SULTANATE OF OMAN
DIRECTORATE GENERAL OF FINANCE

WATER RESOURCES SURVEY OF NORTHERN OMAN

FINAL REPORT

VOLUME I

MAIN REPORT

JUNE 1976

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In association with
THE INSTITUTE OF HYDROLOGY
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The Under Secretary For Finance,
Directorate General Of Finance,
P.O. Box 506,
Muscat,
Sultanate of Oman,

June 1976

Dear Sir,

WATER RESOURCES SURVEY OF NORTHERN OMAN

In accordance with our Agreement dated 10th May 1974 for Consulting Engineering Services for a Water Resources Survey of Northern Oman, we have pleasure in submitting our Final Report, which has been prepared in association with the Institute of Hydrology, Wallingford, England.

The survey was undertaken under the auspices of the Memorandum Of Understanding Between The Governments Of Oman And The United Kingdom Concerning British Technical Assistance dated 24th December 1972. The study period commenced in February 1973 and site activities in Oman terminated in November 1975.

An integral component of the water resources survey was the study of soils and agriculture in the survey area. Our Final Report on Phase 1 of these studies, accompanied by an interim assessment of the water resources of the survey area, was submitted in draft to the Oman Government in April 1975.

This report, the Final Report of the water resources studies, is presented in six volumes. Volume 1 contains the Main Report in which our conclusions and recommendations are presented in Chapter 8. The remaining volumes comprise:—

Volume II — Appendix A, Rainfall And Meteorology

Volume III — Appendix B, Surface Water Flow

Volume IV — Appendix C, Geology And Hydrogeology

Volume V — Appendix D, Survey Of Water Use In Villages

Volume VI — Appendix E, Water Chemistry And Isotope Studies

Additionally, in December 1975 we presented an Instrument Networks Manual the Ministry of Agriculture, Fisheries, Petroleum and Minerals on the conclusion of our site activities in Oman. The Manual described the instrument networks established during t' survey, their operation, principal problems encountered and methods of obtaining and presenting the data. Details of Omani observers trained during the survey were also given.

Those aspects of the Final Report which are of principal importance are summarized in the pages immediately preceding the main text. An Arabic translation of the summary is presented as a separate document.

We should be pleased to discuss with you and answer any questions arising from your study of this Report.

Yours faithfully,

(SIGNED) G. H. COATES

For: SIR ALEXANDER GIBB AND PARTNERS,
in association with
THE INSTITUTE OF HYDROLOGY.

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DIRECTORATE GENERAL OF FINANCE

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FINAL REPORT
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TABLE OF CONTENTS

PART 2 — THE RESPONSE OF THE AQUIFER SYSTEMS TO A PERIOD WITHOUT RAINFALL

PART 3 — RAINFALL, WADI FLOWS AND THEIR EFFECT OF THE AQUIFERS

LIST OF TABLES

LIST OF FIGURES

SUMMARY

The Study Area

The study area, shown in Figure 1, comprised essentially those wadi basins draining the Jabal Akhdar and Jabal Nakhl in northern Oman and extended over an area of some 14 500 km^2. The general topography and drainage is illustrated in Figure 2. The Jabal Akhdar/ Jabal Nakhl mountain backbone is the major watershed of the study area and rises over 2 000 m from 400 m in the north and 650 m in the south. Deeply incised wadis in the mountain flanks generally open out into broad fans on the alluvial plains.

The existence of the high mountain range near the coast of Oman greatly influences the climate of the region but lack of historical coverage makes a detailed appreciation of climatic influences difficult. However, the year can be divided into two distinct seasons, the winter months of November to April with a predominant air flow from the north-west, and the summer months of June to September with a monsoon air flow from the south-west. Moderate but unpredictable rainfall permits settled agriculture in and around the jabal where reliable supplies of water are obtained from aflaj, hand-dug wells and, to a lesser extent, limestone springs.

Most villages and towns in the study area are integrated with areas of cultivation, shown in Figure 3, which have been established near reliable sources of water. They are thus a good indicator of major water sources and drainage lines. On the northern coast wells are used extensively, potable water being obtained from the sweeter wells; inland the principal source is the falaj and irrigated areas are related to reliable aflaj flows, with extra planting of annual crops during periods of water surplus. Recently pump sets have been installed, particularly on wells in the Batinah, and groundwater abstractions are increasing in many areas.

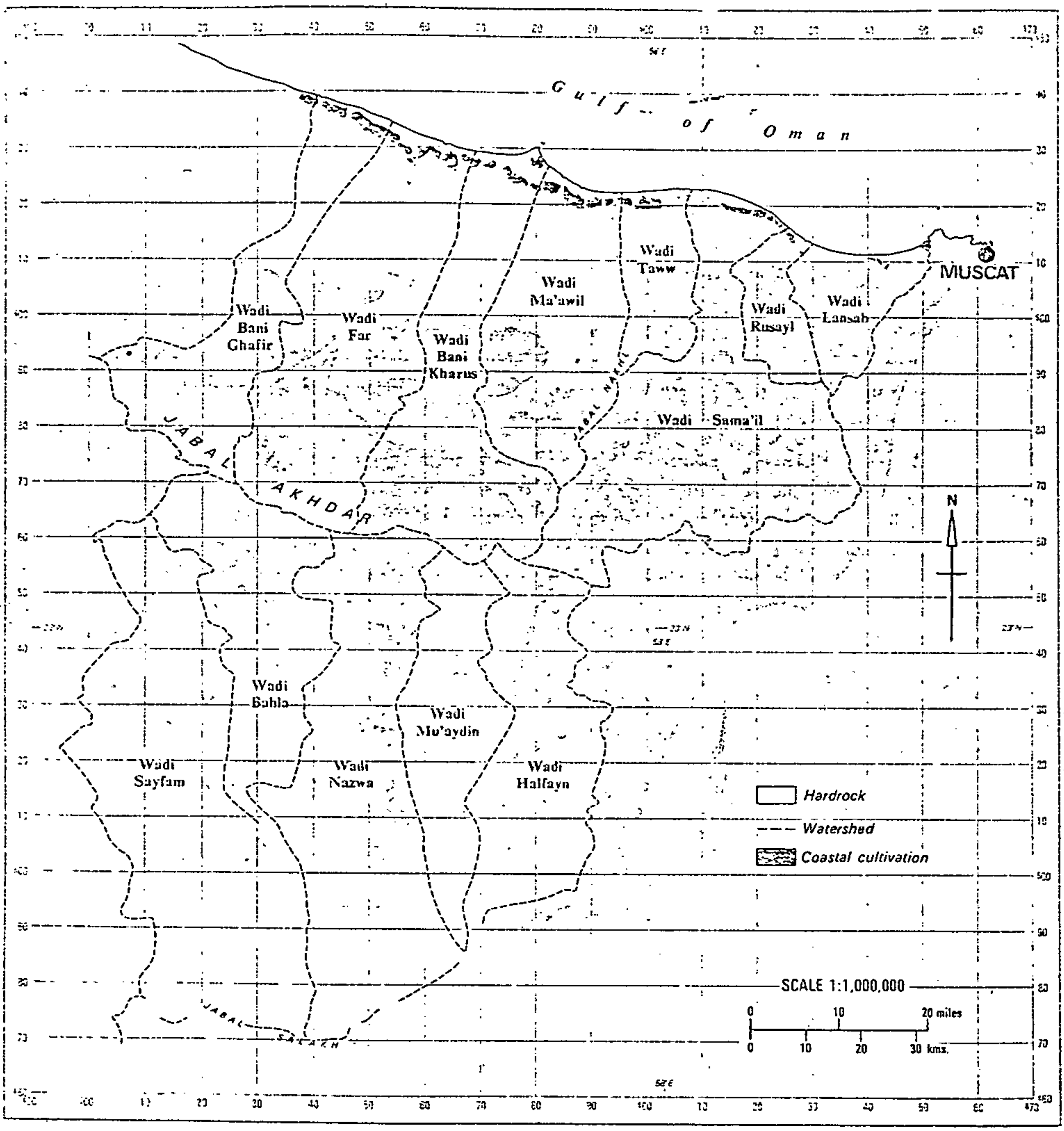
Agricultural areas represent the major water user in the study area except for urban and industrial water abstracted from the Sib fan for the Capital area.

The Survey

At the start of the survey the most promising areas for future development of water resources appeared to be the alluvial deposits north and south of the jabal. Our terms of reference defined four major objectives:—

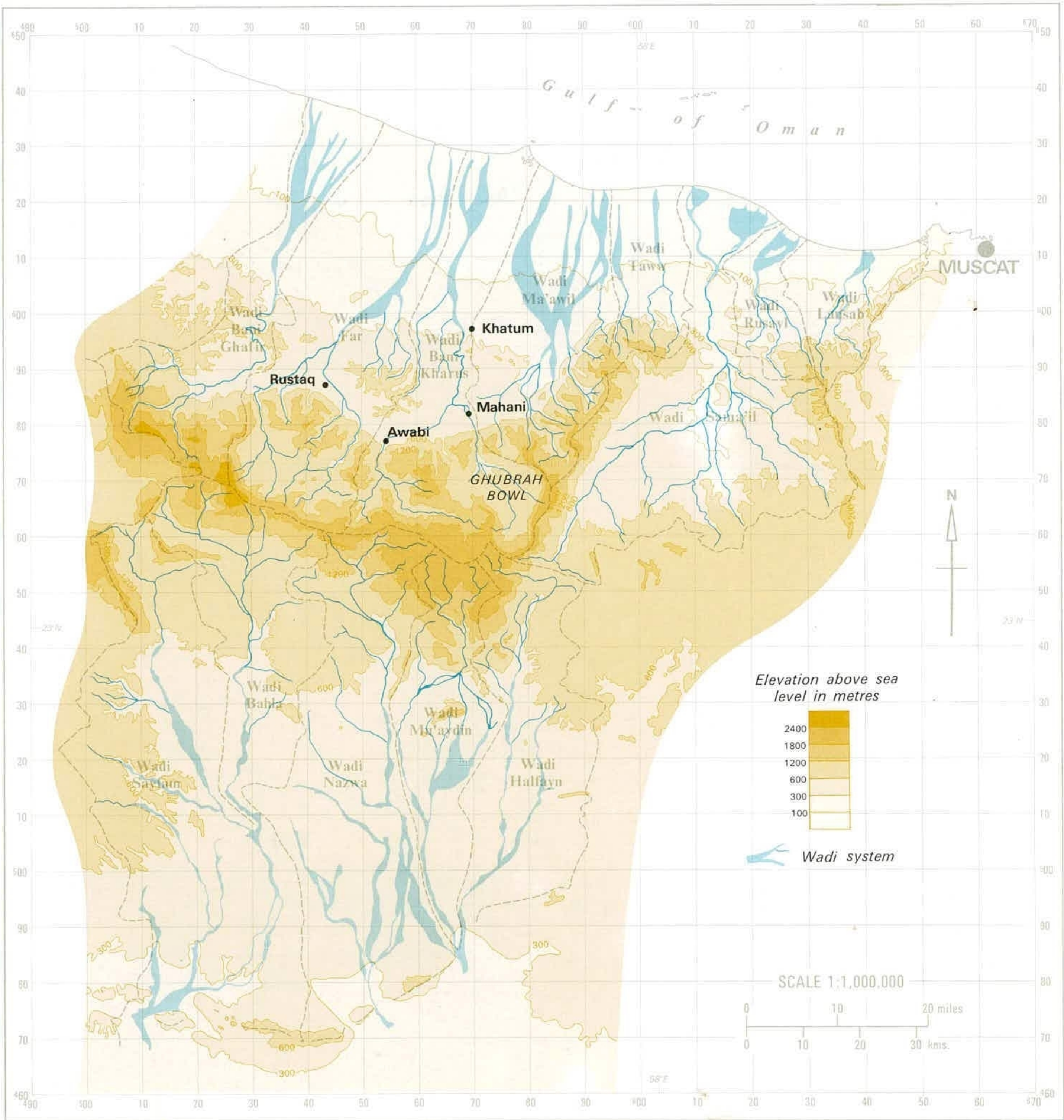
(i) assess the characteristics of the alluvial aquifers,

(ii) determine the major sources of recharge and estimate average rates of replenishment,



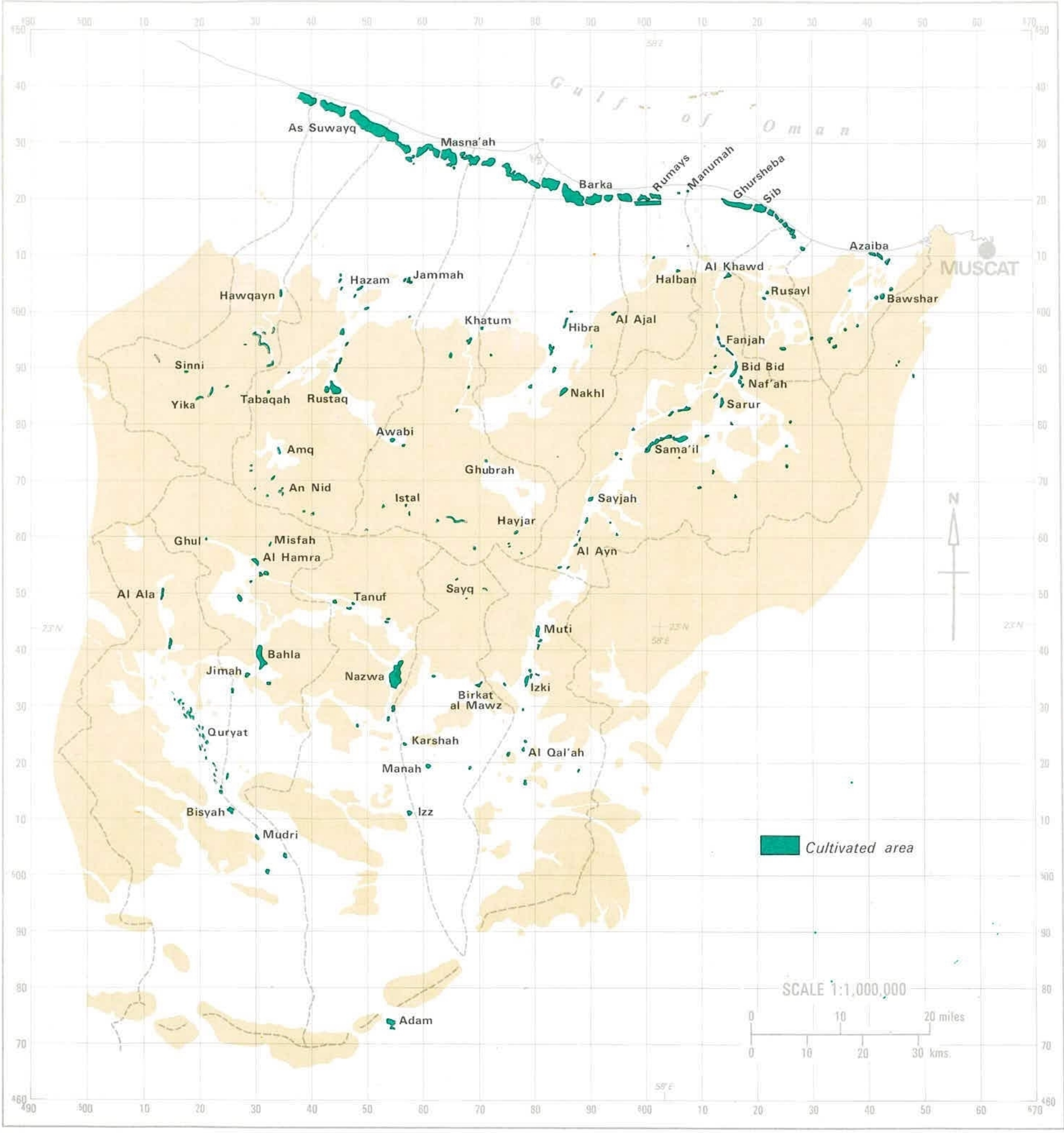
The Study Area

Figure 1



Topography and Drainage

Figure 2



Villages and Cultivated Areas

Figure 3

(iii) examine the possibility of increasing these rates of replenishment,
(iv) assess the aquifer potential of bedrock in the study area.

In view of the general lack of information throughout much of the study area, a major part of our effort was directed at the collection of primary data. We established three related fields of investigation:—

(i) a study of the surface water hydrology of the area,
(ii) a study of the hydrogeology of the aquifer systems aimed at determining flows through the aquifers and relating these flows to changes in groundwater levels,
(iii) a survey of water sources and their utilization in towns and villages.

Rainfall was sampled with altitude across the study area. Seven rain gauges, which were only accessible by helicopter, were set up on the main jabal. Away from the jabal fifteen rain gauges were sited and visited at least once a month and during storms. Meteorological stations were established at Rumays, Nazwa, Rustaq, Sayq and, towards the end of the study period, at Quryat in the Wadi Sayfam area.

There are no major perennial surface flows in the study area but some wadis, particularly Wadi Sama'il and Wadi Bahla have long periods of base flow. Wadi flows are generally violent and of short duration. Wadi gauging stations were set up on all the major wadis in the study area and several stations were set up in the sub-basins of the Wadi Bani Kharus and Wadi Bahla.

Groundwater studies were based on an anticipated programme of exploratory drilling in the alluvial deposits to determine the extent, nature and interdependence of the aquifer systems in each major basin. Our study of the groundwater potential of the hardrock area was based on information collected during the water use survey. In the alluvial areas of the northern basins we adapted an existing tube-well contract using approximately 100 boreholes widely scattered where we examined the lithology of the sediments. This network of boreholes and some existing wells were visited monthly throughout the study period to monitor water level changes. We also examined water quality throughout the area and investigated the coastal saline interface.

In the southern basins indications were that lateral connections between basins did not exist and exploratory drilling was therefore planned along the main wadi channels. Because the proposed exploratory drilling contract was not implemented our main hydrogeological survey of the southern basins did not take place. We did, however, establish routine groundwater level observations at 26 sites, mainly in the Wadi Bahla and Wadi Nazwa basins.

Water samples for chemical analysis, taken at all drilled boreholes and some earlier wells, form the basis of our assessment of groundwater origin. Seven hundred samples were collected during the course of the survey.

During the survey it became clear that the older cemented gravels of the Batinah strongly influence the distribution of groundwater, well yields and recharge. To determine the extent of these gravels we undertook mapping of the Batinah surface geology based on field survey and 1:20 000 November 1974 aerial photography. Similar photography was not available for the southern basins.

The emphasis of our water use investigations was based firmly on the representative basins of Wadi Bahla and Wadi Bani Kharus, and Wadi Sama'il with particular attention given to the Wadi Bani Kharus and Wadi Sama'il coastal areas. Our objectives were to estimate water use in these areas and hence to apply the results to the study areas as a whole, and also to establish the interdependence of various village groups and the variation in available water resources throughout the study area.

The Northern Basins

The alluvial deposits of the Batinah form a single groundwater basin with the best quality water at the mountain front and the poorest at the coast where mixing with brine and sea water occurs. While supporting earlier general conclusions that abstractions of water supplies for Muscat and Matrah have little effect on coastal users, we find that the Wadi Sama'il is the only alluvial basin that appears to have scope for additional groundwater development. We consider that earlier extrapolations of this situation have led to over-optimistic indications of groundwater availability and we find that the hydrogeology of the Batinah is quite different from the general views held in 1973 at the start of the survey. The concept of a simple alluvial basin containing gravel deposits with uniformly good groundwater potential cannot be substantiated. Depth to the water table is generally related to the nature and distribution of sediments, varying from 20 m at the mountain front to 60 m in the mid-plain zone and 2 m at the coast. The occurrence of deep gravel aquifers is restricted to the narrow coastal zone. Although alluvial deposits appear to be water-bearing throughout the area, groundwater is not always present in exploitable quantities due to the extensive occurrence of cemented gravels in the mid-Batinah.

A close balance exists between the availability and use of water with a high degree of interdependence between inland villages. Most water used in the northern basins is extracted from the alluvium, the principal sources being the sediments of the major ancient drainage channels.

The zone of contact between fresh groundwater and seawater on the Batinah forms a complex boundary to the general flow of groundwater towards the coast. The only direct evidence we have of any major freshwater loss to the sea is in part of the coastal area of the Wadi Sama'il. Our detailed survey in Wadi Bani Kharus showed that no freshwater leakage occurs in that basin, and elsewhere along the coast we consider that other major losses are unlikely. At Rumays, where agriculture has recently expanded, the equilibrium between sea water and fresh groundwater has been upset and groundwater quality is deteriorating.

The Southern Basins

Without an exploratory drilling programme our assessments of the broad hydrogeological characteristics of the southern basins must be qualitative rather than quantitative. The evidence suggests that groundwater is associated with the drainage channels of the modern wadi systems. Existing drilling records indicate that the alluvial sediments are thin, less than 70 metres thick, with more prominent deposits of marls and clays than in the northern basins. In the areas between modern wadi channels the sediments are so shallow that their potential as exploitable aquifers is doubtful. However, in the Nazwa-Adam area there appear to be narrow buried gravel channels in places away from the modern wadi channels and these buried channels might yield small local supplies. Annual water use throughout the southern basins is estimated at 44 million m^3/year of which the Wadi Nazwa and Wadi Bahla basins account for over half. The data we have collected did not suggest a general excess of supply over demand in 1974 except possibly in the Wadi Bahla basin.

Water Use and the Role of the Falaj

The falaj system provides the major water source of inland villages. Aflaj construction demonstrates considerable ingenuity and skill reflecting the thoroughness with which the available water sources are normally used. Most aflaj need little maintenance but some require the removal of silt and rebuilding of dams and diversion channels after major surface run-off. Unfortunately this maintenance has often been neglected in the past because of cost.

We have derived a relationship for the decline of falaj flows during periods of drought and we have also been able to relate falaj flows at a given time to the amount of upstream storage.

Falaj flows appear to have rarely reached the lowest flows measured during this survey. The lowest observed falaj flows typically exceed average consumptive use of the associated cropped areas by about 50 percent, the excess water being required for leaching. It is the frequency and duration of these low flows which determines the area of perennial crops and influences the area of annual crops which can be supported in periods of excess. The villages of the study area appear to have assessed drought conditions by experience and adjusted perennial crop areas to suit. Considerable re-use of water is apparent. In the Wadi Sama'il, for instance, flows in the main drainage channel are gradually reduced by transpiration from the long belt of date gardens along its length. This reduction is only partly compensated by inputs from tributaries. Analysis of water use throughout the basin shows that total water application exceeds the primary source inputs by a factor of 2 to 3. Village structures are therefore vulnerable to any new abstractions. Table 1 summarises our analysis of water use throughout the study area.

Water use in the wadi channels, peidmont areas and alluvial plains is predominantly agricultural except in the alluvial plain of the Wadi Sama'il where domestic and industrial supplies are abstracted for the Capital area. Elsewhere, we have ignored current domestic supplies as being insignificant compared with associated agricultural demands.

TABLE 1

SUMMARY OF WATER USE IN THE SURVEY AREA

(million m³/year)

Basin	Water Use	
	Water Channel and Piedmont Areas	Alluvial Plains
NORTHERN BASINS:		
WADI LANSAB	1.2	1.4
WADI RUSAYL	0.3	2.2
WADI SAMA'IL	15.0	11.1[1]
WADI TAWW	1.0	4.7
WADI MA'AWIL	8.0	15.5
WADI BANI KHARUS	7.0	10.0
WADI FAR	12.0	11.7
WADI BANI GHAFIR	4.8	14.6
SOUTHERN BASINS:		
WADI HALFAYN	5.5	1.2
WADI MU'AYDIN	2.0	5.3
WADI NAZWA	8.2	5.2
WADI BAHLA	12.2	2.1
WADI SAYFAM	2.9	4.5

Note: [1] Includes 1.4 million m³/year abstracted from the government wellfields for domestic and industrial water supply.

Storms Observed During the Study

The study period was drier than is usual in northern Oman, although rainfall and runoff were more frequent in 1975 during the latter part of the study period. Major storms occurred in February, July and August 1975 with less widespread storms occurring in October 1974 and May and September 1975.

During the survey we were able to deduce the broad pattern of all major storms. High rainfall intensities do not appear to be restricted to either the winter or summer seasons. On average 60 percent of storm rainfall occurred in less than 1 hour, nearly 90 percent in less than 3 hours and 40 percent of all storms lasted for less than 2 hours. The winter frontal rainfalls tend to be more widespread than the more isolated storms of the summer months.

Generally the effects of minor rainstorms on the aquifers of the study area were limited to the gravels of the wadi channels. More widespread recharge of the alluvial plains normally followed substantial surface flows in the wadi channels when the largest rises in water table levels were observed in or near the main wadi channels with a decreasing response with increasing distance from the mountain front. Aquifer response is even smaller away from the wadi channels and is insignificant in the Batinah mid-plain where depths to the water table are large. There is no evidence of direct recharge to the aquifer from rainfall. The above observations were confirmed by isotopic evidence from groundwaters both north and south of the jabal. Alluvial groundwater in the piedmont and mountain front zones is recent, less than 25 years old, but rainfall and runoff occurring since 1952 has yet to enter the main groundwater body in the mid-Batinah and coastal areas in appreciable quantities. Thus the short-term variability of rainfall and runoff has little effect on the movement of groundwater through the main aquifer bodies.

In general terms the survey established that primary runoff from the hardrock areas appears to be 25-35 percent of rainfall for storm rainfalls in the range 60-120 mm and that between 60 and 85 percent of primary runoff is recharged or lost to evaporation before it reaches the alluvial plains. The relationship between runoff and recharge in the plains is poor but our general conclusion is that less than 10 percent of rainfall eventually reaches the plains as recharge and that 5 percent would be a realistic average.

Because rainfall is heaviest and most runoff produced on the jabal hardrock areas, storages nearest the jabel tend to be recharged preferentially, but under particular conditions runoff can continue downstream before the upstream storages are fully recharged.

We have estimated the long term median recharge to the aquifer from the historic rainfall records and the relationship between rainfall, runoff and recharge observed in 1975. These estimates are generally consistent with the findings of the survey of village water use and with the groundwater flow in the aquifers of the Batinah where we have sufficient information to make independent estimates.

Long Term Water Availability

In general terms we consider that current water use in the northern basins is, at best, in balance with available resources except in the coastal zone of the Wadi Sama'il where we believe that up to 15 million m^3/year of fresh groundwater is being lost to sea.

In the southern basins the evidence suggests the existence of surplus groundwater totalling 6 million m^3/year in the Wadi Halfayn basin, 5 million m^3/year in the Wadi Nazwa basin and 10 million m^3/year in the Wadi Bahla basin if it can be exploited practicably.

We estimate that surface runoff losses from the study area average some 95 million m^3/year to the sea north of the jabal and 65 million m^3/year to the desert in the south.

We have no direct evidence to suggest that potential exists in the study area for further development of groundwater from shallow bedrock sources without adversely affecting established agriculture. Neither is there evidence of the existence of freshwater springs in the sea off the Batinah coast.

Table 2 summarises our analysis of unexploited water resources in the survey area.

TABLE 2

SUMMARY OF ESTIMATED UNEXPLOITED WATER RESOURCES

(million m³/year)

Basin	Groundwater: Overall Groundwater Availability in Basin	Groundwater: Available for Exploitation Either in Wadi Channel and Piedmont Areas or in Alluvial Plains	Groundwater: Available for Exploitation in Alluvial Plains Only	Surface Runoff Losses
NORTHERN BASINS:				
WADI LANSAB	2.1	2.1	—	2.4
WADI RUSAYL	0.8	0.8	—	1.7
WADI SAMA'IL	15.1	15.1	—	20.6
WADI TAWW	(-1.1)[1]	—	—	2.3
WADI MA'AWIL	(-9.4)	—	—	7.0
WADI BANI KHARUS	2.8	2.8	—	27.7
WADI FAR	4.1	4.1	—	13.9
WADI BANI GHAFIR	(-4.2)	—	—	21.2
SOUTHERN BASINS:				
WADI HALFAYN	6.1	5.5	0.6	9.1
WADI MU'AYDIN	(-0.1)	—	—	14.2
WADI NAZWA	5.3	5.3	—	13.2
WADI BAHLA	9.8	8.5	1.3	17.3
WADI SAYFAM	(-1.4)	—	—	12.0

Note: [1] Negative figures in parentheses indicate overall basin deficits between estimated available water resources and current village water use.

The Potential For Development

Our April 1975 Phase 1 Soils and Agricultural Studies Final Report established that, from soils considerations, the major potential for agricultural development in the survey area is confined to the Batinah. Elsewhere, except for Quryat in the Wadi Sayfam, soils suitable for irrigated agriculture are of limited extent and widely scattered.

The only surplus water readily available for development in the northern basins is in the Wadi Sama'il where up to 15 million m³/year of groundwater is currently lost to sea. We recommend that supplies from this source should be reserved for the increasing domestic and industrial demands of the Capital area thus lessening the reliance on costly desalination techniques for these supplies. However, any new development, particularly exporting out of the basin, will have some detrimental effect on water quality in the seaward areas of the Wadi Sama'il. An increase in groundwater salinities will accompany new abstractions until the patterns of groundwater quality and agriculture are similar to those presently seen in other basins. These effects can be minimized by siting new boreholes away from the coast between the existing wellfields and the coastal gardens.

In practice, the increased availability of water is fundamental to any proposal for increased agricultural production. Without increasing the availability of water any increase in water use in the inland villages is likely to have a detrimental effect on existing downstream agriculture. In terms of agricultural demands we do not believe on the grounds of expense that short-term prospective developments in desalination offer any potential in this field. Neither do we believe that cloud-seeding would be effective. Long term storage of surplus flood flows in the mountains is also considered unpromising due principally to the erratic nature of wadi flows and to the major problem of evaporation.

The short-term use of surface storage, however, and the longer term use of subsurface storage are more promising and we recommend that the principal effort to reduce present flood flow losses should concentrate on these techniques of water conservation. We have recommended a series of low barrage-type structures in the mountain wadi sub-basins to reduce the peak flood flows and to increase recharge and storage above aflaj to reduce the frequency of low flows. At the same time we have proposed the implementation of water spreading techniques in the alluvial plains to increase the areal extent of recharge to these aquifers during periods of surface runoff.

Agricultural development on the Batinah will be dependent to a large extent on the effectiveness of measures which can be designed to conserve the estimated 95 million m³/year surface runoff losses to sea. Suggested developments of water resources in the northern basins are:—

Wadi Sama'il	—groundwater from the Sib fan for the Capital area, surface water storage in the old channel north of Al Khawd as an additional resource for Rumays area.
Wadi Ma'awil Wadi Far	—surface water retained by barrages for piedmont villages.
Elsewhere	—water spreading in wadi gravels of the alluvial plains.

South of the mountains, we believe that a small irrigated agricultural development of about 150 ha near Jabrin in the Wadi Bahla basin could be supported by additional borehole abstractions of groundwater. Also, that extension of the agricultural area in Quryat might be possible if estimated 10 million m³/year surface runoff losses in the Wadi Sayfam can be conserved by subsurface storage. Elsewhere in the alluvial plains of the southern basins the evidence suggests that either the soils are not suitable for irrigated agriculture or that groundwater is likely to be widely dispersed and not readily exploitable in significant quantities. Development possibilities are therefore limited to:—

Wadi Halfayn Wadi Nazwa	—piedmont groundwater for local developments.
Wadi Bahla	—piedmont groundwater for development at Jabrin.
Wadi Sayfam	—induced recharge of surface water losses for Quryat area.

Further Studies

In the course of this survey, networks of instruments including five meteorological stations have been established throughout the 14 500 km² of the study area. Regular observations have been made of rainfall and other climatological data, wadi flows, aflaj flows, groundwater levels, and surface and groundwater quality. We consider that it is of utmost importance that the established networks should be regularly maintained and monitored, and extended to provide better coverage. The continued collection of hydrological records is essential if the full potential of the water resources of the survey area is to be realized.

Further exploratory drilling will undoubtedly be required in the study area but, now that this survey has ended, our general view is that future drilling programmes should be associated with specific development projects and specific problems; for example, to obtain a better understanding of the long-term availability of groundwater in the alluvium of those basins offering scope for development. However, further exploratory drilling should not be implemented until an objective evaluation has been completed of the results from this survey and from similar water resources surveys undertaken by other consultants in adjacent areas of northern Oman.

This water resources survey, although broad in scope, was undertaken in detail in the representative basins of Wadi Bani Kharus and Wadi Bahla, and in the basin of Wadi Sama'il in view of its role as a principal water source for the Capital area. An extension of the village water use studies along the whole Batinah coastal strip would confirm if there are any additional fresh groundwater losses to sea.

Throughout most of our survey period there was little base flow in any of the wadi channels. Local knowledge suggests that base flows are more frequent in wetter years. Measurements of base flows should be included in the aflaj network observations.

Incidental Information

During the course of our field observations and by inspection of water analyses, we have encountered indications of various mineral deposits. These were of minor importance to the water resources survey and they are probably too localized to be of economic importance. However, they are included in Appendix D in case they are of use for future mineral surveys.

PREFACE

This the Final Report of the Water Resources Survey of Northern Oman completes a three year study of the region from 1972 to 1975 and it follows our report on the Phase 1 Soils and Agriculture studies submitted in April 1975.

The Soils and Agriculture report of April 1975 was accompanied by an Interim Water Resources Assessment which, being based on data to the end of 1974, did not benefit from any of the runoff data collected during 1975. Thus our interim analysis was of a very preliminary nature. This Final Report remedies many of the earlier deficiencies and includes our additional knowledge of the chemistry of the waters and a survey of current water use throughout the study area.

We have structured this report in a way which reflects the pattern of rainfall encountered during the study, that is, two dry years followed by a wetter year. After describing the study area and our approach to the survey in Part 1, we deal in Part 2 with the response of the aquifer systems to a prolonged period without rainfall. The pattern of water use in the towns and villages forms part of this analysis. In Part 3 we present the data and analysis of the rainfall, wadi flows and aquifer recharge of the third year. Finally, in Part 4 we summarize our findings and discuss the long term implications of the results, the potential for development and the value of further specific studies. All detailed data and supporting material are presented as a series of Appendices and we have, where possible, adopted a computer presentation of the large amount of detailed data collected during the study.

We must emphasize that this study has been a regional one; our task was to study the water resources of the area as a whole and not to examine in detail any specific water supply problems. A principal demand for water, that of the developing area around Muscat and Matrah, has been reported on under a separate contract.

Two important factors have affected the presentation of the results of the study and the inferences we have drawn from the data.

Firstly, the initial two years of the study period were generally very dry and we were thus able to observe the aquifer systems in recession. Only in the final year was there sufficient rainfall to cause substantial flow in the main wadis and recharge to the various alluvial aquifers. Although we recorded a reasonable number of these wadi flows, our sample of data is still relatively small and the relationships we derive between rainfall, runoff and aquifer recharge must therefore be regarded as tentative. In making this qualifying statement, we are mindful of the medium to long term fluctuations in climate which could strongly influence the state of the aquifers such as that of the Batinah coastal plain where total storage continued to decline throughout the study period. Several years of more plentiful rainfall could have resulted in a different emphasis being placed on the relative importance of several factors governing the recharge process. In our final chapter, we recommend that studies should be continued to examine these problems.

Secondly, it was intended that a carefully designed exploratory drilling contract would be let during the course of the study to allow comprehensive testing of aquifer properties both north and south of the jabal. In the event this contract was not let and our knowledge of the aquifers is based on a less suitable programme of drilling intended for water well construction. Although we were able to adapt this programme in part to give some information for the northern (Batinah) area, the alluvial plains south of the jabal are largely unexplored. The outcome of this is a bias in our report towards the alluvial aquifer of the Batinah.

All place name spellings and grid references used in the report are consistent with the 1:100 000 map Sheets Series K668 published by the U.K. Directorate of Military Survey.

CHAPTER 1

THE STUDY AREA

1.1 INTRODUCTION

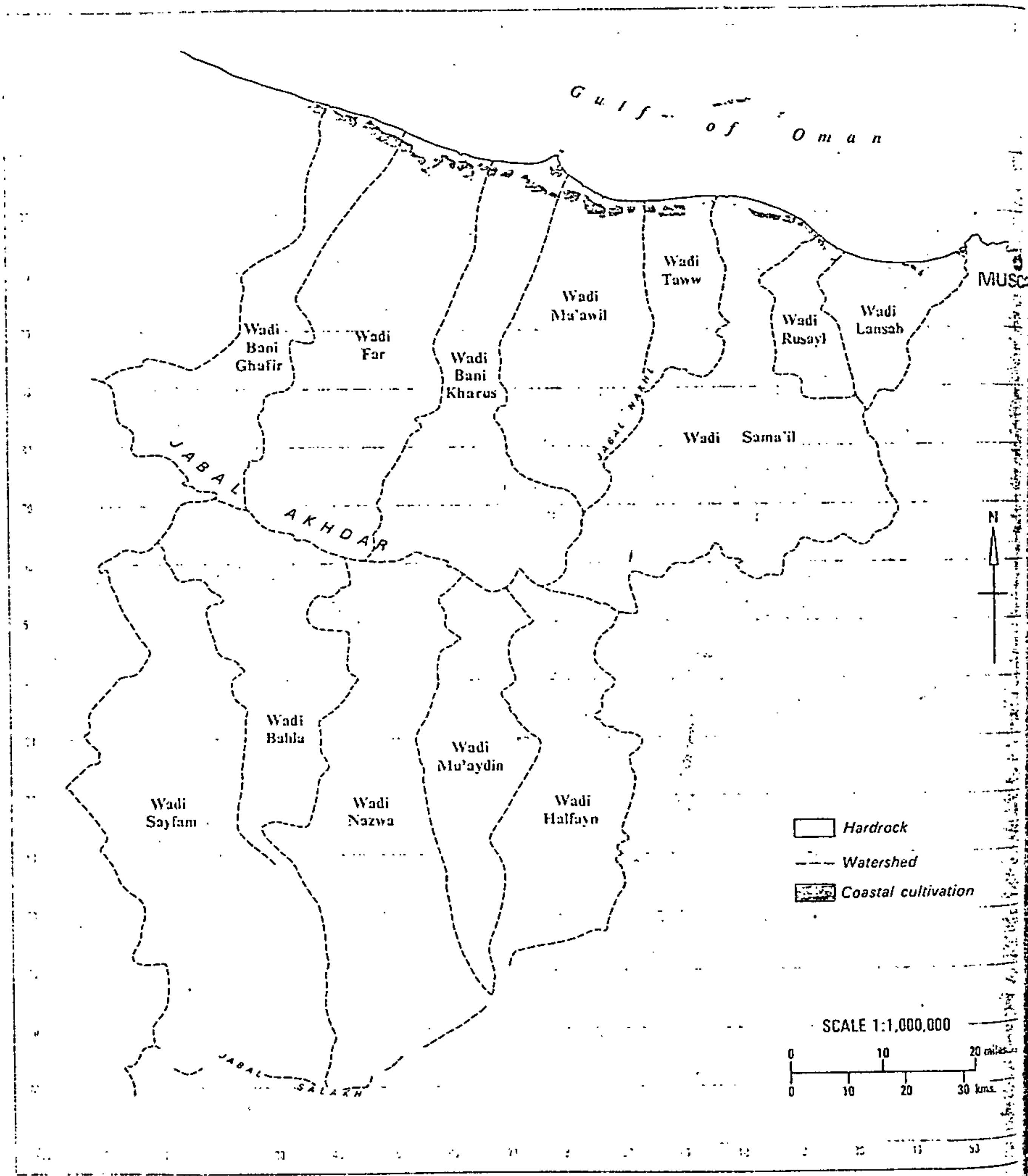
The study area can most simply be described as those wadi basins which drain the Jabal Akhdar and Jabal Nakhl. This massive limestone anticline forms a mountain range 125 km long and over 2 000 m high along much of its length. The moderate but unpredictable rainfall on the jabal distinguishes the region of Northern Oman as one of the few areas of the Arabian peninsula where settled agriculture is possible. In the alluvial areas below the jabal the traditional systems for exploiting the sources of water, notably the aflaj and hand-dug wells, have ensured a reliable supply of water for irrigating date gardens and fodder crops.

The main features of the study area are shown in Figure 1.1. The mountains, largely bare of soil and having very sparse vegetation, are shown in brown; the gently sloping areas of alluvium are shown without colour. The main agricultural areas are shown in green, the narrow strip along the coast being the predominant feature. The major wadi basins are defined by their watersheds. For simplicity we have used a single wadi name to define a whole basin: local names are many, and it is not unusual for a wadi to have several different names along its length.

The precise boundaries of the study area are defined by Figure 1.1. The major difficulty was in defining the southern boundary. In times of heavy rainstorms the southward flowing wadis have been known to carry water several hundred kilometres out into the desert. However, there is little practical value in continuing the study beyond the area of possible agricultural development and therefore we defined a southern boundary along the ridge of hills on the line of the Jabal Salakh.

To the east and west our study area adjoins those studied concurrently by other consultants. The Wadi Sama'il and Wadi Halfayn which drain the eastern flank of Jabal Nakhl, and the smaller Wadi Lansab basin form the eastern boundary of our study. The area further east including the Wadi Aday has been studied by Renardet-Sauti. The area to the west of Wadi Bani Ghafir and Wadi Sayfam, the most westerly wadis draining the main limestone anticline, have been studied by Ilaco.

During the study period we consulted with the Durham University team who were carrying out a broadly based survey including socio-economic studies of the Ibri basin. Because this area has a fundamentally different character to our principal study area we have reviewed those aspects of the Durham team's study which are relevant to an estimation of water resources as a part of Chapter 5.



The Study Area

Figu

Our study does not include the capital area of Muscat and Matrah where there is rapid expansion of industrial and residential areas. Nonetheless it is recognized that the study area and particularly the Wadi Sama'il will continue to be a source area for the water supply to this development. While this fact does not unduly influence the method of study, he rapidly rising demand for potable water emphasizes the need for studies of the coastal area as a whole where competing demands for water might well develop in the near future.

In this chapter we describe the geological factors which have led to the topography and drainage pattern we see today. We also describe the main climatic influences which interact with the dominant topography, the village patterns which have developed and we summarize the results of the soils and agriculture studies carried out by Sogreah and Ilaco, in conjunction with this water resources study, which were reported in April 1975.

1.2 GEOLOGY

The study area is dominated by a doubly curved mountain chain in the form of an asymmetrical limestone anticline. Associated with this feature is the superposition by gravity sliding in the late Cretaceous period of thick sequences of rocks which, though contemporaneous, are of totally different origin. These formations, the Hawasina and Sama'il nappes now appear as large areas of foothills which, except where breached by major wadi systems, completely surround the in-situ sediments of Jabals Nakhl and Akhdar.

Uplift in response to the reversal of continental drift between the Arabian peninsular and Iran, and erosion along the mountain axis reached a peak in mid Tertiary (Alpine) time and has produced the present primary structures and sedimentary basins. Of these, the coastal plain to the north, commonly known as the Batinah, is the most important and extensive with offshore drilling records reporting accumulations of up to 4 km of detrital sediments. South of the mountains a large area of foothills separates smaller, relatively shallow alluvial basins which are connected by the principal wadi systems.

The complex and unusual geological development of the Oman mountains has been the subject of several different interpretations of which the most recent and comprehensive is by Glennie et al, (1974)[1]. We have drawn heavily from this and other information provided by geologists of Petroleum Development (Oman) Ltd.

The simplified stratigraphy shown in Table 1.1 indicates the order in which the various rocks are found overlying one another; the oldest sediments appear at the bottom of the table. Crystalline basement rocks are not exposed. The oldest visible rocks are partly metamorphosed sediments of a Pre-Permian age exposed by deep fault guided erosion in the mountain core. These are overlain by a thick sequence of shallow water marine sediments of mid Permian to late Cretaceous age, deposited in-situ and termed the *autochthonous* rocks of the area. Five major limestone and dolomite formations comprise the Hajar Super-Group which forms the bulk of the autochthonous unit. A further unit, the Muti Formation, composed of limestone conglomerates of late Cretaceous age form the youngest part of the sequence.

The Muti Formation is overlain by deep-sea sediments and igneous rocks transported into the area at the end of the Cretaceous period and termed *allochthonous* units. The lower

[1] The Geology of the Oman Mountains, Volume 31, Transactions of the Royal Dutch Geological and Mining Society.

rocks are referred to as the Hawasina and, as shown in Table 1.1, they comprise several formational units of similar age thrust one upon the other. The highest unit of the Hawasina, the Oman Limestone Exotics associated with some volcanic rocks, are thought to have been formed as coral reefs in the original Hawasina ocean.

TABLE 1.1

STRATIGRAPHIC AND TECTONIC RELATIONSHIPS IN NORTHERN OMAN

Geological Sequence	Geological Ages	Lithology	Simplified Nomenclature
Upper Tertiary and Recent	Miocene to Recent	Wadi gravel deposits	Upper Tertiary to Recent
	Formation of Jabal Akhdar Mountains		
Latest Cretaceous and Lower Tertiary	Maastrichtian to Eocene	Limestones and marls	Lower Tertiary Limestones
	Mid to Late Cretaceous	Ultra-basic igneous rock	Sama'il Nappe
Permian to Late Cretaceous Allochthonous Units	Permian and Triassic	Oman limestone Exotics	
	Triassic and Early Jurassic	Limestones, shales and cherts	Hawasina
	Jurassic and Cretaceous	Cherts, sandstones and limestones	
	Triassic, Jurassic and Cretaceous	Limestones, sandstones and cherts	
	Emplacement of Allochthonous Units		
	Late Cretaceous	Muti limestone conglomerates	
Permian to Late Cretaceous Autochthonous Units	Mid Cretaceous	Wasia limestones	
	Late Jurassic/Early Cretaceous	Kamah limestones	Hajar Super-Group
	Jurassic	Sahtan limestones	
	Triassic	Mahil dolomites	
	Mid to Late Permian	Sayq limestones	
Pre-Permian	Cambrian to Permian	Partly metamorphosed shales, limestones and sandstones	Pre-Permian Basement

The youngest and the highest rocks of the allochthonous formations are mainly igneous ultra-basic, basic and intermediate rocks of mid to late Cretaceous age. They are known as the Sama'il Nappe and are thought to be a fragment of the ocean crust which once underlaid the Hawasina ocean.

Why, how or exactly when the slab of Hawasina and Sama'il rocks became separated from their original oceanic environment or how they were transported to the present positions is not known. The large slab of rock is estimated by Glennie to have covered several hundred thousand square kilometres. Shallow water limestones were being deposited by the latest

Cretaceous period and this process continued over much of the area until a mid-Tertiary uplift began as a result of simple compressional up-folding. The accumulation of continental detritus of Upper Tertiary to Recent age forms the gravel terraces and wadi gravel deposits of the area.

The six major geological sequences which have been used throughout this report are shown in the simplified nomenclature of the stratigraphic table. The main hydrogeological characteristics of these are summarized below; their distribution is shown on the simplified geological map of the area in Figure 1.2.

Pre-Permian Basement

The lower 1 000 m of the exposed Pre-Permain basement comprises conglomerates and quartzitic sandstones with siltstones and shales. They are overlain in places by 100 m of hard, black limestone and up to 500 m of siltstones and shales.

Groundwater is associated with the limestones, and villages occur around small perennial springs in the high mountains between Al Hamra and Rustaq. Other villages such as those in the Sayq area are situated at occasional springs which issue from the contact between the impermeable siltstones of the basement and the overlying limestone formations. However, there is little evidence that these basement rocks are of regional groundwater importance.

Hajar Super-Group

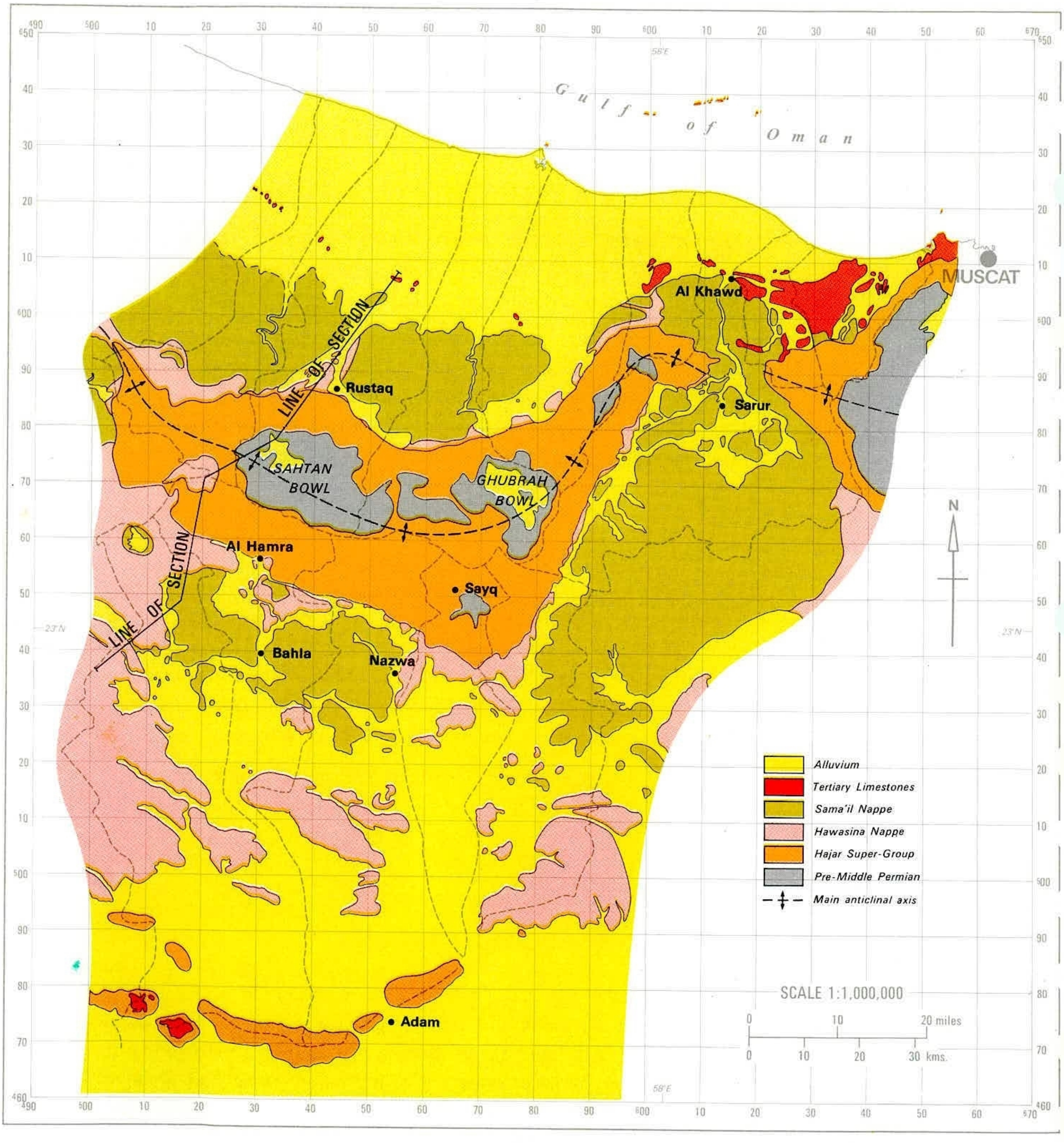
The Hajar Super-Group consists of up to 3 000 m of thick to massive bedded limestones and dolomites with some relatively thin, argillaceous, muddy carbonates which form oil reservoirs in some parts of Oman. These mid Permian to late Cretaceous sediments which we refer to as the "mountain limestone" form the main rock slopes of the Jabal Akhdar—Jabal Nakhl range. They also form the low hills at the southern limit of the study area near Adam, and the hills above the Bosher spring line between Al Khawd and Muscat.

Groundwater occurs in fracture zones in the otherwise impermeable formations which lack significant matrix storage. Solution features such as swallow holes occur in Jabal Akhdar. A spring line of considerable local importance exists at the junction between the limestones and the overlying Hawasina at the foot of the north facing (Batinah) and south-east facing (Wadi Sama'il) slopes.

Hawasina

The lower formations of the Hawasina are of deep water origin and comprise quartz sandstones, cherts, silicified limestones and shales. The higher nappes of shallow marine limestones and cherts occur as isolated blocks ranging in size from small hillocks to mountains of over 900 m. These marine limestones are white, highly brecciated, sheared and recrystallized. A few springs have been found in the larger exposures in the south-west part of the study area. Otherwise the Hawasina appears to be impermeable and lacking any groundwater potential.

The thin outcrop of the Hawasina nappes around the northern foot of the central mountainous area (shown slightly exaggerated in Figure 1.2) is a zone of low relief which has



Simplified Geology

Figure 1·2

been easily eroded due to the much weaker nature of the beds compared with the underlying limestones and the overlying Sama'il rocks. The springs of the Haja Super-Group are found close to the Hawasina junction always within the limestones: the low relief and the impermeable nature of the Hawasina being of less importance than the occurrence of fractures in the limestones in determing the position of the springs.

The extent of the exposures of the Hawasina in the southern basins is shown in Figure 1.2. A thin zone of fairly deeply eroded rocks occurs between Al Hamra and Nazwa. Elsewhere the nappes occur in extensive exposures of rocky hills and low mountains. These form a distinct watershed to the Wadi Sayfam basin at the western limit of our study area. The Wadi Sayfam itself has eroded a channel between this western watershed and a central area of Hawasina which separates the Wadi Sayfam from the more easterly wadis draining from the Nazwa and Izki areas.

Sama'il Nappe

The assemblages of rocks which form the Sama'il Nappe, collectively referred to as the *Ophiolites*, comprise a thick sheet of basic and ultra-basic rocks preserved in tectonic depressions on either side of the main anticlines of the jabal.

The lowest units consist of 1 800 m of peridotite which is sheared and serpentinised along the basal contact of the nappe. A complex transition zone or faulted contact separates the peridotites from overlying gabbros which pass upwards into dolerites, basalts, volcanic breccias and their associated sediments. The full sequence is over 3 000 m thick and in places is occasionally capped by thin radiolarian cherts and mudstones.

Small springs are to be found throughout the Sama'il Nappe. Scattered seepages occur within the peridotites and gabbros associated with a physical discontinuity within the Sama'il Nappe which is often accompanied by thrust faults, breccias, zones of volcanic intrusion and changes in the chemical composition of the rocks. The chemistry of the spring waters is most unusual; they are invariably very alkaline waters and precipitate calcium hydroxide on contact with the atmosphere.

The Sama'il Nappe is exposed in three extensive areas where they form barren, rugged mountainous country. The largest exposure is along the eastern boundary of our study area from Izki to Al Khawd underlying a large area of the Wadi Sama'il basin and forming the headwaters of many tributary streams. The other two areas (Figure 1.2) are arranged symmetrically to the north and south of the Jabal Akhdar where they form the foothill areas. Many important villages exist where the Sama'il rocks have resisted erosion and contained the major wadis within relatively narrow channels. In such situations alluvial groundwater is forced to the surface because of the impermeable nature of the igneous strata. The town of Bahla and the large village complex of Sama'il are examples.

Lower Tertiary Limestones

By Upper Cretaceous times the Hawasina and Sama'il nappes were emplaced and shallow-water limestones formed over much of the present area of the mountains. Deposition of these limestones with minor evaporites and marls continued until the major uplift of the mountains began during the Oligocene period.

Subsequent erosion has considerably reduced this carbonate cover and within our study area exposures are now restricted to the north of the main anticlines (Figure 1.2). West of Nakhl the limestones occur as small inliers along a narrow zone well inland from the coast but some distance to the north of the foothills of the Jabal Akhdar. The inliers appear as the more resistant summits of a buried ridge dissected by the main wadis crossing the Batinah coastal plain. The beds dip gently towards the coast except east of Nakhl where the strata dip more steeply and minor folding and faulting becomes apparent.

Facies range from hard, flaggy or massive, partly recrystallized limestones, through soft nummulitic limestones, to reef limestones. Generally they are not water-bearing although a few boreholes between Sib and Matrah yield groundwater apparently from solution cavities.

Upper Tertiary to Recent

The recent geological history has been one of continued uplift and erosion of the mountain axis and the infilling of depositional areas on the flanks. Erosion of Lower Tertiary, Sama'il and Hawasina rocks has led to the accumulation of up to 4 000 m of conglomerates and gravels with relatively minor sands and silts. The oldest deposits are predominantly carbonate rich conglomerates passing upwards into chalky and cemented gravels. Weakly cemented gravels overlie these and pass upwards into clayey gravels which might be formed by the weathering and decomposition of the ultra-basic pebbles of the gravels.

