Water levels rise a few meters in the well bore during drilling. The confined nature of the aquifer was demonstrated during a pumping test. A rate of 7 l/s produced a drawdown of 8 cm in observation wells 30 m to 40 m from the pumping well during the first 30 seconds of pumping. The drawdown in the pumping well was 10 cm. The quick response almost equal to that of the pumping well indicated a confined highly transmissive system with low storage capacity. The test results were consistent with the spacing of fractures in the upper watershed.

Aquifer water quality appears to be good. Electrical conductivities of samples taken during the test were around 700 us/cm, indicating a concentration of total dissolved solids of 400 to 500 mg/l. Geophysical methods were not used to locate the buried aquifer. In Wadi Fida, the maximum channel width is less than 300 m, and the aquifer would have to be as narrow or narrower. All wells were drilled by the air rotary/stiff foam method, which works well in cemented gravel alluvium and also in the less cemented areas. When properly mixed, the foam keeps the hole open and is easily removed during airlift. The foam does not bias airlift or pumping test results.

No estimates of throughflow have been made yet.

8.4.2 Wadi Halfayn

The project in Wadi Halfayn near Adam (Figure 27) is trying to quantify the groundwater leaving the Wadi Halfayn basin through the Wadi Halfayn gap near Jebel Madmar. This water is considered to be lost to the desert but additional pumping above the gap would recover it.

A transect of 13 wells across the wadi (Figure 28) has uncovered a single paleochannel 10 m to 20 m from the surface near the southwestern edge of the transect. The transect was placed between bedrock outcrops on the west (Wasia limestone of Jebel Madmar) and east (low-permeability sandstone of the Muti Formation). The location of the channel was further confirmed by borings at several points along and across the axis of the channel (Figure 29). The paleochannel wraps around Jebel Madmar in an arcuate shape into which it was forced during uplift.

The aquifer consists of light-to-non-cemented alluvial gravel deposits and water-bearing zones in fractures within cemented alluvium. The non-aquifer materials are similar, except that the degree of cementation is much higher, and are exposed at many points along the surface of the wadi where cemented gravels resembling concrete crop out.

The aquifer is confined and overlaid by hard cemented gravel. Water levels rise a few meters in the well bore during drilling. The confined nature of the aquifer was demonstrated during a pumping test in which an observation well about 400 m away responded within seconds of the initiation of pumping. Water levels in the completed wells are within 8 meters of the surface along the western part of the site and within 2 meters along the eastern part.

The paleochannel was detected by a combination of airlift testing during drilling and electrical conductivity measurements of the returned water. Aquifer materials typically had airlift yields of several liters per second, and non-aquifer materials had yields of less than one liter per second. Water quality was below drinking water standards, with total dissolved solids of 1,500 mg/l or more. Total dissolved solids in non-aquifer materials were even higher.

The results of a surface traverse electromagnetic induction (EM) survey to locate the buried channel were inconclusive. The variable nature of the cementation of the alluvium made it difficult to detect a demarcation between aquifer and non-aquifer zones. Comparison of the EM log and the cross-section produced by drilling showed a subtle definition of the channel in the EM survey. It is not certain that EM would aid the project at this location.

Several types of wells are in use. Pumping wells have 273 mm (10 3/4 in) of steel casing with fully penetrating wire-wound screens. Most observation wells have 50 mm (2 in) of PVC casing, with gravel pack installed in the aquifer interval. Small holes (4-5 mm) are drilled in the PVC to make well screens. A few observation wells have 114 mm (4 1/2 in) of steel casing and wire-wound screens; they were designed for future water quality sampling or low-yield pumping. Wells are completed above grade with either 273 mm (10 3/4 in) or 219 mm (8 5/8 in) steel headworks and 25 mm (1 in) steel access plugs. All wells were drilled by the air rotary/stiff foam method, which has worked as well at Wadi Fida.

One pumping test conducted to date and a series of water level measurements to estimate hydraulic gradient have yielded a tentative flow rate of less than 10 l/s through the buried channel. Neither the test nor the water level measurements are considered to be more than rough estimates at this time. Preliminary throughflow rates of 10 l/s or less are surprisingly low. Even if higher rates appear later, throughflow at the Wadi Haifayn gap is not significant compared with extraction in the basin above.

Some explanations for the low rate that the project continues to explore are:

- Throughflow leaves the basin via other throughflow areas to the west of Jebel Madmar (such as the Adam Gap)

- Groundwater leaves the basin through bedrock such as the Wasia limestone (the rock type exposed in Jebel Madmar)

- Evapotranspiration by the large number of trees and plants in the wadi removes a significant proportion of throughflow in the gap

- Other paleochannels not yet detected in the gap have significant throughflow

- Extraction of groundwater in the basin above equals or exceeds recharge and significantly reduces discharge through the gap

8.4.3 Relevant Concepts and Lessons Learned from Existing Projects

Lessons from the existing projects that can be applied to future projects in the Batinah are discussed below.

8.4.3.1 Wells: Numbers, Locations, and Types

A wadi throughflow project requires from 20 to 50 wells, depending on the width of the gap, the number of buried channels, the morphology of the buried channel(s), and the precision needed in the analysis. It also requires two or three lines of wells across the buried channel(s) to assess variations in aquifer properties and to measure hydraulic gradient down the channel. Both observation and pumping wells are necessary. Observation wells can be finished with 50 mm (2 in) PVC casing with drilled or cut slot screens if a gravel pack is used. A larger diameter may be used if production pumps are planned for a later time. Production wells generally are 273 mm (10 in) in diameter. Wells typically are less than 30 m deep.

8.4.3.2 Testing and Analysis

Both step- and constant-rate tests are needed to analyze aquifer response in the throughflow channel. Step-rate tests assess well efficiencies and set constant-rate tests; constant-rate tests measure aquifer parameters and boundaries.

Confined aquifers occur at the present project sites. Similar conditions are likely to be found at other locations. Confined conditions and high transmissivity caused observation wells to respond before the first measurements were taken at 30 seconds into the tests. This rapid response confirms that the proximity of physical boundaries (indicated by surface bedrock exposures) influences pumping test data within the first minute.

The present method of data collection is not adequate to correctly assess aquifer properties. Many reliable drawdown measurements must be taken during the first minute before boundary effects alter the drawdown curve and encourage erroneous interpretation. A computerized data acquisition system using transducers and a data recording system (such as

DATAPOD™ or AQUISTAR™) is required. Errors of 100 to 300 percent are likely without such equipment. Also, a digital model rather than type curves may be necessary to derive accurate transmissivity and storage coefficients.

Porous media analysis, typically applied to the data from pumping tests in buried wadi aquifers, may not work where one or two fractures dominate flow. Non-porous media equivalent systems may require tests such as packer-pulse tests. Television logging and non-Theis type curves obtained during test pumping will indicate when alternative methods of analysis are appropriate.

8.4.3.3 Geophysical Methods

Geophysical methods of site assessment such as electromagnetic induction (EM) prior to well installation have proved to be of limited value. Other methods such as surface resistivity and seismic refraction have not been applied. The variable nature of cementation, fracture distribution, and cemented gravels overlying less cemented or fractured materials makes these methods unsuitable.

8.4.3.4 Understanding of Throughflow in the Interior

Throughflow aquifers in the Interior, generally of uncemented alluvial gravels or fractures in cemented alluvium, consist of a single paleochannel in a buried wadi or a single channel of interconnected fractures in the cemented deposits of a filled-in wadi. The aquifers typically are confined and overlaid by cemented alluvium. The source of water in throughflow areas near the mountain fronts is mantle sequence ophilite rocks recharged by rain flowing into rock fractures. These ubiquitous low-permeability fractures allow a steady discharge of groundwater for several years after a recharge event. Water from the ophilite rocks discharges into surface streams on top of bedrock or cemented alluvium, eventually enters areas where the alluvium is highly permeable, and becomes groundwater. This groundwater flows beneath the wadi as throughflow and exits the mountain area through narrow bedrock gaps. In the Interior, it is either recovered through aflaj and wells or is lost to the desert.

8.4.3.5 Comparison of Interior and Batinah Throughflow

Throughflow in the Batinah and in the Interior is similar because the geology of the mountain basins feeding wadis that lead to the Batinah in the east and to the desert in the west and southwest is much the same. The mountains contain a high percentage of ophilite rock, much of it from the mantle sequence. Mountain front gaps in both regions are often underlain by low-permeability rocks, such as the crustal sequence ophilite, that are likely to limit groundwater discharge. Most groundwater discharges to the throughflow aquifer beneath the wadi, and only a small volume through fractures in the low-permeability rock along the mountain front.

Throughflow aquifers on both sides of the Jebel are likely to be similar. Aquifers of fractured cemented alluvium and non-cemented gravel have been observed at various sites in the Interior, and well logs in the Batinah report similar materials. It is not known which type of aquifer is predominant in the Batinah.

Because the hydrogeology of throughflow sites on both sides of the Jebel is similar, throughflow projects will probably be similar. Similar numbers of wells, tests, and water level measurements will be necessary.

8.5 Selection of Batinah Throughflow Project Sites

Three basins were selected for possible throughflow analysis, based on a comparison of their hydrogeology with that of an ideal throughflow project site. All three have a high probability of significant throughflow and a physical layout that permits easy measurements. In order of preference, Wadi Ahin is the first choice and Wadi Bani Ghafir and Wadi Hilti are the second.

This section discusses the ideal throughflow project site and the selection criteria based on it. A ranking of six short-listed basins for instrumentation as throughflow assessment sites follows.

8.5.1 Ideal Conceptual Throughflow Project Site

The ideal project site is diagrammed in Figure 35. It would have a large volume of throughflow and a physical situation that permits easy throughflow measurements. Also, it would allow measurement of surface water and groundwater flow to quantify recharge through infiltration of wadi floods, would indicate the potential for additional recharge through portions of the aquifer that remain unsaturated during a flood, and would therefore have potential for storage and transmission of additional infiltrated flood water. The ideal throughflow area would have a large percentage of rock types that store and transmit groundwater during non-flood times. This water is the source of throughflow. The site would be bounded by low-permeability bedrock to limit flow to the mountain gap. Most water would leave the basin as a combination of surface and groundwater flow.

The ideal site would have a wadi flowing entirely over low-permeability bedrock near the gap, permitting the construction of an inexpensive surface water gauge station to measure the entire baseflow without requiring both surface and groundwater measurements. Throughflow leaving the basin could thus be quantified without a network of wells in a dry wadi.

The wadi would widen downbasin from the surface water gauge into an area near the top of the alluvial fan where infiltration of flood water would occur. Ideally, this area would be bounded by low-permeability bedrock so that a throughflow station (two or more lines of wells) and a surface water gauge could be installed. Together, the upstream surface water gauge and the surface and groundwater measuring stations near the apex of the fan would allow a comparison of:

- Throughflow throughout the year
- Flood flows at the mountain front and further down the channel
- Flood flow infiltration at the upper fan area
- Assessment of wadi channel/alluvial fan aquifer storage potential during and after a flood event

The ideal site would have a series of downstream wells and upstream rain and surface water gauges with many years of record to provide information for correlations between surface water, throughflow, and/or rainfall. There would be few complicating factors, such as aflaj or wells in the gap area or recharge dams, that could affect the hydrologic behavior of the basin. The project would be conducted in conjunction with other hydrologic management or assessment projects so as to multiply the information gained and reduce the costs of duplication.

8.5.2 Selection Criteria

Seven selection criteria were developed after a review of the hydrogeology of the Oman mountains and current throughflow projects. The selected basin or basins should have an optimal balance of:

- Medium size
- A high percentage of mantle sequence ophiolite bedrock
- A relatively small and hydraulically isolated bedrock gap at the mountain front
- A point near the mountain front where all surface water flows over low-permeability bedrock
- Adequate past surface water and groundwater data

- Representative features such as elevations, climate, slopes, and aspects

- Moderate downbasin water use and saltwater intrusion

Each of these criteria is discussed below.

8.5.2.1 Medium Size

A basin of medium size based on the areas of basins in the Batinah would be about 500 to 1,000 sq.km, large enough to receive sufficient rainfall to generate runoff and throughflow during the study period. Rainfall, and particularly convective rainfall, is highly variable in Oman (see Chapter 3 for a detailed discussion). One rain gauge might receive 10 mm to 20 mm of rainfall while another less than 5 km away might receive none. A basin that is too small could fall outside the track of a convective cell too often during the study period and not receive rainfall representative of the area. A basin that is too large could introduce complications because of its size. Very large basins tend to have more human activity, more water use, more aflaj, greater variety in geology, and even different climatic zones within their perimeters. A very large basin would be harder to analyze for generalizations applicable to other parts of the Batinah.

8.5.2.2 High Percentage of Mantel Sequence Ophiolite Rocks

Mantle sequence ophiolite rocks are likely to contribute baseflow to the hydrologic system during the periods between rainfall events. This flow (beginning as groundwater discharge to the streams in the upper part of the watershed and continuing as surface water infiltration to the throughflow/groundwater system near the mountain front) could be important to groundwater recharge in the Batinah.

Mantle sequence ophiolite rocks allow the infiltration of precipitation and the generation of a slow but steady groundwater discharge. These rocks have been found in basins that produce surface water baseflow years after precipitation events large enough to have generated recharge (Kaczmarek, 1991c); even small basins 10 sq.km or less have this characteristic. (For example, the team found a small tributary watershed to Wadi Yanqul with an area of less than 20 sq.km and an estimated baseflow of 100 to 200 l/s three years after significant rain had fallen.)

"Hajar Supergroup" carbonate rocks such as the Saiq and Mahil formations also store and transmit groundwater discharged as baseflow to streams, but these rocks are not found in all areas of the mountain basins feeding the Batinah. They are important in the southern but not in the central or northern parts of the Batinah. For this reason, they were not considered for a throughflow study basin. However, they could be considered later if the study of the mantle ophiolite rock basin is successful.

8.5.2.3 Small and Hydraulically Isolated Gap

The throughflow project should be located where the gap at the mountain front is small and hydraulically isolated. A gap that is too large will require too many wells to locate and characterize the aquifer, especially if more than one buried channel is present. A small gap is likely to have only one buried aquifer and require fewer wells.

The gap should be hydraulically isolated, ideally with no aflaj passing through it. (Aflaj bypass the throughflow measuring site and are not measured.) If all the water were consumed and none of it returned to the wadi through aflaj leakage or return flow infiltration, the water removed by the aflaj would not be important to the system. However, many aflaj are known to leak, adding an unneeded complication to the analysis.

8.5.2.4 Surface Flow Over Low-Permeability Bedrock at Gap

The study basin should have a point near the mountain front where surface water flows entirely over low-permeability bedrock not far from where non-storm wadi flow totally infiltrates below ground. A gauge station at this point would facilitate accurate measurement of baseflow, since almost all flow from the basin would pass it, without the cost and less accurate results from a line (or lines) of wells. Surface water infiltrates the wadi bed to become throughflow, usually within a few kilometers of the point where it passes over low-permeability bedrock.

8.5.2.5 Adequate Historical Data

The selected throughflow basin should have adequate historical surface water and groundwater data to construct a statistically based predictive model. If correlations can be found between data collected at the throughflow site and at wells downstream, a database of existing observations would enhance confidence in the model.

If the selected throughflow basin shows past hydraulic behavior similar to that of other basins, the results of the study could be applied to other parts of the Batinah and possibly to the Interior, where geologic and other conditions are alike. Hydraulic behavior includes the delay-and-attenuation response of downbasin wells discussed in Section 8.3.1.3 and any general hydrograph characteristics and/or rainfall-runoff relationships that might develop.

8.5.2.6 Representative Features

The selected basin should have a representative variety of features such as climate, elevations, aspect, and slopes. Basins with extremes should be avoided. The presence of a recharge dam close to the mountain gap (such as the JICA dam on Wadi Jizzi) could affect infiltration in the study area and make the basin non-representative.

8.5.2.7 Moderate Downbasin Water Use and Saltwater Intrusion

The selcted basin should have moderate downbasin water use and saltwater intrusion so that a statistically based model could be developed for the management of the basin before saltwater intrusion made across-the-board reduction in pumping the only solution. Such a model would better serve a basin beginning to demonstrate some of the problems associated with development than one showing no such signs. Conversely, a basin with major intrusion would not need a model to predict water levels one to three years ahead, when it is known that all levels would be too low.

8.5.3 Basin Short List

Six basins were selected for a short list of prospective throughflow sites based on conversations with MWR staff and a review of geologic and hydrologic data. These were Wadi Samail/Al Khawd, Wadi Bani Ghafir, Wadi Ahin, Wadi Hilti, Wadi Salahi, and Wadi Jizzi. Two other basins—Wadi Sahtan and Wadi Sabt (Ghubra Bowl)—were considered but excluded because of the large percentage of Hajar Supergroup carbonate rocks present. Bani Kharus was excluded because of complications from the capture of surface water drainage and also the large percentage of Hajar Supergroup carbonate rocks. Other basins were excluded for want of sufficient data.

The results of the assessment of the six basins are summarized in Table 20. The assessment was based on a review of maps, reports, MWR files, and a field reconnaissance.

Elevations were derived from 1:100,000 series topographic maps of the country. Drainage basin areas were obtained from MWR files. The basins were being remeasured during the project period so the values shown are subject to change. Gap widths were based on topographic maps and field reconnaissance. Geology was based on three sources: the new French BRGM 1:100,000 maps where available; the older Open University ophiolite project maps; and the 1:500,000 map of Glennie et al (1974) in areas (such as the southern portion of the Wadi Bani Ghafir basin) where neither of the first two was available.

The number of gauges in each basin (rain and surface water) and length of data records were based on information in MWR files. Only gauges in the mountain basin feeding the Batinah were included in the table. Saltwater intrusion was based subjectively on a scale of none-minor-moderate-major from information in MWR files and conversations with MWR personnel. The category "downbasin monitoring wells" refers to a line of wells from the piedmont region to the coast installed to detect the time-lag-and-attenuation response discussed in Section 8.3.1.3. Among miscellaneous factors included in the table is the presence of recharge dams. Siltation above (and in some instances below) each dam affects the hydraulic behavior of the area.

Two of the short-listed basins are suggested for study in the Basin Characteristics and Representative Basins portion of the overall WASH project. Studying two or more projects in the same basin is not necessary but desirable.

The field reconnaissance of each basin and the basin's suitability for a throughflow project are discussed below. The location of each basin is shown in Drawing No. 2 and the mountain front gaps (as potential throughflow project sites) are shown in Figures 30 through 34.

8.5.4 Wadi Samail/Al Khawd

8.5.4.1 Field Reconnaissance

The mountain front gap of Wadi Samail/Al Khawd was visited on February 14, 1991 (Figure 30). The gap consists of a bed of cemented alluvium between outcrops of crustal sequence ophiolite gabbro and is about 300 to 400 m wide. The depth to bedrock in the wadi is probably less than 10 m and only minor excavation would be required to construct a surface water low-flow gauge.

Water was flowing in the wadi on the day of observation. The flow, coming from the wadi and a falaj fed by a hyperalkaline spring, was estimated at 500 l/s. The flow in a second falaj fed by the wadi upstream from the gap and on the east side of the wadi was not measured but appeared to be comparable with that in the wadi itself. This falaj was leaking at some points. In addition, there were many small irrigation pumps in the wadi. Use of this water would be difficult to quantify accurately.

Basin reconnaissances conducted on January 25 and 27, 1991 included observation of water use and rock types. The basin is the largest under consideration for this project and has a number of farms, villages, and towns. In addition, a large municipal well field lies downbasin from the gap.

An MWR surface water gauge station just below the gap was not visited during the reconnaissance.

8.5.4.2 Suitability for a Throughflow Project

The Wadi Samail/Al Khawd basin gap does not appear to be suitable for a throughflow project. Although the gap is narrow, there is no outcrop of low-permeability bedrock along the wadi bed and it would not be possible to construct a surface water gauge without removing the alluvium. Without a surface water gauge on low-permeability bedrock, throughflow would have to be measured by a series of wells.

The basin has the longest surface water records of any of the six basins and relatively long records for rainfall and downgradient wells.

This area also has a falaj that could complicate the assessment of flow from a line of wells and a surface water gauge just below the gap. The irrigation pumps and the municipal well field would add more complications. The well field has probably altered gradients below the gap, possibly affecting flow from the basin. The large number of settlements and farms in the basin has probably reduced throughflow to a small volume. The very size of the basin would make it inappropriate to apply study conclusions to other basins. For all these reasons, Wadi Samail/Al Khawd does not appear well suited for a throughflow assessment project.

8.5.5 Wadi Bani Ghafir

8.5.5.1 Field Reconnaissance

The mountain front gap of Wadi Bani Ghafir was visited on February 7, 1991 (Figure 31). The gap consists of a wadi bed of cemented alluvium between outcrops of crustal sequence ophiolite gabbro. The bed is incised into a terrace of cemented alluvium that occupies the southern portion of the valley between gabbro outcrops and is generally less than 500 m wide, although the valley is about 1 km wide.

At one point near the southern part of the investigation area, gabbro crops out across the entire wadi bed. A surface water low-flow gauge could be constructed here. Water was flowing in the wadi on the day of observation and was estimated at 200 l/s. The wadi flow infiltrated within 1 to 2 km of the bedrock exposure. Beyond this point no surface flow was observed.

A falaj fed by a dam upstream from the bedrock exposed area had an estimated flow of 500 l/s. The falaj had several major leaks that returned flow to the wadi.

There was a small dug well in the northern part of the area. The static water level was about 5-6 m below ground surface, indicating the static water level of the subsurface aquifer through which throughflow passes.

An MWR surface water gauge station just below the gap was not visited during the reconnaissance.

8.5.5.2 Suitability for a Throughflow Project

The Wadi Bani Ghafir gap may be suitable for a throughflow project, although some complications exist. The gap is narrow and has low-permeability bedrock outcrops for the construction of a surface water gauge. The dam supplying the falaj could be modified to serve as a weir for surface water measurements. It would have to be sealed to reduce leakage.

The basin has relatively long surface water and rainfall records and also records for rainfall and downgradient wells.

This area has a falaj that could complicate the assessment of flow from a line of wells and a surface water gauge just below the gap because of irrigation water withdrawn at varying rates. Some of this water would leak back to the wadi and would be difficult to measure. Site observations found no evidence of a buried channel to the east of the exposed bedrock gap in the alluvial terrace. But further work would be necessary to rule out this possibility.

A minor complicating factor is an elevation distribution that includes the highest point in Oman. Since rainfall is higher at higher elevations, the basin may receive a slightly disproportionate amount of rainfall. This distortion is likely to be less than the natural variation in the rainfall patterns of the area and therefore of little concern.

A combination of the detailed 1:100,000 geologic maps (Stanger, 1985) and a photograph of the 1:500,000 map of Glennie et al. (1974) indicated that the basin is only 25 to 30 percent mantle ophiolite. The lower percentage of mantle sequence ophiolite bedrock may help to explain the relatively small amount of wadi flow observed in the gap area.

In summary, Wadi Bani Ghafir may be suitable for a throughflow assessment project. A bedrock surface gauge and a combined throughflow well system and surface water gauge a few kilometers downstream appear feasible. A leaky falaj would pose some complications. The relatively small flow observed indicates that little water is actually discharging as throughflow at the gap.

8.5.6 Wadi Ahin

8.5.6.1 Field Reconnaissance

The interior of the Wadi Ahin basin, the area near the gap, and the area opening onto the alluvial fan on the piedmont were all visited on February 16, 1991 (Figure 32).

The gap consists of a wadi bed of cemented alluvium between outcrops of crustal sequence ophiolite gabbro. The alluvium forms a terrace on both the north and south sides of the valley (area A-1). Part of the wadi bed and valley approximately 100 to 200 m downstream from the JICA surface water gauge near the village of Hayl consists entirely of gabbro. The stream is generally straight with a constant slope and appears suitable for construction of a low-flow surface water gauge. The gabbro exposure across the entire wadi bed indicates that almost all the flow from the basin can be measured as surface flow at this point. Only a small volume of groundwater discharges from the mountain front directly to the piedmont area through fractures in the low-permeability gabbro.

Wadi flow was observed on the day of the field reconnaissance and was estimated to be about 1000 l/s. Agriculture in the village of Hayl is served by a falaj, presumably fed upstream from the potential low-flow gauge site. The falaj does not pass directly by the potential gauge site but supplies fields along the terrace to the north. Leaks from the falaj would flow into the fields and only a portion of this water would return to the wadi below the potential gauge site.

An upper basin reconnaissance, also conducted on February 16, 1991, observed water use and rock types. The basin is of medium size and only a few farms and villages were observed. There is a second surface water gauge about 1 km above the JICA gauge in an area where the wadi bed consists of alluvium. Some of the baseflow of the basin probably passes this gauge as groundwater but it cannot be measured with the surface gauge.

The wadi area below the JICA gauge was also visited. Wadi surface flow infiltrates the wadi bed about 2 km downstream. The area where surface flow ceased is shown as area A-2.

The last exposure of low-permeability bedrock (between the mountains and the coast along Wadi Ahin) observed during the reconnaissance was found about 8 km further downstream (area A-3). It consists of low-permeability siltstones, shales, and fine-grained sandstones of the Hawasina Formation. The distance between outcrops on either side of the wadi is about 1 1/2 km. The wadi bed is about 1 km wide.

No aflaj villages were seen in the area below Hayl. The wadi is deeply incised and its banks are so steep that the four-wheel-drive vehicle used in the reconnaissance could be driven up at only one or two places. The difficulty of building where wadi floods would cause damage may explain the absence of villages and aflaj.

8.5.6.2 Suitability for a Throughflow Project

Wadi Ahin appears to be a suitable project site. The wadi basin has a large baseflow, a suitable spot near the gap at Hayl (area A-1) for a low-flow surface water gauge station, and an area downstream for a throughflow station and surface water flood gauge. A small concrete weir and a data-recording installation along the side of the wadi would have to be constructed.

A throughflow station and surface water flood gauge could be constructed in an area bounded by low-permeability Hawasina bedrock (area A-3) and relatively far from the surface water gauge station so that flood infiltration could be assessed. The disappearance of the wadi flow below ground observed at area A-2 indicates that infiltration occurs within this reach. Throughflow characterization wells could be located in the vicinity of the alignment indicated within area A-3.

The return from excess irrigation from the falaj at Hayl could create a minor problem in the assessment of flow. But the flow in the falaj could be regulated if this site is selected. Since the lower Wadi Ahin basin does not have a line of monitoring wells from the coast to the piedmont area, these wells will have to be constructed to supply groundwater data for the development of a statistical model.

The advantages of this basin outweigh its disadvantages. The basin has long records of rainfall and surface water good for the development of the model. It has a high percentage of mantle sequence ophiolite bedrock that may explain the large volume of wadi flow in the gap area. This flow is likely to make throughflow more significant in the hydrology of the lower basin in the Batinah.

Wadi Ahin appears suitable for a throughflow assessment project. A bedrock surface gauge and a combined throughflow well system and surface water gauge 10 km downstream appear feasible. The presence of a small falaj in the vicinity may be a problem, and the construction of four or more monitoring wells will be required. Past data will not be available for a statistical model.

8.5.7 Wadi Hilti

8.5.7.1 Field Reconnaissance

The interior of the Wadi Hilti basin, the area near the gap, and the area opening onto the alluvial fan on the piedmont were all visited on February 17, 1991 (Figure 33).

The gap consists of a wadi bed of cemented alluvium between outcrops of crustal sequence ophiolite volcanic rock. The alluvium forms a terrace on both the north and south sides of the valley (area H-4). There are outcrops of volcanic rock on the south side of the wadi (partially in the wadi bed) and low-permeability sediments of the Hawasina Formation in the hills north of the wadi. The distance between these outcrops is between 1/2 and 1 km. No surface water was observed.

The MWR surface water gauge about 1 km downstream from area H-4 was not visited during the reconnaissance.

An attempt to find a point where surface water flows entirely over low-permeability bedrock was unsuccessful. Access to the interior of Wadi Hilti is via a major tributary, Wadi Suhayl. No surface water was observed well into Wadi Suhayl at area H-2 nor where the track diverges from Wadi Hilti at area H-3. It was observed at area H-1, however. The wadi flows over crustal sequence ophiolite gabbro at the village of Al Abiah and probably at other places further downstream. A more detailed reconnaissance would be needed to verify this.

The point where surface flow totally infiltrates the wadi bed was not located either. It must lie between areas H-1 and H-2, as the former had flow while the latter was dry. A more detailed reconnaissance would be needed to find this as well.

Wadi flow observed in the upper basin only was estimated at 500 l/s. This rate may not be indicative of the flow from the basin at the mountain front.

The basin appears to have several small villages and agricultural areas, but difficult access ruled out reconnaissance of much of the basin. Difficult access may also have limited population.

8.5.7.2 Suitability for a Throughflow Project

Wadi Ahin may be suitable for a throughflow project if a site for measuring low-flow surface water can be found. If not, throughflow can be measured with a series of wells lower down the basin. But an estimate of wadi-flood infiltration will not be possible with only one throughflow site.

For its size, the upper basin of Wadi Hilti has a large baseflow, which is needed for throughflow to be a significant component of flow to the coastal basin.

A throughflow station and surface water flood gauge could be constructed at area H-4, an area bounded by low-permeability volcanic and Hawasina bedrock and relatively far from a potential bedrock surface water gauge station.

The lower Wadi Hilti basin has a line of monitoring wells extending from the coast to the piedmont area to measure the attenuation-and-delay response discussed earlier. Data from these wells could be used for the development of a statistically based model.

The basin has a relatively short record of rainfall and a moderate record of surface water data. The surface water data are acceptable for a statistical model; the rainfall data may not be important.

Wadi Hilti may be suitable as a project site if a bedrock surface gauge location can be found. A combined throughflow well system and surface water gauge downstream to measure throughflow and floodflow infiltration appears feasible. Downbasin well data are available for a statistical model.

8.5.8 Wadi Salahi

8.5.8.1 Field Reconnaissance

The lower portion of the mountain basin of Wadi Salahi was visited on February 17, 1991 (Figure 33). Because access was difficult and reconnaissance of the gap indicated that the basin was unlikely to be a first or even a second choice for a throughflow project, the interior of the basin was not inspected.

The gap at area S-1 consists of crustal sequence ophiolite volcanic rock of low permeability. The gap is only about 200 m wide, and a throughflow project at the site would require only a few wells for measurement.

The wadi bed consists of cemented alluvium, which has not been incised to form terraces in the valley as in the other wadis observed. Flood peaks have probably been much smaller and not strong enough to cut through the cemented alluvium to form terraces.

No wadi flow was observed on the day of the field reconnaissance. There may have been surface flow upstream but difficult access prevented its verification. There were no active aflaj in the gap but the ruins of a falaj were seen.

There is a surface water gauge about 10 km downstream that has the shortest records of those on the short list. Geologic maps indicate that the gauged area consists of alluvium. Bedrock outcrops are not noted. The gauge was not visited.

A recharge dam in the coastal basin is not expected to affect hydrologic processes near the mountain gap.

8.5.8.2 Suitability for a Throughflow Project

Wadi Salahi is not suitable for a throughflow project. Access is difficult, the basin is small, and the small percentage of mantle sequence ophiolite bedrock means a correspondingly small baseflow. It has no exposed low-permeability bedrock for construction of a low-flow gauge station. The existing surface water gauge is in an alluvial area and probably does not indicate true outflow from the upper basin if infiltration occurs between it and the mountain front.

8.5.9 Wadi Jizzi

8.5.9.1 Field Reconnaissance

The mountain front gap and lower portions of the Wadi Jizzi basin were visited on February 17, 1991 (Figure 34) and the interior of the basin the next day.

The gap consists of a wadi bed of cemented alluvium between outcrops of crustal sequence ophiolite volcanic rock and is about 300 to 400 m wide (area J-1). Based on this width and the presence of volcanic rocks in the southern wall of the wadi, the depth to bedrock is estimated at less than 10 m. Still, it does not appear to be shallow enough for the construction of a surface water low-flow gauge on bedrock. There were no areas downstream where the wadi flowed entirely on bedrock.

Water was flowing in the wadi on the day of observation and was estimated at 500 l/s. Groundwater flow under the wadi could not be estimated. All surface water flowing past the gap infiltrated the wadi bed as groundwater within 1 to 2 km. The gap lies below the confluence with Wadi Hayl (area J-3).

The basin is moderately large but there were only a few farms and villages in the mountainous part.

The Wadi Jizzi recharge dam is different from the other recharge dams in the Batinah. It lies near the mountain front, not near the coast as the others do. It stores and then slowly releases flood water to the downstream wadi, where theoretically the water infiltrates the basin. The silt behind the dam was more than 1 km upstream. The flood pool probably extends even further, possibly up to the area considered for the throughflow study.

A smelter within 2 km of the gap (area J-2) is known to be contaminating the wadi. According to Laver (1991b), two types of contamination have been detected: saline water leaking from a supply pipeline from the coast, and sulfate and metals leaking from evaporation ponds connected with the smelting process.

A surface water gauge about 2 km above the gap (area J-3) was not visited.

8.5.9.2 Suitability for a Throughflow Project

Wadi Jizzi is not suited for a throughflow project. It is flawed by the JICA recharge dam, the position of the gap relative to the mouth of Wadi Hayl, and the contamination from the smelter.

The recharge dam will complicate the assessment of throughflow and the infiltration of wadi floods. The backwater it creates could cause more recharge than is normal during a flood. On the other hand, siltation behind the dam may have the reverse effect by reducing the permeability of the surface. The site would be a poor choice for a project designed to verify throughflow and the infiltration of flood water.

The project cannot be located upstream because of the closeness of the confluence with Wadi Hayl, which makes separation of flow from the two wadis next to impossible. Moving the project site above the confluence is not satisfactory because the wadi flows at the surface throughout this reach. The project must be located where the wadi flows at the surface, where all flow infiltrates the subsurface, and where there is a suitable site for a throughflow well system and surface gauge. No areas above Wadi Hayl have all three features.

Contamination by the smelter will complicate a throughflow analysis, since samples collected during the study may be affected by the saline water or high sulfates. Isotopic data may also be impaired.

Wadi Jizzi clearly is not suited for a throughflow assessment project.

8.5.10 Ranking of Selected Basins

Wadi Ahin is the basin most suited for the study and is most likely to generate significant throughflow. It offers ease and reliability of measurement of both throughflow and of wadi recharge during a flood. Wadi Bani Ghafir and Wadi Hilti are also suitable but are likely to generate throughflow either at a lesser rate or under circumstances that will make it difficult to quantify it in relationship to wadi flood recharge. Projects in these basins would be more complicated. The three remaining basins do not merit further consideration.

These rankings are based on a rating system shown in Table 21. The data in Table 20 were assigned points according to the spread observed in the six basins and the study team's best professional judgment. The range of values reflects the relative importance of each factor in selecting a project location. The more the points, the more important the factor.

For example, a large percentage of mantle ophiolite and a large observed baseflow indicate that the basin has a high potential for generating significant throughflow. These factors can be given a rating of up to 7 points. A basin with these features is a good candidate for selection. On the other hand, a longer surface water record is desirable but not essential. The maximum rating for this category is 2 points, so that a basin without a long surface water record could still be a candidate when other factors are considered.

Although other reviewers could well assign different values for each category and choose different divisions for each point value, the team believes that the overall ranking would not differ significantly and that Wadi Ahin would still be the preferred choice for the first throughflow project in the Batinah.

8.6 Recommended Throughflow Project

Using Wadi Ahin as the most likely site, this section describes the recommended throughflow assessment project and the requirements for surface water gauges, well installation, testing, monitoring, and data acquisition systems.

8.6.1 Project Overview

The recommended throughflow assessment project would require two stations: a surface water measuring station near the mountain gap, and a combined surface water measuring station and well system to measure throughflow near the top of the alluvial fan entering the Batinah piedmont. A schematic of the project is shown in Figure 35.

The first station (station 1) would be near the village of Hayl (area A-1 in Figure 32), where the wadi flows entirely over outcrops of mantle sequence ophiolite gabbro. It would consist of a low concrete weir or flume and a measuring and recording system, such as a stilling well, a pressure transducer, and a DATAPOD™ unit. It would measure the baseflow that becomes throughflow within 2 km of the site. The JICA gauge would be rehabilitated to measure flood flow if the baseflow gauge was deemed inadequate to provide flood flow data for calculation of infiltration farther downstream.

The second station (station 2) would be about 10 km downstream from Hayl at area A-3 and would combine a surface water gauge and a well system to measure throughflow. The surface water gauge would measure wadi floods only, as there is no surface water baseflow at this site. The wells would be drilled in two or more lines across the wadi and spaced according to the results of testing during placement. They would be pumped to determine aquifer properties, and water levels would be measured to determine hydraulic gradient. These results would be used to calculate throughflow rate in the aquifer beneath the wadi.

A system of four to six wells would be installed below station 2 and extend from the piedmont to the coast. They would be analogous to wells below other main wadis in the Batinah, such as those discussed above and reported in Rendell (1991) and Laver (1991a).

Inexpensive crest gauges would be installed between the two stations to give a general indication of where infiltration occurs during smaller floods.

Data would be collected from these stations and the downwadi wells over time. During low-flow conditions, throughflow at the well site (station 2) generally would be equal to baseflow at the surface water station in the bedrock gap (station 1). Differences could be used to adjust and calibrate the results of the pumping tests. During flood events, flow measurements would be made at the surface water stations and also from the wells. The differences between the surface gauges would indicate the rate of infiltration along the 10 km of wadi. Throughflow measurements would be used to verify this rate and to determine whether additional storage capacity is available in the sub-wadi aquifer. The end result would be a better understanding of the relative importance of these two major sources of recharge to the Batinah aquifers.

Chemical and isotope data would also be collected from the wells and surface water stations and analyzed to validate the partitioning of the surface and groundwater as well as to verify the sources during various points in the hydrologic cycle.

Water level data would be statistically analyzed after several years of data collection for correlations between water levels in the downwadi wells and:

- Throughflow rates
- Water levels in the throughflow wells
- Surface water baseflow rates at station 1, and/or
- Wadi flood infiltration rates and volumes

If it can be developed, a statistical model linking hydraulic behavior at the mountain front and water levels lower down the Batinah would be able to predict both good and bad water periods two to three years ahead. Data would then be collected over the long term at the intervals appropriate for the model.