The sedimentary history of the Batinah appears to have been dominated by the Wadis Far, Ma'awil and Sama'il. The modern channels cut through older terraces along the foothill areas where boulder beds, coarse gravels and cemented conglomerates are exposed at the surface. The wadi channels broaden as they cross the coastal plain and bury the older terraces beneath finer gravels of the many braided channels of the area. Drilling has indicated that poorly sorted gravels of up to 100 m thickness underlie parts of the mid-Batinah area. These gravels rest upon the clayey and cemented beds of the older sediments. The main occurrence of groundwater is within the surface gravel deposits. Thin gravel lenses have been proved within the underlying clayey and cemented sequences but generally all the major producing boreholes have been constructed within the upper gravels.

At the coast the wadis are again confined within relatively narrow channels. The coastal sediments are generally fine grained with silts and clays at the surface overlying coarse marine sands which are interbedded with and overlie fine gravels of terrestrial origin.

The fairly extensive alluvial sediments of the Wadi Sama'il basin consist in the west of boulder beds derived from the Jabal Nakhl passing into ophiolitic gravels in the east. The thickness of these deposits varies from a few metres to several tens of metres. The few water supply boreholes constructed in the area indicate that groundwater in the upper reaches is more likely to be associated with ophiolitic gravels than with the boulder beds. North of Sarur the sediments become intermixed but confined within a relatively narrow channel containing groundwater throughout the whole length of the wadi to Al Khawd.

The wadi sediments of the southern basins appear to form relatively thin sheets of gravels, partly from the Jabal Akhdar but containing in addition significant volumes of locally derived material from the Hawasina and Sama'il outcrops. Little is known of the subsurface distribution of the sediments and we were unable to carry out any exploration drilling. A preliminary resistivity survey carried out between Nazwa and Adam for the Water Resources Centre indicated that fresh groundwater was confined to a few narrow buried wadi channels and that large areas between these channels were underlain by thin dry gravels or by either clayey or brackish water bearing gravels. These findings do not suggest the occurrence of extensive major aquifers in the area.

The Structural Setting

The study area spans two major subdivisions of the mountain range which extends for over 700 km along the north eastern margin of the Arabian subcontinent. To the west of the Wadi Sama'il the geological structure is dominated by the relatively narrow anticline of the Jabal Akhdar-Jabal Nakhl range which forms part of the Central Oman Mountains. A deep seated discontinuity underlying the Wadi Sama'il marks the eastern limit of this central zone and a much broader continuation of the anticline occurs to the south-east of the study area in the region known as Saih Hatat.

The structural relationships between the six major formations in the Jabal Akhdar are shown in a geological cross-section in Figure 1.3. The limestones of the Hajar Super-Group dip north and south on either limb of the anticline which was formed in the zone of major Tertiary uplift. The Pre-Permian basement, exposed by deep fault guided erosion in the core of the anticline, floors the bowls and plateau areas within the mountains. The Batinah is underlain by the northward dipping Hajar Super-Group limestones, the southern basins by a gentle syncline. In the cross-section, the simplicity of the Tertiary structures is obscured by the complex relationships of the Hawasina. The numerous low-angle thrusts were formed during the emplacement of these rocks and, although some earth-movements probably took place in Tertiary times, the thrusts are of late Cretaceous origin. The rock sequence is imbricated, tectonically repeated and the rocks are frequently overfolded. The Sama'il Nappe forms a number of plates that are more or less detached from one another and these plates are now found embedded in tectonic depressions created during or after nappe emplacements.

One of the most significant features of the geological structure is the sweep of the anticlinal axis to the north-east resulting in the displacement of the Jabal Nakhl towards the coast and the narrowing of the coastal plain in the area to the east of the Wadi Ma'awil. This flexure has also resulted in the formation of the Wadi Sama'il as a basinal structure to the south of the main anticlinal axis between the Jabal Nakhl and the Saih Hatat. Between these structures, the Sama'il and the underlying Hawasina nappes form a syncline which plunges gently to the south. Drainage, however, is to the north crossing the axis of the main anticline at Fanjah where the structure is depressed and the mountain limestones plunge beneath the Sama'il Nappe.

To the east of the Wadi Sama'il a small part of the study area lies to the north of the anticlinal axis. The watershed in the Wadi Rusayl and the Wadi Lansab is formed by exposures of the Hajar Super-Group limestones in the north-western flank of the Saih Hatat dome. These dip to the north and north-west beneath the most extensive exposures of Lower Tertiary limestones in the study area.

1.3 TOPOGRAPHY AND DRAINAGE PATTERN

Our knowledge of the topography of the area is based on the contouring available on the 1:250 000 contoured maps produced by the United Kingdom Ministry of Defence in 1968. The more recent 1:100 000 maps revised by the Ministry of Defence from 1968 aerial photography are not contoured although they show some spot heights. These larger scale maps are the main source of information on wadi channels particularly in the hard rock areas. Our base maps have been prepared from these sources and Figure 1.4 shows selected contours and the pattern of major wadi channels.

The mountain limestones form the major watershed separating the northern coastal plain from the interior plateau. The mountains which rise to over 2 000 metres are dissected by deeply incised streams often opening into small basins floored with boulders and gravels. The narrow mountain wadis terminate with regularity at the junction between the mountain limestones and the Hawasina where they open into broader wadis formed by extensive erosion of the narrow Hawasina outcrop.

The Wadi Far, Wadi Bahla and Wadi Nazwa are examples of the development of piedmont alluvial areas flanked by the mountain limestones and the overlying ophiolites. Where the ophiolite cover no longer exists the mountain wadis enter the alluvial plains directly as on the western side of the Jabal Nakhl and the Wadi Mu'aydin in the south. The Wadi Bani Kharus and Wadi Bani Ghafir are the only wadis which have long winding channels through the ophiolites. The Wadi Bani Kharus is a clear example of river capture. Formerly the upper part of the wadi which leaves the jabal at Awabi flowed westwards along the broad alluvial channel towards Rustaq; the Wadi Sabt which drains the Ghubrah Bowl flowed north-eastwards to join what is now the Wadi Ma'awil. Now both these mountain wadis join near Mahani to flow due north through the ophiolites emerging on the alluvial plain near Khatum.

Drainage from the piedmont basins occurs through relatively narrow gaps in the more competent ophiolites. To the north of the jabal, the wadis discharge to the coastal plain above the outcrop of the Tertiary limestones. This is at an elevation of about 300 m. To the south of the jabal a more complicated drainage pattern has developed. The piedmont basins drain through gaps in the ophiolites at an elevation of about 600 m into a series of shallow alluvial basins underlain by Hawasina rocks. These basins extend southwards for about 100 km to a peripheral range of limestone hills where the wadis pass through to the relatively featureless interior at an elevation of 300 m.

The Wadi Sama'il and to some extent its southward draining counterpart, the Wadi Halfayn, have a different drainage pattern from this general picture. The main wadis, and the main villages in each basin are located along the line of a major fault zone and are flanked to the west by the mountain limestones and to the east by the Sama'il ophiolites. Geologically they occupy similar positions to the piedmont basins south of the jabal but receive runoff from an east facing mountain limestone slope of the Jabal Nakhl.

On the assumption that it is the high jabal hardrock areas which receive most rainfall and thus generate the runoff which subsequently recharges the alluvial aquifers, we can usefully examine the distribution of these hardrock areas with altitude. Also for the northern basins where the alluvial plain is delimited by the sea, we can compare the relative sizes of the hardrock and alluvial areas.

Much of the Jabal Akhdar range and its foothills is drained by the Wadis Bani Kharus, Far and Bani Ghafir to the north and by the Wadis Mu'aydin, Nazwa and Bahla to the south. Table 1.2 shows the sub-division of these basin hardrock areas into altitude ranges defined by the contours on Figure 1.4. Areas for the Wadi Sama'il are shown for comparison.

TABLE 1.2

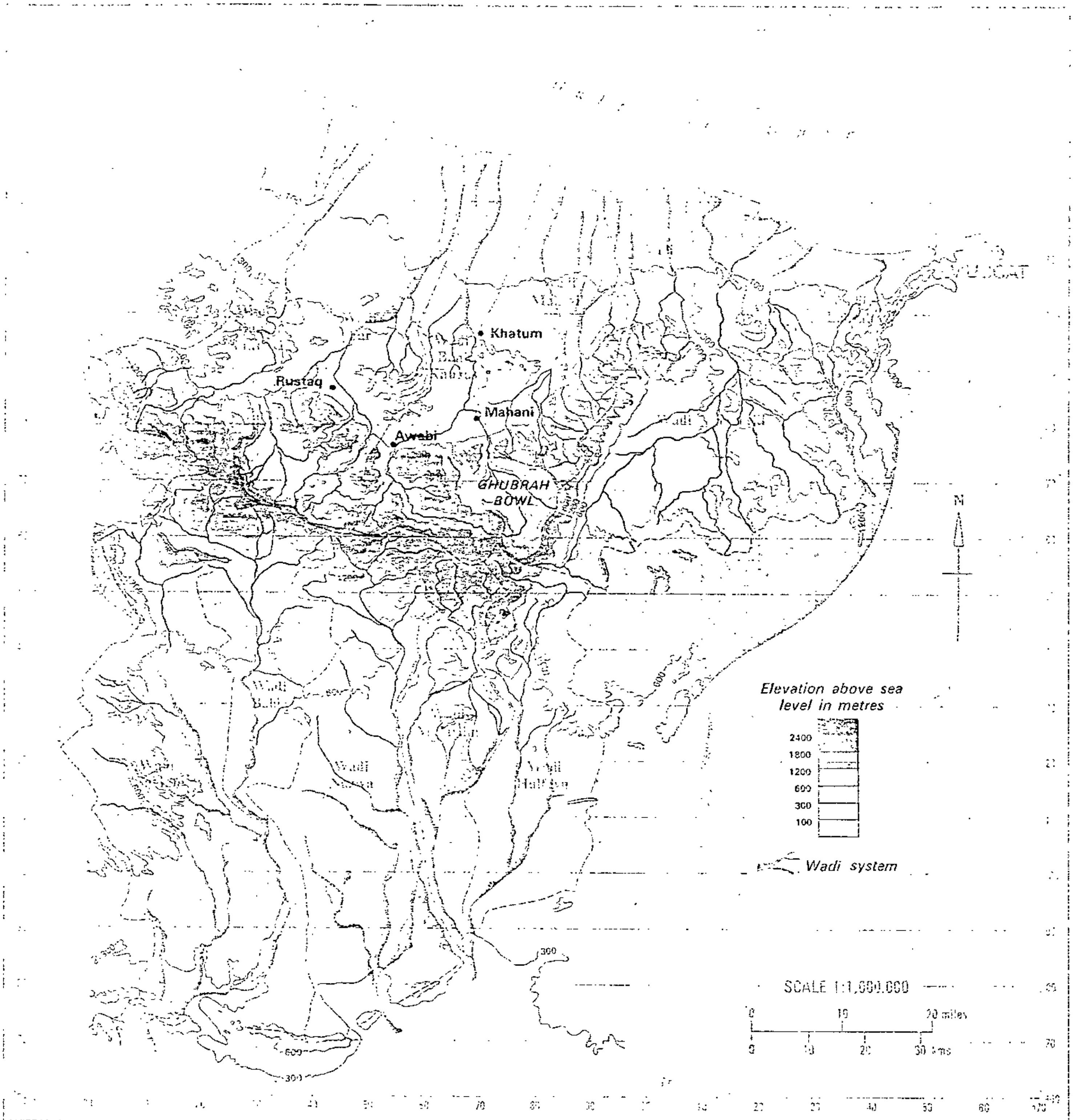
AREAS OF HARDROCK IN THE MAJOR BASINS AND BASIN GROUPS BY ALTITUDE RANGES

(km^2)

	Altitude Range (m)						Total
	100-300	300-600	600-1 200	1 200-1 800	1 800-2 400	>2 400	
Draining to the north							
Wadi Bani Kharus	15	224	253	176	104	—	772
Wadi Far	44	292	299	129	21	8	793
Wadi Bani Ghafir	25	218	210	112	57	11	633
TOTAL	84	734	762	417	182	19	2 198
Draining to the south							
Wadi Mu'aydin	—	9	78	71	104	—	262
Wadi Nazwa	—	56	238	98	83	—	475
Wadi Bahla	—	25	388	143	59	11	626
TOTAL	—	90	704	312	246	11	1 363
Wadi Sama'il	153	622	472	93	19	—	1 359

The northward draining group of basins has a total hardrock area over 50 percent larger than the southward draining group. However, the difference is largely within the altitude range 100-600 metres and is attributable to the lower altitude of the hardrock-alluvium boundary to the north of the jabal. By contrast the Wadi Sama'il has a much greater proportion of its hardrock area at lower altitude. The eastern slopes of the Jabal Nakhl account for only 30 percent of the total hardrock area; the remainder is an extensive area of ophiolites at an altitude generally below 1 200 metres.

Table 1.3 shows the major sub-division of the wadi basins into areas of hardrock, piedmont alluvium and alluvial plain, except for the southern basins where the extent of the alluvial plain is not delimited. The ratio of total alluvial area (including the piedmont alluvium) to the hardrock area varies from 0.33 for the Wadi Sama'il to 1.53 for the Wadi Ma'awil. The latter high value is a consequence of the river capture discussed earlier whereby hardrock areas which used to drain to the alluvial plain in the Wadi Ma'awil and to some extent the Wadi Far basins now drain to the alluvial plain of the Wadi Bani Kharus.



Topography and Drainage

Figure 1·4

TABLE 1.3

HARDROCK AND ALLUVIAL AREAS IN THE WADI BASINS

	Total Area (km²)	Jabal Hardrock (km²)	Piedmont Alluvium (km²)	Alluvial Plain (km²)	Ratio Alluvium/ Hardrock
Northern basins					
Wadi Lansab	371	222	0	149	0.67
Wadi Rusayl	278	150	47	81	0.85
Wadi Sama'il	1 809	1 359	272	178	0.33
Wadi Taww	392	174	0	218	1.25
Wadi Ma'awil	1 056	418	104	534	1.53
Wadi Bani Kharus	1 250	772	84	394	0.62
Wadi Far	1 625	793	126	706	1.05
Wadi Bani Ghafir	939	633	0	306	0.48
	7 720	4 521	633	2 566	
Southern basins					
Wadi Halfayn		348	71		
Wadi Mu'aydin		262	0		
Wadi Nazwa		475	70		
Wadi Bahla		626	119		
Wadi Sayfam		288	31		
		1 999	291		

1.4 CLIMATE

The existence of a high mountain range near the coast of northern Oman greatly influences the climate of the region. While the rainfall on and near the jabal is sufficient to support irrigated agriculture in small areas where there is aquifer storage, much of the region remains arid.

In the absence of a good coverage of synoptic data it is difficult to develop an understanding of the complex local interaction between the mountain range and the large scale climatic influences. The most useful general pattern has been developed by Pedgley[1] of the Anti Locust Research Centre, London from data collected during periods of a few years before 1970. During the present study we have had valuable discussions with Mr. T. Hoopes, the meteorologist at Seeb International Airport, on the cause of the storms of February, July and August 1975.

The climatic year can be divided into two distinct periods, the winter months of November to April with a predominant air flow from the north-west, and the summer months of June to September with a monsoon air flow from the south-west. May and October are months of transition between the winter and summer conditions.

Winter conditions arise from a general area of low pressure over the Indian Ocean extending over the low coastal areas of Oman. Modified polar troughs from the eastern

[1] Pedgley D. E. The Climate of Interior Oman, The Meteorological Magazine *99* No. 1171, February 1970.

Mediterranean can migrate in a south-easterly direction and orographic rain can result when these disturbances, usually led by a cold front, encounter the Jabal Akhdar or moist air moving inland from the Gulf of Oman.

Summer conditions are strongly influenced by the formation of the inter-tropical convergence zone, ITCZ, over the Arabian peninsula. This zone is the junction between two main air streams, the north-westerlies which are dominant over the Arabian Gulf and the south-west monsoon which is deflected to a south-easterly by the Arabian land mass. Normally the monsoon flow is shallow giving little rain inland. However, inputs of more humid air from the east or troughs crossing the Gulf of Oman from Iran trigger local storms.

The ITCZ forms in May and normally lies across the Arabian peninsula from Musandam to Aden. During September or October the north-westerlies replace the south-west monsoon and the ITCZ moves rapidly to the south away from the area. During some recent years the ITCZ has been forming further south than usual which has resulted in more stable and generally drier summer conditions.

During the transition months between summer and winter conditions, cyclones or cyclonic storms originating over the Arabian Sea migrate westwards towards the Oman coast usually near Salalah but occasionally as far north as the Gulf of Oman. There is little evidence that these storms penetrate as far inland as the study area. On the coast at Masirah, Pedgley[2] estimates that in the long term they account for as little as 5 percent of the rainfall.

In summary, the major factors governing the amount of rainfall and its geographical distribution and frequency of occurrence would appear to be the number of cold fronts crossing the area in the winter months and the position of the ITCZ in the summer. Generally May, June, October and November would be expected to have little rainfall.

The only historic rainfall records for the study area are the monthly rainfalls at Muscat and Nazwa shown in Tables 1.4 and 1.5. The daily records which have been traced are incomplete but serve to show that rainfall is usually intense with significant falls on only a few days each year. In no month is rainfall reliable and there is considerable variability from year to year. At Muscat the average annual rainfall from the 24 complete years of record is 99 mm. Seven out of the 25 years have less than 50 percent of the average and four of these, 1954, 1964, 1967 and 1974, have less than 25 percent of the average annual rainfall. At Nazwa the record is shorter and incomplete. However, 1964 and 1974, and possibly 1969, were years of low rainfall.

Despite the high variability from year to year there is a distinct seasonal pattern shown by the records. At Muscat rainfall tends to occur in the winter months December to April; only occasionally are there summer storms. At Nazwa the winter rainfall appears to occur mainly in February and April, less often in January and March, and rarely in December. However, there is rainfall in July in most years of the record with less frequent falls in August and September.

[2] Pedgley D. E. Cyclones along the Arabian Coast, Weather *24* No. 11 November 1969.

MONTHLY RAINFALL AT MUSCAT

(mm)

Year	J	F	M	A	M	J	J	A	S	O	N	D	Total
1951	0	0	62	0	0	0	0	0	0	1	0	6	69
1952	52	0	0	1	0	0	0	0	0	0	0	16	69
1953	2	27	0	0	5	0	0	0	0	0	0	15	49
1954	11	10	1	2	0	0	0	0	0	0	0	1	25
1955	97	7	70	0	0	0	0	0	0	0	0	14	188
1956	12	13	0	1	0	0	37	0	0	0	0	171	234
1957	109	0	0	62	9	0	0	0	0	0	9	36	225
1958	53	0	0	0	2	0	5	0	0	0	0	16	76
1959	11	0	24	0	0	0	0	0	0	0	69	12	116
1960	14	18	37	0	0	0	0	0	0	0	24	16	109
1961	2	0	2	12	14	0	1	0	0	0	2	1	34
1962	20	0	0	7	0	0	72	0	0	0	0	20	119
1963	0	2	0	25	94	0	0	0	0	0	8	11	140
1964	11	0	10	0	0	0	0	0	0	0	0	5	26
1965	23	0	0	83	0	0	0	0	0	0	2	0	108
1966	0	88	1	7	0	0	0	0	0	0	0	0	96
1967	0	0	1	8	6	0	2	0	0	0	0	6	23
1968	9	104	0	2	0	0	0	0	0	0	1	2	118
1969	26	2	15	2	0	0	0	0	0	0	0	0	45
1970	27	3	0	0	0	0	0	86	0	0	1	2	119
1971	15	0	0	0	0	0	0	0	0	0	38	45	98
1972	50	130	0	0	0	0	0	0	0	0	0	0	180
1973	97	0	0	0	0	0	0	0	0	0	0	0	97
1974	0	3	0	0	0	0	0	0	0	0	0	0	3
1975	0	64	0	0	0	0	0	0	0	0			

Note: 1. These data refer to a gauge at the British Embasy, except for the period March 1966 to December 1970 when the date refer to a gauge observed by PD(O) at Mina Al Fahal.

Of particular relevance to this study, it is evident that the period from August 1973 through the whole of 1974 to January 1975 was one of very much less than average rainfall over the study area. At Muscat this dry period started in February 1973. Thus the first 18 months of our period of field work were exceptionally dry and we were unable to observe the surface runoff and aquifer recharge processes until the widespread rainfall of February 1975. Also, because the study period was atypical of average conditions, it is more difficult to estimate the long term availability of water. In Chapter 7 we shall return to this problem which is essentially one of relating rainfall observed during the study period to the historic records.

TABLE 1.5

MONTHLY RAINFALL AT NAZWA

(mm)

Year	J	F	M	A	M	J	J	A	S	O	N	D	Total
1963	0	0	0	4	131	0	28	0	14	0	29	0	206
1964	6	12	7	29	0	0	21	0	0	0	0	7	82
1965	56	0	0	109	0	0	13	9	0	0	0	0	187
1966	0	20	0	0	0	5	48	6	6	26	0	0	111
1967	0	0	15	128	0	47	11	0	0	0	0	0	201
1968	5	157	0	24	0	0	0	0	0	0	0	0	186
1969							0	0	0	0	0	0	
1970		(62)					147	132	102				
1971												(75)	
1972	64	135	60	235	0	3	89	6	17	0	0		
1973	(54)						140						
1974			8	4	0	0	0	10	0	2	0		
1975	2	107	0	4	17	1	74	8	2	0			

Notes: 1. The gauge is at the experimental farm Nazwa.
2. Missing data are indicated by no entry in the Table.
3. Figures in parenthesis may not be a complete record for the month.

1.5 VILLAGES

Apart from a few small fishing villages, most of the villages and towns in northern Oman are integrated with areas of cultivation. Date gardens, often interplanted with fodder crops, account for much of the cultivated area, although south of the jabal cereals and vegetables are widely grown. The larger towns such as Nazwa, Bahla and Rustaq are important communication and market centres. Nevertheless they also have large cultivated areas which are usually divided among several sub-villages. Figure 1.5 shows all the principal villages and most of the smaller villages in the study area with the cultivated areas drawn to scale.

Throughout the region agriculture is dependent upon irrigation; rainfall is neither adequate nor reliable. Consequently villages have developed only where there was a reliable source of water which could be exploited by aflaj and hand-dug wells. Furthermore studies in similar environments suggest that the villages have grown to an extent whereby all the reliable water which could be exploited by these traditional methods is fully utilized.

Along the coast the villages and their gardens are arranged in an apparently haphazard distribution, each garden drawing water from a shallow hand-dug well. Separate wells situated in the zones of sweetest water are used for domestic purposes. Inland where aflaj are the main sources of water, wells are less common. The villages of mud-brick and, more rarely stone houses, are situated furthest upstream on the aflaj in order to utilize the best quality water for domestic purposes. Immediately downstream the main gardens extend to an area which is probably related to the reliable flow in the aflaj. At times of excess water other land is irrigated for annual crops and otherwise left fallow.

In recent years the input of modern technology has been having some effect on the traditional methods of cultivation. Deep boreholes enable groundwater resources to be tapped in areas where previously they could not be exploited, and pump-sets allow an increased rate of abstraction of groundwater. These developments have taken place principally on the Batinah coast where most wells now have pump-sets, and new farms not related to the traditional village structure are being brought into production. However, the boreholes which supply these farms are situated inland from the traditional gardens and are developing groundwater which previously would have been available to maintain the flow in the aquifer for use in the existing cultivated areas.

1.6 SOILS AND AGRICULTURE

Separate studies of the soils and agriculture in the study area have been undertaken by Sogreah and Ilaco as an integral part of this water resources study and the results presented in a draft final report dated April 1975[1]. We summarize here the principal findings of the studies.

The extent of land under cultivation in 1974 is shown in Table 1.6 classified by crop type and by region. Nearly half the 12 294 hectares under cultivation are on the Batinah coastal strip. The predominant crop is dates which account for 70 percent of the total hectarage.

TABLE 1.6

LAND UNDER CULTIVATION IN 1974

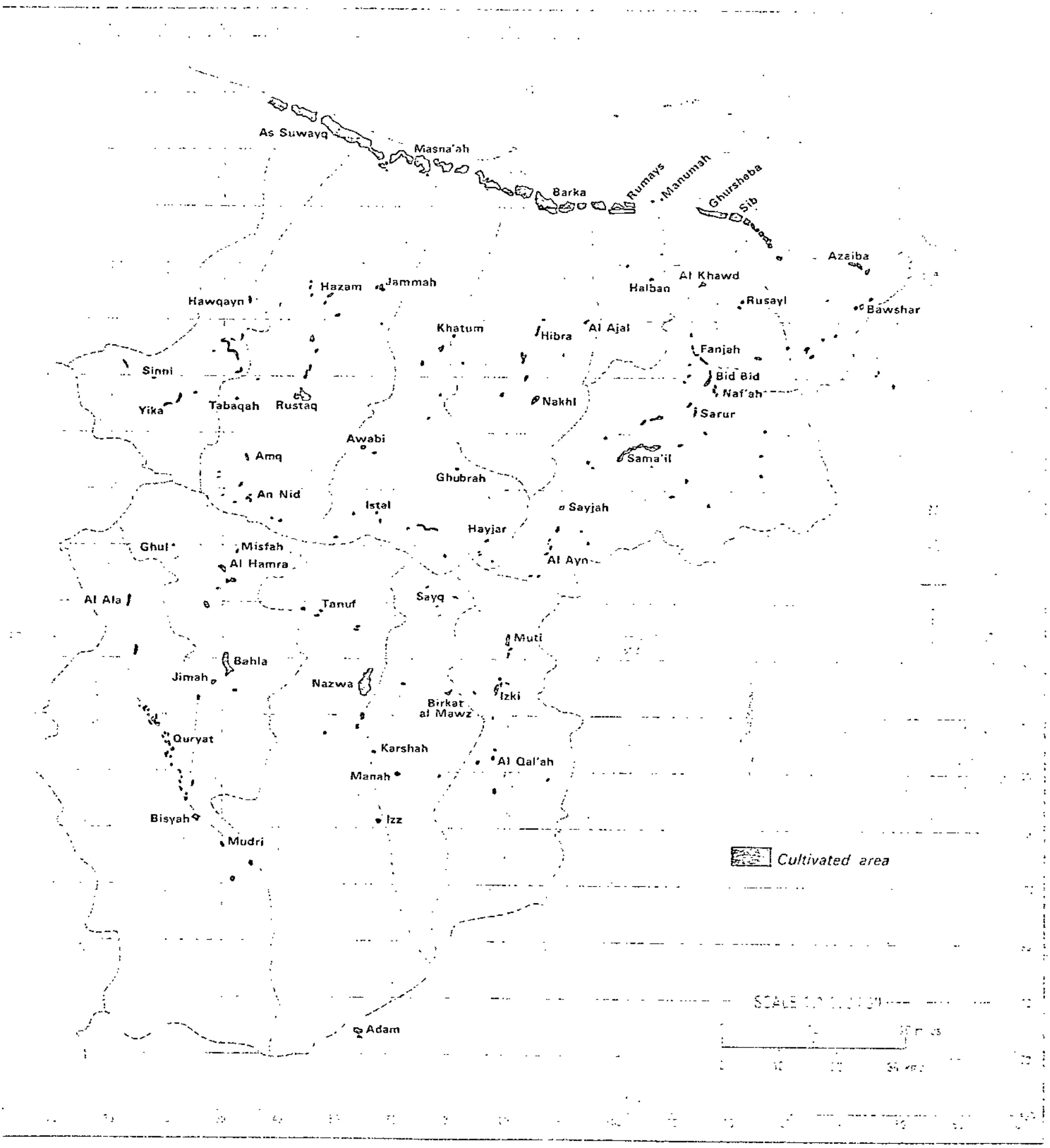
(ha)

Crop	Batinah Coastal Area	Northern Foothill Villages	Southern Foothill Villages	Southern Basins	Total
Date palms	4 800	2 367	866	675	8 708
Cereals (wheat)		121	634	626	1 381
Alfalfa	750	317	305	140	1 512
Vegetables	60	127	227	53	467
Fruit trees	200	—	—	—	200
Sugar cane	—	—	26	—	26
TOTAL	5 810	2 932	2 058	1 494	12 294

Note: This table is reproduced from "Water Resources Survey of Northern Oman, Draft Final Report on Phase 1 Soils and Agricultural Studies, April 1975".

The annual water use in those areas relying on groundwater, namely the Batinah coastal strip and those areas termed the "southern basins" in Table 1.6, was estimated to be 65 million m^3 and 20 million m^3 respectively. For the Batinah this figure is broadly in balance with our interim water resources assessment presented with the soils and agriculture report.

[1] Water Resources Survey of Northern Oman, Draft Final Report on Phase 1 Soils and Agricultural Studies with an Interim Water Resources Assessment.



Villages and Cultivated Areas

Figure 1·5

The constraints on agriculture development from the point of view of soil were judged to be salinity, principally on the Batinah, and the shallow arable layer and impeded drainage of the inland areas. Using the USBR standards for land classification there are 31 500 hectares of land suitable for cultivation on the Batinah of which 5 800 hectares are in use at present. Elsewhere there are additional areas not under cultivation amounting to 2 900 hectares at Quryat, 510 hectares bordering on cultivated areas and 675 hectares widely scattered. A further 1 700 hectares were considered suitable for crop intensification.

From the interim water resources assessment it is likely that agricultural development on the Batinah coast and at Quryat will be limited by the available water resource. Elsewhere the major constraint will be the absence of large compact areas suitable for development.

The recommendations for development were therefore cautious. From a study of the domestic market for agricultural products it was recommended that 50 percent of the cultivated area should be devoted to fodder crops combined with livestock production, the remaining 50 percent being retained for crops of lower commercial value including dates, cereals and groundnuts. Also in the long term it was considered that there was a strong case for relocating the cultivated area at the coast a few kilometres inland to take advantage of less saline soils. Production units of 100-200 hectares were recommended.

CHAPTER 2

THE METHOD OF STUDY

2.1 THE HYDROLOGICAL SYSTEM

The principle of continuity is fundamental to our analysis of the hydrology of the study area. Stated simply, the input to the hydrological system must be balanced by the output together with any increase in storage within the system. In practical terms the rainfall on the study area must be balanced by losses to the sea in the north or to the desert in the south together with losses by evaporation, and by changes in the storage of the various aquifers. This principle can be applied on any smaller scale within the study area. For example we can analyse the water balance of the hardrock areas separately or regard any of the aquifers as an individual sub-system.

Using the northern basins as an example, we have illustrated the hydrological system in Figure 2.1. On a simplified cross-section of the northern flank of the Jabal Akhdar and the Batinah alluvial plain we have superimposed the input and outputs of the system and the main transfers of water within it.

Rainfall, the input to the area, will tend to be higher on the hardrock jabal areas where some of the rainfall will form surface runoff in the wadi channels, and some will be lost by direct evaporation of the water held in shallow depressions or soil storage. The remainder of the rainfall will infiltrate the mountain limestone aquifer to increase its storage and hence maintain the outflow from this storage through springs. On the alluvial areas which are at lower elevation, rainfall will generally be insufficient to cause direct recharge of the aquifers. Our initial hypothesis is that this rainfall is held in shallow storage and is lost to the system by direct evaporation or through transpiration from the natural vegetation.

Following rainfall on the jabal the flows in the wadis will leave the hardrock areas and enter the piedmont areas and the alluvial plains still in confined but broader wadi channels. Some of this flow will reach the sea and be lost from the system, some will remain in the wadi channels when the flood wave has passed and be lost by evaporation, and some will infiltrate to cause an increase in storage in the alluvial aquifers. Further recharge to the alluvium can occur by direct transfer of water from the hardrock units through springs. Several major springs are visible and it is possible that sub-surface springs exist where the spring line in the Hajar Super-Group is overlain by the wadi gravels of the piedmont areas.

Within the aquifer of the alluvial plains there will be a gradual movement of groundwater towards the coast and under natural conditions there would be a loss of fresh water to the sea. Because of the potential for storage of groundwater and the relatively high resistance to flow within the aquifer, the highly variable recharge inputs are damped to give a much more slowly varying output. This means that even during a prolonged dry period with little recharge, the movement of groundwater through the aquifer would continue for a substantial period of time.

Superimposed on this essentially natural system there are various transfers and losses as a result of man's use of water for agricultural, industrial and domestic purposes. We have shown some of these transfers on Figure 2.1. The falaj systems of the jabal foot villages take water from springs in the hardrock areas or from storage in the gravels of the wadi channels. Shallow wells particularly near the coast draw water from the alluvial aquifer as does the increasing number of deeper modern boreholes. The total abstraction may be such that there is no longer a natural loss of freshwater to the sea.

All these activities cause a loss of water from the system but some care is needed to define the losses correctly. At the coastal date gardens for example not all the water withdrawn from the wells is lost. A proportion of the irrigation water will return to the aquifer because of the tendency to over irrigate. Where there is export of water from one basin to another such as the abstraction in the Wadi Sama'il basin for the water supply of the Capital area, the quantity must be accounted as a loss from the Wadi Sama'il and in this case from the study area, despite the fact that some of this water might appear as recharge to local aquifers in the area of use.

Finally there are losses which are more difficult to define related to the movement of water along the fracture zones of the massive limestone formation of the jabal. It is possible that water infiltrating the mountain limestones could reappear over a long period of time in other parts of the formation far from the study area. A wider and more detailed study would be required to identify these losses.

2.2 OBJECTIVES AND METHOD OF STUDY

At the start of the study the most promising areas for future development of water resources appeared to be the alluvial deposits to the north and south of the jabal. Thus our terms of reference defined four major objectives:—

(i) to assess the characteristics of the alluvial aquifers in terms of their ability to accept, store and transmit water,

(ii) to determine the major sources of recharge to these aquifers and to make a preliminary estimate of their average rate of replenishment and hence their long term yield,

(iii) to examine the possibility of enhancing this rate of replenishment by reducing losses of freshwater to the sea or elsewhere,

(iv) to assess the potential of the bedrock as an aquifer.

Our method of study was fundamentally influenced by the general lack of data throughout much of the area. Thus the major part of our effort had to be directed toward the collection of primary data before any worthwhile analysis could take place. It was expected that in this varied and difficult terrain accurate measurement of many of the variables would not be easy. We recognized that it would be necessary to build up a basic qualitative understanding of the processes of runoff, recharge and groundwater flow in order that the relatively sparse data could yield useful quantitative estimates of water resources.

In order to meet the major objectives we established three related fields of investigation.

The first, a study of the surface water hydrology, was concerned with collecting sufficient records of rainfall and the resulting wadi flows to determine the proportion of rainfall which is available for recharge in the alluvial areas. In this way, we could endeavour to use the limited historic rainfall records to derive preliminary estimates of the long term flows.

The second field of investigation was concerned with the hydrogeology of the aquifer systems. We aimed to determine the physical constraints governing the availability of groundwater by considering the lithology of the aquifers and the transmissivity and storage characteristics of the various horizons. Since the basic data required for these analyses were available for only a very limited area we needed to devise an extensive programme of field exploration over the large area of alluvium north of the jabal. Using the techniques of flow net analysis and a groundwater model we then aimed to determine the flow through the aquifer and to relate this to the configuration of the water table and the changes observed following recharge.

Our third field of investigation was to survey the sources and use of water in the towns and villages. It was anticipated that the balance between resource and use would be close and that abstractions for irrigation would play a significant part in the water balances of the alluvial areas. Also in the absence of any direct hydrogeological exploration of the bedrock areas, the survey would provide the information necessary to assess the aquifer potential of the bedrock.

2.3 CHOICE OF BASINS FOR INTENSIVE STUDY

The extent of the study area, some 14 500 km², of which almost 6 000 km² is alluvium, suggested that a better understanding of the hydrology of the whole region would be achieved by more intensive study of a few carefully selected basins. The more detailed knowledge of the behaviour of these "representative" basins could then be used as a basis for interpreting the less intensive observations on the remainder of the study area.

The validity of this approach depends on there being groups of wadi basins which respond hydrologically in a broadly similar manner. The general patterns of geology, topography and climate discussed in Chapter 1 suggest that there are three distinct basin groups: the basins to the north of the jabal, those to the south, and the group comprising the Wadi Sama'il and Wadi Halfayn.

The choice of basins representative of these groups was influenced mainly by the difficulty of finding suitable sites for wadi gauging stations. Our aim was to gauge wadi flows at the boundary of the hardrock area, at the points where the piedmont gravels gave way to the main alluvial tracts and also at the boundary of the study area. A lesser constraint was that the representative basins should contain substantial cultivated areas. These criteria were best met by the Wadi Bani Kharus of the northern basin group and the Wadi Bahla in the south. The Wadi Sama'il because of its importance as the source area for water supply to the Capital area, required detailed study in any event and was therefore selected as the third representative basin.

The main effects of this approach, whereby some basins were observed more intensively than others, were limited to the programmes for the survey of existing water use and gauging of surface flows in the wadis. The distribution of raingauges and the exploration of the alluvial aquifers were little affected: the measurement of rainfall is equally important in all basins and the estimation of groundwater flows requires detailed knowledge of the lithology and hydrogeological characteristics of the aquifer units in each basin.

2.4 RAINFALL AND METEOROLOGICAL MEASUREMENTS

Raingauge Network

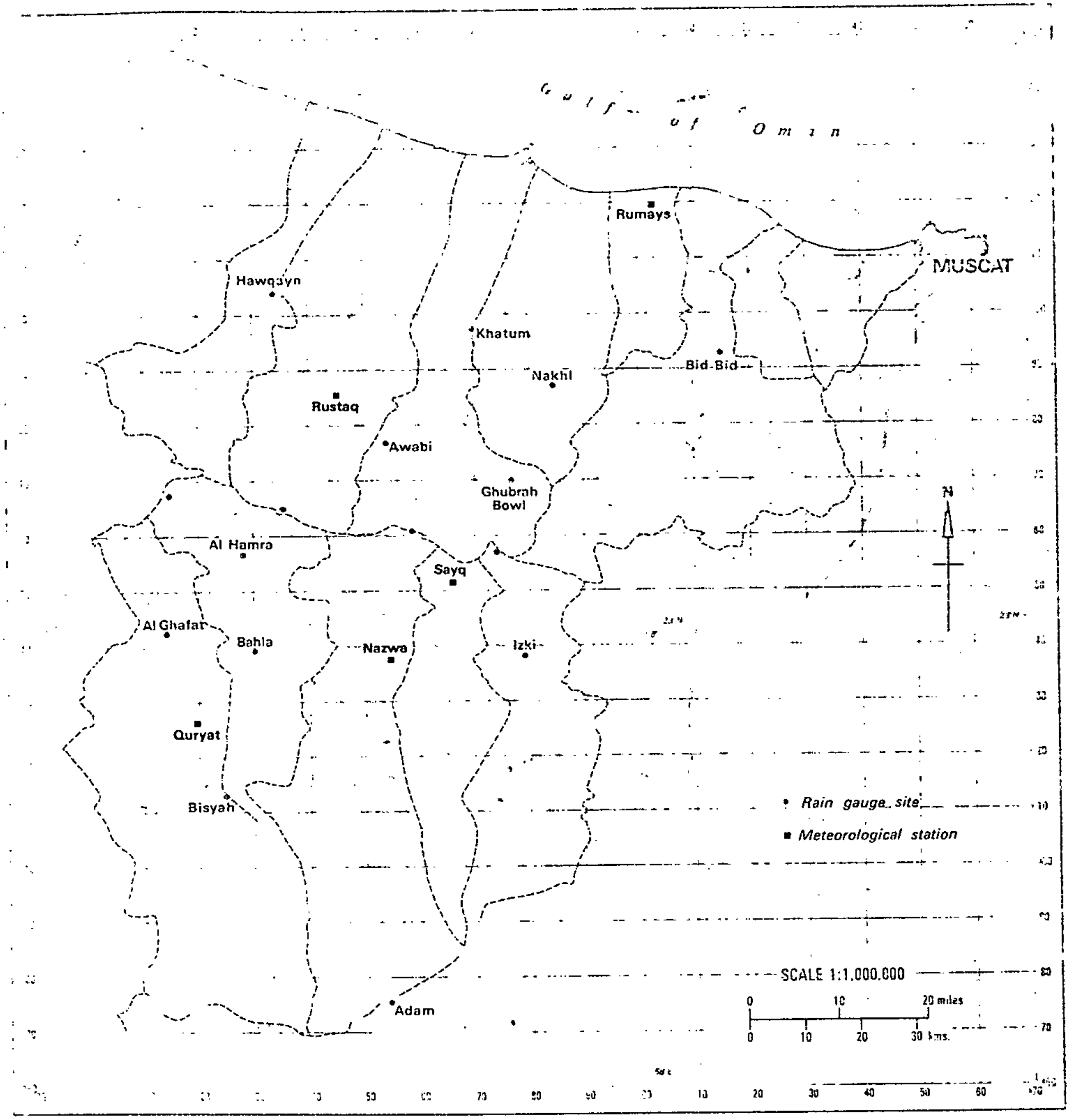
Prior to 1973 the only raingauges in the study area were at the Nazwa experimental farm and the army camp at Bid Bid. Records from the Nazwa gauge have been presented in Chapter 1 together with a longer record from gauges at Muscat and Mina al Fahal which are just to the east of the study area. Records from the Bid Bid gauge are available only from March 1972. Thus at the start of the study there was little information on the distribution of rainfall in the area and none on the rainfall which might be expected on the high jabal.

Our principal aim in setting up a regional network of raingauges was to determine the average rainfall on the hardrock areas in each wadi basin for each major storm. While sites for gauges were not difficult to establish in villages in and around the foothills of the jabal, ease of access to the high altitude areas severely limited the number of gauges which could be deployed. We were assured of regular helicopter support and it was possible to install 5 gauges on the jabal in addition to one at the army camp at Sayq. The location of these gauges is shown on Figure 2.2; four of the locations are unnamed, the fifth is in the Ghubrah Bowl.

A further 15 gauges were installed in villages around the jabal. They were all accessible by Land Rover and were visited at least once per month and more frequently during periods of rain. We anticipated that ultimately local observers could be found to ensure daily observations of these gauges. Meanwhile at four locations, Rumays, Nazwa, Rustaq and Sayq, recording raingauges were installed as part of comprehensive meteorological equipment. These gauges give a continous record on a daily chart from which the duration and intensity of rainfall can be determined.

Meteorological Stations

The transpiration of water by irrigated crops and the evaporation of water directly from wet soil is controlled largely by the prevailing meteorological conditions assuming an adequate supply of water to the crops. Thus it is possible, using meteorological records alone, to estimate the rate of water use in the cultivated areas. We set up four meteorological stations early in the study period: two are on experimental farms, those of Rumays and Nazwa,



Location of Raingauges and Meteorological Stations

Figure 2·2

one is at Rustaq to show whether there is a significant variation in meteorological conditions between the coast and the foothill villages on the Batinah, and one is at Sayq which samples the high altitude area of the main jabal. Towards the end of the study period we set up a fifth station at the Quryat experimental farm.

Each station is equipped with instruments to measure the variables required in the Penman equation which is one of the best methods available for estimating potential evaporation and transpiration. Solar radiation is measured directly by Kipp solarimeter attached to a Lintronic integrating counter which gives a total for each day. A Campbell-Stokes sunshine recorder is used as a secondary measure of radiation. Wind spead is measured in kilometres per day by an anemometer mounted at a height of ten metres above ground level. The wet and dry bulb temperatures and the maximum and minimum temperatures are recorded when the station is visited at 0800 hours local time each day.

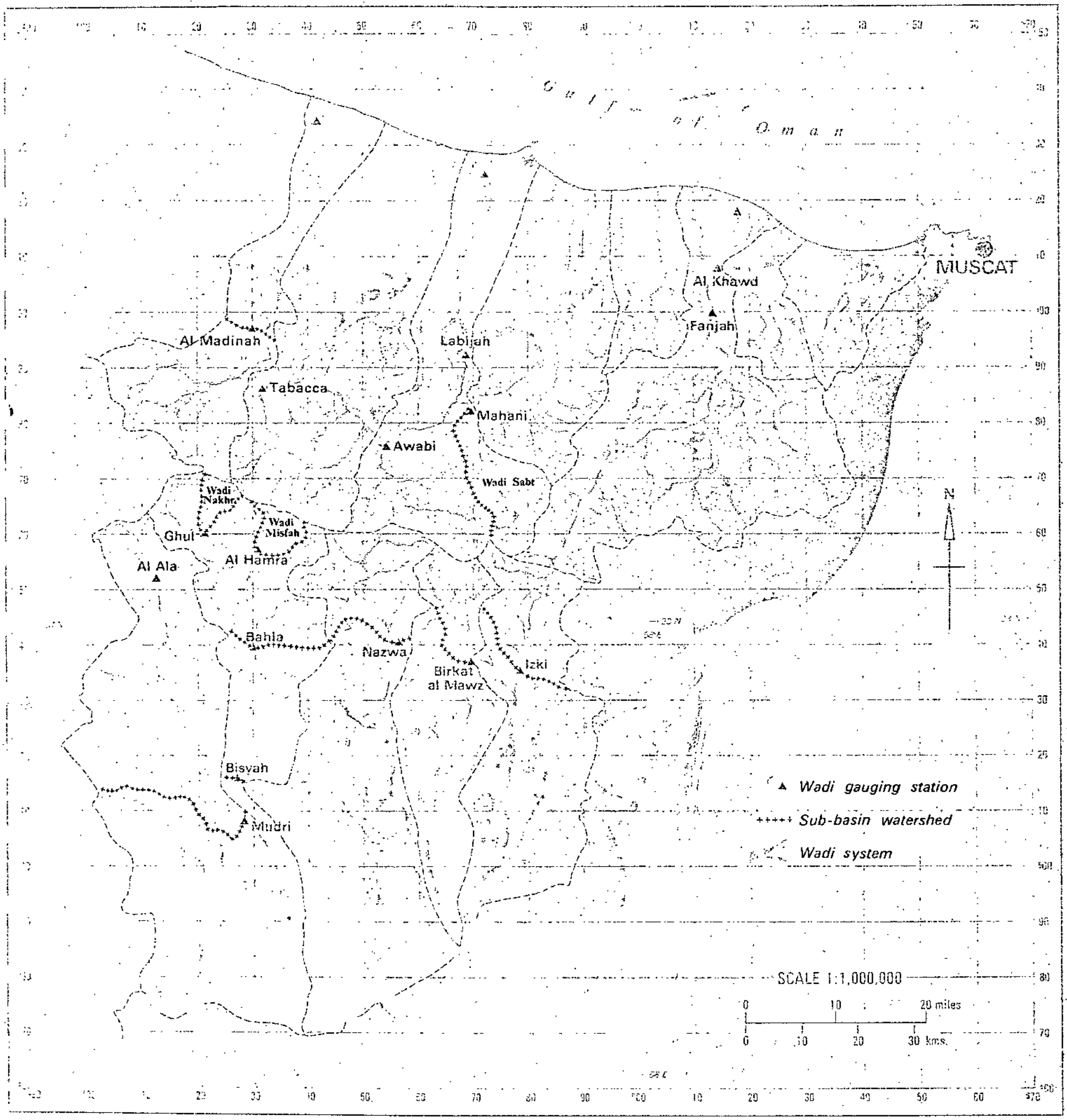
2.5 MEASUREMENT OF WADI FLOWS

There are no permanent surface flows in the wadi basins of the study area but some wadis such as the Wadi Sama'il above Al Khawd and the Wadi Bahla at Bahla do have long periods of base flow. Where the wadis pass through areas of impervious rock these flows appear mainly on the surface. However, there is only one site, at Bahla, where the rock bar is clear of the wadi gravels and the total flow is seen on the surface; elsewhere there is a small sub-surface component of flow in the gravels.

After periods of heavy rain the flows in the wadis are short, violent events. Debris left after floods prior to this study indicated that even in wadi channels up to fifty metres wide, water levels reached several metres in depth. Because the channels are relatively steep, velocities of flow would be high and these flood flows would represent substantial volumes of water which could be a significant source of recharge to the alluvial aquifers.

The method of measurement had to be indirect; the wadis particularly in the hardrock areas are inaccessible during floods so that direct observation and measurement is rarely possible. Consequently we installed float operated water level recorders mounted on stand-pipes anchored to solid rock at the side of the wadis. A careful survey of each site was made immediately after each major flood and, using an empirical method, we related area of flow and velocity to the recorded depth of flow and hence obtained the flow rate for each depth. We used Manning's equation which is described fully in Appendix B.2.

The sites chosen for wadi flow measurement are shown in Figure 2.3. Most of the major wadi basins have at least one gauging station. In some basins there was no suitable site on the main wadi channel but a large area of the basin could be covered by a station located on one of the tributaries of the main wadi. In the representative basins we selected sites at several points on the wadi system. In the Wadi Bahla basin we installed gauging stations on two sub-basins in the hardrock areas, the Wadi Nakhr near Ghul and the Wadi Misfah just east of Al Hamra. Further downstream we installed a station in the main wadi near the town of Bahla, and also at Bisyah after the wadi has crossed some 30 km of alluvium. By means of these successive gauging points we could observe where gains and losses to the wadi flows occurred and relate them to rainfall and recharge respectively.



Location of Wadi Gauging Stations

Figure 2·3

The pattern of measurement in the Wadi Bani Kharus is similar to that of the Wadi Bahla. The two major sub-basins are gauged at Awabi and Mahani, and the total flow is gauged just upstream of Labijah where the wadi passes through the ophiolites. In addition we installed gauging stations on the upstream side of the coast road in the Wadi Bani Kharus, Wadi Bani Ghafir and the Wadi Sama'il in order to assess the reduction in surface flow as these wadis cross the Batinah coastal plain. Inevitably these coastal sites are relatively poor because the wadis are very wide and shallow near the coast.

2.6 GROUNDWATER STUDIES

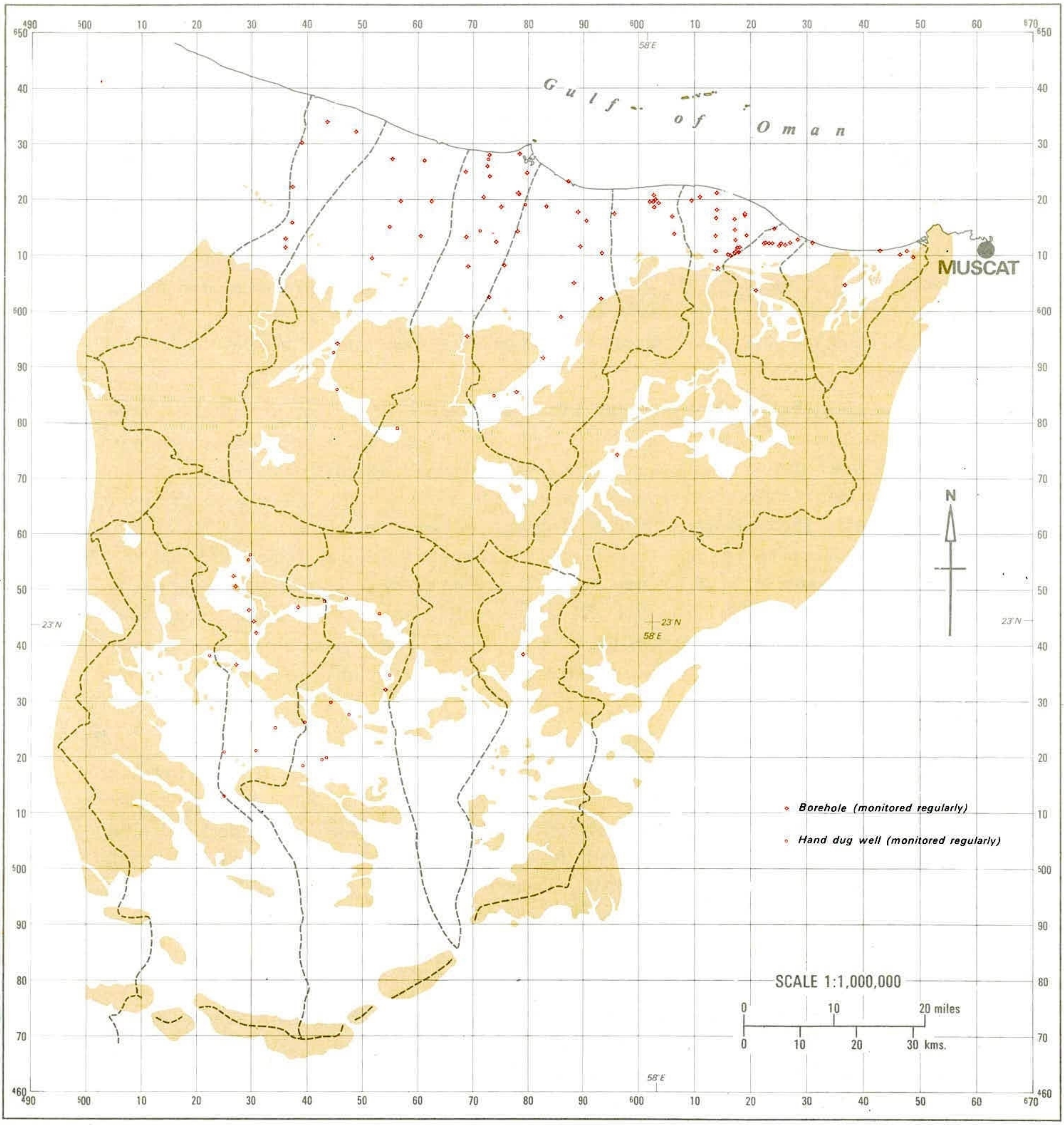
The groundwater studies were based on a programme of exploratory drilling in the alluvial deposits whereby we could determine the extent, nature and interdependence of the aquifer systems in each major basin from the foothill valleys through the wadi gravels of the water courses to the sediments of the plains. We have not made a direct study of the groundwater resources of the hardrock areas but we have based an evaluation of their potential on information collected in the foothill villages during the survey of existing water use.

The Northern Basins

With the exception of a narrow coastal strip and a small inland area in the Wadi Sama'il basin, the alluvial aquifers were largely unexplored prior to this study. However, a contract for tube-well construction was in progress with the purpose of establishing groundwater supplies outside the main village areas. We were able to use part of this contract as the first stage of an exploratory drilling programme and we sited 38 boreholes at widely scattered locations across the Batinah plain, usually near major tracks. Five boreholes were located in the piedmont zone primarily to observe groundwater transfers to the Batinah plain. These were at Al Khawd in the Wadi Sama'il, near Nahkl in the Wadi Ma'awil (2 wells), at Labijah in the Wadi Bani Kharus and in a narrow neck of gravels downstream of Rustaq in the Wadi Far. The remaining 33 boreholes were constructed between the piedmont zone and the coastal villages.

The existing contract covered the construction of boreholes up to 70 m deep. Special contractual arrangements were made for deeper exploration of the lithology in those areas of the Batinah plain where depths to groundwater were known to exceed 60 m. Nearer the coast the water table was closer to the surface but we needed more information on the nature of the deeper layers of the aquifer than was being provided by the production boreholes. We were able to site 13 boreholes along the 120 km coastline. Nine of these provided sites for monitoring water levels and determining the nature of the coastal sediments and the quality of groundwater in the zone where saline intrusion was expected. Also four 300 m deep observation boreholes were drilled to penetrate the saline groundwater zone which had been intersected by the shallow drilling. These boreholes were perforated throughout their depth below the water table so that using in-situ logging we could determine the movement of the saline interface and examine whether any fresh water was present below the main interface.

This network of boreholes together with some of the existing wells were visited regularly to monitor water level changes. The full network is shown in Figure 2.4. Monthly



Location of Wells and Boreholes

Figure 2·4

observation was sufficient during periods of recession; following periods of recharge from wadi flows we undertook more frequent observations.

Despite the technique of mud-flush drilling used in the existing contract, we were able to examine the lithology of the sediments at most of the borehole sites. Also the yield/depression characteristics obtained during test pumping enabled us to derive a rough estimate of the transmissivity of the aquifers. We could not carry out detailed pumping tests to improve these estimates or to determine storage coefficients because the existing contract did not provide for the construction of observation boreholes.

The Southern Basins

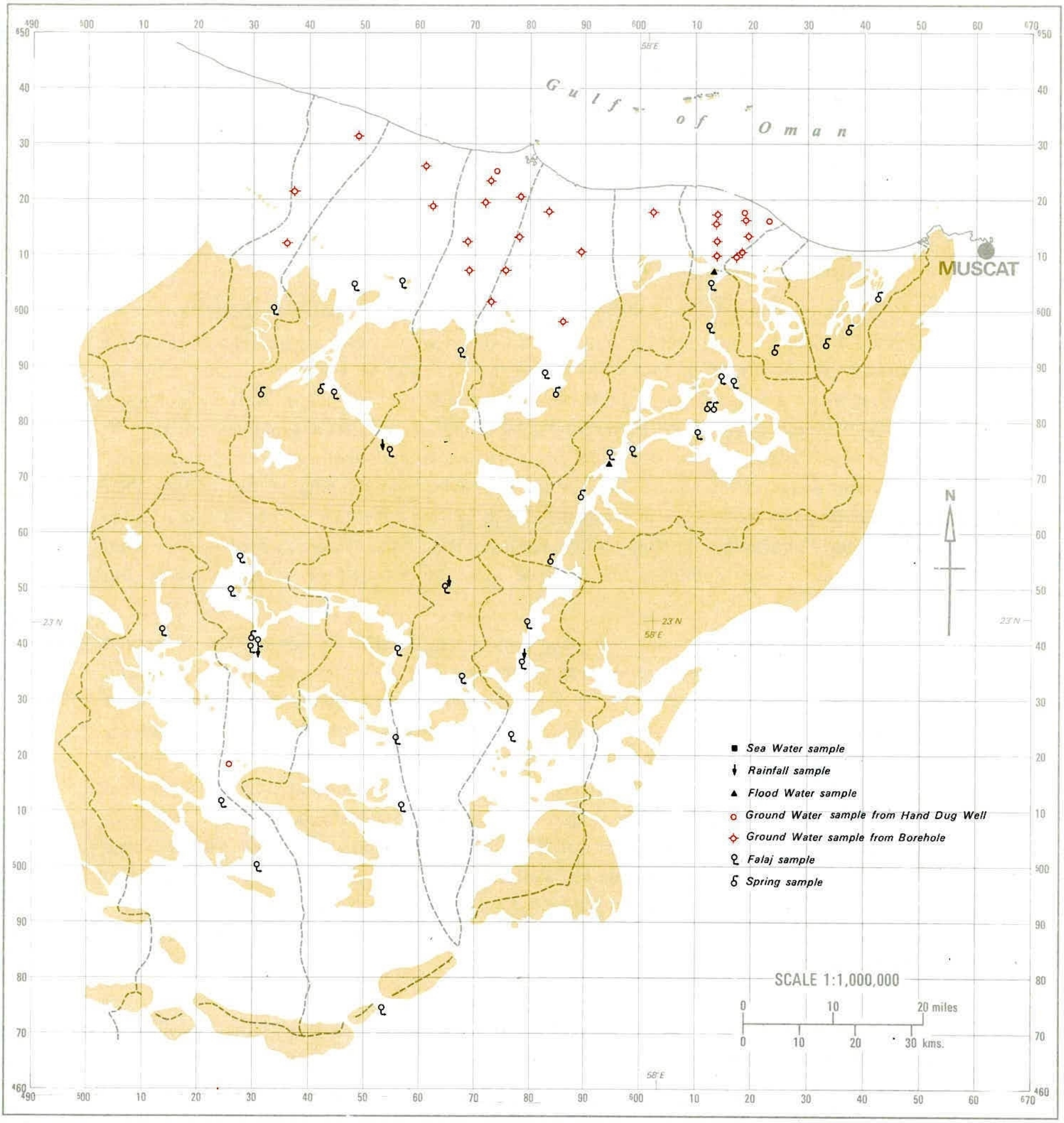
Our study of the alluvium of the southern basins had a different emphasis from that followed in the north: the shallow alluvium and the numerous rock outcrops indicated that extensive lateral connections between basins did not exist. Exploration was therefore planned along the main wadi channels and particularly at those sites where the alluvium was confined within narrow channels.

Early in the study, proposals were made for the construction of exploratory boreholes through the existing drilling contract being carried out in the north. However, we were unable to move the drilling rig south of the jabal because of priorities for the construction of production wells and our own exploration work in the northern basins. Detailed specifications were therefore prepared for a complete programme of exploration and test pumping in the south as a major part of a special water resources contract which was to include similar work for Ilaco and Renardet in their study areas. The recommended contract also called for the construction of boreholes in the Batinah area where detailed pumping tests with observation boreholes would improve our estimates of transmissivity. In the event, this programme was not implemented and our main hydrogeological survey of the southern basins could not take place.

Notwithstanding, we established routine water level observations in 18 wells and 8 abandoned boreholes located mainly in the Wadi Bahla basin. Thus we were able to collect some information on aquifer response during the period of the study. Sub-surface exploration was limited to a reconnaissance resistivity survey between Nazwa and Adam organized by the Water Resources Centre in Oman. The preliminary results obtained by the Compagnie Generale de Geophysique were made available to us and they form the only other hydrogeological data collected in the southern basins during the period of our study.

Supporting Studies

Water samples for chemical analysis were taken at all boreholes drilled after the start of the study and at many of the wells visited during the study. While largely a matter of routine, this intensive sampling programme provided a basis for assessing the origin of the groundwaters. During the study we extended this part of our programme to include samples for Tritium, Deuterium and Oxygen-18 analysis. Tritium concentrations can indicate the relative age of groundwaters and can, in certain situations, provide a basis for estimating the proportions of "old" hardrock and "young" wadi gravel water in the aquifers. The sites where samples were taken for isotope analysis are shown on Figure 2.5. Chemical analyses are



Location of Samples Selected for Isotope Analysis

Figure 2·5

also available for these sites but we have not attempted to show the location of all 700 chemical sampling points; full details of these are given in Appendix E.3.

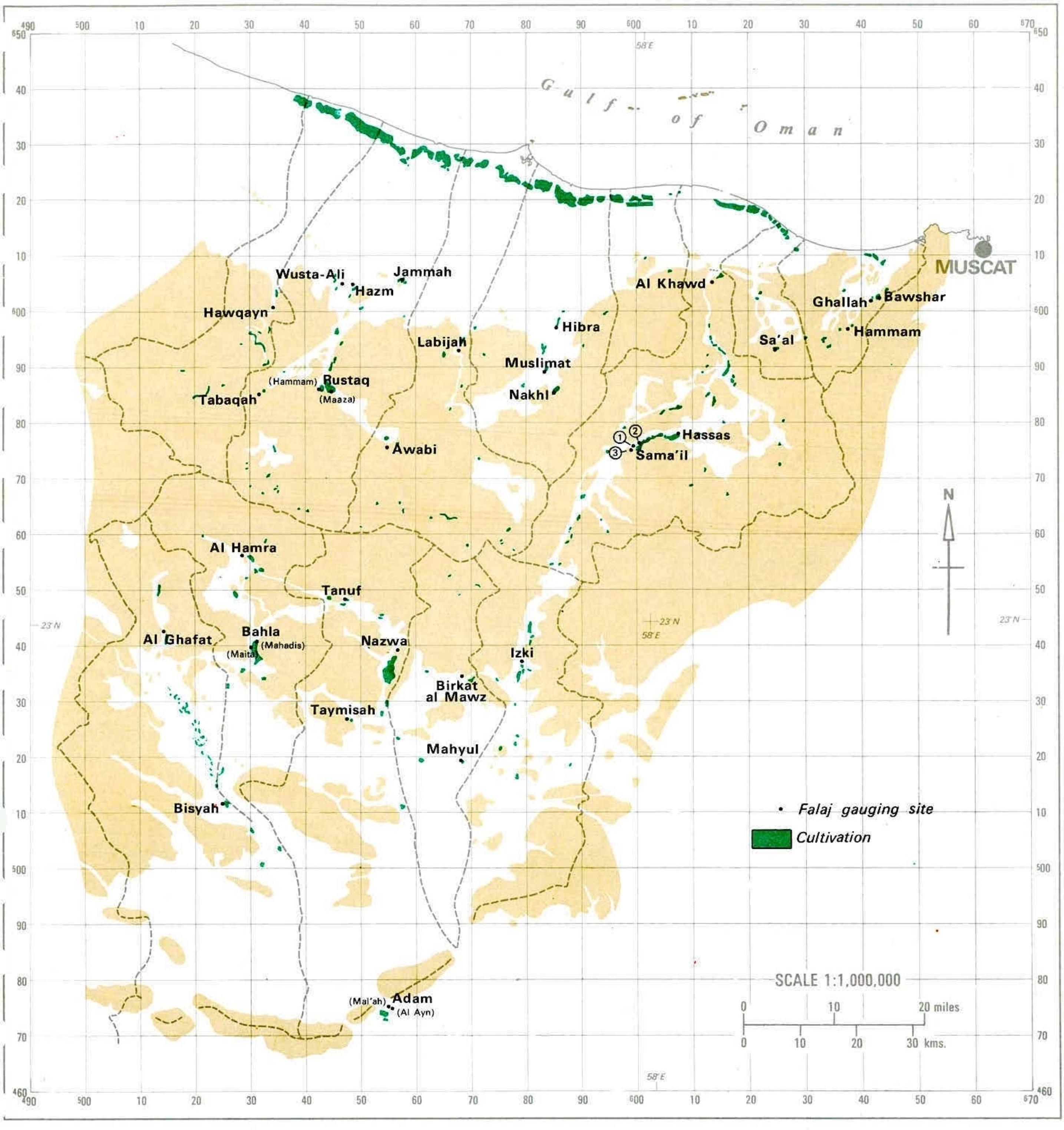
During the study it became clear that the older cemented gravels of the Batinah plain strongly influence the distribution of groundwater, well yield and recharge potential. We therefore made detailed geological studies of the distribution of these gravels and the results are summarized in the geological maps presented in Appendix C.1. The maps were prepared from field notes supplemented by photogeological interpretation of the 1:20 000 scale aerial photography flown in November 1974. We were unable to extend this detailed work to the southern basins as the photographs of this area were not available to us.

2.7 SURVEY OF EXISTING WATER SOURCES

It is evident that the villages and their associated agricultural areas have been established in places where there is a reliable source of water which can be exploited by the traditional methods of aflaj and hand-drawn wells. Although village development could be constrained by poor soil, salinity or flood hazard, the pattern of villages is likely to be a good indicator of the major sources and drainage lines for reliable water. In general these agricultural areas represent the major water use in the study area excepting only the demand for industrial and domestic water in the Capital area which is drawn from the alluvial fan of the Wadi Sama'il. Within the framework of the hydrological system described earlier in this chapter the villages have two functions. They are major points of loss in the system through transpiration from the cropped areas and they are involved in artificial transfers of water within the system.

Our survey of water use had three main aims. Firstly, we determined the source of water in each village and attempted to define the origin of the water using its chemical and isotopic characteristics as indicators. Secondly, we estimated the quantity of water available by measuring the falaj flows and monitoring well yields. Sampling techniques were necessary to cover the large number of water sources, and the larger aflaj indicated on Figure 2.6 were monitored regularly to assess the variability of flow. Thirdly, we estimated the volume of water lost by transpiration and evaporation from the soil in the irrigated areas. We have relied to some extent on the studies carried out by Ilaco and Sogreah although the new large scale aerial photography of November 1974 allowed a revision of their estimate of cropped area. As far as possible we have taken account of the seasonal variations in water use although the effects of the long dry period in limiting supplies to many villages has tended to obscure the normal seasonal pattern.

The survey has concentrated on the basins chosen for intensive study. The importance of the agricultural areas near the coast was recognized and intensive studies of water use were undertaken in the coastal areas in the Wadi Sama'il and Wadi Bani Kharus basins. In these representative basins our aim was to determine the pattern of water availability and use in the basins as a whole thereby determining the degree of interdependence of the village groups and their response to variations in the availability of water.



Location of Falaj Gauging Sites

Figure 2·6

CHAPTER 3

THE AQUIFER SYSTEMS OF THE NORTHERN BASINS

3.1 INTRODUCTION

The alluvial deposits of the Batinah, the major aquifer of the northern area, form a single groundwater basin composed of sediments deposited in a series of coalescing gravel fans. Boulders and coarse gravels occur near the mountains and become progressively smaller in size as the distance from the mountains increases. The alluvium contains relatively fresh groundwater which drains northwards toward the sea, the best quality water being present at the mountain foot, and the poorest at the coast where freshwater mixes with sea-water and brines.

The boundaries of the alluvial aquifer system are defined to the north by the coast and to the south by the mountain foot. The topographical watershed of the Wadi Bani Ghafir marks the western extent of our investigations but not the western limit of the groundwater basin. To the east the main groundwater basin includes the gravels of the Wadi Rusayl but does not extend into the Wadi Lansab basin where a thin alluvial cover overlies Tertiary limestones of poor aquifer potential[1].

In this chapter we examine the nature of the alluvial sediments and the characteristics of the aquifer system leading to an estimate of groundwater flow to the coast, using flow-net and simple mathematical modelling techniques. For the period which included most of 1974 when there was little rainfall and therefore no recharge from surface flows in the wadis, we estimate the changes in storage in the aquifer and discuss the extent of sub-surface base flow inputs at the mountain foot. Recharge from surface flows in the wadis forms part of the analysis of observed storm events in Chapter 6.

An outline of the groundwater resources of the Batinah by Burdon[2] provides the first basin-wide hydrogeological appraisal of the area. This work which was part of a Preparatory Assistance Mission of FAO included a detailed review of most of the geological and hydrogeological studies prior to 1972. Burdon recommended that there was no justification for an immediate study of the hardrock aquifers, but that hydrogeological controls affecting yields from the alluvial aquifers should be studied since boreholes had been constructed only where water was required and that some rather poor results had been obtained.

[1] Water Resources Survey Wadi Lansab Area, Brian Colquhoun and Partners, May 1975.
[2] Burdon D.J., Technical Notes on Water Resources of the Sultanate of Oman, FAO Preparatory Assistance Mission, December 1972.

Burdon's assessment was based on data contained in a series of reports on water supplies to the Petroleum Development (Oman) complex at Mina al Fahal and to Muscat and Matrah. These studies were concerned only with the alluvial deposits of the Wadi Sama'il and the resources estimates were based upon the size and storage characteristics of the aquifer and on the probable recharge to the system using records of base flow in the wadi at Al Khawd. Our analysis supports the general conclusion that current abstractions for water supply have little effect on existing users at the coast. However, we have found that the Wadi Sama'il is the only alluvial basin which appears to have scope for additional groundwater development and that extrapolation of these results to other basins has led to an over optimistic indication of groundwater resources in the FAO report.

The drilling carried out during the present study has included general exploration in areas other than those of most obvious groundwater potential, and has shown that the Batinah alluvial deposits are not uniformly good aquifers. They are poorly sorted deposits with thick sequences of conglomerates and cemented gravels. The presence of these beds was recognised in all of the previous investigations. In the earliest, van de Meer Mohr[3] described them as gravel conglomerates while Newbery[4,5] reports the occurrence of lime-cemented and marly gravels of poor aquifer potential below thin deposits of loose gravels. Bolliger[6,7] described the sediments as polygenic conglomerates and sands, partly with dolomite cement, but probably with silty material. Two investigations by Scott Wilson, Kirkpatrick and Partners[8,9] refer to cemented gravels and secondary cementation of gravel, and described the relatively plentiful occurrence of groundwater as being limited to areas where the coastal plain is narrow.

3.2 BASE FLOW INPUTS TO THE ALLUVIUM

There are two sources of base flow recharge to the alluvial aquifer. These are groundwater flow through the boulder beds and thin gravel deposits of the mountain valleys, and direct transfers from the hardrock springs at the mountain foot. The relationship between drainage pattern, hardrock geology and the distribution of alluvial deposits, illustrated in Figure 3.1, determines the relative importance of these two processes.

Most of the mountain wadis reach the alluvial plain only after passing through deeply incised valleys in the foothills of Hawasina or Sama'il rocks. Springs where they exist are small, seldom more than seepages, and they do not form an important source of base flow. Any recharge must derive from dewatering of the thin alluvial deposits of the wadi channels and any small alluvial basins within the hardrock area. We show in Chapter 4 that these flows are significant but are used largely for irrigation in the villages at the mountain foot so that the net recharge to the alluvial aquifer is small.

[3] van de Meer Mohr H.E.C., Water Possibilities for the Sayah at Maleh Camp Site, International Training Centre for Aerial Survey-Delft, January.1966.
[4] Newbery J., Preliminary Evaluation of Groundwater Sources, Muscat and Matrah Water Supply, Scott Wilson, Kirkpatrick and Partners, May 1966.
[5] Newbery J., Report on Borings for Water in the Sib Fan, Muscat and Matrah Water Supply Report, Scott Wilson, Kirkpatrick and Partners, October 1969.
[6] Bolliger W., Sib Water Supply, Petroleum Development (Oman) Ltd., August 1971.
[7] Bolliger W., Fresh Water Prospects in the Area Mezoon, Petroleum Development (Oman) Ltd., August 1971.
[8] Water Supply Investigations: Northern Oman Geophysical Survey, Scott Wilson, Kirkpatrick and Partners, 1971.
[9] Report on Water Supply Investigation, Northern Oman, Scott Wilson, Kirkpatrick and Partners, 1972.

In the Wadi Ma'awil and Wadi Far basins the coastal plain sediments extend through the piedmont zone to the edge of the main limestone massif. There the base flows from the mountain wadis are less important than the groups of large springs such as those at Rustaq and Nakhl which have discharges of at least 100 l/s. The survey of current water use in Chapter 4 shows that these flows are used for irrigation within the piedmont areas. However, the spring flows are sufficiently large to suggest that sub-surface groundwater transfers could exist in these wadi basins. This hypothesis is supported by chemical and isotopic evidence from water in the coastal plain which displays characteristics similar to those of the spring waters. This is most evident in the Wadi Ma'awil basin, but less so in the Wadi Far basin where the coastal groundwater shows a mixed limestone spring and wadi gravel origin.

The Wadi Sama'il basin is a special case: the extensive area of alluvium upstream of the incised channel through the Sama'il rocks has a potentially large base flow storage. Outflows from this storage are seen on the surface at Al Khawd and gaugings by Petroleum Development (Oman) Ltd. over nearly 10 years indicate an average flow of 14 million m³ per year although there have been long periods with little or no flow. As this flow can have a substantial effect on the water balance of the main alluvial aquifer between Al Khawd and the coast, we have deferred further discussion until later in this chapter.

3.3 THE BATINAH ALLUVIUM

The extent of the alluvium, the lithology and thickness of the deposits, and the hydrogeological characteristics are quite different in each of three zones:—

(i) a zone at the mountain front inland from the Tertiary Limestone outcrops of the coastal plain, and including the piedmont alluvium,

(ii) a mid-Batinah zone extending up to 15 km to the north of the Tertiary outcrops,

(iii) a coastal zone.

The characteristics of each zone are the result of tectonic movement and deposition since mid-Tertiary times when the Jabal Akhdar-Jabal Nakhl mountain range became emergent and downwarping began in the Gulf of Oman. The zone between the mountains and the Tertiary Limestone is an area where gentle uplift and erosional downcutting has taken place. The alluvial sediments are thin, large areas of old deposits exist, and recent sediments are contained in narrow incised wadis. The Tertiary outcrops are an area of stability between the inland zone of gentle uplift and the coastal zone which is an area of active deposition associated with downwarping. To the north of the Tertiary Limestone the mid-Batinah zone is a large area of gravel terraces. Ancient erosion surfaces are preserved and there are stony pavements of dark, desert varnished and wind etched boulders and pebbles. The alluvial channels of the modern wadis begin to widen in this zone and gradually bury the terrace gravels beneath modern outwash fans which form an indistinct boundary with the coastal zone of fine grained sediments and shallow groundwater.

Surface Geology

The surface distribution of the alluvium is shown in Figure 3.2 which is based on field mapping and photogeological interpretation presented in greater detail in the geological maps of Appendix C.1.

The alluvium is of very variable composition in the mountain front zone. Boulders and coarse gravels are present in the modern wadi channels and hard boulder conglomerates are quite common in the wadi beds close to the mountains. The banks of the incised wadis reveal thin, well sorted deposits of gravels in the terraces adjacent to the modern channels. The materials of the outwash fans of the smaller wadis are not as well sorted and large boulders and fine gravels are found. Between the wadis the alluvium is fine grained and composed of angular fragments of the underlying rock.

The Tertiary Limestones appear as a series of small, isolated outcrops in the west but tend to increase in size and elevation when traced eastwards along the Batinah. West of Nakhl they dip to the north-east at about 20°-25° increasing to 45° in the Wadi Sama'il basin. This increase in dip probably results in the formation of a deeper basin of deposition in the east than in the west. However, there is a structural complexity within the eastern basin, indicated by the outcrops of Tertiary Limestone which form a headland at the coast in the Wadi Bani Kharus basin and form the Daymaniyat Islands. There is either major faulting or folding of the limestones within the coastal zone but the field data is insufficient to trace the structure in detail.

The Tertiary Limestones are overlain by probably the oldest alluvial deposits, which form terraces parallel to the main sweep of the Jabal Akhdar and the Jabal Nakhl and extend completely across the coastal plain in parts of the Wadi Sama'il and Wadi Rusayl. The beds consist of carbonate rich deposits, the basal beds being similar to the Tertiary Limestone and composed of hard chalky deposits with occasional chert pebbles. Above these the cemented beds which gradually increase in pebble content through a sequence of mountain limestone, gabbro and peridotite pebbles, form extensive deposits of peridotite conglomerates interbedded with occasional gravels.

The younger gravel deposits of the coastal zone overlie the cemented beds and are poorly sorted boulder beds, gravels, sands and silts. The material becomes progressively smaller in size as the distance from the mountains increases. Wadis bring gravel and occasional boulders almost to the sea but these are contained within relatively narrow channels crossing wide flat areas of sandy silts. Stretches of dune sand and some sabkha occur at the coast.

Sub-surface Geology

The location of the principal boreholes and their reference numbers is shown in Figure 3.3. The strata details recorded by the drilling contractor and the geologist are given in Appendix C.4 where we have adopted a computer presentation to summarize the large amount of detailed information.

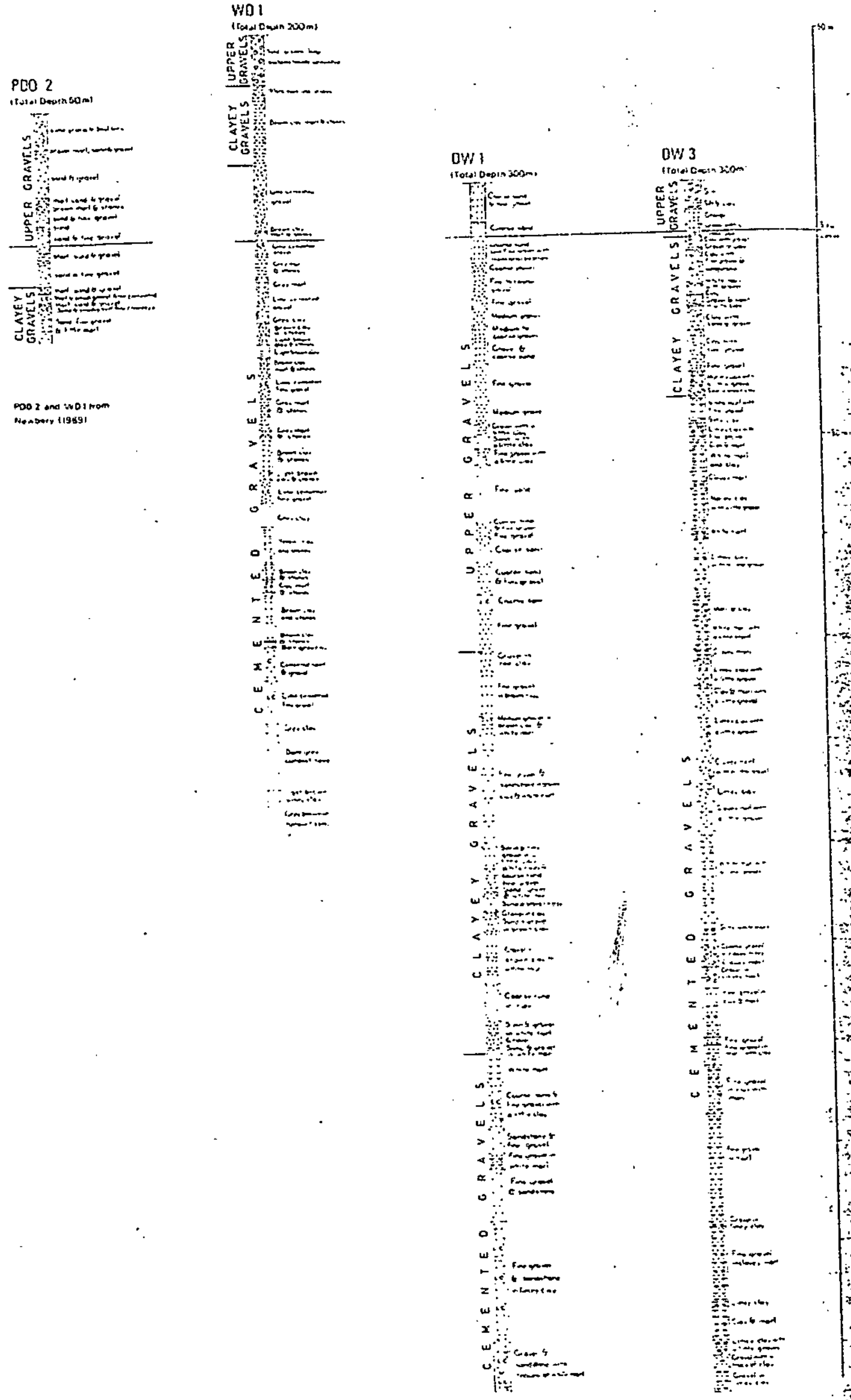
The thickness of the alluvium can be broadly related to the main alluvial zones. Boreholes near the mountain front proved at least 35 m of alluvium at Rustaq and over 70 m at Mazahit in the narrow neck of the piedmont area of the Wadi Far. The alluvium appears to be thinner in the piedmont zone of the Wadi Ma'awil; the maximum thickness proved in the Nakhl area was only 38 m. We have little information regarding the thickness of alluvium elsewhere in the mountain front zone, although two boreholes in the Wadi Bani Ghafir basin proved 10 m and 52 m of alluvium above thick sequences of Sama'il sediments. Generally the alluvium appears to increase in thickness from the Tertiary Limestone outcrop to the coast. The maximum recorded thickness is in the Wadi Sama'il basin where an early water supply borehole was constructed to a depth of 600 m at a site on an alluvial terrace. Elsewhere in the mid-Batinah zone the maximum thickness is unknown, the deepest drilling being to depths of only 140 m. In the coastal zone at least 300 m of alluvium were proved in the Wadi Sama'il basin. There is a local thinning of the gravels against the Tertiary Limestone headland in the Wadi Bani Kharus basin and borehole DW4 appears to have encountered limestones at a depth of 200 m. The total thickness of the alluvium beneath the Batinah plain is therefore unknown but probably exceeds 600 m in most places.

Geophysical studies[1] failed to determine the presence of Tertiary Limestone beneath alluvium. This may partly have been due to the depth but was also associated with the lithology of the gravels. Vertical changes in the composition of the alluvial deposits due to original sedimentary characteristics appear to be obscured by secondary changes taking place underground. These mainly affect the more recent gravels and seem to take the form of in-situ weathering of peridotite pebbles which break down to give clayey gravels.

These clayey gravels have been recorded between the gravels and boulders at the surface and the grey and white marly gravels which represent the cemented beds at depth. They appear as brown and red coloured marly gravels and clayey sands. Their extensive development is an important feature of the alluvial basin and has formed the basis of a simple classification which has a close relationship to the water bearing properties of the aquifer system. Beds of clean gravel and sand with boulders occur in the upper layers and have been termed the *Upper Gravel* aquifer. The first appearance of clays or marls are rarely followed by any deeper occurrences of thick beds of clean gravels and this *Clayey Gravel* sequence has frequently been accompanied by significant reductions in groundwater supplies. The underlying *Cemented Gravels* are an impermeable formation normally recorded as white or grey, gravelly marls and clays which are undoubtedly the equivalents of the cemented gravels of the terraces. Conventional lithological logs from four representative boreholes are shown in Figure 3.4 to illustrate typical sequences for materials in each of the three categories.

Variations in the thickness of the *Upper Gravels* are shown in Figure 3.5. Three areas of deep deposits have been found underlying the main outwash fans of the Wadis Sama'il, Ma'awil and Far. A maximum thickness of just over 100 m has been recorded in the Wadi Sama'il where the shape of the isopachytes (lines of equal thickness) show that the gravels increase in thickness towards the coast and probably reach their maximum thickness offshore. The Wadi Ma'awil and Wadi Far deposits form closed basins with the greatest thickness of gravels some 10-15 km inland from the coast. The maximum thickness of the *Upper Gravels* at the Wadi Far proved by drilling is 70 m, and 47 m in the Wadi Ma'awil. However, the total depth of the gravels is not known. The shape of the isopachytes suggests that a fourth basin might exist beneath the Wadi Bani Ghafir. The appearance of *Clayey Gravels* at fairly shallow depths along the coast of the Wadis Bani Ghafir, Far and Bani Kharus could be indicative of fairly shallow Tertiary strata.

[1] [illegible] Report, Geophysical Survey of Northern Oman. Compagnie Generale de Geophysique, April 1975.



Selected Strata Logs

Fig

Insufficient data exist to prepare an isopachyte map of the *Clayey Gravels*. The occasional boreholes which fully penetrate the beds indicate separate basins on either side of the Wadi Bani Kharus which itself is an area not only of thin *Upper Gravels* but of shallow *Clayey Gravels* with cemented beds at depths of about 70 m providing a ridge-like structure between the Tertiary limestones of the inland and coastal areas.

The process of formation of these *Clayey* and *Cemented Gravels* is important in view of their extensive development and their effect in severely restricting the depth of clean water bearing gravels. We have therefore investigated this process in some detail and the results are presented in Appendix C.1. The widespread occurrence of clayey material interspersed throughout the *Clayey Gravels* is regarded as an early stage of a process involving reaction between gravels and groundwater leading eventually to the formation of conglomerates. We would suggest that the clays are formed in situ by weathering of serpentinite and peridotite pebbles, although we are uncertain whether this is a shallow sub-surface process associated with tropical weathering conditions or a deeper sub-surface reaction linked with fluctuating water tables.

4 GROUNDWATER IN THE BATINAH

The alluvial deposits appear to be water bearing throughout the Batinah. However, groundwater is not always present in exploitable quantities and the concept of a single groundwater basin arises from physical considerations regarding the hydrodynamics of the system rather than from an expression of the aquifer potential. The basin has been treated mainly as a water table system. Nevertheless silts in the coastal area, some thick developments of clay in the *Clayey Gravels* and the more massive cemented beds may locally result in confining conditions.

The depth to water level and water table contours are shown in Figures 3.6 and 3.7. These are related to the thickness and distribution of the sediments in the three physiographic zones described earlier in this chapter. The zone at the mountain front has groundwater within 10 m of the surface and a hydraulic gradient of about 0.010. The areas of terrace gravel in the mid-Batinah zone have the steepest hydraulic gradient, 0.014, and deep water table levels up to 65 m below surface. A depth to water of 30 m marks the approximate northern limit of the mid-Batinah zone and towards the coast the depth to water gradually decreases to about 10 m at the coastal vegetation and to less than 2 m between the gardens and the shore. The hydraulic gradient shallows in this zone to about 0.002.

Figure 3.6 indicates that the general shallow depth to water in the mountain front zone has been maintained despite the long period without rainfall. As the alluvial sediments are relatively shallow along these boundary areas, except in the piedmont areas of the Wadi Ma'awil and Wadi Far, base flow inputs would be expected in order to maintain water levels. The general pattern of water table contours at the mountain foot does not show recharge mounds which would normally be associated with base flow. However, the borehole network is very sparse and it may be that base flow recharge is confined to narrow buried channels. This would not be unreasonable since the main occurrence of groundwater is in the gravels and boulder beds of the wadi channels. Groundwater is also known to be present in the alluvial sediments flanking the wadis but in very limited quantities where these sediments are cemented. Few boreholes were constructed in the large area of low gravel hills to the west of the Wadi Bani Kharus where the alluvial cover between wadis appears to be relatively thin and therefore unlikely to be important water bearing sediments. The contact between the alluvium and the underlying igneous and sedimentary rocks of the Sama'il and Hawasina Nappes was explored in boreholes JT19, JT20 and JT56 but no major groundwater supply was indicated. To summarize our conclusions concerning the mountain front zone, we regard it as an area of transmission of groundwater. Some storage is provided in the wadi gravels and the adjacent terraces but the shape of the water table contours suggests transfer of groundwater from the mountains.

Exploration of the water bearing properties of the Tertiary limestones were limited to two boreholes, JT17 and JT33, which gave poor results, supporting the general conclusions reached for the large outcrop areas of the Wadi Lansab. Extra drilling was proposed in the main exploration programme to examine the limestones in more detail. Meanwhile they are not shown as an impermeable barrier in Figure 3.6 because there are strong indications that they are in hydraulic connection with the alluvial deposits.

The area of deepest groundwater is in the mid-Batinah zone to the north of the Tertiary limestone outcrop. Nearly all exploration boreholes which failed to produce sufficient water for testing were in this zone. It is an area where groundwater moves out from the narrow channels of the wadis and into the gravels of the main alluvial system. Groundwater is present in the cemented beds of the terrace gravels but in small quantities except where thin lenses of uncemented gravels occur. Generally water levels are below the base of *Upper Gravel* deposits except in the main wadi channels.

The general shape of the water table surface in the mid-Batinah zone indicates recharge mounds in the Wadi Sama'il, Wadi Taww, and Wadi Ma'awil basins, suggesting that these are principal areas of recharge to the coastal zone. The apparent recharge mound beneath the Wadi Taww is surprising, because there are no major wadis to provide dry weather inflow to sustain such a piezometric surface. Geological mapping of the alluvial boundary in the Wadi Taww has indicated several dried-up ancient springs in the vicinity of major geological disturbances in the Sama'il and Hawasina formations of the mountain foot. Transfers of groundwater from the bedrock to the alluvium are therefore possible in this area. However, in view of the extensive terrace gravels and the poor coverage of boreholes between the Wadi Taww and Wadi Ma'awil the configuration of the water table might occur simply because of the flexing of the contours parallel to the sweep of the Jabal Nakhl.

Depth to water decreases downstream towards the coast and the hydraulic gradients shallow. The water table is within the *Upper Gravels* and retains a configuration which implies recharge in the Wadi Sama'il and Wadi Taww basins. The shape of the contours in the vicinity of the surface watershed between the Wadi Bani Kharus and the Wadi Far suggest another recharge mound. Because of the widespread observation network, it is not clear which wadi is controlling the recharge. The Wadi Far is the most obvious source, because the main channel is close to the watershed and the piedmont area provides a possible origin for dry weather

... flows. The major characteristics of the coastal zone are the low elevation of the water ... (the 2 m contour is some 5 km inland) and the steeper hydraulic gradient in the narrow ... to the east.

Over much of the Batinah groundwater levels are below the base of the *Upper Gravels* which are water bearing mainly in the fairly narrow coastal zone. Figure 3.8 shows the saturated thickness of these beds. The distribution of the main zone of water bearing material is along an east-west axis. It reaches a thickness of about 100 m at the coast at Sib in the vicinity of the modern fan of the Wadi Sama'il but thins to about 30 m at Rumays. The coastal areas of the Wadi Ma'awil and the Wadi Far basins are underlain by at least 35 m of saturated *Upper Gravels*. It is these *Upper Gravels* which form the major productive zone of the Batinah groundwater system.

3.5 AQUIFER CHARACTERISTICS

The ability of alluvial sediments to store and transmit water is very varied. Aquifer properties depend upon primary structure within the gravels such as grain size, the degree of sorting and the thickness of individual layers. Secondary features such as carbonate cement, or the weathering of peridotite pebbles to form clayey deposits, lead to a reduction in the volume of void space available for storage of water and to a lower aquifer permeability. Generally, the aquifer properties of alluvial sediments are well known, they have been extensively studied in many environments. However, there is very little information concerning the water bearing characteristics of sequences of the type which we have classified as *Clayey Gravels* and *Cemented Gravels*.

The main source of pumping test information available for assessment of the aquifer properties in the Batinah is the drilling contract which started early in 1972. We took over direction of this work after the construction of some 50 wells. In all, a further 82 boreholes were drilled, 47 of which were constructed specifically for this study to give geological information and to establish a network of water level observation boreholes. Simple yield tests were made in the first 50 boreholes. We introduced more extensive test pumping operations which took the form of three stage step-drawdown tests designed to assess yield, efficiency and development of the boreholes. This was necessary due to the use of torch slotted screens in the construction of the wells, a practice specified by the contract but which led to inefficient borehole design. Consequently, water level data are from pumped wells and the most useful information for the assessment of aquifer properties is restricted to water levels collected during the first stage of step-drawdown testing. It is therefore of limited application, suitable only for approximate evaluation of transmissivity. As there are no data from observation wells, storage coefficients could not be determined. This more detailed information was to have been collected during the additional programme of borehole construction and testing which ultimately did not proceed.

Yields from Boreholes

Details of the pumping tests at each borehole are given in Appendix C.4. Rates of abstraction vary from 500 to 900 m³/day. In *Upper Gravel* boreholes, drawdown varied from 0.1 m to about 15 m although most values were about 1 m at an abstraction of 500 m^3/day. In the *Clayey Gravels* yields of between 300 and 500 m^3/day were obtained for pumping drawdowns in the range 2 to 10 m. The greatest drawdowns in water level were normally found in *Cemented Gravel* boreholes. Examples of yields from production sites in the Wadi Khawd and Wadi Sama'il basins gave drawdowns of 33 m at 350 m^3/day at the Mawalih wellfield, and of up to 50 m at 375 m^3/day at the Al Khawd wellfields.

Step-drawdown tests have been analysed to determine the two components of drawdown in the pumped well. According to Jacob[1] total drawdown comprises the "formation loss" which arises from the resistance of the water bearing formation, and the "well loss" due to head losses accompanying the flow of water into the boreholes. We have adapted a method of analysis after Rorabough[2] and have assessed the efficiency of the boreholes as the ratio of formation loss to total drawdown expressed as a percentage.

The results from about 50 step-drawdown tests emphasize the problem of borehole construction well using torch slotted screens. Only 30 solutions were possible because development continued during test pumping, despite extensive pre-test work. Well efficiencies were low and early tests indicated large well losses with efficiencies of about 50 percent, attributable to the small open area of the torch slotted screen. Increasing the total open area to about 3 percent resulted in an overall improvement in well efficiency giving values of 70 to 90 percent in some boreholes. However, other boreholes, particularly those with screens in *Clayey* and *Cemented Gravels,* continued to give low efficiencies and to show well development characteristics. Consequently their data are not suitable for rigorous application of well test theory. The large well losses and the changing response of the system due to development during testing detract from the value of the water level data which otherwise was of a high standard.

Transmissivity Estimates

We have assessed groundwater flow through the aquifer using two techniques, a method of flow-net analysis and a digital modelling method. Both require a knowledge of the hydraulic gradients of the water table and the transmissivity of the aquifer. The transmissivity estimates used in the analyses have been derived by the following alternative methods:—

(i) using Jacob's modification of the Theis method from water level data collected during the first stage of step-drawdown testing,

(ii) where pumping test information was not capable of solution or was not available, transmissivity estimates were derived from specific capacity data (yield in m^3/day divided by water level drawdown in metres).

The results obtained from pumped wells and shown in Tables 3.1 and 3.2 are slightly higher than those quoted in our Interim Water Resources Assessment[3]. This has arisen from a re-examination of the pumping test data and by development of solutions paying particular attention to water levels collected during the first 50 minutes of the tests. The procedure is fully described in Appendix C.2.

[1] Jacob C.E., Drawdown Test to determine the effective radius of Artesian Wells, Proceedings Amer. Soc. Civil Engineers, Vol 72, (1946).
[2] Rorabough M.I., Graphical and theoretical analysis of step-drawdown test of Artesian wells. Proceedings Amer. Soc. Civil Engineers, Vol 79, (1953).
[3] Water Resources Survey of Northern Oman, Final Report on Phase 1 Soils and Agricultural Studies with an Interim Water Resources Assessment, April 1975.

TABLE 3.1

AQUIFER PROPERTIES OF UPPER GRAVELS AND GRAVEL LENSES

Basin	Transmissivity (m²/day)		Hydraulic Conductivity (m/day)
	From Pumping Tests	From Specific Capacity Data	
Wadi Rusayl			
JT 75	—	707	71
ADG 13	—	163	8
ADG 14	—	1 814	75
Wadi Sama'il			
JT 3	—	1 329	84
JT 4	—	936	64
JT 28	300	360	14
JT 29	759	656	32
JT 30	392	1 054	19
JT 38	—	794	56
JT 51	2 420	475	48
JT 73	711	1 476	14
JT 80	66	75	10
JT 85	—	437	70
JT 86	262	437	44
ADG 1	—	562	62
ADG 15	—	281	17
Wadi Taww			
JT 43	590	464	11
JT 44	—	587	49
JT 45	—	608	47
JT 46	—	191	16
JT 47	404	472	34
JT 48	574	576	48
JT 49	256	310	20
JT 50	662	258	47
JT 66	265	531	22
JT 76	—	517	45
Wadi Ma'awil			
JT 63	225	104	19
ADG 16	—	183	9
ADG 17	—	146	8
ADG 22	—	33	2
Wadi Bani Kharus			
JT 23	—	547	16
JT 24	426	70	19
JT 57	204	258	9
JT 67	220	308	9
ADG 23	—	153	10
Wadi Far			
JT 13	—	473	22
JT 15	—	468	20
Wadi Bani Ghafir			
JT 22	1 325	1 171	58

TABLE 3.2

AQUIFER PROPERTIES OF CLAYEY AND CEMENTED GRAVELS

Basin	Transmissivity (m²/day)		Hydraulic Conductivity (m/day)
	From Pumping Tests	From Specific Capacity Data	
Wadi Rusayl			
JT 53	59	34	1
WRP 1	—	13	19
WRP 2	—	20	23
GP 2-15	—	3- 11	<1
Wadi Sama'il			
(JT 32[1])			
JT 31	106	343	4
JT 81	11	6	<1
JT 82	2	5	<1
JT 83	10	3	<1
PDO 9	34	6	<1
PDO 10	38	6	<1
Wadi Taww			
(JT 42[1])			
JT 25	—	37	2
JT 37	292	101	13
JT 41	86	117	4
JT 74	94	114	4
Wadi Ma'awil			
(JT 7[1], JT 52[1], JT 56[1])			
JT 5	0.3	6	<1
JT 10	316	73	15
JT 11	14	21	1
JT 12	4	9	<1
JT 33	1 070	130	20
JT 72	1 276	277	25
Wadi Bani Kharus			
(JT 68[1])			
JT 58	92	98	2
JT 69	316	222	6
JT 70	326	115	6
JT 71	526	60	11
ADG 24	—	48	3
Wadi Far			
(JT 16[1], JT 17[1])			
JT 18	176	36	7
ADG 19	—	51	4
ADG 20	—	84	5
ADG 27	—	65	7
Wadi Bani Ghafir			
(JT 19[1], JT 21[1])			
JT 20	59	36	3
ADG 25	—	36	3
ADG 26	—	168	11

* Boreholes reported dry, but subsequently made water.
[1] Water level too deep to test.

The test pumping solutions gave transmissivities ranging from less than 1 m^2/day to over 2 000 m^2/day. The 18 solutions obtained from boreholes in *Upper Gravels* gave an average value of 550 m^2/day. The transmissivity of the *Clayey* and *Cemented Gravels* is lower. 22 test solutions gave an average value of 223 m^2/day. This contrast between the *Upper Gravels* and the lower formations is emphasized by the transmissivity estimates derived from specific capacity data, an average of 75 m^2/day from 31 solutions in *Clayey* and *Cemented Gravels* compared with 525 m^2/day from 38 solutions in *Upper Gravels.*

The sources of error arising from the use of specific capacity data are discussed in Appendix C.2 where we conclude that the errors introduced are small. Nevertheless the estimates of transmissivity from the pumped wells constructed with torch slotted screen must be treated with caution. More reliable estimates would be obtained from observation borehole data or from pumped wells constructed using factory made screens.

Hydraulic Conductivity

In order to use the transmissivity estimates in calculating flow through the aquifer, we have derived aquifer permeability by dividing the transmissivity by the screen length. This gives an effective hydraulic conductivity, which when applied to the full saturated thickness of the lithological unit sampled, generates higher values of transmissivity. Essentially this procedure is a form of correction for partial penetration.

The hydraulic conductivities are given in Tables 3.1 and 3.2. The deepest zones of *Upper Gravels* have produced the highest values and where the gravels are replaced by sands and clays in the coastal area of the Wadi Bani Kharus, hydraulic conductivities are about 10 m/day compared with 20 m/day to 84 m/day in the main aquifer zone. The regional average conductivity is 34 m/day which compares well with a published value of 41 m/day for similar gravels to the west of our study area[4].

The *Clayey* and *Cemented Gravels* are not as permeable and values of less than 25 m/day are indicated. These results suggest slightly higher hydraulic conductivities in the western basins (between 2 and 11 m/day) compared with several values in the Wadi Sama'il of less than 1 m/day. This appears to be a reversal of the trend seen in the *Upper Gravels*. However, there are 10 boreholes in the area to the west of Wadi Taww which failed to produce sufficient groundwater for test purposes and the location of these boreholes in the terrace areas indicates even lower hydraulic conductivities than were found in the Wadis Sama'il and Rusayl.

These results emphasize the poor aquifer properties of the alluvial material classified as *Clayey Gravel* and *Cemented Gravel*. Some of the boreholes were designed to examine the most likely water bearing horizons in these formations by locating screens only in the occasional and obvious gravel lenses. These occur for example in borehole JT67 between the *Clayey Gravels* and the *Cemented Gravels*, and have aquifer properties similar to the *Upper Gravels*. However, the lenses have a limited vertical thickness and are of local rather than regional importance.

[4] Water Resources Survey of the Trucial States, Sir William Halcrow and Partners, December 1967.

Storage Coefficient

Only three pumping tests suitable for determining the storage coefficient of the aquifer have been carried out in the study area. These tests in the Wadis Lansab, Rusayl and Sama'il formed part of various water supply development studies in which survey staff co-operated. The results are shown in Table 3.3.

TABLE 3.3

STORAGE COEFFICIENTS ESTIMATED FROM PUMPING TESTS

Basin	Well Number	Storage Coefficient (Percent)	Aquifer Type
Wadai Sama'il	JT 84/SAG 1	0.3	Upper gravel
--	JT 84/SAG 2	0.2	
	JT 84/SAG 3	0.8	
Wadi Rusayl	WRP 1/GP 7	0.1	Old terrace cemented gravel
	WRP 2/GP 13	0.5	
Wadi Lansab	TW 1/OBS 1	0.4	Clayey gravel with interbedded clays
	TW 3/OBS 1	0.6	

The storage coefficients obtained from the Wadi Sama'il pumping tests in the *Upper Gravels* are surprisingly low. These boreholes were sited in a typical *Upper Gravel* sequence and also in a most favourable aquifer setting in the main outwash fan of the Wadi Sama'il adjacent to a major wadi channel. The pumping test data fitted a well known form of time-drawdown curve (Boulton[5]) indicating a water table condition for the aquifer with groundwater slowly draining from the alluvium after the initial dewatering caused by pumping. Even allowing for this dewatering effect, a storage coefficient of between 0.2 and 0.8 percent seems very low for this *Upper Gravel* sequence. The Wadi Lansab and Wadi Rusayl results are in accord with the generally poor aquifer conditions at those sites.

There do not appear to be any other estimates of storage coefficient derived from pumping tests in similar gravels elsewhere in northern Arabia. Storage has usually been estimated by reference to the general lithology of the aquifer, an approach used in early water resources studies in Oman by van de Meer Mohr and Scott Wilson, Kirkpatrick and Partners when storage coefficients of 10 percent were assumed for the alluvial deposits. Although this value is reasonable for a normal gravel aquifer, it is not appropriate to the cemented materials or to the beds of gravels with clay, which must have lower storage coefficients.

The Wadi Sama'il result must also cast some doubt on the validity of a value of 10 percent for the *Upper Gravels*. However, the pumping test results can be questioned on the basis of the small water level drawdowns, less than 0.1 m in the observation boreholes, due to the low capacity of the pumping equipment. Also the estimates of transmissivity are unrepresentative; values of between 2 700 m²/day and 7 066 m²/day were obtained from the three observation wells used in the tests.

[5] Boulton N.S., Analysis of data from non-equilibrium pumping tests allowing for delayed yield from storage. Proc. Inst. Civil Engineers, Vol 26, 1963.

It became clear toward the end of the study that a method would have to be found to assign regional values of storage coefficient of the alluvium in the absence of the anticipated pumping tests. A field method was used to determine whether boreholes exhibited water table conditions with a free water surface and a high storage coefficient, or were semi-confined with groundwater under pressure below relatively impermeable strata. This semi-confined situation would be accompanied by low storage coefficients. Groundwater in semi-confined conditions, unlike that in water table aquifers, responds to changes in atmospheric pressure. Thus detailed measurements of water level and pressure fluctuations for short periods of time can be used to distinguish between the alternative aquifer conditions. These measurements were undertaken at 30 sites shown in Figure 3.9.

Four broad storage zones were established. The areas adjacent to the hardrock-alluvium boundary along the active wadi channels have been given a storage coefficient of 10 percent, high, because of the very coarse material found in this zone. The mid-Batinah is an area of mixed water table and semi-confined aquifers; storage coefficients of 1 percent and 0.1 percent respectively have been assigned to this area as it is composed of older terraces and heavily cemented beds. Near the coast a value of 2 percent was adopted instead of the lower value indicated by the Wadi Sama'il pumping tests. The coastal zone exhibited mixed water table and semi-confined aquifer conditions and it is an area where silts and clays are commonly exposed at the surface. All the storage coefficients are low, but we cannot justify using higher values in the absence of adequate data from good pumping tests. Figure 3.9 delimits the distribution of storage coefficients that have been used in subsequent resources calculations for the Batinah.

3.6 GROUNDWATER FLOW TOWARDS THE COAST

An assessment of the quantity of groundwater flowing across the Batinah groundwater basin towards the coast has been a primary objective of the study in the north. Abstractions for irrigation, losses due to direct evaporation from shallow water tables and leakage to sea, are processes that determine the water balance near the coast. They are considered in later chapters; here we are concerned with flow as an input to the coastal zone.

Two alternative methods have been used to assess this flow: a form of flow net analysis whereby the amount of water passing across an arbitrarily defined section of the aquifer is calculated, and a simple mathematical model of the whole system. The model, which reproduces steady state flow in the aquifer, provides a comparative assessment from wider considerations than are given by the flow net method. Both techniques depend upon similar information, a knowledge of the hydraulic gradient of the water table and of the transmissivity in the various units which comprise the aquifer system.

Flow Net Analysis

The flow net analysis has been used to compute groundwater flow through the acquifer across a section defined by the +2 m contour of water table elevation. This section has been chosen partly because of its position immediately inland from most of the coastal areas of abstraction but mainly because it enables the saturated thickness of the aquifer to be fixed at the interface between the fresh groundwater and the underlying saline water. This body of saline water has been recorded in the aquifer at about a depth of −80 m in the vicinity of the +2 contour. The position of the interface may vary a little from place to place, and although the chemistry of the saline water indicates that connate and ancient sea waters are present, the freshwater aquifer thickness can be taken with some confidence as 82 m.

The flow Q beneath the +2 m contour is given by the equation:—

$$Q = T\ i\ w$$

where T is the transmissivity, i is the hydraulic gradient, and w the width of the aquifer. The units of Q will follow from the units used for the independent variables.

The +2 m contour line has been divided into 42 flow segments using a flow net geometry constructed from the water table configuration. The hydraulic gradients were derived from the distance between the +2 m and +5 m contours. Transmissivities for each segment were compiled from a detailed cross section along the 98 km length of the +2 m contour. Values of hydraulic conductivity were allocated according to the distribution of the *Upper, Clayey* and *Cemented Gravels,* the transmissivity in each segment being the sum of the product of depth and hydraulic conductivity for each of the main lithological units present.

In the east between Wadi Rusayl and Wadi Taww the numerous boreholes and the presence of terraces of old gravels near the coast allowed a detailed reconstruction of the cross section. For example an average conductivity of 66 m/day could be given to the *Upper Gravels* in the main channel of the Wadi Sama'il, which extend to a depth of 47 m below the water table and have a width of 6 km. The terraces flanking the wadi channels have hydraulic conductivities of 1-4 m/day, values also given to the *Clayey Gravels* underlying the wadi channel.

Such detailed reconstruction was not possible west of Rumays. Boreholes were widely scattered, up to 8 km apart, and the position of the +2 m contour was in an area of apparently uniform surface geology where fine gravels and silty sands occupied large areas crossed by many narrow wadi channels. No indications of buried channels exist; the drilling records show a rather uniform sub-surface distribution of gravels with a hydraulic conductivity of 11 m/day to depths of about 30 m underlain by up to 25 m of *Clayey Gravels* with lower conductivities of 4 m/day. In the Wadis Ma'awil, Far and Bani Ghafir no boreholes have been drilled below about −40 m at the +2 m water table contour. Evidence from deeper inland boreholes has therefore been used to allocate hydraulic conductivities of 20 m/day to the deeper horizons.

The details of the flow net analysis are summarized in Table 3.4 where hydraulic gradients, transmissivity values and computed flows are shown for each of the 42 flow segments. Large flows occur in only a relatively small number of segments where steep hydraulic gradients and large transmissivities combine. A flow of over 17 million m^3/year is estimated for the 6 km wide main channel of the Wadi Sama'il and 4.4 million m^3/year for the main channel of the Wadi Rusayl. Shallow hydraulic gradients and low transmissivities yield relatively low flows in all other basins.

GROUNDWATER FLOW ACROSS THE +2m CONTOUR

Basin	Width of Flow Segment (km)	Hydraulic Gradient (×10³)	Transmissivity (m²/day)	Groundwater Flow (million m³/year)	
Wadi Rusayl	2.1	1.88	250	0.4	
	1.7	1.50	180	0.2	
	1.0	1.88	180	0.1	
	0.5	1.88	2 135	0.7	
	1.5	3.75	2 135	4.4	5.8
Wadi Sama'il	1.8	3.33	360	0.8	
	1.4	3.00	3 150	4.8	
	2.5	2.31	3 150	6.6	
	2.3	2.14	3 165	5.7	
	1.5	2.14	420	0.5	
	0.8	2.00	420	0.3	
	2.5	2.00	420	0.8	
	3.3	1.76	420	0.9	
	0.5	1.76	1 185	0.4	20.8
Wadi Taww	3.8	0.65	1 185	1.1	
	1.5	1.25	1 185	0.8	
	2.3	1.25	845	0.9	
	2.8	0.79	675	0.5	
	1.0	0.79	900	0.3	
	2.5	0.83	1 460	1.1	4.7
Wadi Ma'awil	1.8	0.86	1 460	0.8	
	1.2	0.75	1 460	0.5	
	2.5	0.91	1 460	1.2	
	3.8	1.00	1 460	2.0	
	3.0	0.81	1 460	1.3	
	0.8	0.81	1 180	0.3	
	1.3	0.67	1 180	0.4	
	2.5	0.67	1 440	0.9	7.4
Wadi Bani Kharus	3.0	0.58	795	0.5	
	3.8	0.75	750	0.8	
	2.8	0.86	685	0.6	
	3.8	0.94	730	1.0	2.9
Wadi Far	4.5	0.91	1 159	1.7	
	3.8	0.50	1 215	0.8	
	3.8	0.41	1 215	0.7	
	2.8	0.45	1 215	0.6	
	1.0	0.45	1 340	0.2	4.0
Wadi Bani Ghafir	3.8	0.45	1 340	0.8	
	3.2	0.45	1 340	0.7	
	1.3	0.45	1 270	0.3	
	3.8	0.48	1 270	0.9	
	2.0	0.90	1 270	0.8	3.5
			TOTAL		49.1

The estimates of flow to the coast in the western basin are lower than we believe to actually exist. We do not consider that this is a result of under estimation of the aquifer properties of the lower horizons. Rather we believe there are channels of high conductivity in this part of the western Batinah, but the boreholes are too widely spaced to have located them. The inadequacy of the field data cannot be overcome by any objective approach to simulation in the flow net analysis, because there is no upper limit that can be established for frequency, depth or aquifer properties of the postulated channels.