Two other sites and methods for data collection were considered but were excluded for the reasons explained below:

- Wells finished in bedrock near the gap to monitor hydraulic relationships between the gabbro and the wadi. (Unlikely to produce significant data as only a few fractures in the gabbro have been shown to be water bearing. Intersection of two or more of these fractures near the gap would be a serendipitous discovery.)
- Tensiometers below the wadi bed to monitor infiltration as unsaturated flow. (Unlikely to produce significant data because installation of tensiometers in a borehole disrupts the natural vertical flow path. In addition, review of well logs from wadi beds shows either fractures or uncemented gravels as the dominant flow path. Unsaturated flow is unlikely to be significant.)

8.6.2 Surface Water Gauges

Surface water gauge stations should be constructed at stations 1 and 2. The gauge at station 1 will consist of a concrete weir or flume with a low profile to withstand wadi floods, a stilling well, a transducer, and a data recording system such as DATAPOD™. The weir will allow measurement of low-flow rates in the 2000 l/s or less range and will be connected by a pipe to a stilling well attached to bedrock cropping out along the side of the channel. The placement and design of the weir and stilling well will be based upon a thorough reconnaissance of the wadi channel near Hayl by a qualified surface water hydrologist and geologist to ensure that the gauge is placed on a cross-section of the wadi channel consisting entirely of gabbro. The site chosen should enable the optimal measurement of baseflow and be able to withstand flood events.

If the design of the gauge makes it unsuitable for measuring flood flows, the nearby JICA gauge, which is full of silt and in need of cleaning, should be reactivated. The upstream MWR gauge, which Curry (1991a) indicates is more accurate, should be used to adjust the measurements of the JICA gauge.

The second surface water gauge, to be constructed at station 2, should consist of a stilling well (casing and well screen), a transducer, and a data recording device such as DATAPOD™. It should be located near the throughflow well site. An outcrop of Hawasina siltstone and sandstone there looked like a suitable site, but a qualified surface water hydrologist should choose the best location.

A series of crest gauges about 2 km apart should be constructed below and between the two stations. These gauges consist of one or more pipes each about 1.3 m long with a meter stick and powdered cork inside. The pipes are vertically mounted along the wadi bank. A flood causes the cork to rise and cling to the meter stick at the highest level of the flood. A comparison of crest heights (factoring in the effects of channel geometry) will indicate the distance traveled by small floods that pass station 1 but do not reach station 2 and also the infiltration areas and, possibly, the percentage of infiltration in each area. Floods passing station 2 can be assessed in like manner but without the control of a gauging station below.

8.6.3 Wells

8.6.3.1 Locations

Two series of wells should be installed, the first along the line of dashes shown in area A-3 and the second between station 2 and the coast. The first series will consist of an initial line of wells drilled at intervals of 300 m to 500 m across the wadi to locate the aquifer beneath. A second line, drilled 500 m to 1,000 m upstream from the initial line and filling the gaps between the first wells, will identify the sections of the aquifer with high transmissivity. Airlift tests (discussed below) can help to locate the aquifer.

The second series of wells should be drilled into the aquifer at 5 km intervals below station 2 in or near the wadi. If a significant unsaturated zone is found and is underlain by low-permeability materials so that a perched zone could form during flood water infiltration, double completion wells should be constructed—one in the aquifer, the other in the unsaturated high-permeability zone above it. These wells will track recharge as it progresses toward the coast.

8.6.3.2 Design and Numbers

The two types of wells to be installed are pumping wells and wells for observation/water quality monitoring. Pumping wells should be at least 273 mm (10 3/4 in) in diameter and have steel casings with fully penetrating wire-wound screens. Two to four of these will be required at the throughflow site.

The observation/water quality monitoring wells (hereafter called observation wells) should have 50 mm (2 in) PVC casings, installed with gravel packs in the aquifer interval, and be equipped with commercial cut-slot PVC well screens to permit a rapid response to pumping tests. These small-diameter wells can be sampled with small-diameter pneumatic, electric, or nitrogen driven sampling pumps. Larger-diameter wells could be equipped with 114 mm (4 1/2 in) steel casing and wire-wound screens if low-yield pumping is anticipated. About 20 to 22 observation wells will be required at the throughflow site and four to six at downwadi locations.

Multiple completion wells may be needed at the downwadi sites and possibly at the wadi throughflow site (station 2). They will also be equipped with two 50 mm (2 in) PVC casings and screens. The space between the two screens will be filled with pressure-injected cement grout (supplemented with bentonite) or bentonite slurry to seal the annulus between the wells.

Wells should be completed above grade with either 273 mm (10 3/4 in) or 219 mm (8 5/8 in) steel headworks and 25 mm (1 in) steel access plugs. A very sturdy reinforced concrete headwork assembly should be used. The steel casing should extend several meters below grade and be secured to the wadi bed with reinforced concrete poured into a mold outside the well and inside the casing. The protection should be streamlined for easy passage of wadi-flood bedload.

8.6.3.3 Installation Method

Any suitable drilling method is acceptable, but experience has shown that the air rotary/stiff foam method is successful in the difficult drilling environment of the wadi bed and should be considered for this project. The large number of boulders at the site indicate that drilling could be difficult.

8.6.4 Pumping Tests

8.6.4.1 Types

The project will use three types of pumping tests: the airlift test, the step-rate test, and the constant-rate test.

The airlift test uses air pressure through the drill rods to measure the rate of water return; it should last for one-half to one hour. This test is not a true aquifer test because it does not measure drawdown, but it does give a general indication of the water-bearing properties of the aquifer. Little or no flow indicates that the well is completed in an aquitard; low flows of 2 l/s or less indicate that the well is completed outside the high-yield portion of the aquifer; flows greater than 10 l/s indicate that the well is completed in the high-yield portion of the aquifer.

The step-rate test evaluates well efficiency and sets the rate for the constant-rate test. A three-to-four-step test of two to four hours should suffice.

The constant-rate test measures drawdowns at the observation wells in the throughflow site. The rate should not be so high that well loss is a major percentage of drawdown or the aquifer dewaters if confined. Experience at other throughflow sites suggests a rate between 5 and 40 l/s. The length of the test will depend on the nature of the aquifer. If the aquifer is confined, all the data needed should be obtained within 24 hours. If it is semi-confined or shows delayed yield, the test may last several days.

8.6.4.2 Data Collection

Pumping test data should be collected with pressure transducers and electronic data recording equipment such as DATAPOD™, AQUISTAR™, or equivalent. Experience in other wadi pumping tests indicates that measurements of water levels by hand will not be adequate. The aquifer boundaries near the pumping well cause hydraulic boundary effects within the first few minutes of the pumping test, in some cases even before the first hand measurement at 30 seconds. Electronic equipment can provide 10 or more readings during the first minute.

8.6.4.3 Data Analysis

The pumping tests should be analyzed by traditional methods if possible. Step-rate tests should be analyzed by the Walton (1962), Birsoy and Summers (1980), or similar acceptable methods. Constant-rate tests should be assessed by the Theis, Boulton, or Neuman methods. The straight line Cooper-Jacob method is unlikely to work, as the boundary effects occur too soon for the method to be applied.

If the aquifer system is too complex, a digital model may be required to assess aquifer parameters. If delayed yield, boundary effects, and/or leakage occur simultaneously at the beginning of the test, analytical methods may not be appropriate because they require too many simplified assumptions.

8.6.5 Water Level Measurements for Throughflow Analysis

Water levels should be measured initially by hand (with electric well-sounders) to the nearest 5 mm. Wells should be surveyed with a similar resolution. Monthly measurements can be used to calculate hydraulic gradient. In addition, data recording systems on four wells should monitor changes over time. The monthly measurements will indicate which wells are representative, and water levels in these (using the data recording systems) can be used to generate the approximate gradients over time, after typical gradients have been determined.

8.6.6 Water Chemistry and Isotope Analysis

Samples for water chemistry and isotope analysis should be collected periodically from the surface water gauge site, the throughflow wells, and the downwadi monitoring wells. Gas-driven bladder, pneumatic, gas or hand-driven piston, or electric pumps are all suitable. Gas-displacement pumps are not recommended because the gas can alter sample concentrations, and peristaltic pumps are not feasible because the lift is likely to be too high.

Major ion and total dissolved solids analyses of the samples may help to show the sources of the various waters and, immediately after a flood event, the origin of water in the throughflow aquifer. Higher concentrations in the aquifer before a flood event followed by decreasing concentrations may indicate downward infiltration of wadi flood waters. Increasing concentrations in the aquifer several months or years after a recharge event may indicate that groundwater (ophiolite) discharge to the wadi in the upper basin is entering the throughflow aquifer.

Isotope analyses will also indicate the origin of the waters. Tritium analyses may help to separate flood infiltration from throughflow originating as wadi baseflow. The age difference may not be large enough, however, to make the distinction. Stable isotope analyses (deuterium and C^{13}) will help to identify high-altitude and low-altitude recharge. Recharge in the mountain front area is usually from high-altitude rainfall. Recharge to the downwadi wells may also include infiltration of direct precipitation.

8.6.7 Statistical Analysis and Predictive Model

After collecting several years of data on water levels, throughflow rates, and flow volumes, the average time lag between hydraulic behavior in the throughflow project area and water levels lower down in the Batinah should be calculated. A transfer function model and Gelhar's spectral analysis technique may be suitable methods of analysis. The hydrologist analyzing the data will decide on the best technique to use.

8.7 Implementation

The MWR will probably manage the project, analyze the data, and assign the field work to contract employees.

If the project is undertaken, it could be conducted:

- by the regional office at Sohar (under James Laver)
- by the Groundwater Division (under Brian Eccelston)
- as a part of Regional Assessments (under Harley Young)
- as a special project (under Don Davidson)
- as part of Management (under Remy de Jong or Simon McNeilage), or
- as part of some other division of the MWR

The statistical analyses would probably be conducted under the direction of Mohammed Chebaane. The surface water gauges would be installed under the direction of Wayne Curry and/or Mel Johnson. Because of his special interest, Mike Kaczmarek may have some part in data interpretation. Data collection would come under the direction of a regional office. If Wadi Ahin is the selected site, it would be Sohar.

8.7.1 Project Requirements

8.7.1.1 Time

The installation of the two stations and the line of downwadi monitoring wells is likely to take six months. If baseflow data collected during this period show throughflow rates in excess of 10 mcm/yr, throughflow is likely to be significant. The baseflow rates at Wadi Ahin are in this range.

It will take three to five years to collect data on throughflow, wadi flood infiltration, and downwadi well response. A dry period will lengthen, while a wet period will shorten, the data collection period. If a statistical model can be developed, data collection will be continued indefinitely.

8.7.1.2 Staff

Staff requirements will vary with each phase of the project. The six-month installation phase will require:

- Field Staff: senior field hydrogeologist, junior field hydrogeologist, drilling supervisor, and senior surface water hydrologist
- Office Staff: project manager, senior hydrogeologist, junior hydrogeologist, senior surface water hydrologist, and various technicians

The field staff will work full time; the office staff will probably work on other projects as well. Staff to support the drilling contractor and the surface water weir contractor will be paid from subcontract costs and are not listed here.

Data collection will begin after the installation phase. Data recording systems will be downloaded to office computers and routine analysis will be made after each download. After three to five years, a comprehensive analysis will be conducted by a senior statistical hydrologist. Data collection and reduction will require the equivalent of one part-time technician and junior hydrogeologist, or 1.5 person-months per quarter. The analysis by the senior statistical hydrologist will take a few weeks to a month.

Data collection and reduction will continue after the model is completed. Use of the model will require the services of a senior hydrogeologist or hydrologist for two to four weeks per year.

8.7.1.3 Subcontracting

The installation of the wells and the construction of the surface water gauge weir will be subcontracted. Renovation of the JICA gauge and installation of the surface water gauge at the throughflow site could be done by the MWR but may also require subcontracting.

The project calls for 30 or more wells—at least four pumping wells and 26 observation wells. The pumping wells and 20-22 of the observation wells will be installed at the throughflow station; the remaining observation wells will be installed downwadi. The estimated depth of the wells is 30 m.

Subcontracts will also be required for the well elevation survey, down-hole geophysics or video logging of completed borings, and construction of the surface water weir.

Wells at the throughflow station should be surveyed with an accuracy of 0.5 cm, wells downwadi with an accuracy of 0.5 m. Horizontal position should be determined either by survey or by a global positioning system.

Down-hole geophysics and/or video logging of the completed borings should run logs for resistivity, spontaneous potential, natural gamma, and caliper. Neutron logging should also be considered. Experience has shown that down-hole television observation of subsurface geology can be valuable.

The reinforced concrete surface water weir or flume at the upper station structure is estimated to be 10 m or more wide and about 1 m high. The design will be developed after the surface water hydrologist has surveyed the site.

8.7.1.4 Equipment

The project will require six to 10 water level monitoring and recording systems. Four or more transducer and data acquisition systems (such as DATAPOD™ or AQUISTAR™) will be needed for each of the pumping tests conducted at the throughflow station. These systems should be multi-channel units so that two or more transducers can monitor two or more observation wells when placed together. After testing, they will be installed on the finished wells. Only four data acquisition systems should be needed to establish the hydraulic gradient of the aquifer. They should be supplemented by manual measurements of water levels each quarter. Similar systems are required for the two surface water gauges.

Other equipment for the project includes field meters for pH and conductivity, sampling pumps, and sample storage and transport supplies. These have not been assigned to the project as they are likely to be used at various times on other projects as well.

8.7.2 Cost

The project is expected to cost about R.O. 199,000 for installation and approximately R.O. 22,000 each year thereafter, making a total of about R.O. 309,000 for a five-year period. Project costs are summarized in Table 22; unit costs are listed in Tables 23, 24, and 25.

Drilling costs were estimated from the Wadi Halfayn project (Ministry of Water Resources, 1990). Surface water gauging and data collection costs were based on information from Curry (1991b). Personnel costs were based on information from Kay (1990). The costs are approximate and should be used only for planning purposes. A detailed scope of work should precede a more precise cost estimate.

Chapter 9

GROUNDWATER RECHARGE ENHANCEMENT

9.1 Summary and Recommendations

9.1.1 MWR Role in Recharge Assessment Recommended

Over 10 years ago, prior to any recharge dam construction in Oman, the United Nations Food and Agricultural Organization (FAO) warned that detention storage-recharge dams could have prohibitively high maintenance costs and adverse effects that would outweigh their benefits. The FAO cited instances where silting of dam detention areas sealed off recharge and released water, which, after dropping its sediment load, caused greater erosion downstream with its enhanced capacity for sediment transport. The FAO did not completely reject large dams, but suggested that less costly alternatives be considered carefully. This has not been done, nor has the effectiveness of completed recharge dam projects in Oman been assessed adequately.

In October 1989, WASH recommended the formation of a permanent monitoring team within the MAF. The OAJC, which sponsored the report, made repeated requests that it be discussed and implemented, but to no avail. Whether or not the MAF has plans for monitoring, the study team believes the MWR should undertake this task, even though the effort could be redundant.

9.1.2 Artificial Recharge Projects Sections

The MWR should have a staff of three within the Water Protection Department to monitor recharge dams: a section chief (engineer hydrologist), a groundwater specialist, and a surface water engineer.

As work expands, additional staff may be necessary. The cost for first-year staffing would be about R.O. 165,000.

Many of the wells near the dams are of no value in monitoring recharge because of the way they have been constructed. In addition, there are not enough of them. An effective network of recharge monitoring wells at seven dam locations in the Batinah region should cost about R.O. 425,000.

9.1.3 Alternative Recharge Methods—Pilot Program Selection

The study team reviewed 15 recharge methods, of which two offered the best prospects for successful application. The Leaky Sand Dam method and the Dry Well/Recharge Pit method should both be further investigated through pilot programs.

9.1.4 Pilot Program of Leaky Sand Dams

The leaky sand dams are illustrated in Figures 46 and 47. About six to 10 could be built in the upper catchment area of a wadi. The dams are termed leaky because the gabion construction allows water to pass through after it has deposited wadi sand and gravels above the axis of the dam. Much of the troublesome silt passes through the structure.

Construction would be by means of an initial lift of 2 meters, followed by successive lifts that would gradually enlarge the structure. The water detained in the accumulated sand and gravel drains slowly after a flood event.

The dams would reduce peak surface flows and flood problems, and the delayed drainage would allow the downstream wadi gravels, which are thought to be fully saturated during flood flows, to drain after the main flood wave has passed. Additional recharge that would otherwise have been a part of the flood flow and lost to evaporation or the sea would occur.

A five-year pilot program should cost about R.O. 550,000.

9.1.5 Pilot Program of Dry Wells/Recharge Pits

In many areas of the Batinah, deep percolation of surface water is retarded by shallow cemented layers and the water is lost to evaporation. A simple but effective remedy is to capture the surface water in pits in which silt quickly seals the bottom but the sides continue to receive water.

These recharge pits could be excavated at fords in roadways where minor wadis cross or at culverts. Many other sites are possible. Two applications are illustrated in Figures 48 and 49.

The pilot program would have two phases: the test of a single site using either a flood event or water pumped from a well, and a study of operating conditions at 20 to 30 locations.

The cost of the first phase would not exceed R.O. 50,000. The cost of the second phase would be clear after initial testing.

9.2 Introduction

9.2.1 Purpose of the Groundwater Recharge Study

The objectives of this study to assess the need for investigating alternative groundwater recharge techniques were:

- To evaluate enhancement techniques used to date and, by reference to work done elsewhere, provide a basis for the use of other techniques that may be appropriate

- To review recharge enhancement work done in Oman and elsewhere (such as California), to outline a suitable recharge program, to identify and design pilot projects, and to examine the effectiveness of recharge augmentation in Oman to date

9.2.2 Scope of Work

The scope of work covered:

- A review of recharge projects conducted to date in Oman to identify potential alternative or supplementary recharge methodologies

- The design of investigations to:

  - Audit the effectiveness of recharge augmentation in Oman to date

  - Identify other methodologies

  - Outline a recommended assessment program

  - Provide preliminary designs for pilot projects

9.2.3 Conduct of Study

The team held several meetings and discussions and made field trips to the Wadi Ma'awil dam construction site, proposed project sites at Bani Kharus, Rubkhah, and Taww, and areas upstream from these four sites. The team also visited potential sites in the Sohar district that might be suitable for recharge projects as an alternative to the dams.

The rest of this chapter covers a review of previous studies, a review of recharge projects constructed to date, monitoring and evaluation needs of existing facilities, identification of alternative recharge methods, alternatives to large dams, and pilot programs to examine alternative recharge methods.

9.3 Review of Previous Studies

9.3.1 Identification and Discussion

The earliest discussion of recharge is in "Water Resources Survey of Northern Oman" by Sir Alexander Gibb and Partners. But a number of other studies of the groundwater system carried out for and by different government ministries also provide useful information.

9.3.2 Geologic/Hydrologic Conditions Related to Recharge

On Oman's northern coast (Batinah), overdraft of water has caused a lowering of water levels and saline intrusion from the Gulf of Oman. Figure 36 illustrates the imbalance of groundwater recharge and utilization by showing how far inland the zero elevation groundwater contour line has moved. This contour represents sea level. Saline intrusion occurs seaward of this line. Comparison of Figure 36 and Figure 37 (taken from the JICA report of 1986) shows further inland movement of water level elevations caused by greater groundwater withdrawals. To halt further saline intrusion, both artificial groundwater recharge and a reduction of groundwater use are necessary.

The progressive lowering of groundwater levels and increasing saline intrusion appear to be most serious in the Barka-Rumais area. The subsurface formations from this area through Sohar, while complex and not fully defined, are generally similar according to reviews of various reports. (See Barka-Rumais geological cross-sections—Figures 38 and 39 and Figures 40 and 41 for Wadi Ahin in Sohar area). Although the imbalance on the Batinah is most severe, there is little scope for increasing available resources with recharge dams in the Interior.

Previous reports have advanced conflicting theories on how natural recharge occurs, but the process remains largely a mystery. The throughflow studies recommended in Chapter 8 should help toward a better understanding.

9.4 Review of Recharge Projects Constructed to Date

9.4.1 Overview and Background

The U.S. Army Corps of Engineers study of 1979 recommended eight wadi sites for a recharge structure and identified four more for consideration. After further input from the Public Authority for Water Resources (PAWR) and Tetra Tech International, Inc., Wadi Al

Khawd was selected under a plan that agreed with the general impoundment scheme recommended by PAWR. Stanley Consultants completed a feasibility study in December 1981 and construction was completed between March 1983 and April 1985. Aquifer recharge studies that concentrated on water for the Capital Area were carried out by Brown and Root in 1984.

Hydroconsultant carried out a number of studies in the early 1980s for individual recharge schemes and completed a reconnaissance study encompassing over 60 dam sites in 1985. This document has been the basis of much of MAF's work on recharge.

Since the Al Khawd project, all the recharge projects completed have been the subject of preliminary and feasibility studies.

To date, the MAF has implemented nine groundwater recharge schemes: the seven listed below and the Ma'awil and Bahla dams now under construction.

Name of Project	Location
Al Khawd	Capital District
Hilti-Salahi	Batinah
Jizzi	Batinah
Quriyat	Interior
Ghul	Interior
Tanuf	Interior
Ibri	Interior

The nine are shown in Figure 42.

In the Salalah area, dam construction is under way at Wadi Sahalnawt. The 1989 Mott MacDonald feasibility study recommended two other sites, Wadi Jarsis and Wadi Nahiz.

9.4.2 Specific Recharge Project Descriptions

The team visited all the dams shown in Figure 42 (except for Quryat), including the Ma'awil dam and the Sahalnawt dam in Salalah, where work is in progress.

In the reservoir area of the Ghul dam, silt had been removed for a distance of only 150 m upstream from the dam, and at Tanuf for only 100 m directly behind the sloping concrete apron upstream from the dam. At Al Khawd there was evidence of extensive silt removal in the past, but silt from the 1987-90 wet period still covered much of the storm water retention area behind the dam. It is obvious that a net deficit of recharge could result if silt within the reservoirs is not removed after flood events.

9.4.2.1 Wadi Al Khawd

The recharge dam at Wadi Al Khawd was the first aquifer recharge project to be constructed. It was designed as a pilot project to develop a database and performance data for planning other recharge facilities. The dam is about 10 km west of Seeb International Airport in an area of existing and planned development, and stores flood flows that originate in the catchment area of Wadi Sumayil and exit in Wadi Al Khawd. The catchment area at the dam is 1,800 sq.km, and the dam is 5.1 km long and 7.5 m high.

At spillway crest (elevation 38.5 m) the reservoir has a storage capacity of 12.4 mcm. The dam has 11 1.2 m-diameter culverts, nine of which are provided with stoplogs; the other two are equipped with manually operated sluice gates. The spillway over the top of the dam is 3,000 m long. Although the dam does provide some flood protection, it cannot be counted on in a major storm. A concrete channel flume upstream is monitored by an automatic water level recorder at the dam, two stream gauging stations on downstream channels, and several monitoring wells.

Nearly two years after its completion in April 1985, the dam was visited by flood flows from three major storms between February 20 and April 7, 1987 that provided the first opportunity to observe the aquifer recharge system in operation.

During the first storm, the actual infiltration rate of the wadi channels downstream from the dam was less than had been calculated during the design phase of the project. The storm also indicated the need for a better distribution of the flow to these channels. Subsequently, 10 stoplogs were installed to block the flow from one of the culverts and to greatly restrict the flow from the other five so that now greater depths of water are stored for a longer time when there is a storm.

The channels leaving the stilling basin to the east carried away most of the outflow from the dam until the flow was regulated by raising the stilling basin end wall. Also, because the monitoring equipment was not measuring high flow rates accurately, the DATAPOD™ recorder was supplemented with a bubbler system.

9.4.2.2 Wadi Hilti/Salahi

The recharge dam at Wadi Hilti/Salahi about 15 km southwest of Sohar on the Batinah Plain was the second to be constructed. The dikes and retention reservoirs are used to interrupt and store storm flows for release to the agricultural area known as Sohar Farms. The catchment areas of Wadi Hilti and Wadi Salahi are 256 sq.km and 106 sq.km, respectively. The dike at Wadi Hilti is 5.7 km long and 3.5 m high and has two spillways 100 m and 180 m long, respectively. At spillway crest, Wadi Salahi has a storage capacity of 0.38 mcm. The spillway and overflow weirs are designed to convey the 100-year flood (flood which theoretically occurs once every 100 years) without its overtopping the earthfill embankment. Monitoring facilities include observation wells and a flow measuring station upstream from the spreading basins. Storm flows at this site have prompted modifications to the downstream apron that distributes water to these basins.

9.4.2.3 Wadi Quryat

The first recharge facilities in the Interior were constructed on Wadi Sayfam to replenish groundwater supplies for the Quryat farms. The catchment area is 375 sq.km. The storage reservoir, on the eastern branch of Wadi Sayfam, is formed by an earthfill embankment running north-south on the farms side of the wadi and an overflow gabion weir with a spillway 80 m long across the riverbed. Flow from the reservoir to the spreading grounds is through a culvert discharging into an open channel. At spillway crest, the reservoir has a storage capacity of 0.125 mcm; the spreading grounds provide additional storage of 0.065 mcm. The spillway crest is 3.0 m below the top of the embankment and the design flood can be passed with a freeboard of 0.6 m. The monitoring facilities include observation wells, and water level recorders in the reservoir, spreading basin, and connecting channel.

9.4.2.4 Wadi Al Jizzi

The dam recently completed on Wadi Al Jizzi is the third recharge facility on the Batinah Coast and is intended to compensate for the overpumping of wells in the area. It is about 24 km west of Sohar village, which is about 220 km northwest of the Muscat capital area. Cultivation around Sohar has been affected by the salinity of groundwater.

The project consists of a detention dam and storage reservoir with two spillways and dispersion facilities about 3 km downstream. The catchment area is 812 sq.km and the dam is 835 m long (excluding spillways) and 17 m high. At spillway crest (elevation 163.9 m) the reservoir has a storage capacity of 5.4 mcm. The dam has a service spillway 184 m long and an emergency spillway 278 m long whose crest is 1.8 m higher, and a 1.5 meter-diameter steel conduit with sluice gate control.

Monitoring facilities include an automatic water level recorder for the reservoir and five monitoring wells (four downstream from the dispersion facility and one upstream from the dam). The wells have been in service during the construction period and will provide information not only on the groundwater table, but on groundwater quality that could be affected by saltwater intrusion and/or chemical pollution from a copper mine in the western part of the catchment.

9.4.2.5 Wadi Ghul

The recharge dam on Wadi Ghul is about 40 km northwest of Nizwa and about 5 km northwest of the village of Al Hamra. Construction began in July 1988 and was completed prior to the 1989-90 rains. The wadi bed is nearly 400 m wide at the dam site and moderately steep slopes ascend from each end of the dam. The catchment area is 155 sq.km and the average slope of the wadi channel upstream from the dam is more than 10 percent. Because the catchment has little soil cover and alluvium begins in the wadi less than 12 km upstream, it is considered to have a very high runoff potential. The dam and spillway have been designed to pass the maximum flood. The spillway consists of three vertical weirs one above the other, with a gabion-lined stilling basin. The gabions on the upstream face have a sand asphalt mastic and on the downstream face are capped with concrete. The dam is 330 m long and has an average height of 5 m. At spillway crest (elevation 756.1 m) the reservoir has a storage capacity of 0.450 mcm. Monitoring facilities include water level recorders in the reservoir and in the well field of the recharge site 1.5 km downstream from the dam.

9.4.2.6 Wadi Tanuf

This dam is situated about 20 km northwest of Nizwa in a limestone gorge carved by Wadi Tanuf. Construction began in December 1988 and was completed prior to the 1989-90 rains. The dam is only 110 m long and the rock abutments at each end rise steeply. The catchment area is 171 sq.km and consists of limestone virtually barren of vegetation and soil, with alluvium appearing immediately upstream from the damsite. Because of these conditions it is considered to have a very high runoff potential. The dam is a sloped gabion weir designed to act as an overflow spillway during a flood, with a stilling basin that has a counter weir downstream and is sized so that the hydraulic jump occurs in the basin. The downstream slope of the gabion weir is protected from scouring by anchored reinforced concrete slabs, while the upstream slope is grouted. The overflow section is provided with a 3 m-wide crest designed to pass a probable maximum flood with a 4.57 m head. The dam has an average height of 12 m, and at spillway crest (elevation 808 m) the reservoir has a storage capacity of 0.680 mcm. The dam has a cutoff wall that goes 5 m below the surface and a mastic grouted gabion mattress on the upstream face that reduces the potential for piping and seepage losses. Monitoring facilities include water level recorders in the reservoir and in the well field of the recharge site. The dam suffered structural damage when it was overtopped in February 1990, and repairs were in progress at the time of this report.

9.4.2.7 Wadi Ma'awil

This dam is under construction at a site about 8 km upstream from the main Muscat-Sohar highway, just east of the road to Al Abyad and some 22 km east of the road to Rostaq. It was part of a 13-volume feasibility study by MMP in 1989 of the Barka-Rumais area that included studies of dams on three wadis near Wadi Ma'awil. The catchment area is reported to be 595 sq.km. The gross storage volume allows for a 2 m depth of sedimentation over the 30-year design life of the dam. Volumes 1 and 3 of the MMP report warn that unless all the silt is removed as soon as possible after deposition, the dam will reduce rather than increase recharge.

9.4.2.8 Wadi Bahla and Ibri Dams

The dam at Wadi Bahla has been started and the dam at Ibri is almost complete.

9.5 Monitoring and Evaluation Needs—Existing Facilities

9.5.1 Previously Identified Monitoring Needs

The 1989 WASH report on recharge enhancement recommended that the MAF establish a monitoring section with the following duties:

- Make preliminary evaluations of the effectiveness of recharge facilities from existing data
- Provide recommendations to the MAF Planning Department for direction of the recharge program
- Establish and maintain relations with other public sector institutions for data exchange to avoid duplication of effort
- Review and assess current monitoring networks and make improvements where necessary
- Collect and interpret hydrological data from recharge facilities
- Establish baseline hydrological conditions at proposed recharge sites
- Develop technical training programs for Omani staff

9.5.2 Current Prospects and Problems

9.5.2.1 General Discussion

Mott MacDonald International, Ltd. and Watson Hawksley (MM/WH) have recently completed the draft of a national water resources master plan that stresses the importance of reviewing the recharge program. They recommend that the MWR, which is responsible for issuing water extraction permits, should be authorized to evaluate the impact of recharge dams on the country's water resources and to approve the feasibility studies and preliminary designs of recharge projects proposed by other ministries. The MWR does monitor a large number of wells, including some adjacent to MAF monitoring wells, but has made no assessment of the recharge program.

Throughout the Batinah, there is essentially no monitoring of the upper layer of dry sands and gravels where much of the recharge from water released from the dams presumably takes place. Some wells are in place for the Wadi Al Khawd dam and others are planned for the four dams to be completed in the Barka-Rumais area. But at least seven new shallow wells for each of the three existing dams and the four under construction in Barka-Rumais are necessary if meaningful studies of groundwater conditions after flood events are to be made.

9.5.3 Recommendations

The team's recommendations for an independent MWR monitoring program are described below.

9.5.3.1 Establishment of a Recharge Assessment Unit

The MWR should set up a unit to examine the technical and economic feasibility of all proposals for recharge dams, perhaps within the Water Resources Protection Department, which already has drawn up a plan for recharge assessment. The unit would receive advance information of any recharge facilities the MAF intends to consider or construct, and a list of all MAF projects with a recharge component and any reports pertaining to them. It would also be responsible for the continuing evaluation of all recharge dams in service, with special attention to the impact of siltation.

9.5.3.2 Staff Recommendations

The unit would be staffed by a:

Section Chief—an engineer/manager with a minimum of 10 years of experience in groundwater, geohydrology, or hydrology and a knowledge of recharge techniques

Groundwater Assistant—a hydrogeologist with a minimum of 10 years of experience

Surface Water Assistant—a civil engineer with a minimum of 10 years of experience in water resources and substantial project management experience

Four Omani trainees would be added during the first year.

9.5.3.3 Operating Budget

A general operating budget is presented in Table 26. Equipment estimates are based on the assumption that wadi gauges and rain gauge information will be provided by the MAF, and that the only well installations during the first one or two years will be at the seven dams on the Batinah.

9.6 Recharge Alternatives

9.6.1 Injection Wells

Injection wells have some potential in Oman as recharge tools, but there are problems. In order to achieve satisfactory performance, the injected water normally needs to be treated nearly to a drinking water standard. Even then problems arise. Such highly treated water has been utilized for injection wells serving as a barrier system for saline intrusion in California and elsewhere. The high costs of processing water for injection and alternative use for irrigation, however, suggest that injection wells have limited scope in Oman. Recharge wells are probably not cost effective except where land availability or site specific problems preclude alternative methods.

9.6.2 Small-Scale Water Management

There are several methods of water conservation in areas where rainfall is scarce. Water harvesting (Dutt et al., 1981) encompasses micro-catchments, dry land farming, and flood water farming (spate irrigation). These techniques use the soil to collect and hold water. In some instances runoff from an elevated catchment is routed to a surface water storage reservoir, or an upland fallow field provides overland flow to a lower planted one. Underlying clayey soils are plowed and compacted to increase run-off potential. Soil layering, slopes of 1 to 3 percent, and plants that require little water are essential.

Spate irrigation, which uses temporary dikes to divert flood waters to nearby cultivated areas, is carried out in northern Oman, but there is little awareness of the method elsewhere.

A program to popularize these techniques, which are oriented more to water use than recharge, would require personnel with a knowledge of crop types, irrigation needs, growth cycles, and root systems, and soil scientists to identify areas with suitable soil types.

9.6.3 Recharge Criteria

There are many successful artificial groundwater recharge projects throughout the world, each one designed and managed according to the purpose of the recharge and the particular climate, water quality, topography, soils, and substrata of the site. The excellent 1980 FAO irrigation and drainage paper "Arid Zone Hydrology" points out that any means to slow down and store runoff and allow it to percolate is beneficial for artificial recharge.

The following criteria can be used to identify sites favorable for recharge enhancement:

- Sites should be in or near an active channel so that water will be available

- Sites should have coarse surface material of high permeability
- Depth to groundwater should be more than 10 m
- Sites should not have natural recharge
- Construction and maintenance of recharge structures must be feasible
- Sites should not be encumbered by land use or other legal problems
- Sites should not have layers of poorly permeable soil or cemented alluvium that the selected recharge method cannot overcome
- The recharge must serve a useful purpose, not merely shift recharges from one place to another

9.6.4 Initial Screening of Specific Alternatives

Recharge methods are generally categorized as follows:

- Land flooding
- Flow spreading
- Ditch and furrow systems
- Water level control spreading
- Percolation basins
- Natural or existing basins
- Conventional stream channel modification
- Subsurface and sand damse
- Leaky sand dams
- Inflatable dams

- Recharge through natural openings
- Percolation pits/dry wells

Each method is discussed below.

9.6.4.1 Land Flooding

Recharge by land flooding is possible only where the topography permits diversion channels from a wadi, as shown in Figure 43. Another requirement is that the area have a slope of 1 to 3 percent to form a uniform sheet flow.

Advantages:

- Low cost
- Minimal maintenance (except for probable siltation problems)
- Can be located so that it operates only in severe storm events and therefore does not upset the normal recharge balance in the catchment

Disadvantages:

- Subject to high evaporation losses if shallow impermeable layers of soil are present

9.6.4.2 Flow Spreading

Many roads in Oman are elevated above the surrounding land and often end up forming low dikes. Surface flow intercepted by them can be diverted by culverts down the side of the road. The culverts generally are too small to carry peak runoff so ponds form upstream from the embankments. Most of the silt is carried from the ponds to the land below the road grade along with the water discharged by the culverts.

Advantages:

- Spreads flow over a greater area and, if soil and substrata permit, recharge may occur
- Cost is low; the major cost is the roadway itself
- Maintenance is minimal

Disadvantages:

- Impermeable strata can prevent deep percolation. This may be partially overcome by constructing leaking culverts of perforated pipe in gravel-filled trenches that cut through any cemented layers, and/or by providing dry-well/percolation pits described elsewhere

9.6.4.3 Ditch and Furrow Systems

In this method, water from a wadi is diverted into ditches or furrows dug perpendicular to the diversion ditch, as shown for the land flooding method in Figure 43. Another configuration, also shown in Figure 43, is not unlike the natural braided stream wadi pattern in the lower Batinah plain.

Advantages:

- Low cost
- Low maintenance if gradients are sufficient to increase velocity and minimize silt deposits
- Can be located so that they operate only in severe storm events, allowing smaller events to continue along natural recharge routes

Disadvantages:

- Water spread by normally shallow ditches may evaporate unless runoff is frequent
- Even during a major storm event, the method could benefit a higher area to the detriment of a lower area

9.6.4.4 Water Level Control Spreading

This method essentially is the same as the ditch and furrow method, except that it uses the smaller wadi channels, many of which remain dry during most runoff events, instead of dug ditches. Diversion barrages could be constructed to spread water from the more deeply incised primary channels into the smaller channels.

Advantages:

- Can divert large quantities of water to potential recharge sites

Disadvantages:

- Effective only during intermediate storm events, as major channels would be expected to provide recharge in minor events and channels to which flow would be diverted would be flooded during major events
- Minor channels to which flow is diverted in intermediate storm events might be subject to high evaporation losses
- Difficult design problems in achieving appropriate distribution
- High cost since level control works would need periodic rebuilding

9.6.4.5 Percolation Basins

In countries with high urban densities, percolation basins are the most favored method of recharge. Numerous examples can be found in the southwestern United States, the Netherlands, and Germany. Basins are either excavated or enclosed by dikes (Figure 44). Generally, basins are constructed in series, with upstream basins acting as clarifiers. Bypasses permit periodic cleaning. The single basins created by large dams on the Batinah could be considered as one form of recharge basin.

Advantages:

- Simple uncomplicated design
- Can be constructed to any size to accommodate an adopted retention volume
- Conventional earth removal equipment can be utilized for cleaning

Disadvantages:

- Cost of construction and maintenance may outweigh recharge benefits
- May not be an efficient and ecologically acceptable use of the land

9.6.4.6 Natural or Existing Basins

Where natural basins or manmade excavations (e.g., former gravel quarries) show recharge potential, the diversion of flood flows can be a cost-effective means for augmenting recharge.

A former quarrying operation just inland of the dual carriageway in the Sohar area is an example of such an application.

Advantages:

- Low cost, since basin already exists
- Minimal maintenance when sides of the excavation receive the recharge and accumulated silts are not removed

Disadvantages:

- Is a hazard for children. Fencing to restrict access is necessary.