Digital Model Studies

In principle, a computer based groundwater model avoids some of the shortcomings of a flow net analysis because it allows the whole aquifer system to be studied simultaneously. The simplest form of model, a steady state simulation, attempts to reproduce the known water table configuration for a given distribution of transmissivity by formulating appropriate patterns of recharge and abstraction. Because it is a steady state simulation, total recharge and total abstraction are equal and represent, in the case of the Batinah, the total flow through the aquifer south of the irrigated area at the coast.

In practice, the modelling method requires much data, particularly aquifer properties. Although sufficient transmissivity estimates were available to derive a first approximation to the complete distribution across the Batinah, there were no long term estimates of recharge with which to test the validity of the transmissivity distribution. Thus a measure of subjective judgement was necessary to reach an acceptable solution.

Our starting point was a distribution of transmissivity developed from the thickness of the *Upper, Clayey* and *Cemented Gravels* and average values of hydraulic conductivity. The first simulation generated large recharge inputs (along the mountain front) which had to be removed in the mid-Batinah zone if hydraulic gradients at the coast were to be realistic. Such mid-plain abstractions do not occur in practice and it was necessary in subsequent simulations to reduce the transmissivity in the mountain front zone, where our field data are the least extensive, and thereby reduce the simulated recharge.

Full details of these studies are given in Appendix C.3. Figure 3.10 shows the pattern of recharge and the deviations from the true water levels which resulted from the best simulation. The implied recharges which are equivalent to the flow through the aquifer, are shown for each wadi basin in Table 3.5.

The predicted base flow inputs, equivalent to the flow through the aquifer, totalled 54 million m^3/year compared with 49 million m^3/year from the flow net. In the Wadis Taww, Ma'awil and Far the model generated flows significantly greater than were indicated by the flow net, but gave a much lower flow in the Wadi Sama'il. These discrepancies are related to the patterns of deviation of the simulated water levels from the observed levels and they probably result from an over simplification of the base flow recharge pattern and the transmissivity distribution.

Concentration of recharge along a single nodal line simulating high transmissivity in a wadi channel would have been a better representation of the apparent field conditions in some basins. It would have allowed groundwater routing of flows in excess of 10 million

TABLE 3.5

GROUNDWATER FLOW TO THE COAST

(million m³/year)

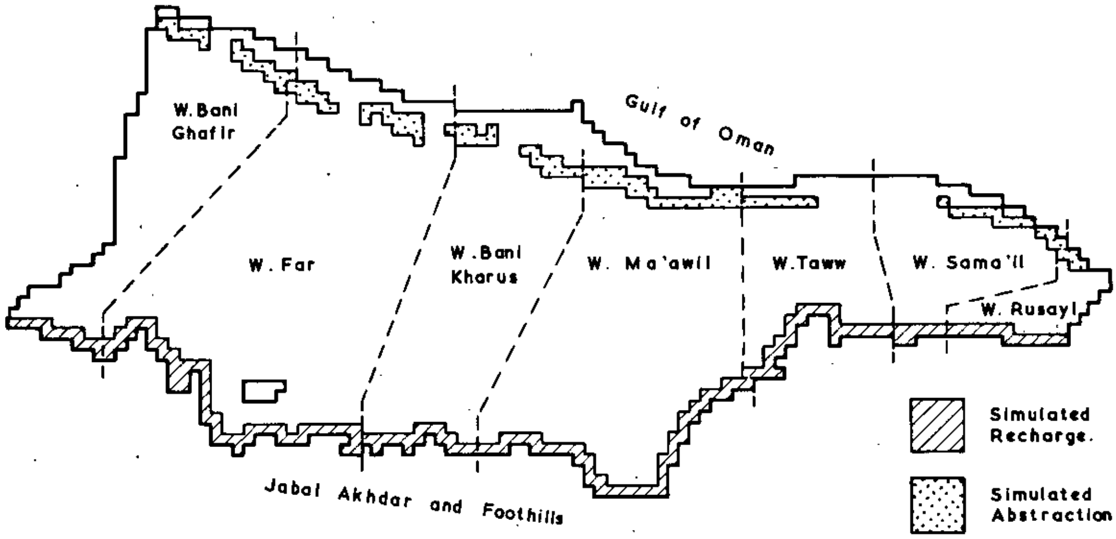
Basin	Implied Recharge Digital Model	Flow Net
Wadi Rusayl	6.0	5.8
Wadi Sama'il	10.6	20.8
Wadi Taww	8.9	4.7
Wadi Ma'awil	11.2	7.4
Wadi Bani Kharus	3.4	2.9
Wadi Far	11.6	4.0
Wadi Bani Ghafir	2.8	3.5
TOTAL	54.5	49.1

m^3/year in the Wadi Sama'il. However, the evidence for preferred channels of flow is less obvious in the Wadi Taww and the high elevation of the simulated water table might be due to over-estimation of the transmissivity values and therefore of implied recharge. The Wadi Ma'awil gave the best correlation between simulated and observed levels with small positive deviations. It is significant that this is the only basin where modern gravels have buried most of the Tertiary Limestone and terrace gravel areas, and a distributed recharge input in the model is therefore the most likely representation of the physical condition. The Wadi Far modelling gave a poor result. Simulated water levels were lower than the observed levels, despite the large implied recharge in this basin. Generally the limitation of the model are similar to the shortcomings of the flow net, namely that groundwater flow across the Batinah is associated with preferred movement along narrow channels which are inadequately described by the available data.

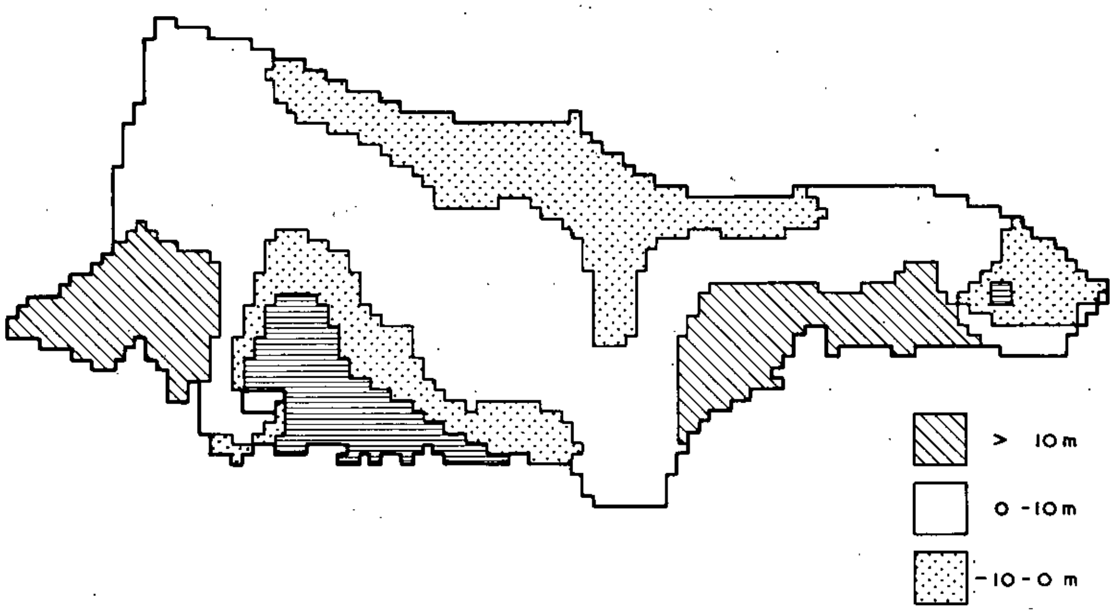
3.7 WATER LEVEL FLUCTUATIONS AND CHANGES IN STORAGE

Selection of a water table configuration in flow net studies, or for simulation in steady state modelling is a subjective decision, because changes in the shape and elevation of the water table occur continuously. Estimates of groundwater flow are therefore regarded as representative of average conditions and as such they can lead to anomalies if used in a short term water balance. Nevertheless, it is useful to compare the amount of dewatering during the long recession prior to February 1975 with the estimates of groundwater flow, to provide a check on the assumptions made in the flow net and the model.

Monthly observations of water levels from the network of 90 boreholes and 6 wells show that the recession was interrupted by minor recharges following small local storms. These mainly affected the mountain front zone in the summer and autumn of 1974. The use of water level data from March to May 1974 in the compilation of the water table map approximates to the average recession condition without these recharge complications. The estimation of aquifer dewatering during the long recession cannot avoid the effect of these minor recharges although we can allow for any recharge from surface runoff such as occurred in October 1974.



Distribution of Recharge and Abstraction



Deviation of Simulated Water Levels from Observed Water Levels

Deviation of Simulated Water Levels

Figure 3·10

Water Level Changes During the Recession

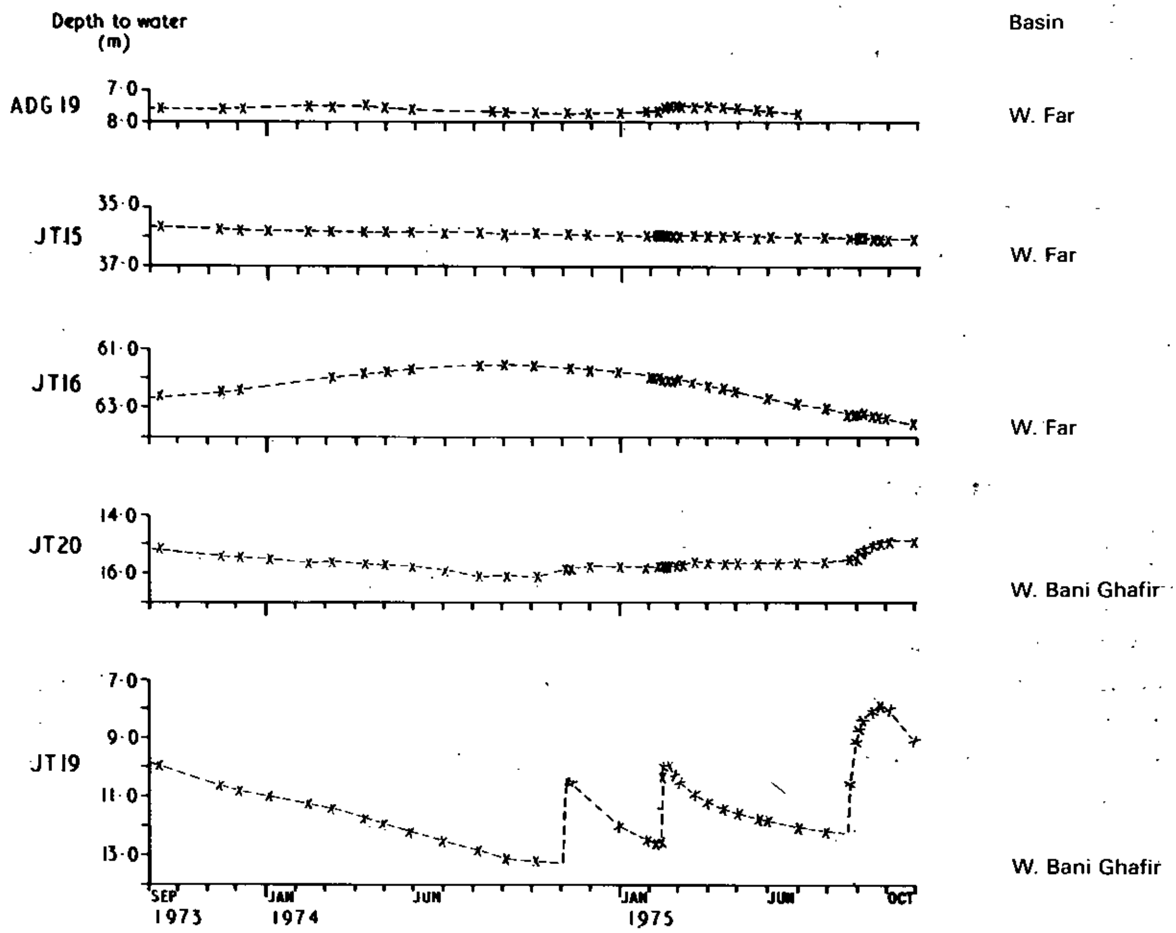
The recession is illustrated by the groundwater hydrographs shown in Figure 3.11 which have been selected as typical for the alluvium of the Batinah north of the hardrock and piedmont zone. JT19 which is in wadi alluvium south of the Tertiary Limestone outcrop falls at a steady rate for the whole of 1974 until October, when the aquifer immediately responds to local runoff. JT20, however, which is off the main wadi channel, recesses at a lower rate and although it is affected by the October runoff, its response is very limited. To the north of the Tertiary Limestone, the mid-Batinah water levels tend to be insensitive to the isolated storms. JT16 for example, has rising water levels for the whole of 1974 probably as a result of groundwater redistribution following a much earlier storm. JT15 on the other hand has falling water levels for the whole of the study period and seems to be quite insensitive to recharge. The groundwater hydrograph of ADG19 is typical of the coastal area. It has a very low rate of recession and responds only slightly to major runoff such as that of February 1975.

The complexity of the fluctuations across the Batinah can best be illustrated by contouring the change in water level over the twelve month period, December 1973 to December 1974. Figure 3.12 shows that in general water levels declined throughout the Batinah. The largest falls of 3.5 m occurred at the hardrock alluvial boundary; the smallest falls, less than 0.2 m, took place in the coastal zone. Wellfield abstractions in the Wadis Rusayl and Sama'il basins account for the large area where water levels have fallen between 1 and 2 m. Falls of up to 10 m were recorded in observation boreholes within the wellfields but these local interference effects are not shown in Figure 3.12.

The contours appear to indicate a leakage of groundwater from the Al Khawd area along the old course of the Wadi Sama'il to the west of the basin, to give an increase in water level at the coast. This also occurs in the Wadi Ma'awil where an increase in water level of up to 0.5 m is observed at the mouth of the piedmont zone. The pattern of contours suggests that this water, which must represent recharge from the Nakhl area, moves along the old channel to the west of the basin and not along the modern wadi channel to the east. Although the borehole network is more sparse in the west, a similar recharge area is apparent in the old fan of the Wadi Far which might be associated with groundwater transfers from the Rustaq area.

Storage Changes

The estimates of the volume of dewatering for the 12 month period are derived from the changes in water level within each of the storage coefficient zones shown in Figure 3.9. The results, corrected for the October 1974 recharge are shown in Table 3.6. The zone along the mountain front where large water level changes are associated with high storage coefficients accounts for 60 percent of the dewatering, while only 5 percent occurs along the coast. The total reduction in storage was 29 million m^3 of which an unduly large proportion occurred in the Wadi Far basin.



Borehole Hydrographs

Figure 3·11

TABLE 3.6

DEWATERING OF THE NORTHERN GROUNDWATER BASIN DECEMBER 1973 TO DECEMBER 1974

(million m^3)

Basin	Wadi Channels and Mountain Front	Mid-Batinah Zone	Coastal Zone	Total
Wadi Rusayl	0.5	0.6	0.1	1.2
Wadi Sama'il	1.5	0.4	0.5	2.4
Wadi Taww	—	0.8	—	0.8
Wadi Ma'awil	1.3	1.0	0.1	2.4
Wadi Bani Kharus	3.3	1.2	0.1	4.6
Wadi Far	10.9	2.5	0.3	13.7
Wadi Bani Ghafir	1.9	1.8	0.3	4.0
			TOTAL	29.1

3.8 SUMMARY OF THE HYDROGEOLOGY OF THE BATINAH

The hydrogeological characteristics that emerge from our study of the Batinah are in some respects quite different from the general views current in 1973. The concept of a simple alluvial basin containing gravel deposits having uniformly good groundwater potential cannot be substantiated. Aquifer properties vary considerably according to the nature of the sediments and the occurrence of deep gravel aquifers is restricted to a relatively narrow zone near the coast.

Small changes in storage occurred in these coastal areas during the long recession of 1974. Water levels were maintained by groundwater flows of the order of 49 to 55 million m^3/year estimated by flow net and model studies. Comparison of Tables 3.5 and 3.6 indicates that the origin of this flow is partly from dewatering within the alluvial basin. However, we recognize that the estimates of storage coefficients are perhaps the most unreliable of the hydrogeological data. This is evident particularly from the unusually large storage change computed for the Wadi Far. Nevertheless these are the best estimates we can obtain and they imply base flow transfers from the mountains and piedmont zones to maintain the groundwater flow.

Transfer of base flow recharge across the Batinah appears to take place along the relatively narrow wadi channels. This is supported particularly by the borehole hydrographs. By comparison with the estimated storage changes, these base flow inputs could be quite significant even during the period of recession. Surface water flow from the upper basin of the Wadi Sama'il at Al Khawd amounted to 4.5 million m^3 between December 1973 and May 1974. Groundwater flow from the piedmont areas of the Wadi Ma'awil and Wadi Far are estimated at 5 and 4 million m^3/year respectively from consideration of aquifer thickness, hydraulic gradient and aquifer properties. Less important groundwater transfers associated with gravels in the larger mountain wadis, such as Wadi Bani Kharus and Wadi Hawqayn, together with leakages through bed rock or minor springs along the mountain front, could reasonably be expected to yield additional supplies.

An approximate groundwater balance can thus be obtained for the recession period. Groundwater flow to the coast amounts to about 50 million m^3/year comprising about 30 million m^3 from storage and 15 to 20 million m^3 from recharge. However, simple comparisons of this nature are misleading. For example, the flow to the coast in the Wadi Far is unlikely to be less than the storage change since there are few abstraction losses in the mid-plain area. The apparent shortfall in resources could therefore result from either under-estimation of groundwater flow or of over-estimation of dewatering. Following examination of groundwater abstractions and water use, in Chapter 4, we shall show that the groundwater flows derived from the flow net and model studies are less than estimated annual consumptive use in some basins. While it is possible to argue that temporary deficits could be expected during an abnormally dry period, some of the anomalies can only be explained in terms of the inadequacies of the primary hydrogeological data.

CHAPTER 4

CURRENT WATER USE IN THE NORTHERN BASINS

4.1 INTRODUCTION

A principal requirement of the field programme was to determine all major sources of water currently exploited, the quality of the water and its availability. The extent of our survey of the towns and villages of the northern basins is shown in Figures 4.1 and 4.2. Inland and in the foothill areas, we have covered all the major villages; near the coast we have concentrated, in our detailed survey, on the coastal agriculture of the Wadi Sama'il and Wadi Bani Kharus basins. Inland, water availability was assessed by regular monitoring of a representative selection of aflaj; at the coast, where water is obtained from several hundred shallow wells, seasonal variation in abstraction rates was determined from observed pumping rates and duration of pumping of a sample of wells. Water samples were taken for full chemical analysis for the record, and as an indicator of water origin. These data, which were supported by additional selected analyses of isotopic content, are presented in the appendices.

A summary of the major findings is presented in this chapter where we show how the sources of water, their reliability and quality are related to the agricultural practices and irrigation demands. We shall demonstrate that inland there is a close balance between availability and use, and a high degree of interdependence between the villages and village groups in the major basins. At the coast, the constraints of water availability are replaced by those of water quality and, although it is difficult to draw a water balance for the coastal zone because of the complex inter-relationships, we shall define the principal factors which influence this balance.

Our analysis relies heavily on the basic agricultural data of cropped areas and water use of the various crops presented in our report on the soils and agricultural studies[1]. We have made one major revision of these data: using the November 1974 1:20 000 aerial photography we have been able to improve the estimates of cropped area at the coast. For the inland villages, we have confirmed the areas quoted in the earlier report.

The estimates of consumptive use for the major crops quoted in the soils and agricultural report were based on the Blaney-Criddle method which uses certain empirically derived coefficients. In view of the importance of these estimates in any analysis of the balance between resource and use, we have used the data now available to provide both a theoretical and a practical check on their validity. From the meteorological data presented in Appendix A.4,

[1] Water Resources Survey of Northern Oman, Draft Final Report on Phase 1 Soils and Agricultural Studies April 1975.

we have estimated open water evaporation using the Penman method. These are shown together with the Blaney-Criddle estimates for dates, alfalfa and wheat in Table 4.1. Although there are uncertainties in the use of the Penman method in an arid environment due to advection of energy and the representativeness of the meteorological data, the open water evaporation estimates broadly indicate the maximum rate of evaporation. In less arid conditions, potential transpiration from crops would be about 20 percent less than open water evaporation. Thus the Blaney-Criddle estimates would seem to be slightly low and to underestimate the seasonal variation.

However, a practical check on consumptive use was possible at Sama'il village where circumstances allowed the measurement of inflow and outflow from the agricultural area. The detailed data are discussed fully in Appendix D.2 and they show that the annual consumptive use of the cropped area, mainly dates, is between 1 527 and 1 654 mm. These figures support the Blaney-Criddle estimates which we have therefore adopted in order to provide a measure of consistency with the earlier report.

TABLE 4.1

COMPARISON OF OPEN WATER EVAPORATION (PENMAN) AND CONSUMPTIVE USE ESTIMATED BY THE BLANEY-CRIDDLE METHOD

(mm)

	J	F	M	A	M	J	J	A	S	O	N	D	Total
Open water evaporation													
Nazwa													
1974			183	210	253	246	252	232	201	172	122		
1975	86	94	164	199	244	251	226	209	189				
average	86	94	174	204	248	248	239	220	195	172	122	(100)[2]	2 102
Rustaq													
1974			197	218	263	276				172	122	91	
1975	90	108	173	203	268	263	236	222	203				
average	90	108	185	210	266	270	236	222	203	172	122	91	2 175
Rumays													
1974	109	132	196	239	284	303	277	238	238	197	136	105	
1975	100	119	204	237	289	294	256		222				
average	104	126	200	238	286	298	266	238	230	197	136	105	2 424
Sayq													
1974	131	132	183	230	260	274	269	253	229	185	135	106	
1975	122	131	189	202	245	262	254	235	252				
average	126	132	186	216	252	268	262	244	240	185	135	106	2 352
Consumptive use (Blaney-Criddle)													
Dates	100	100	120	135	160	160	165	155	140	130	105	95	1 565
Alfalfa	110	110	135	150	180	180	185	175	160	145	120	105	1 755
Wheat	105	130	70[1]							110	100	105	620

Notes: [1] The consumptive use for wheat in March is for half a month only.
[2] Estimated.

Table 4.2 shows the estimates of consumptive use adopted. Because of the considerable range of quality and degree of ground cover in the date gardens at the coast, we have used three estimates of consumptive use for dates. The third, class 3, is further modified by a variable factor representing the degree of ground cover determined by analysis of the aerial photography. For simplicity, in what is essentially a water resources study, we have derived composite values for annual and mixed crops, classes 4 and 5, based on the average proportions of these crops.

TABLE 4.2

ESTIMATED CONSUMPTIVE USE OF THE MAJOR CROPS

Class	Description	Consumptive Use	
		(mm/year)	(l/s/ha)
1	Good quality dates with total ground cover	1 565	0.50
2	Dates with incomplete ground cover	1 200	0.38
3	Poor quality dates, thinly spaced, and with scrub in places	1 000[1]	0.32[1]
4	Annual crops, chiefly alfalfa, sorghum and vegetables		0.41[2]
5	Mixed crops under modern agricultural management		0.46[2]

Notes: [1] The consumptive use indicated for class 3 crops is modified by a factor ρ which represent the crop density.
[2] For classes 4 and 5, composite estimates have been derived from the figures quoted in the Soils and Agricultural Report. For these crops the annual rate of consumption is misleading because they have a limited growing season.

4.2 THE INLAND BASINS

Between the watershed of the jabal and the main Batinah plain lies a complex region of deeply dissected mountains, foothills and piedmont alluvium, where a variety of water sources support about 20 percent of the Northern Oman agricultural area. In this inland region, villages rely on aflaj for irrigation and thus depend on the scattered and limited water sources obtained from springs or from upstream alluvial storage.

There are four distinct divisions whose relative importance varies between basins; these are the mountain limestone inliers, the limestone piedmont, the ophiolite foothills and the alluvial plain. The extent of each is shown in Figures 4.1 and 4.2. Inland from the main Batinah plain, there are four major wadi systems; Wadis Bani Ghafir and Bani Kharus have incised into the ophiolite foothill regions, while tongues of alluvium stretch inland from the main Batinah edge up Wadis Far and Ma'awil to abut directly on to the limestone massif of the Jabal Akhdar.

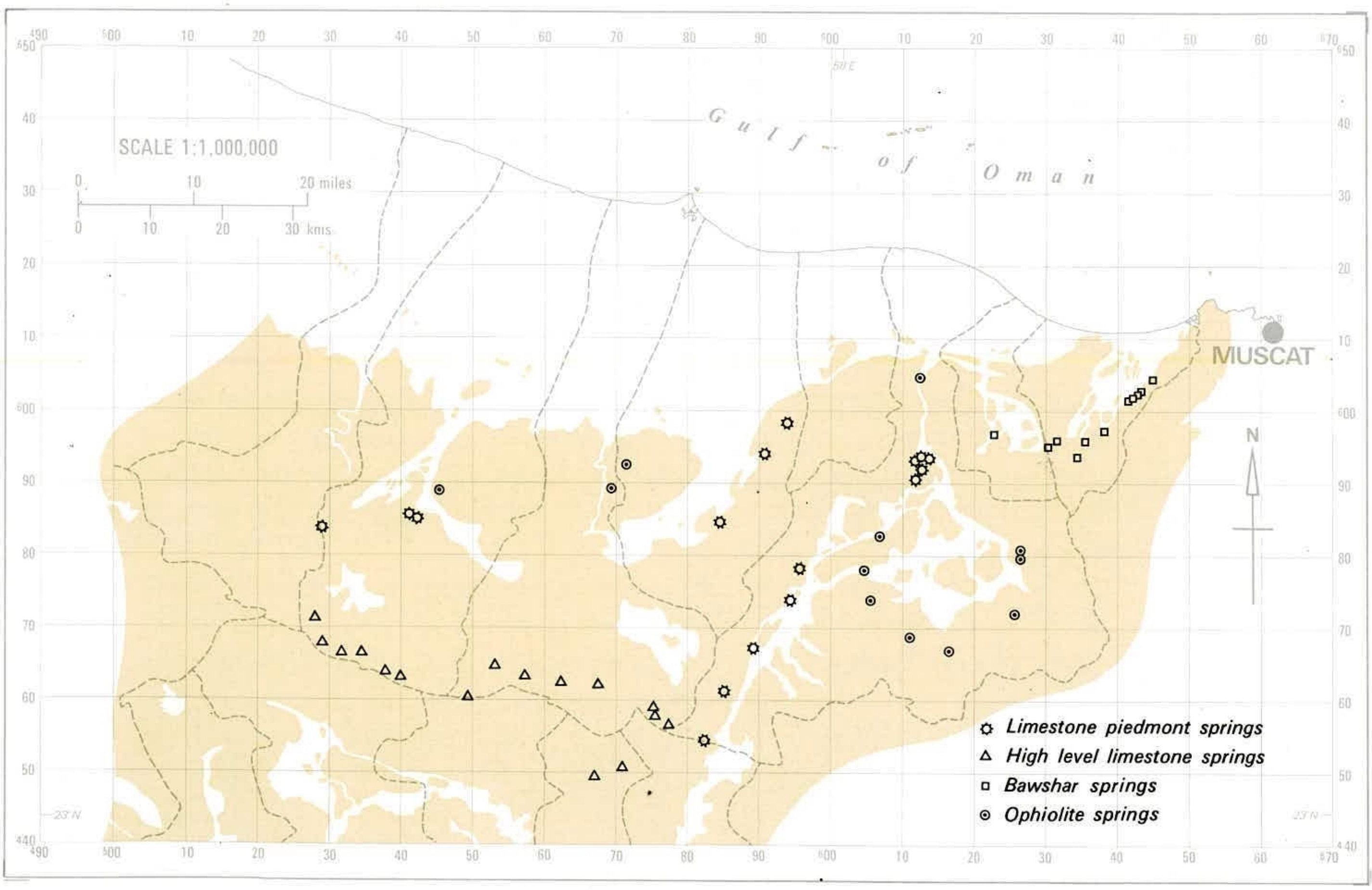
Throughout the length of the wadi systems within the inland region, village agriculture is established wherever surface and shallow groundwater is available, even where soils and salinity are less favourable. Only in the smaller eastern basins of Taww, Rusayl and Lansab are villages restricted to points along the mountain front. The most complex basin, Wadi Sama'il, is considered separately in Section 4.3. The village survey was mainly concerned with the larger village groups but most other inland areas were also sampled and surveyed. The data, presented in detail in Appendix D, have enabled us to define all the primary water sources and to examine the processes involved in their transfer and use in irrigation.

The three primary sources are limestone springs, ophiolite springs and alluvial water.

The Limestone Springs

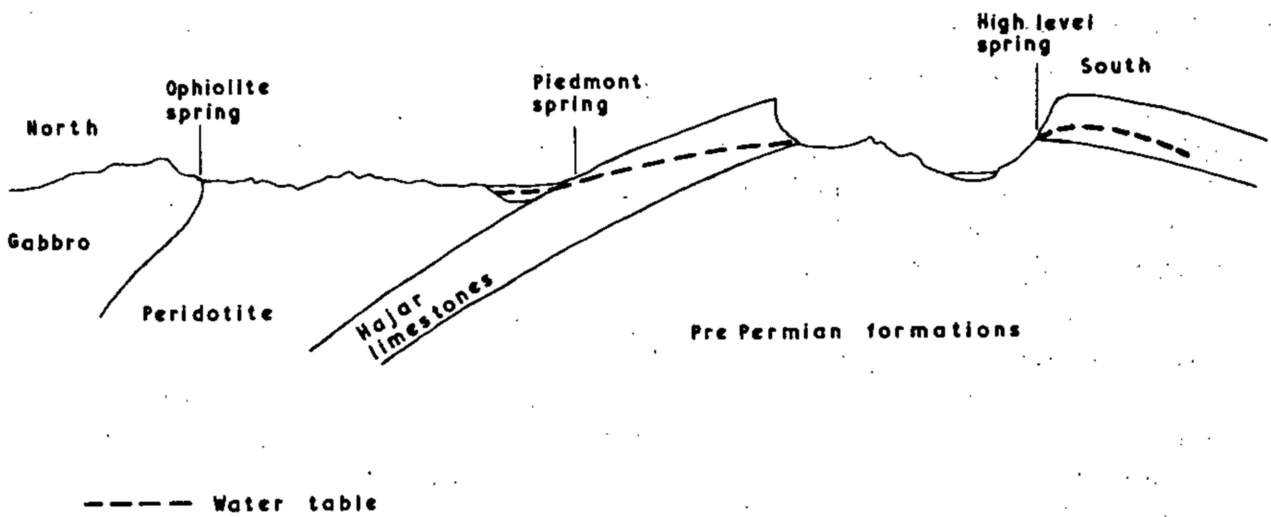
Three spring types occur: a high level spring line along the base of the limestone sequence, a "piedmont" spring line along the perimeter of the Hajar limestone massif and a genetically different spring line at the northern edge of Jabal Bawshar. All three give rise to distinctive water chemistry with low electrical conductivity (400 to 900 μmhos[1]) and high calcium content. The distribution of these springs is shown in Figure 4.3 and their structural occurrence is illustrated in Figure 4.4

[1] Electrical conductivity was measured in micromhos per cm, adjusted to 25°C; throughout the text this is referred to as "conductivity" in units of "μmhos".



Spring Locations

Figure 4·3



Geological Section to Show Spring Occurrence

Figure 4·4

Numerous high-level limestone springs occur within the major inliers of the Jabal Akhdar. The spring line varies in altitude up to 1 800 m but always originates from the same geological horizon, an unconformity between the major limestone massif and the underlying impermeable Pre-Permian formations. The springs are restricted to the north-facing scarp due to topographic influences and typical discharges are 5-10 l/s. Regular gauging was not practical but locally they are regarded as unreliable sources.

Piedmont springs occur at many horizons within the limestone formation near the contact with the overlying Hawasina and Sama'il Nappes and are associated with solution along planes of weakness. Apart from Fanjah, where spring discharge some 50 m above wadi level permits terrace irrigation, the springs occur at the edge of the limestone and frequently emerge from a thin cover of boulder gravel or travertine. They are consistently warmer than normal groundwater; typical temperatures are 35-42°C (see Appendix D.4). These springs are widespread around the perimeter of Jabals Nakhl and Akhdar and are the most important spring source in Northern Oman. Discharges vary greatly from large point sources (65 l/s at Rustaq Hammam) to lines of very small springs and seepages as in eastern Nakhl and Taww. Piedmont springs tend to recede slowly and are therefore regarded as a reliable source; small villages with date gardens clustered around the springs minimize water losses.

The Bawshar spring line differs from the piedmont spring line in several ways. Spring temperatures are highly variable (30-60°C); tritium values throughout the area were zero, indicating a water age over twenty five years, whereas tritium values from high level and piedmont springs indicate an age of less than twenty five years; there is often disparity between flow and catchment area and the minimum flows of these springs are remarkably reliable. Their origin is discussed in Appendix D.4.

The Ophiolite Springs

The ophiolite foothills contain a number of springs of exceptionally high pH (up to pH 11.9) and high sodium chloride content. They usually occur where low relief coincides with the contact between peridotite and the overlying impervious gabbroid rocks, which bring groundwater to the surface. The low temperatures (less than 30°C) and isotopic data suggest that deep circulation is unlikely, but the depth and properties of the peridotite aquifer are unknown.

Ophiolite spring water is used either by small gardens in situ or channelled from a line of seepages into a falaj of up to 20 l/s. The precipitate from such springs produces many limestone terraces suitable for cultivation in the foothills; hence these springs are more important than their yield alone would suggest.

Alluvial Groundwater

Three quarters of the water used in the northern basins is abstracted from alluvium. The most important sources are in the deep sedimentary basins which have developed in major ancient drainage channels and fans at the mountain front. Narrow bands of alluvium between the limestone and ophiolite hills, and in enclosed mountain basins, provide important storages for the inland villages. Terraces of older alluvium cemented by calcium carbonate also occur; they tend to have poor aquifer properties but are useful in bringing groundwater to the surface.

Within the limestone mountains, the only large tracts of alluvium are in the inliers of Wadis Sahtan and Mistal and provide an aquifer of thin cemented conglomerates of limited extent. Wadis Hawqayn and Bani Kharus have alluvial storages in the narrow channels.

Chemistry

Before discussing in detail the transfer of water from source to village, a brief account of the chemistry is useful because the source of water can often be deduced from its chemical characteristics.

The dominant lithology of Northern Oman, limestones and basic and ultramafic igneous rocks with their derived alluvial sediments, has resulted in alkaline groundwater throughout the study area. We have used trilinear diagrams of cationic and anionic proportions to illustrate the chemistry. In general, the cation proportions show provenance, while ionic projections on to the diamond-shaped field show such trends as ionic exchange with passage through a wadi system. The main trends are illustrated in Figure 4.5 which shows the chemical characteristics of the five principal groups of waters.

The diagram shows 5 fields within which plotted analyses from each of the major groups fall. Briefly the limestone spring waters (field 1) are characterised by high calcium and low chloride values. There is a general trend in the cations, line A on Figure 4.5, in which sodium and magnesium increase at the expense of calcium in the gravel waters of the mountain wadis and piedmont areas (fields 2 and 3). In the coastal sediments the increase in residence time of groundwater affects the chemistry and is indicated by increases in the sodium and chloride ions resulting in ionic ratios approaching those of sea water (field 4). The ophiolite springs possess a separate and quite unique chemistry shown by field 5 in Figure 4.5. Magnesium is absent from these waters which are characterised by high proportions of sodium and chloride ions.

The general chemistry of the waters reflects these major geochemical trends. Limestone springs have a relatively low pH and electrical conductivity varying from about 390 to 700 μmhos. At the other extreme the ophiolite springs are very alkaline with pH between 11.2 and 11.9 and conductivities of up to 3 400 μmhos. The gravel waters have an intermediate chemistry, with pH of 8 and conductivities of up to about 2 500 μmhos, except at the coast where mixing with saline groundwater raises the conductivity to 10 000 μmhos and above.

In addition to natural chemical processes, urban pollution and irrigation result in greatly increased salinities, particularly downstream of the larger villages. Pollution is seldom at a serious level, but high sulphate and chloride levels in some downstream areas have led to the use of separate wells for domestic water supply. The effect of successive irrigation is considered in Section 4.3.

To illustrate how chemical evidence can be useful, we have taken a specific case. Knowledge of the groundwater sources and their typical composition during dry weather has been applied to estimate the proportion of sources in the foothill area of Wadi Bani Kharus contributing to the Batinah recharge. The low sulphate content precludes significant input from the sulphate rich Ghubrah area; thus the possible groundwater sources for the wadi channel are from limestone and mountain wadi gravels, from storage within the minor ophiolite tributaries, from the alluvium of the main channel itself, and from ophiolite springs at the gabbro-peridotite boundary, Figure 4.1. Using these data, presented in Appendix C, we have calculated the relative proportions of the ophiolite gravel water and limestone water components required to produce the composition at Subaykhah where only 20 percent of the flow appears to be of limestone origin, either from springs or gravels. Using Subaykhah falaj and ophiolite spring chemistry, a similar calculation for the downstream mixture at Labijah falaj, confirmed independently from sodium and chlorine concentrations, indicates 28 percent ophiolite spring water and 72 percent alluvial water. This calculation could underestimate the proportion of ophiolite spring water because of increases in sodium and chloride with residence time.

The Falaj System

Water collection and transfer systems, particularly in less accessible mountainous areas, often demonstrate considerable ingenuity and skill in the construction of aflaj, aqueducts and inverted siphons and reflect the thoroughness with which water sources are normally used.

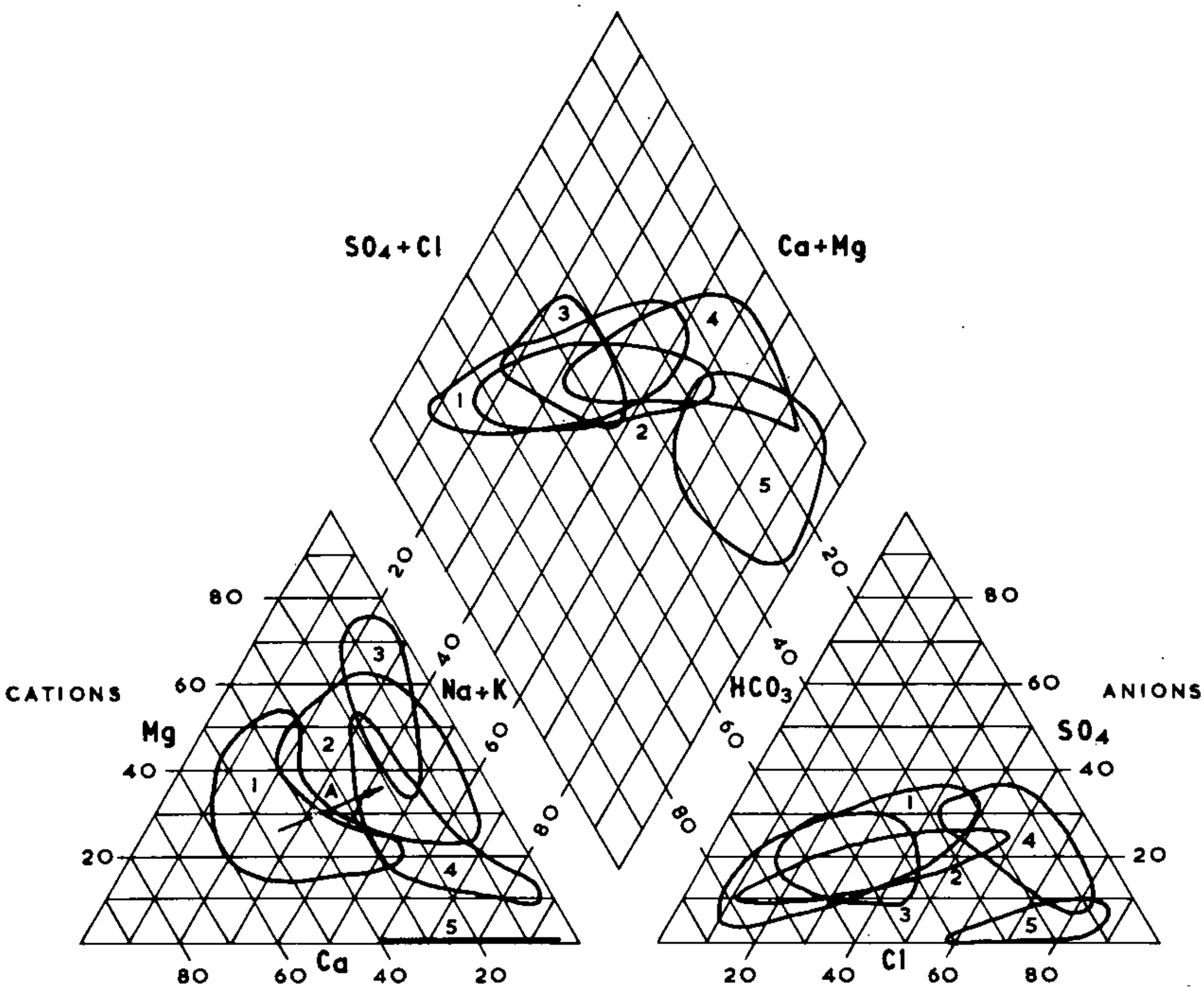
In Oman, the term "falaj" is wider than the Iranian qanat and means any artificial or underground watercourse. Some aflaj are simply concrete, stone or even mud diversion channels collecting water directly from a spring or stream. More commonly, they are narrow tunnels excavated at a gradient less than the land slope and extending upstream far enough to intersect the watertable or to reach hardrock sources, sucn as limestone to gravel seepages. These aflaj, and those dug through cemented terraces to tap wadi gravels, are of a point source type. However, the large flow of many aflaj suggests drainage from a "line sink". In favourable circumstances, where the gravels are laterally confined, aflaj collect a high proportion of the total groundwater flow.

Most aflaj need little maintenance but some require removal of silt and rebuilding of dams and diversion channels after major surface runoff. Some attempts are made to improve their efficiency but maintenance is often neglected because of cost.

Falaj Discharge

The rate of recession of falaj discharge varies according to upstream storage and aquifer geometry. The decline of primary water supply during drought is usually exponential. We have used a recession constant derived from the hydrograph as a measure of individual falaj behaviour, defined as the time taken for the flow to recede by $1/e$ (63.21 percent); this can be measured from the slope of the hydrograph plotted in semilogarithmic form and can be shown to be an index of the upstream storage. Four hydrographs, typical of the inland basins, are shown in Figure 4.6, and illustrate the variety of response to rainfall.

Where alluvial storage is limited as in Wadi Hawqayn, hydrographs vary rapidly in periods of recharge and drought, and short-term water excess recharges to the Batinah alluvium. Slower recessions are illustrated by the Sama'il falaj where a recession constant of 60×10^6s indicates one of the most reliable flows encountered. Seasonal variation is more marked in the Al Khawd falaj hydrograph where the extent of the alluvial storage moderates the effects of



1. LIMESTONE SPRING WATER
2. MIXED GRAVELS
3. OPHIOLITE GRAVELS
4. COASTAL SEDIMENTS
5. OPHIOLITE SPRINGS

Principal Geochemical Fields

Figure 4·5

individual storms. Individual falaj hydrographs are presented in Appendix D.1. Falaj Hammam at Rustaq is one of the few regularly gauged spring sources. These sources indicate a recession towards a long-term base flow and although recharge after rainfall is observed, the recession is not exponential as with aflaj in the wadi gravels.

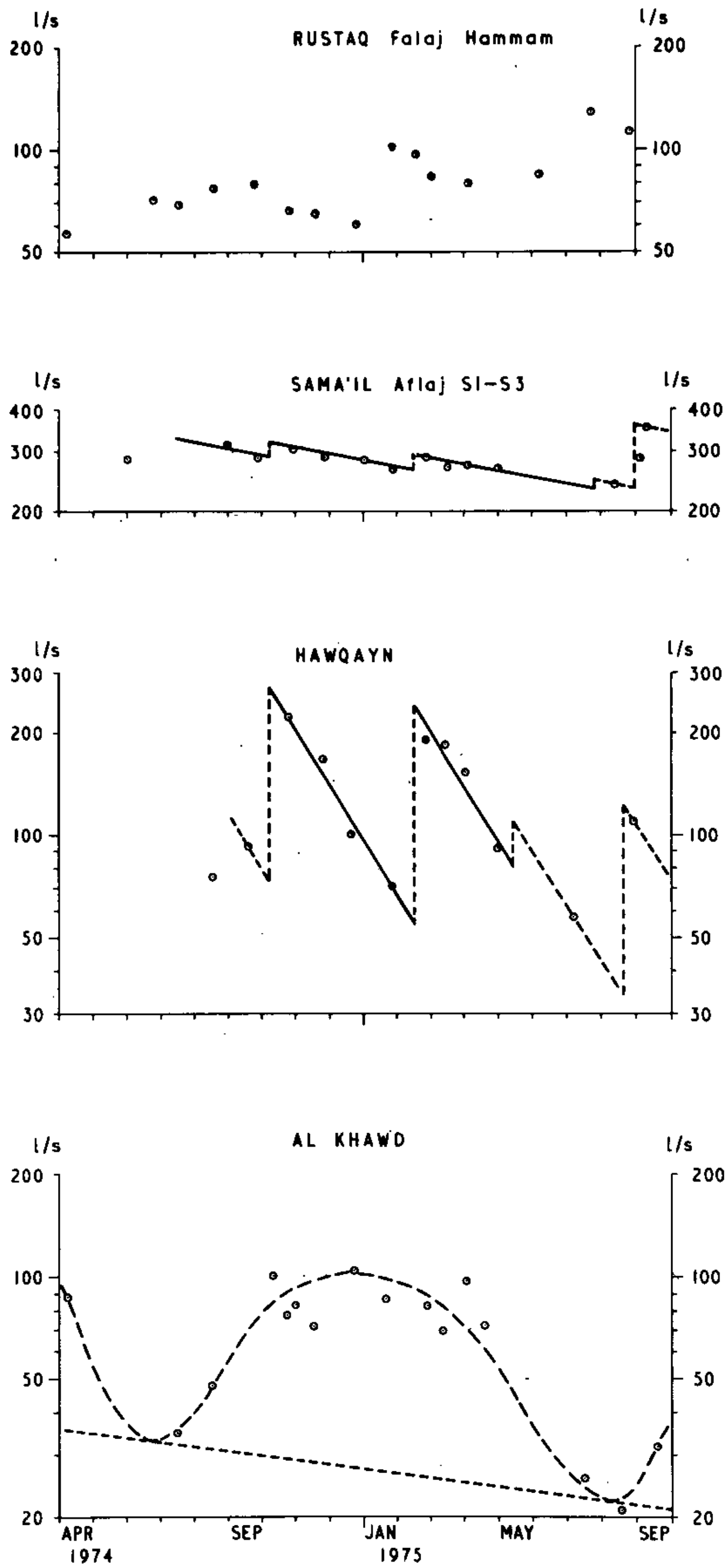
The Constraint of Minimum Water Supply

Continuous drought would ultimately result in falaj failure but in practice aquifer replenishment from rainfall or from hardrock outflows is sufficient to maintain some flow during drought periods. Local experience suggests that flows have rarely reached the lowest falaj flows measured during our study. A relationship between the lowest measured flows and the minimum village perennial crop requirement is shown in Figure 4.7. The lowest observed falaj flow typically exceeds the average consumptive use by about 50 percent; some excess is necessary to leach out salts concentrated around plant roots by transpiration. The leaching requirement in fact varies between 30 and 200 percent, according to the groundwater salinity, as shown in Figure 4.8. Thus high salinity in a few inland areas demands that a greater proportion of available water be used for leaching and thus returned to the watertable.

The frequency of low flows is important as it determines the maximum area of perennial crops and influences the area of annual crops which can be supported in times of excess. The drought flows have evidently been assessed by experience by the villages over the years and the areas of perennial crops have been adjusted. The village structure is therefore vulnerable to any new upstream abstraction as a reduction in minimum flow would result in reduced leaching and consequent soil salination. This could be endured for short periods but prolonged decline below this limit would lead to transpiration stress and finally reduction in the extent of date gardens.

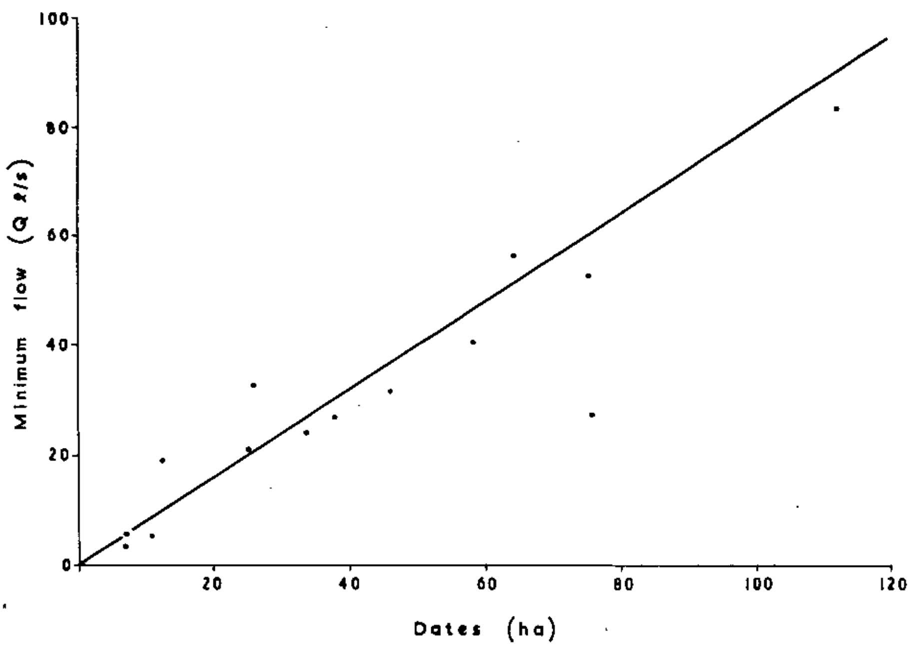
Summary of Survey of Inland Villages

Details of annual and perennial cropped areas were determined primarily from the November 1974 photography and are listed for each village in Table 4.3. The various supplies of water within each village are differentiated according to source, the falaj supply is included as the gauged flow at the time of the survey or, where data are available, as a range of flows. Estimates of supply were made throughout 1974 and therefore relate to the latter part of the drought period.



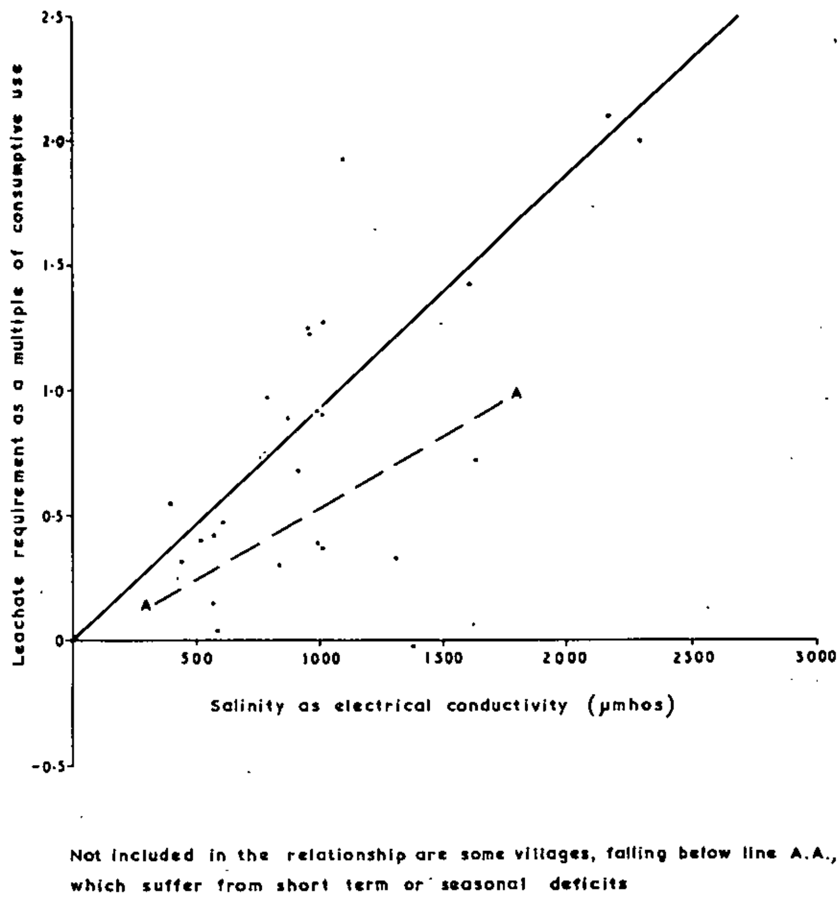
Selected Falaj Hydrographs of the Northern Basins

Figure 4·6



Date Area to Minimum Falaj Flow Relationship

Figure 4·7



Empirical Relationship between Water Salinity and Leachate Requirement

Figure 4·8

TABLE 4.3

SUMMARY OF SURVEY OF INLAND VILLAGES

(i) Wadis Lansab to Taww excluding Wadi Sama'il

Location	Agriculture (ha)			Sources of Water (l/s)			Consumptive Use (l/s)
	Dates	Other	Total	Limestone Springs	Other Springs	Alluvial Sources	
Wadi Lansab							
Sad	5.2		5.2			2.3	2.3
Jal	1.4		1.4	2.3			0.6
Fath	0.5		0.5	1.0			0.2
Falaj	11.8		11.8	11.4			5.1
Bawshar	21.4		21.4	20.3			9.3
Ghallah	11.4		11.4	11.3			4.9
Sunub	8.0		8.0	5.3			3.9
Hammam	6.6		6.6	3-6			3.3
Aqbiyah	4.2		4.2	1.5			1.7
Falaj ash Sham	0.5		0.5			1.0	0.2
Lansab	1.0		1.0			5.7	0.5
Jifar	1.5		1.5			2.9	1.2
Wadi Rusayl							
Misfah Al Ali	0.8		0.8	2.2			0.4
Misfah As Safil	6.2		6.2	6.7			3.0
Mughrah	2.4		2.4	4.7			1.2
Sa'al	8.5		8.5	6-10			4.2
As Sukhnah	1.0		1.0			1.0	0.5
Jafnayn	1.3		1.3			0-4.5	0.6
Rusayl	2.3		2.3			?	1.1
Wadi Taww							
Taww	33.4	2.9	36.3	13.0		3.0	17.7
Halban	9.5	0.7	10.2	12-15			5.0
Buwah	13.5		13.5	25.0			6.7
Asam	2.8		2.8			3.5	1.4

TABLE 4.3
(Continued)

SUMMARY OF SURVEY OF INLAND VILLAGES

(ii) Wadis Ma'awil and Bani Kharus

Location	Agriculture (ha)			Sources of Water (l/s)			Consumptive Use (l/s)
	Dates	Other	Total	Limestone Springs	Other Springs	Alluvial Sources	
Wadi Ma'awil							
Nakhl	166.0	48.4	214.4	64.0		32.2	101.3
Tawiyah	7.4		7.4			4.2	3.6
Muslimat	37.7	27.6	65.3			56.5	29.8
Afi	84.2	5.8	90.0			61.8	44.0
Hibra	75.5	2.8	78.3			41-61	38.4
Wasit	10.2		10.2			3.2	5.0
Al Ajal	26.6	7.7	34.3	23.4		0.7	16.2
Wadi Bani Kharus							
Hadith Sidkir area	30.0		30.0				14.8
Ghubrah	2.0	12.0	14.0		inaccessible	9.0	7.0
Firaq-Saqlah	10.0		10.0		inaccessible		4.9
Musayna'ah	41.5	16.5	58.0		inaccessible		27.2
Misfah area	10.6	4.3	14.9				7.0
Hayjar	10.2	10.2	20.4		inaccessible		9.1
Shaww area	8.6	5.2	13.8				6.3
Istal	29.0	11.1	40.1				18.8
Al Hijir area	10.1	0.7	10.8		inaccessible		5.3
Awabi Layjah	74.5	20.8	95.3				45.3
Mahalil	6.1		6.1				3.0
Subaykhah	17.0	6.2	23.2				10.9
Labijah	45.5	2.4	47.9				23.5
Khatum	0.6	7.7	8.3				3.4
Wukabah-Slayah	9.5	1.3	10.8		inaccessible		5.2

TABLE 4.3
(Continued)

SUMMARY OF SURVEY OF INLAND VILLAGES

(iii) Wadi Far

Location	Agriculture (ha)			Sources of Water (l/s)			Consumptive Use (l/s)
	Dates	Other	Total	Limestone Springs	Other Springs	Alluvial Sources	
Wadi Far							
Fashah-Amq area	19.6		19.6				9.7
Dahaz	6.7		6.7				3.3
Rustaq	374.6	70.2	444.8	98.0		306-825	213.6
Tabaqah	16.9		16.9	27-56			8.3
Mazahit	13.5	8.7	22.2			13.5	10.2
Wishal	52.7	12.6	65.3			45.9	31.1
Mizfar	9.8	3.9	13.7			16.3	6.4
Shubaykah	18.9	2.6	21.5			26.0	10.3
Hazam	33.9	5.9	39.8			24-97	15.3
Ali, Wustah, Daris	24.7	5.2	29.9				14.4
Jammah	41.1	7.1	48.2			51-58	23.3
Mansur	7.2	1.9	9.1			2.3-7.0	4.3

4.3 WADI SAMA'IL BASIN

The Wadi Sama'il basin, the largest studied in detail by the Water Resources Survey, has an area of 1 615 km^2 south of Al Khawd. Unlike the other wadis the Wadi Sama'il rises to the south of the main limestone anticline which it crosses in a long incised channel and ends in a well developed alluvial fan on the north coast. While the "Sib Fan" is a relatively small part of the basin, its role as a major groundwater source at the mouth of this principal wadi system and its proximity to the Capital area make it important.