9.6.4.7 Conventional Stream Channel Modification

This method includes any works that extend the duration of the wadi flow or widen the flow pattern to expose a greater area for infiltration. Examples are shown in Figure 45. A check dam could either be a temporary ridge and furrow series extending across the wadi or a channel dike. Most stream channel modifications are made by excavating and ditching materials at the site. They are essentially temporary and may be destroyed seasonally.

Advantages:

- Low cost
- Inexpensive maintenance even though most works may need reconstruction following storm events
- Design and supervision minimal following proper site selection

Disadvantages:

- Roads through the wadi could be an interference

9.6.4.8 Subsurface and Sand Dams

Subsurface and sand dams have been used in India and a number of African countries (Figure 46) to minimize evaporation and conserve water for village use during the dry season. The method can be integrated with leaky sand dams discussed below.

9.6.4.9 Leaky Sand Dams

Leaky or flow-through sand dams are a variation of check dams across a wadi, with short detention of runoff rather than long-term storage. They are permanent and retain water in sands and gravels deposited behind them during successive storm events. Leaky rockfill dams were investigated and reported by Tetra Tech (Hendrick, 1977) for possible use in Oman. The prototype dam height for their study was 6 m. and gabions were only considered for 1 m and 2 m heights for reinforcement of the toe of the dam. The 1 m or 1:6 height ratio of gabions to total dam height was reported as inadequate.

Hydrologic investigations must be undertaken at each site to determine suitable design elements such as freeboard, controlled outlets, emergency spillway design, and dam operation, and also the availability of materials, foundation present, and equipment limitations.

The placement of gabions in successive 1 m lifts, allowing a buildup of gravel in one before the next is placed, does not involve special engineering. There are examples of these on Wadis Ahin and Bani Ghafir. The Bani Ghafir dam, which is the source of a falaj, is 6 m high and has retained gravels and sediments brought in by flood waters to its full height. It has also withstood a flood crest of 6 m.

A cross-section of a leaky dam is shown in Figure 47.

Advantages:

- Retain water in sands and gravels deposited behind them and permit the water to drain downstream over time
- Moderate cost
- Require minimal maintenance

Disadvantages:

- Require more complex engineering than simpler flow-retarding techniques
- Need bypass provisions to permit vehicular wadi travel

9.6.4.10 Inflatable Dams

Inflatable dams have worked successfully in a number of places, chiefly Japan and California, and in several countries have been tried experimentally. Seven are in operation in Thailand.

They are inflated during the recessional flow after the heaviest sediment load of the flow has passed. This also allows self-cleansing of sediments left from the last retention by the higher flows of the rising stage of the stream.

The dam is placed on a reinforced concrete foundation. Flow under the foundation is controlled by a reverse filter. The dam is inflated with a blower that pumps in air or air and water. Both the air and the combined air and water have a tendency to depress the center, concentrating flow and necessitating erosion control for higher dams.

Concern about the ability of the dams to withstand high temperatures has been allayed by manufacturers who claim that seasonal temperatures of 49°C (120°F) would have little, if any, adverse effect. The Japanese have reported that temperatures of 80°C (176°F) have not damaged the dam fabric.

Advantages:

- Enables self-cleansing of the impoundment/recharge area

Disadvantages:

- Susceptibility to vandalism and other damage. Bullet holes can be plugged but cuts can totally destroy the fabric. At least one manufacturer is attempting to produce a fabric that would resist knife cuts.

- Use of wadis for vehicular travel

- Distance from electric power for both automatic control and inflation

- Protection, maintenance, and operation of generators, pumps, and air blower at remote locations

9.6.4.11 Recharge through Natural Openings

Knowledgeable MWR staff report that solution channels and other openings in the Saiq limestone/dolomite formation are a source of recharge. The Mahil formation serves a like function. High-level diversions could be constructed to route runoff to such openings, inducing recharge to these two formations. Little is known of their storage capability. Because access to these areas is difficult, costs are likely to be high.

Another form of recharge by way of natural openings is the use of caves. Not many are known to be suitable for storage and recharge, but if water can be diverted to them at low cost, the method is worth considering, provided it benefits an area near them.

9.6.4.12 Percolation Pits/Dry Wells

Dry wells are used around the world to dispose of runoff. A dry well is essentially a pit filled with gravel where runoff after a storm collects and is gradually absorbed by the soil surrounding the pit. Dry wells often have a central chamber (sewer manhole riser) through which silt and grit accumulations can be reached and removed. The dry well introduces a large quantity of water to the soil at depths that are less affected by evaporation. Dry wells can also be deep enough to introduce water below shallow impermeable strata.

Widespread use of dry wells could add a significant amount of recharge. Covered pits are expensive, and silt and sand are hard to remove. Open pits, similar to the configuration shown in Figure 48, would be more appropriate for Oman. They permit water to enter the ground below shallow cemented layers and with less chance of evaporation. Two styles are shown. One type can be sited where roadway culverts are flooded by peak storm flows. Since such areas should not be built upon, the pits would make use of the land. The second type can be sited at any depression in a road where overland flow crosses the road during storms.

Figure 49 shows a variation of a roadway dry well that might be used with a frequently flooded culvert.

Advantages:

- Low initial cost
- Some maintenance but not excessively costly
- Makes use of land unsuitable for building

Disadvantages:

- Easements for sites may be difficult to obtain
- Pits may create traffic hazards

9.6.5 Review of Alternatives

All the recharge enhancement alternatives described are site specific. What may work successfully at one location may not work at another. Yet two of the alternatives stand out: the leaky sand dams and the dry well/percolation pits. Although the other alternatives should be researched further, these two merit primary attention and are suggested for a pilot program.

9.7 Pilot Programs—Alternative Recharge

9.7.1 Leaky Sand Dams

9.7.1.1 Objective

Leaky sand dams create small artificial aquifers by retaining the coarser and more permeable stream sediments and allowing the finer sediment that causes siltation to be carried downstream. Expensive dam construction can be avoided by successive lift construction from simple materials.

The porosity of the sand, gravel, and silt deposited behind a dam is about 25 percent. A 6 meter high dam would probably not hold more than 70,000 cu.m. of water, but a series of five small dams could detain more than 200,000 cu.m. When fully completed, a dam might consist of 2,000 cu.m. of gabions. The cost of gabion construction is approximately R.O.11 per cu.m. Even adding site cost and planning costs, each small gabion leaky dam should cost about R.O.30,000, or R.O.150,000 for five dams. A leaky dam releasing some 200,000 cu.m. of water is an attractive alternative to a dam like that at Wadi Quryat, which retains 190,000 cu.m. in a reservoir and spreading ground at a construction cost of R.O.500,000. If the rock-filled design that uses only a few toe gabions proved feasible, the leaky dam could be constructed for still less.

Three other points need to be considered:

- There must be enough unsaturated gravel downstream from the retention structures to absorb the delayed flow.
- There must be provisions for vehicular travel over the dams and through the retention area.
- There may be interference with existing falaj systems.

9.7.1.2 Location

There are suitable sites on almost all the main wadis of the Batinah, many of them now occupied by dams constructed by the local population to provide water for a falaj. A good location for a pilot project is Wadi Bani Ghafir.

9.7.1.3 Approach

Since the MWR does not have the staff to undertake the required preliminary testing and economic analysis, it has two options:

- Bring in an engineering firm to do the job
- Turn the job over to the proposed recharge assessment unit, which could then obtain consultant assistance

The second alternative is better, since the tasks of assessing existing recharge projects and investigating alternative methods are closely related.

The questions to be answered are:

- Where are the best sites for the alternative recharge methods?
- How many dams, and of what height, should there be?
- How cost effective are the dams?

9.7.1.4 Time-scale

It may take five years or more to construct and test a leaky sand dam, because several flood events must be observed to determine the necessary fill and floods are infrequent. Site selection and final design should take less than a year and a series of test dams could be built within 18 months. Where sufficient floods occur, a second lift could be added within four years of the initial construction.

9.7.1.5 Costs

The cost estimates in Table 27 are based on a stand-alone program. These could be reduced by combining the dam study with other studies such as the representative basins project.

9.7.2 Dry Well/Percolation Pits

9.7.2.1 Objective

Dry-well recharge pits would capture surface water that is now lost by evaporation or flows into the Gulf of Oman.

9.7.2.3 Approach

A pilot program to determine the effectiveness of this method would be divided into two phases.

Phase I would cover the following activities:

- Investigate legal implications such as property ownership, permits, and easements
- Establish a site with access to a well that could be used in testing (possibly BF-1 in Wadi Far or others with a high yield)
- Study a number of sites before making a final selection
- Establish a work plan for testing that includes, but is not limited to, the following:
  - Select a minimum of four pits close to a productive well
  - Draw up a checklist of items to be observed during the test and prepare a plan to ensure that all test parameters are covered
  - Invite tenders for bulldozer excavation (and backfill following testing), pumping, instrumentation, e.g., lysimeters and well-level recorders, evaporation pans, and observation piezometers to the bottom of upper gravels at 2 and 5 m from the pit edge
  - Review tenders submitted and proceed with testing
- Carry out these recommended test procedures:
  - Check water availability; since it is necessary to simulate a flood event, scale down the size of the test pits or pump water from bowsers to gain this effect
  - Determine the best construction techniques in consultation with excavation contractors

— Select some pits adjacent to one another; flood one pit and observe the flow through the natural embankment between them

— Seal the bottom of test pits with bentonite clay to simulate the effect of silt accumulations

— Note evaporation rates at several points around the site; compare pan evaporation with the rate of recession of water in the pits.

— Monitor water levels in shallow groundwater with piezometer installations near the site; two-level piezometers could be used

Phase II of the pilot project would cover the excavation of about 30 recharge pits and monitoring their performance after storm events to ascertain the need for any design modifications (e.g., soil cement stabilization of inlet ramp), to observe infiltration rates over time (a visit to 15 locations per day for a week), and to determine additional data collection from instrumentation adopted during Phase I.

9.7.2.4 Timescale

Phase I would cover 6 to 9 months following staffing of the recharge assessment unit. This could be shortened if desired, by engaging a consulting firm to do the job.

9.7.2.5 Costs

Phase I carried out by a consulting firm would cost between R.O. 40,000 and 50,000. This would cover the cost of observation wells, pumping, and auxiliary works but not piezometers or monitoring wells. Actual costs at the completion of Phase I would provide an accurate estimate of the cost of Phase II.

9.7.2.6 Added Study Considerations

Other locations than those suggested should be considered during the pilot project. It might be that elongated trenching of minor non-incised wadi channels would be appropriate for some locations or that a series of dry well/pits would be more cost effective.

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TABLE 1

Basic Data for Musandam Rainfall Gauging Stations Used in Data Analysis

DATE OF RAINFALL		STATION RAINFALL IN MM							
YEAR	DAY	KHASAB AT KHASAB	KHASAB NEAR KHASAB	SILIAN	MEHAS	SIMAH	GHUMDAH	LIMAH	SALAL A'LA
1981-82	JAN 17	10.0	11.0	12.0	23.0	6.0	0.0	0.0	2.0
	FEB 09	36.0	37.0	32.0	38.0	25.0	42.4	5.8	13.0
	FEB 13	12.0	48.0	29.0	38.0	39.0	0.0	10.0	0.0
	MAR 27	39.0	46.0	48.0	57.0	47.0	36.6	33.0	37.0
1982-83	JAN 21	53.0	37.3	15.3	23.0	15.0	83.0	0.0	8.0
	FEB 12	12.0	16.5	30.5	30.4	40.1	3.9	0.0	78.0
	MAR 15	15.0	0.0	36.0	42.4	32.5	0.0	0.0	20.5
	DEC 19	17.0	0.0	0.0	24.0	21.3	20.7	10.0	20.5
1983-84	MAR 18	13.0	23.7	0.0	27.6	23.7	28.7	0.0	16.2
	DEC 27	4.3	4.0	4.0	3.0	6.0	0.0	0.0	6.5
1985-86	FEB 10	0.0	11.9	17	11.4	16.4	5.7	8.5	0
	MAR 16	1.2	0.0	9.2	14.3	12.4	0.0	12.0	4.2
	DEC 05	0.6	13.9	15.8	13.2	27.3	5.7	0.0	0.0
	DEC 20	1.8	1.5	1.8	2.4	2.9	6.7	32.0	0.0
	DEC 27	13.4	14.2	4.4	10.5	9.0	3.4	0.0	2.8
1986-87	MAR 30	45.2	50.9	40.2	37.2	23.4	0.0	40.3	30.0
	DEC 05	40.1	28.0	19.4	20.7	6.0	0.0	0.0	7.9
	DEC 07	2.8	6.9	5.1	4.7	6.1	2.3	0.0	0.8
1987-88	JAN 09	22.0	26.6	23.6	25.3	19.2	14.5	3.0	13.2
	FEB 11	0.3	19.0	17.8	22.0	17.7	6.6	0.0	12.3
1988-89	MAR 15	9.0	12.6	16.0	10.6	8.8	0.0	3.0	0.0

DISTANCE BETWEEN STATIONS (KM)								
	KHASAB AT KHASAB	KHASAB NEAR KHASAB	SILIAN	MEHAS	SIMAH	GHUMDAH	LIMAH	SALAL A'LA
KHASAB AT KHASAB	0	5.5	9.0	12.0	16.5	15.5	32	20.5
KHASAB NEAR KHASAB	5.5	0	3.4	6.5	11.2	11.0	27.5	17
SILIAN	9.0	3.4	0	4.5	8.0	11.6	24	12.5
MEHAS	12.0	6.5	4.5	0	7.5	9.3	23.6	14
SIMAH	16.5	11.2	8.0	7.5	0	16.5	16.5	6.4
GHUMDAH	15.5	11.0	11.6	9.3	16.5	0	31	23
LIMAH	32	27.5	24	23.6	16.5	31	0	11.5
SALAL A'LA	20.5	17	12.5	14	6.4	23	11.5	0

TABLE 2

Analysis of Variation of Daily and Monthly Rainfall Records for Seven Closely Spaced Rain Gauges

DAILY RAINFALL IN MM FOR RANDOMLY SELECTED LARGE STORMS

	DATE							
STATION NAME	1981 DEC 18	1982 NOV 2	1983 MAR 17	1984 DEC 29	1985 JAN 31	1986 DEC 6	1987 JULY 20	
SILIAN	1.4	9.0	24.8	7.3	17.5	5.8	29.0	
MEHAS	8.8	15.0	26.6	9.8	22.9	3.4	32.0	
KHASAB NEAR KHASAB	1.0	5.5	23.7	7.4	12.7	3.3	45.0	
GHUMDAH	3.7	0.0	28.7	8.8	23.0		0.0	
SIMAH	1.0	15.0	23.7	6.6	19.0	2.8	39.0	
SALAL 'ALA	1.0	0.0	16.2	4.9	9.5	7.0		
KHASAB AT KHASAB	1.0	5.5	23.7	7.4	12.7	3.3	45.0	
MEAN OBSERVATION	2.6	7.1	23.9	7.5	16.8	4.3	31.7	AVERAGE COEF
STD DEVIATION	2.7	5.79	3.6	1.44	4.9	1.56	15.4	OF VARIATION
COEF OF VARIATION FOR SAMPLE	1.1	0.81	0.15	0.19	0.29	0.37	0.49	0.48

MONTHLY RAINFALL IN MM FOR RANDOMLY SELECTED RAINY MONTHS

	MONTH							
STATION NAME	1982 NOV	1983 DEC	1985 JAN	1987 FEB	1982 APR	1980 MAY	1987 JULY	
SILIAN	16.5	6.5	17.5	65.1	46.0	48.0	29.0	
MEHAS	26.3	4.0	22.9	90.2	36.5	42.2	32.0	
KHASAB NEAR KHASAB	20.8	4.5	12.7	72.4	37.3	25.1	45.0	
GHUMDAH	0.0	13.0	23.0	45.2	9.9	29.7	0.0	
SIMAH	38.5	6.5	19.0	71.1	41.0	35.2	39.0	
SALAL 'ALA	0.0	6.5	9.5	70.9	28.0	40.9		
KHASAB AT KHASAB	15.1	4.3	14.2	68.5	29.1	19.4	7.6	
MEAN OBSERVATION	16.7	6.5	17.0	69.1	32.5	34.4	25.4	AVERAGE COEF
STD DEVIATION	12.8	2.9	4.7	12.25	10.9	9.4	16.3	OF VARIATION
COEF OF VARIATION FOR SAMPLE	0.76	0.44	0.28	0.18	0.34	0.27	0.64	0.42

TABLE 3

Analysis of Variation of Annual Rainfall Records
Seven Closely Spaced Rain Gauges in the Musandam, Oman

ANNUAL RAINFALL IN MM FOR HYDROLOGIC YEARS FROM 1981 TO 1988

STATION NAME	1981-82	1982-83	1983-84	1984-85	1985-86	1986-87	1987-88	
SILIAN	229.7	190.8	36.5		71.5		163.2	
MEHAS	279.2	209.2	37.7	34.9	85.9	191.4	210.6	
KHASAB AT KHASAB		309.3	24.3	10.2	73.1	200.2	147.8	
GHUMDAH	345.5	372.9	50.9	46.3	59.7	340.7	165.6	
SIMAH	198.5	212.4	32.1	28.6	91.5	234.5	189.8	
SALAL 'ALA		168.2	26.5	13.5	32.9			
KHASAB NEAR KHASAB	259.8	202.9	33.6	27.9	93.2	183.0	256.5	
SEVEN GAUGE MEAN ANNUAL RAINFALL	262.5	238.0	34.5	26.9	72.5	230.0	188.9	
STANDARD DEVIATION OF THE ANNUAL RAINFALL	49.7	68.8	8.1	12.3	19.6	58.1	36.4	
COEF OF VARIATION OF THE RAINFALL SAMPLE	0.19	0.29	0.23	0.46	0.27	0.25	0.19	AVERAGE COEF OF VARIATION 0.27

TABLE 4

Calculated Value of Mehas Daily Rainfall Based on Two Adjacent Rain Gauges
Compared with Actual Rainfall Observed at Mehas

MEHAS DAILY RAINFALL IN MM					
YEAR OF RAINFALL	DAY	INTERPOLATED RAINFALL	ACTUAL RAINFALL	DIFFERENCE (ERROR)	RELATIVE % ERROR
1981-82	JAN 17	8.3	23.0	14.7	178
	FEB 09	35.2	38.0	2.8	8
	FEB 13	20.0	38.0	18.0	90
	MAR 27	44.5	57.0	12.5	28
1982-83	JAN 21	36.3	23.0	13.3	37
	FEB 12	22.3	30.4	8.1	37
	MAR 15	24.8	42.4	17.6	71
	DEC 19	6.4	24.0	17.6	274
1983-84	MAR 18	8.9	27.6	18.7	210
	DEC 27	2.8	3.0	0.2	9
1985-86	FEB 10	13.5	11.4	2.1	16
	MAR 16	6.3	14.3	8.0	125
	DEC 05	12.7	13.2	0.5	4
	DEC 20	3.3	2.4	0.9	28
	DEC 27	4.1	10.5	6.4	157
1986-87	MAR 30	27.7	37.2	9.5	34
	DEC 05	13.4	20.7	7.3	55
	DEC 07	4.2	4.7	0.5	11
1987-88	JAN 09	20.8	25.3	4.5	22
	FEB 11	14.3	22.0	7.7	54
1988-89	MAR 15	11.0	10.6	0.4	4
			MEAN RELATIVE % ERROR OF INTERPOLATED ESTIMATE		58.0
			STANDARD DEVIATION OF RELATIVE % ERROR		72.8
			WEIGHTED DISTANCE TO ADJACENT GAUGES		6.1 KM

INTERPOLATION FORMULA :

MEHAS DAILY RAINFALL = 0.31 (GHUMDAH DAILY RAINFALL)
+ 0.69 (SILIAN DAILY RAINFALL)

TABLE 5

Calculated Value of Silain Daily Rainfall Based on Three Adjacent Rain Gauges Compared with Actual Rainfall Observed at Silian

SILIAN DAILY RAINFALL IN MM					
YEAR OF RAINFALL	DAY	INTERPOLATED RAINFALL	ACTUAL RAINFALL	DIFFERENCE (ERROR)	RELATIVE % ERROR
1981-82	JAN 17	14.1	12.0	2.1	15
	FEB 09	34.4	32.0	2.4	7
	FEB 13	42.2	29.0	13.2	31
	MAR 27	50.2	48.0	2.2	4
1982-83	JAN 21	26.6	15.3	11.3	42
	FEB 12	27.4	30.5	3.1	11
	MAR 15	23.4	36.0	12.6	54
	DEC 19	14.0	0.0	14.0	100
1983-84	MAR 18	25.1	0.0	25.1	100
	DEC 27	4.1	4.0	0.1	3
1985-86	FEB 10	12.8	17	4.2	32
	MAR 16	8.2	9.2	1.0	12
	DEC 05	17.0	15.8	1.2	7
	DEC 20	2.2	1.8	0.4	17
	DEC 27	11.6	4.4	7.2	62
1986-87	MAR 30	39.1	40.2	1.1	3
	DEC 05	19.9	19.4	0.5	2
	DEC 07	5.9	5.1	0.8	14
1987-88	JAN 09	24.3	23.6	0.7	3
	FEB 11	19.8	17.8	2.0	10
1988-89	MAR 15	10.9	16.0	5.1	46

MEAN RELATIVE % ERROR OF INTERPOLATED ESTIMATE	27.4
STANDARD DEVIATION OF RELATIVE % ERROR	29.4
WEIGHTED DISTANCE TO ADJACENT GAUGES	5.1 KM

INTERPOLATION FORMULA :

SILIAN DAILY RAINFALL = 0.39 (KHASAB NEAR KHASAB DAILY RAINFALL)
+ 0.36 (MEHAS DAILY RAINFALL)
+ 0.25 (SIMAH DAILY RAINFALL)

TABLE 6

Calculated Value of Khasab Near Khasab Daily Rainfall
Based on Two Adjacent Rain Gauges Compared with Actual Rainfall
Observed at Khasab Near Khasab

KHASAB NEAR KHASAB DAILY RAINFALL IN MM					
YEAR OF RAINFALL	DAY	INTERPOLATED RAINFALL	ACTUAL RAINFALL	DIFFERENCE (ERROR)	RELATIVE % ERROR
1981-82	JAN 17	11.3	11.0	0.3	2
	FEB 09	33.4	37.0	3.6	11
	FEB 13	22.9	48.0	25.1	110
	MAR 27	44.8	46.0	1.2	3
1982-83	JAN 21	28.9	37.3	8.4	29
	FEB 12	23.8	16.5	7.3	31
	MAR 15	28.4	0.0	28.4	100
	DEC 19	6.1	0.0	6.1	100
1983-84	MAR 18	4.7	23.7	19.0	406
	DEC 27	4.1	4.0	0.1	3
1985-86	FEB 10	10.9	11.9	1.0	9
	MAR 16	6.3	0.0	6.3	100
	DEC 05	10.3	13.9	3.6	35
	DEC 20	1.8	1.5	0.3	17
	DEC 27	7.6	14.2	6.6	86
1986-87	MAR 30	42.0	50.9	8.9	21
	DEC 05	26.9	28.0	1.1	4
	DEC 07	4.3	6.9	2.6	62
1987-88	JAN 09	23.0	26.6	3.6	16
	FEB 11	11.5	19.0	7.5	65
1988-89	MAR 15	13.5	12.6	0.9	7

MEAN RELATIVE % ERROR OF INTERPOLATED ESTIMATE	57.9
STANDARD DEVIATION OF RELATIVE % ERROR	86.3
WEIGHTED DISTANCE TO ADJACENT GAUGES	4.5 KM

INTERPOLATION FORMULA :

KHASAB NEAR KHASAB DAILY RAINFALL = 0.36 (KHASAB AT KHASAB DAILY RAINFALL) + 0.64 (SILIAN DAILY RAINFALL)

TABLE 7

Calculated Value of Simah Daily Rainfall Based on Two Adjacent Rain Gauges Compared with Actual Rainfall Observed at Simah

SIMAH DAILY RAINFALL IN MM					
YEAR OF RAINFALL	DAY	INTERPOLATED RAINFALL	ACTUAL RAINFALL	DIFFERENCE (ERROR)	RELATIVE % ERROR
1981-82	JAN 17	11.0	6.0	5.0	46
	FEB 09	23.8	25.0	1.3	5
	FEB 13	16.3	39.0	22.7	.139
	MAR 27	45.6	47.0	1.4	3
1982-83	JAN 21	14.5	15.0	0.6	4
	FEB 12	57.5	40.1	17.4	30
	MAR 15	29.9	32.5	2.6	9
	DEC 19	22.0	21.3	0.7	3
1983-84	MAR 18	21.1	23.7	2.6	12
	DEC 27	5.0	6.0	1.0	20
1985-86	FEB 10	4.9	16.4	11.5	235
	MAR 16	8.5	12.4	3.9	45
	DEC 05	5.7	27.3	21.6	381
	DEC 20	1.0	2.9	1.9	181
	DEC 27	6.1	9.0	2.9	47
1986-87	MAR 30	33.1	23.4	9.7	29
	DEC 05	13.4	6.0	7.4	55
	DEC 07	2.5	6.1	3.6	146
1987-88	JAN 09	18.4	19.2	0.8	4
	FEB 11	16.5	17.7	1.2	7
1988-89	MAR 15	4.6	8.8	4.2	93

MEAN RELATIVE % ERROR OF INTERPOLATED ESTIMATE	71.2
STANDARD DEVIATION OF RELATIVE % ERROR	94.5
WEIGHTED DISTANCE TO ADJACENT GAUGES	7.4 KM

INTERPOLATION FORMULA :

SIMAH DAILY RAINFALL = 0.57 (SALAL A'LA DAILY RAINFALL) + 0.43 (MEHAS DAILY RAINFALL)

TABLE 8

Spatial Variation of Daily Rainfall During Regional Storm of December, 1989
for Rain Gauges Closely Spaced in Oman

LOCATION	STATION NAME	DISTANCE APART	DAILY RAINFALL IN MM BY DATE 7 DEC.	8 DEC.	15 DEC.	16 DEC.	17 DEC.	AVERAGE VARIATION BETWEEN STATIONS
PIEDMONT OF BATINAH	WADI SALAHI	6 KM	12.0		7.0	38.0	8.0	
	DHOHARAT		15.5		1.0	22.5	7.5	
	STATION TO STATION VARIATION %		22 %		85 %	40 %	6 %	38 %
BATINAH COASTAL PLAIN	LIWA		16.2		23.0	73.0		
	FIZH	8 KM	10		12.0	22.0		
	STATION TO STATION VARIATION %		38 %		47 %	69 %		51 %
BATINAH COASTAL RAGION	BARKA		10.5	2.5		33.5	27.0	
	SHI KHATUM	10 KM	53.0	2.5		32.5	32.0	
	STATION TO STATION VARIATION %		80 %	0 %		3 %	16 %	25 %
INTERIOR MOUNTAINS	DAQIQ		11.5		0.5	32.5	16.5	
	KITNAH	6 KM	16.0		--	35.0	13.0	
	STATION TO STATION VARIATION %		28 %			9 %	21 %	19 %
CENTRAL MOUNTAINS	AL ZAMMAH	10 KM		22.5			15.5	
	MISFA			14.6			4.6	
	STATION TO STATION VARIATION %			35 %			70 %	52 %
CENTRAL MOUNTAINS	HAJIR	8 KM	1.0	14.0			2.5	
	ZAMMAH		1.5	22.5			15.5	
	STATION TO STATION VARIATION %		33 %	35 %			83 %	51 %

TABLE 9

Rain Gauge Network Expansion Preliminary Capital Cost Estimate

CAPITAL COST SCHEDULE

Item or Cost Center	QUANTITY	Unit Price (R.O.)	Amount (R.O.)
PLANNING & PRELIMINARIES COST			
1. Consultant Planning assistance including housing & vehicle	4 months	3500	14000
2. Misc. planning outlays	L.S.	1000	1000
3. Land acquisition as required	L.S.	25000	25000
PLANNING & PRELIMINARIES SUB TOTAL :			40000
CONSTRUCTION & INSPECTION COSTS			
1. Project inspection & supervision	8 monts	3500	28000
2. Rain sensors, direct purchase	70 Nos.	150	10500
3. Rain gauge shelters	70 Nos.	350	24500
4. Datapod data loggers, direct purchase	70 Nos.	1500	105000
5. Spares, inventory for gauges and loggers	L.S.	10000	10000
6. Preparation of concrete foundation for gauges (Contractor)	55 Nos.	175	9625
7. Installation of fencing at some sites (Contractor)	20 Nos.	675	13500
8. Final Gauge Installation	70 Jobs	60	4200
9. Construction Contengencies	L.S.	20000	20000
CONSTRUCTION & INSPECTION SUB TOTAL :			225325

APPROX. TOTAL PROJECT COST	R.O.	265000
APPROX. CAPITAL COST PER GAUGE	R.O.	3600

TABLE 10

Rain Gauge Network Expansion Project Recurrent Cost Estimate

LONG TERM RECURRENT COSTS

Item or Cost Center	Interval	Annual Cost (R.O.)	Quantity	Approximate Total Annual Cost
1. Replacement of gauges	15 years	20	70	1300
2. Replacement of datapods	10 years	55	70	3500
3. Other installation upkeep	as required	40	--	2500
4. Additional gauge maintenance work	as required	20	70	1400
5. Additional data handling reduction and storage 16 hours/year @ 10 RO/hr.	Continuous	160	66	10500
6. Gauge overseer fees	Continuous	120	40	4800

Approximate annual cost = R.O. 24000

Approximate annual cost per site = R.O. 350

TABLE 11

Flow Data from Selected Wadi Gauging Stations

STATION	DRAINAGE AREA SQ.KM.	FLOW VOLUMES IN MILLION CU. MTR.				RUNOFF
		DEC. 1989	JAN. 1990	FEB. 1990	3-MONTH TOTAL	
W. Bani Ghafir nr. Falaj as Saidi	617	8.782	0.4569	3.943	13.1819	21.4
W. Al Abyadh nr. Hajar	757	5.252	0.086	1.392	6.730	8.89
W. Afi nr. Afi	313	4.417	0.021	1.067	5.505	17.59
W. Al Khawd nr. Al Khawd	1653	4.612	0.8635	3.736	9.2115	5.57
W. Aday nr. Al Bajariyan	323	3.052	0.2324	0.4344	3.7188	11.5
W. Ahin nr. Hayl	765	1.641	0.9282	13.010	15.5792	20.4
W. Al Hinti nr. Riqqah	242	1.355	1.518	4.846	7.719	31.9
W. Fizh nr. Sabakh	262	4.294	3.467	2.997	10.758	41.1
W. Misfah nr. Al Hamra	58.0	0.3672	0.2058	1.860	2.433	41.9
W. Al Abyadh nr. Nizwa	395	0.4758	0	7.809	8.2848	21.0
W. Tanuf nr. Tanuf	157	0.0101	0	7.989	7.9991	50.9

TABLE 12

Rainfalls for Period Dec. 1989-Feb. 1990 at Selected Locations

Description	Dec.1989	Jan.1990	Feb. 1990	3 Month Total in MM
Wadi Ahin nr. Hayl				
Hayl Ashkharin	84.5	28.5	79.0	192.0
Qufays	33.5	22.0	71.5	127.0
Wuqbah	14.5	23.0	75.0	112.5
		3-Station Average	=	143.8 mm
		3-Month Runoff	=	20.4 mm
		Runoff/Rainfall	=	14.2 %
Wadi Bani Ghafir nr. Falaj as Saidi				
Al Houqain	64.5	14.5	105.5	184.5
Yiqa	66.5	19.5	91.0	177.0
Daba	72.5	45.0	77.5	195.0
		3-Station Average	=	185.5 mm
		3-Month Runoff	=	21.4 mm
		Runoff/Rainfall	=	11.5 %
Wadi Al Hilti nr. Riqqah				
W. Hilti nr. Riqqah	51.0	30.0	52.0	133.0
W. Salahi nr. Yanbu	74.0	33.0	89.0	196.0
Hayl Ashkharin	84.5	28.5	79.0	192.0
		3-Station Average	=	173.7 mm
		3-Month Runoff	=	31.9 mm
		Runoff/Rainfall	=	18.4 %
Wadi Fizh nr. Sabakh				
Wadi Fizh	66.0	21.0	74.0	161.0 mm
		1-Station Average	=	161.0 mm
		3-Month Runoff	=	41.1 mm
		Runoff/Rainfall	=	25.5 %

TABLE 12 (continued)

Rainfalls for Period Dec. 1989-Feb. 1990 at Selected Locations

Wadi Al Khawd nr. Al Khawd

Al Khawd	13.7	25.0	22.0		60.7
Samail	45.0	32.0	31.0		108.0
Al Khadrak	20.5	25.0	68.0		113.5
		3-Station Average		=	94.1 mm
		3-Month Runoff		=	5.57 mm
		Runoff/Rainfall		=	5.9 %

Wadi Aday nr. Al Bajariyah

Seeb	35.7	43.4	33.5		112.6
Wadi Aday	68.0	43.5	31.5		143.0
		2-Station Average		=	127.8 mm
		3-Month Runoff		=	11.5 mm
		Runoff/Rainfall		=	9.0 %

Wadi Misfah nr. Al Hamra

Misfah	43.4	31.2	92.7		167.3
Al Hamra	57.0	16.9	90.0		163.9
		2-Station Average		=	165.6 mm
		3-Month Runoff		=	41.9 mm
		Runoff/Rainfall		=	25.3 %

Wadi Abyadh nr. Nizwa

Nizwa	31.0	0.0	137.4		168.4
Saiq	58.0	19.0	128.5		205.5
Tanuf	39.0	0.0	85.0		125.0
		3-Station Average		=	166.0 mm
		3-Month Runoff		=	21.0 mm
		Runoff/Rainfall		=	12.6 %

TABLE 13

Rainfall Data for Wadi Ahin Basin

Raingage	Date	Time	Rainfall in MM.	Average Intensity in MM per hour
Al Wuqbah	Dec.7	1230-1300	3.5	7.0
	Dec.7	0845-0930	6.0	8.0
		1315-1345	11.5	23.0
	Feb.8	1030-1100	1.5	3.0
Al Qufays	Dec.7	1300-1430	1.0	1.0
	Feb.7	1200-1330	14.5	9.7
	Feb.8	1030-1100	11.5	23.0
Hayl Ashkiriyan	Dec.7	1030-1100	11.0	22.0
		1145-1200	2.0	8.0
		1300-1400	11.0	11.0
		1400-1500	4.0	4.0
	Feb.7	0900-1000	2.0	2.0
		1230-1300	7.5	15.0
	Feb.8	1030-1130	12.5	12.5

TABLE 14

Rainfall Data for Wadi Bani Ghafir Basin

Raingage	Date	Time	Rainfall in MM	Average Intensity in MM per hour
Daba	Dec.17	0100-0130	1.0	2.0
		0330-0430	24.0	24.0
		0430-0530	3.0	3.0
		0530-0730	2.0	1.0
	Feb.7	1100-1700	5.0	0.8
	Feb.8	1200-1630	22.0	4.9
	Feb.21	1930-2230	17.5	5,8
Yiqa	Dec.17	0345-0415	11.0	22.0
		0415-0545	6.0	4.0
		0630-0800	4.0	2.7
	Feb.7	1000-1830	9.0	1.1
	Feb.8	1200-1600	19.0	4.8
	Feb.21	1730-1800	1.5	3.0
		2000-2200	32.0	16.0
Houqain	Dec.17	0400-0500	11.0	11.0
		0500-0800	4.0	1.3
	Feb.7	1100-1400	1.0	0.3
		1400-1430	5.0	10.0
		1500-1600	20.0	20.0
		1600-1700	1.0	1.0
	Feb.8	1215-1245	7.0	14.0
		1315-1330	3.0	12.0
	Feb.21	1615-1630	12.5	50.0
		1915-2015	9.0	9.0
		2015-2115	3.0	3.0

TABLE 15

Rainfall Data for Wadi Bahla Basin

Raingage	Date	Time	Rainfall in MM	Average Intensity in MM per hour
BAHLA	Feb.25, 1990	2240-2250	14.6	87.6
	Feb.26, 1990	0100-0120	1.6	4.8
		0120-0130	9.0	54.0
		0215-0240	0.8	1.9
		0240-0300	0.8	2.4
		0350-0400	9.6	57.6
		0400-0420	4.0	12.0
		0420-0430	2.0	12.0
		0450-0500	4.0	24.0
		0500-0520	3.6	10.8
		0520-0540	0.2	0.6
		0830-0840	4.5	27.0
		Feb.26 Total =	40.1mm	
		Feb.25 & 26 Total =	54.7mm	
MISFAH	Feb. 25, 1990	1640-1645	0.2	2.4
		1840-1900	2.8	8.4
		2030-2040	0.4	2.4
		2150-2200	0.6	3.6
		2200-2220	5.0	15.0
		2220-2235	6.8	27.2
		2345-2400	1.2	4.8
		Feb.25 Total =	17.0mm	
	Feb. 26, 1990	0000-0020	1.6	
		0020-0045	1.8	
		0220-0240	6.0	
		0240-0300	0.4	
		0310-0315	0.8	
		0330-0350	6.6	
		0530-0540	0.6	
		1030-1040	0.2	
		Feb.26 Total =	18.0mm	
		Feb. 25 & 26 Total =	35.0mm	

TABLE 16

Channel Geometry Program—Wadi Flows
Time and Cost Estimates

Classification	Number Required	Total Time in Personnel-Months	Annual Salary, Including Allowances	Total Cost
Personnel			(R.O.)	(R.O.)
Senior hydrologist	1	8.0	45,000	30,000
Staff hydrologist	1	24.0	15,000	30,000
Engineer	1	39.0	12,000	39,000
Technician	1	39.0	8,000	26,000
		Total Cost	R.O.	125,000
Equipment				
2 four-wheel-drive vehicles @ R.O. 5,000/each				10,000
2 personal computers w/printer @ R.O. 2,000/each				4,000
Survey equipment				1,000
		Total Cost	R.O.	15,000
Allowance				
For travel, telephone, printing, supplies, and miscellaneous expenses				12,000
		Grand Total	R.O.	152,000

TABLE 17

Representative Basin—Pilot Program
Time and Cost Estimates

Classification	Number Required	Total Time in Man-Months	Annual Salary including Allowances	Total Cost
Personnel			(R.O.)	(R.O.)
Senior Hydrologist	1	15.0	45,000	56,250
Staff Hydrologist	1	64.0	15,000	80,000
Engineer	2	115.0	12,000	115,000
Technician	2	105.0	8,000	70,000
		Total Cost	R.O.	312,250
Equipment				
2 four-wheel-drive vehicles @ R.O. 5,000 each				10,000
3 personal computers w/printer @ R.O. 2,000 each				6,000
Survey equipment				1,000
12 Rain gauge stations @ R.O. 3,000/each				36,000
17 Wadi flow gauge stations @ R.O. 6,000/each				102,000
		Total Cost	R.O.	155,000
Allowance				
For travel, telephone, printing, supplies, and miscellaneous expenses				32,000
		Grand Total	R.O.	508,250

TABLE 18

Estimated Costs—
Aflaj Monitoring Upgrade

Equipment	Number	Unit Cost (R.O.)	Total Cost (R.O.)
Omnidata Datapod II Recorder	40	1,600	64,000
Datalogger Module Reader	10	500	5,000
Porcelain Enameled Staff Gauge	360	15	5,400
		Total R.O.	74,400

Construction	Number	Unit Cost (R.O.)	Total Cost (R.O.)
Continuous Monitoring Station (Materials and Installation)	40	500	20,000
Aflaj Channel Reconstruction	40	1,500	60,000
		Total R.O.	80,000
Total Cost—Aflaj Monitoring Upgrade		R.O.	154,400

TABLE 19

Estimated Costs—Aflaj Inventory

Personnel	Number	Labor	Salary and Allowance (R.O.)	Total Cost (R.O.)
Surface Water Hydrologist	3	3 yrs.	45,000 ea/yr.	405,000
			Total R.O.	405,000

Equipment	Number	Unit Cost (R.O.)	Total Cost (R.O.)
Magellan GPS Receiver	3	1,650	4,950
GPS Vehicle Aerial Kit	3	200	600
Rotating Current Meter	3	350	1,050
Conductivity Probe	3	250	750
Brunton-type Compass	3	60	180
		Total R.O.	7,530

Total Cost—Aflaj Inventory R.O. 412,530

TOTAL PROJECT COSTS

Aflaj Monitoring Upgrade	=	R.O.154,400
Aflaj Inventory	=	R.O.412,530
Total Project Costs	=	R.O.566,930

TABLE 20

Basin Data Summary

		WADI					
		SAMAIL (KHAWD)	BANI GHAFIR	AHIN	HILTI	SALAHI	JIZZI
Geography	Discharges to:	Lower Batinah	Low-mid Batinah	Mid-Batinah	Mid-Batinah	Mid-Batinah	Upper-mid Batinah
	Area: (km2)	1596	600	734	242	87	630
	Approx. Gap Width: (km)	0.5 to 1	0.5 to 1	1 to 2	0.5 to 1	0.3 to 0.5	1 to 2
	Elev. Max/Min: (m)	2302/ 75	2980/ 150	1632/ 250	1619/ 100	1379/ 150	1460/ 300
Geology	% Mantle Ophilite*	30%	30%	60%	40%	30%	60%
	Bedrock at Gap:	Crustal Ophilite Gabbro	Crustal Ophilite Gabbro	Crustal Ophilite Gabbro	Hawasina Siltsone and Shale	Crustal Ophilite Volcanic	Crustal Ophilite Volcanic
	Bedrock Surface Gauge Possible:	Maybe	Yes	Yes	Unknown	Unknown	Maybe
Existing Data	Number of Gauges:*	S:1 R:3	S:1 R:3	S:1 R:5	S:1 R:1	S:1 R:1	S:1 R:6
	Record From:	S:'82 R:'74	S:'84 R:'74	S:'84 R:'73	S:'84 R:'86	S:'86 R:'73	S:'84 R:'73
	Basin SWI:	Major	Minor	Minor	Moderate	Moderate	Moderate
	Down-basin Monitoring Wells:	Yes	Yes	No	Yes	Yes	Yes
Miscellaneous	Recharge Dams:	Yes	No	No	Yes	Yes	Yes
	Suggested for Basin Study:	No	Yes.	Yes	No	No	No
	Other Considerations:	Capital wellfield down-gradient Much water use in basin Falaj at gap	Includes highest point in Oman Falaj at gap		Difficult access	Long and thin	Mouth close to Wadi Al Hayl Mine water quality problems

NOTE: Percentage of areas for geological distribution are approximated to an estimated accuracy of one part in ten
R indic tes rain gauges, S indicates surface water gauges.