Division of the Wadi Sama'il into alluvial sub-basins bounded by well defined hard-rock watersheds has allowed the study of individual areas to be integrated into a water balance for the whole basin. The village survey was therefore more comprehensive here than in other basins. A summary is presented in Table 4.4 in which areas of annual and perennial crops are listed, together with the various sources of water, for each village. Comparison with other basins shows that despite the unusual drainage and geometry of Wadi Sama'il, cropping patterns are similar to the other northern basins but the proportion of perennial to total crop area is 25 percent higher than in the southern basins. The cropped areas indicate a striking concentration of about half the agriculture in the upper part of the basin with Sama'il village alone accounting for 260 ha or 33 percent of the total area of dates. The principal cultivated areas are concentrated either where the main alluvial channels are constricted, as at Sama'il and Bid Bid, or around limestone springs at the foot of Jabal Nakhl as shown in Figure 4.2. Differentiation of the various water sources shows that limestone and ophiolite springs provide at least 110 l/s and 27 l/s respectively, while a total of 2 130 l/s is derived from alluvial sources, although the last figure includes a substantial element of recirculated water. This is abstracted, usually with a high degree of efficiency, by aflaj within or just upstream of the constricted wadi sections, although a few villages such as Luzuq and Mudrah tap the main wadi channels in wider alluvial areas. There has been a small recent increase in the number of pumped wells which supplement the falaj supply but pumped abstraction is a small proportion of the water balance. For example, Sama'il village, with most wells, pumps less than 30 l/s compared with a primary falaj supply of 250-320 l/s. Because the few existing hand-dug wells are ill-placed to monitor regional watertable variation and no observation wells have been drilled in the upper Wadi Sama'il, heavy reliance has been placed on chemical and isotope analysis in estimating the relative importance of water sources.

TABLE 4.4

SUMMARY OF SURVEY OF WADI SAMA'IL VILLAGES

Upper Sub-catchments

Location	Agriculture (ha)			Sources of Water (l/s)			Consumptive Use (l/s)
	Dates	Other	Total	Limestone Springs	Other Springs	Alluvial Sources	
Wadi Bani Ruwahah							
Hamma	2.7		2.7	14.2			1.3
Wughlah-Mughbariyah	2.6	0.8	3.4			3.0	1.6
Rissah-Muhal	4.2	2.0	6.2			2.0	2.9
Al Ayn-Jinah	26.9	2.4	29.3	?		<15.2	14.3
Kuri	4.5	0.5	5.0			4.0	2.4
Sa id	4.5	5.5	10.0			< 6.3	4.4
Wabal Biyad	15.7	4.0	19.7			<18.5	9.4
Sayjah	24.3	8.3	32.6	15.9			15.4
Falaj	5.0	1.0	6.0			5.2	2.9
Buri	1.0		1.0			0.3	0.5
Hayl, Minabak	24.0	13.4	37.4	24.1			17.3
Wadi Sama'il							
Sama'il villages	260.0	34.0	294.0		10.0	950-980[2]	142.8
Hassas	2.7	4-20	7-23			12.9-81	3.1-9.4
Wadi Al Uqq							
Mudrah	1.9		1.9			1.5	0.9
Tawiyah	4.8		4.8		4.5[1]		2.4
Dasir	3.6	4.4	8.0			7.1	3.6
Wadi Al Uqq villages	8.2	1.2	9.4		12.0[1]		4.6
Wadi Sayjani villages	7.5		7.5			10.0	3.7
Nidab	9.4	1.7	11.1		15.5[1]		5.4
Shuwahi	0.5		0.5		0.3		0.2
Luzuq	14.0	1.1	15.1			23.8	7.3
Sarur	56.5	18.0	74.5			163.5	35.3

Notes: [1] Ophiolite spring sources in which a part of the flow is probably of alluvial origin.
[2] This apparent alluvial source at Sama'il is much higher than the primary source of 250-320 l/s.

TABLE 4.4
(Continued)

SUMMARY OF SURVEY OF WADI SAMA'IL VILLAGES

Lower Sub-catchments

Location	Agriculture (ha)			Sources of Water (l/s)			Consumptive Use (l/s)
	Dates	Other	Total	Limestone Springs	Other Springs	Alluvial Sources	
Wadi Bani Jabir							
Hubi	4.4	3.2	7.6	5.4			3.5
Qaylah, south west	6.0		6.0	No supply during survey			3.0
Qaylah, main falaj	17.5	2.5	20.0			24.5	9.7
Firjat	8.0	8.0	16.0			4.0	7.2
Hijra'	10.0	1.0	11.0			2.5	5.4
Karku	19.5	1.6	21.1		12.1[1]		10.3
Multaqa Alwiyah	2.0		2.0			2.0	1.0
Multaqa Hadriyah	3.0		3.0			3.3	1.5
Wadi Hamim							
Al Farfarah	9.0	1.0	10.0			17.1	4.9
Thumayd	2.4		2.4	3.8			1.2
Qarn	3.8		3.8	2.3			1.9
Waghlah	1.0		1.0	5.2			0.5
Wadi Mansah							
Musabit-Bleha	5.9	0.4	6.3		9.1[1]		3.1
Mughrabah-Jirmanah	15.1	0.2	5.3		4.5[1]		2.6
Naf'ah	49.0	0.8	49.8			147.2	24.6
Lower Wadi Sama'il							
Saadi	2.0		2.0	2.3			1.0
Qayd	6.0		6.0	5.7			3.0
Qurta	2.4		2.4			17.7	1.2
Hamim	4.5		4.5	6.9			2.2
Bid Bid	40.1	10.5	50.6			219.7	24.2
Amqat	28.3	5.5	33.8			74.6	16.2
Fanjah (springs)	22.0	1.6	23.6	25.6			11.5
Fanjah (wadi)	12.8		12.8			206.1	6.3
Tawi Mansur	9.9		9.9			49.1	4.9
Tasawir	3.0	0.5	3.5			20.0	1.7
Al Khawd	24.6	5.0	29.6			228-122	14.2

796.7 160.1 947.1 454.8

Note: [1] Ophiolite spring sources in which a part of the flow is probably of alluvial origin.

The Distribution and Re-Use of Water

The main spring source in the basin is the limestone piedmont spring line which drains mainly into Wadi Bani Ruwahah but also contributes throughout the western margin of the basin. Chemical evidence suggests that little spring water drains into the alluvium of Wadi Mansah from the corresponding limestone massif of the north eastern basin boundary. Ophiolite springs occur wherever wadis cross the peridotite-gabbro discontinuity; because of the basin structure of the Sama'il nappe this contact takes the sub-circular form shown in Figure 4.2. The discharges are usually less than 2 l/s, but are used to supplement supplies from the normal wadi gravel waters. In eastern Sama'il village and Karku the springs are sufficiently numerous to be collected into single aflaj of local importance.

One of the main areas of alluvial storage, Wadi Bani Ruwahah, lies at the foot of the mountains at the western watershed. Much of this alluvium consists of old cemented boulder gravel exposed by deep erosion with a thin and narrow covering of modern gravels. Storage probably originates from both the coarse piedmont conglomerates and the uncemented ophiolite gravels on the eastern margin, and is sufficient to maintain water supply to a large part of the upper basin. Apart from two minor villages within the ophiolite gravel tributaries, villages dependent on alluvial water lie near the western margin where the water chemistry resembles that of limestone springs. However, chemical and isotope data show that groundwater entering Sama'il village at the northern end of Wadi Bani Ruwahah is not primarily of limestone spring origin.

Further east the largest areas of alluvium in the basin, the ophiolite gravels of Wadis Al Uqq and Mansah, are distinctive in that they drain exclusively peridotite and gabbroid rocks. As in Wadi Bani Ruwahah the depth of the alluvium is unknown but an important role in the basin's water balance is suggested by the surface extent and the calcium poor, relatively high pH chemistry, which points to little carbonate cementation and hence large storage. Several villages are situated at the wadi mouths upstream of the alluvial plain but there is little development of this source downstream before it reaches the main Wadi Sama'il channel.

The minor sub-basins of Wadis Bani Jabir and Hamim are almost closed systems and do not normally make a significant groundwater contribution into Wadi Sama'il. Several villages in Wadi Bani Jabir, particularly part of Qaylah and the downstream area of Multaqa were suffering from severe water shortage apparently due to infrequent recharge of the limited upstream alluvial storage which resulted in falaj and well failure, transpiration stress and abandonment of gardens.

In the downstream area, the Tasawir sub-basin storage is limited to recent uncemented gravels of the main wadi channels. Indirect evidence suggest that these gravels are thin but they are the primary channels of groundwater flow from which all the major aflaj are derived. Fifteen aflaj supply a long narrow belt of date gardens on either bank of Wadi Sama'il for 13 km from Bid Bid to Tasawir. These aflaj tap the shallow water table by means of trenches in the wadi gravel. As they often parallel the wadi for several kilometres and as they are mostly unlined, leakage back into the wadi often occurs.

Finally a minor input to the system occurs between Amqat and Al Khawd in the form of further ophiolite springs, a hot saline seepage at Fanjah, and suspected seepage from limestone to alluvium.

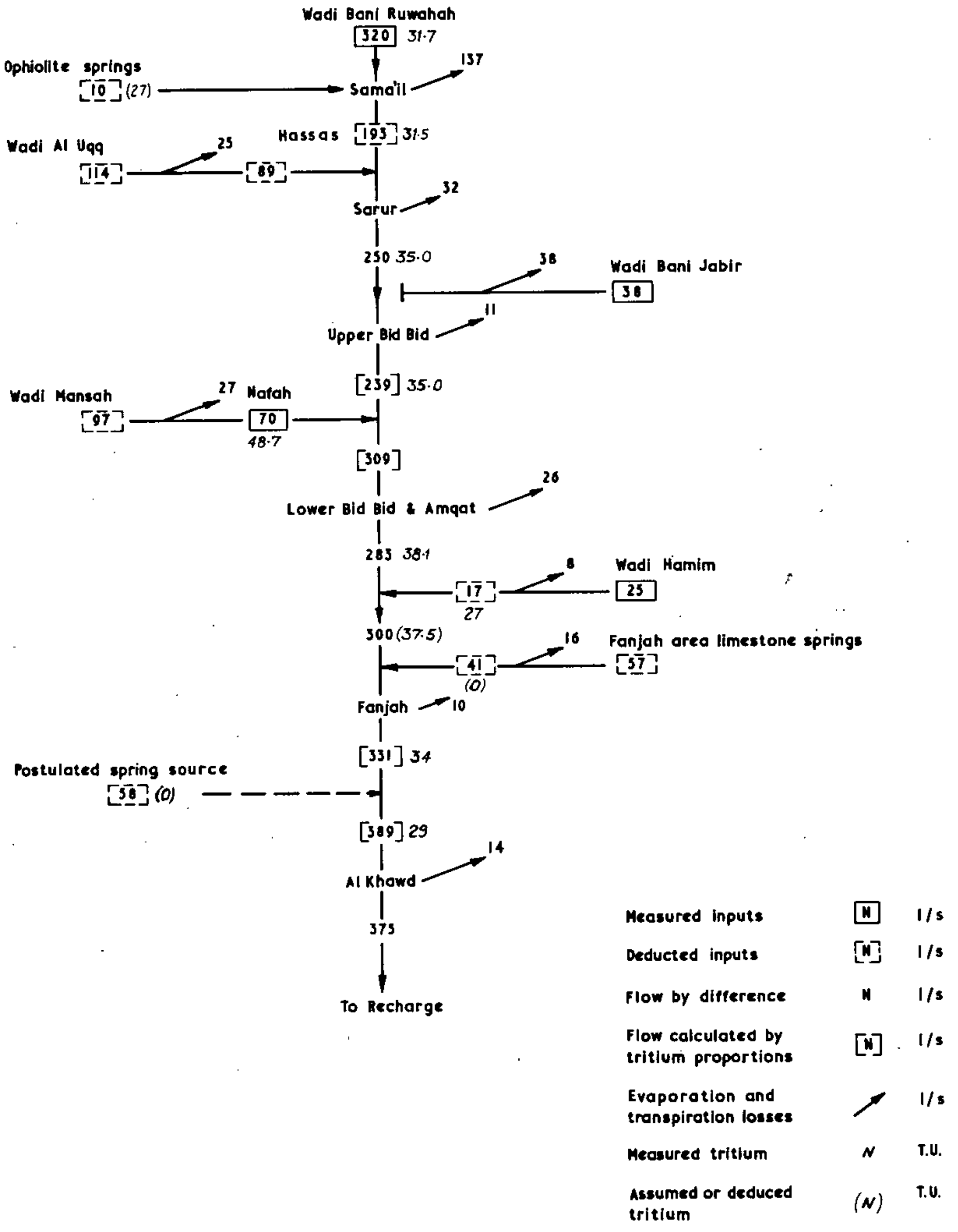
The configuration of the Wadi Sama'il basin is such that the main drainage channel suffers a gradual consumptive loss from the long belt of date gardens at its edge. This loss is only partly compensated by point inputs from the sub-basin tributaries and there is evidence of a re-cycling process. This is most evident at Sama'il village where three aflaj supply a primary source of 250-320 l/s to the upstream date gardens. The remaining ten aflaj downstream re-use the irrigation excess as it percolates back to the wadi and the apparent supply is three times the real input. Each water application involves a soil leaching cycle which results in a rapid increase of the more soluble salts as shown in the Sama'il village conductivity distribution (Figure 4.9). This leachate mixes with subsequent groundwater inputs east of Sama'il and is re-used still further in the villages of Sarur, Bid Bid and Amqat.

The use of water by one village affects the quantity and quality of water available to successive downstream villages. Analysis of water use through the whole basin shows that total water application exceeds the estimated primary sources by a factor of about 2-3. Whereas upstream villages may be partially or, in the case of spring line villages, completely independent of other sources, the villages furthest downstream utilise an increasing proportion of irrigation excess and are therefore sensitive to further agricultural development upstream.

The Water Balance

Estimation of the total water transfer at a section of Wadi Sama'il has been possible only at the rock bar in central Sama'il village. Working from this known value, the water balance of the area downstream can be drawn up; the downstream transpiration losses are known, but groundwater inputs from tributary wadis are not and have had to be assessed indirectly. Chemical sampling through the basin has been useful in the recognition of provenance and the degree of deterioration in downstream water quality. However, variations due to evaporation, residence time, re-use of water and other processes are too complex to allow quantitative assessment of the many water sources involved. We have therefore used the more stable index of tritium concentration together with the village survey data to compile a water balance for the winter of 1974-75, Figure 4.10. We have used the principle that the product of water transfer and tritium concentration is constant upstream and downstream of any confluence. As the tritium concentration of Wadi Al Uqq could not be determined, we have constructed the flow diagram from Wadi Mansah using probable upper and lower limits of groundwater input from Nafah of 70 and 58 l/s to estimate the probable groundwater input from Wadi Al Uqq at between 45 and 90 l/s, which implies an important source which we could not observe.

The high tritium concentration from ophiolite gravel areas, measured as 48.7 TU (Tritium Units) at Wadi Mansah and estimated as 46-51 TU from Wadi Al Uqq, contrasted with the other main alluvial area Wadi Bani Ruwahah, with a much lower value of 31 TU. In the absence of tritium analyses for some of the minor groundwater inputs to the system like Wadi Hamim and the Fanjah springs, we have assumed probable isotopic compositions to give conservative estimates of resources. The groundwater available for recharge downstream of Al Khawd is thus estimated as between 295 and 375 l/s. About 100 l/s of this bypasses the P.D.(O) gauging site through Al Khawd falaj. As there were no reports of surface flow during the winter of 1974-75, we assume that groundwater leakage to the Batinah past Al Khawd may be up to 275 l/s. The much reduced summer flow at Al Khawd is of high tritium concentration (40 TU compared with the winter value of 28 TU) and indicates a greater proportion of ophiolite gravel water during the summer. This is consistent with the field evidence because gaugings at Hassa falaj east of Sama'il village vary from 13 l/s in summer to 81 l/s in winter. This, and surface flow during some of the winter months, demonstrate the strong variation caused by seasonal crop water requirements in Sama'il. Hence, as the flow downstream from



Wadi Sama'il Flow Diagram (based upon isotopic and flow data for Winter 1974/75)

Figure 4·10

Sama'il diminishes, the proportion of undeveloped ophiolite gravel water of higher tritium content increases. A similar seasonal variation in downstream recharge is seen in most of the larger villages and in the outflow from the basin as a whole as indicated by the Al Khawd falaj hydrograph in Figure 4.6.

To summarize, intensive and highly efficient water use throughout the basin is maintained mainly from storage in two contrasting environments. In the south, Sama'il village is sustained by dewatering of the Wadi Bani Ruwahah alluvium, while supply to the more downstream villages, being limited by the large upstream demand, depends on the ophiolite gravels of the eastern sub-basins.

4.4 THE COASTAL REGION

The cultivated area of the Batinah coast is a discontinuous mosaic of small gardens in a narrow strip within 5 km of the sea and accounts for about 50 percent of the cultivation within the whole study area. The total area of the gardens is 68 km^2 and they are irrigated from an estimated 2 700 hand-dug wells fitted with pumps. The gardens lie in a zone of generally fine calcareous silt or loess of low organic content and varying salinity. Near Sib, Barka and As Suwayq, date gardens are separated from the sea by a belt of saline soil upon which salt bush and low stable sand dunes are established. In general the density of gardens is highest near the principal wadi systems.

There are many kinds of garden, ranging from ornamental gardens with luxury crops to abandoned date gardens with only dead or dying date palms. Along most of the coast this variation can be categorized into seaward, central and landward gardens. Of these, the central gardens are the most productive and representative of the coastal region. While dates are the predominant crop, a number of annual and perennial crops are interplanted with the dates in some areas to give a complete vegetation cover. Limes and bananas are grown in intensive plantations and as individual plants in apparently random distribution. Limes constitute the second most abundant perennial crop, despite their sensitivity to high salinity and the moderate boron content of some areas. Alfalfa is widely grown and there are significant areas of sorghum and green barley. Irrigation follows a 7 to 9 day rotation with more frequent application where intercropping occurs. Pumping rates and hours vary greatly from one area to another and with the time of year but typically range between 4 and 12 l/s for several hours in the early morning and in the evening. Individual date palms are mostly planted in depressions ("jayl") of about 1 m^3 capacity which retains the irrigation water close to the tree roots, although where interplanting occurs, the practice of flooding larger rectangular areas ("jelba") to a shallow depth is sometimes used.

In areas further from the main wadis, there is a gradation to the seaward gardens in which intercropping ceases, leaving only thinly spaced dates. The brackish conditions defeat any attempt at intensive farming. The few pumps in this area are low powered and used only for young date palms and any vegetables that can withstand the unfavourable conditions. In many of the northern gardens, these dates are left to draw naturally on the shallow water table and are regarded by the owners as a supplement to the locally important fishing industry.

The landward gardens are recent, and at present, less extensive than the central gardens. Few new date palms have been planted, but interception by the wells of the relatively fresh groundwater allows cultivation of the more sensitive crops, such as bananas. Vegetables, melons and other market produce are increasingly grown to meet the expanding demands of the Capital area. For the most part this extension is in small land units using traditional methods. An important exception is Rumays where a rapid increase in the number of large farms using piped or concrete lined channels fed from pumped boreholes has occurred in recent years.

Fresh and Saline Water Interface

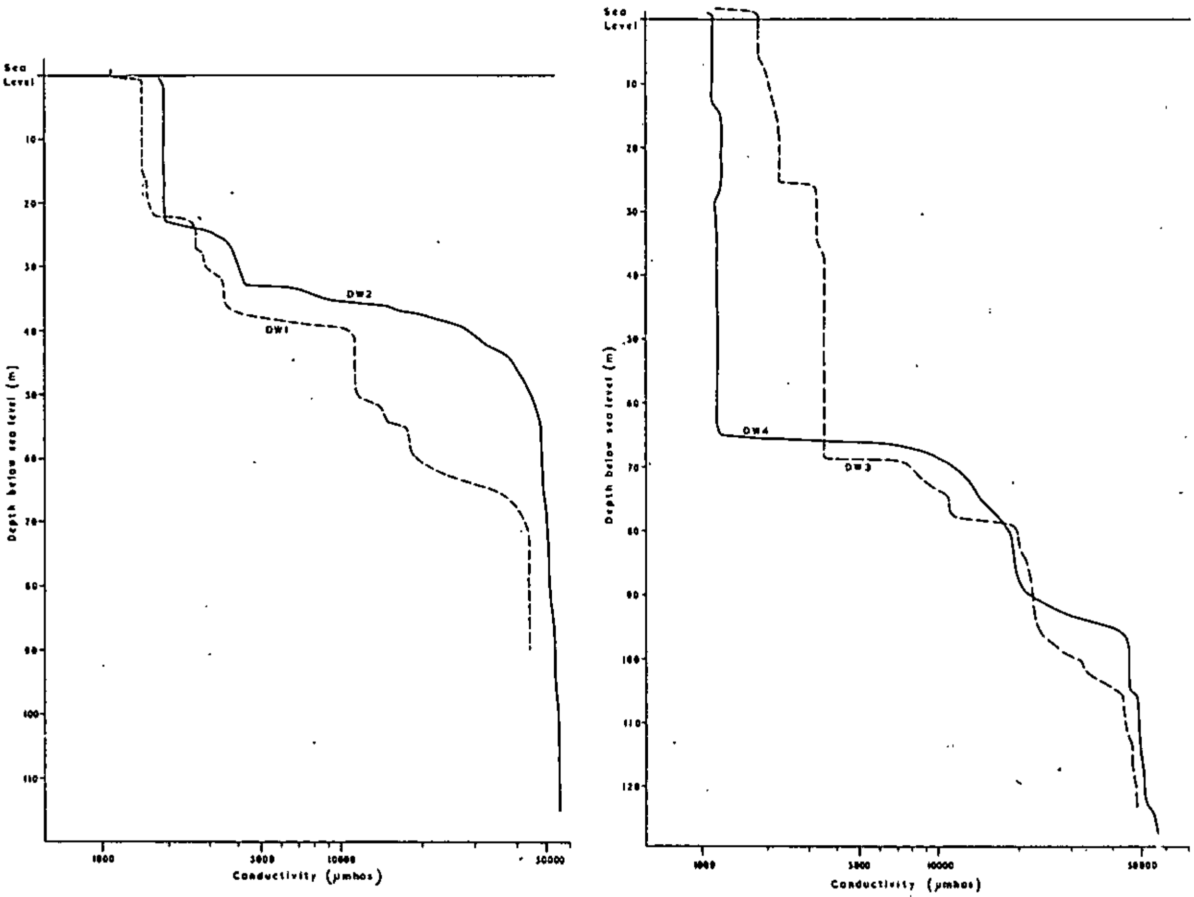
Although the coast provides a simple geographical boundary to the Batinah and thus to our study area, the zone of contact between the fresh groundwater and seawater provides a complex boundary condition to the general flow of groundwater towards the coast. Flow through the aquifer could be lost by direct leakage to the sea, by evaporation from areas of shallow groundwater, by soil water evaporation, and by crop transpiration in irrigated areas. Before assessing these components in turn, we will examine the boundary condition as a whole.

As fresh water is less dense than sea water, the fresh water will "float" on the sea water. The Ghyben-Herzberg relationship states that the salt water will occur at a depth below sea level of about forty times the height of fresh water above sea level. With a watertable within one or two metres of sea level, within the thick alluvial aquifer, salt water must underlie the Batinah date gardens at shallow depth; its precise position depends on the watertable gradient.

Direct evidence of this interface is provided by conductivity profiles in selected boreholes, immediately inland from the agricultural areas of Wadi Sama'il and Wadi Bani Kharus (Figure 4.11). A layer of fresh water 23 m deep at Sib and about 70 m deep in the Wadi Bani Kharus overlies a transitional zone, where conductivity increases over a depth of about 20 m to a value equal to or even exceeding that of sea water.

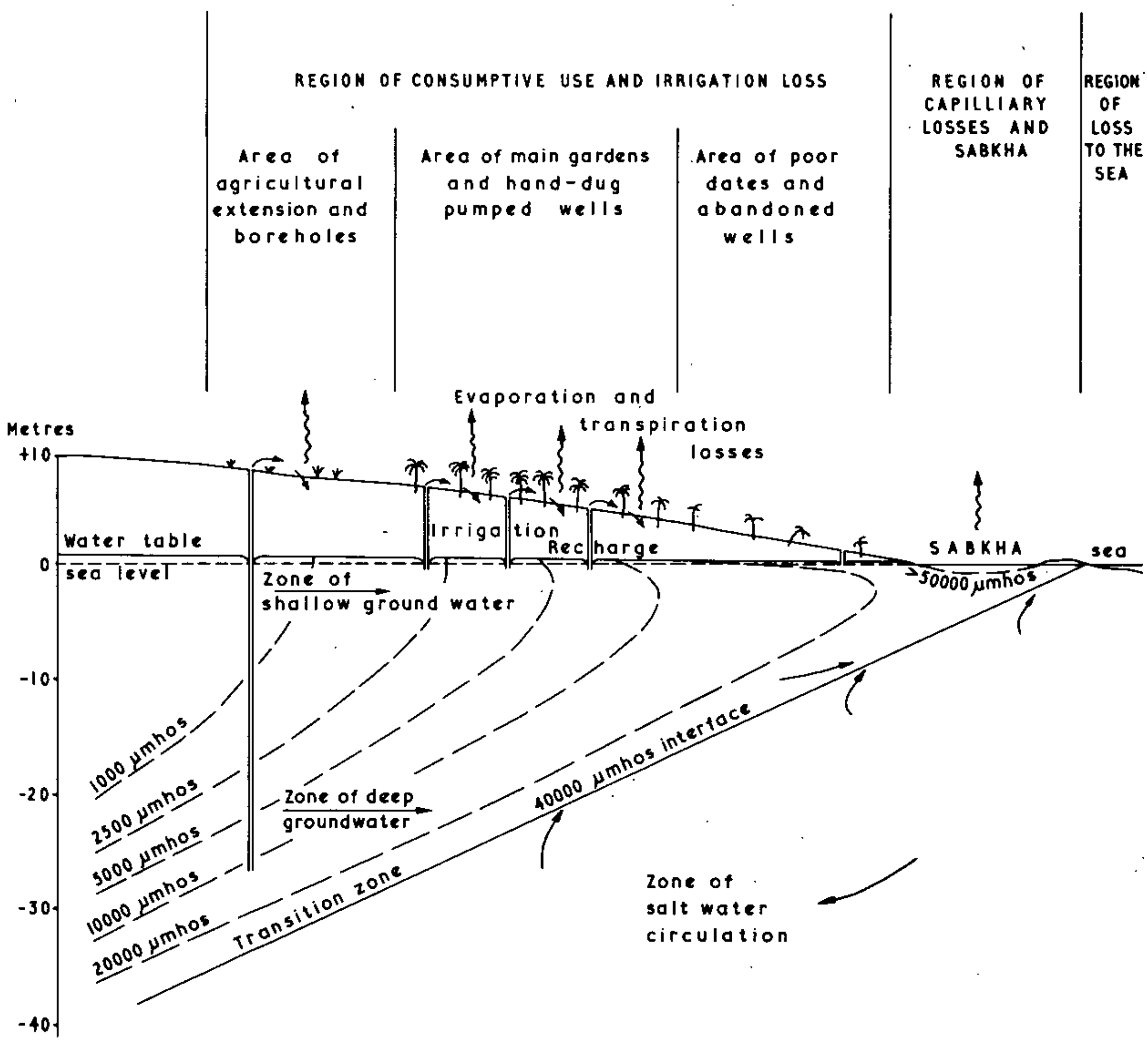
As the watertable falls towards the sea, the freshwater thickness must decrease. There is a progressive increase in salinity of the freshwater from the inland to the seaward. margins of the gardens from about 1 000 μmhos to 10 000 μmhos. This primarily reflects an increase of up to 4 000 mg/l in chloride content. As recycling of irrigated water in the inland villages results in much smaller increases from 500 to 1 500 μmhos, it is evident that diffusion occurs above the saline interface. This effect has been demonstrated by regular conductivity monitoring of boreholes at Rumays where more seaward wells with a shallow interface such as JT50 and R36 have had salinities increasing to 7 000 μmhos within days of commencement of pumping. Rumays has had a rapidly increasing rate of abstraction, but complaints of salination have also been received from some seaward date gardens in the western Sib fan and in Wadi Bani Kharus.

The general coastal situation is illustrated in Figure 4.12; the most significant feature is the disappearance of the freshwater wedge either by irrigation loss or by mixing with salt water in the transition zone. This disappearance, which implies a lack of direct freshwater losses to the sea, occurs throughout the coastal area of Wadi Bani Kharus as shown by the position of the 10 000 μmhos contour inland from the coast in Figure 4.13.



Salinity Profiles of Deep Boreholes

Figure 4·11



Generalised Cross Section at the Coast

Figure 4·12

Figure 4.14 demonstrates a different situation in the Wadi Sama'il at Sib and further west. The 10 000 μmhos contour is inland, but to the east of Sib the 5 000 μmhos contour at the shore implies some freshwater leakage to the sea. This is the only direct evidence of loss of fresh groundwater along the Batinah, although local losses may occur in some of the narrow wadi channels at Barka and at As Suwayq.

Before the introduction of coastal cultivation, a natural equilibrium between fresh and salt groundwater would have resulted in a stable interface influenced only by seasonal groundwater flow and tidal variations. Since then two phases of agricultural development have affected this equilibrium. The first was the gradual establishment of date gardens using bailed wells and the second was the introduction of pumps, mainly in the last decade, which resulted in greatly increased abstraction. The abstraction of water must exceed the consumptive use in order to satisfy the leaching requirement, so that the salinity in the upper layers of the aquifer will reflect irrigation return. The leaching requirement also implies that there must be a residual groundwater flow from the gardens to the sea to prevent a continuous build-up of salts. In each phase, the saline interface would have migrated inland until new stable conditions were reached. The rate of this migration is likely to be of the order of only centimetres per day and would not have been observed directly during the period of survey. However, we consider that approximate equilibrium conditions probably exist at present, except where agriculture has recently expanded as at Rumays.

Water Use

An essential item in the Batinah water balance is the consumptive use from irrigated areas. The November 1974 photographic coverage of the coastal area has been used to compile Table 4.5, showing detailed crop distribution and water requirement. This shows considerable variation in cropping pattern as was also noted from the village survey of the two detailed study areas, the Sib fan in the Wadi Sama'il and Wadi Bani Kharus. The Sib fan is one of the most productive areas of the Batinah coast with some 16 km of continuous cultivation and outlying areas at Manumah in the west and Mawalih in the east. The coastal cultivated area of Wadi Bani Kharus is similar to that of Wadi Sama'il but date gardens are less continuous and often of lower planting density. The gardens are poorer with higher proportions of natural vegetation between the gardens.

Total abstraction in the survey areas was determined by assessment of about 440 pumped wells in the Sib fan and 520 pumped wells in Wadi Bani Kharus. The annual abstraction for Wadi Sama'il is 20.6 million m^3 per year compared with consumptive use of 8.8 million m^3 per year; the equivalent figures for Wadi Bani Kharus are 13.1 and 8.9 million m^3 per year. There is a 40 percent difference in abstraction between the two regions although the consumptive use is the same. Although the Sib fan was surveyed during autumn and winter while Wadi Bani Kharus was surveyed in the spring, the abstraction measured at Rumays during a detailed survey showed a difference in abstraction between these periods of only 13 percent. The different abstraction rates are evidently a regional rather than a seasonal difference. As the soil texture, water salinity and water table depth are similar in the two areas, we attribute the main difference in abstraction rate to crop type and density. In the Wadi Sama'il coastal region, where groundwater is adequate, there is high density planting with large areas of annual crops and intercropping with alfalfa; the high proportion of shallow rooted crops requires more frequent irrigation with higher returns to the water table. Wadi Bani Kharus with lower crop density and acacia scrub around the gardens is more typical of the coastal region.

TABLE 4.5

CROPPED AREAS AND CONSUMPTIVE USE AT THE COAST

Agricultural Classes[1]	Wadi Lansab	Wadi Rusayl	Wadi Sama'il	Wadi Taww	Wadi Ma'awil	Wadi Bani Kharus	Wadi Far	Wadi Bani Ghafir
Cropped Area (ha)								
1	30	76	221	26	106	50	60	211
2	67	37	242	142	786	567	437	392
3	16	30	211	116	468	159	904	740
4	4	11	95	55	151	58	106	166
5		2		91	2			
Total	117	156	769	430	1 513	834	1 507	1 509
Crop Proportions (percent)								
1	26	49	32	6	7	6	4	14
2	57	24	29	33	52	68	29	26
3	14	19	23	27	31	19	60	49
4	3	7	16	13	10	7	7	11
5		1		21				
Consumptive Use (l/s)								
1	14.9	37.7	109.6	12.9	52.6	24.8	29.7	104.6
2	25.5	14.1	92.1	54.0	298.8	215.6	166.1	149.0
3	1.5	5.1	40.0	9.2	32.6	18.6	97.4	100.8
4	1.6	4.5	38.6	22.4	61.5	23.6	43.2	67.6
5		0.9		37.1	0.9			
Total	43.5	62.3	280.3	135.6	446.4	282.6	336.4	422.0
ρ^2	0.30	0.54	0.60	0.25	0.22	0.37	0.34	0.43

Notes: [1] See Table 4.2 for description of agricultural classes.
[2] Crop density factor for calculating consumptive use of the more scattered class 3 date palms.

Direct Evaporation Losses From the Water Table

Between the date gardens and the sea, the depth to groundwater generally varies from about 3 m to less than 1 m with seasonal and diurnal fluctuations of about 5 cm. In this situation capillary groundwater rise may result in evaporation and an increase in soil salinity.

Direct losses are most likely to occur in the 104 km^2 of highly saline sodic soils delineated by Sogreah[1]. The soils are not homogeneous and vary between a coarse sandy material at the water table to a fine sandy loam at the surface. Estimates of evaporation from different soils vary considerably. Losses equivalent to 25 percent of open water evaporation have been reported for fine sandy loams with a water table at 1 m, which is equivalent to 1.7 mm/d over the Batinah. Relationships developed by De Ridder[2] between maximum capillary rise and water depth indicate larger losses from fine sandy loams of 2 mm/d with a water level at 1.8 m.. He estimated losses from silty clay loams of about 2 mm/d with a water level at 1 m and 0.8 mm/d at 1.5 m.

Direct evaporation can thus vary considerably along the Batinah coast according to water depth and soil type. We show in Table 4.6 the losses within each basin for assumed capillary rises of 0.8 and 2.0 mm/d, amounting to between 30 and 76 million m^3 per year. At the higher rate, they would exceed the consumptive use of the coastal agriculture in some areas.

TABLE 4.6

ESTIMATES OF EVAPORATION LOSSES FROM SHALLOW GROUNDWATER

Basin	Area of Saline Soils km^2	Evaporation Loss Due to Capillary Rise of 0.8 mm/day (million m^3/year)	2.0 mm/day (million m^3/year)
Wadi Lansab	12.5	3.7	9.1
Wadi Rusayl	2.5	0.3	1.8
Wadi Sama'il	9.0	2.6	6.6
Wadi Taww	13.0	3.8	9.5
Wadi Ma'awil	15.0	4.4	11.0
Wadi Bani Kharus	19.5	5.7	14.2
Wadi Far	21.0	6.1	15.3
Wadai Bani Ghafir	12.0	3.5	8.8
Total	104.5	30.5	76.3

However, these losses are not solely from freshwater sources. Direct evaporation is occuring within an area where tidal and storm surges inject sea water. It is also the zone where subsurface mixing occurs at very shallow depth between saline groundwater and any groundwater flowing from beneath the coastal gardens. This water entering the zone of direct evaporation possesses a conductivity of 10 000 μmhos in many areas and thus already comprises a significant proportion of saline water. Separate identification of the fresh and saline losses to direct evaporation has not been possible. The situation is dynamic with the relative proportions changing from season to season and from year to year. We consider, however, that freshwater losses by direct evaporation from the water table are probably a small component of overall water balance considerations.

[1] Final Report on Phase 1 Soils and Agricultural Studies, Sir Alexander Gibb & Partners, April 1975.
[2] N. A. De Ridder, Integrated planning of irrigated agriculture in the Varamin and Garmsar plains, FAO Report AGL: SF/IRA 12.

4.5 THE SYSTEM AS A WHOLE

In the previous sections of this chapter we have described the different sources of water and the way in which the water is used for irrigation in the villages of the northern basins. The main sources of water are the limestone springs recharged from the rainfall on the high jabal, the ophiolite springs recharged from rainfall on the foothill areas, and the alluvial storages of the mountain wadis, the piedmont and the Batinah plain. Of these, the main source of water is the alluvium.

Many of the inland villages in the valleys along the foothills and in the piedmont draw water mainly by aflaj from the surface wadi channels or from the gravels near these main channels. These storages are recharged by surface runoff following rainfall on the jabal as is the coastal alluvium, north of the foothills. Apart from a number of recent abstractions of groundwater for supply in the Capital area, groundwater flow in the alluvium of the plain is intercepted by a continuous line of villages along the coast.

Water supplies in the inland villages are largely dependent on spring or falaj flows. A falaj supply declines, sometimes rapidly, during a period without recharge of the alluvial storage it taps. During the 1973/74 drought, supplies declined to a level sufficient only to provide irrigation for the perennial date crops. Indeed, some villages were facing a serious water shortage immediately before the October 1974 rainfall.

Groundwater availability to the coastal villages was not affected by drought to the same extent as the villages fed by aflaj. The drop in groundwater level of 0.2 m between December 1973 and December 1974 may have led to shorter periods of pumping in individual wells, but it is unlikely that water supply was drastically curtailed. Water quality would have deteriorated as the head declined and fresh water was skimmed from the upper surface of the water table. Thus the constraint of water supply was manifest in terms of deteriorating water quality.

It is not possible to estimate actual consumptive use for the drought period. It would certainly have been less than the average annual consumptive use determined from cropped areas and water use of the major crops summarized in Table 4.7. At the coast where alfalfa and fruit comprise 94 percent[1] of "other" crops, we have assumed continuous irrigation of all crops. In the inland villages, perennial alfalfa and winter irrigated annual crops occur in about equal proportions; allowance has therefore been made for the shorter growing season of the winter crops.

The average annual consumptive use exceeds 100 million m^3 of which 58 percent is at the coast. A classification has been adopted in the table in order to separate the villages of the piedmont and the alluvial channels of the mountain front from those of the mountains and the spring line at the mountain foot. This allows comparison of the consumptive use in villages developing alluvial storages along the margin of the mountains with those either well within the mountains or at piedmont springs where groundwater bypasses the wadi channels. Consumptive use in the piedmont is about 24 percent of the total and about 18 percent is used in the mountains and spring line villages. There is little variation in the relative use of water by dates and other crops; regionally 86 percent is consumed by dates, but at the coast in Wadi Taww the modern agricultural developments lower the proportion of dates to 56 percent.

[1] Final Report on Phase 1 Soils and Agricultural Studies, Sir Alexander Gibb & Partners, April 1975.

TABLE 4.7

CROPPED AREAS AND ANNUAL CONSUMPTIVE USE IN NORTHERN BASINS

Basin	Mountain and Mountain Foot		Piedmont and Mountain Front		Coast		Total
	Dates	Others	Dates	Others	Dates	Others	
Cropped Areas (ha):							
Wadi Lansab	70	—	3	—	113	4	190
Wadi Rusayl	19	—	4	—	143	13	179
Wadi Sama'il	129	29	658	115	674	95	1 706
Wadi Taww	56	4	3	—	284	146	493
Wadi Ma'awil	166	48	242	44	1 360	153	2 013
Wadi Bani Kharus	226	81	77	96	776	58	1 314
Wadi Far	418	70	202	48	1 401	106	2 245
Wadi Bani Ghafir	—	—	247	48	1 343	166	1 804
Total	1 084	232	1 436	351	6 094	741	9 938
Consumptive Use (million m³/year):							
Wadi Lansab	1.1	—	—	—	1.3	—	2.4
Wadi Rusayl	0.3	—	—	—	1.8	0.2	2.3
Wadi Sama'il	2.0	0.3	10.3	1.1	7.6	1.2	22.5
Wadi Taww	0.9	—	—	—	2.4	1.9	5.2
Wadi Ma'awil	2.6	0.5	3.8	0.4	12.1	2.0	21.4
Wadi Bani Kharus	3.5	0.8	1.2	0.9	8.2	0.8	15.4
Wadi Far	6.5	0.7	3.2	0.5	9.2	1.4	21.5
Wadi Bani Ghafir	—	—	3.9	0.5	11.2	2.1	17.7
Total	16.9	2.3	22.4	3.4	53.8	9.6	108.4

Water Balance of the Wadi Sama'il Basin

At any point within the basin, the amount of upstream dewatering during the drought is equal to the actual consumptive use and any other evaporatiive losses, plus the surface and subsurface flow at that point. Throughout the lower part of the basin the natural evaporative losses are likely to be small and probably insignificant compared with the consumptive use of agriculture.

Transfer of water, however, can be large; the Wadi Sama'il data which are the most detailed available, demonstrate this variability. Our estimates of subsurface flow at Al Khawd show a variation from 375 l/s during the winter of 1974/75 to probably less than 100 l/s during a summer season. Thus although there would appear to be a surplus for additional winter crops, the balance between supply and use is close for that part of the basin above Al Khawd.

During the winter of 1973/74 there were surface flows measured by PD(O), totalling 4.5 million m³ between December and March, and this would have been accompanied by a similar groundwater leakage. Our estimate of total water transfer to the coastal plain below Al Khawd for the period December 1973 to November 1974 is given in Table 4.8 where we draw a water balance for the coastal plain. Groundwater abstractions for the Government and PD(O) wells have been estimated elsewhere[2].

TABLE 4.8

WATER BALANCE FOR THE WADI SAMA'IL COASTAL PLAIN FOR DECEMBER 1973-NOVEMBER 1974

	(million m³)	
Surface water transfers		
(Dec 1973-Mar 1974)		4.5
Groundwater leakage		
Dec 1973-Mar 1974		3.9
Apr-Oct 1974		2.0[1]
Nov 1974		1.0
Groundwater abstractions		
(Al Khawd wellfields)	1.4	
Change in groundwater storage		2.4
Consumptive use by agriculture	8.8	
	10.2	13.8
Loss to sea and direct evaporation	3.6	

[1] Groundwater leakage for the summer period is an estimated value. Insufficient data is available to determine the transfer using isotopic information.

The surplus balance is in keeping with the field observations of groundwater conductivity (Figure 4.14). Reports of increasing salinities in some wells probably reflect long term changes in the area due to readjustments because of the wellfield abstractions and the introduction of pumped wells superimposed on the short term effects of the particularly dry period.

We are hampered by lack of data in the other basins for direct estimates of base flow transfer to the Batinah. Our detailed survey was during the latter part of the drought period. However, in broad terms, the transfer from the mountains can be assessed from the difference between consumptive use at the coast and the dewatering over the Batinah (Table 3.6) during the drought year. Large transfers are implied from this comparison; dewatering accounts for about half the annual consumptive use and transfers from the mountains might therefore be assumed to account for the remaining half (Table 4.9).

[2] Water Supply to Muscat and Mutrah, Sir Alexander Gibb & Partners, Nov. 1974.

TABLE 4.9

THE NORTHERN BASINS
ESTIMATED GROUNDWATER TRANSFER FROM THE PIEDMONT TO THE ALLUVIAL PLAINS

(million m^3)

Basin	Dewatering of the Groundwater Basin Dec 1973-Nov 1974	Annual Consumptive Use at the Coast	Implied Transfers
Wadi Rusayl[1]	1.2	2.0	0.8
Wadi Sama'il	2.4	8.8	6.4
Wadi Taww	0.8	4.3	3.5
Wadi Ma'awil	2.4	14.1	11.7
Wadi Bani Kharus	4.6	9.0	4.4
Wadi Far	13.7	10.6	—[2]
Wadi Bani Ghafir	4.0	13.3	9.3
Total	29.1	62.1	36.1

Notes: [1] Estimates of dewatering were not made for Wadi Lansab which is outside the main groundwater basin and has few observation wells in the scattered alluvial deposits.
[2] Estimated dewatering exceeds consumptive use in Wadi Far. However, field observations indicate base flow transfers from the piedmont to the plain.

By comparison with the Wadi Sama'il water balance, these estimates of baseflow transfer do not seem too unrealistic. However, it would be misleading to regard them as precise estimates. We have previously indicated that the aquifer storage coefficient data, from which the dewatering estimates are derived, are amongst the least certain of our hydrogeological data. Furthermore the capability of the individual basins to transfer base flows vary considerably. We further discuss the water balance of the alluvial plains in Chapter 7.

Groundwater Flow to the Coast

The comparison between consumptive use and dewatering as an estimate of water transfer does not take into account groundwater losses to the sea or direct evaporation. Our field evidence shows that only in the vicinity of Sib in the Wadi Sama'il was there groundwater flow to the sea. Elsewhere, the conductivity of groundwater indicates consumption of most of the freshwater in the coastal gardens and although we have shown that large direct evaporation losses are possible, we believe these are largely from saline water sources.

General confirmation of this is provided from the estimates of groundwater flow to the coast given in Chapter 3. Groundwater flow corresponds in total, but not in detail (Table 4.10), to the consumptive use. The flow net and model estimates confirm the field observations of leakage to the sea in the Wadi Sama'il where groundwater flow exceeds the consumptive use. The relatively large differences between consumptive use and groundwater flow in the Wadis Bani Kharus and Bani Ghafir are attributed to the lack of sufficient detailed hydrogeological information. Overall, we believe the most reliable estimates of groundwater flow to be from the detailed flow net for the eastern basins and from the model in the western basins.

TABLE 4.10

THE NORTHERN BASINS
RELATIONSHIP BETWEEN AVERAGE CONSUMPTIVE USE AND GROUNDWATER FLOW AT THE COAST

(million m³)

Basin	Consumptive Use	Groundwater Flow	
		Model	Flow Net
Wadi Lansab	1.3	—	—
Wadi Rusayl	2.0	6.0	5.8
Wadi Sama'il	8.8	10.6	20.8
Wadi Taww	4.3	8.9	4.7
Wadi Ma'awil	14.1	11.2	7.4
Wadi Bani Kharus	9.0	3.4	2.9
Wadi Far	10.6	11.6	4.0
Wadi Bani Ghafir	13.3	2.8	3.5
Total	63.4	54.5	49.1

CHAPTER 5

THE SOUTHERN BASINS

5.1 INTRODUCTION

In this chapter, we present the data which establish the broad hydrogeological characteristics of the alluvial deposits of the southern basins. Without the exploratory drilling programme the assessment is qualitative rather than quantitative and the description of the groundwater system depends largely on our survey of water use in the Wadi Bahla basin.

Hydrogeological appraisal, without drilling, is insufficient to establish the extent of gravels and thus the dimensions of the aquifers. Evidence suggests, however, that groundwater is mainly associated with the drainage channels of the modern wadi system. Existing drilling records suggest that the alluvial sediments are thin, less than about 70 m, with more prominent deposits of marls and clays than in the northern basins. In the areas between the wadi channels the sediments are so shallow that their potential as exploitable aquifers is doubtful.

There have been two previous studies in the southern area: a reconnaissance of the Wadi Sayfam, upstream of Al Ghafat, made by Sogreah[1] noted no limestone springs, despite extensive solution in the mountain limestones (karstic conditions). Village water supplies upstream of Al Ghafat came from shallow wells in the weathered zone of the Sama'il nappe; the alluvial deposits of the wadi bed were apparently very thin and did not provide a permanent source of groundwater.

The second study[2] involved the construction of 19 boreholes after seismic refraction and resistivity exploration. These drilling records provide the main subsurface information for the southern basins. The water supply available from the alluvium deteriorated across the area from north to south in response to thinning of the alluvial sands and gravels and the appearance of clays.

5.2 GENERAL SETTING AND GEOLOGY

The general structure of the alluvial basins is similar to the piedmont and mountain front zones of the north. The mountain area extends about 10 km south and south-east of the Jabal Akhdar-Jabal Nakhl watershed. Three piedmont basins occur within a 30 km wide zone at the foot of the mountains and contain the major towns of Izki, Nazwa and Bahla. A gravel plain

[1] Sogreah, the development of the Ghafat valley, 1971.
[2] Report on water supply investigation, Northern Oman, Scott Wilson Kirkpatrick and Partners, 1972.

extends for 60 km to the southern boundary of the study area and beyond. The area is flanked to east and west by extensive outcrops of bedrock and is broken by many rocky outcrops rising from a few metres to several hundred metres above the plain. A mid-plain range of hills, 30 km south of the piedmont, gives rise to a group of villages, where the wadi channels are confined between rocky outcrops. This marks the southern limit of the main villages; only one, Adam, is further south, at the final range of hills before the desert of the interior.

Relationships between drainage pattern, hard rock geology and the distribution of alluvium are shown in Figure 5.1. The piedmont alluvial basins are associated with the outcrop of the ophiolites at the foot of the limestone mountain massif. Stream erosion and subsequent deposition of outwash material from the mountains has taken place predominantly along the wadi channels. Local runoff from the smaller mountain basins and from the hardrock areas of the piedmont has resulted in the extension of alluvial deposition into tributary valleys on the flanks of the main wadis. In particular, ophiolite gravels occur within and to the south of the piedmont exposures of the Sama'il nappe.

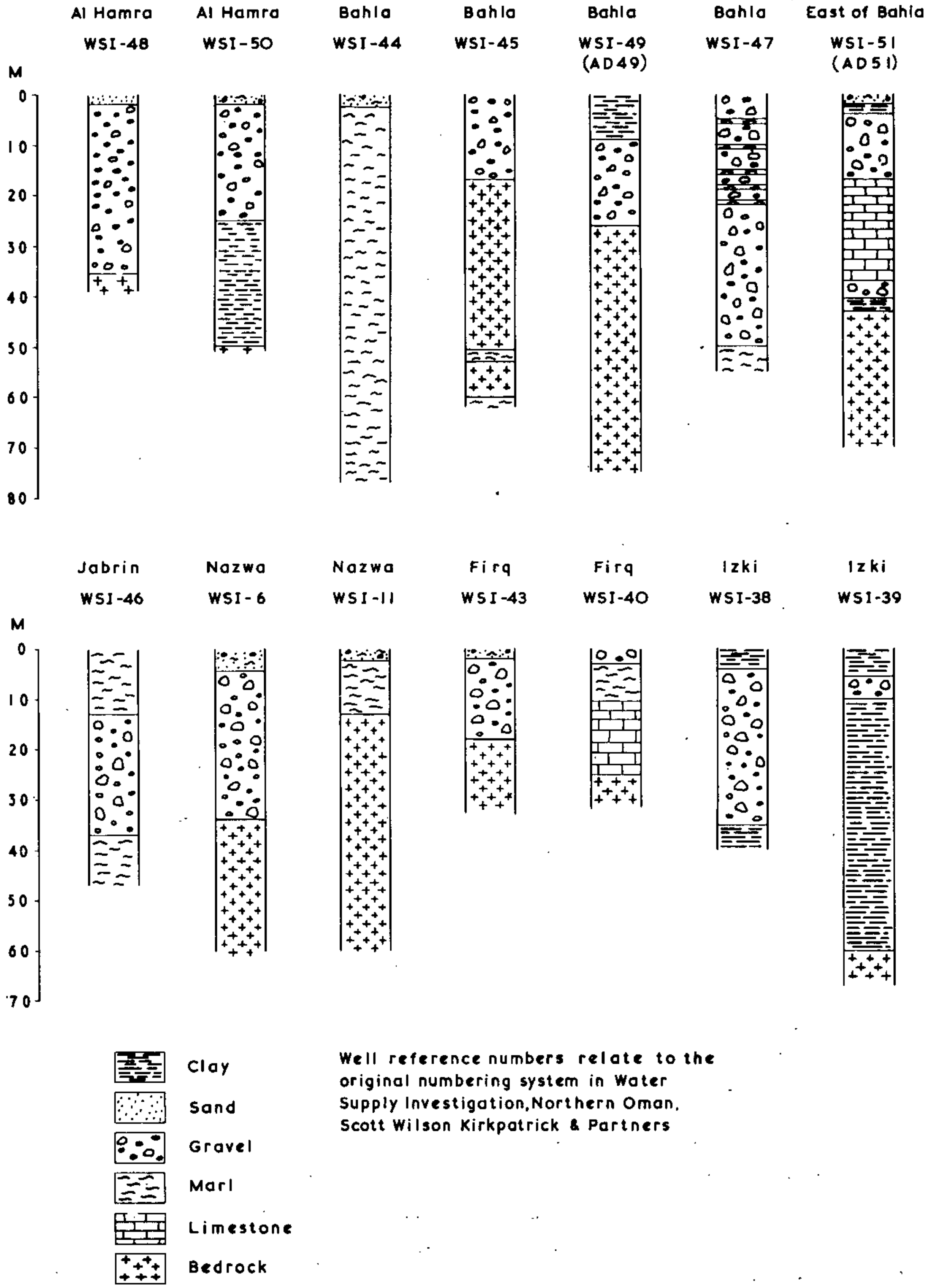
The alluvial sediments of the main gravel plain are very varied. They comprise the boulder trains of the active wadis, which merge with ophiolite gravels along the flank of the piedmont immediately south of Bahla and Nazwa. The rock outcrops in the plain provide a third source of material. Most of the hills are surrounded by scree slopes, particularly those of Oman Exotic Limestones. A wide range of rock types are present in the Hawasina; locally, minor wadis contain gravels of chert, limestone and shale. In the interfluvial areas of the plain, thin loess and old terrace deposits form an irregular stoney pavement, crossed by many minor surface channels.

The drainage pattern appears to have been fairly stable in the west, but in the east at various times Wadis Halfayn and Mu'aydin have drained either to the south or to the south-west of where they emerge from the piedmont. They are also associated with an alluvial plain containing fewer outcrops of bedrock.

5.3 HYDROGEOLOGY

The lithological logs from 14 of the boreholes drilled in 1972 are shown in Figure 5.2. The most abundant material is gravel, locally cemented, and containing thin bands of limestones. Clays, marls and thicker limestone deposits provide half the material above bedrock, and in places these materials form the entire sequence. It is difficult to relate lithological characteristics with location; several boreholes could not be found and others that we have found do not correlate with construction details. However, a broad reconstruction of the subsurface situation is possible in the piedmont areas, where most of the drilling occurred.

The thickness of alluvium increases irregularly down the piedmont valleys and thins laterally against bedrock on the flanks. In Wadis Bahla and Nazwa it also thins at the southern limit of the piedmont zone, where the wadis are constricted to narrow channels. The depth of gravel beneath the main wadi channels is unknown, as boreholes have been located either on the wadi banks or in terrace areas, away from the main channels. The Al Hamra boreholes show that the alluvial sequence can be quite thick, even at the head of piedmont valleys. The thickest gravel sequence, 50 m in borehole WSI 47, is at a site to the north of Bahla. A similar



Lithological Logs

Figure 5·2

increase in total thickness of alluvial sediments is recorded in the Wadi Halfayn at Izki where a thick clay sequence was also found.

The clays and marls which are not an obvious feature of alluvial sedimentation close to the mountains, seem to be associated with ophiolites and with areas of ophiolite springs. The precipitation of carbonates from alkaline springs can give rise to limestones, as in boreholes WSI 40 and 51. Weathering of serpentinite and peridotite gravels to a greater extent than was observed in the *Clayey Gravels* of the north is a possible mechanism which could lead to clay formation. Some records of clay and marl probably refer to deposits of light textured shallow water carbonates, similar to the soils at Bahla.

Recent water supply drilling confirms the results of the 1972 exploration. At Al Hamra, borehole JT88 encountered boulders, gravel and clayey gravels to 15 m above limestones. Two Department of Defence boreholes at Nazwa encountered 18 m of cemented gravels and 92 m of conglomerates, clayey gravels and thin limestones. The more detailed strata records of these boreholes indicate that clean gravels are infrequent and that clayey and cemented gravels could be as widespread as in the older gravels in the north.

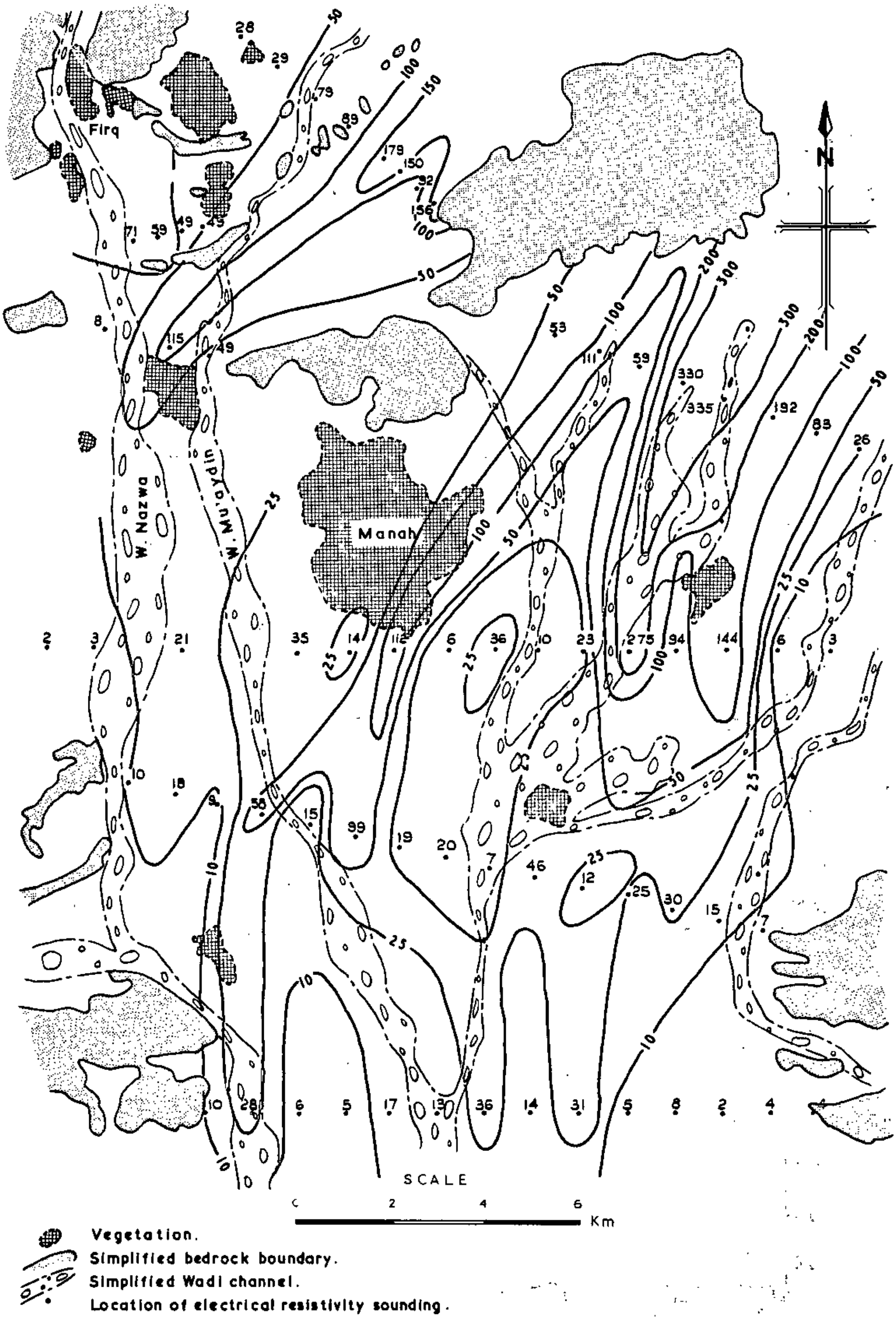
South of the piedmont zone, there are few boreholes and the log of WSI 46 (Figure 5.2) is the only detailed record available. Hand-dug wells provide some information; for example, 55 wells in the Wadi Sayfam between Al Ghafat and Bisyah proved an alluvial cover of about 15 m. Loess and sandy gravels overlie cemented gravels, limestones, siltstones and silty conglomerates, but gravel lenses are infrequent. Few wells have been sunk in the beds of the active wadi channels, but our experience of subsurface conditions suggests that they consist of relatively thin deposits of gravel overlying cemented and clayey materials.

Geophysical surveys confirm the shallow alluvial cover in the inter-fluvial areas and the limited development of wadi bed gravels. A recent study in the Nazwa-Adam area[3], involving 8 resistivity traverses and 103 electric soundings, recorded narrow buried channels in places away from the modern wadi channels, separated by either clayey gravels or brackish water-bearing gravels or bedrock. A map of part of the study area (Figure 5.3) illustrates these findings. The geophysical data are interpreted as showing that 5.15 m of dry, coarse alluvium overlie variable thicknesses of water-bearing material in the buried channels. The report concludes that groundwater supplies in the plain can only be expected from the buried channels.

Groundwater in the Alluvium

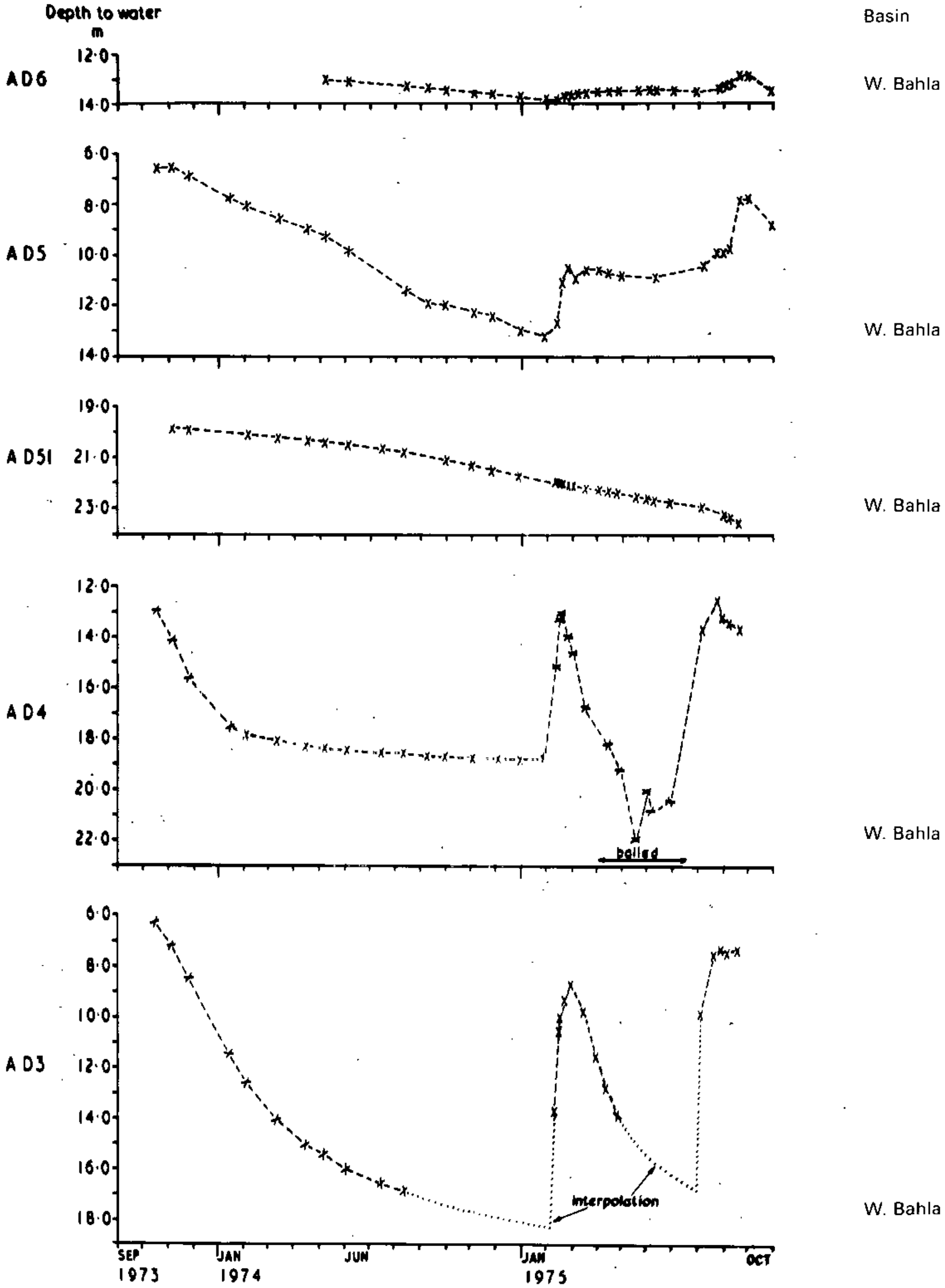
Depth to groundwater varies from less than 2 m to 25 m, according to the geology and drainage pattern; shallow groundwater occurs in confined wadi channels and in areas of thin alluvium. The depth increases downstream of a constriction in the alluvium as the groundwater slope exceeds the land slope. However, fluctuations in the water table can cause large variations in depth. Figure 5.4 shows hydrographs for boreholes upstream of Bahla. The greatest falls in water table occur near the main wadi channels, as at AD3, where the recession following a July 1973 recharge was steep and prolonged. Hydrographs for AD4 and AD5, away from the main channel, show a slower recession in water level of about 7 m over a 16 month

[3] Interim report, Compagnie Generale de Geophysique, April 1975.



Apparent Resistivity of the Manah Area

Figure 5·3



Borehole Hydrographs

Figure 5·4

period. In other areas, well away from the active wadi channels, the response is usually small. In AD6 between Al Hamra and Bilad Sayt, the fluctuations follow the pattern found near the wadi channel but on a reduced scale. However, AD51, in a tributary wadi to the east of Bahla, shows a steady decline. The recession in wells to the south of the piedmont is normally small with minor fluctuations.

The network of regularly observed boreholes in Figure 5.5 shows the groundwater surface for May 1974, assuming hydraulic continuity throughout the network. The groundwater flow is essentially from north to south. Recharge occurs from minor side wadis but the network is too sparse to show individual flows.

Widespread occurrence of groundwater in the alluvium is not confirmed by borehole records. The pumping test results show that 6 boreholes, about 30 percent, failed to produce a supply, but a further 6 might have developed groundwater from bedrock. Only 40 percent definitely produced groundwater from alluvial sources.

The test information is summarized in Table 5.1. Comparison of the specific capacity data with records for the northern basins, indicate transmissivities of about 150 m^2/d for the four largest producers, with values of 2-100 m^2/d in the smaller yielding boreholes.

TABLE 5.1

BOREHOLE YIELDS

Borehole		Depth to Water (m)	Depth of Alluvium (m)	Yield (m^3/d)	Pumping Drawdown (m)	Specific Capacity (m^2/d)	Water Bearing Horizons (m)
Wadi Bahla							
Al Hamra	WSI 48	10	35	840	4	210	11-36
	WSI 50	5	50	912	11	83	10-22
	JT 88	Dry		—	—	—	—
Bahla	WSI 44	25	77+	108	28	4	—
	WSI 45	4	16	600	22	27	6-16*
	WSI 47	5	55+	1 020	3	309	17-51
	WSI 49	9	25	662	18	37	9-38
	WSI 51	20	42	1 008	3	305	38-40
Jabrin	WSI 46	11	47+	1 229	3	409	13-35
Wadi Nazwa							
Nazwa	WSI 6	6	34	324	31	11	—
	WSI 9	6	20	528	30	18	*
	WSI 11	5	13	288	38	8	*
	Army Camp 1	62	92	0	—	—	—
	Army Camp 2	8	18	200	1	200	70-88*
Firq	WSI 40	8	15	648	7	89	23-28
	WSI 42	9	9	840	4	210	9-10*
	WSI 43	10	19	552	10	56	10-20*
Manah	WSI 53	6	3	566	17	34	6-36*
Wadi Mu'aydin							
Birkat Al Mauz	WSI 41	Dry	12	—	—	—	—
Wadi Halfayn							
Izki	WSI 37	16	42+	96	22	4	16-38
	WSI 38	4	40+	1 104	3	345	6-34
	WSI 39	6	60	0	—	—	—

* Water produced at base of alluvial sediments or from bedrock.

5.4 SOURCES OF WATER FOR AGRICULTURE

Although agriculture in the southern basins depends mainly on alluvial groundwater, the main wadi channels are the principal sources of supply to the towns and larger villages. However, our detailed survey in the Wadi Bahla basin shows that wells are an important feature of groundwater development in some areas and that there is not total reliance on aflaj as in many villages of the northern basins. Limestone springs in the piedmont are far less important than in the northern basins, while small ophiolite springs support scattered villages.

Spring Sources

The cultivated areas are shown in Figure 5.6. In the mountains, the most important agriculture is near Sayq in the Wadi Mu'aydin basin, where water supplies are obtained from springs at the Pre-Permian unconformity with the overlying limestones. Misfah in the Wadi Bahla, the only other important mountain village, receives a supply from a perennial seepage out of gravels flooring a fault eroded gorge; the water originates from a buried spring in the Hajar Super-Group limestones, a pattern which is repeated at other water holes along the flanks of the mountains.

Springs at the foot of the mountains are small and widely spaced. A perennial spring flow of 28 l/s was recorded at Muti in the Wadi Halfayn. Two springs were found in the Wadi Nazwa basin; that at the ruined town of Tanuf was dry during much of the field survey but had an estimated discharge of about 30 l/s after rain. The only piedmont limestone spring in the Wadi Bahla is at Al Qaylah to the east of Al Hamra where water is channelled by a falaj from gravels overlying the limestones.

The total discharge from the principal limestone springs in the southern basins is about 100 l/s (Table 5.2). They are not a significant regional source of groundwater. Ophiolite springs occur at Nazwa, Bahla and Al Ghafat and at scattered locations between these villages. Some twenty seepages between Nazwa and Jill have a total flow of about 20 l/s while the largest single spring is at Bahla with an estimated discharge of 8 l/s. These ophiolite springs are locally important but of little significance in the regional pattern of water supply.

TABLE 5.2

PRINCIPAL LIMESTONE SPRINGS IN THE SOUTHERN BASINS

Location	Grid Reference	Flow (l/s)		Source
Wadi Halfayn				
Muti	57875431	27.6	July 1975	Hajar Super-Group
Wadi Mu'aydin				
Al Ayn	56755512	16.3	Sept 1974	Pre-Permian unconformity
Sayq	56535533	5.5	Sept 1974	Pre-Permian unconformity
Wadi Nazwa				
Kamah	55585456	6.7	Sept 1974	Hajar Super-Group
Tanuf	54795490	0-30	—	Hajar Super-Group
Wadi Bahla				
Misfah	53215594	18.4	Feb 1974	Mountain flank spring
Al Qaylah	53045523	11.0	Feb 1974	Hajar Super-Group

Alluvial Sources

The falaj, which has traditionally dominated groundwater extraction, is still the principal source of water at many villages. Our detailed survey of the Wadi Bahla shows that aflaj provide all major supplies in the alluvial plain for that area. However, in the piedmont there are large numbers of wells; our survey in 1974 located 210 between Al Hamra and Bahla. The wells were probably playing a more important role than usual when the area was surveyed, because falaj supplies were low due to the drought. However, the wells have a different role from the aflaj since they do not only develop groundwater from primary alluvial sources. They are often sited within date gardens, or in areas adjacent to wadi channels, where annual crop production is maintained by groundwater from local storages replenished in part by infiltration from falaj irrigation.

Measurement of primary water supply was therefore almost impossible; errors were introduced because well abstractions varied from day to day and the amount of re-used water could not be estimated. Instead we have assessed the roles of well and aflaj in terms of the extent and distribution of annual and perennial crops. Before developing these relationships, examples of the pattern of alluvial groundwater development are given.

Groundwater supplies are obtained at the foot of the limestone massif where wadis from the mountains enter the piedmont. Aflaj develop water from the alluvial sediments in these active wadi channels. Al Hamra falaj (Figure 5.7) is one of the largest and taps water from the Wadi Ghul. Although the total groundwater flow through the alluvium is unknown, the outflow from the falaj is highly variable. Falling groundwater levels had a marked effect on the falaj supply after a long period without recharge and the supply was reduced by over 50 percent in the five months following August 1974.

To the east of Al Hamra are a group of villages with only two small aflaj; one from the limestone source at Qal'ah, the other from gravels at the mouth of a mountain wadi tributary. This falaj was not gauged regularly but was flowing at only 26 l/s in February 1974, when the main water supplies came from 63 pumped wells in wadi gravels and in deep silts underlying the cultivated areas. Rock bars across the mountain wadi channels indicate that the piedmont gravels of this area were not recharged from alluvium in the wadis and the source of the well supplies is not clear. They may have been obtained entirely from local storage but recharge by seepages from the mountain limestones is possible. A second important area of agriculture occurs in a similar geological situation in the Wadi Nazwa at Tanuf and also depends upon wells in gravels adjacent to the mountain foot.

Bilad Sayt is the only village in the central piedmont area. This village is in a state of decline; two aflaj exist where there were said to have been twelve, 20 years ago. The main falaj takes water from the bed of the principal wadi channel downstream of Al Hamra, and 19 pumped wells supplement the falaj supply from a depth of about 14 m in shallow ophiolite gravels around the village. The apparent absence of groundwater development in these central piedmont areas is at first sight rather surprising. However, the major aflaj of Nazwa and Bahla extend into these areas, taking groundwater from the main wadi channels. In times of drought, as in 1974, the falaj flows fall rapidly, as shown in Figure 5.7. Falaj Maita, the principal source for Bahla, fell from 100 l/s to 20 l/s during a nine -month period without recharge. Despite the large alluvial area of the piedmont, groundwater storage was only able to sustain a flow in Bahla falaj similar to that at Al Hamra. Nazwa falaj shows a similar response, but receded from 200 l/s to less than 80 l/s during the same period.

In Bahla, a surprisingly large number of sources supplement falaj Maita. Open channel flow is collected from the stream bed of the main wadi north of the town. Three aflaj provide supplies from alluvial sources in tributary wadis up to 8 km to the north-east, and three minor aflaj draw from local gravel sources to the west. There are 94 pumped wells within the area of the gardens, which take water from the thick sequence of soft textured carbonate silts underlying the town. There is no evidence of buried gravel channels and this supply must come either from underflow or from irrigation drainage. The origins of individual wells cannot be assessed because of the variety of sources and groundwater chemistry.

The water supply to Bahla is particularly complex and a detailed survey was necessary to locate the various sources. More general surveys of other major villages, such as Nazwa and Izki, show that their supplies are less complicated and that there is a greater reliance on aflaj from the main wadi channels.

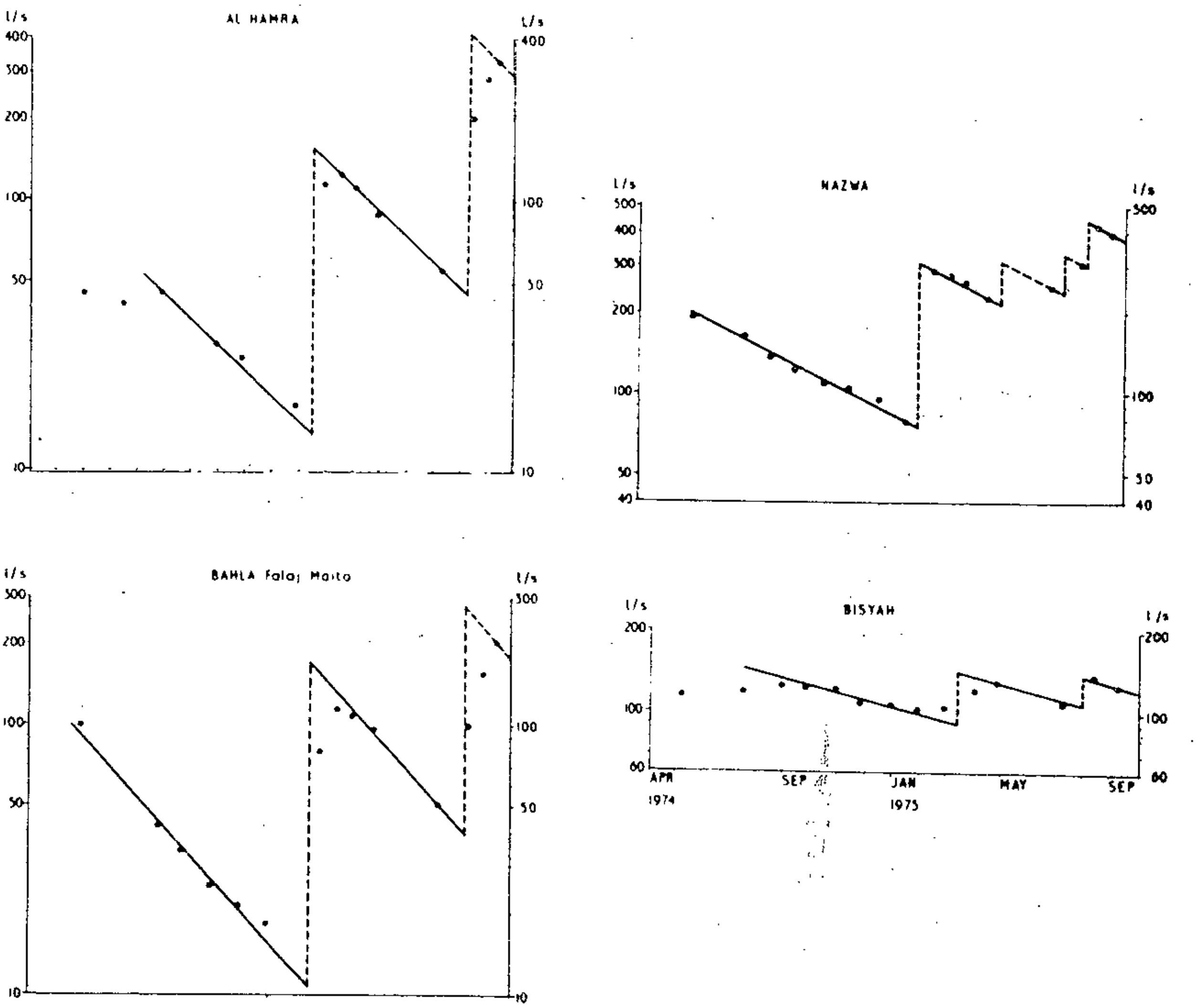
To the south of the large towns of the piedmont are areas of scattered cultivation, such as Jimah and Firq, which appear to use any surface flow available after flooding and thereafter to rely on temporary supplies from irrigation excess in the towns.

Further south, the first villages of the alluvial plains, such as Manah in the Wadi Mu'aydin and Jabrin and Nattalah to the south of Bahla, tap groundwater from storages in the main wadi channels supplemented from local storages in the alluvial tract along the edge of the piedmont. Jabrin draws water from the Wadi Bahla at a site where the channel is constricted by bedrock. In the past, this site appears to have been the source of an extensive network of surface channels, distributing water across the plain to the south-west, towards what is now the wheat growing area around Quryat in the Wadi Sayfam; this system of collection and distribution now appears to be neglected. Jabrin and Nattalah take main wadi water and the aflaj from local storages have fallen into disuse.

We are unable to assess the availability of groundwater in these northern areas of the plain, where drilling exploration is particularly needed to determine the thickness and aquifer properties of the sediments. The aflaj at Jabrin and Nattalah appear to command a much larger groundwater supply than we observed, although this amounted to about 100 l/s in March 1974.

Further south, villages exist across the plain at points where wadi channels are contained by bedrock and groundwater flows are concentrated. Bisyah, at the confluence of the Wadis Bahla and Sayfam, is the largest of villages with a very reliable falaj supply. The rapid fluctuations of the piedmont aflaj are not present and the source varied only between about 100 and 150 l/s through the period of our survey (Figure 5.7). The precise origin of the falaj is not known but it probably commands groundwater from the main channel of Wadi Bahla.

Scattered wells throughout the plain, frequently in minor wadi beds, are the only evidence of groundwater in the large areas between the main wadi channels. One extensive development, along the east bank of the Wadi Sayfam, supports an area of 300 ha of annual crop production by 55 wells and 4 boreholes. This is an area of traditional agriculture which appears to have been watered by aflaj from the bed of the Wadi Sayfam and by surface channels



Falaj Hydrographs

Figure 5·7

from Jabrin in the past. The wells are wide shafts about 15 m deep and occasionally require adits to provide a supply. The most successful obtain water from lime cemented gravel conglomerates but others develop rather unreliable sources from cemented sands and clayey gravels.

There are several origins for the supplies. The northern farms take groundwater associated with the gravels of the Wadi Sayfam. The central and southern farm wells have joint sources partly from the wadi and partly from falaj flow from the Wadi Bahla at Jabrin. Bedrock and old terraces indicate that the alluvial sediments between Jabrin and Wadi Sayfam are thin; several of the wells prove bedrock at between 15-20 m. Large groundwater flows are therefore unlikely.

Chemical Characteristics

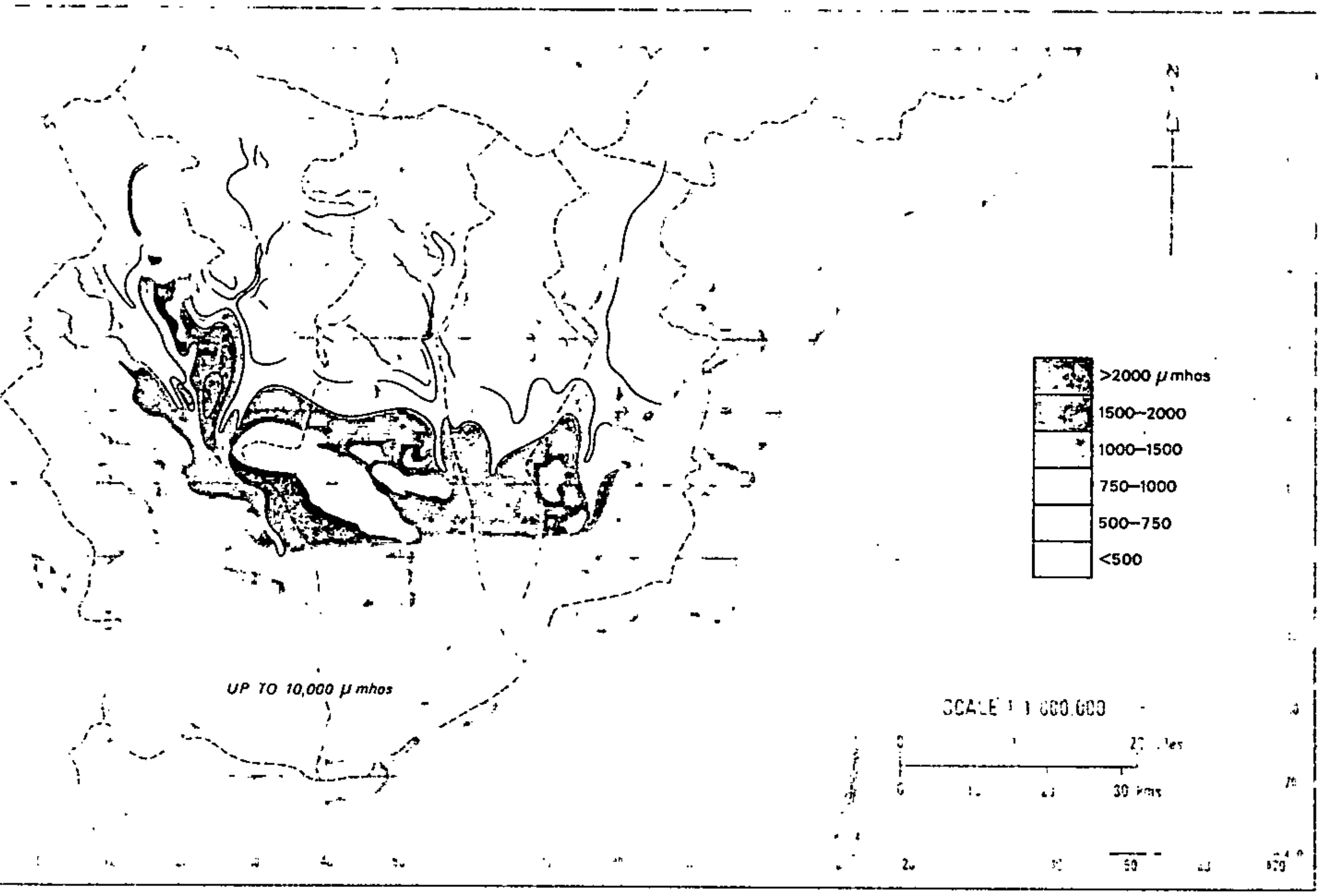
An electrical conductivity map of the southern basins is shown in Figure 5.8. The map is based on field measurements and on laboratory analyses of water samples (Appendix E). The conductivity changes result from an increase in salinity along the groundwater flow pathways away from areas of recharge. The main conductivity gradient is to the south of the piedmont. Electrical conductivities up to 750 μmhos/cm at 25°C are found in most aquifers throughout the piedmont. Tongues of fresher water are found in the vicinity of the active wadi channels to the south of the piedmont but scattered sampling points prevent precise location of these zones. The conductivity pattern between the Wadi Bahla and the Wadi Sayfam is complicated by the occurrence of high salinities related to increased dissolved solids, particularly sulphates.

The isotopic composition of groundwater demonstrates curious relationships within the fairly simple pattern of salinity change. These are discussed in Appendix E.1. They show that the increase in salinity across the piedmont can be accounted for by evaporative losses. However, samples from the alluvial plain have lower isotopic contents and suggest that the origin of the alluvial plain groundwater is more likely to be from flood recharge than from groundwater recharge from the piedmont. Tritium samples were confined to the piedmont and they show recent water in the alluvium at Al Hamra, Bahla and Nazwa.

5.5 WATER USE IN THE SOUTHERN BASINS

The general patterns of groundwater abstraction involve complicated interrelationships between traditional use of wells in conjunction with aflaj, modern use of pumped wells, and varying emphasis between the production of annual and perennial crops. Reliability of groundwater supply underlies these relationships. Well and falaj sources are found together in the piedmont where there are large variations in groundwater level and hence in falaj supply. In the alluvial plain, where water level fluctuations are smaller and aflaj more reliable, there are few wells in the traditional areas of crop cultivation. New developments such as that at Quryat in the Wadi Sayfam are changing established patterns by the introduction of pumped wells.

Several of these relationships can be illustrated by information collected in the detailed survey of the Wadi Bahla basin. They provide a broad structure which enables the



Electrical Conductivity of Water

Figure 5·8

groundwater resources to be described even though aquifer properties and dimensions are not known. The basis for these descriptions is the consumptive use determined from the areas and water use of crops as described in Chapter 4.

Survey of Water Use in the Wadi Bahla Basin

A summary of the detailed survey is given in Table 5.3. Dates constitute 47 percent of the agriculture overall but are more important than annual crops in mountain villages such as Misfah and Ghul, and in the villages of the alluvial plain south of Bisyah. Annual crops predominate in the piedmont and in the alluvial plain immediately south of Bahla. Consumptive use by agriculture is estimated as 510 l/s for the irrigation season, or 14.2 million m^3 for the whole year; the piedmont area accounts for 74 percent of the total consumptive use, Bisyah and the southern villages for a further 18 percent.

TABLE 5.3

WADI BAHLA VILLAGE SURVEY SUMMARY

Location	Agriculture (ha)			Sources of Water (l/s)				Consumptive Use (l/s)
	Dates	Other	Total	Limestone Springs	Other Springs	Alluvial Aflaj[2]	Sources Wells[3]	
Misfah	28.4		28.4	18.4				14.0
Ghul	5.0		5.0					2.5
Al Hamra	46.0	63.4	109.4			25-325	71	48.5
Al Qaryah, Wadi Misfah	45.0	76.0	121.0	11.0			65	53.1
Dat Hayl—Qaylah	42.9	54.3	97.2	14.6			46	43.3
Ghumar	7.4	29.4	36.8				9	15.6
Bilad Sayt	44.6	52.0	96.6			23.9	18	43.2
Bahla	155.2	255.2	410.4		8.4	37-276	76	180.6
Fat Al Bahla (Jalah)	1.9	7.8	9.7			8.9		4.1
Wihil Al Murr	0.8		0.8		5.1			0.4
Jimah		22.8	22.8			34.8		9.3
Jabrin	5.9	16.9	22.8			34.7		9.8
Nattalah	2.6	5.2	7.8			37.2		3.4
Bisyah[1]	54.0	16.9	70.9			103-133		33.6
Mudri-Fill	27.7		27.7			33.1		13.7
Al Hubi	41.8		41.8			?		20.6
Ma Murah	28.3	7.4	35.7			51.1		17.0
Total	538	607	1 145	44	14	389-958	285	510

Notes: [1] Bisyah is included with the Wadi Bahla. The villages downstream derive part of their supply from Wadi Sayfam groundwater.
[2] Falaj flows give the range of gaugings between May 1974 and September 1975; they do not reflect the absolute range and the mean flow is closer to the minimum than the maximum.
[3] Well yields include recirculated water.

Well irrigation is such a prominent feature of the piedmont that it deserves special comment. Many of the wells recorded by the survey existed, and were operated by animals, before the introduction of pumps. It is unlikely that these wells were used as a main, or even a supplementary, supply to date gardens and they appear to have been used during the winter months for irrigating annual crops.

The development of large numbers of these wells in the piedmont of the Wadi Bahla seems to be a local feature related to wheat cultivation. Well irrigation appears to have been necessary to augment falaj water supplies during the winter months, presumably because of large fluctuations in falaj flow. It is surprising that this technique is largely restricted to the wheat growing areas.

Annual crop production is expanding as pumps are fitted on traditional wells and consumptive use is therefore increasing. The changes are rapid: in the piedmont area, 210 pumps have been fitted during the past 10 years. Data from the Durham University Project[1] show that a pump increases abstraction to between 2½ and 25 times that of a traditional well. The assumption that the areas of annual crops between Al Hamra and Bahla have increased by 2½ times to the present 530 ha (Table 5.3) in the past 10 years, while the areas of dates remained constant, implies that the total annual groundwater abstraction increased by 40 percent. This is such a large increase that some evidence of its effect must be felt, particularly by the traditional aflaj.

There is some indirect evidence of over-development of groundwater in the piedmont of the Wadi Bahla, where the minimum falaj flows recorded by the survey were not sufficient to provide irrigation and leaching of the date gardens. However, this was during an exceptional drought.

Ibri Area

Several villages occur in a tributary of the Wadi Al Kabir between the western watershed of the Wadi Sayfam and the main study area of the Durham University Oman Project. The tributary, Wadi Al Ayn, forms part of the drainage system of the Ibri area. Our village survey was extended to cover the villages between the two studies (see Figure 5.9).

The wadi lies within the high limestone massifs of the Jabals Akhdar, Misfah and Khawr. At Al Ayn and Amlah, two of the larger villages, aflaj supply 45 l/s and 5 l/s from wadi gravel sources. Other villages along the valley are supplied by about 40 wells pumping from a water table in wadi gravels at depths of between 2-8 m. Along the foot of Jabal Khawr the villages of Al Mays, Ma'wal and Dann are supplied by springs in limestones of the Oman Exotics. Total discharge is small, only 7.5 l/s, but this groundwater is the only evidence of aquifer conditions in this formation.

Water use in the main area of the Ibri catchment is still being assessed by the Durham Project from data collected by them. However, there are close similarities between the Ibri area and the Wadi Sayfam and Wadi Bahla basins. Although falaj supplies are still important in both areas, the number of wells is increasing with the introduction of diesel-engined pumps. Subsurface information at selected sites in the Ibri area is required to estimate groundwater transfers into the Wadi Al Kabir from tributary valleys and to assess flow out into the desert. Exploration of these sites was postponed by the delay in the drilling programme.

[1] Wells in the Dhahirah, Durham University Research Report No. 21, December 1974.

5.6 SUMMARY

Estimates of consumptive use throughout the southern basins have been obtained from cropping patterns determined from a variety of aerial photographic sources using large scale (1:20 000) material wherever possible. An unusually low proportion of dates in the Wadi Bahla basin and in the alluvial plain of the Wadi Sayfam is shown by these data (Table 5.4). In the other basins dates comprise an average of about 75 percent of the cultivated areas where annual crop production accounts for only between 4 and 38 percent of the total.

TABLE 5.4

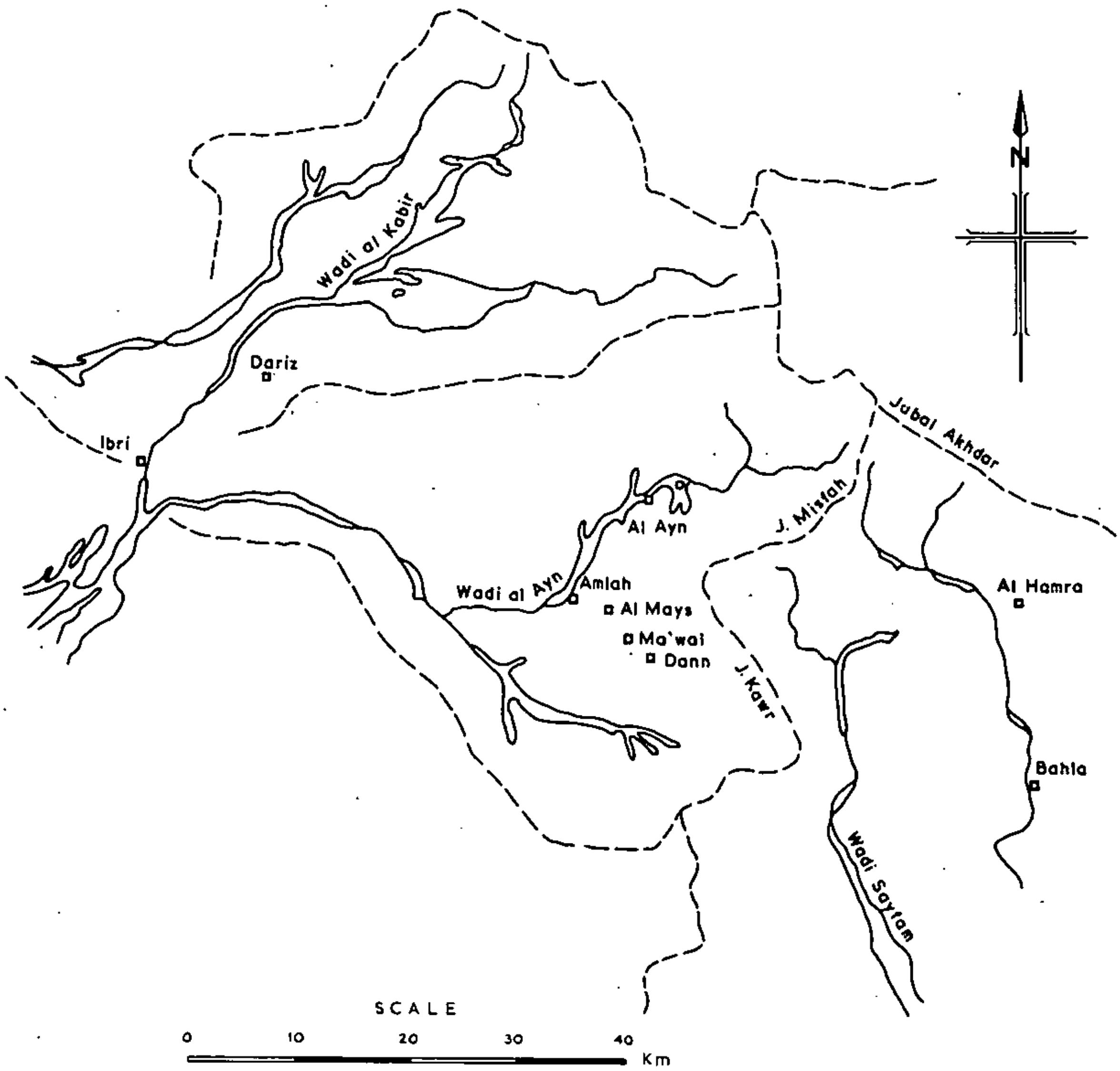
CROPPING PATTERNS IN THE SOUTHERN BASINS[1]

Basin	Piedmont				Alluvial Plain			
	Dates		Other Crops		Dates		Other Crops	
	(ha)	(%)	(ha)	(%)	(ha)	(%)	(ha)	(%)
Wadi Halfayn	225	62	156	38	60	75	20	25
Wadi Mu'aydin	82	96	3	4	225	59	157	41
Wadi Nazwa	367	67	184	33	256	75	86	25
Wadi Bahla	346	39	530	61	11	17	53	83
Wadi Sayfam	129	80	33	20	16	5	301	95
Wadi Bahla/ Wadi Sayfam[2]	—	—	—	—	152	86	24	14

Notes: [1] Variations from cropped areas given in the April 1975 Soils and Agricultural Studies Report are due to the use of 1:20 000 aerial photography not available at the time of the earlier studies and to additional field observations.
[2] Bisyah and villages tc south below confluence of Wadi Bahla and Wadi Sayfam.

The nature of the alluvial sediments and their distribution are sufficiently similar throughout the south to suggest that these variations in cultivation do not reflect primary hydrogeological differences between basins. It is apparent from the falaj hydrographs in Figure 5.7 that there are not large differences in the nature of falaj flows from basin to basin; the largest differences are across the basins from north to south with less variation in supply in the southern villages. The feature which accounts for the large difference in cropping pattern is the use of pumped wells for annual crop production. Even though our detailed survey did not cover all villages, the more general studies outside the Wadi Bahla basin showed fewer wells and less emphasis on pumped water supplies. We are unable to determine the underlying reason for this, but we are confident that it is not a result of hydrogeological factors.

Water use, as total annual consumptive use, is shown in Table 5.5. It will be recalled from Chapter 4 that the consumptive use is a measure of crop transpiration and soil evaporation only and does not include an allowance for leaching or for conveyance losses. Throughout the south, annual water use on this basis is 44 million m^3. The Wadis Nazwa and Bahla together account for over half the total with the piedmont of Wadi Bahla taking 24 percent.



The Ibri Basin

Figure 5·9

TABLE 5.5

ANNUAL CONSUMPTIVE USE IN THE SOUTHERN BASINS

Basin	Mountains (l/s)[2]	(million m³)	Piedmont (l/s)	(million m³)	Alluvial Plain (l/s)	(million m³)	Total Volume (million m³)
Wadi Halfayn			190	5.0	37	1.1	6.1
Wadi Mu'aydin	16	0.5	42	1.3	176	4.8	6.6
Wadi Nazwa	—	—	257	7.5	165	4.7	12.2
Wadi Bahla	16	0.5	385	10.5	28	0.6	11.6
Wadi Sayfam	10	0.3	77	2.3	131	2.8	5.4
Wadi Bahla/ Wadi Sayfam[1]	—	—	—	—	85	2.6	2.6
Total		1.3		26.6		16.6	44.5

Notes: [1] Bisyah and villages to the south below confluence of Wadi Bahla and Wadi Sayfam.
[2] The consumptive use in l/s is the average use in the irrigation season.
[3] The annual consumptive use in million m³ is based on Table 5.4 for the areas of dates and other crops, with the latter divided into 70 percent wheat and 30 percent alfalfa in the piedmont, and 80 percent wheat and 20 percent alfalfa in the alluvial plain. The water requirements are taken from Chapter 4.

For the Wadi Bahla basin, where we have been able to estimate water availability (Table 5.3), the supply from primary sources, assuming all wells are drawing on irrigation excess, is just sufficient for consumptive use. A shortfall in supply developed during 1974 when falaj flows declined considerably from their March levels. Although we shall show in Chapter 7 that 1974 was an exceptionally dry year, the data do not suggest a general excess of supply over demand in the southern basins.

CHAPTER 6

STORMS OBSERVED DURING THE STUDY

6.1 INTRODUCTION

In the review of climate in Chapter 1 we discussed the historic rainfall records for Muscat and Nazwa and concluded that major rainfalls could be expected on only a few days each year. Unfortunately the study period proved to be drier than usual; 1974 is the driest year in the 25 year record at Muscat. Apart from a storm over some of the southern basins in July 1973, before the instrument networks were established, and some very local rainfalls in mid 1974, the first substantial rainfall was in October 1974 producing runoff in several northern basins. During 1975, rainfall and runoff were more frequent and a number of flood hydrographs were recorded at the wadi gauging stations.

Our main concern in this chapter is the effect of these occasional storms on the alluvial aquifer systems and particularly on the distribution and extent of recharge following heavy rainfall on the jabal. We shall aim to determine relationships between the volume of rainfall on the hardrock areas, the surface flows in the wadi channels, and the change in storage of the aquifers. Thus our analysis will concentrate on those events for which we have comprehensive records.

Some previous studies of a reconnaissance nature have attempted to estimate the availability of water for development and have necessarily had to assume an average rainfall on the jabal and the proportion of this rainfall which produces runoff and ultimately recharge of the alluvial aquifers. Burdon[1], a member of an FAO Preparatory Assistance Mission, developed a tentative water balance for the Batinah plain. He assumed an average rainfall on the hardrock areas of 150 mm of which 33 percent reached the mountain front, 19 percent as rapid surface runoff and 14 percent as base flow in the wadi gravels. Allowing for water use in the inland villages and infiltration in the hardrock areas, Burdon concluded that nearly 27 percent of the rainfall on the hardrock areas eventually recharged the alluvial aquifers. Losses of surface runoff to the sea were assumed to be very small. On the area of the Batinah covered by the present study, Burdon's assumptions would suggest an annual recharge of about 200 million m^3.

[1] Burdon D. J. Technical notes on water resources of the Sultanate of Oman, FAO Preparatory Assistance Mission, 1972.

Sogreah[2], in a reconnaissance mission to report on the development potential of the Ghafat Valley (part of the Wadi Sayfam basin), used the historic rainfall records for Nazwa to estimate runoff from the hardrock area above Al Ala. They assumed zero runoff from a monthly rainfall of less than 10 mm in January and 20 mm in July. Above these threshold levels of rainfall, Sogreah assumed that the percentage runoff would increase exponentially to reach 60 percent for a monthly rainfall of 100 mm.

In our interim water resources assessment of April 1975, derived before the rainfall and wadi flow records for 1975 were available, we based our rainfall and runoff estimates on data published by Sutcliffe and Carpenter[3] for the Zagros mountains in Western Iran. This area has similar geology and topography to northern Oman but has rainfall only in the winter months with some snow at high altitudes. Basin rainfalls were estimated using a rainfall gradient with altitude of 300 mm per 1 000 m from an average rainfall of 100 mm at the coast. The annual runoff, calculated for each of several altitude zones, was assumed to be rainfall less an average 300 mm loss by evaporation, 75 percent being rapid surface runoff and 25 percent being base flow. After allowing for water use in the inland villages, recharge was assumed to be base flow together with 10 percent of the rapid surface flows. For the Batinah alluvial aquifer, recharge amounted to about 90 million m^3 per year on these assumptions; for the southern basins potential recharge was estimated to be 70 million m^3 per year. With the data now available it is possible to improve substantially the basis for these estimates.

6.2 STORM RAINFALLS

Major storms occurred during February, July and August 1975 causing flows at many of the wadi gauging stations. The less widespread storms of October 1974, May and September 1975 also produced flows in some wadis but the local storm in the vicinity of Awabi and Rustaq in May 1974 did not give rise to flows at any of the gauging stations. Table 6.1 shows the rainfall records for those months when wadi flows were observed. The detailed rainfall records including the daily and hourly records from the gauges at the meteorological stations are presented in Appendix A.2.

[2] Sogreah, The development of the Ghafat valley, 1971.
[3] Sutcliffe J. V. and Carpenter T. G., the assessment of runoff from a mountainous and semi-arid area in Western Iran. Proc. General Assembly IASH 1967.

TABLE 6.1

SUMMARY OF STORM RAINFALLS

(mm)

Gauge	Grid Ref	Altitude (m)	Oct 1974	Feb 1975	May 1975	Jul 1975	Aug 1975	Sep 1975	
Rumays	60266195	15	<1	48	0	0	5	0	<54
Bid Bid	61505925	225	2	47	0	0	0	0	49
Nakhl	58495868	300	<1	75	3	0	4	14	97
Khatum	57005970	171	7	58	4	0	2	3	74
Awabi	55415765	500	72	54	46	0	67	45	284
Rustaq	54525855	350	83	47	6	6	82	11	235
Hawqayn	53426039	225	25	64	6	10	0	0	105
Ghubrah Bowl	57695697	670		56					–
	57425566	2 240		66					–
Gauges on	55875605	2 110		76					–
Jabal Akhdar	53545648	2 290		>145					–
	51515673	1 350	0	81					–
Sayq	56585514	2 000	4	95	37	71	86	31	324
Izki	57925381	580	0	135	23	39	30	4	231
Nazwa	55445373	550	2	109	17	74	8	2	212
Bahla	53055392	600	0	73	33	22	50	6	184
Al Hamra	52825566	625	0	82	16	47	13	10	168
Al Ghafat	51435424	560	0	47	6	44	8	6	111
Quryat	51955264	470				23	18	3	–
Bisyah	52485127	400	0	12	0	10	4	4	30
Adam	55424752	277	0	10	0	5	0	0	15

Notes: [1] The February 1975 total includes rainfall from 25th January 1975.

The poor return of data from the jabal gauges is disappointing. During the early months of the study these gauges were continually damaged or stolen. Efforts were made to improve their security and a good return of data was achieved following the widespread rainfall of February 1975. Subsequently, helicopter support became unavailable and we were not able to visit the gauges from March 1975 onwards. However, the gauges at lower altitude have a substantially complete record so that despite the uncertainty over the amount of rainfall on the high jabal we have been able to deduce the broad pattern of rainfall in all the major storms.

The February 1975 rainfall was caused by a frontal system associated with a depression to the north of the study area. The rain fell in a series of intense showers over a period of three days and was heaviest along the southern flank of Jabal Akhdar despite the frontal system crossing the area from the north. This is not unreasonable; the maximum uplift and therefore cooling of the moist air could well occur downwind of the relatively narrow ridge of the jabal.

The rainfalls of October 1974 and May 1975 were also caused by disturbances in the general northwesterly airstream, although the precise direction of movement is unknown. The tendency for both rainfalls to be concentrated in the western half of the study area suggests that the disturbances may have approached the jabal from the west rather than the north as was the case in February 1975.

The July, August and September 1975 rainfalls were caused by local instability associated with the intertropical convergence zone with the result that intense local showers occurred over relatively small areas on a number of days during the three months. In contrast to the February rainfall, which tended to occur at all stations at the same time, the July, August and September rainfalls show a more random pattern of occurrence particularly for the heavier falls.

High rainfall intensities do not appear to be restricted to either the winter or summer season. Very intense rainfalls occurred in both February and July 1975; 53 mm fell in 1 hour at Nazwa on 9 February, and 82 mm fell in such a short period at Rustaq on 18 August that the meteorological site was flooded and the recording mechanism on the Dines rain recorder jammed. An analysis of the hourly rainfalls for storms exceeding 15 mm suggests that on average 60 percent of the storm rainfall occurs in less than 1 hour and nearly 90 percent in less than 3 hours. About 40 percent of the storms last for less than 2 hours.

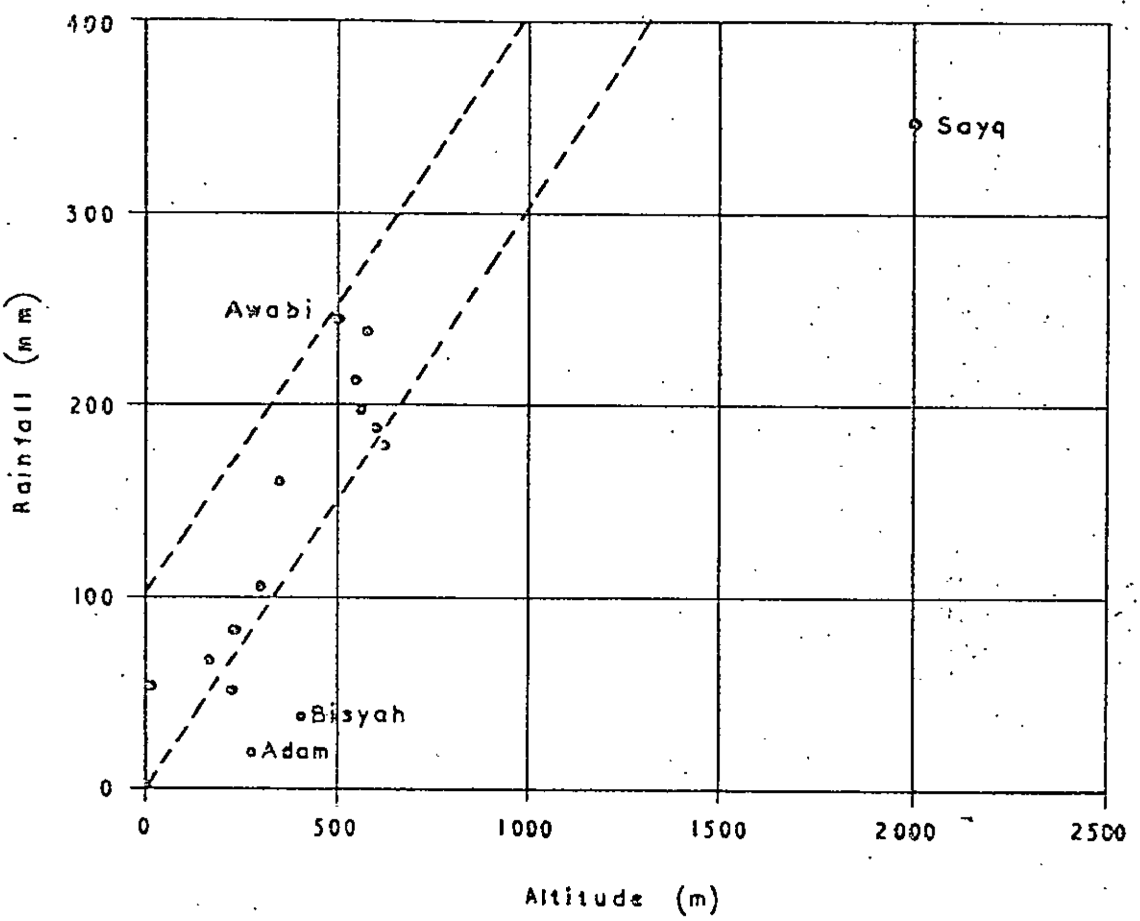
In summary, the records indicate that while rainfall intensities can be equally severe at all times of the year, the winter frontal rainfalls tend to be more widespread than the more isolated storms of the summer months.

Estimation of Rainfall Volumes

The relatively sparse nature of the raingauge network and the lack of records for the jabal gauges other than for February 1975 means that it is impossible to define accurately the areal extent of individual storms particularly those of July and August 1975. However, plausible isohyetal maps can be produced if the total rainfalls for each rainy period are used. Exceptions are the October 1974 storm which affected only the Awabi, Rustaq and Hawqayn gauges, and the widely scattered rainfalls of September 1975 which were insufficient to cause significant runoff.

Before drawing the isohyetal maps, it was necessary to confirm the dependence of rainfall on altitude. This was particularly important for the interpretation of those storms for which the observations at Sayq were the only record of rainfall on the high jabal areas. Table 6.2 shows the total rainfall for the period January to October 1975 for all gauges which have a complete record. The variation of rainfall with altitude is shown in Figure 6.1, the dotted lines indicating a rainfall gradient of 300 mm per 1 000 m of altitude from rainfalls at sea level of zero and 100 mm.