TABLE 21

Basin Selection Ratings

	WADI					
	SAMAIL (KHAWD)	BANI GHAFIR	AHIN	HILTI	SALAHI	JIZZI
Area: (km2) <200 =1, 200-499=2, 500-999=3, >1000=2	2	3	3	2	1	3
Approx. Gap Width (km): <0.5=1, 0.5-1=2, >1=1	2	2	1	2	1	1
Percent Mantle Ophilite: 1 per 10%	3	3	6	4	3	6
Bedrock at Gap: Carbonate=0, Gabbro=3, Other=2	3	3	3	2	2	2
Bedrock Surface Water Gauge: Yes=7, Probable=3, Unknown=2, No=0	3	7	7	2	2	0
Observed Wadi Baseflow (l/s): None=0, 200-500=3, 600-900=5, >1000=7	3	3	7	3	0	3
Surface Water Record Period: Before '85=2, After '85=1	2	2	2	2	1	2
Down-basin Saltwater Intrusion: None=0, Minor to Moderate=2, Major=1	1	2	2	2	2	2
Down-basin Monitoring Wells: Yes=2, No=0	2	2	0	2	2	2
Obstructing Recharge Dam: No=1, Yes=FATAL FLAW	1	1	1	1	1	Fatal Flaw
Suggested for Basin Study: Yes=1, No=0	0	1	1	0	0	0
Falaj at Gap: No=2, Minor=1, Major=0	0	0	1	2	2	2
Tributary Wadi too Close Yes=0, No=3	3	3	3	3	3	0
OVERALL RATING:	25	32	37	27	20	Fatal Flaw
RANK:	4	2	1	3	5	6

TABLE 22

Throughflow Project Cost Estimate Summary

PROJECT COST SUMMARY*

PHASE I
(Well and Gauge Installation)

	Labor	Well Installation Subcontract	Surface Water Gauge Subcontract	Laboratory	Equipment		
	(R.O.)	(R.O.)	(R.O.)	(R.O.)	(R.O.)		
	54,000	109,000	19,000	3,000	14,000		
PHASE I TOTAL						R.O.	199,000

ONGOING COSTS
(Per Year)

	18,000	0	0	4,000	0		
PER YEAR TOTAL						R.O.	22,000
TOTAL FOR FIVE YEAR PROGRAM						R.O.	309,000

* Note: All costs rounded to nearest R.O.1000

TABLE 23

Subcontract Cost Estimate for 30-Well Throughflow Project

Estimated Drilling and Testing Subcontract Costs

		Unit	Estimated Quantity	Unit Cost (R.O.)	Total Cost (R O.)
Mobilization					
	(to job)	Number	1	2000	2000
	(on site)	Per Well	30	150	4500
	(down wadi)	Per Well	5	500	2500
Surface Casing					
	Drill	Per meter	150	25	3750
	Install	Per meter	150	25	3750
Test Well (est 4 @ 30m deep)					
	Drill	Per meter	120	20	2400
	Case	Per meter	60	3	180
	Screen	Per meter	60	20	1200
	Gravelpack	Per m3	8	25	200
	Develop	Per Well	4	200	800
	Misc. Hourly	Per Hour	50	40	2000
Observation Well (est 26 @ 30m deep)					
	Drill	Per meter	780	15	11700
	Case (single)	Per meter	780	2	1560
	Case (dual)	Per meter	200	2	400
	Gravelpack	Per m3	40	25	1000
	Develop	Per Well	26	100	2600
	Centralizers	Number	60	30	1800
	Misc. Hourly	Per Hour	150	40	6000
Well Heads					
	Sup /Install	Number	30	200	6000
	Protect	Number	30	400	12000
Well Tests					
	Air lift	Number	26	25	650
	Set up	Number	4	200	800
	Pumping	Per Hour	300	20	6000
Miscellaneous					
	Supplies	Number	1	2500	2500
	Standby	Per Hour	50	25	1250
	Survey	Per Well	30	50	1500
	Geophysical Log	Per meter	900	8	7200
Support					
	Accommodations	Per Month	6	500	3000
	Relocation	Number	1	500	500
	Demobilization	Number	1	1000	1000

SUBTOTAL		R O.	90740
CONTINGENCY	@20%	R.O.	18148
TOTAL		R.O.	108888

TABLE 24

Cost Estimates for Technical Labor, Laboratory Analyses, and Equipment

INITIAL SIX-MONTH PROGRAM (Installation and Testing)

LABOR	Labor (wks)	Unit Cost (per wk) R.O.	Labor Cost (subtotal) R.O.	
Field Installation and Testing				
Sr. Hydrogeologist	26	850	22100	
Jr. Hydrogeologist	26	300	7800	
Sr. Hydrologist	4	850	3400	
Office Analysis				
Project Manager	13	1115	14495	
Sr. Technical Support Staff	13	300	3900	
Jr. Technical Support Staff	13	175	2275	
LABOR TOTAL (First Six Months)			R.O.	53970

LABORATORY ANALYSES	Number	Unit Cost R.O.	Total Cost R.O.	
Major Ion Aqueous Chemistry	20	100	2000	
Tritium and Stable Isotope Analysis	5	250	1250	
LABORATORY TOTAL (First Six Months)			R.O.	3250
EQUIPMENT				
Data Pods and Transducer	8	1600	12800	
Extra Cables, Modules, Reader, etc.	1	1000	1000	
EQUIPMENT TOTAL (First Six Months)			R.O.	13800
PROJECT TOTAL (First Six Months)			R.O.	71020

ONGOING PROGRAM (per year basis)

LABOR	Labor (wks)	Unit Cost (per wk) R.O	Labor Cost (subtotal) R.O.	
Sr. Hydrogeologist	4	850	3400	
Sr. Statistical Hydrologist	4	850	3400	
Project Manager	4	850	3400	
Sr. Technical Support Staff	26	300	7800	
Jr. Technical Support Staff	2	175	350	
LABOR TOTAL (Ongoing, Per Year)			R.O	18350

LABORATORY ANALYSES	Number	Unit Cost R.O.	Total Cost R.O.	
Major Ion Aqueous Chemistry	15	100	1500	
Tritium and Stable Isotope Analysis	10	250	2500	
LABORATORY TOTAL (First Six Months)			R.O	4000
ONGOING PROGRAM TOTAL (Per Year)			R.O.	22350

TABLE 25

Subcontract Cost Estimate for Surface Water Gauge Installations

ESTIMATED SURFACE WATER GAUGE SUBCONTRACT COSTS

	Estimated Quantity	Unit Cost (R.O.)	Total Cost (R.O.)	
STATION 1 GAUGE				
Mobilization	1	2000	2000	
Concrete (per m3)	15	300	4500	
DATAPOD Recorder Shelter	1	3500	3500	
Dewatering (per day)	5	200	1000	
STATION 1 GAUGE TOTAL			R.O.	11000
INTERMEDIATE AND DOWNWADI CREST GAUGES				
Fabrication and Installation	10	250	2500	
CREST GAUGE TOTAL			R.O.	2500
STATION 2 GAUGE				
Mobilization	1	2000	2000	
Concrete (per m3)	1	200	200	
DATAPOD Recorder Shelter	1	3500	3500	
STATION 2 GAUGE TOTAL			R.O.	5700
SURFACE WATER GAUGE SUBCONTRACT TOTAL			R.O.	19200

TABLE 26

Cost Estimates for Monitoring and Assessing Batinah Dams

SUPPLEMENTAL WELL INSTALLATIONS AT BATINAH DAMS

LABOR (Exclusive of Section Staff)	Labor (wks)	Unit Cost (per wk) (R.O.)	Labor Cost (Subtotal) (R.O.)	
Field Installation and Testing				
Sr. Hydrogeologist	26	850	22100	
Jr. Hydrogeologist	26	300	7800	
Sr. Hydrologist	4	850	3400	
Office Analysis				
Project Manager	13	1115	14500	
Sr. Technical Support Staff	13	300	3900	
Jr. Technical Support Staff	13	175	2300	
LABOR TOTAL				54000
LABORATORY ANALYSES	**Number**	**Unit Cost**	**Total Cost**	
Major Ion Aqueous Chemistry	28	100	2800	
Tritium and Stable Isotope Analysis	14	250	3500	
LABORATORY TOTAL				6300
PIEZOMETERS (Observation Wells)	84	3800	319200	319200
(Installation of 12 Wells/Wadi X 7)				
EQUIPMENT				
Data Pods and Transducers	21	1600	33600	
Extra Cables, Modules, Reader, etc.	3	1000	3000	
Extra Well Protection (Data Pod Units)	21	500	10500	
EQUIPMENT TOTAL				47100
TOTAL—Batinah Dams Program; exclusive of Section Staff Labor				426600

TABLE 26 (continued)

Cost Estimates for Monitoring and Assessing Batinah Dams

OVERALL PROGRAM (First Year Basis)

	Labor (wks)	Unit Cost (per wk) (R.O.)	Labor Cost (Subtotal) (R.O.)	
TOTAL FROM PRIOR PAGE				426600
SECTION STAFF LABOR *				
Section Chief	52	1115	57980	
Asst. Hydrologist	52	850	44200	
Asst.Engr./Hydrogeologist	52	850	44200	
Second Technician (Trainee)	52	155	8060	
SECTION STAFF LABOR TOTAL				162600
LABORATORY ANALYSES (Additional - First Year)				
Major ion Aqueous Chemistry	14	100	1400	
Tritium and Stable Isotope Analysis	14	250	3500	
Sediment Sample Physical Analysis	14	50	700	
FIRST YEAR ADDED ANALYSIS TOTAL				5600
FIRST YEAR PROGRAM TOTAL				594800

BATINAH DAMS MONITORING AND EFFECTIVENESS ASSESSMENT
(Annual Costs, After First Year)**

SECTION STAFF LABOR *		
Section Staff First Year Total	162600	
Added Staff	60400	
LABORATORY ANNALYSES (Including Interior and Salalah)	12200	
ANNUAL PROGRAM TOTAL		235200

* Staff involvement from other departments not included

** Anticipates expansion into Interior and Salalah in second year of the Section with possible addition of one assistant engineer of R.O 850/-week rate and two added technicians, no new wells, but no factor added for inflation or salary increases, and no reoccurring costs from the prior page.

TABLE 27

Cost Estimates for Multiple Leaky Dam Program

FIRST YEAR PROGRAM (Exclusive of MWR Artificial Recharge Section Labor)		
Labor Total	54,000	
Drilling and Testing Subcontract Costs	109,000	
Equipment Costs (Well Instrumentation	14,000	
Water Gauge Subcontract Costs	13,000	
Laboratory Analysis	3,000	
SUBTOTAL of Well Installation Costs - 26 Wells		193,000*
Dam Construction Subcontract Costs (based on 8 dams at R.O.30,000)	249,000	
Equipment Costs (datapod per dam)	18,000	
Water Gauging at Dams Subcontractor costs	13,000	
SUBTOTAL of Dam Construction & Instrumentation		280,000
PROJECT INCEPTION REPORT - (First 6 months)		
Labor Costs for Preliminary Work Plan/ Site Selection & Economic Analysis)	*	
Outside Professional augmentation- Planning Unit, Initial Direction	8,500	
Review of Product	8,500	
SUBTOTAL of Inception Report		17,000
TOTAL of first page		490,000

* Labor costs of MWR - Artificial Recharge Section - Salary cost included under staffing this Section previously included under costs for monitoring and assessing effectiveness of existing recharge dams.

TABLE 27 (continued)

Cost Estimates for Multiple Leaky Dam Program

TOTAL of Prior Page		490,000
FEASIBILITY STUDY - to year 1.5		
Labour and Other Costs for:		
Aerial Mapping of Dam Area	10,000	
Engineering & Hydrogeologic Investigations	*	
Confirming Dam Sites	*	
Determination Number & Size of Dams	*	
Establishing Dam Construction Materials	*	
Construction Procedures & Schedules	*	
Reporting	*	
Sub-contract (Detailed Economic Analysis)	5,000	
Outside Professionals augmenting Planning Unit		
60 percent Completion Review	11,500	
Final Report Review	11,500	
SUBTOTAL of Feasibility Report		38,000
FINAL DESIGN AND DAM CONSTRUCTION SUPERVISON - to year 2.5		
Consulting Firm	40,000	40,000
TOTAL COST EXCLUSIVE OF MONITORING		568,000

* Labor costs of MWR - Artificial Recharge Section - Salary cost included under staffing this Section previously included under costs for monitoring and assessing effectiveness of existing recharge dams.

FIGURE 1

Location of Seven Rainfall Gauge Sites in the Musandam Peninsula, Oman

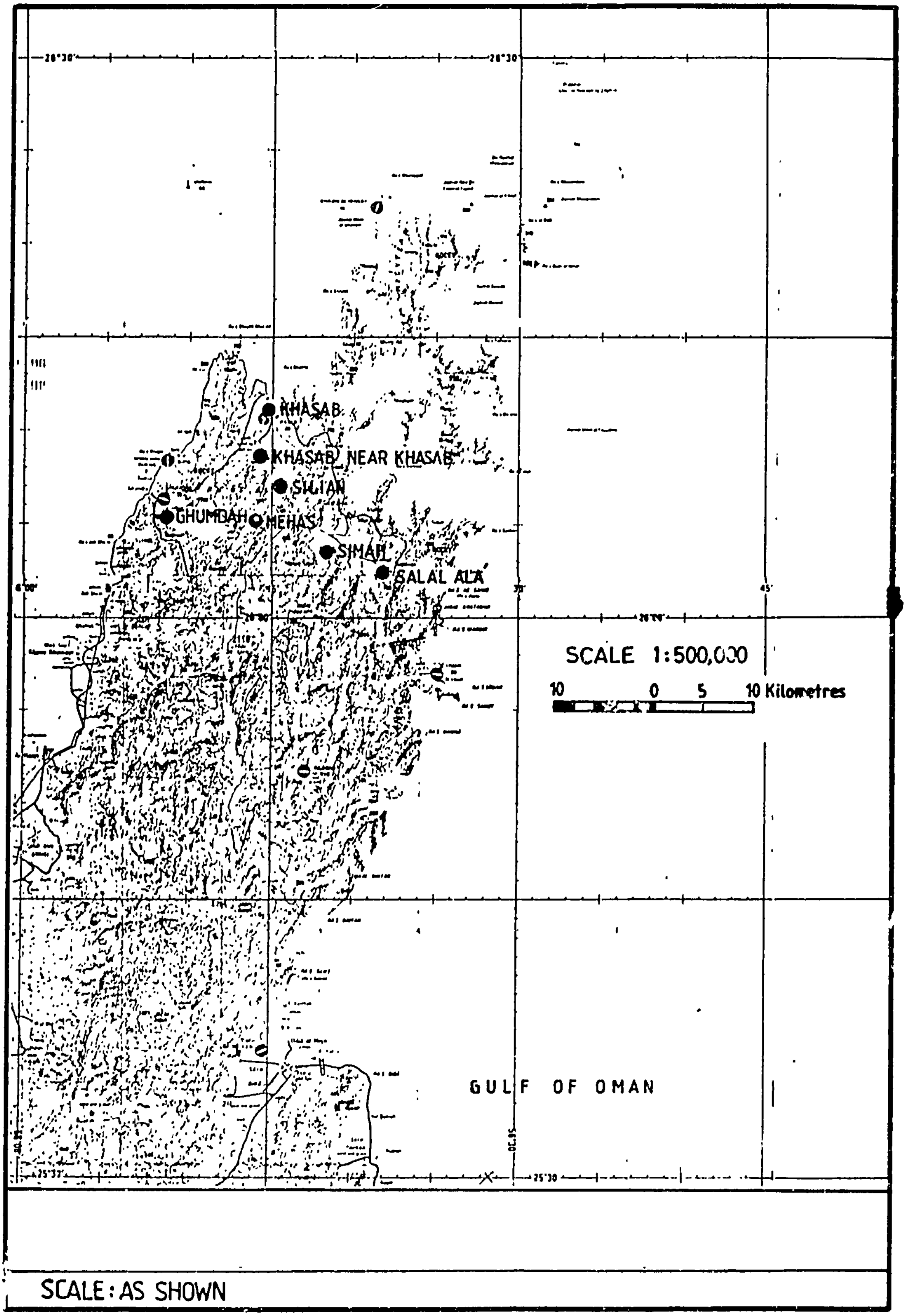
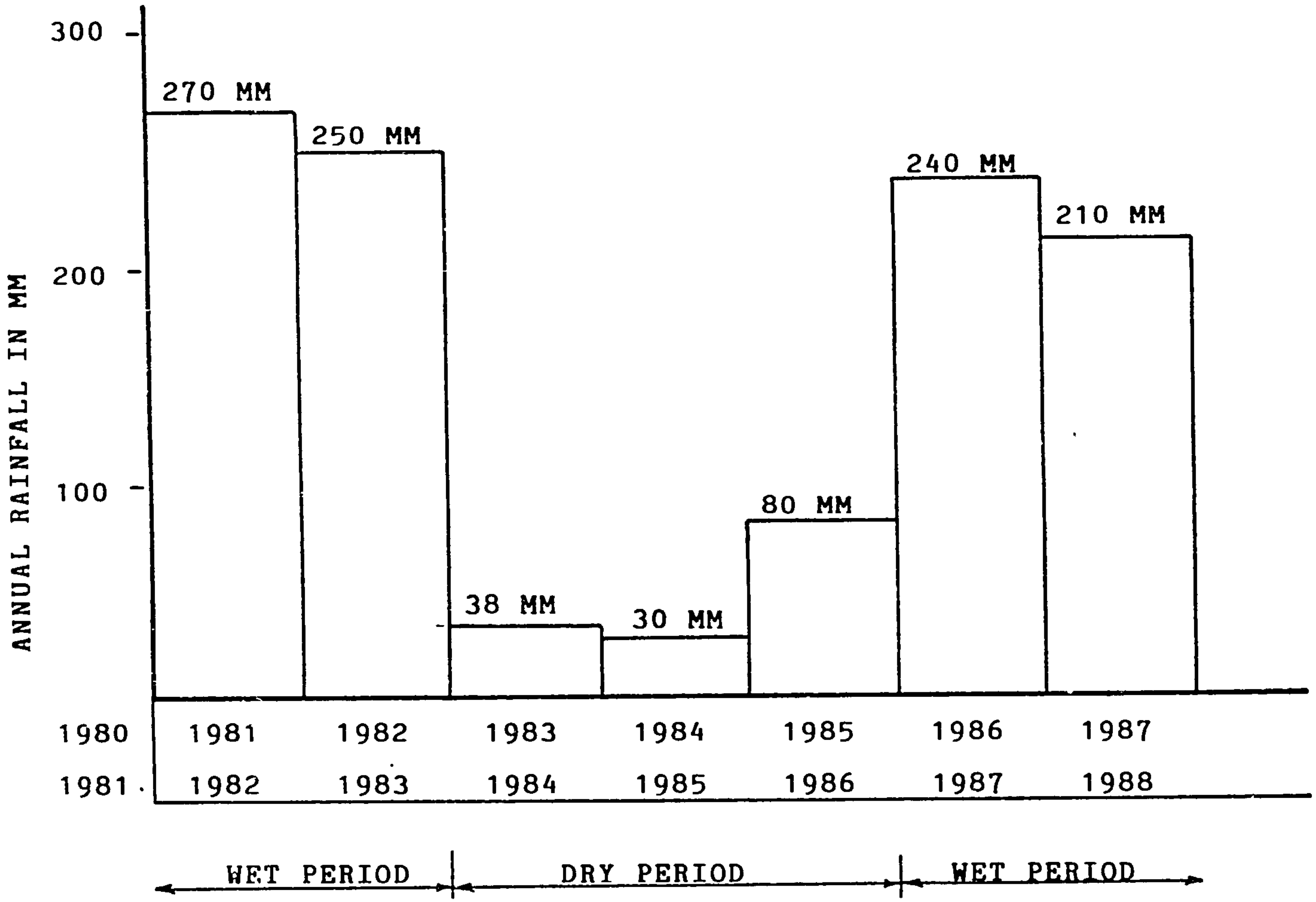


FIGURE 2

Average of 4 Station Annual Rainfall from Oct. 1981 to Sept. 1988
Musandam Peninsula



WET PERIOD AVERAGE ANNUAL RAINFALL = 240 MM
DRY PERIOD AVERAGE ANNUAL RAINFALL = 50 MM

FIGURE 3

Relationship Between Drainage Area and Runoff for Storm Period Dec. 1989-Feb. 1990

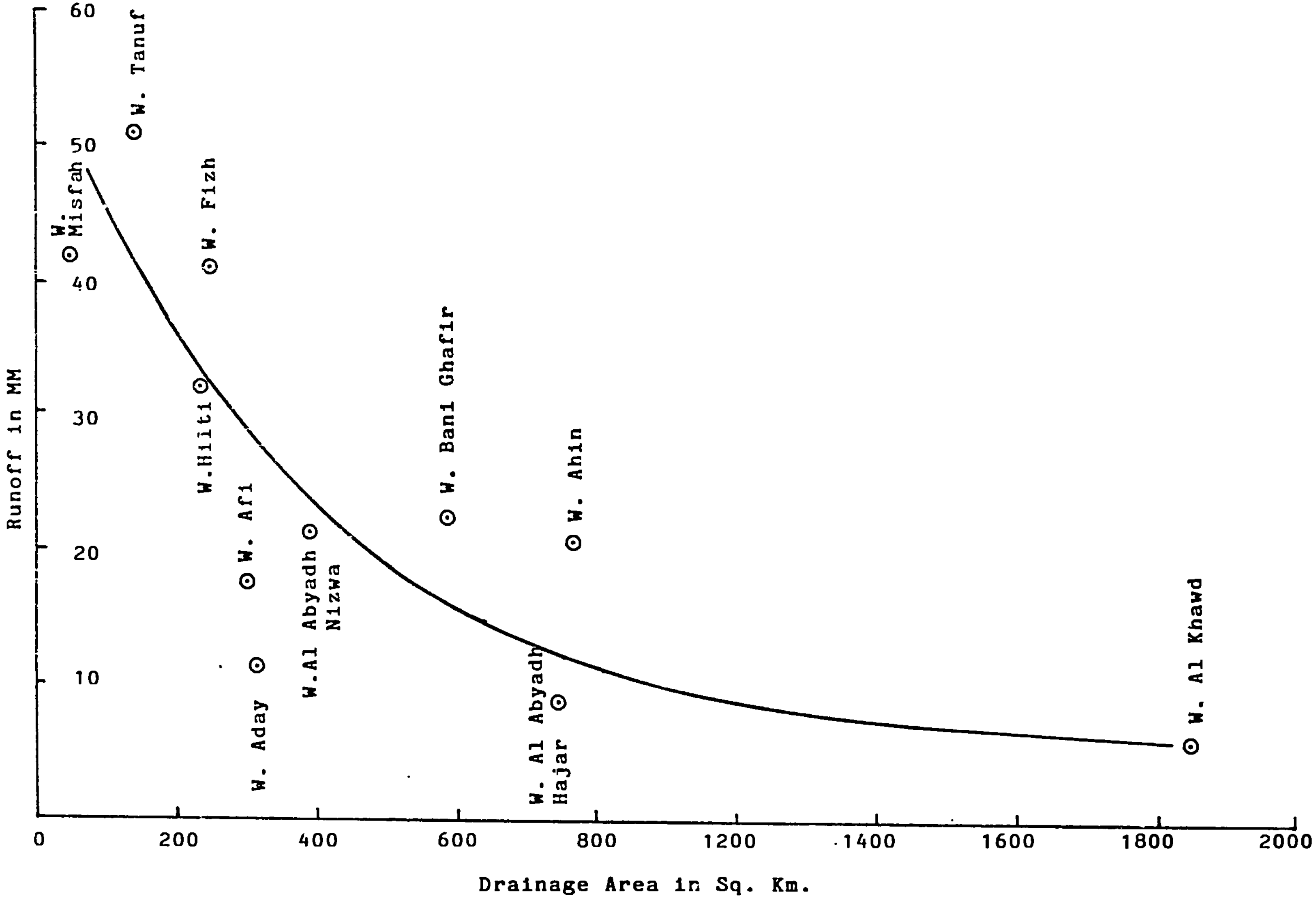


FIGURE 4

Relationship Between Drainage Area and Rainfall Runoff for Storm Period Dec. 1989-Feb. 1990

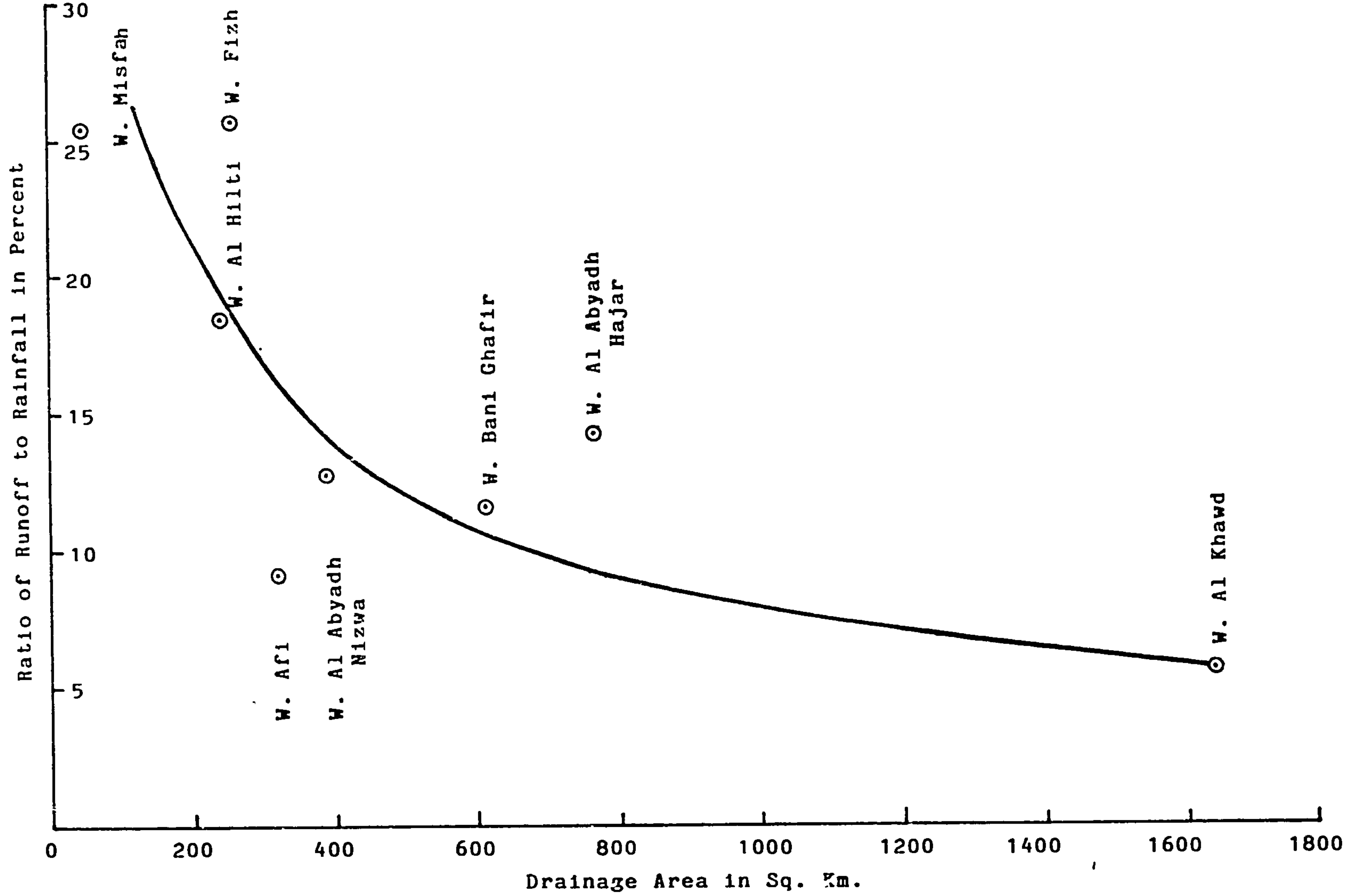


FIGURE 5

Wadi Misfah at Al Hamra
(Catchment = 58.6 sq.km)

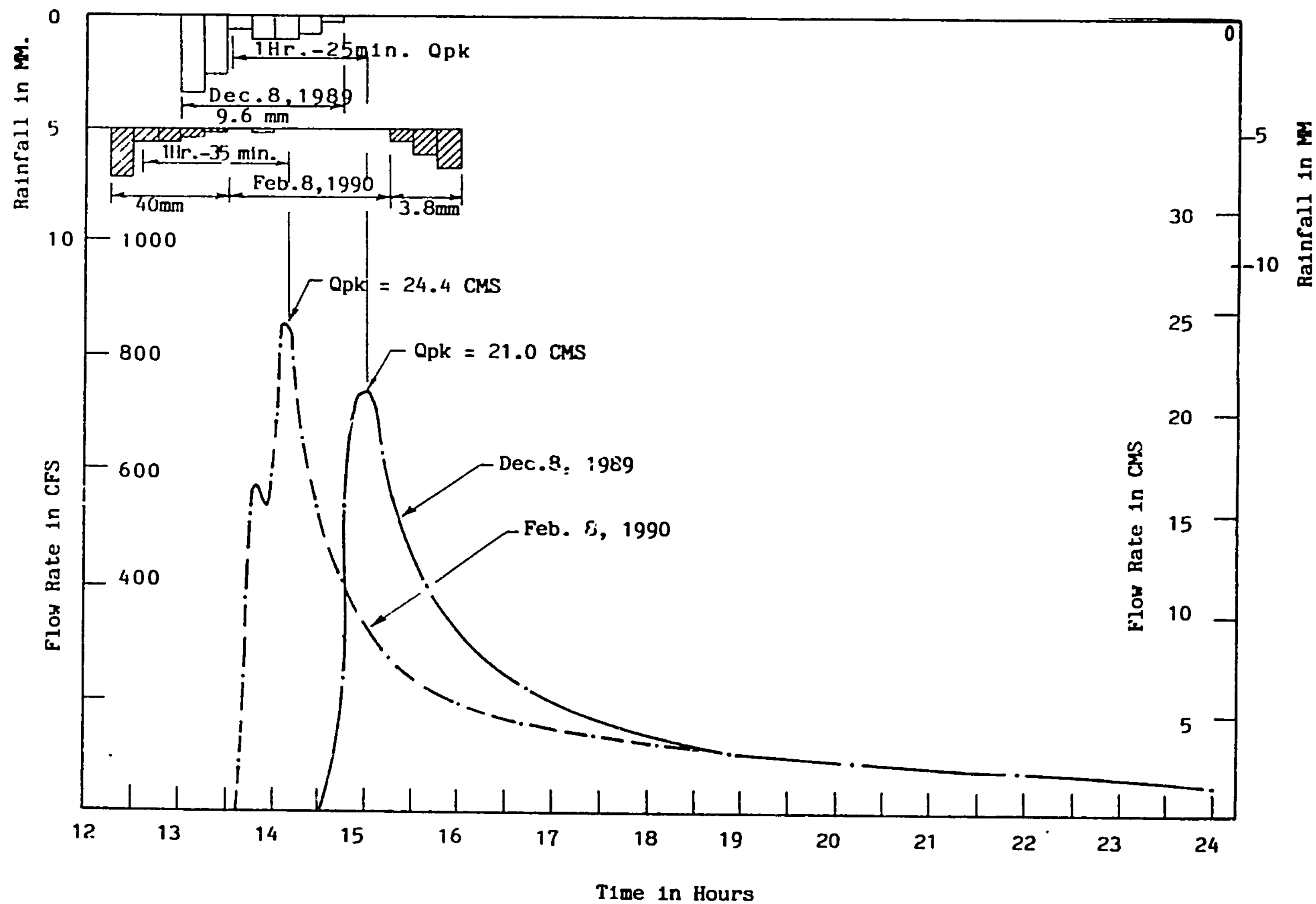


FIGURE 6

Wadi Bahla at Bahla
(Catchment = 611.5 sq.km)

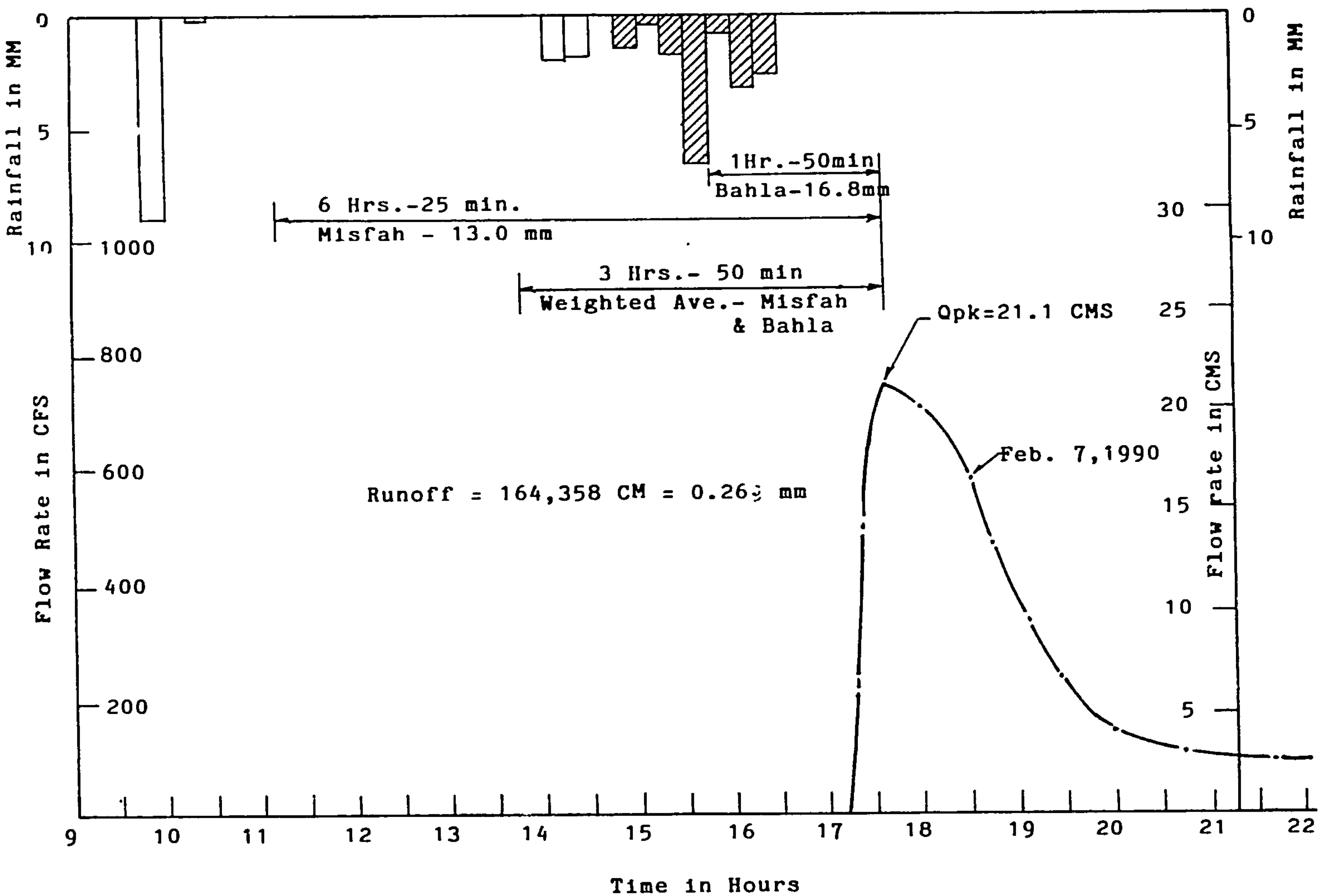


FIGURE 7

Basin Area of Wadi Ahin
Drainage area: 765 sq.km

(see back pocket)