Most of the points lie within the range expected from the Zagros data referred to in the introduction to this chapter. However, the records from Bisyah and Adam indicate that rainfall beyond the southern foothills of the jabal is lower than altitude alone would suggest and the record for Sayq suggests lower than expected rainfall on the high altitude areas of the jabal. This latter result is the more important since it is the jabal hardrock areas which produce the surface runoff.



Variation of Rainfall with Altitude for
January to October 1975

Figure 6·1

RAINFALL FROM JANUARY TO OCTOBER 1975

Northern Basins			Southern Basins		
Gauge	Altitude (m)	Rainfall (mm)	Gauge	Altitude (m)	Rainfall (mm)
Rumays	15	53	Sayq	2 000	347
Bid Bid	225	51	Izki	580	239
Nakhl	300	107	Nazwa	550	215
Khatum	171	67	Bahla	600	188
Awabi	500	245	Al Hamra	625	180
Rustaq	350	160	Al Ghafat	560	197
Hawqayn	225	81	Bisyah	400	38
			Adam	277	19

Rainfall on the jabal could be generally higher than the Sayq gauge indicates because of some local effect perhaps related to the siting of the gauge at Sayq. However, the rainfall distribution for February 1975 when there are records from all gauges on the jabal, and the field observation that storms often tend to move along the jabal flanks, suggest that the Sayq gauge is reasonably representative. On the evidence available we must assume that the relationship of rainfall with altitude does not hold for the higher areas.

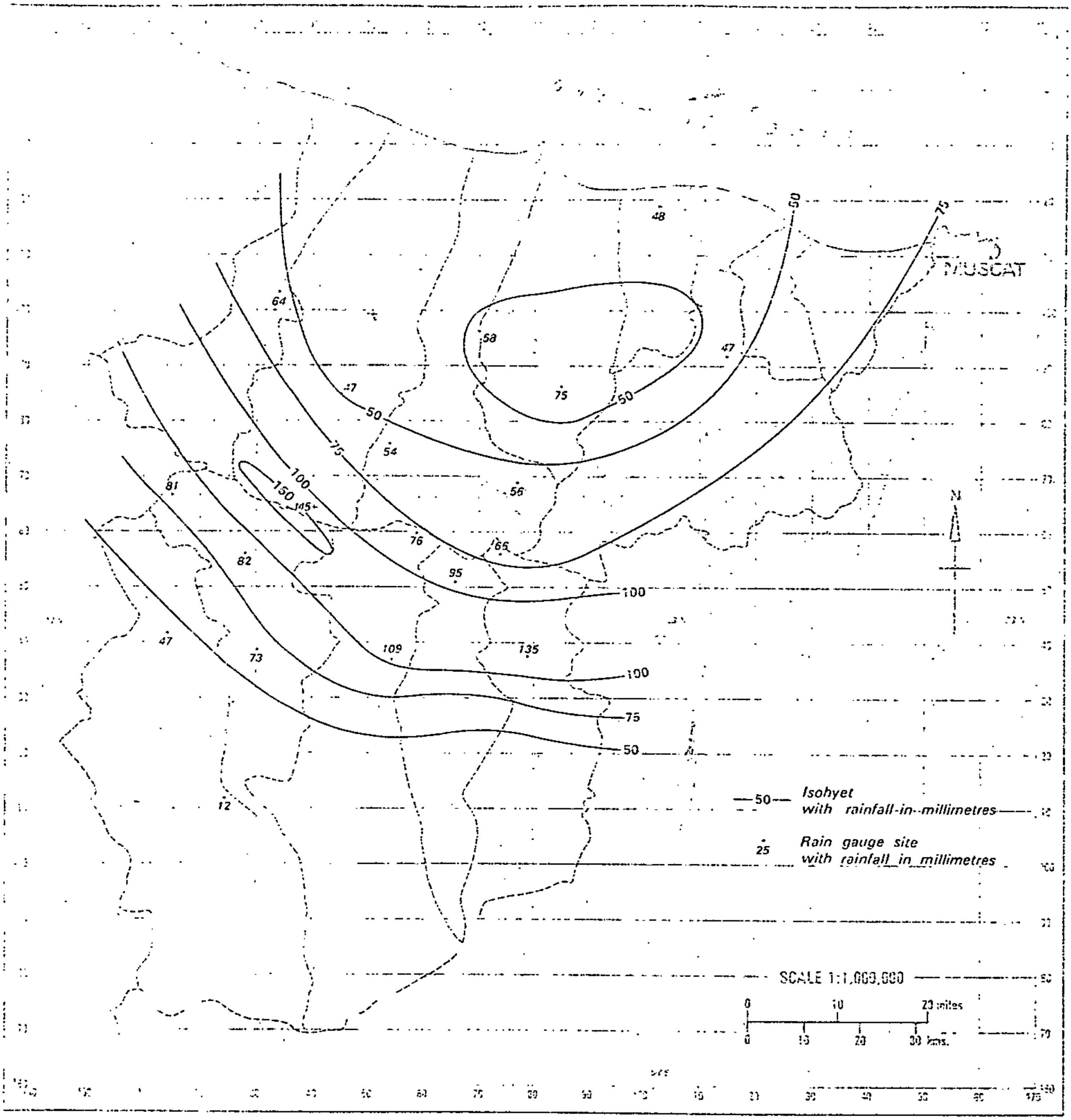
The isohyetal maps for the periods February, May and July/August 1975 are shown in Figures 6.2-6.4. Average basin rainfalls and rainfall volumes have been calculated for the hardrock areas in each wadi basin and presented in Table 6.3

TABLE 6.3

RAINFALL VOLUMES AND AVERAGE RAINFALLS ON THE HARDROCK AREAS

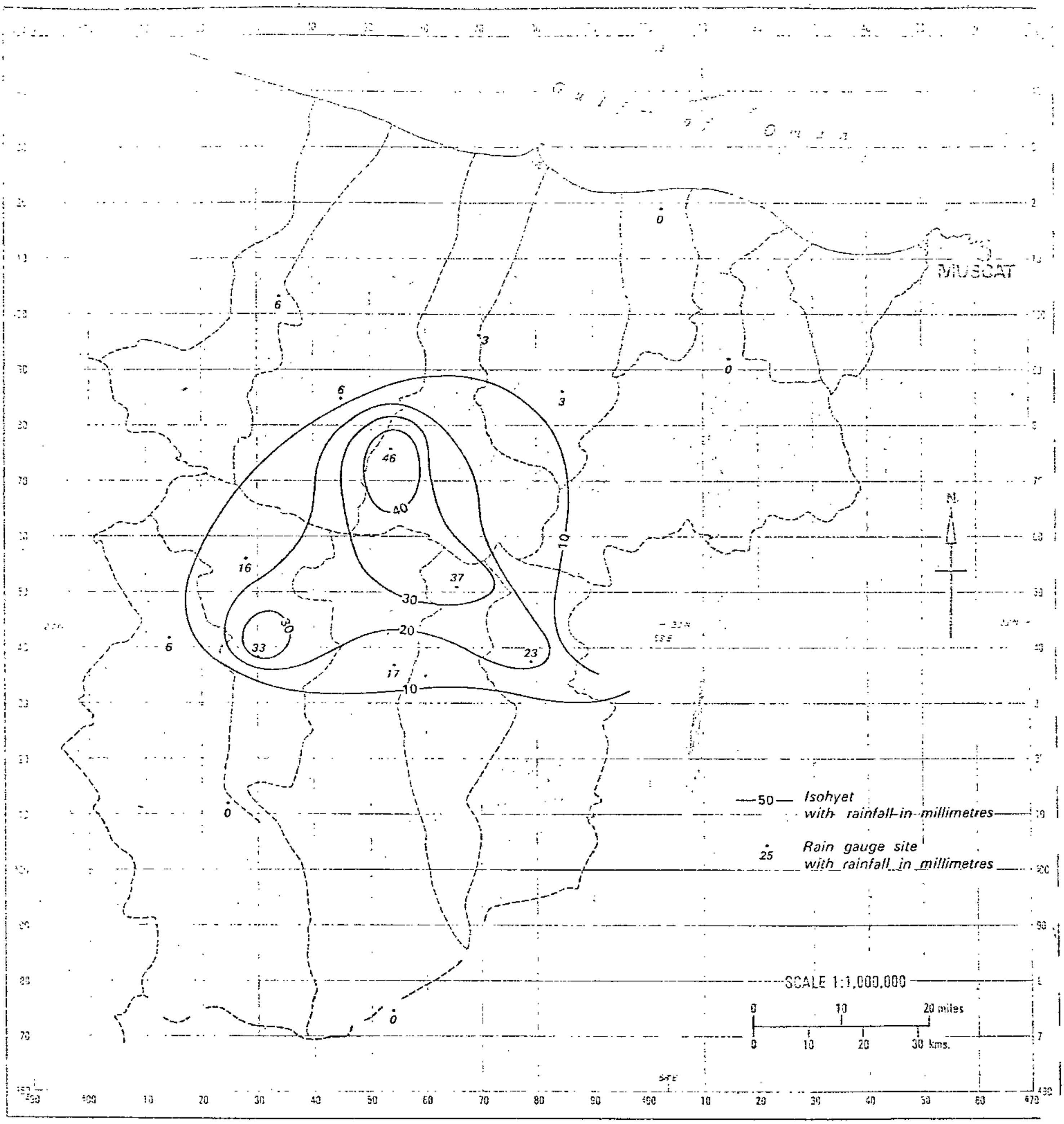
Basin	Hardrock Area in Basin (km²)	Rainfall					
		Feb 1975		May 1975		Jul/Aug 1975	
		Volume (million m³)	Average depth (mm)	Volume (million m³)	Average depth (mm)	Volume (million m³)	Average depth (mm)
Northern Basins:							
Wadi Lansab	222	14.4	65	0	0	0	0
Wadi Rusayl	150	8.2	55	0	0	0	0
Wadi Sama'il	1 359	92.7	68	*	*	*	*
Wadi Taww	174	8.9	51	*	*	0	0
Wadi Ma'awil	418	24.0	57	2.8	7	15.4	37
Wadi Bani Kharus	772	46.3	60	18.6	24	53.1	69
Wadi Far	793	62.3	79	9.6	12	53.9	68
Wadi Bani Ghafir	633	61.0	96	*	*	43.4	69
Total		318		31		166	
Southern Basins:							
Wadi Halfayn	348	34.9	100	5.9	17	26.8	77
Wadi Mu'aydin	262	28.1	107	6.9	26	27.4	105
Wadi Nazwa	475	50.1	105	11.9	25	44.4	93
Wadi Bahla	626	57.6	92	10.2	16	48.9	78
Wadi Sayfam	288	16.9	59	*	*	22.4	78
Total		188		35		170	

Notes: * Indicates slight rain on part of the wadi basin.



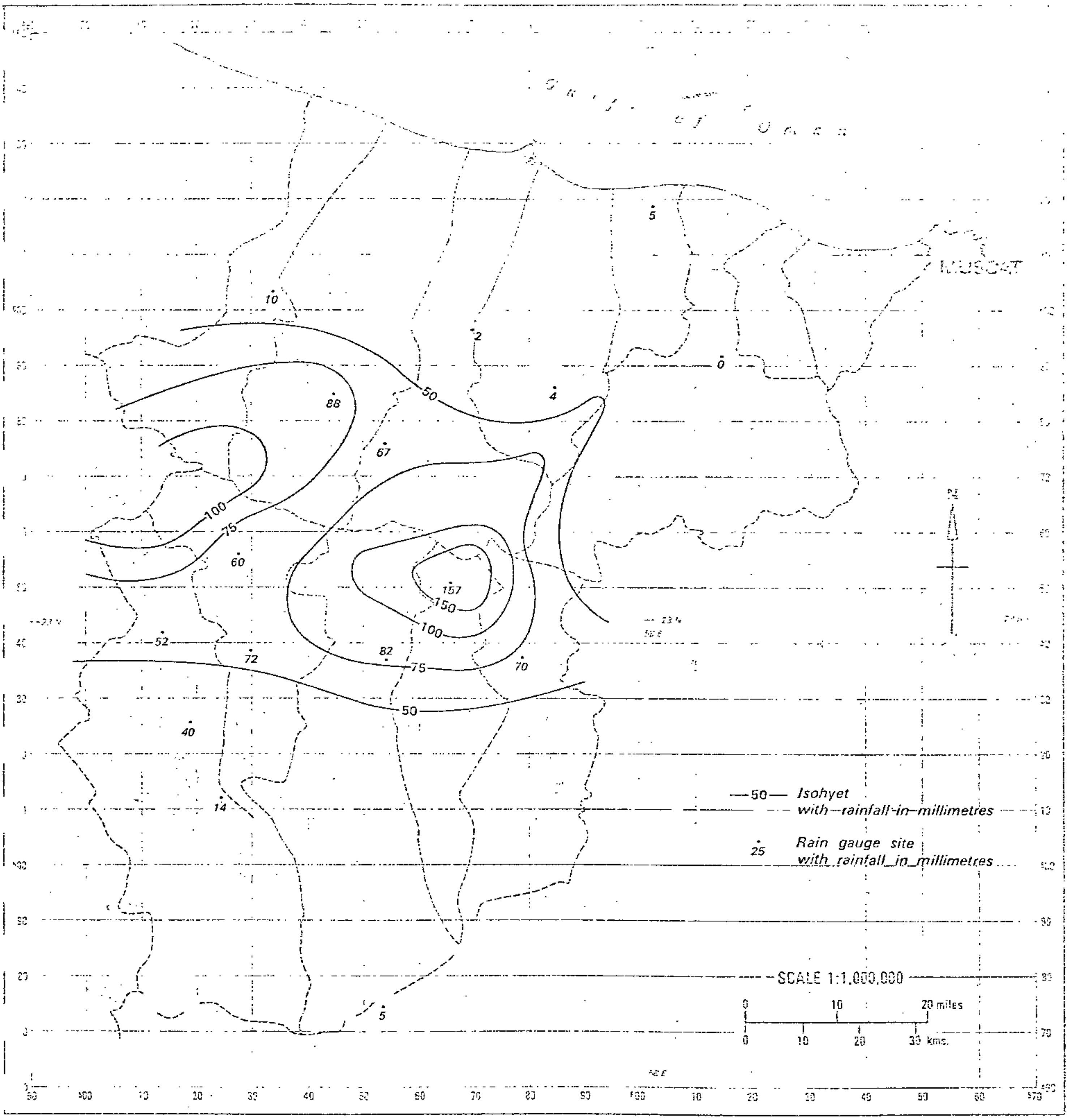
Isohyetal Map for February 1975 (25th Jan. — 11th Feb.)

Figure 6·2



Isohyetal Map for May 1975

Figure 6·3



Isohyetal Map for July/August 1975

Figure 6·4

6.3 WADI FLOWS

The occurrence of surface flows in the wadi channels naturally follows the periods of heavy rainfall. Thus we have observations of wadi flow only for October 1974, February, May, July and August 1975. For two of these periods, October and February, we have been able to compile Figures 6.5 and 6.6 which show the distribution of wadi flows from aerial reconnaissance supported by ground observation. We have not attempted to illustrate all the wadi channels flowing in the hardrock areas nor could we cover all the channels in the alluvial areas and thus the maps contain a measure of interpolation. On both occasions some northern wadis were observed to flow to the sea and during February 1975 all the major southern wadis flowed beyond the southern boundary of the study area.

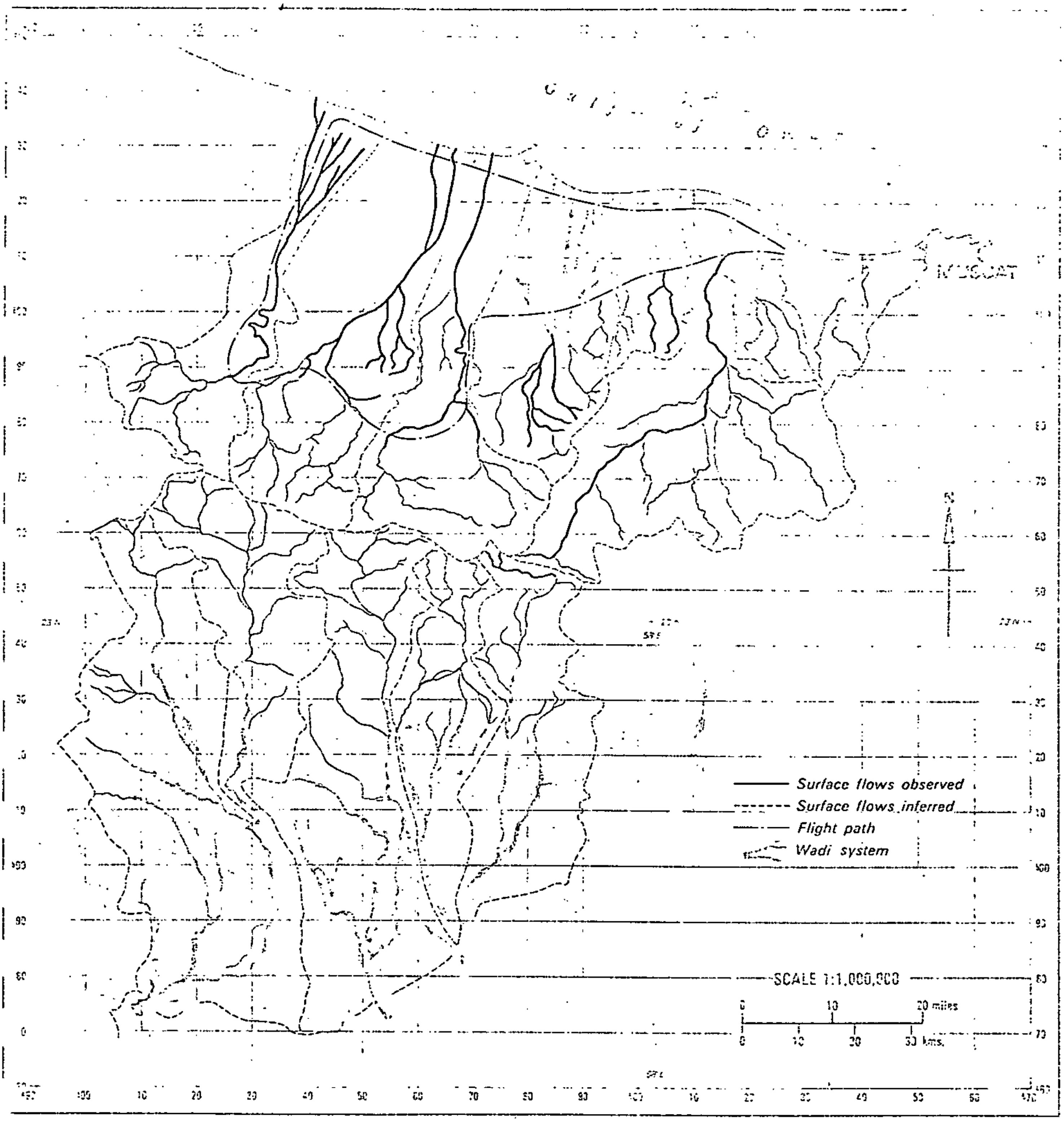
After February 1975, facilities for aerial reconnaissance were not available. However, during the August 1975 storms, the Wadi Bani Ghafir and Wadi Far carried flows which were observed to reach the sea. In the southern basins, flows were observed at Bisyah on the Wadi Bahla and at Mudri on the Wadi Sayfam.

All these observations support the local information received during the fieldwork which suggests that direct surface flows to the sea in the north are not uncommon and that there are significant wadi flows across the southern boundary of the study area every few years.

The measurement of wadi flows was one of the most formidable problems faced in the study, especially where we attempted to measure flows near the coast. Most of the stations remained untried until the runoff of February 1975 and unfortunately we have records for only the Wadi Sama'il and Wadi Bani Ghafir for that period. The later events in May, July and August 1975 were well recorded especially at the stations in the southern basins where there were several multiple runoff events.

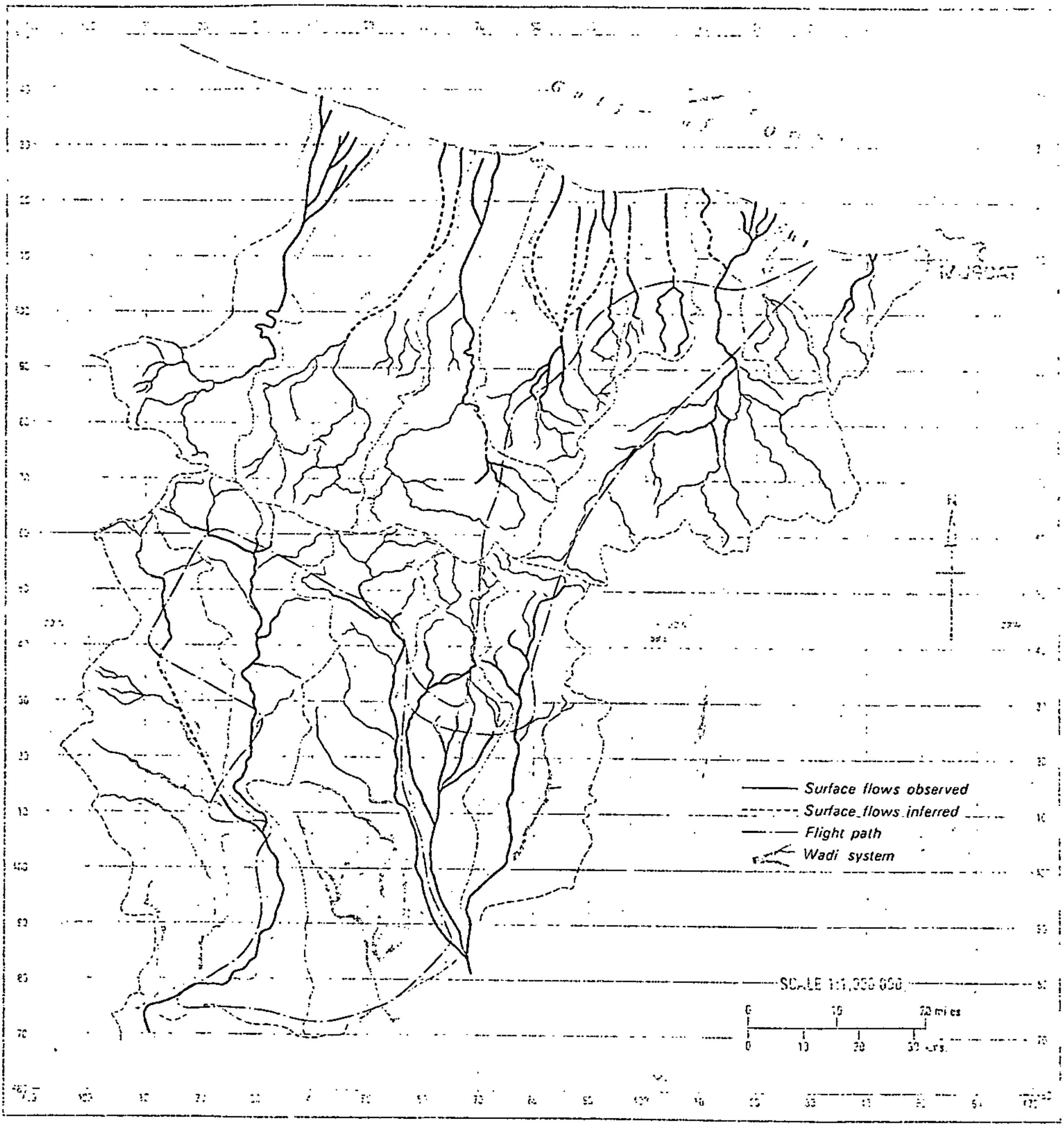
In general the best results have been obtained from the gauging stations in the confined wadi channels at the jabal foot and in the ophiolites. The gauge at Awabi was an exception being insensitive to all but the highest flows. This was because the gauge, which had to be mounted against the wadi bank for protection during floods, was nearly 80 m away from the low flow channel in the middle of the wadi. Near the coast the wide shallow channels made the three coastal stations very insensitive: large changes in flows were accompanied by relatively small changes in water level. However, the stations were useful in that they indicated when floods reached the coast road.

Four gauges were damaged by floods: at Labijah on the Wadi Bani Kharus the gauge was washed out by the October 1974 flood before the contractor had completed the strengthening work; the gauge at Bahla was partially undermined by the February 1975 flood and sited temporarily further downstream, the gauge near Fanjah on the Wadi Sama'il was washed out in February 1975; and the August 1975 flood destroyed the gauge near Al Madinah on the Wadi Bani Ghafir. This last flood had a peak water level 4.5 m above bed level corresponding to an estimated flow of 750 m^3/s.



Distribution of Surface Flows in October 1974

Figure 6·5



Distribution of Surface Flows in February 1975

Figure 6·F

Interpretation of the Hydrographs

Wadi flows were estimated from the recorded water levels using Manning's equation which relates flow velocity to the hydraulic mean depth, wadi slope and an index of channel roughness. Survey data for the wadi channel at the gauging station was used to relate area of flow and hydraulic mean depth to water level, whence velocity and rate of flow were calculated.

This procedure and the choice of an appropriate roughness index are described fully in Appendix B.2. Using velocity measurements at Al Khawd on the Wadi Sama'il during the flood of 9 February 1975, we were able to determine the roughness coefficient empirically. The value obtained, 0.035, is within the range expected for wide gravel channels[1] and, in the absence of velocity measurements elsewhere, the same value was used for all stations. Generally, it will be reasonably valid for all except the low flows when the roughness index should increase as the granular roughness of the bed becomes significant with shallow depths of flow.

This indirect method of rating the gauging stations cannot lead to a high order of accuracy. We estimate that an accuracy of + 50 percent would be realistic. Given the nature of the wadi channels, their shifting gravel beds and the short violent floods which occur, it would require a considerable investment in engineering works to improve on this accuracy. While such a cost might be appropriate for specific studies, it was not considered justifiable for this regional study where little was known beforehand of the nature of the floods to be measured. Nonetheless the results presented in this report give a consistent indication of the volume of runoff which can be expected from a given rainfall.

The detailed data for all the recorded floods are presented in Appendix B.4. A summary of the volumes of runoff in each flood together with the date of the flood peak is given in Table 6.4. Asterisks indicate where floods were known to have occurred but were not recorded.

6.4 THE RESPONSE OF THE AQUIFER SYSTEM

Following heavy rainfall on the hardrock areas of the jabal some and occasionally all the runoff will be held in storage in the alluvial deposits downstream. The gravels of the wadi channels of the mountain massif, those of the piedmont areas and those forming the alluvial plains are all potential storages. Where the wadis pass through deeply incised valleys in the ophiolites, bedrock is at or near the surface and thus there is a natural division between the alluvial storage upstream and the alluvial plains. In some basins, such as the Wadi Far and Wadi Halfayn, there is no natural division and the gravels of the mountain wadi channels are continuous with those of the piedmont areas and the alluvial plain beyond.

[1] Roughness characteristics of Natural Channels, USGS Water Supply Paper 1949.

TABLE 6.4

VOLUMES OF RUNOFF AT THE WADI GAUGING STATIONS

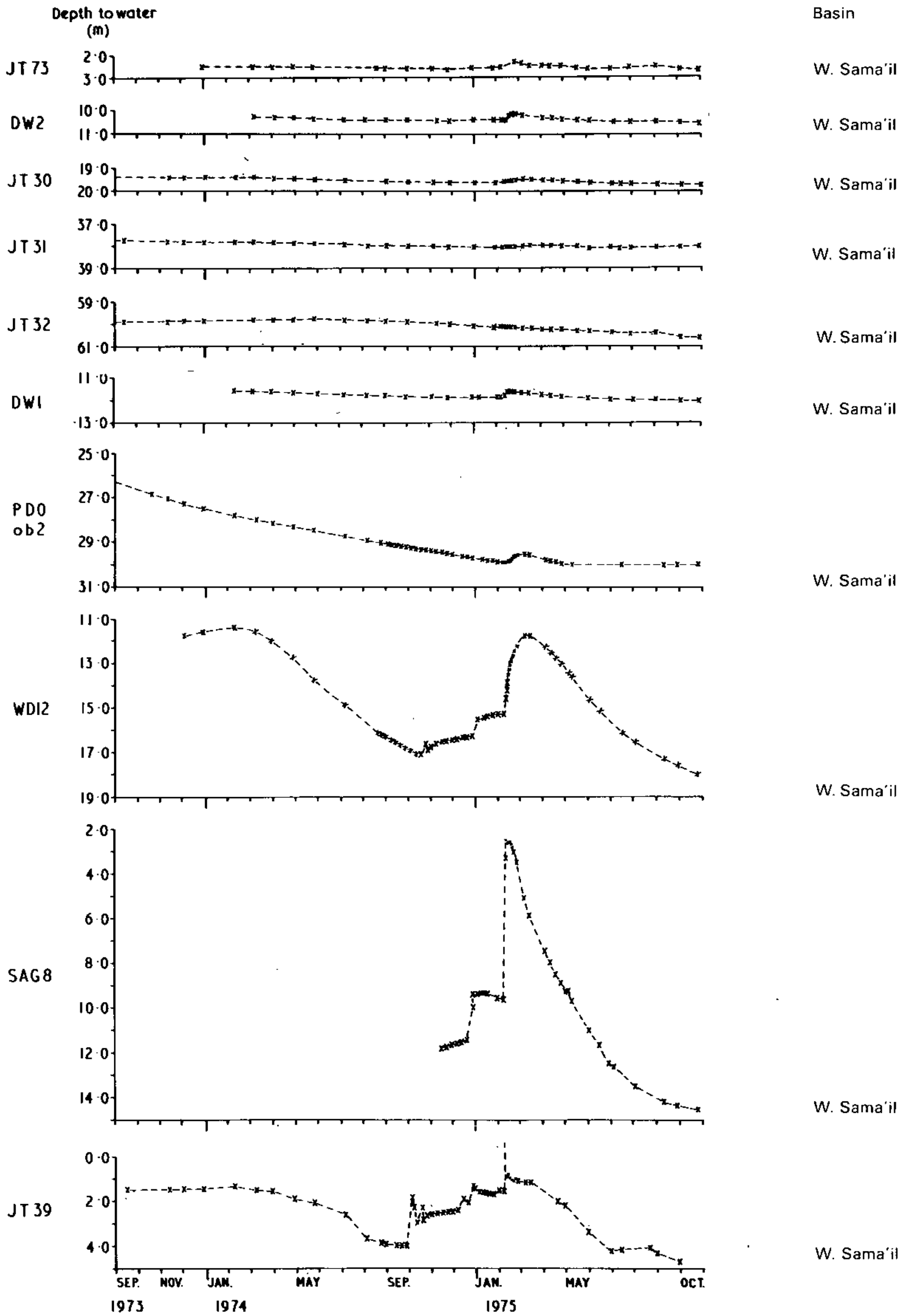
(million m^3)

Basin	Station	October 1974	February 1975	May 1975	July/August/September 1975				
Wadi Sama'il	Fanjah/ Al Khawd	0.27 (3 Oct)	5.54 (9, 11 Feb)	0	0				
Wadi Sabi	Mahani	0.29 (1, 2, 4, 6 Oct)	*	0.07 (12 May)	0.93 (16, 17 Aug)				
Wadai Bani Ghafir	Al Madinah	*	0.74[2] (11 Feb)	0.03 (13 May)	*				
Wadi Halfayn	Izki	0	*	0	0.18 (20 Jul)	0.004 (29 Jul)	1.03 (18 Aug)	0.12 (24 Aug)	
Wadi Mu'aydin	Birkat	0	*	0			0.66 (18 Aug)	0.09 (26 Aug)	
Wadi Nazwa	Nazwa	0	*	0.33 (14 May)	0.08 (21 Jul)		1.59 (18 Aug)	0.02 (26 Aug)	
Wadi Misfah	Al Hamra	0	*	0	0.13 (18 Jul)	0.70 (30 Jul)	0.25 (18 Aug)		0.02 (12 Sep)
Wadi Nakhr	Ghul	0	*		0.05 (14 Jul) 0.24 (31 Jul)	0.79 (21 Jul)	0.51 (18 Aug)	0.17 (26 Aug)	0.01 (15 Sep)
Wadi Bahla	Bahla	0	*	0.02 (13 May)	0.10 (21 Jul)	2.67 (31 Jul)	0.006 (5 Aug)	1.12 (18 Aug)	0.02 (16 Sep)
Wadi Bahla	Bisyah	0	*	0			0.06 (1 Aug)		
Wadi Sayfam	Mudri	0	*	0			0.33 (18 Aug)	0.01 (27 Aug)	

Notes: 1 Asterisks indicate when flow occurred but was not recorded.
2 The runoff volume at Al Madinah for February 1975 refers only to the flood of 11 February, a possible flood on 9 February was not recorded, due to instrument failure.

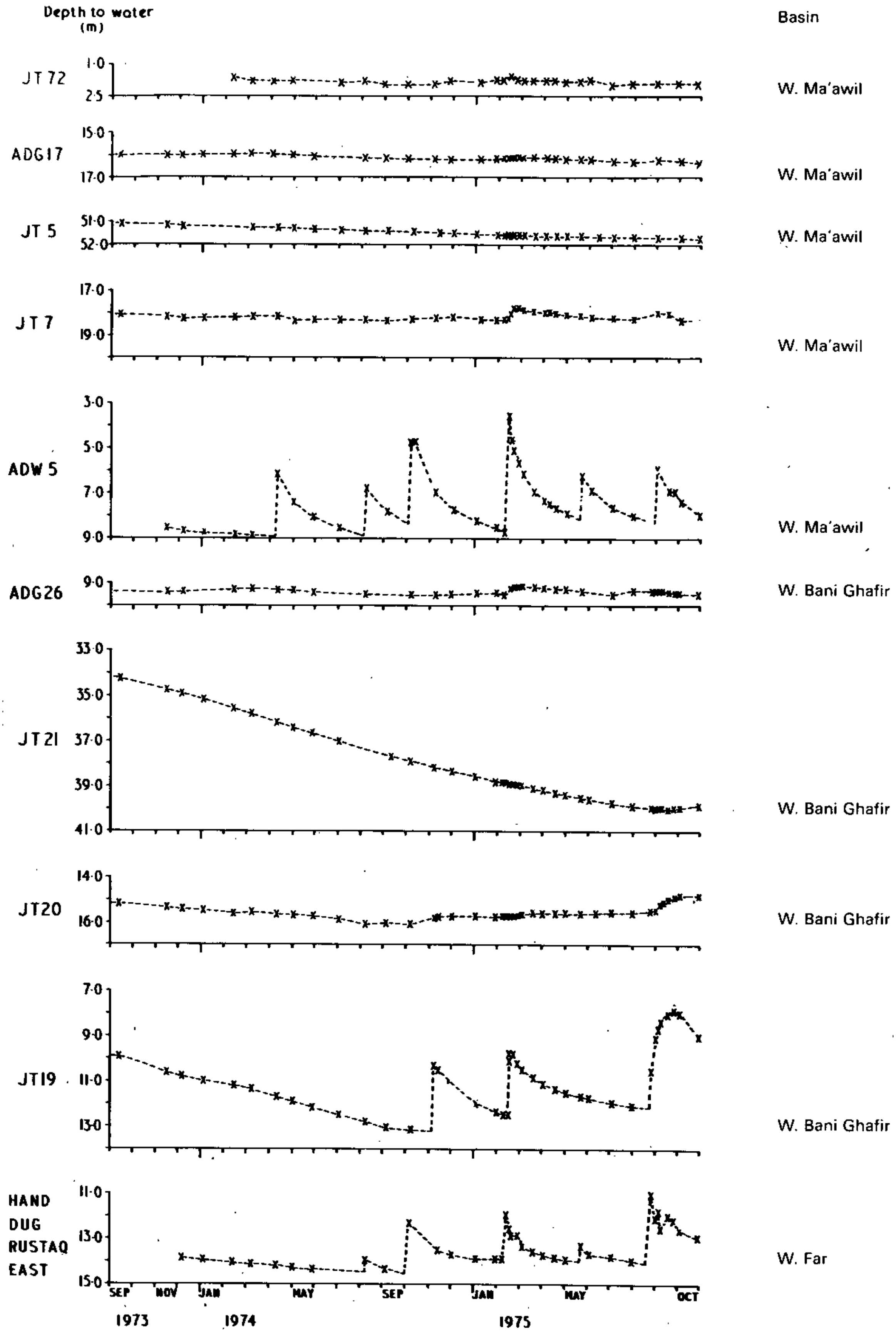
The borehole network provides direct measurements of the rise in water table associated with recharge of the alluvium and Figures 6.7 and 6.8 show selected hydrographs to October 1975 for the northern basins. Rises in water level are usually correlated with known rainfalls, although there are occasional recharges from minor storms which have not been detected by the raingauge network and which did not produce surface runoff in the wadi channels. The response of well ADW5 in the Wadi Ma'awil basin is an example of this. Generally, the effects of these minor sub-surface events are limited to the gravels of the wadi channels and there is little recharge of the adjacent terraces.

The more widespread recharge of the alluvial plains normally follows substantial surface flows in the wadi channels entering the plains. The general pattern of events is shown by the hydrographs. The larger rises in water table occur in those wells in or near the main wadi channels and although the response tends to decrease with distance from the mountain, moderate rises occur in those boreholes near the coast. Away from the channels, the response is smaller and, on the Batinah plain, it is insignificant in those mid-plain areas where depths to groundwater are large. Direct runoff from the mountain front and foothill areas tends to cause recharge adjacent to the hardrock boundary although there is no evidence of direct recharge from rainfall.



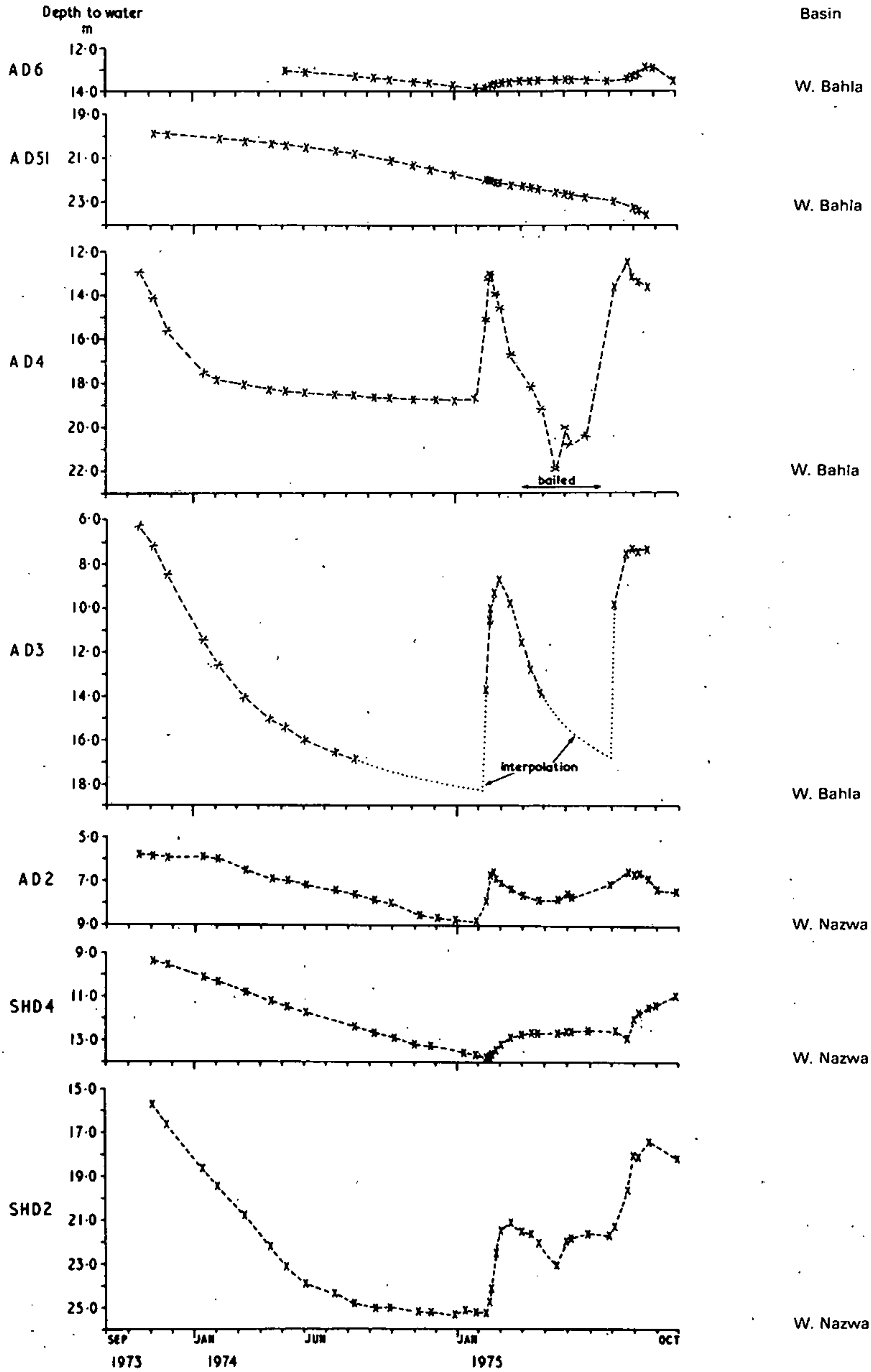
Borehole Hydrographs

Figure 6·7



Borehole Hydrographs

Figure 6·8



Borehole Hydrographs

Figure 6·9

In the wadi channels of the mountain foot and in the piedmont areas there are few boreholes. Furthermore their position relative to the active wadi channels, particularly in the southern basins, makes a general interpretation difficult. For the northern basins, hydrographs for ADW5 and the hand-dug well at Rustaq (Figure 6.8), both sited in the active wadi channel, show a large and rapid response to runoff. For the southern basins, Figure 6.9 shows hydrographs for boreholes upstream of Bahla and Nazwa. AD4 and AD3, adjacent to the wadi channel, show a large response while at AD6 and AD51, which are located away from the active channel, the response is small and even negligible. It is impossible therefore, with this sparse coverage of boreholes, to estimate recharge volumes from these data alone.

However, indirect estimates of recharge can be made from the hydrographs of falaj flow for those villages and towns which rely on water abstracted from the wadi and piedmont gravels. Figure 6.10 shows hydrographs from those aflaj which have been gauged regularly and which have been identified, by analysis of their water chemistry, as having their source primarily in the wadi gravels. Generally, the response to rainfall and runoff is as rapid and marked as that observed in the wells in the wadi channels. There is little difference in response between the aflaj which tap the wadi gravels of the mountain wadis, (Awabi, Hawqayn, Al Hamra) and those in the piedmont alluvium, (Sama'il, Rustaq, Izki, Nazwa and Bahla) although a much attenuated response is apparent in the aflaj of the southern alluvial plain, (Bisyah and Adam) which are shown for comparison.

In summary, the nature of these data and the methods we can use to analyse them, have made an arbitrary division of the alluvial storages necessary. Recharge in the wadi channels and piedmont areas are estimated from aflaj records, recharge of the Batinah alluvium from the borehole observations. The alluvial plain in the south does not have an adequate network of boreholes and it has not been possible to estimate recharge directly.

Recharge in the Wadi Channels and Piedmont Alluvium

Where villages abstract water from the wadi gravels by falaj, the rate of flow in the falaj must be related to the volume of water in storage. We have shown in Chapter 4 that falaj flows follow an exponential decay in the absence of further recharge. It follows therefore that the relationship between flow and storage must be linear. Thus when recharge causes a rapid increase in flow, we can calculate the amount of this recharge knowing only the flow before and after recharge and the recession constant of the storage.

Table 6.5 shows the calculated increases in storage for the major storm periods for the aflaj whose hydrographs are shown in Figure 6.10. The classification into mountain wadi channel and piedmont alluvium is not precise. As a general rule we have classified as piedmont alluvium those areas which are substantially wider than the active flood channel. The two aflaj for the southern alluvial plains are also included in Table 6.5 as they provide the only indication we have of storage changes south of the piedmont areas in the southern basins.

TABLE 6.5

INCREASES IN STORAGE UPSTREAM OF FALAJ LOCATIONS

(million m^3)

Location	October 1974	February 1975	May 1975	July/August 1975
In mountain wadi channels				
Awabi	0	0.46	0.36	2.02
Hawqayn	1.40	1.31	0.21	0.63
Al Hamra	0	1.73	0	4.51
In piedmont alluvium				
Sama'il	1.90	1.70	0.80	7.60
Rustaq	0.80	0.74	0.51	3.43
Izki	—	0.97	0	1.69
Nazwa	0	5.36	2.12	5.35
Bahla	0	1.66	0	2.45
In alluvial plains				
Bisyah	0	2.19	0	1.34
Adam	0	1.90	0	1.50

Storage Changes in the Alluvial Aquifer of the Batinah

The regional pattern of water level changes in the Batinah alluvial plain has been derived from the monthly differences in water level at the boreholes of the regularly monitored network. Figure 6.11 shows contour maps of these monthly changes for January, February and March 1975. Both January and March show a general pattern of falling water levels typical of the dry months; the map for February shows that the aquifer response to the rainfall and runoff of 9-11 February was complete by the end of the month as there was little if any redistribution of this groundwater recharge in March.

The greatest rise in water levels occurred along the wadi channels, adjacent to the hardrock boundary and in the coastal area. This pattern of change was also true of the October 1974, May and August 1975 recharge. Using the distribution of storage coefficient derived in Chapter 3 and shown in Figure 3.9, these water level changes have been reduced to changes in water content and integrated areally to give recharge volumes. The results for each wadi basin, adjusted to allow for the loss of storage that would have occurred during the month in the absence of recharge, are shown in Table 6.6. We have shown the recharge volumes separately for those areas which can be defined broadly as the active wadi channel and mountain front zone (10 percent storage coefficient), mid-plain alluvium (1 and 0.1 percent) and the coastal zone (2 percent). In general, the wadi channels and the areas adjacent to the hardrock boundary account for between 62 and 86 percent of the recharge with the coastal zone accounting for between 2 and 20 percent. The recharge volumes in the mid-plain zone are usually small except in the case of the Wadi Taww basin, where the general classification into zones is not applicable. The zone adjacent to the hardrock boundary has a storage coefficient of only 1 percent.

TABLE 6.6

RECHARGE OF THE BATINAH ALLUVIAL PLAIN

(million m^3)

Basin	Storm	Recharge Volume			Total
		Wadi Channel and Mountain Front	Mid-Plain Zone	Coastal Zone	
Wadi Rusayl	Oct 1974				—
	Feb 1975	0.29	0.11	0.01	0.41
	May 1975				—
	Aug 1975				—
Wadi Sama'il	Oct 1974				—
	Feb 1975	0.88	0.16	0.28	1.32
	May 1975				—
	Aug 1975				—
Wadi Taww	Oct 1974				—
	Feb 1975	—	0.18	0.02	0.20
	May 1975	—	0.19	—	0.19
	Aug 1975				—
Wadi Ma'awil	Oct 1974	—	0.11	—	0.11
	Feb 1975	2.44	0.32	0.17	2.93
	May 1975	1.37	0.19	0.03	1.59
	Aug 1975	1.15	0.34	0.03	1.52
Wadi Bani Kharus	Oct 1974	0.31	0.12	—	0.43
	Feb 1975	0.78	0.22	0.11	1.11
	May 1975	—	0.32	—	0.32
	Aug 1975	1.48	0.37	0.20	2.05
Wadi Far	Oct 1974	2.16	0.41	0.04	2.61
	Feb 1975	2.76	0.58	0.32	3.66
	May 1975	4.45	0.87	0.07	5.39
	Aug 1975	7.46	1.02	0.26	8.74
Wadi Bani Ghafir	Oct 1974	0.66	0.29	0.03	0.98
	Feb 1975	1.16	0.27	0.37	1.80
	May 1975				—
	Aug 1975	1.09	0.39	0.26	1.74

Note: The results for October 1974 in Wadi Ma'awil and for May 1975 in Wadi Bani Kharus are anomalous due to redistribution of groundwater within the monthly observation period.

6.5 THE RELATIONSHIP BETWEEN RAINFALL, RUNOFF AND RECHARGE

So far in this chapter we have presented the available data for rainfall, runoff and recharge of the various alluvial storages without regard to their inter-relationship. The data show that additions to storage in the wadi channels and the alluvium of the piedmont zones can exceed the runoff which is observed entering the alluvial plains. For example, in July and August 1975, we estimate additions to storage of 4.51 and 2.45 million m^3 in the wadi channels and piedmont areas upstream of Bahla, while 3.90 million m^3 were observed as surface flow and runoff will depend on the magnitude and frequency of storms. The combined runoff from the Wadi Nakhr and Wadi Misfah for July/August 1975 is probably near to an average value as a percentage of rainfall. The heavier rainfalls of February 1975, which were of shorter total duration, may have produced a high percentage of runoff from the hardrock areas; the lighter May 1975 rainfall and other scattered showers through the year almost certainly produced less.

As soon as runoff reaches the main wadi channels, the potential for recharge of the alluvial storages is dominant in determining the runoff observed at points downstream. Recharge of the wadi gravels and piedmont alluvium is probably limited by the duration of the surface runoff since the wadi flows usually exceed the infiltration rate of the gravels. Consequently the storages are not always filled. Although the piedmont areas respond in much the same way as the wadi gravels, it is only the area close to the active channels which responds fully. Much of the direct runoff from the hardrock areas surrounding the piedmont alluvium is probably lost to local storage and evaporation.

Runoff available for recharge of the aquifers of the alluvial plain is therefore the excess after recharge upstream together with a small direct runoff from the hardrock area adjacent to the plains. Again the quantity of recharge will be dependent on the duration of runoff, the more so because the infiltration rate of the gravels is much less in the wadi beds of the plains than it is upstream. It may make little difference to the amount of recharge whether or not the upstream channel and piedmont storages are full, since the duration of surface flow depends more on the duration of the storm rainfalls than on the quantity of runoff progressing downstream. Any additional runoff would merely increase the losses from the area to the sea in the north or to the desert in the south.

Interpretation of Data from the Whole Study Area

Table 6.11 shows a summary of the contemporary rainfall and runoff data for the three major storm periods of 1975. The rainfall volumes relate to the hardrock areas draining to the wadi gauging stations and thus they are somewhat less than the volumes for the whole wadi basins quoted in Table 6.3.

TABLE 6.11

RAINFALL AND RUNOFF FROM THE MAJOR STORMS OF 1975

(million m^3)

Basin	Drainage Area (km^2)	February 1975		May 1975		July/August 1975	
		Rainfall	Runoff	Rainfall	Runoff	Rainfall	Runoff
Wadi Sama'il above Al Khawd	1 325	91.3 (69)	5.54 (4.1)				
Wadi Sabt above Mahani	228			3.4 (15)	0.07 (0.3)	17.9 (78)	0.93 (4.1)
Wadi Bani Ghafir above Al Madinah	519	53.9 (104)	5.00[2] (9.6)			39.5 (76)	4.50[3] (8.7)
Wadi Halfayn above Izki	231					19.7 (85)	1.34 (5.8)
Wadi Mu'aydin above Birkat	186					26.2 (141)	0.75 (4.0)
Wadi Nazwa above Nazwa	316			9.3 (29)	0.33 (1.0)	32.7 (104)	1.69 (5.3)
Wadi Misfah above Al Hamra	63					4.1 (65)	1.08 (17.1)
Wadi Nakhr above Ghul	49					5.1 (104)	1.76 (35.9)
Wadi Bahla above Bahla	524			8.4 (16)	0.02 (0.04)	43.0 (82)	3.90 (7.4)

Notes: [1] The figures in parenthesis are the equivalent depths of rainfall and runoff in mm.
[2] The runoff at Al Madinah in February 1975 has been estimated in part by analogy with the flows at Al Khawd.
[3] The runoff at Al Madinah has been estimated from the peak flow and an assumed recession curve based upon the recession after the February flood.

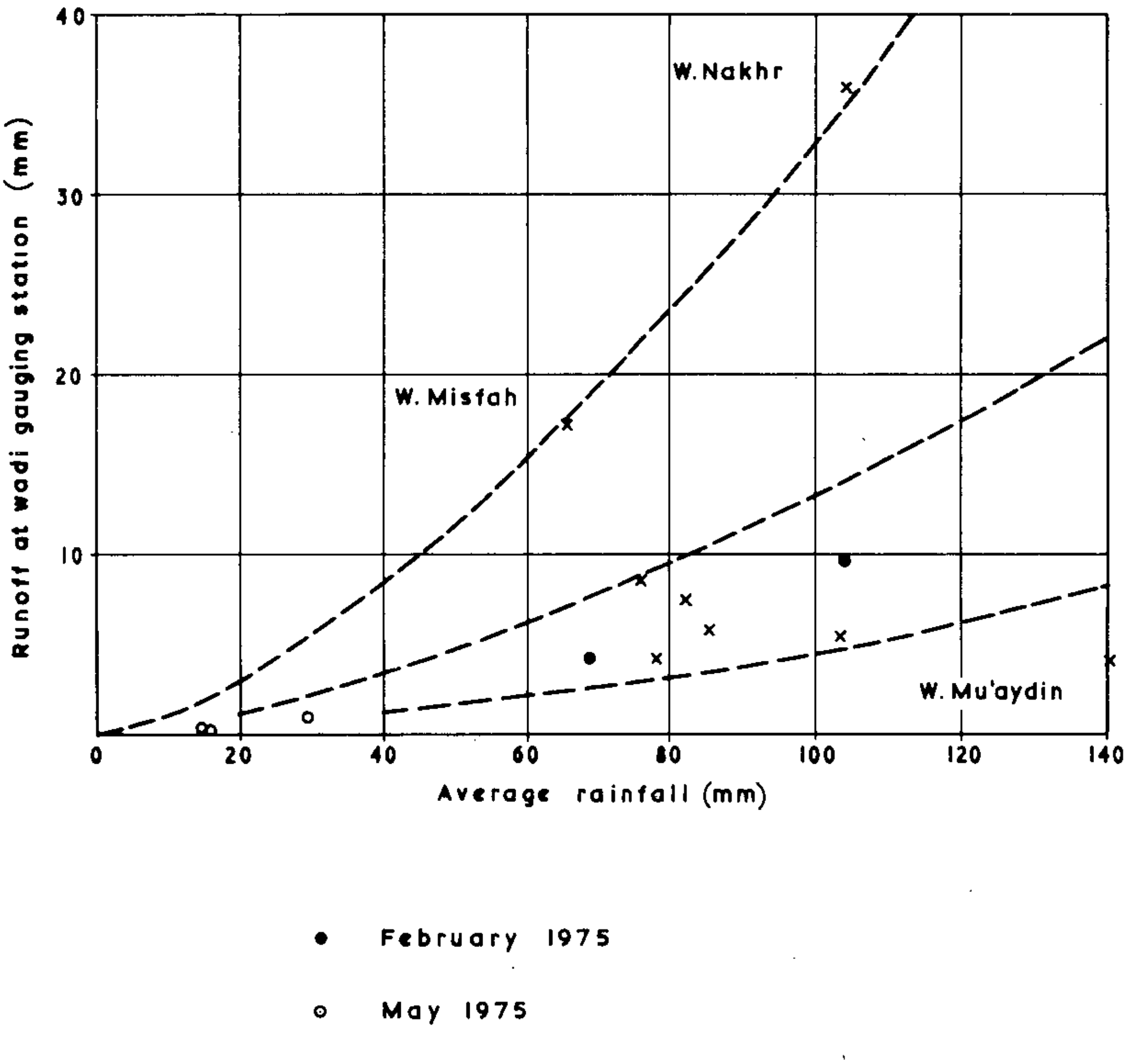
A graph of runoff against rainfall is shown in Figure 6.14, both variables being plotted as average depths over the hardrock area in order to remove the effect of basin size on the relationship. As expected, the points corresponding to the Wadi Nakhr and Wadi Misfah data plot well to the left of those for the other larger basins whose runoff is much reduced by the effects of recharge to the alluvium of the wadi channels and peidmont areas.