FIGURE 8

Hydrograph Comparison for Wadi Ahin near Hayl
Feb. 1990 Storm
(Catchment - 765 sq.km)

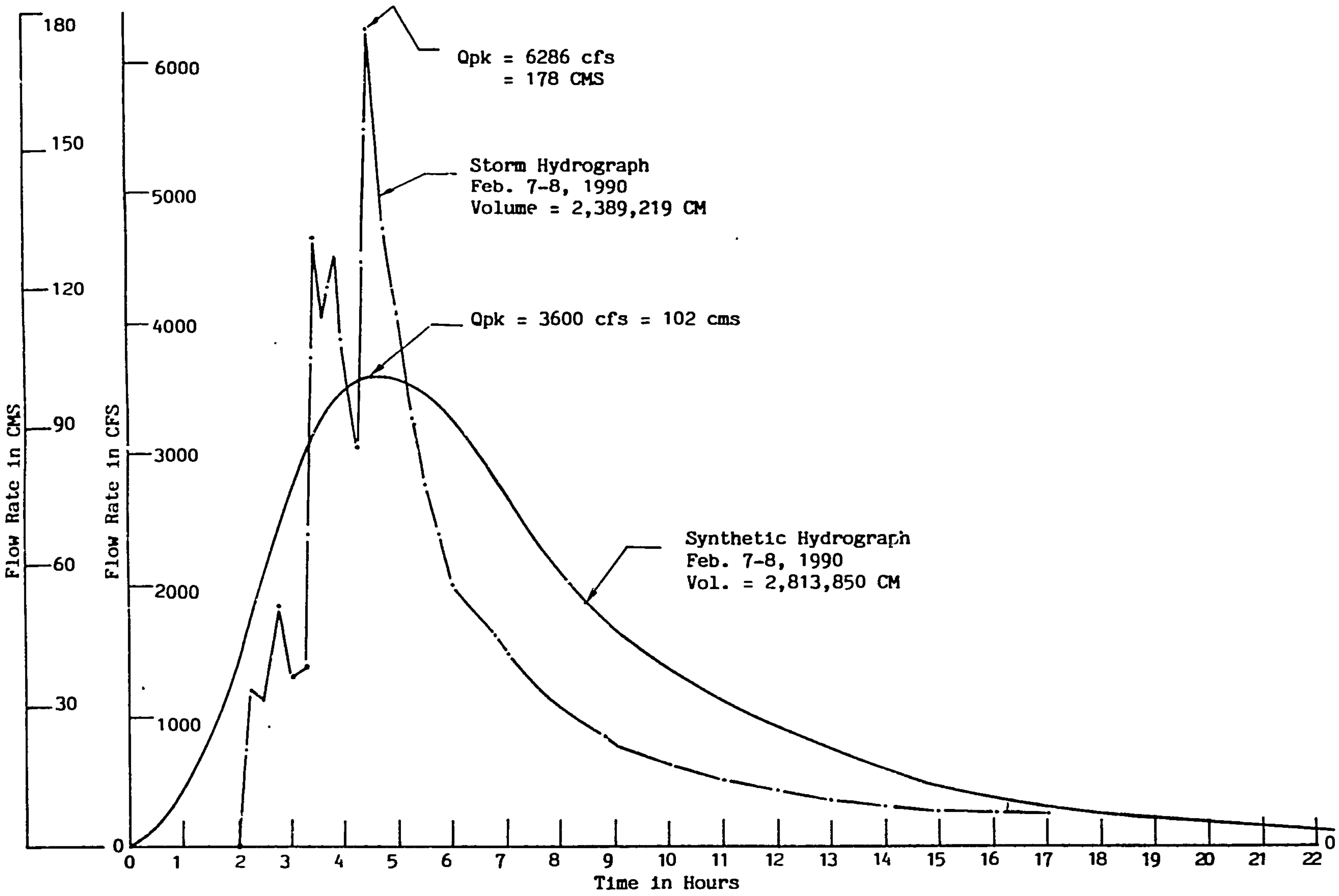


FIGURE 9

Basin Area of Wadi Bani Ghafir
Basin Area of Wadi Ghul, Wadi Misfah, and Wadi Bahla

(see back pocket)

FIGURE 10

Hydrograph Comparison for Wadi Bani Ghafir near Falaj as Saidi
(Catchment = 617.05 sq.km)

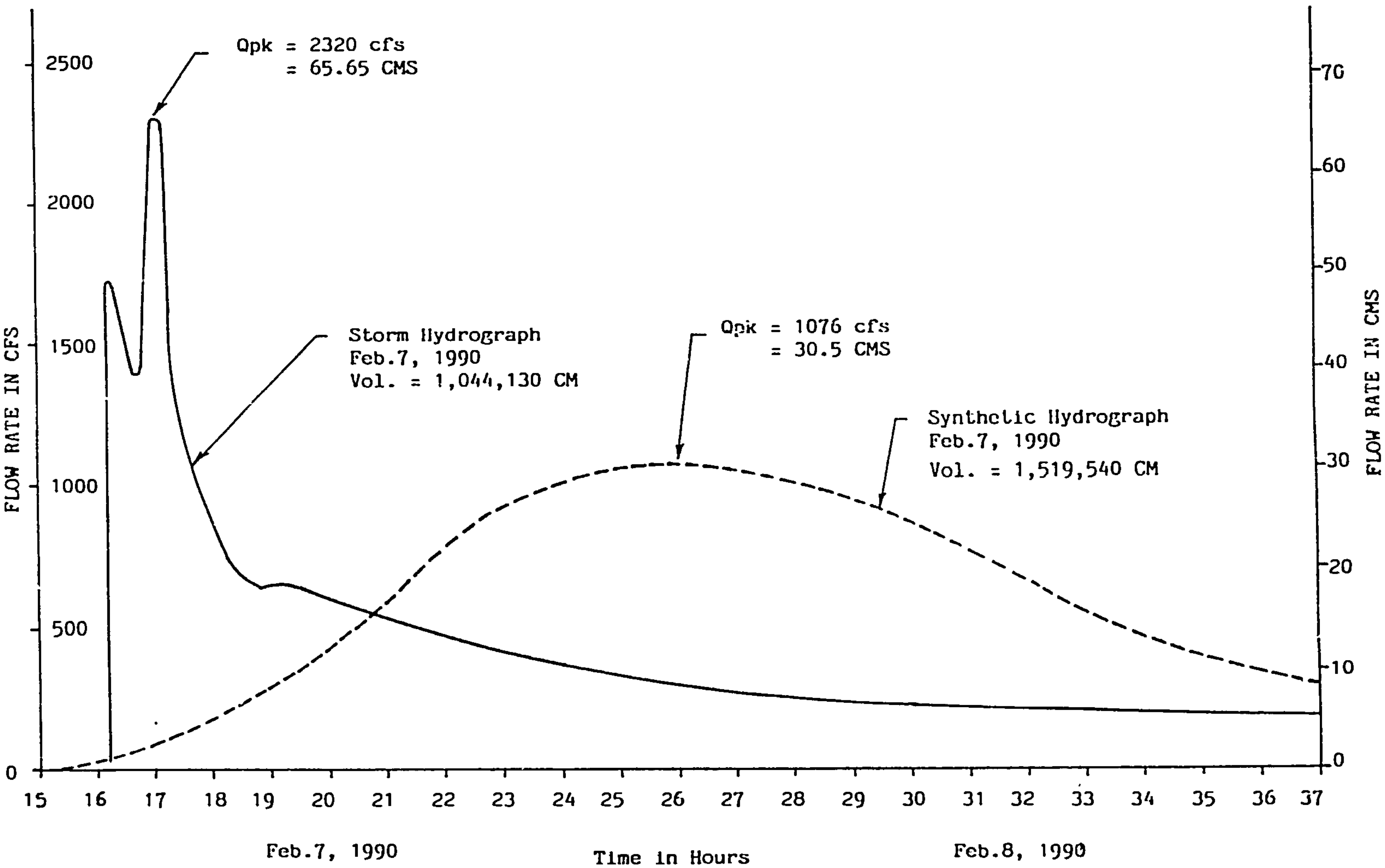


FIGURE 11

Hydrograph Comparison for Wadi Bani Ghafir near Falaj as Saidi
(Catchment = 617.05 sq.km)

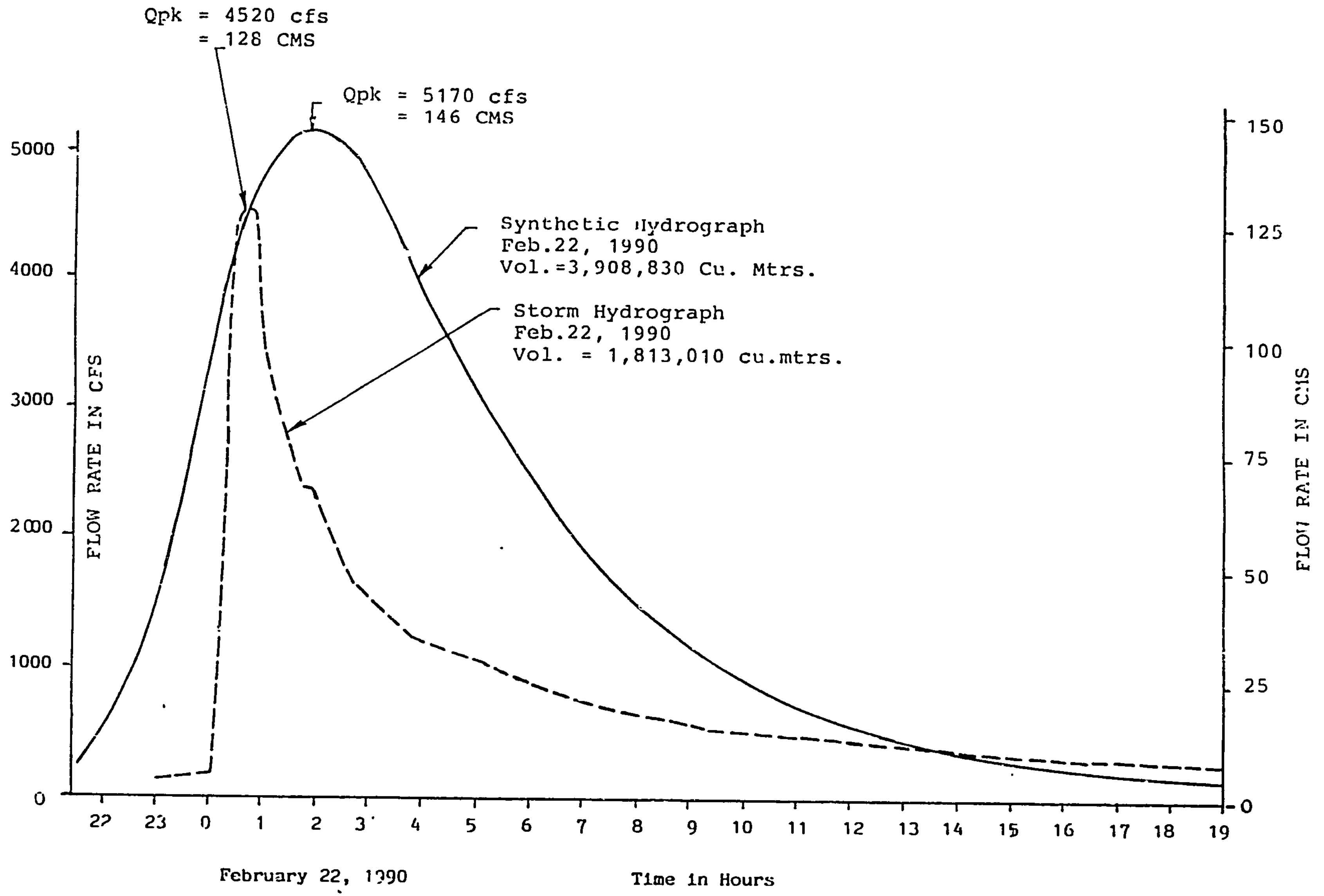


FIGURE 12

Hydrograph Comaprison for Wadi Misfah at Al Hamra
(Catchment = 58.6 sq.km)

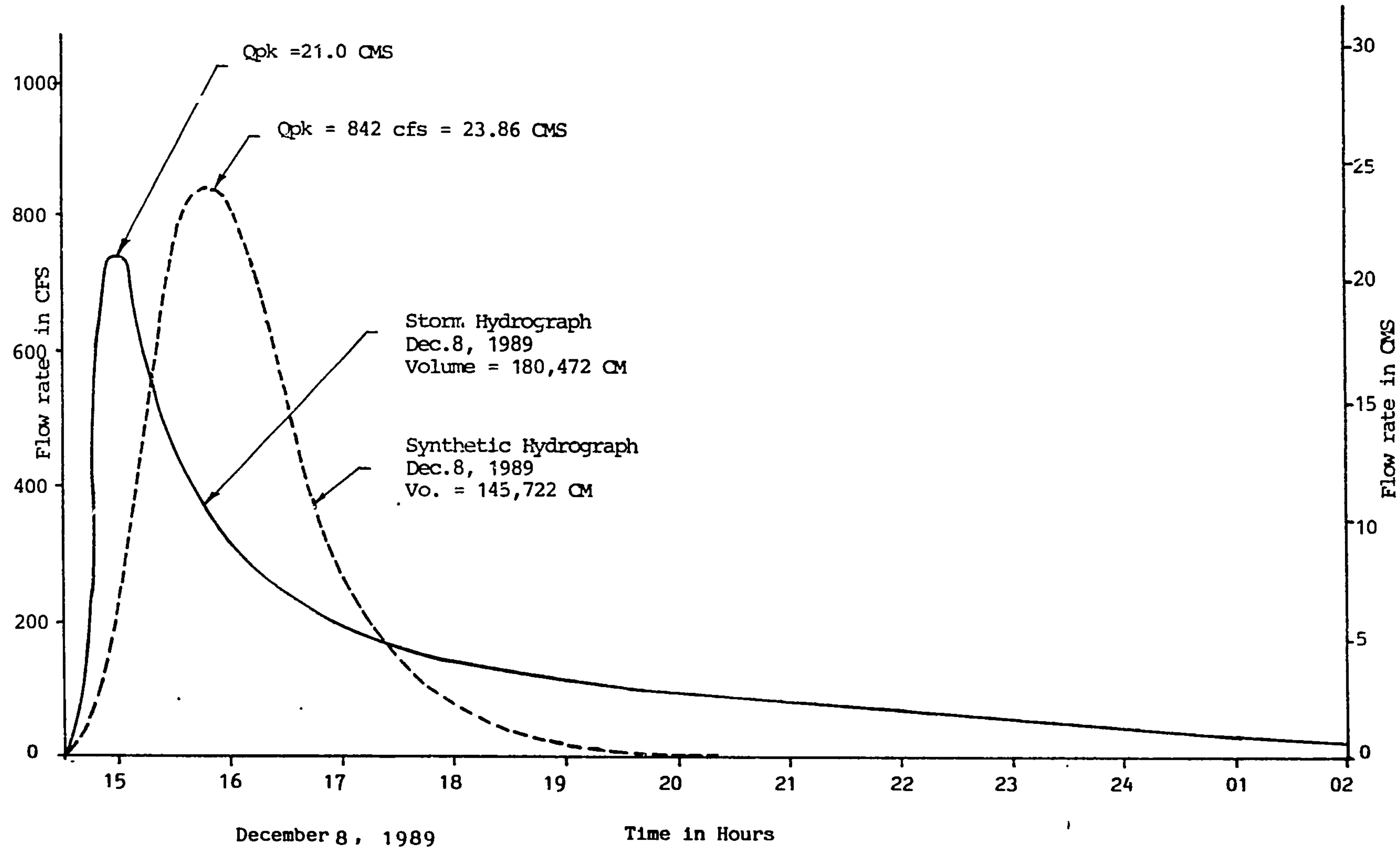


FIGURE 13

Hydrograph Comparison for Wadi Bahla at Bahla
(Catchment = 611 sq.km)

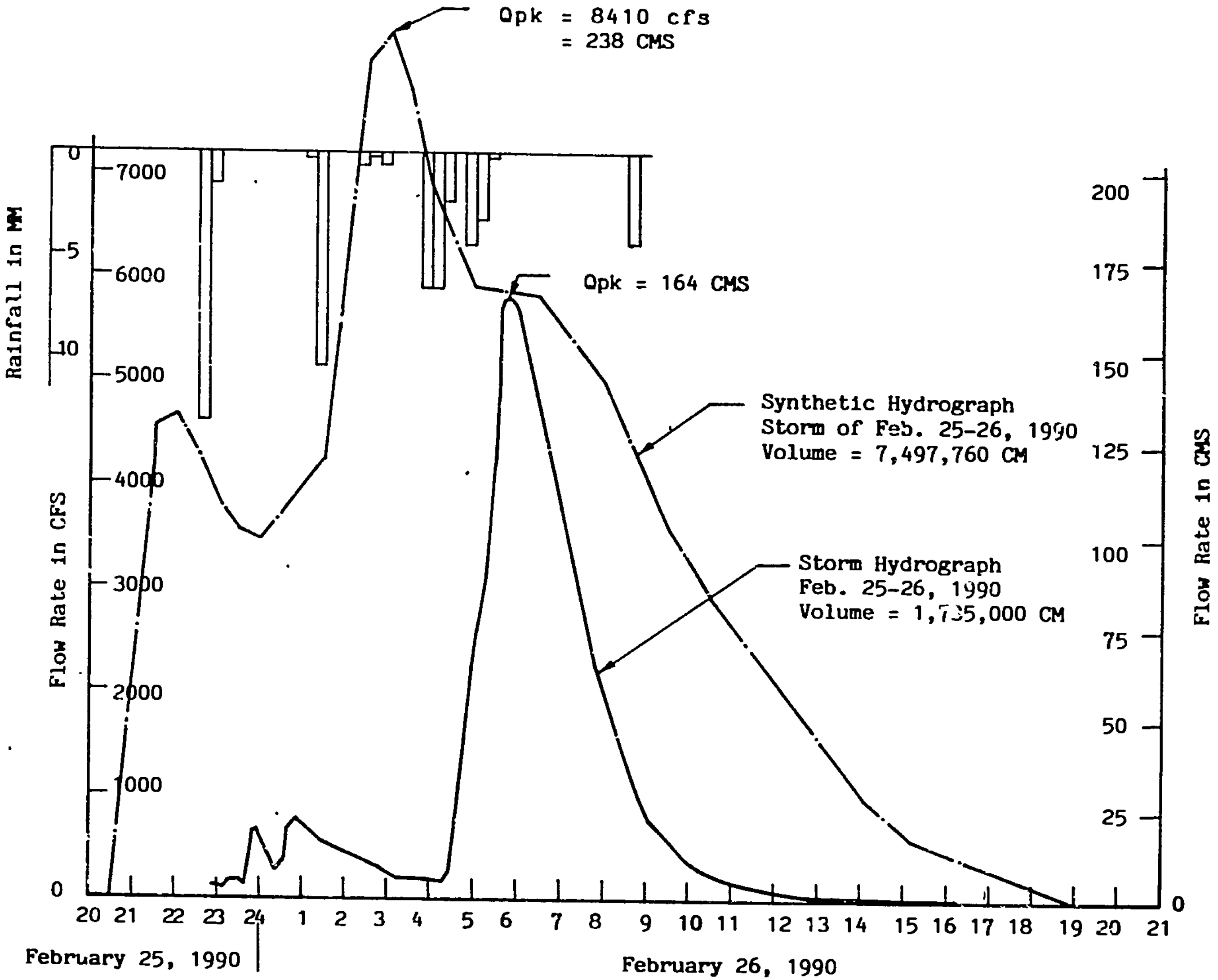


FIGURE 14

Channel Geometry Program—Wadi Flows

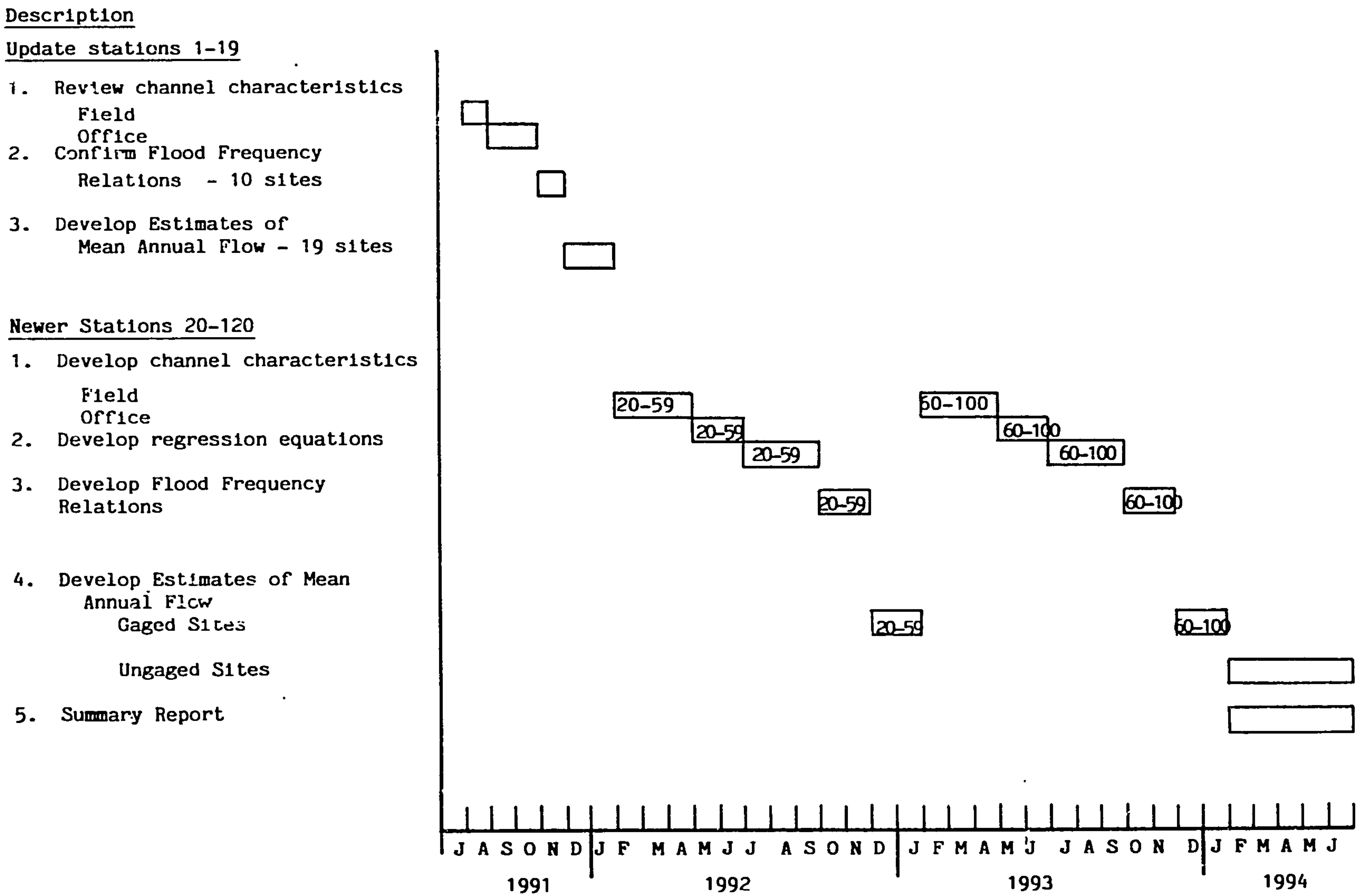


FIGURE 15

Representative Basin—Pilot Program

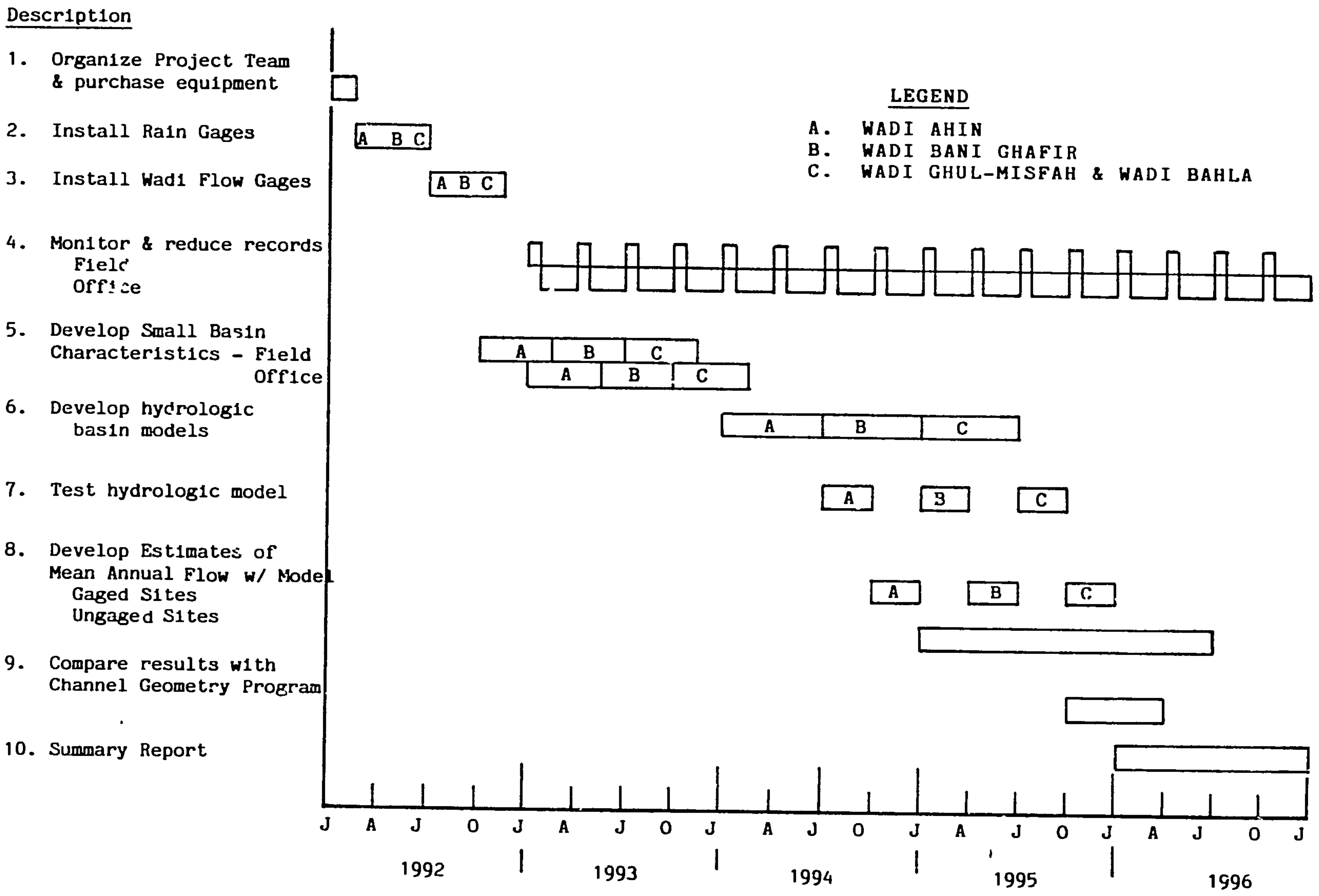
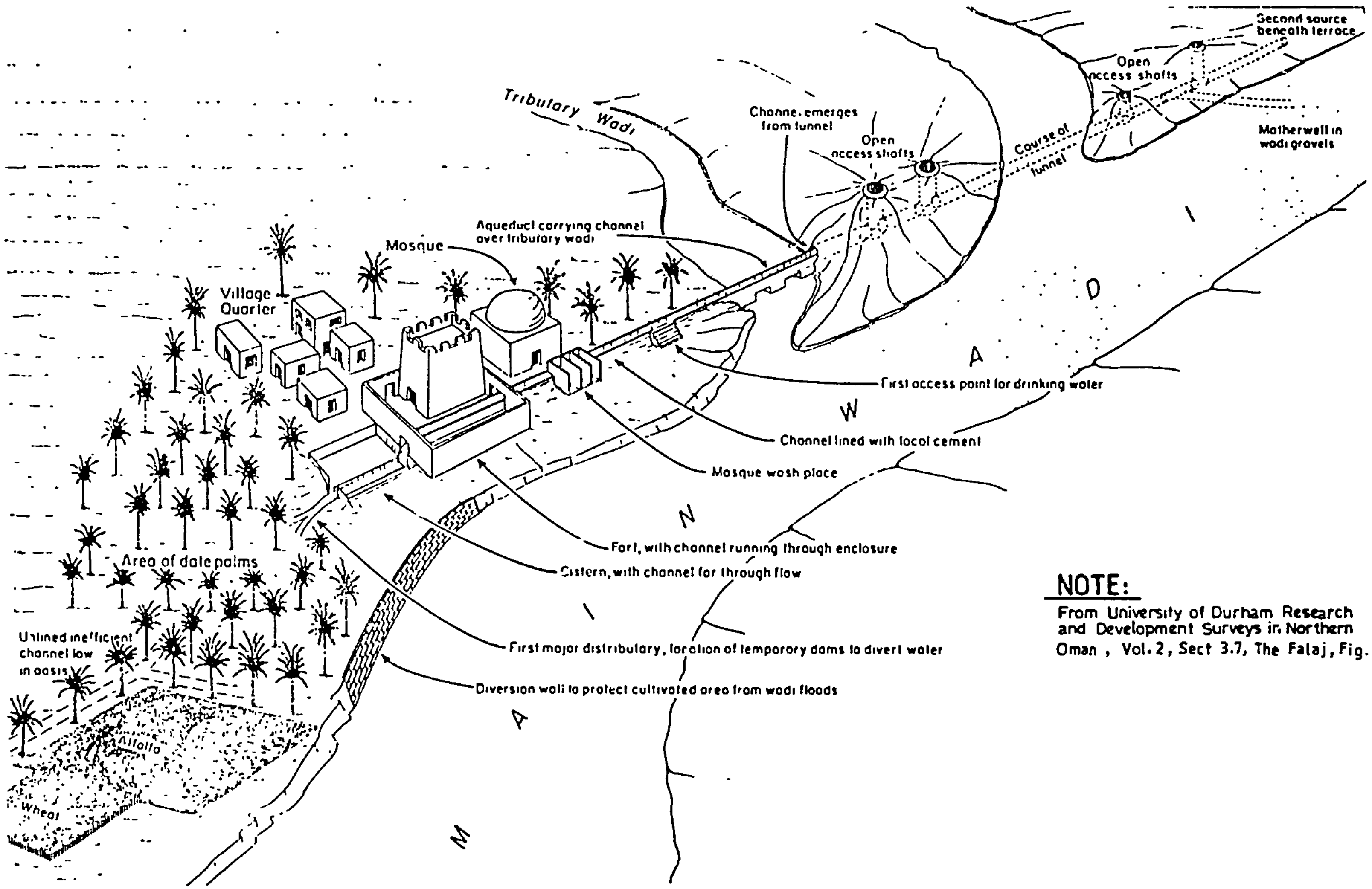


FIGURE 16

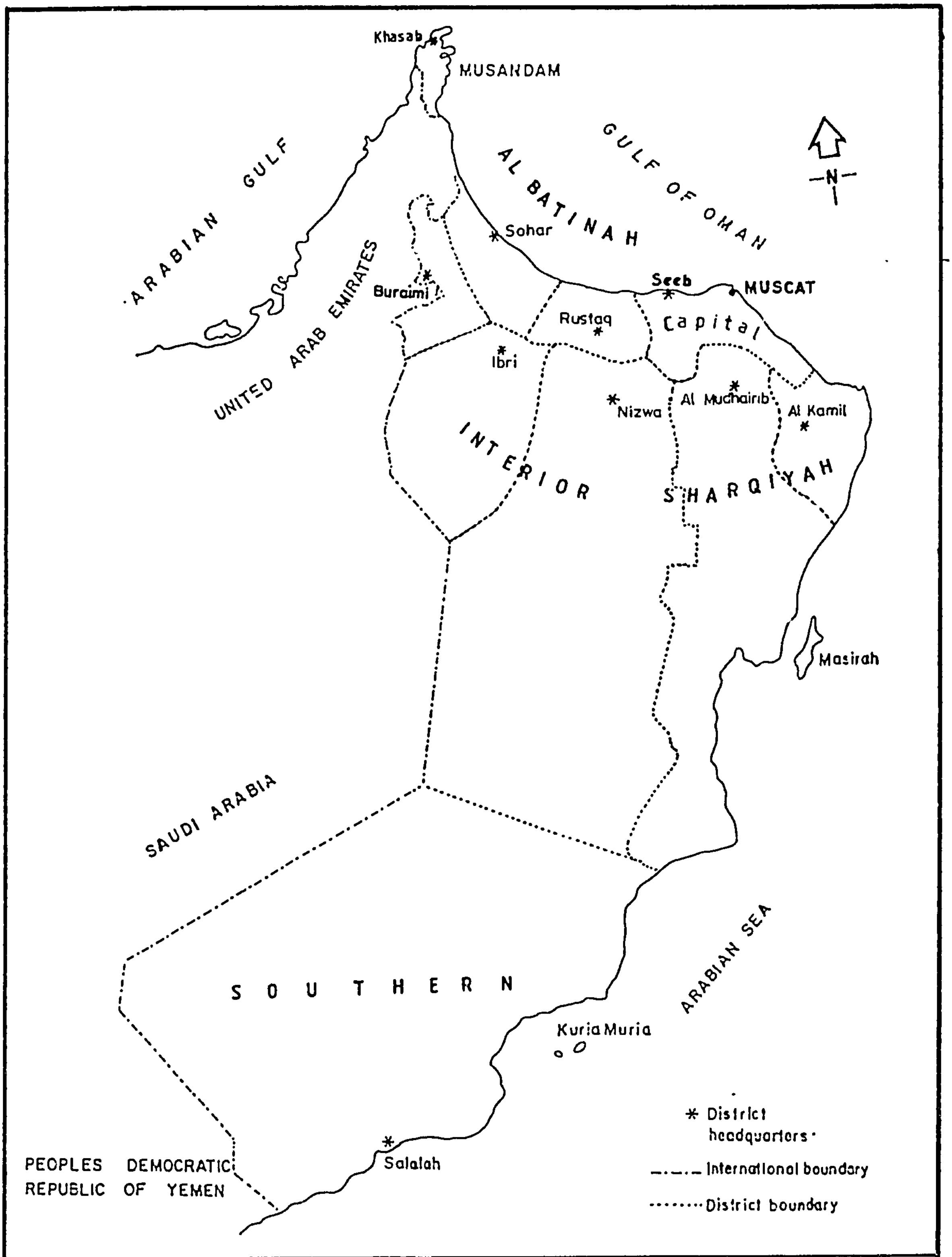
Sketch of a Typical Daudi Type Falaj



NOTE:
From University of Durham Research and Development Surveys in Northern Oman , Vol. 2, Sect 3.7, The Falaj, Fig. 3.7.3.

FIGURE 17

Districts of the Ministry of Water Resources



SCALE: NOT TO SCALE

FIGURE 18

Flow Hydrograph Falaj al-Bilad at Huqain

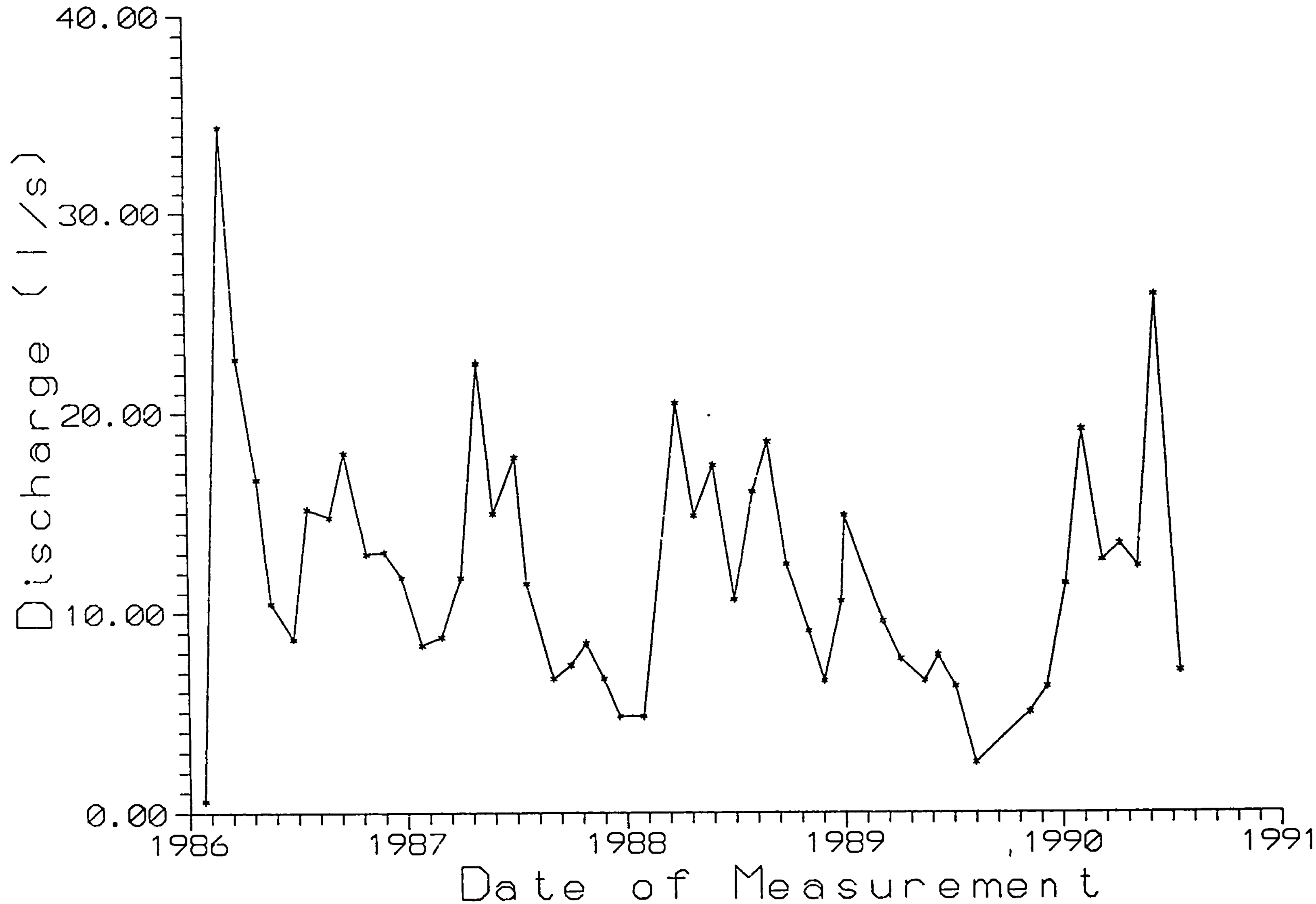
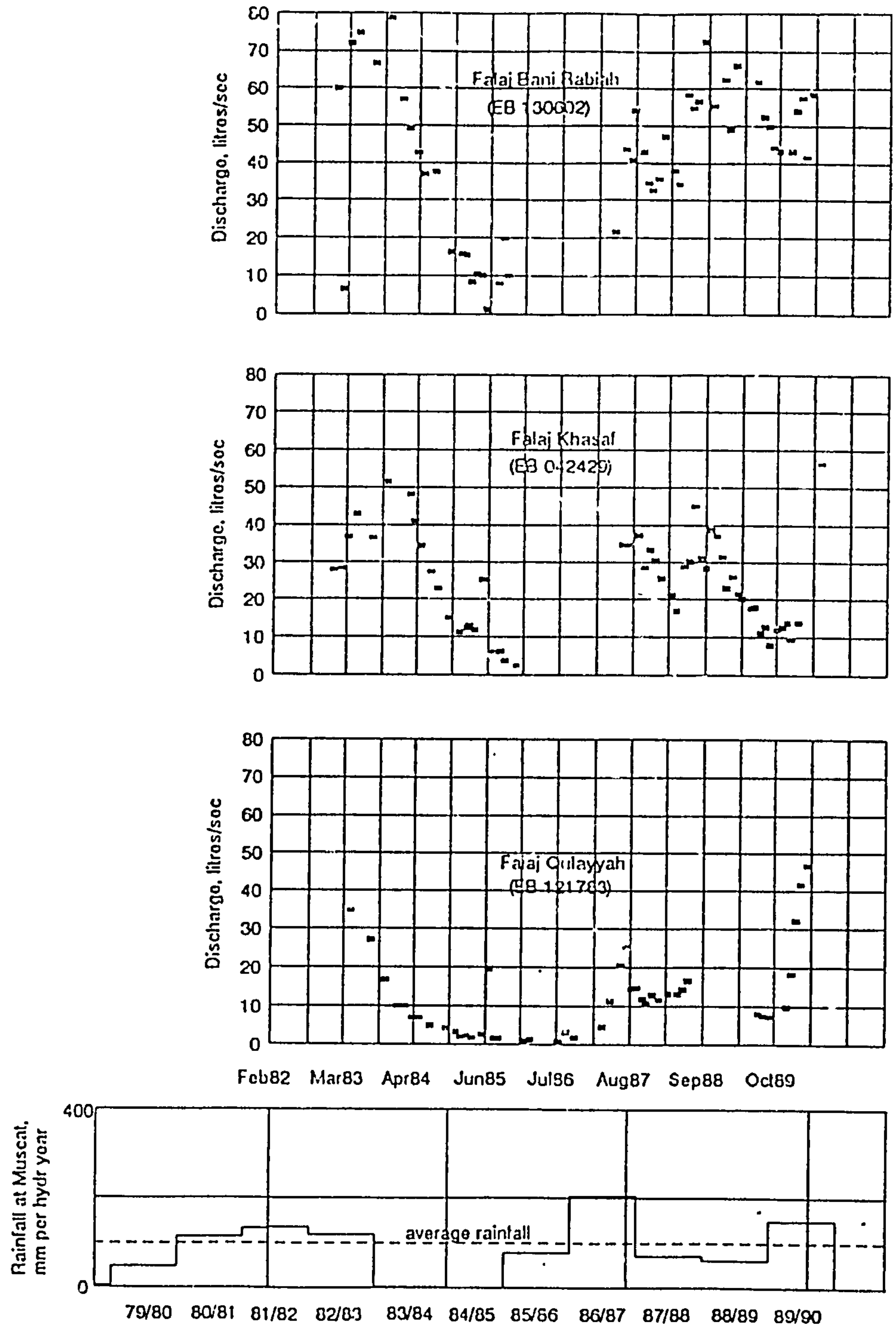


FIGURE 19

Aflaj Discharge in Wadis Halhal and Bani Umar (1982-1990)
from Rendell, 1991



SCALE: NOT TO SCALE

FIGURE 20

Depth versus Discharge Falaj al-Bilad at Huqain

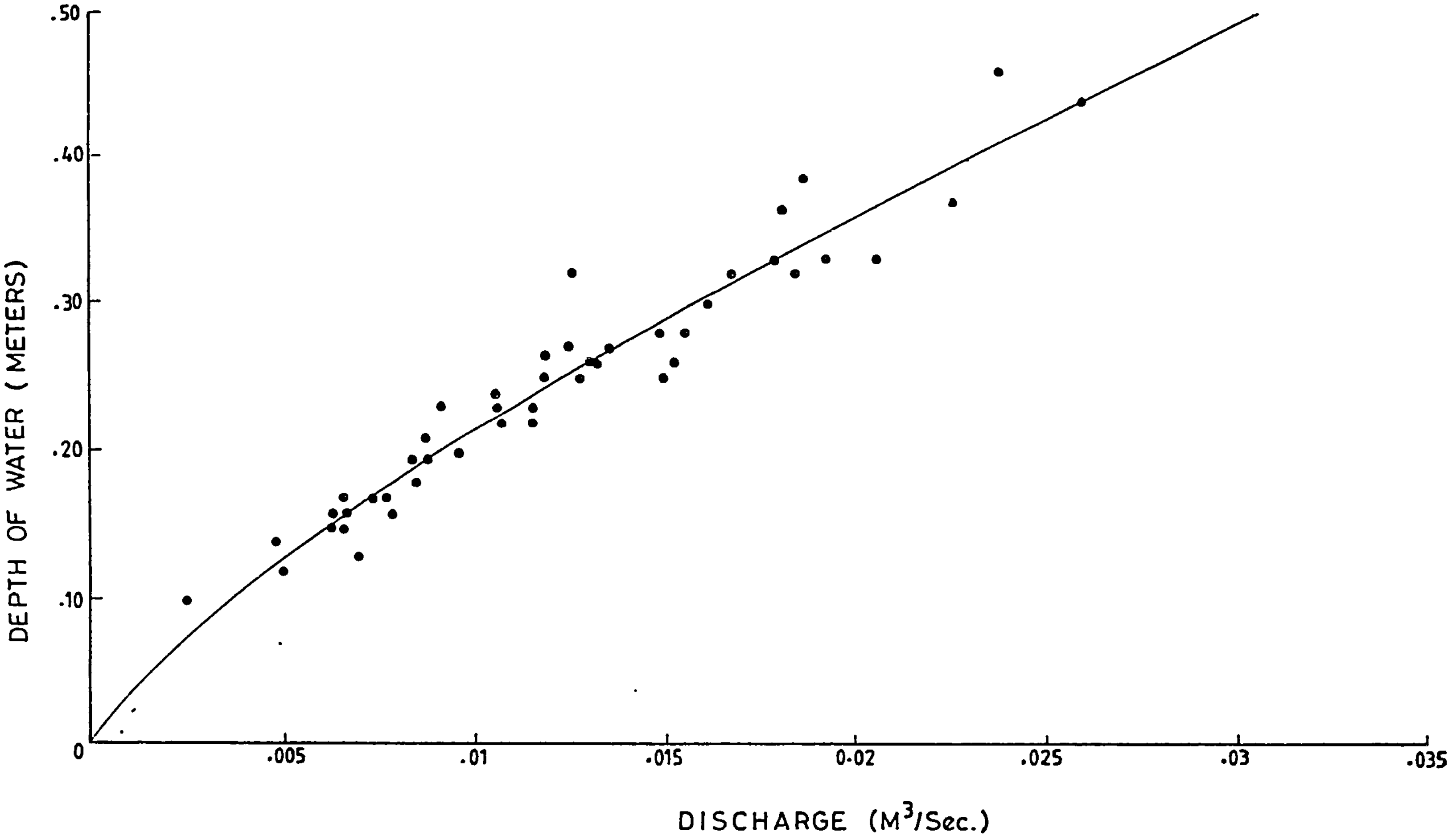


FIGURE 21

Depth versus Discharge Falaj Bilad at al-Hayl

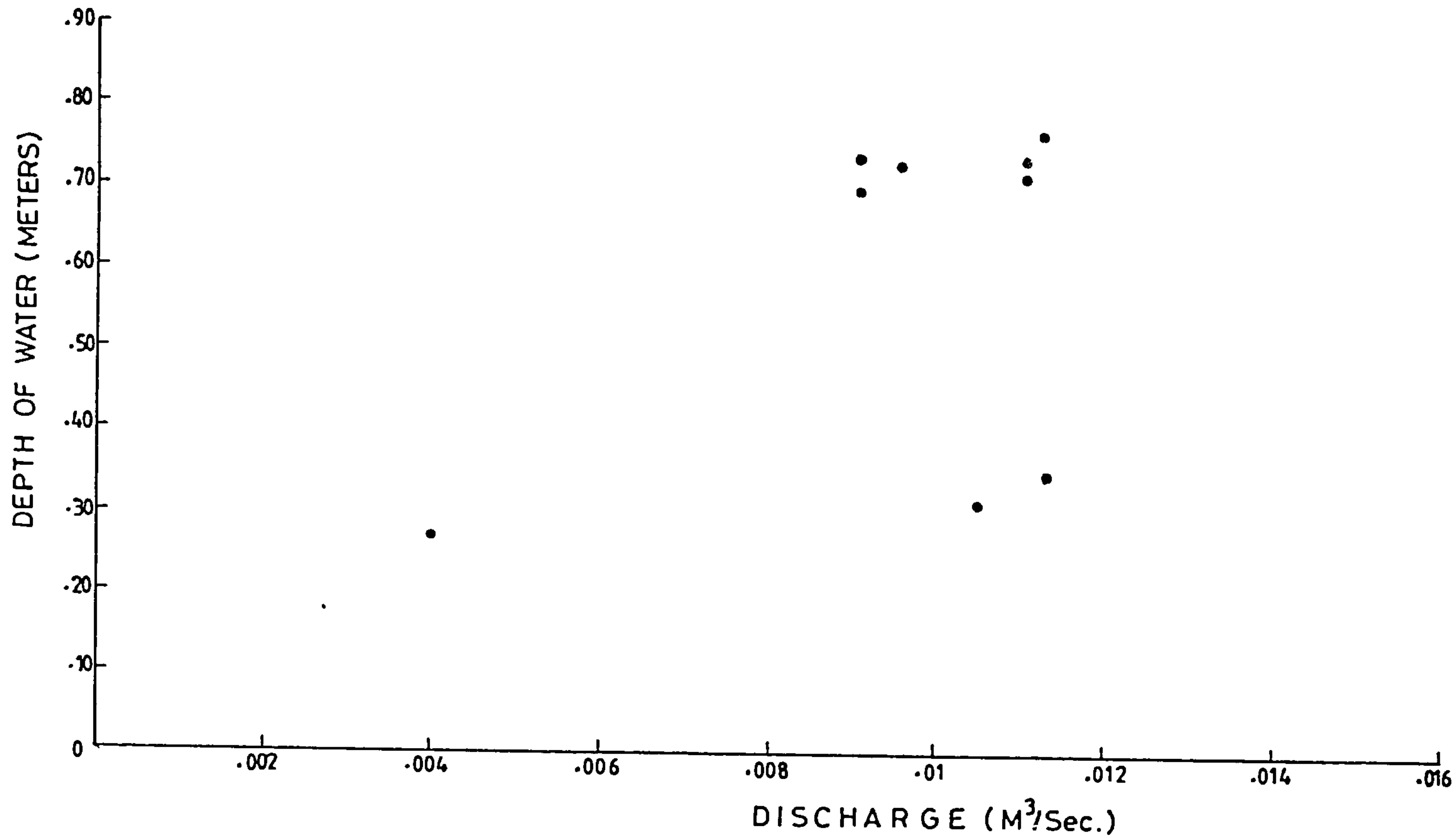
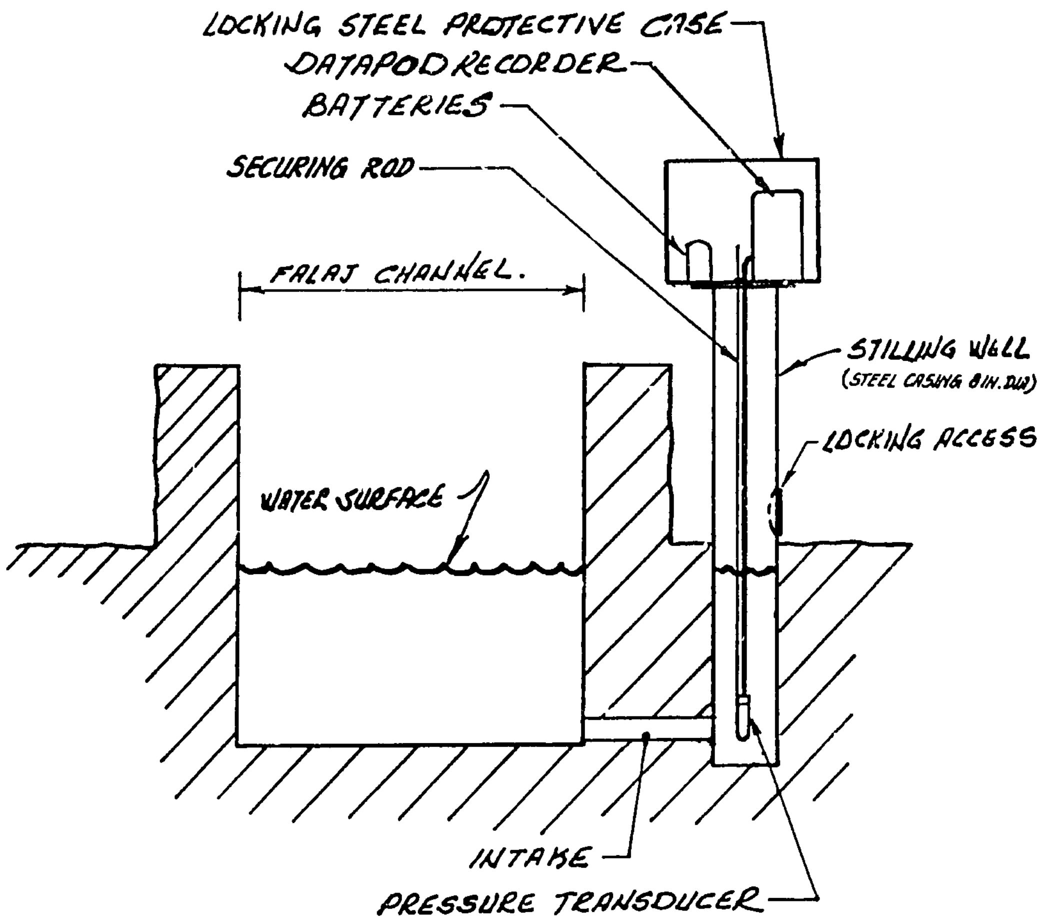


FIGURE 22

Conceptual Design
Continuous Monitoring Station



SCALE: NOT TO SCALE

FIGURE 23

Falaj Inventory Sheet

1.a. Name of Falaj ....

b. Any other name

2. Wilayat ....Village ....

3. Catchment/Wadi..

SOURCE

4. Location of mother well :-

Latitude ....Longitude ....

Grid reference: E ....N ....

ID No. ....

5. Condition of mother well ....

6. Description of location of mother well ... .
....
....
....

7. Type of Falaj: .....Ghaily........Da'udi........Spring.......Dam.

8. No. of Sa'ad feeding the falaj ....

9. Any dug well or borehole to support the falaj: well borehole none

Details of wells/boreholes:

Depth.........m,bgl. SWL.........m,bgl. Dia.......mm. Yield......lps.

EC...........umhos/cm at degrees C

Depth.........m,bgl. SWL.........m,bgl. Dia......mm. Yield......lps

EC...........umhos/cm at degrees C

10. Geological information about the source ....
....
....

CHANNEL :

11. a. General depth of channel ....cm
b. General width of channel ....cm
c. Approximate length of channel ....m

12. Channel lined or unlined ....

a. Length of underground channel ....
b. Length of lined channel ....
c. Length of unlined channel ....
d. Channel lined with ....Clay or Cement

FIGURE 23 (continued)

Falaj Inventory Sheet

13. Remarks: .(bifurcation of channel or any other modification)........
....
....
....
....

14. Falaj: Perennial or Seasonal....................................
....
....

15. Condition of falaj channel...
If not properly maintained, whether MAF plan to repair it or not.
YES/NO.

16. Wakil of the Falaj: Single owner / Group of people / Community
Name(s): ....
....

USAGE:-

17. Use: Irrigation or Domestic or Both

18. Approximate total area irrigated thru falaj water ....Hectares

19. Major crops grown by falaj water ....
....

20. No. of villages served ....
Approximate population served ....

21. If dried up recently:
Is there any plan to revive it in future? ....
If yes then what action has been taken so far? ....
....
....

22. LOCATION and details of the measuring point (with grid reference, and
width, length & depth of channel) ....
....
....
....
....
....

Grid ref. E..............:N..............

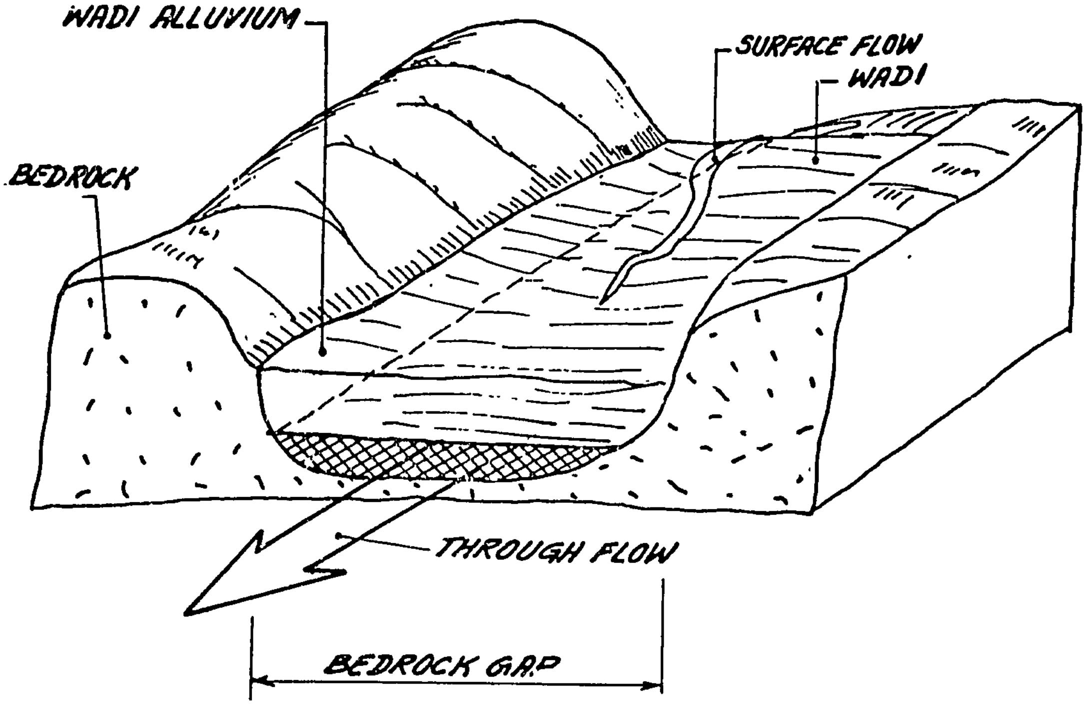
23. PREVIOUS WORK..
....
....
....

Attach copy of 1:100,000 map.(Sheet:...............No..................

Aerial photograph.(Run.........Shot no.............Year................

FIGURE 24

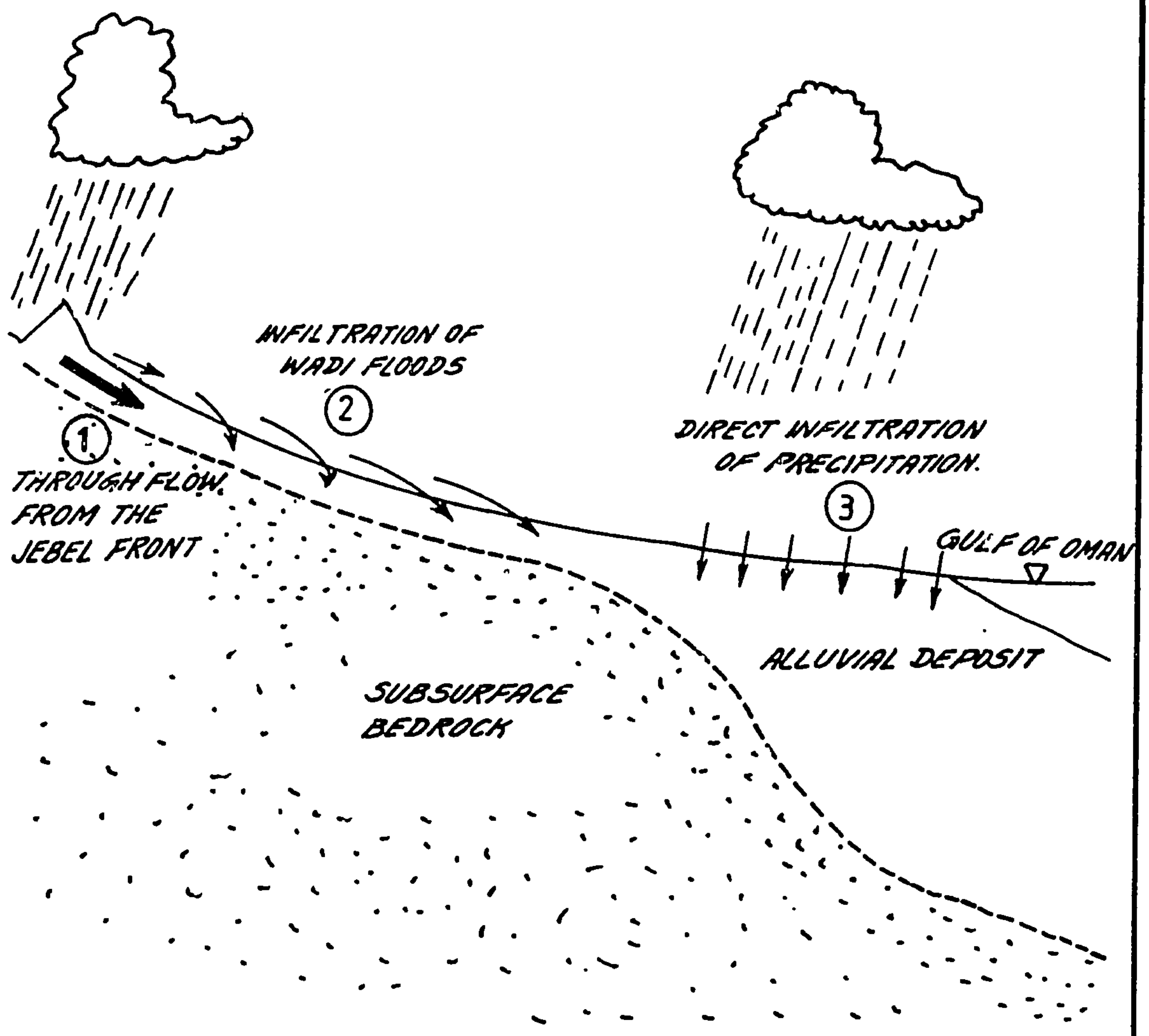
Schematic Cutaway Diagram of Wadi Throughflow



SCALE: NOT TO SCALE

FIGURE 25

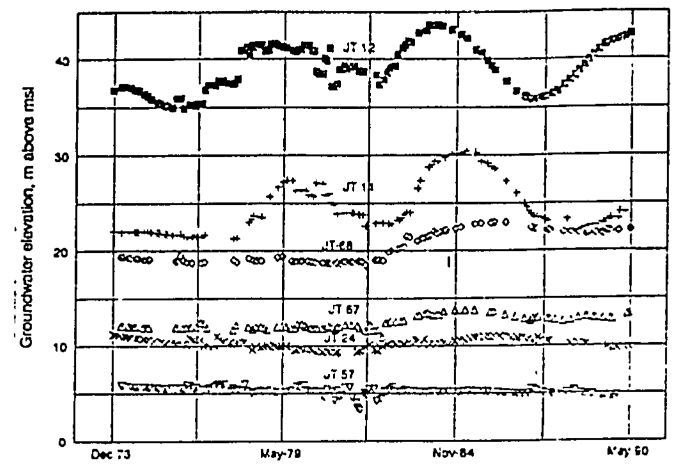
Schematic Diagram of Three Recharge Mechanisms in the Batinah



SCALE: NOT TO SCALE

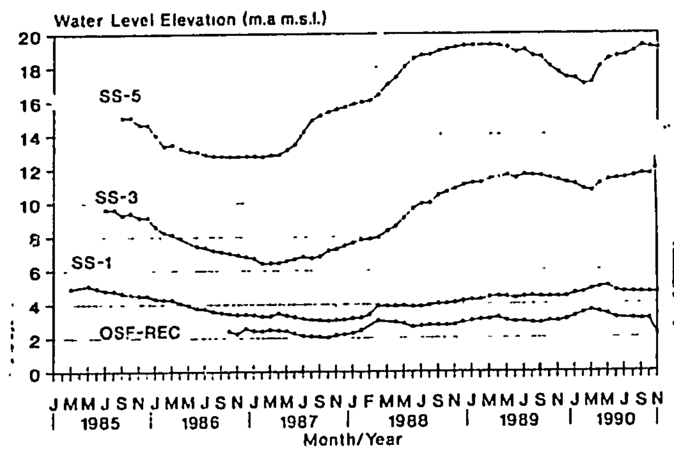
FIGURE 26

Time Lag in Well Hydrographs
Batinah and Interior

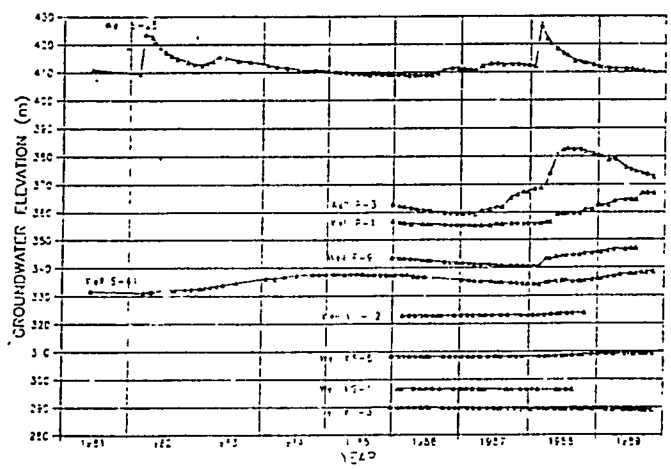


GROUNDWATER HYDROGRAPHS 1973-1990

BANI KHARUS
(AFTER RENDELL,91)



WADI HILTI
(AFTER LAVER,91a)



WADI SAFWAN
(AFTER KACZMAREK,91b)

SCALE : NOT TO SCALE

FIGURE 27

Throughflow Project Site in Wadi Halfayn

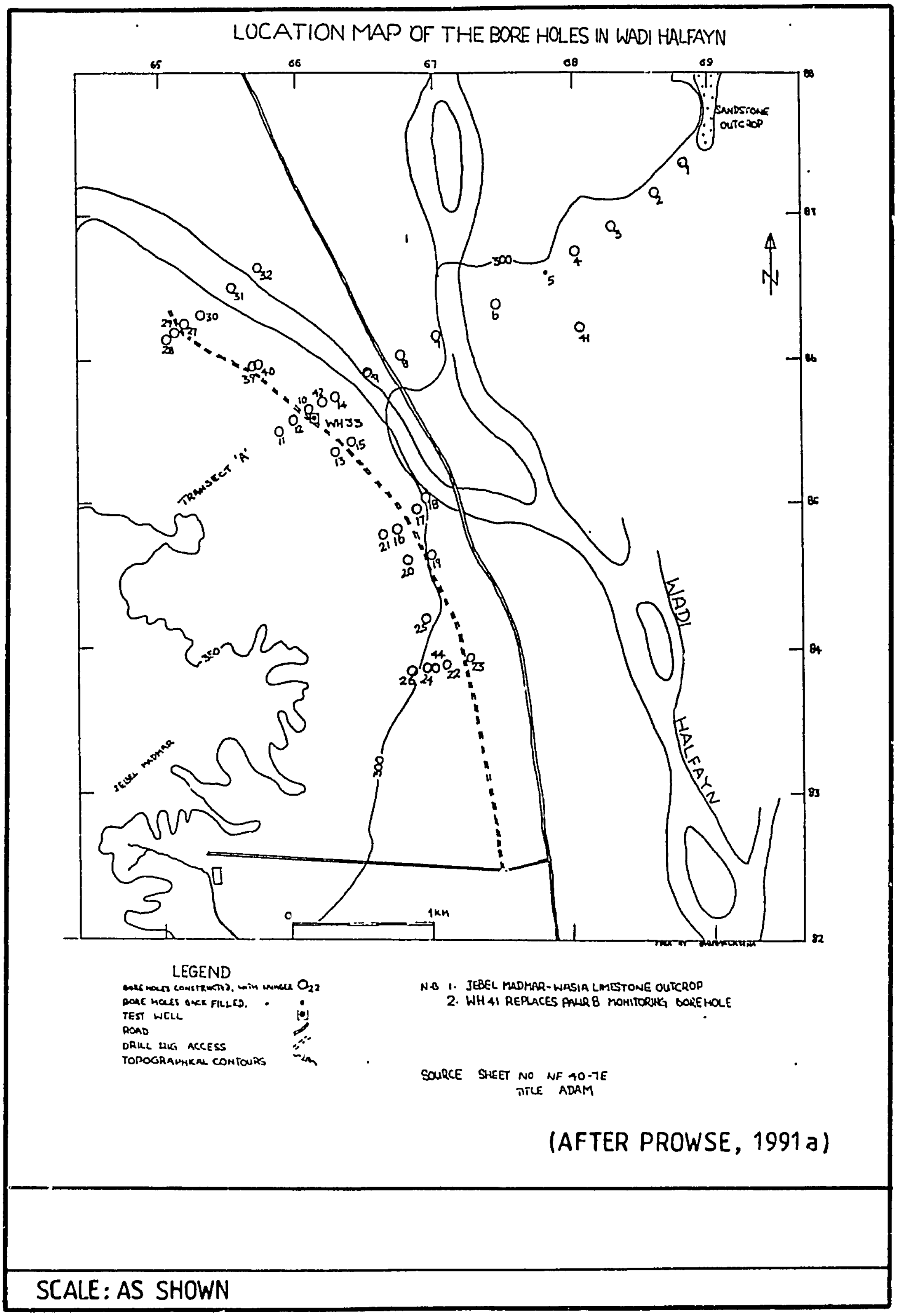
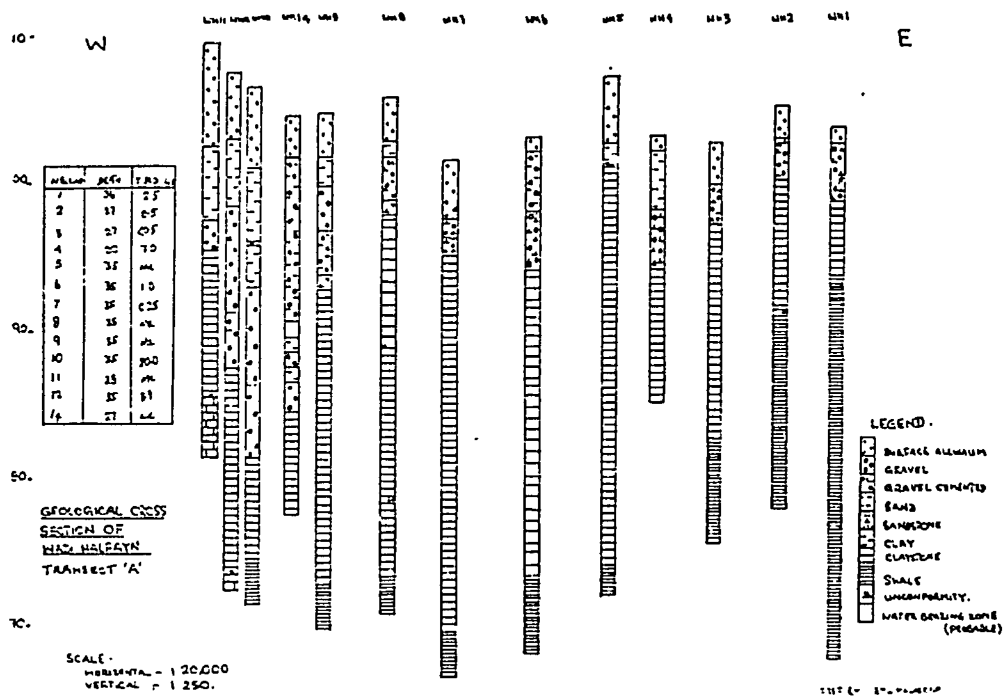


FIGURE 28

Geologic Cross Section from Wadi Halfayn



(AFTER PROWSE, 1991a)

SCALE: AS SHOWN

FIGURE 29

Paleo Channel in Wadi Halfayn

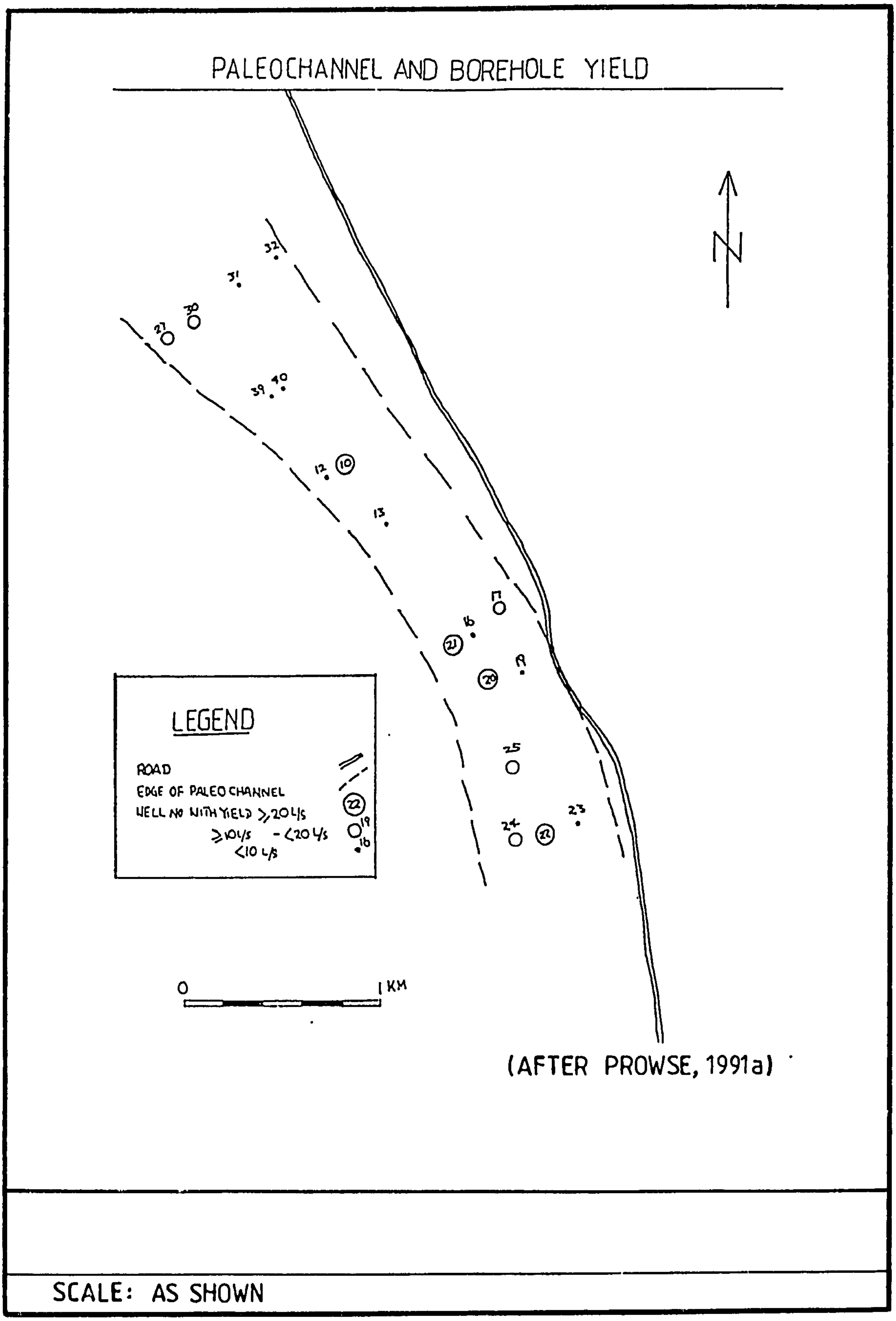


FIGURE 30

Throughflow Site Reconnaissance
Wadi Samail/Khawd

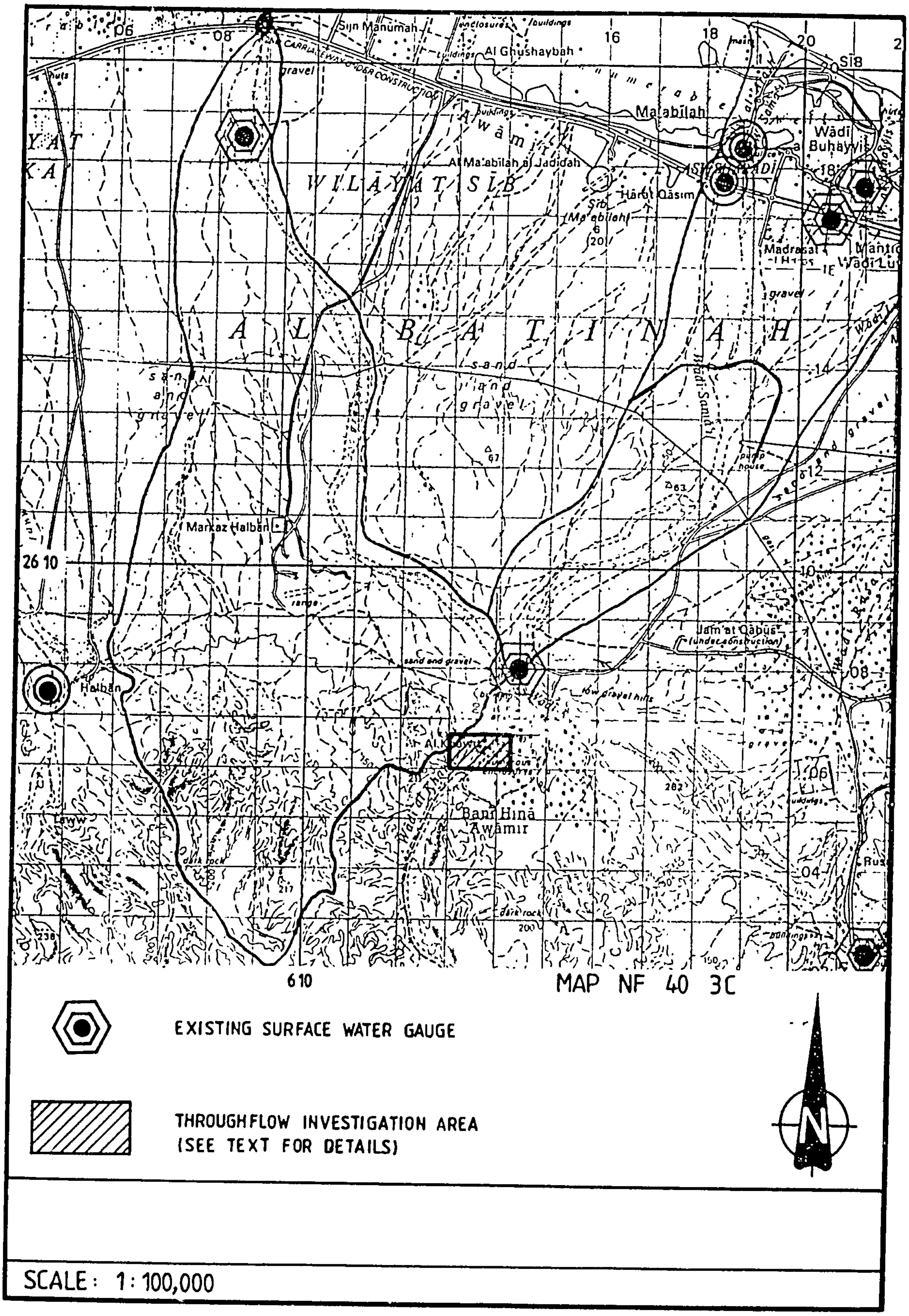


FIGURE 31

Throughflow Site Reconnaissance
Wadi Bani Ghafir

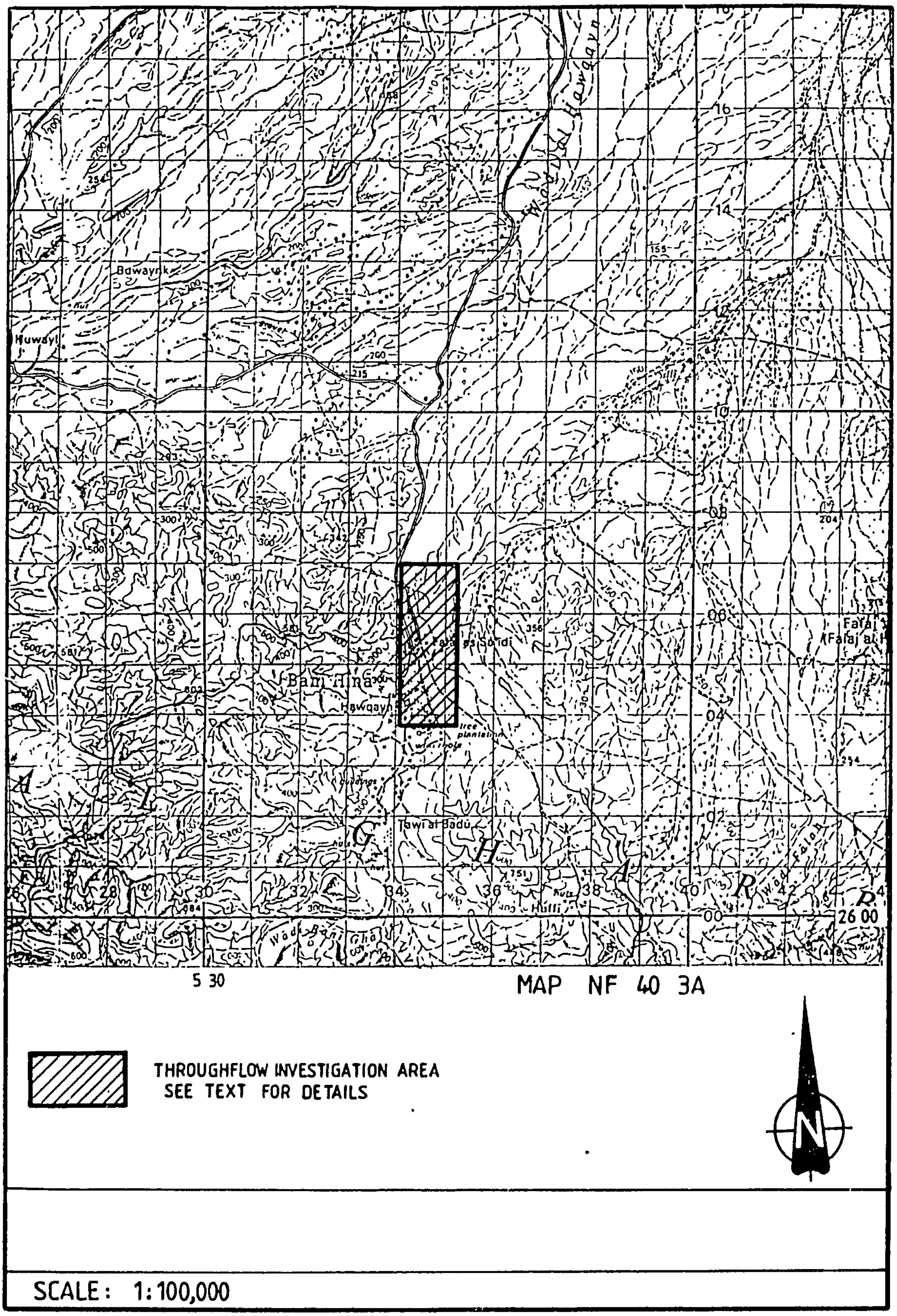


FIGURE 32

Throughflow Site Reconnaissance
Wadi Ahin

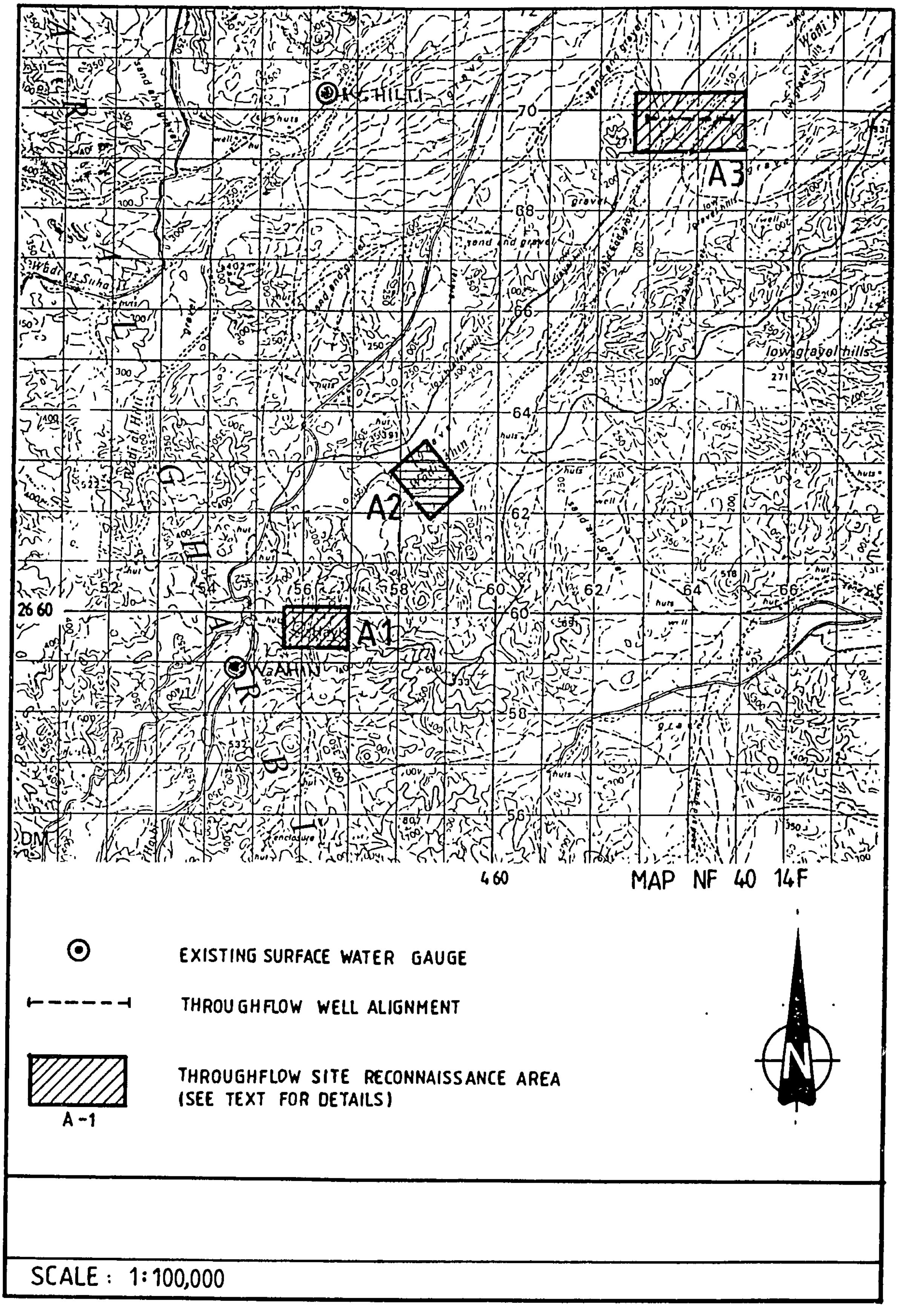


FIGURE 33

Throughflow Site Reconnaissance
Wadi Hilti and Wadi Salahi

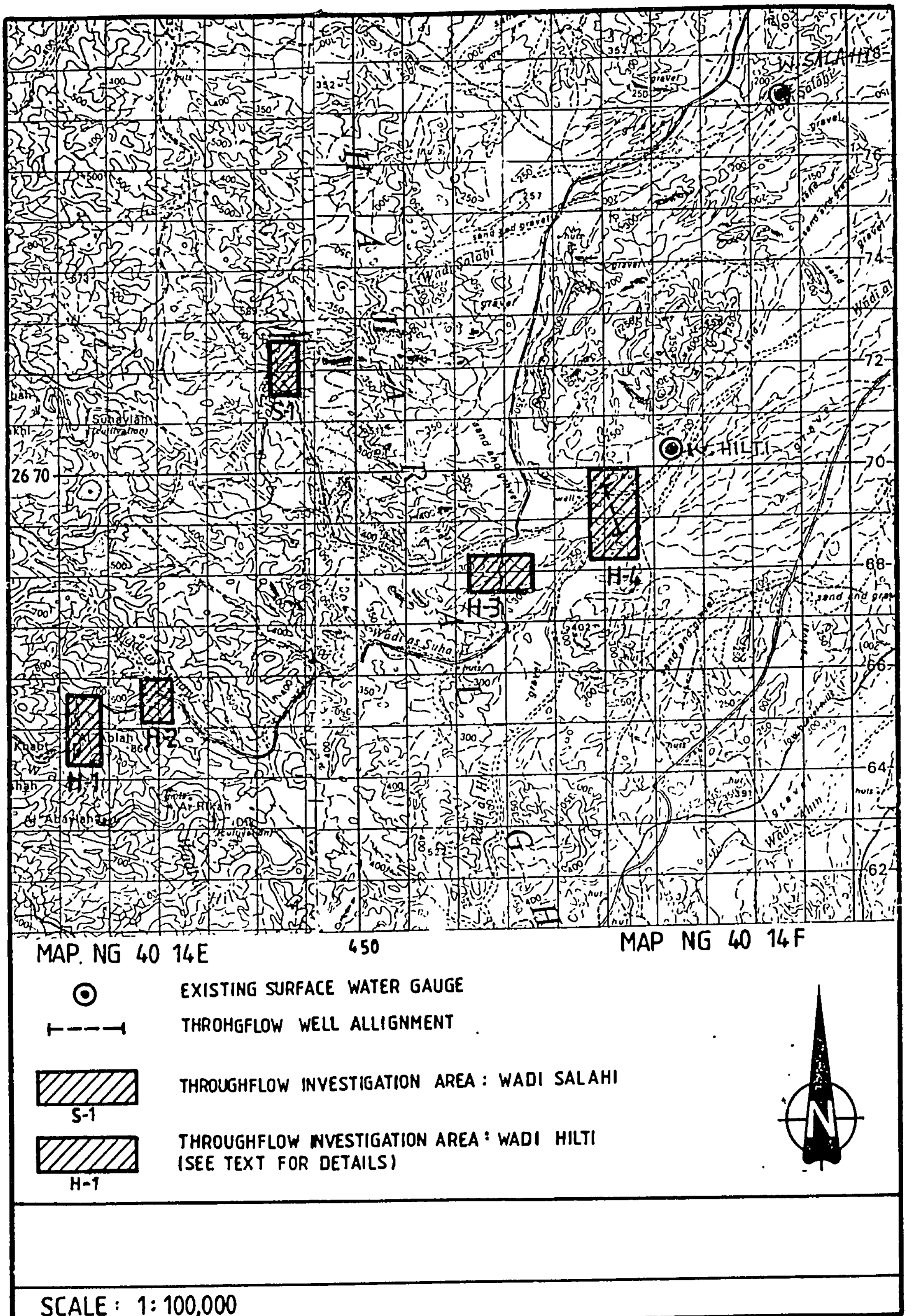


FIGURE 34

Throughflow Site Reconnaissance
Wadi Jizzi

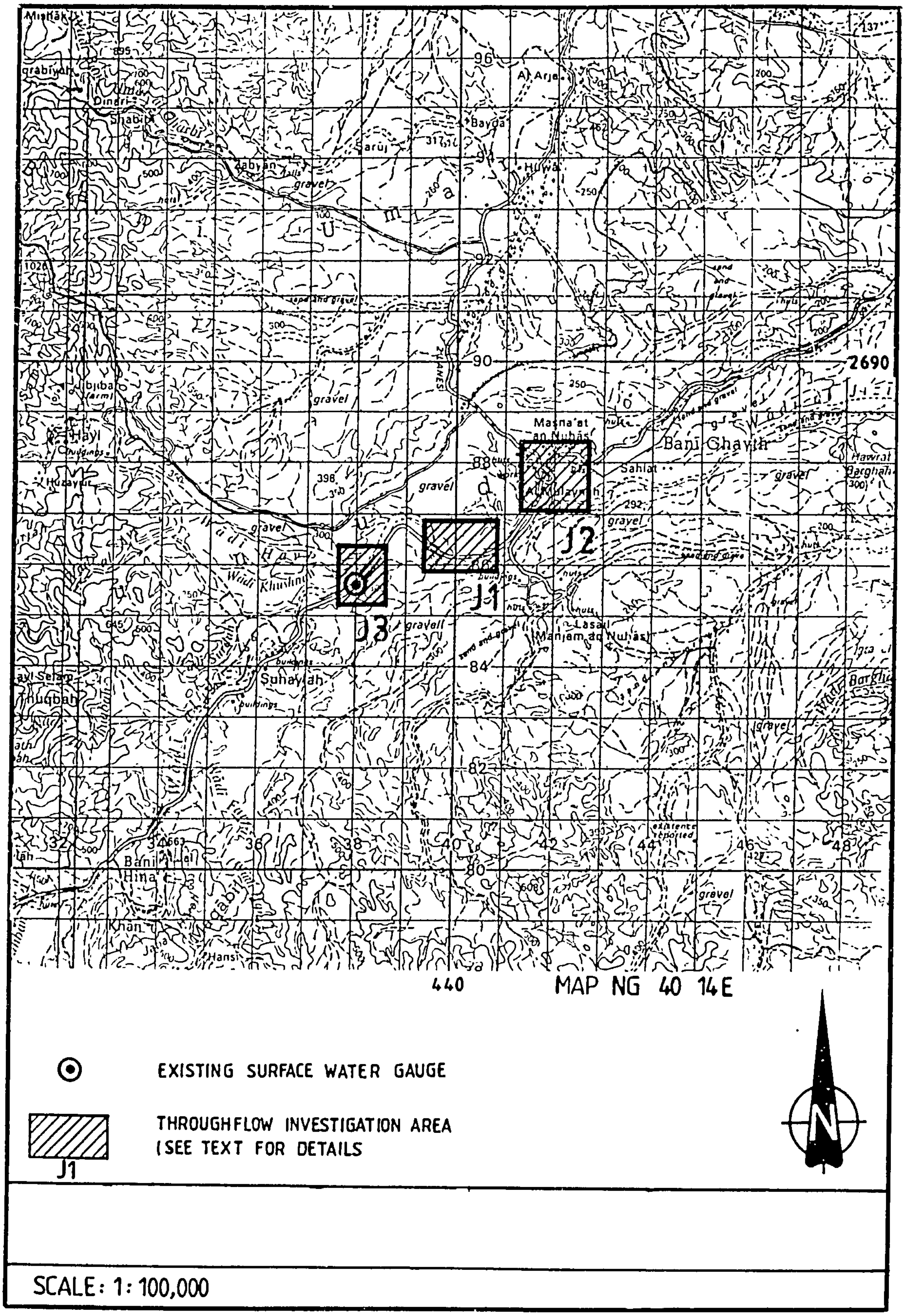
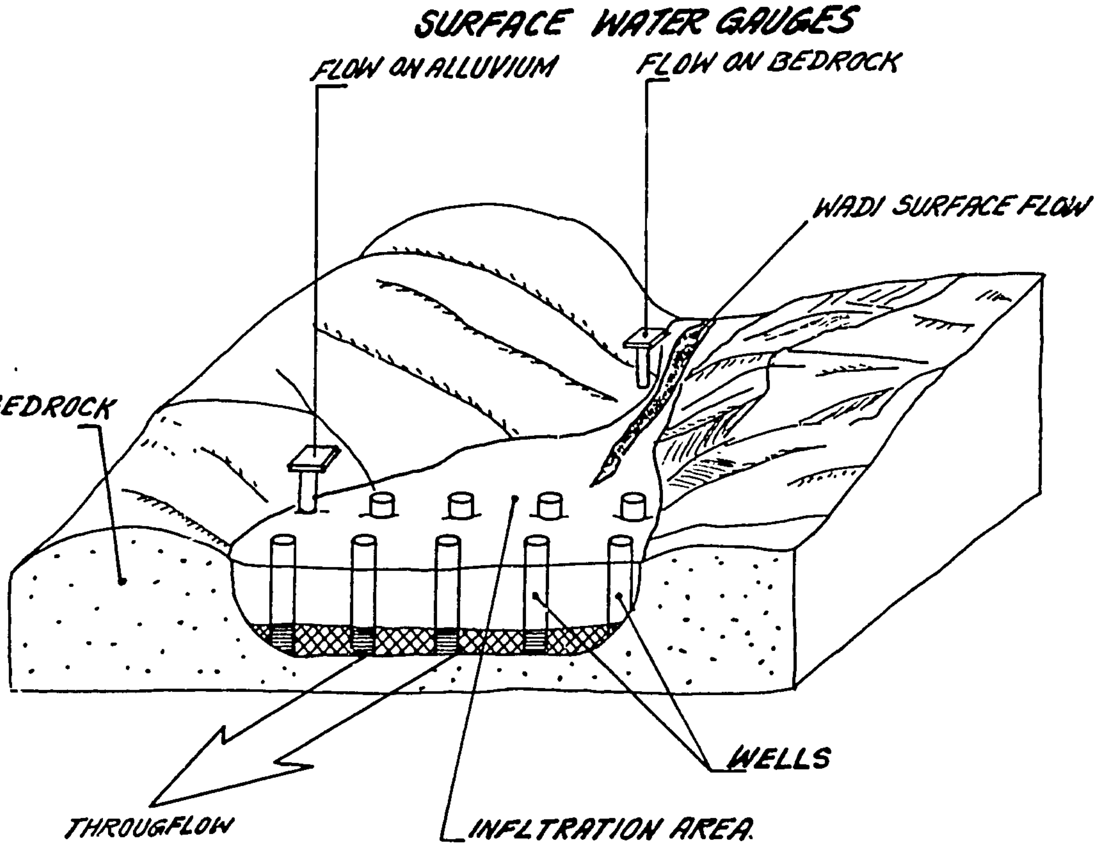
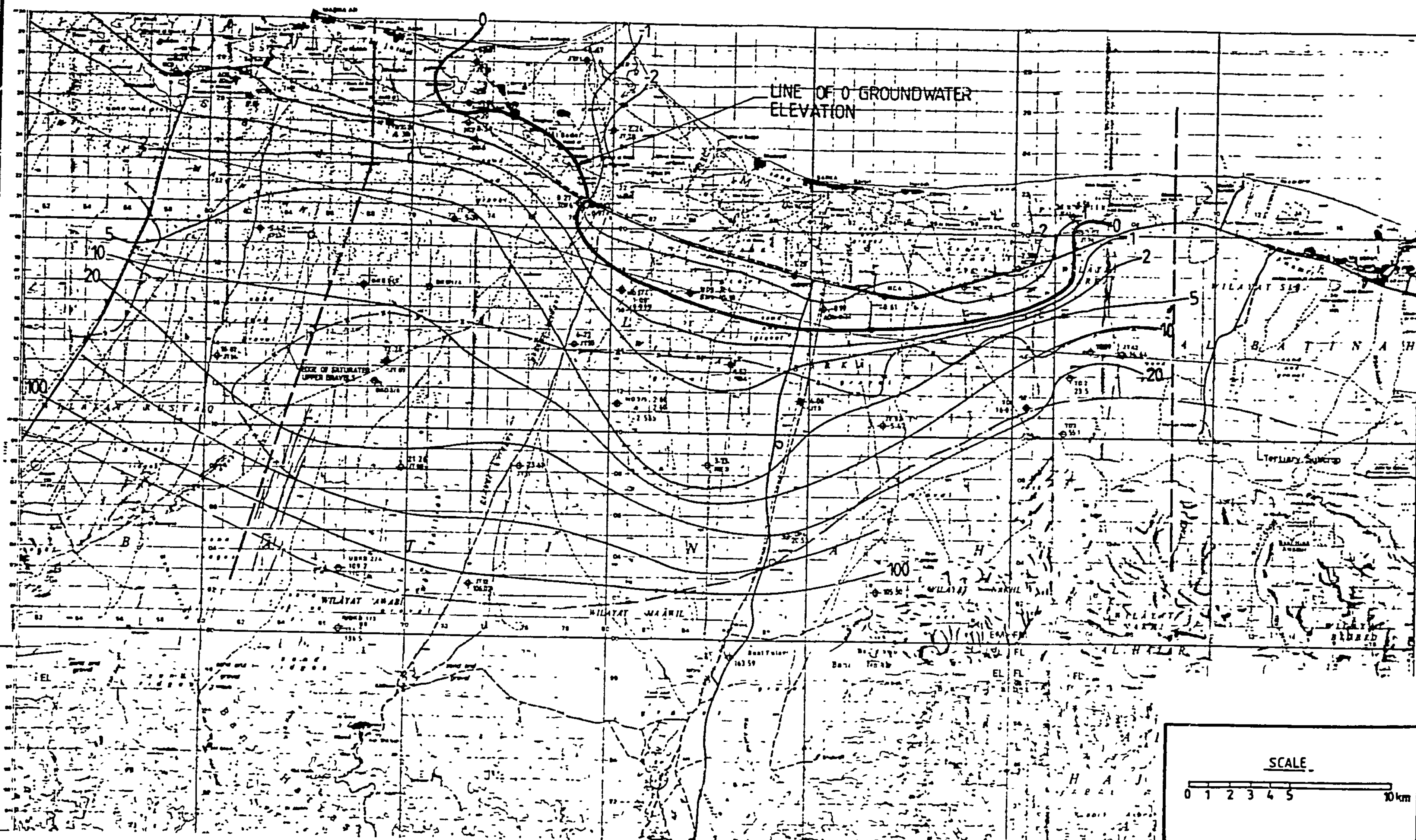


FIGURE 35

Schematic Diagram of Throughflow Project



SCALE : NOT TO SCALE



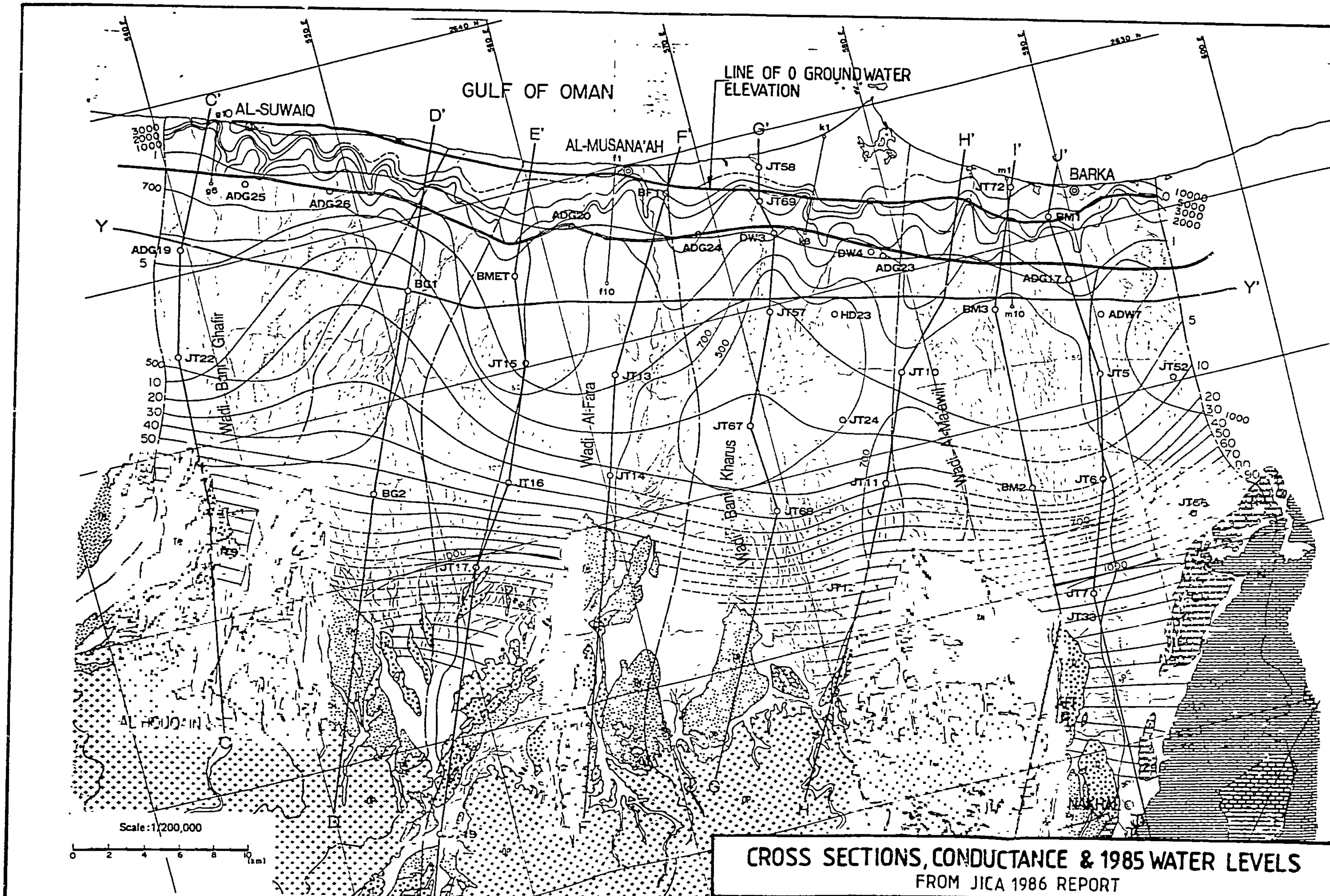
GROUND LEVELS IN METRES ABOVE SEA LEVEL
AFTER MACDONALD 1989

WATER LEVELS - JUNE 1987

FROM MMP 1989 REPORT FIG. 5-18

SCALE: AS SHOWN

FIGURE 36

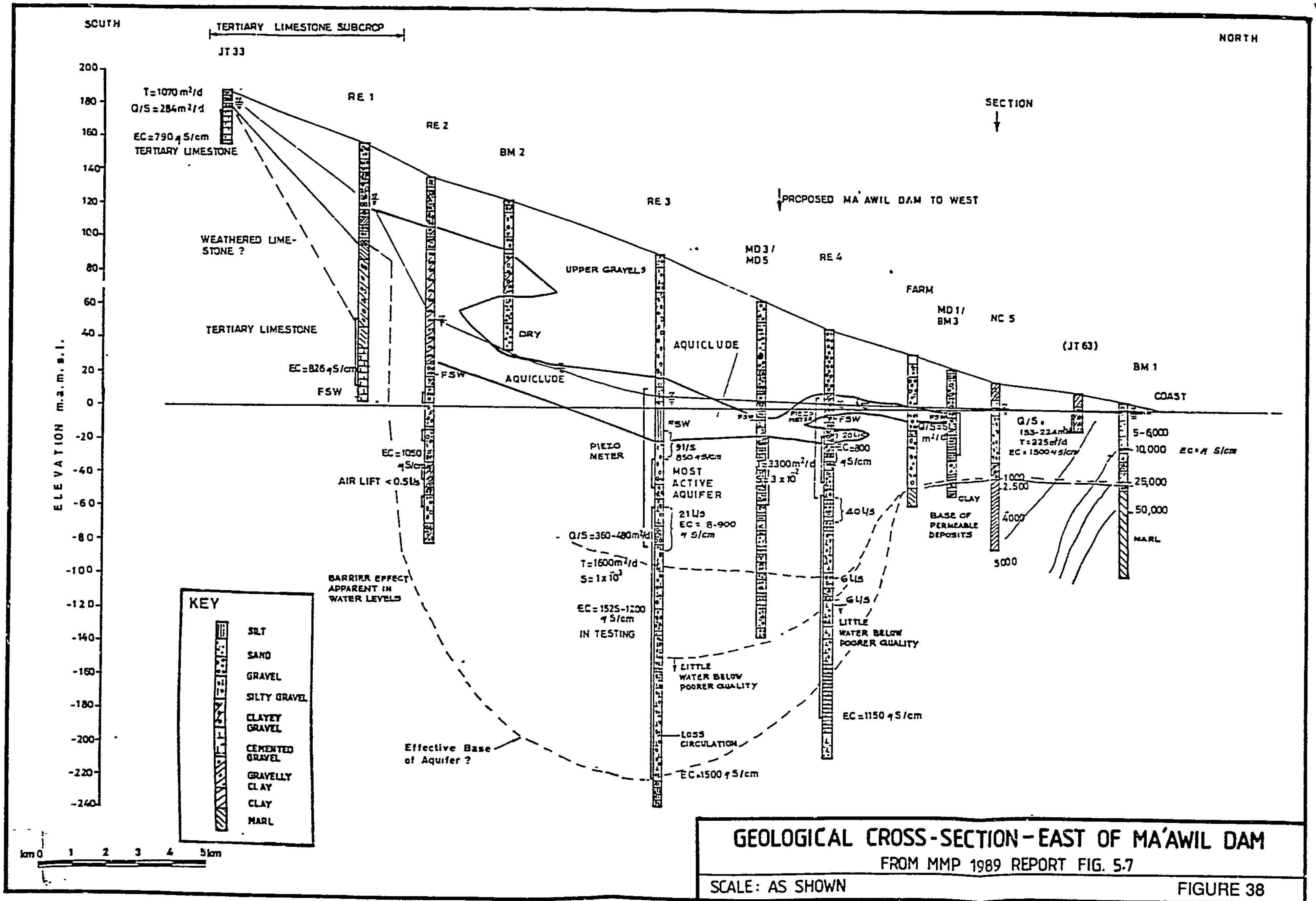


CROSS SECTIONS, CONDUCTANCE & 1985 WATER LEVELS

FROM JICA 1986 REPORT

SCALE: AS SHOWN

FIGURE 37



GEOLOGICAL CROSS-SECTION - EAST OF MA'AWIL DAM

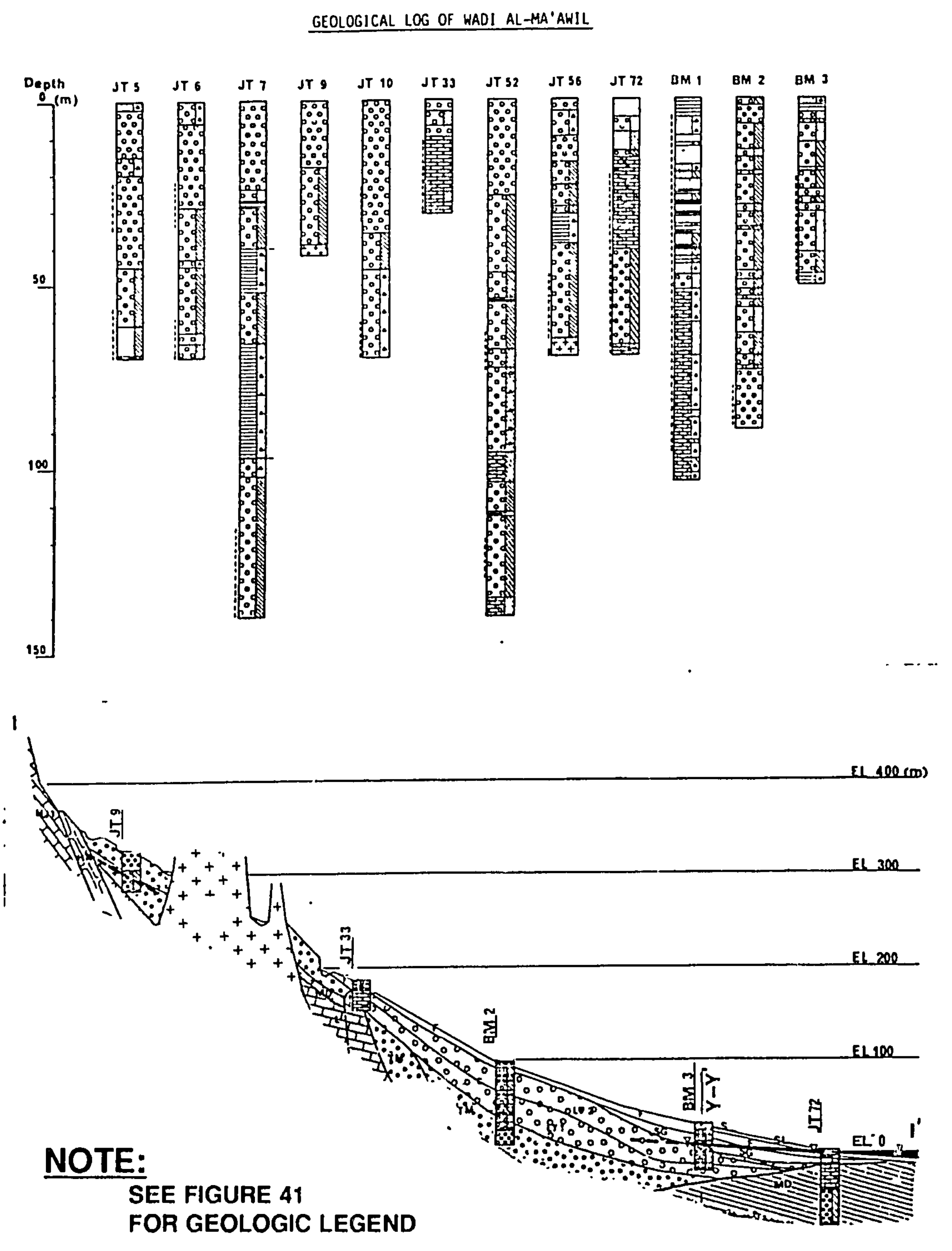
FROM MMP 1989 REPORT FIG. 5.7

SCALE: AS SHOWN

FIGURE 38

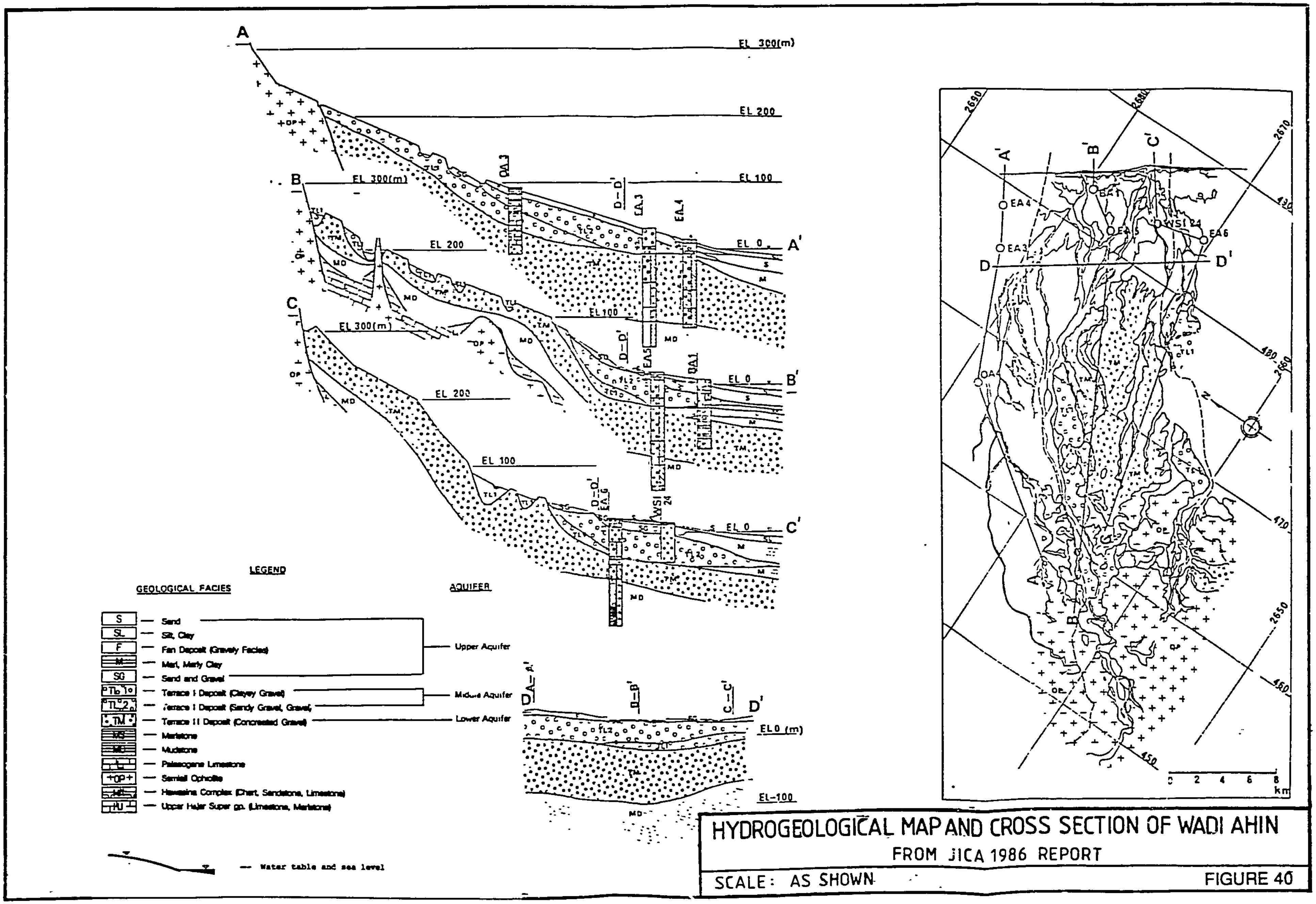
FIGURE 39

Geologic Cross Section and Well Logs for Wadi Ma'awil
from JICA 1986 Report



NOTE:
SEE FIGURE 41
FOR GEOLOGIC LEGEND

SCALE: AS SHOWN



HYDROGEOLOGICAL MAP AND CROSS SECTION OF WADI AHIN

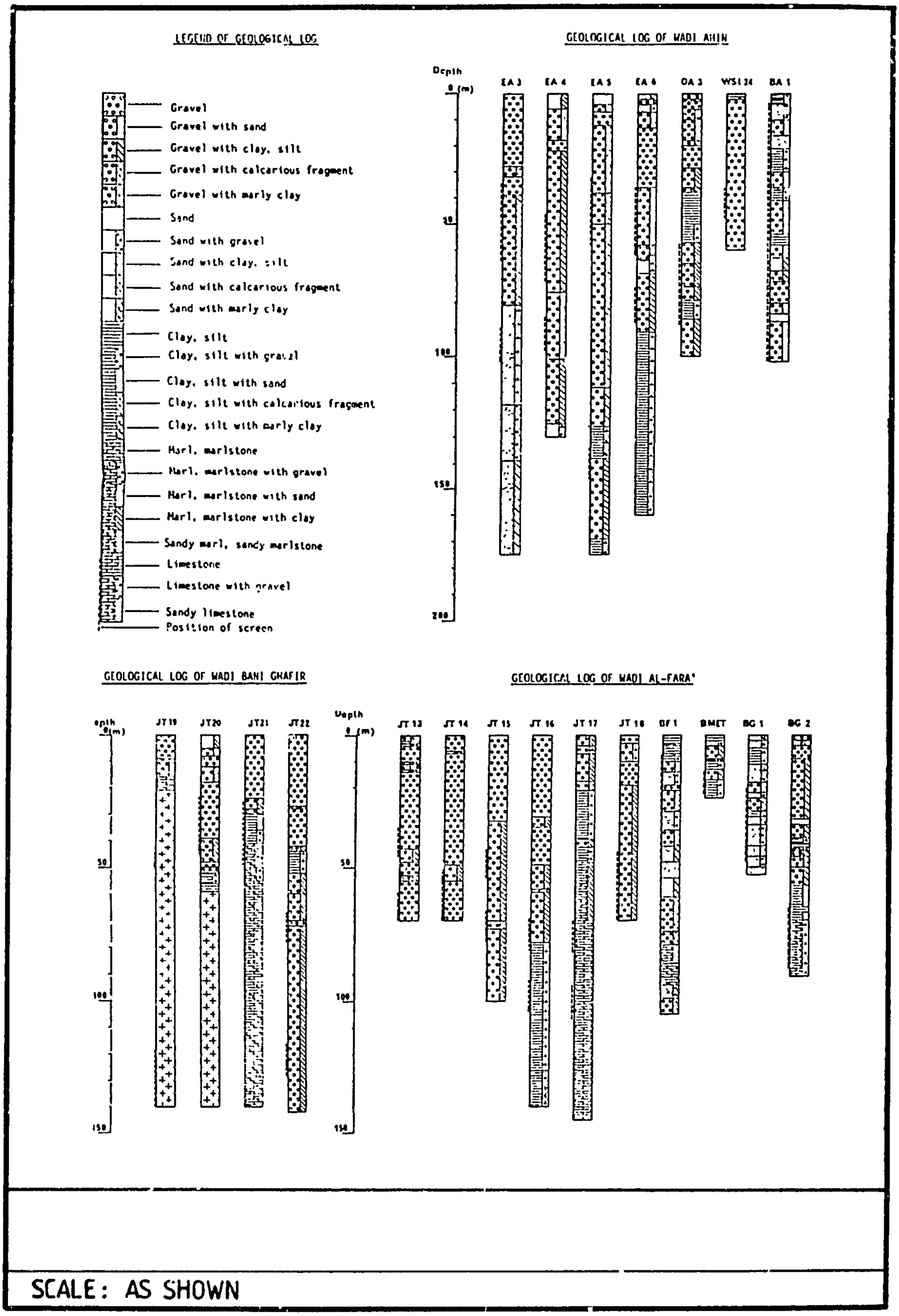
FROM JICA 1986 REPORT

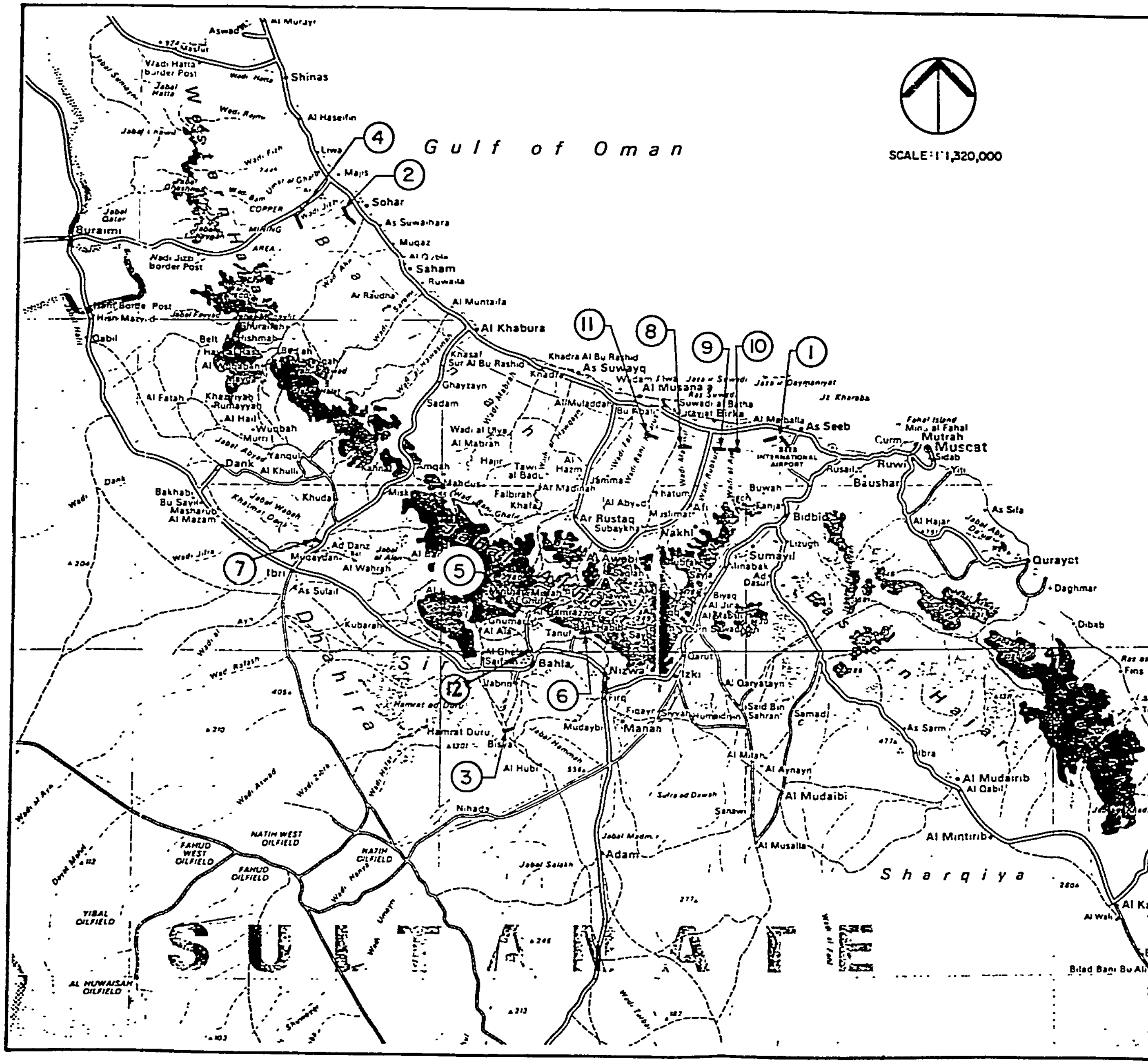
SCALE: AS SHOWN

FIGURE 40

FIGURE 41

Geological Legend and Well Logs
from JICA 1986 Report





MAP SHOWING LOCATION OF AQUIFER RECHARGE DAMS CONSTRUCTED BY MINISTRY OF AGRICULTURE AND FISHERIES

FIGURE 42

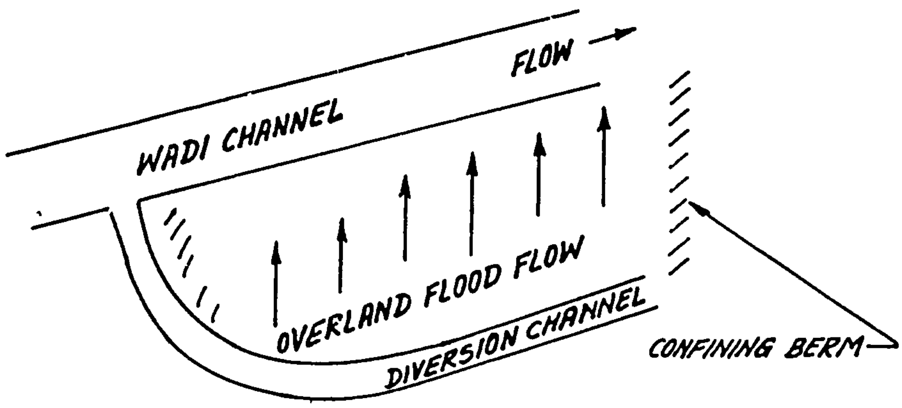
	Project Name	Date
1.	Al Khawd	1984-85
2.	Hilti-Salahi	1984-85
3.	Quryat	1985-86
4.	Jizzi	1988-89
5.	Ghul	1988-89
6.	Tanuf	1988-89
7.	Ibri	1990-91
8.	Ma'awil	1990-91
9.	Rubkhah	*
10.	Taww	*
11.	Bani Kharus	*
12.	Bahla	1990-91
13.	Sahalnawt (Salalah)	**

* Tenders were sought for these three dams in late 1989 but no construction has been initiated.

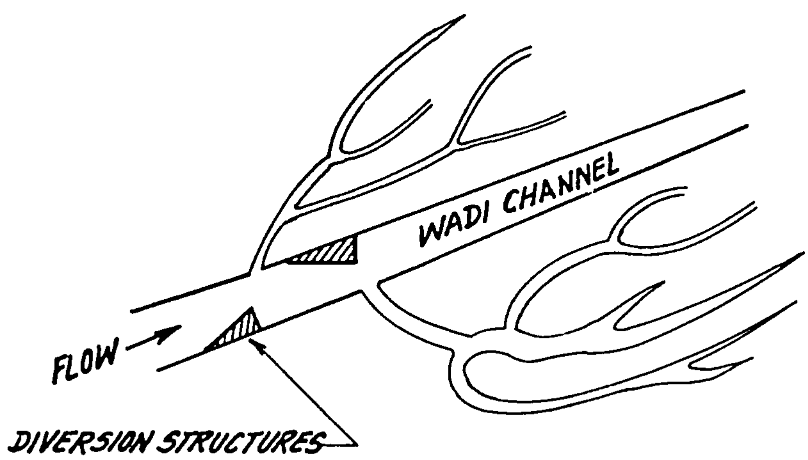
** Construction of this dam in Salalah is in its early stages and may be completed early in 1992, or before.

FIGURE 43

Examples of Recharge Methods with Direct Surface Techniques



FLOODING RECHAGE METHOD



ONE FORM OF DITCH AND FURROW METHOD

NOTE: FOLLOWING CONTOURS IN LESS FLAT LAND WOULD FORM A DIFFERENT PATTERN.

SCALE: NOT TO SCALE

FIGURE 44

Recharge by a Series of Recharge Basins

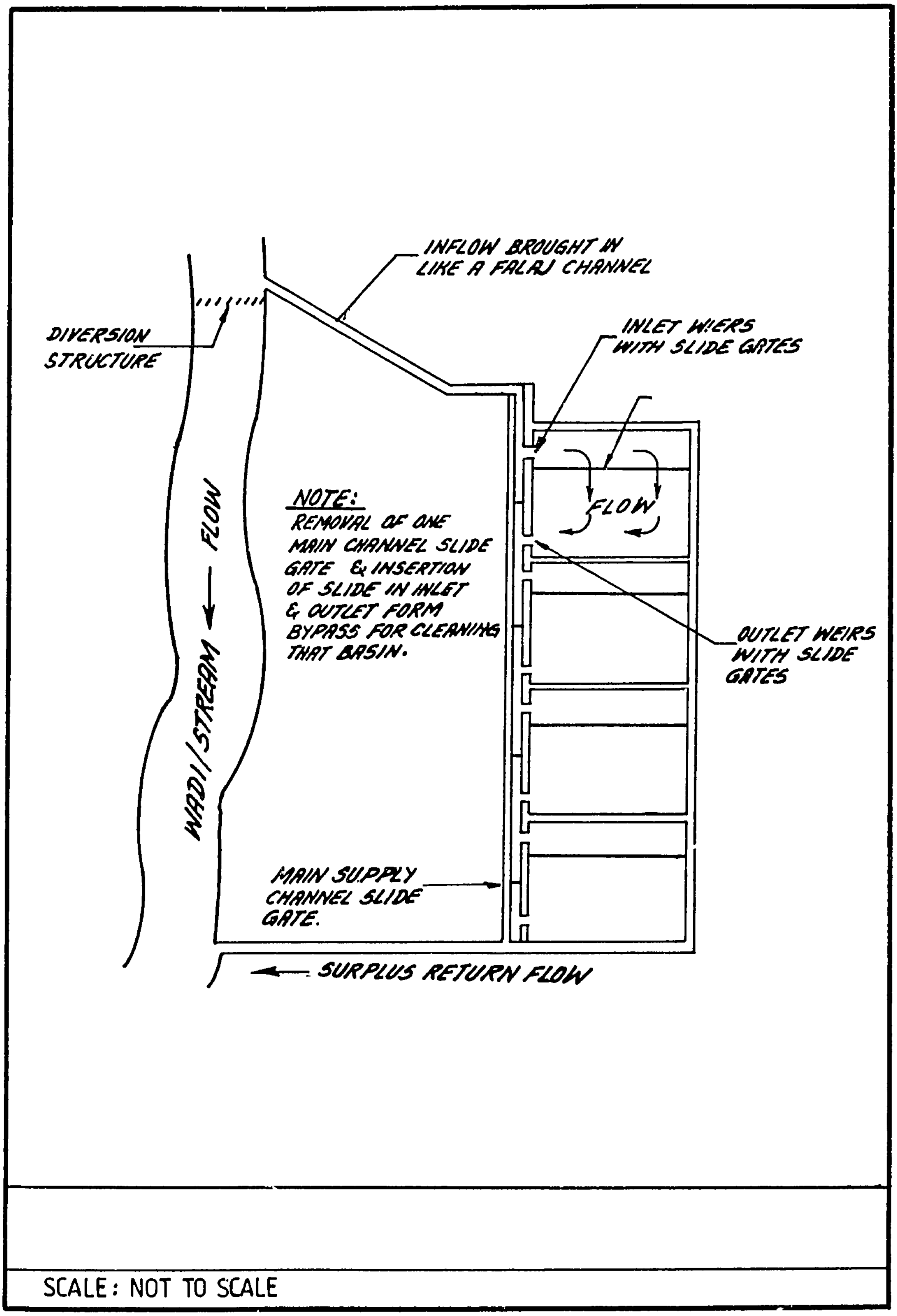


FIGURE 45

Recharge by Stream Channel Modification

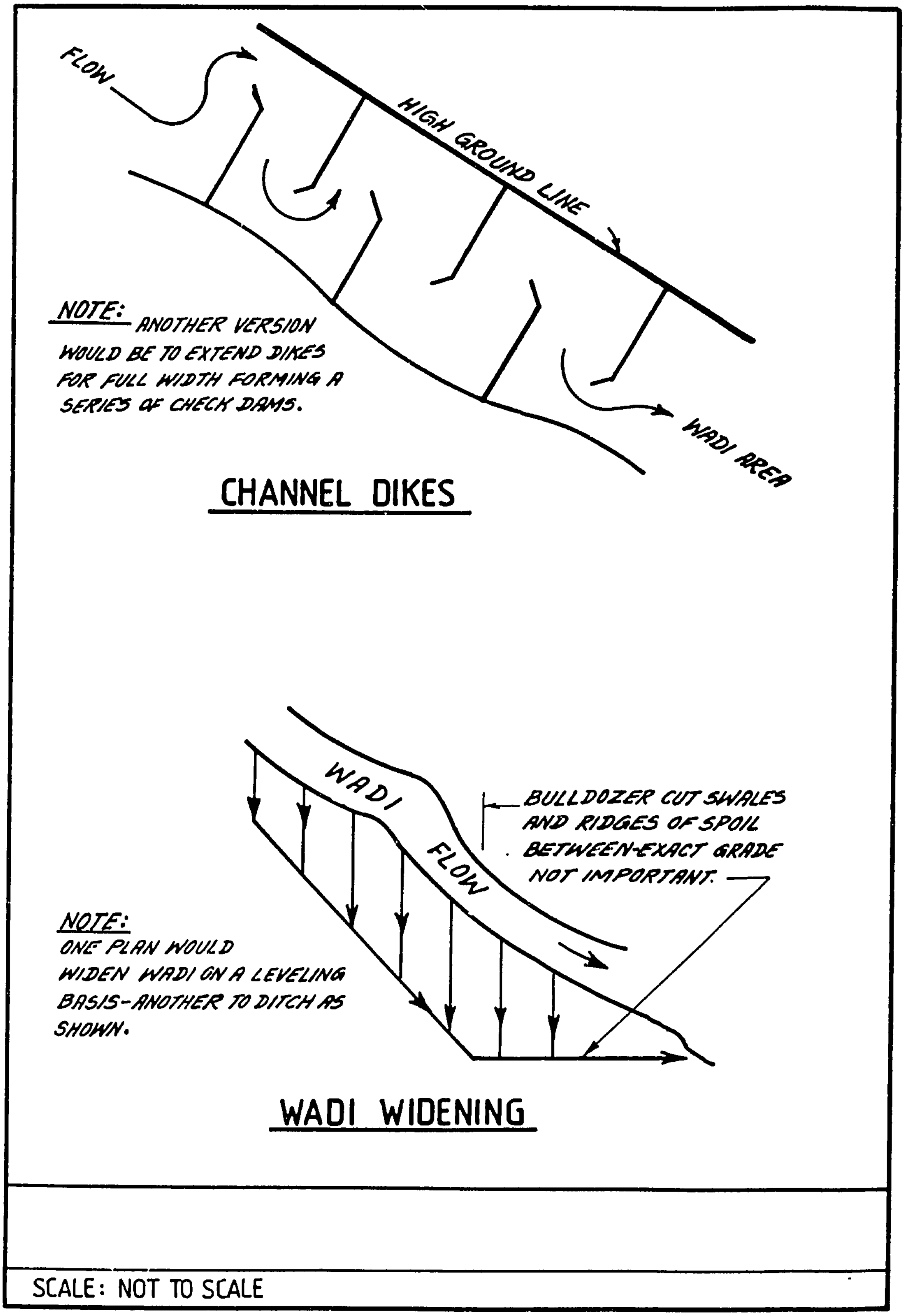


FIGURE 46

Dams for Subsurface Impoundments

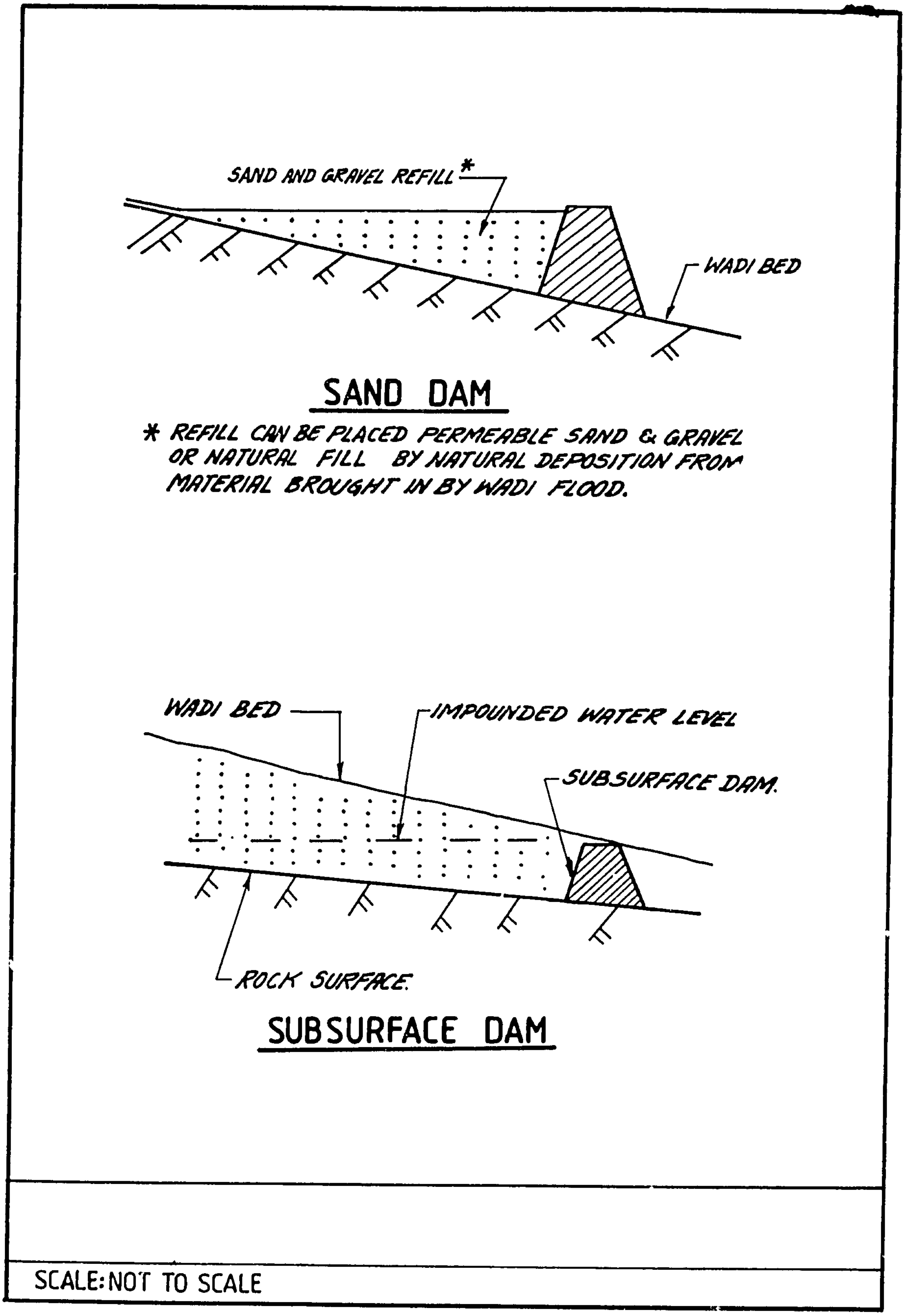


FIGURE 47

Leaky Sand Dams of Rockfill/Gabion Toe or All Gabion

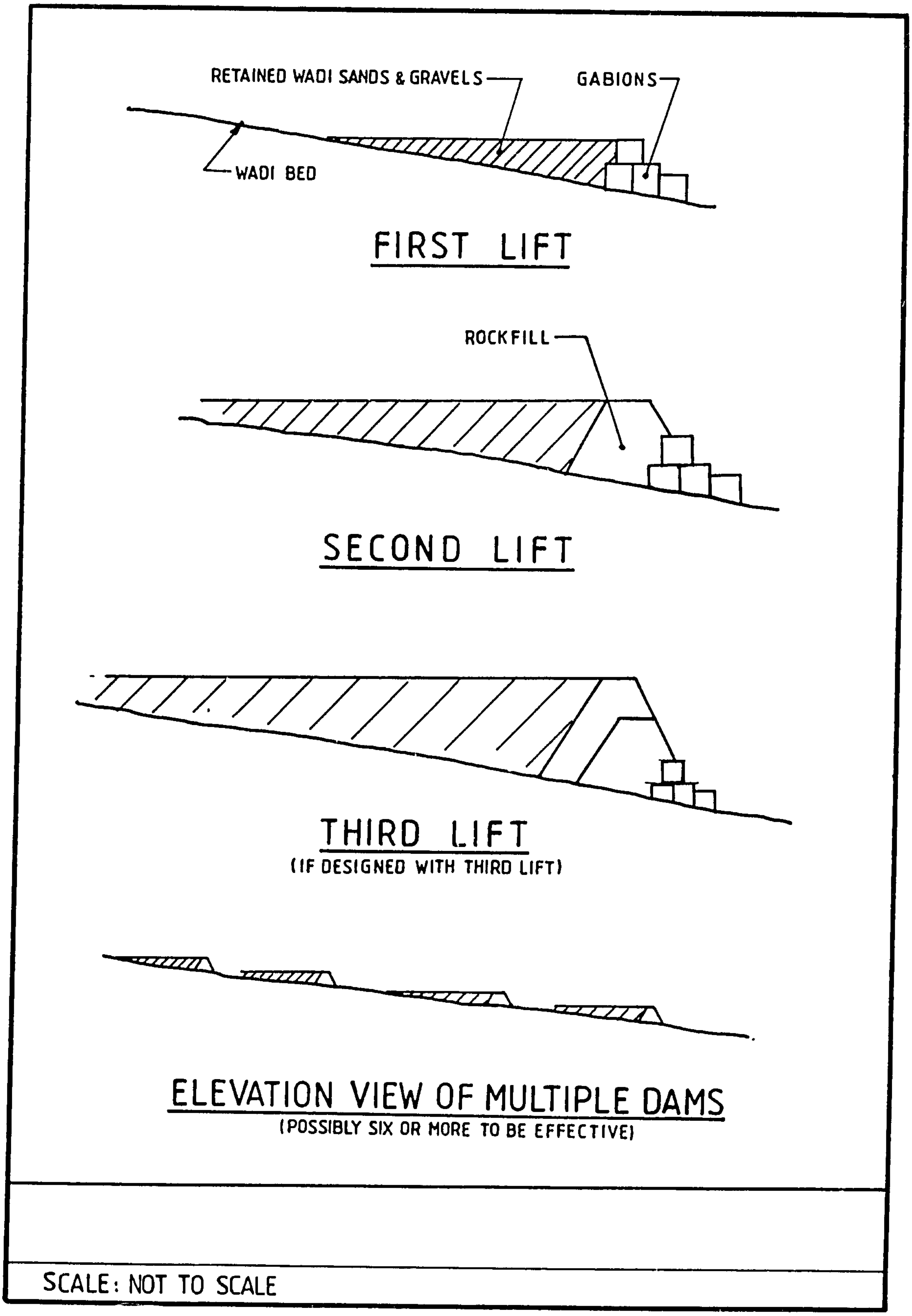
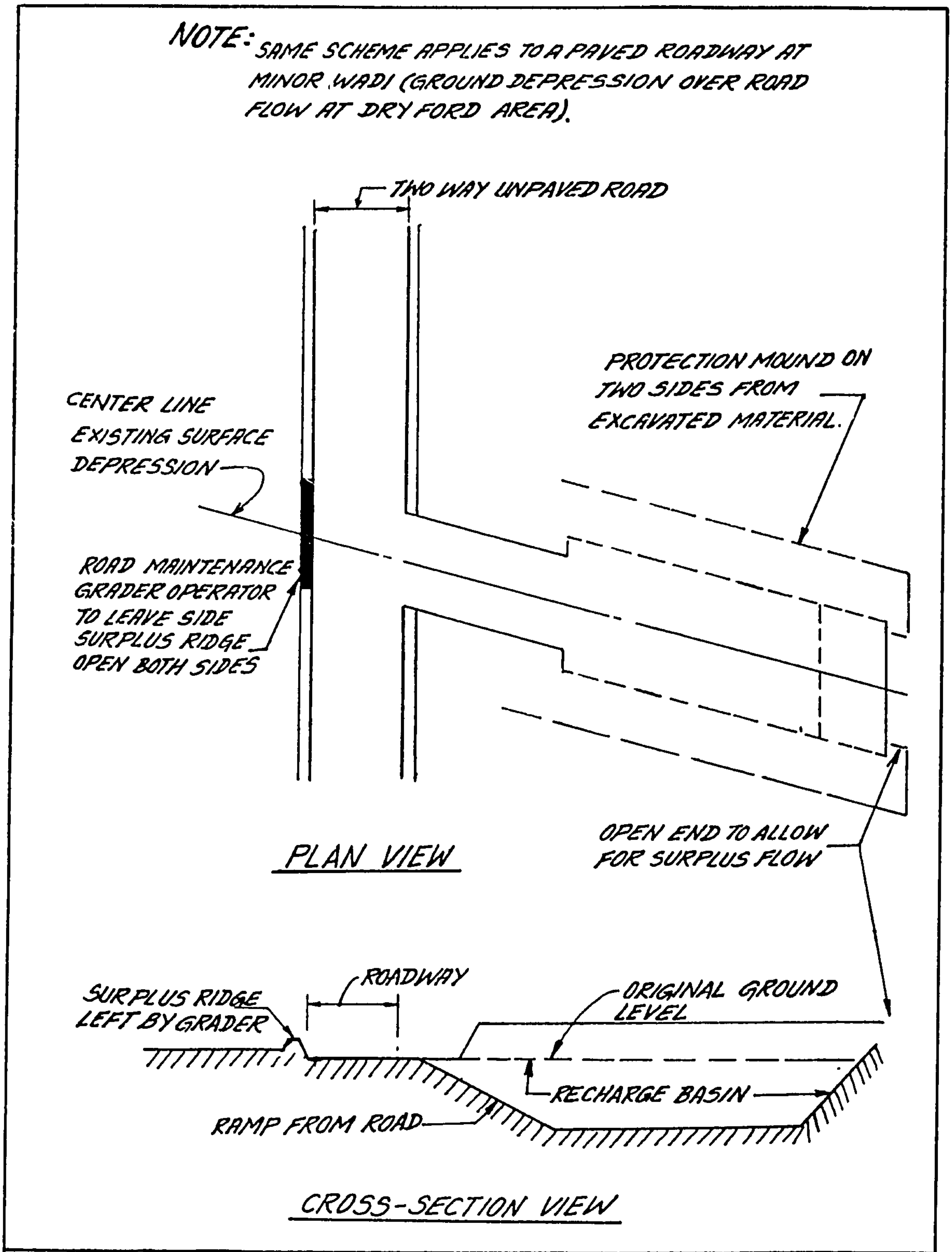


FIGURE 48

Roadway Dry Well Alternatives
Scheme "A"



SCALE: NOT TO SCALE

FIGURE 49

Roadway Dry Well Alternatives
Scheme "B"

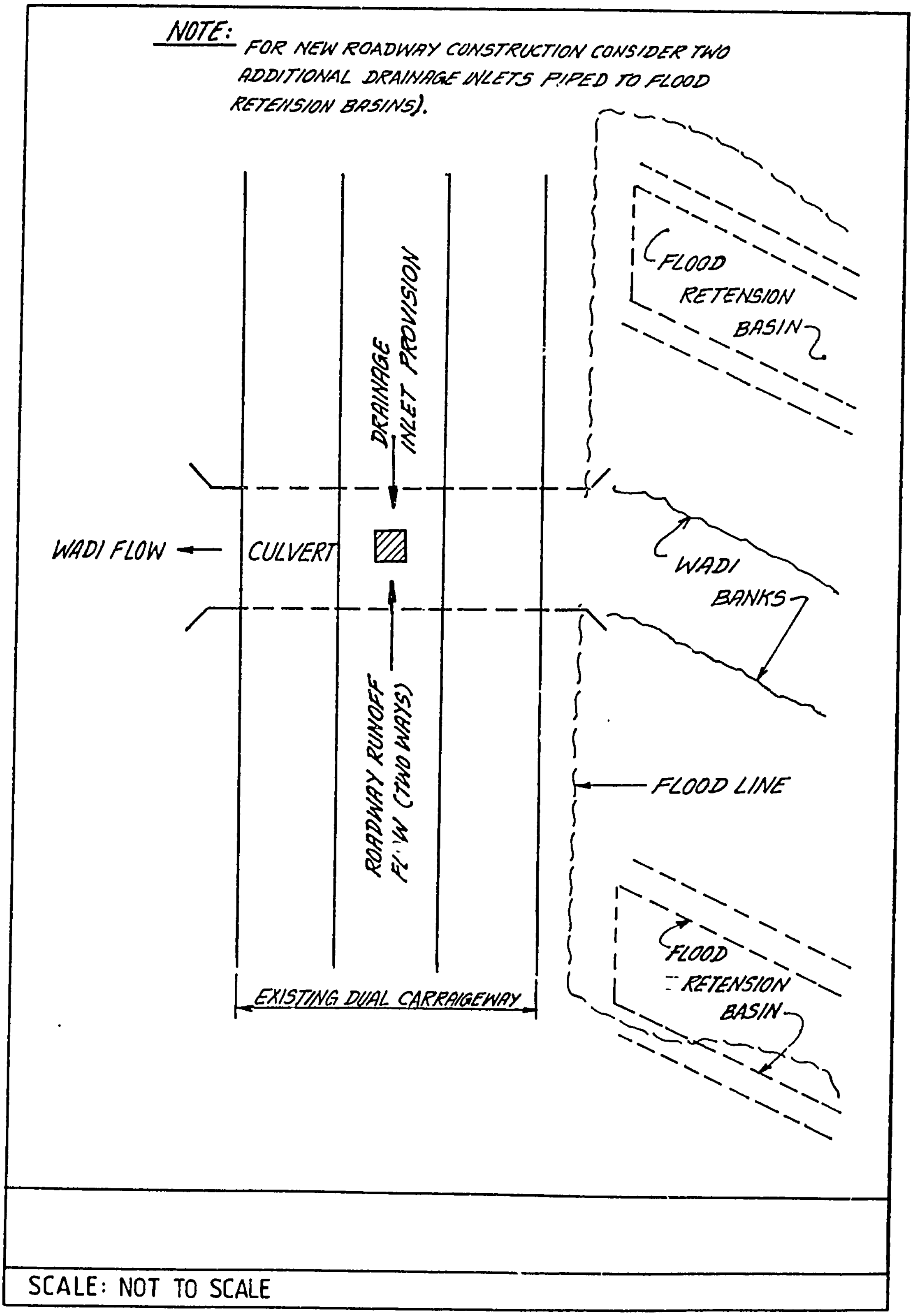


FIGURE 50

Feasibility Elements
from Hydroconsult 1985 Report