The simple relationship between runoff and rainfall, consistent with our discussion of the factors influencing the process of runoff, would be of the form:—

$$Q = a R^b$$

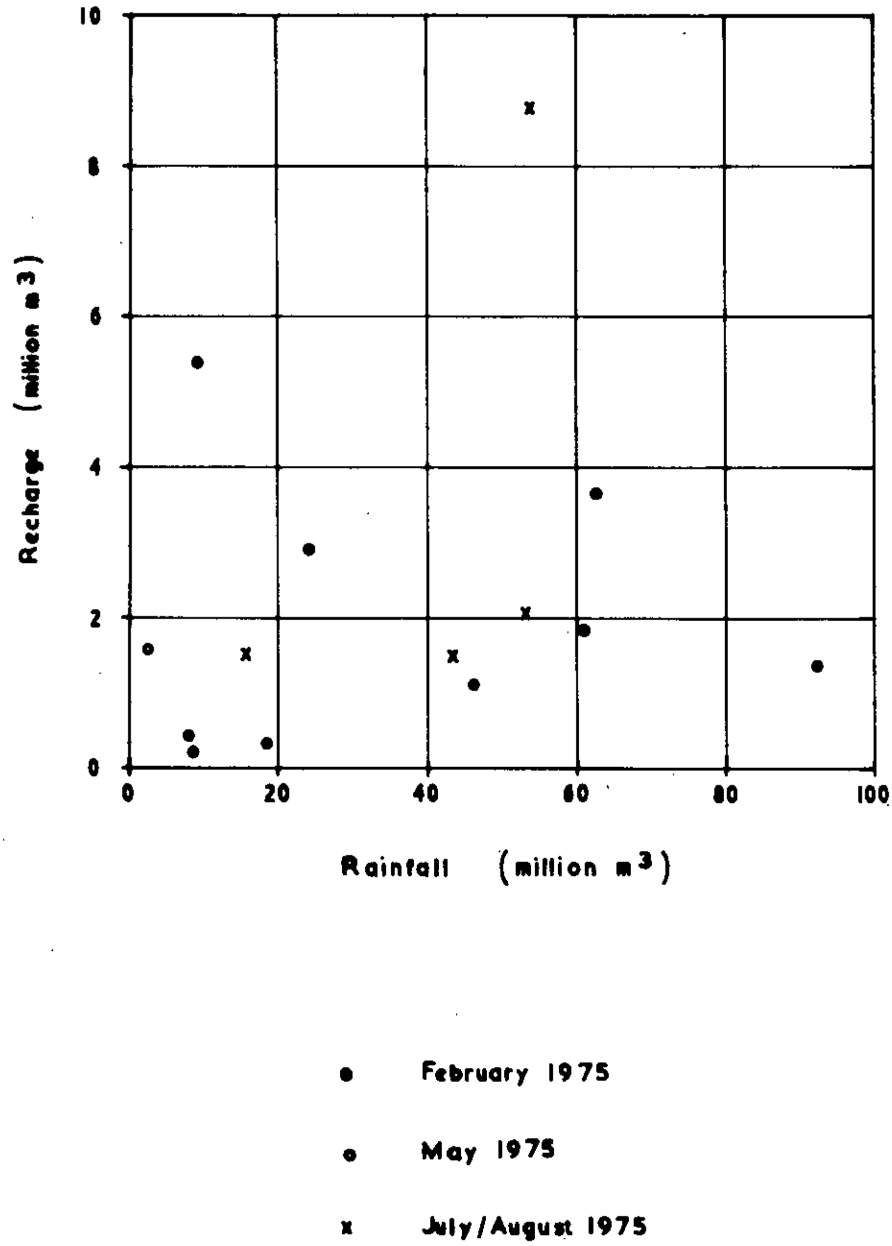
Where Q is runoff and R is rainfall in mm; a and b are constants.

Although more data are required to verify this relationship and to establish values for the constants with confidence, the data from the two small sub-basins suggests values for a and b of 0.033 and 1.5 respectively. Thus primary runoff from the hardrock areas is of the



Relationship between Rainfall and Runoff

Figure 6·14



Relationship between Recharge of the Alluvial Plain and Basin Rainfall

Figure 6·15

order of 25 to 35 percent of rainfall for storm rainfalls in the range 60 to 120 mm, the range covered by the February and July/August storms. There is of course a further qualifying statement necessary. We are using composite figures for rainfall and runoff. The July/August period contained several individual storms and if the equation above was applied strictly to each separate storm a lower runoff would result. At present there is too small a sample of storms to resolve this difficulty of interpretation.

Below the curve for primary runoff on Figure 6.14, we have drawn geometrically similar curves, which envelope the points representing the data from the larger wadi basins. Only the point for the July/August storm on the Wadi Mu'aydin lies outside the envelope and we suspect that in this case, runoff was underestimated due to insensititivity of the recorder in this wide wadi channel. The enveloping curves correspond to 40 and 15 percent respectively of the primary runoff indicating that between 60 and 85 percent of the primary runoff is recharged or lost to evaporation before it reaches the alluvial plains. Following our earlier discussion of the processes involved, a wide variation in this proportion might be expected because of the influence of the state of these storages at the start of the storm.

In attempting to relate the recharge of the alluvial plains to the runoff entering the plains, we are hampered by a lack of comparable data. The best estimates for recharge refer to the northern basins, where there is an adequate borehole network, whereas the best coverage of runoff information is by chance in the southern basins following the July and August storms. We have therefore attempted to relate recharge in the plains shown in Table 6.6 to the rainfall volumes given in Table 6.3. Figure 6.15 shows the data plotted in terms of volume. The relationship is rather poor; there are too many processes involved to expect a simple pattern. However, the general conclusion is that less than 10 percent of rainfall eventually reaches the plains as recharge and that a figure of 5 percent is a realistic average.

Summary

The various data collected during the storms of 1975 have enabled us to build up a good picture of the processes involved in recharging the various alluvial storages following heavy rainfall on the jabal. Unfortunately, even 1975 was not a very wet year; only after the August storms did the wadi channel and piedmont storages reach capacity and this was not followed by further rain during the period of our field work to October 1975. Also, these events followed an exceptionally dry year when the alluvial, and possibly the hardrock aquifers, reached their lowest level of storage for many years. Thus the quantitative relationships which we have developed in this chapter are not yet adequately proven and should be used with caution. For any specific basin, the best form of analysis is by water balance where all available data are assembled in a systematic way, thereby allowing a check on any uncertain quantities. Unfortunately, we have been able to apply this approach only to the Wadi Bahla basin with the data available.

The more general relationships are useful in that they indicate the order of magnitude of the runoff and recharges resulting from a given rainfall. In summary, they suggest that for a rainfall volume of 100 units on the hardrock area, 25 to 35 units will appear as runoff in the drainage channels at the jabal foot. Of this 18 to 24 units will recharge the alluvium of the main wadi channels and the piedmont areas, leaving 7 to 11 units as surface runoff entering the alluvial plains. Here, an average of 5 units will recharge the aquifer, the remainder being lost to evaporation or as flows out of the study area. The total effective recharge would therefore be of the order of 23 to 29 percent of the rainfall and this recharge would occur predominantly in the wadi channels and piedmont areas near the jabal.

CHAPTER 7

WATER RESOURCES IN THE LONG TERM

7.1 THE PROBLEM OF LONG TERM PREDICTION

Two of the principal objectives of this study are concerned with long term average conditions. Firstly, we must estimate the average recharge of the alluvial aquifers and hence their long term yield and, secondly, we must estimate the losses of freshwater which, by appropriate engineering works, could be made available for irrigation, or to fulfil other demands. We should also consider the variability of recharge from year to year, particularly in the context of the wadi gravel and piedmont alluvial storages which, as is evident from the falaj hydrographs, require frequent recharge to maintain their flow.

It is necessary to base predictions on relevant long term records which could be of rainfall, runoff or water levels in the aquifers. Interpretation by statistical analysis coupled with relationships between the variables would usually yield a reasonable forecast.

However, several factors severely hamper this approach in northern Oman. Firstly, there are two distinct climatic influences governing rainfall on the jabal, giving rise to two rainfall seasons. The only long term rainfall record near the study area is that for Muscat and it is relevant only to the winter rainfall season. The record for Nazwa, which has rain in both seasons, is incomplete and rather short for statistical analysis. Neither station is at high altitude and, prior to this study, there were no records of rainfall on the jabal. Secondly, there are no long term records of runoff or of changes in water level in the alluvial aquifers. Although valuable, the record of base flows at Al Khawd is, as we have shown in Chapter 4, heavily influenced by the complex interaction between irrigation demand and water availability in the Wadi Sama'il basin and does not represent a primary source of water. Only during this study have records of storm runoff and groundwater levels been taken. Thirdly, our interpretation of the storms of 1975 has shown that recharge is strongly influenced by the duration of runoff and hence of rainfall, and by the state of the wadi gravel and piedmont storages at the start of the storm. Thus a simple interpretation of the monthly records of rainfall cannot give a complete answer; some allowance, albeit of a qualitative nature, must be made for the effects of these secondary factors.

Although we shall follow as far as possible the line of analysis discussed above, it is prudent, in this situation, to use any other indicator of the long term state of the hydrological system. The most obvious and widely used assumption in arid regions is that the extent of the cultivated area reflects the long term availability of water. However, this approach, although useful, must take into account the limitations imposed by the traditional methods of winning water and, in such dynamic situations as exist on the Batinah coast, of the considerable changes which occur when pump-sets are installed on a wide scale in a relatively short time.

We have placed some emphasis already on the value of chemical analysis of the water, including its isotopic character, in order to relate source to area of use. These same data can indicate trends such as over-exploitation of aquifers, causing a local deterioration in water quality. The isotope data in particular can be used to indicate travel time through the various aquifers thereby indicating, in broad terms, the relationship between storage and throughflow.

Finally, we should aim to put the years of the study in the context of the historic sequence. By any measure, 1974 was a very dry year and, in some inland villages, one of acute water shortage. 1975 was one of substantial recharge in the wadi gravels and piedmont alluvium and lesser recharge of the plains. Whether this was an average or wetter than average year is of some importance in assessing the relevance of the processes we have observed.

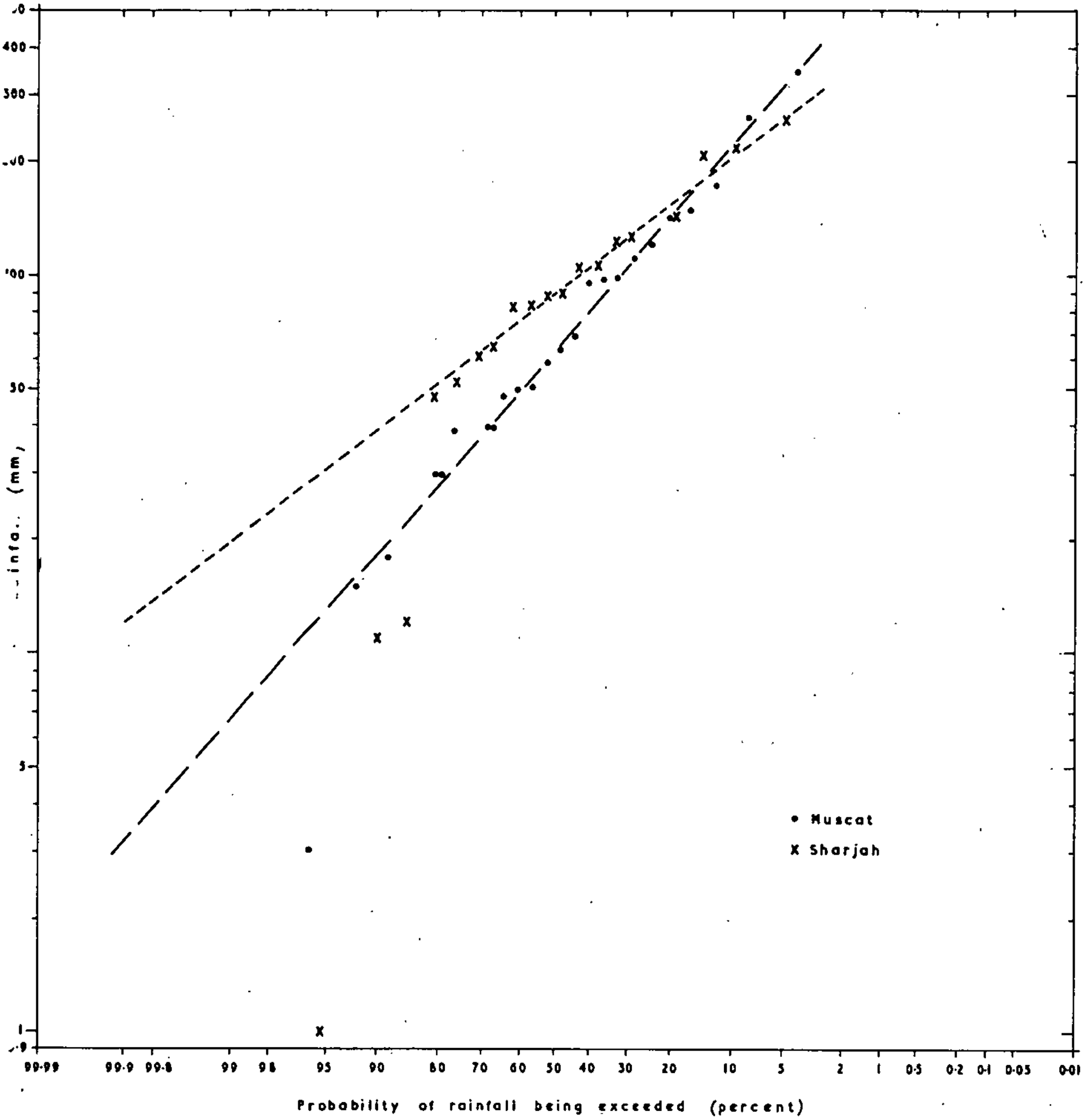
7.2 ESTIMATES BASED ON HISTORIC RAINFALL RECORDS

In the discussion of climate in Chapter 2, we concluded that May and October are months of transition between winter and summer seasons. Although rainfall in these months is unusual, it tends to be associated with winter climatic influences when it occurs. Thus we have defined the two seasons as October to May and June to September. Table 7.1 shows the data for Muscat, Nazwa and Sharjah arranged by season. The Sharjah data are included for comparison with the Muscat record because the occurrence of heavy rainfall in winter could affect a wide area bordering the Arabian Gulf. Our statistical analysis is based on these seasonal totals since rainfall in any one month is not reliable and the frequent occurrence of zero monthly rainfall would make prediction doubly difficult.

Winter Rainfall

The winter rainfalls for Muscat and Sharjah have been plotted on logarithmic normal probability paper as shown in Figure 7.1. The points will plot on a straight line if the data, transformed by taking logarithms, conform to the normal distribution. This is so, except for the very low rainfalls which tend to occur rather more frequently than the distribution would suggest, particularly at Sharjah.

Although the rainfall at Sharjah is about 10 percent higher on average than at Muscat, its variability is substantially less; the 80 percent confidence limits encompass a 12-fold range at Muscat but only a 5-fold range at Sharjah. This is consistant with the underlying causes of winter rainfall. As depressions move from west to east down the Arabian Gulf, they will become weaker and, in drier than average years, heavy rainfall will not occur as often as far east as Muscat. In wetter than average years, there would appear to be an equal likelihood of heavy rain at both stations.



Frequency Distribution of Winter Rainfall at Muscat and Sharjah

Figure 7·1

TABLE 7.1

SEASONAL RAINFALL AT MUSCAT SHARJAH AND NAZWA

(mm)

Winter Rainfall				Summer Rainfall		
Year	Muscat	Sharjah	Nazwa	Year	Muscat	Nazwa
1950/51	—	—		1951	0	
1951/52	59	104		1952	0	
1952/53	50	84		1953	0	
1953/54	39	89		1954	0	
1954/55	175	206		1955	0	
1955/56	40	65		1956	37	
1956/57	351	259		1957	0	
1957/58	100	105		1958	5	
1958/59	51	142		1959	0	
1959/60	150	48		1960	0	
1960/61	70	90		1961	1	
1961/62	30	1		1962	72	
1962/63	141	219		1963	0	42
1963/64	40	127	83	1964	0	21
1964/65	111	124	172	1965	0	22
1965/66	98	61	20	1966	0	65
1966/67	15	11	169	1967	2	58
1967/68	121	83	186	1968	0	0
1968/69	48	142	—	1969	0	—
1969/70	30	52	(62)	1970	86	381
1970/71	18	12	—	1971	0	—
1971/72	263		(569)	1972	0	115
1972/73	97		(54)	1973	0	(140)
1973/74	3		(0)	1974	0	10
1974/75	64		132	1975	0	85

Notes: 1 The winter season is from October to May; the summer season from June to September.
2 Figures in parenthesis may not be the true seasonal rainfall; they have been derived from incomplete data.
3 Monthly and annuâl rainfall data for Muscat and Nazwa are presented in Chapter 1.

The logarithmic normal distribution is highly positively skewed which means that serious deficiencies in rainfall are more common than they would be if the distribution were normal, the mean being made up by the occasional occurrence of large excesses. In this situation, the mean is an unsatisfactory estimator of the likely rainfall, the median (the value which is exceeded in 50 percent of the years) being more suitable. This reasoning is also justifiable on other grounds. The years of very high rainfall are not necessarily those of very high recharge. We have implied in Chapter 6 that the marginal value of high rainfall is small; the result is most likely to be a substantial increase in losses by surface flow to the sea to the north or the desert to the south.

The record for Nazwa is broken and insufficiently long for a statistical analysis of the same form as the other stations. We have therefore used the median value estimated from the shorter record as the basis for comparison with the Muscat record and our estimate of confidence limits assumes that rainfall variability at Nazwa is the same as that at Muscat. The basic statistics for all three stations are shown in Table 7.2

TABLE 7.2

ESTIMATED STATISTICS OF WINTER RAINFALL

(mm)

Station	Mean Rainfall	Median Rainfall	Confidence Limits	
			80 Percent	60 Percent
Muscat	90	63	18 and 220	28 and 140
Sharjah	101	90	39 and 205	52 and 155
Nazwa	145	105	30 and 367	47 and 233

Notes: The 80 percent confidence limits mean that on average the rainfall in 8 winters out of 10 will lie between the values quoted. One winter in 10 will be wetter, one will be drier.
These statistics are derived from the data presented in Table 7.1

Summer Rainfall

At Muscat, summer rainfall is infrequent; there are only three appreciable falls in the 25 years of record. While these add almost 8 mm to the mean rainfall, the median rainfall is zero. At Nazwa, and by observation during 1975 over much of the jabal, summer rainfall is common and occasionally very substantial. Despite the rather short record, the Nazwa data are reasonably well fitted by the logarithmic normal distribution, Figure 7.2, although there is some uncertainty about a few years of possibly very low rainfall and some years (shown in parenthesis on Table 7.1) where rainfall might be underestimated due to incomplete records. Unfortunately, there is no station with a longer record of summer rainfall by which the short record can be extended. The estimated statistics are shown in Table 7.3 and it is evident that the variability of rainfall, represented by the confidence limits, is more severe in summer than in winter.

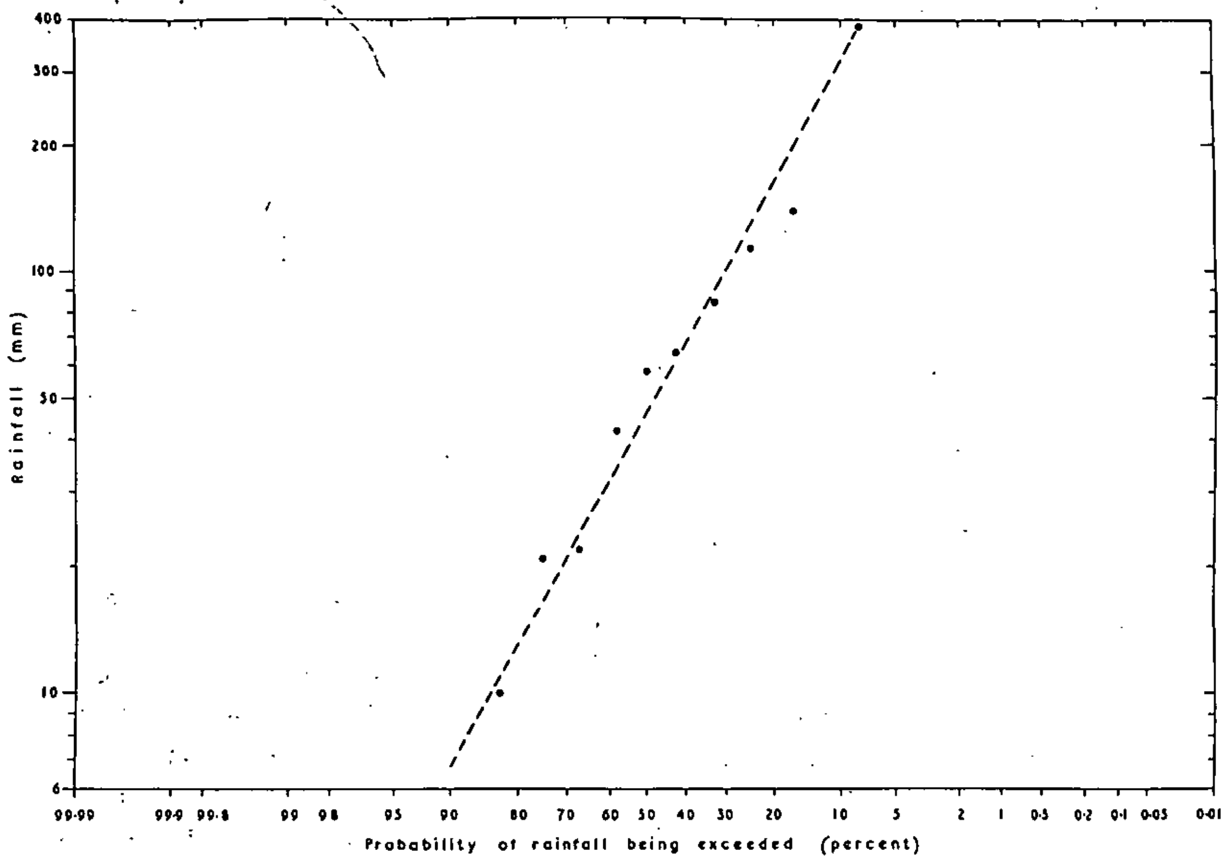
Annual Rainfall

There is no evidence from the Nazwa or Muscat data to suggest serial correlation between successive winter and summer rainfalls. We can therefore assume that they are independent and that the variability of annual rainfall lies between the variabilities of the separate seasons. The median annual rainfall is estimated from the sum of the median rainfalls of the two seasons, giving 63 mm at Muscat and 152 mm at Nazwa. While both values are substantially less than the mean annual rainfall, they represent a more realistic estimate of average rainfall.

TABLE 7.3

ESTIMATED STATISTICS OF SUMMER RAINFALL

Station	Mean Rainfall	Median Rainfall	Confidence Limits	
			80 Percent	60 Percent
Nazwa	85	47	7 and 330	13 and 170



Frequency Distribution of Summer Rainfall at Nazwa

Figure 7·2

Rainfall during the study period is compared with the estimated median rainfalls in Table 7.4. The shortfall in the winter season October 1973 to May 1974 was particularly severe at both stations and this was followed by summer rainfall at Nazwa of only 20 percent of the median value. From October 1974 the situation improved; winter rainfall was at the median value at Muscat and about 30 percent above the median at Nazwa. The following summer rainfall was nearly double the median value at Nazwa.

TABLE 7.4

RAINFALL DURING THE STUDY PERIOD RELATED TO ESTIMATED MEDIAN RAINFALL

(mm)

Station	Winter Season October to May			Summer Season June to September		
	Median	1973/74	1974/75	Median	1974	1975
Muscat	63	3	64	0	0	0
Nazwa	105	(12)	132	47	10	85

Notes: The figure in parenthesis is derived from an incomplete record although it is unlikely that any appreciable rainfall was missed.

In order to extrapolate the rainfall estimates to the study area as a whole and thereby estimate annual rainfall on the hardrock areas of the major basins, we must re-examine the gradient of rainfall with altitude. The median annual rainfalls derived above suggest a gradient of 162 mm per 1 000 m. This is much less than the 300 mm per 1 000 m suggested by the Zagros data which formed the basis of our interim resources assessment and which was partially supported by Figure 6.1. However, it is perhaps significant that the lower gradient would bring the Sayq rainfall on Figure 6.1 near to the expected value for that altitude. A final judgement is impossible without several years more rainfall data for stations on and around the jabal. In this current analysis, it would be prudent to adopt the lower gradient. Thus the equation for rainfall variation with altitude is:—

$$R = 63 + 0.162h$$

where R is the median annual rainfall in mm
and h is the altitude in m.

Estimates of median annual rainfall for the major basins are shown in Table 7.5. These are based on the altitude zones shown in the topography and drainage map (Figure 1.4) and the area of hardrock in each zone.

TABLE 7.5

ESTIMATED MEDIAN ANNUAL RAINFALL ON THE HARDROCK AREAS OF THE MAJOR WADI BASINS

Basin	Hardrock Area (km^2)	Rainfall Volume (million m^3)	Average Rainfall (mm)
Northern Basins:			
Wadi Lansab	222	27	124
Wadi Rusayl	150	19	128
Wadi Sama'il	1 359	234	172
Wadi Taww	174	26	150
Wadi Ma'awil	418	80	191
Wadi Bani Kharus	772	180	234
Wadi Far	793	158	199
Wadi Bani Ghafir	633	138	218
Southern Basins:			
Wadi Halfayn	348	83	238
Wadi Mu'aydin	262	81	310
Wadi Nazwa	475	121	254
Wadi Bahla	626	157	251
Wadi Sayfam	288	68	236

Estimates of Recharge from Median Annual Rainfall

Our general conclusions on the relationships between rainfall, runoff and recharge, summarized at the end of Chapter 6, were based on an analysis of storm periods of one or two months duration within which there were a few days of heavy rain. Before attempting to interpret the median annual rainfall in terms of runoff and recharge, we must ascertain whether the pattern of rainfall occurrence observed in 1975 is typical of most years and estimate the proportion of annual rainfall which may be expected to fall in such periods.

Table 7.6 shows the larger daily rainfalls observed at Nazwa for the period of record. These data suggest that the pattern of heavy rainfalls observed in 1975 was reasonably typical of most years although there is some variation in the proportion of the total monthly fall which occurred as heavy showers.

TABLE 7.6

THE LARGER DAILY RAINFALLS AT NAZWA

Year	Month	Daily Falls	Total for the Month (mm)
1963	May	76 mm	131
1965	January	45 mm	56
	April	36 mm	109
1967	May	128 mm in less than 3 hours	128
1968	February	29, 68 and 32 mm in consecutive days	157
1970	February	62 mm	(62)
	July	144 mm	147
	August	12, 45, 15, 0 and 50 mm in consecutive days	132
	September	63 mm	102
1971	December	75 mm	(75)
1972	January	32 mm on two occasions	64
	February	37, 32 and 40 mm	135
	March	52 mm	60
	April	87 mm (8 day total = 235 mm)	235
	July	74 and 15 mm	89
1973	January	17, 32 and 5 mm in consecutive days	(54)
	July	25, 68 and 47 mm	140
1975	February	54 and 51 mm	107
	July	33 and 28 mm	74

Notes: The records for 1969 and 1971 are incomplete.
There were no heavy rainfalls during 1974.

Using the monthly data for Nazwa (Table 1.5) for the years of complete record, 1963-68 and 1975, about 88 percent of the total rainfall occurred in months having more than 15 mm of rain. A similar result is found from the Muscat record. The choice of a lower limit of effectiveness of rainfall is arbitrary and clearly subjective on the data available. However, we consider it reasonable to adopt a limit of 15 mm and to reduce the median annual rainfalls by 12 percent to allow for ineffective showers which contribute neither to runoff nor recharge.

We have applied the relationships between rainfall, runoff and recharge deduced in Chapter 6, directly to the modified median annual rainfalls. Where, largely on the basis of the Wadi Bahla analysis, we had obtained a range of values—for example primary runoff was estimated at between 25 and 35 percent of rainfall—we have taken the mid-range value. We have also made one adjustment to the relationships suggested in Chapter 6. On the grounds that in an average year storage in the wadi channel and piedmont areas would be at a higher level than was observed in 1975, the potential for recharge would have reduced. Thus we estimate that recharge to these areas is likely to be about 50 percent of runoff, rather than the 70 percent indicated in the 1975 data.

The estimates of runoff and recharge for each wadi basin are shown in Table 7.7. Because of the short period of record on which these extrapolations are based, the results must be treated with some caution particularly for those basins which are least similar to the Wadi

Bahla. We present the calculation in this form in order to show most clearly how well or how poorly the model of rainfall, runoff and recharge is consistent with the pattern of water use.

TABLE 7.7

RUNOFF AND RECHARGE VOLUMES ESTIMATED FROM MEDIAN ANNUAL RAINFALL

(million m³/year)

Basin	Median Annual Rainfall	Effective Median Annual Rainfall	Primary Runoff	Recharge to Wadi Channels and Piedmont	Recharge to Alluvial Plains	Surface Runoff Losses
Northern Basins:						
Wadi Lansab	27	24	7.1	3.5	1.2	2.4
Wadi Rusayl	19	17	5.0	2.5	0.8	1.7
Wadi Sama'il	234	206	61.8	30.9	10.3	20.6
Wadi Taww	26	23	6.9	3.4	1.2	2.3
Wadi Ma'awil	80	70	21.1	10.6	3.5	7.0
Wadi Bani Kharus	180	158	47.5	23.8	7.9	15.8
Wadi Far	158	139	41.7	20.9	6.9	13.9
Wadi Bani Ghafir	138	121	36.4	18.2	6.1	12.1
Southern Basins:						
Wadi Halfayn	83	73	21.9	11.0	3.6	7.3
Wadi Mu'aydin	81	71	21.4	10.7	3.6	7.1
Wadi Nazwa	121	106	31.9	16.0	5.3	10.6
Wadi Bahla	157	138	41.4	20.7	6.9	13.8
Wadi Sayfam	68	60	18.0	9.0	3.0	6.0

Note: These figures have been rounded to the precision shown; thus minor inconsistencies are possible in the balance for a basin.

Before making this essential comparison, there are two factors which should be borne in mind. Firstly the recharge observed in the wadi channel and piedmont areas in 1975 could have been exceptional since the storages were probably at their lowest level for many years. In a sequence of years of more plentiful rain, the storages could well be maintained at a higher level, thus reducing the potential for recharge. Secondly, our model does not allow for groundwater transfers from the piedmont to the plains. These transfers were small during the drought period although local knowledge and our own qualitative observations early in 1973 suggest that they are substantial following years of plentiful rain.

7.3 COMPARISON OF ESTIMATED RECHARGE AND VILLAGE WATER USE

In Chapters 4 and 5 we developed estimates of consumptive use for all the towns and most of the villages in the major basins. For use in a water balance we have augmented these estimates of consumptive use by 10 percent, to allow for conveyance losses and a net loss of leachate, as suggested in the report of the soils and agricultural studies. We have not made any allowance for transpiration by natural vegetation or for direct evaporation of surface base flow in wadi channels. This would imply a precision in the analysis which is not yet possible.

Water Balance of the Wadi Channel and Piedmont Areas

The estimated median annual recharge to these areas (from Table 7.7) are compared with the water use in Table 7.8 and the data are plotted in Figure 7.3. For the larger basins, the results illustrate two distinct patterns. The majority of points suggest that water use is about 50 percent of the estimated median annual recharge. This could be because the high proportion of perennial crops means that water use is related to a lower and therefore more reliable rainfall than the median; or that the villages cannot utilize the recharge fully due to the natural groundwater flow causing a transfer of resources to the alluvial plains; or simply that recharge is over-estimated. We cannot determine the relative importance of these factors but would suggest that the first and second are probably important.

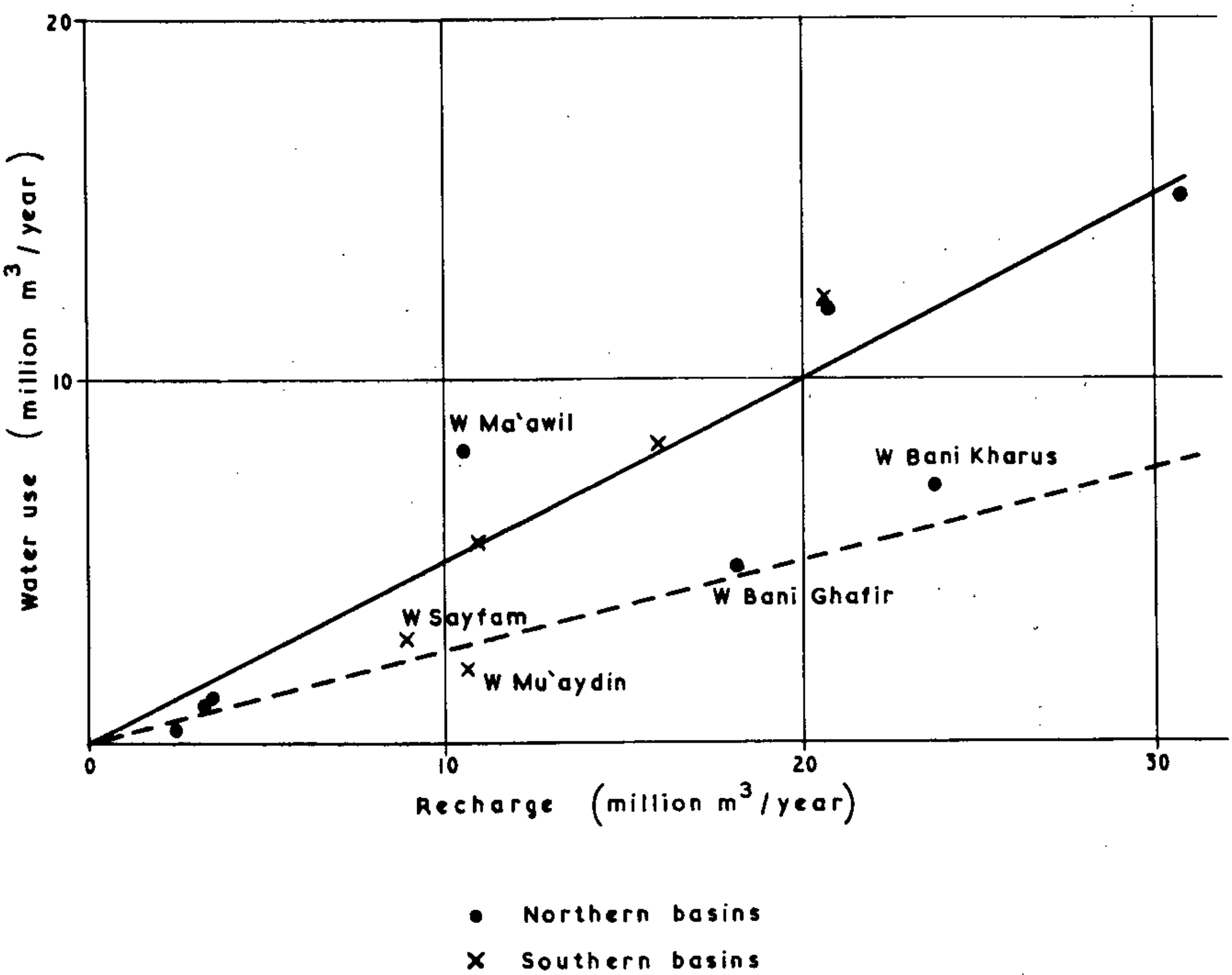
TABLE 7.8

COMPARISON OF ESTIMATED MEDIAN ANNUAL RECHARGE AND VILLAGE WATER USE

(million m³/year)

Basin	Wadi Channel and Piedmont Area		Base Flow Transfer to the Plains	Alluvial Plains		
	Recharge	Water Use		Direct Recharge	Total Recharge	Water Use
Northern Basins:						
Wadi Lansab	3.5	1.2	2.3	1.2	3.5	1.4
Wadi Rusayl	2.5	0.3	2.2	0.8	3.0	2.2
Wadi Sama'il	30.9	15.0	15.9	10.3	26.2	11.1[1]
Wadi Taww	3.4	1.0	2.4	1.2	3.6	4.7
Wadi Ma'awil	10.6	8.0	2.6	3.5	6.1	15.5
Wadi Bani Kharus	23.8 (11.9)[2]	7.0	4.9	7.9	12.8	10.0
Wadi Far	20.9	12.0	8.9	6.9	15.8	11.7
Wadi Bani Ghafir	18.2 (9.1)	4.8	4.3	6.1	10.4	14.6
Southern Basins:						
Wadi Halfayn	11.0	5.5	5.5	3.6	9.1	1.2
Wadi Mu'aydin	10.7 (5.4)	2.0	3.4	3.6	7.0	5.3
Wadi Nazwa	16.0	8.2	7.8	5.3	13.1	5.2
Wadi Bahla	20.7	12.2	8.5	6.9	15.4	2.1
Wadi Sayfam	9.0 (4.5)	2.9	1.6	3.0	4.6	4.5

Notes: [1] The water use in the alluvial plain of the Wadi Sama'il basin includes 1.4 million m³/year abstracted from the Government wellfields for domestic and industrial water supply.
[2] The values in parenthesis under recharge in the wadi channel and piedmont areas are adjusted values as described in the text.



Water Use and Estimated Recharge in the Wadi Channel and Piedmont Areas

Figure 7·3

The subsidiary set of points comprising the Wadis Bani Kharus, Bani Ghafir, Mu'aydin and Sayfam basins indicate a lower water use of about 25 percent of estimated recharge. It is significant that these basins have a less well developed piedmont area than the other major basins and we would suggest that the results are indicative of a lower potential for recharge and hence that the estimated recharges are too high in these four basins. If we assume that the water use is of the order of 50 percent of the true recharge as suggested by the results for basins with an appreciable piedmont area, we should adjust the recharge estimates accordingly.

The difference between estimated recharge and water use will form the base flow transfer to the alluvial plains where we can assume that it is a total gain to the aquifer. These transfers are shown in Table 7.8 and they are derived from the amended recharge values for the wadi channel and piedmont areas.

The data from the PD(O) gaugings of surface flow at Al Khawd on the Wadi Sama'il provide a measure of confirmation of these estimates of base flow transfer. The gaugings were made about once per month and as a data set they can be taken as generally representative of monthly average flows (Table 7.9). Excluding the very high values, they indicate an average surface base flow of 14 million m^3/year which, with the 7 million m^3/year groundwater flow indicated by the Wadi Sama'il water balance in Chapter 4, gives a total transfer of about 21 million m^3/year. However, this is a mean flow in the statistical sense, whereas our estimates of transfer in Table 7.8 are median values. Thus the 15.9 million m^3/year estimated for the Wadi Sama'il is probably of the right order.

TABLE 7.9

SURFACE FLOWS AT AL KHAWD

(m^3/day × 10^3)

Year	J	F	M	A	M	J	J	A	S	O	N	D
1965									44	39	42	60
1966	63	150	47	38	27	12	6	3	0	519	10	17
1967	26	7	9	5	12	0	297		7	4	10	
1968		391		81	111	70	46	62	58	59	76	87
1969		65	72	54	49	23	62	19	17	25	0	24
1970	32	28	10		0	0	0		5	5	4	
1971	8		9	0	0	0	0	0	0	0	0	
1972		104	93	33	105	103		66		80	101	100
1973	93	103	95	79	85	36	305	35	0	0	30	33
1974	47	31	30	20	10	0	0	0	0	0	0	0
1975	0				0	0	0	0	0			

Notes: 1. These data are derived from PD(O) gaugings up to January 1974 and thereafter from information collected during this survey.
2. The values underlined probably refer to flood flows.

Water Balance for the Alluvial Plains

The total recharge to the plains, base flow transfers plus direct recharge from storm runoff, is compared with water use in Table 7.8 and the data are plotted in Figure 7.4. While the data for many of the basins lie tolerably close to the line indicating 100 percent water use, there are several significant exceptions.

The data for the Wadis Sama'il, Nazwa, Bahla and Halfayn plot below the line indicating 50 percent water use. We have shown that there is substantial loss of groundwater to the sea in the Wadi Sama'il basin, thus that result is not surprising. The other basins in this group are all in the south and the results could be indicative of poor aquifer conditions not conducive to recharge. Thus our estimates could be in excess of actual recharge. However, the two remaining southern basins, Wadis Mu'aydin and Sayfam would not be expected to differ substantially from the others in terms of their aquifer conditions. But in these two cases it may be that our correction for poor piedmont recharge was excessive and that all the southern basins should plot as a group on Figure 7.4.

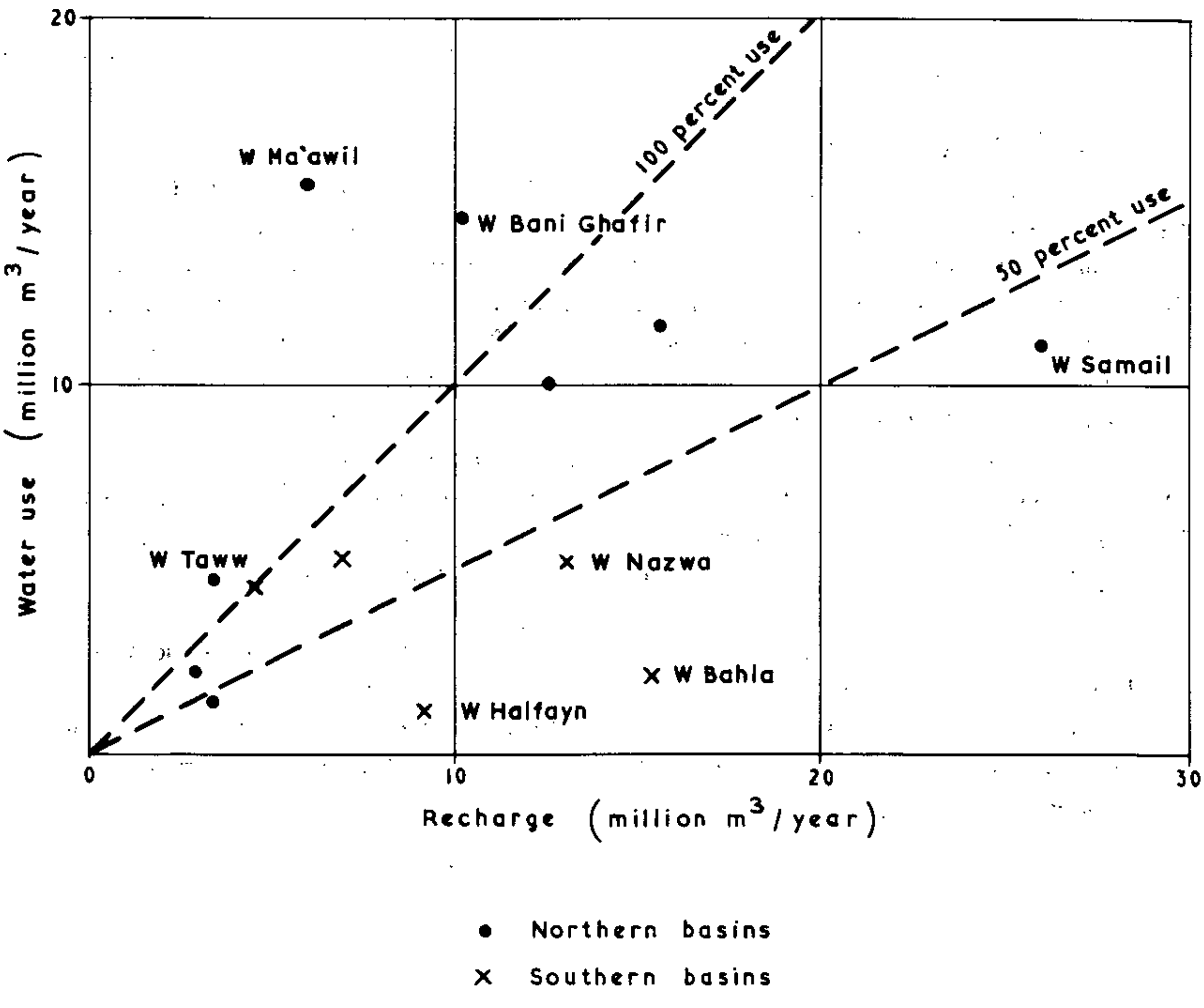
At the other extreme the data for Wadi Ma'awil suggests a significantly greater water use than recharge. This basin has a much larger piedmont area than the other northern basins and a more extensive wadi system in the plain. Thus it is possible that recharge to the piedmont area was under-estimated, as is also suggested by Figure 7.3, and that the baseflow transfer and therefore the recharge to the alluvial plains is under-estimated correspondingly.

In summary, we have shown that the estimates of water use generally support the estimates of median annual recharge, as shown (with modifications) on Table 7.8, and subject to the detailed provisos discussed above. As expected, there is no simple model of rainfall, runoff, recharge and water use which can be applied equally to all the basins.

We have neglected the effect of spring flows in this analysis because springs are not uniformly distributed through the study area. Their effect is appreciable only in the Wadi Ma'awil and Wadi Far basins where additional resources of about 2 and 4 million m^3/year are likely. The inclusion of these figures would have the effect of reducing the apparent deficit in the alluvial plains of Wadi Ma'awil and increasing the apparent surplus in the Wadi Far basin.

7.4 GROUNDWATER AT THE COAST

In the coastal zone we are concerned with the balance between groundwater resource and use, and with the balance between freshwater and saline water. In Chapter 4 we described the field evidence for the existence of a saline body of water in the aquifer beneath the coastal gardens. We also showed that in many areas we could not detect fresh groundwater moving seawards from beneath the garden areas towards the coast; salinities expressed in terms of conductivity were up to 10 000 μmhos which is above the normal limit for agricultural purposes. Thus we must conclude that water use is at best in balance with the available resources in these areas.



Water Use and Estimated Recharge in the Alluvial Plains

Figure 7·4

The survey at the coast also indicated an area to the east of Sib in the Wadi Sama'il where the groundwater conductivities were lower and freshwater losses to the sea could be expected. However, it is not reasonable to assume that these conditions are static. Our survey was of short duration by comparison with the slow rates at which adjustments occur between saline and fresh water in coastal aquifers. Neither are there any historic records of water quality which might be used to determine trends along the coast. At this time we have to rely mainly upon comparisons between estimates of groundwater flow and water use and hence determine the water balance and thus infer the state of equilibrium.

Trends at the Coast

Large changes are taking place in the coastal zone. Pumps are being fitted to hand-dug wells; the survey of Wadi Sama'il and Wadi Bani Kharus recorded 440 and 550 pumped wells respectively and we estimate as many as 2 500 pumped wells in all. These will have been introduced during the past decade and abstractions of groundwater must have increased significantly during this period. The use of boreholes to provide additional supplies for irrigation is even more recent. These are being established immediately inland from the areas of traditional agriculture and are intercepting groundwater before it reaches the garden areas. One development at Rumays in the Wadi Taww basin is particularly ambitious in view of the apparent resources; over 70 boreholes are now established along a 16 km wide zone. There are also new abstractions associated with the need to supply water to the developing areas around Muscat and demands on groundwater are increasing at a rapid pace.

It is obvious that abstraction of groundwater, and hence water use, is increasing steadily. Our estimates of water use from detailed analysis of cropping patterns and crop types cannot adequately take this into account although the consequences are apparent both from reports of increasing salinities at hand-dug wells and from direct observations in boreholes at Rumays (Appendix D.6).

Comparison of Groundwater Flow and Estimated Recharge

In Chapter 3 we derived independent estimates of groundwater flow to the coast using a digital model of the Batinah and a flow net analysis. These are compared with the estimated median annual recharge to the Batinah, derived from the model of rainfall, runoff and recharge, in Table 7.10. Only the Wadi Lansab shows a surplus of flow over use from all three methods of estimation while water deficits are indicated by each for the Wadi Ma'awil and the Wadi Bani Ghafir. In the Wadis Taww, Bani Kharus and Far differences range from deficits to small surpluses of up to 4 million m^3/year. A large surplus balance is indicated for the Wadi Sama'il alone by both the recharge model and flow net methods.

TABLE 7.10

A COMPARISON OF ESTIMATED GROUNDWATER FLOW TO THE COAST AND ESTIMATED RECHARGE

(million m^3/year)

Basin	Recharge[1]	Flow to the Coast		Water Use	Possible Excess[2]
		Digital Model	Flow Net		
Wadi Lansab	3.5	—	—	1.4	2.1
Wadi Rusayl	3.0	6.0	5.8	2.2	0.8 to 3.8
Wadi Sama'il	26.2	10.6	20.8	11.1[3]	-0.5 to 15.1
Wadi Taww	3.6	8.9	4.7	4.7	-1.2 to 4.2
Wadi Ma'awil	6.1	11.2	7.4	15.5	-9.4 to -4.3
Wadi Bani Kharus	12.8	3.4	2.9	10.0	-7.1 to 2.8
Wadi Far	15.8	11.6	4.0	11.7	-7.7 to 4.1
Wadi Bani Ghafir	10.4	2.8	2.5	14.6	-12.1 to -4.2

Notes: [1] These figures are derived in Table 7.7.
[2] Negative values indicate possible deficits.
[3] The water use in the alluvial plain of the Wadi Sama'il basin includes 1.4 million m^3/year abstracted from the Government wellfields for domestic and industrial water supply.

In summary, the estimates of groundwater flow to the coast, which are based entirely on the aquifer characteristics and the configuration of the water table support the balance presented in Table 7.8.

Evidence from Isotope Concentrations

The concentration of isotopes in the alluvial waters provides some confirmation for the operation of the aquifer systems and the processes of recharge which we have formulated. We have used tritium to provide a measure of the relative ages of groundwater, relating its occurrence in detectable quantities to recharge since thermonuclear explosions began in 1952. Concentrations of naturally occurring stable isotopes of deuterium and oxygen-18 have also been used to examine the history and provenance of groundwaters within the basins. The detailed results of these studies are presented in Appendix E.1; only our main conclusions are summarized here.

Alluvial groundwater in the piedmont and mountain front zones of the northern and southern basins is recent. Tritium concentrations of 20-40 TU show this clearly. However, 12 out of 15 groundwater samples from the mid-Batinah and coastal areas did not contain any tritium. The main implication of this is simple and most important: water originating as rainfall or runoff since 1952 has not entered the main groundwater body in appreciable quantities. Of the three samples that contained tritium only one from a well in the coastal gardens at Sib had a concentration approaching that of the piedmont alluvial waters (37 TU). Groundwater at one other site at Sib contained 7 TU, one borehole in the Wadi Ma'awil 3 TU, but elsewhere tritium concentrations were zero.

The results provide strong support for the quantitative findings of the model of rainfall, runoff and recharge. Frequent recharges in the piedmont are confirmed by the presence of modern water, and the relatively unimportant recharge of the coastal plain is confirmed by the pre-1952 age of the groundwater.

Deuterium and oxygen-18 concentrations vary considerably and indicate groundwater originating from many different storms. Insufficient information of the isotopic composition of rainfall precludes definite assessments of the relative importance of summer and winter rainfall, but superficially the composition of groundwater resembles that of winter rainfall on the mountains. Increases in isotopic content across the piedmont areas indicate concentration by evaporation. Some distinctly lower concentrations in the alluvial plains of both northern and southern basins point to a groundwater origin from flood flow recharge at some unknown time before 1952. Large variations within basins and from basin to basin show that quite different processes and different storms combine to give the present isotopic composition and that the groundwater is poorly mixed throughout most of the plains. In terms of recharge the results point to isolated events scattered in time and space.

In summary, the isotope studies confirm that recent recharge, presumably at frequent intervals, occurs in the piedmont areas. On the other hand, the aquifer systems of the alluvial plains are such that, although recharge occurs perhaps as often as in the piedmont areas, it takes some years before this water reaches the main groundwater body. Thus the variability of recharge in the short-term should have little effect on the movement of groundwater through the main aquifer units.

7.5 SUMMARY AND DISCUSSION

Our prediction of long term average recharge and hence of the potential long term yield of the alluvial aquifers has been based on the median annual rainfall. We have shown that the variability of rainfall from year to year is high and that there is a tendency for seasons of very low rainfall to recur at a greater frequency than would be expected from the logarithmic normal distribution which is otherwise well fitted by the data. The records of rainfall, runoff and recharge obtained during the single wet year of the study period 1974-75, are insufficient to allow us to translate this variability in rainfall to a corresponding variability in runoff and recharge. The differences in response of the major basins are too little understood and the effect of a sequence of average or above average years of rainfall could not be observed.

We have, however, drawn some useful conclusions from the variability in water supplies to the towns and villages. The falaj hydrographs (Figure 6.10) show that, in the wadi channel and piedmont areas flows can decline rapidly in a period without recharge. The storage supporting these flows is relatively small (Table 6.8) so that regular recharge is necessary to maintain flows at a high level; an inference which is supported by the high tritium levels in these waters. As a general rule falaj flows are halved in a period of 85-170 days without recharge. Such was the severity of the drought period prior to February 1975 that falaj flows in many villages in the southern basins declined to below 10 percent of their estimated maximum yield.

Where there are large areas of wadi and piedmont alluvium, as above Sama'il village, and in the alluvial plains of the southern basins, falaj flows decline more slowly; flows are halved in periods of 350-500 days without recharge. At the coast in the northern basins, where water is obtained from wells, supplies are more even because of the much larger groundwater storage and the gradually varying flow of groundwater to the coast. Much lower tritium levels in these waters indicate that current abstractions are of water recharged many years ago.

Thus we conclude that it is the inland villages which are most vulnerable to the occasional drought periods; while the flow of groundwater to the coast might be reduced slightly in the short-term, water availability is not seriously affected by high variability of rainfall, runoff and recharge. The only major exceptions to this general pattern are those few inland villages which can draw a substantial proportion of their water from springs. These supplies, although responsive in part to rainfall, appear to have a much slower rate of decline than most falaj flows relying on alluvial storage.

Losses of Surface Flow and Groundwater from the Study Area

In the model for rainfall, runoff and recharge, any excess of runoff over recharge is accounted as a surface water loss to the sea in the north or across the southern boundary of the study area. The difficulty of gauging flows in the broad shallow wadi channels at these boundaries means that we cannot support these estimates from measurements. There is, however, adequate evidence from local knowledge and from field reconnaissance during 1975 that large volumes of water are lost across these boundaries during floods.

We have attempted to estimate these losses in Table 7.11 which is based essentially on the estimates shown in Tables 7.7 and 7.8 with the detailed adjustments discussed in the text. On the grounds that water use is substantially less than the recharge plus baseflow transfer in three of the southern basins (Table 7.8), we have reduced the direct recharge to the alluvial plains in these basins by a factor of 2. For the Wadi Sama'il, we also show a loss of 15 million m^3/year as groundwater flow to the sea. While we cannot estimate this loss with any precision, we have included the figure for emphasis because the Wadi Sama'il basin is the only major basin with a known appreciable groundwater loss to sea.

The estimates of losses by surface flow are based on median rather than mean rainfall and thus they are probably underestimates. We have shown that the marginal value of high flood flows, which would result from the occasional exceptional rainstorms, is small because it is the duration of runoff rather than its magnitude which governs recharge. Thus the mean losses might be greater than median by more than the simple ratio (about 1.4) of mean to median rainfall. However, because these exceptional flows are of low reliability we have not attempted to adjust the estimates of median losses by surface flow.

TABLE 7.11

ESTIMATED LOSSES OF SURFACE FLOW AND GROUNDWATER FROM THE STUDY AREA

(million m^3/year)

Basin	Primary[1] Runoff	Recharge[2] Wadi Channels and Piedmont	Recharge[2] Alluvial Plains	Surface Runoff Losses	Groundwater[3] Losses
Northern Basins:					
Wadi Lansab	7.1	3.5	1.2	2.4	
Wadi Rusayl	5.0	2.5	0.8	1.7	
Wadi Sama'il	61.8	30.9	10.3	20.6	15
Wadi Taww	6.9	3.4	1.2	2.3	
Wadi Ma'awil	21.1	10.6	3.5	7.0[4]	
Wadi Bani Kharus	47.5	11.9	7.9	27.7	
Wadi Far	41.7	20.9	6.9	13.9	
Wadi Bani Ghafir	36.4	9.1	6.1	21.2	
Southern Basins:					
Wadi Halfayn	21.9	11.0	1.8	9.1	
Wadi Mu'aydin	21.4	5.4	1.8	14.2	
Wadi Nazwa	31.9	16.0	2.7	13.2	
Wadi Bahla	41.4	20.7	3.4	17.3	
Wadi Sayfam	18.0	4.5	1.5	12.0	

Notes: 1 Estimates of primary runoff are taken from Table 7.7.
2 The values for recharge refer only to direct recharge from runoff and have been adjusted to allow for differences in response between basins as discussed in the text.
3 The groundwater loss quoted for Wadi Sama'il cannot be estimated precisely.
4 The estimate of surface runoff loss for Wadi Ma'awil could be overestimated due to uncertainty in the estimate of recharge to the alluvial plains.

From the nature of the rainfall, these surface flow losses will ocur during only a few days each year and in general it will be the higher floods which contribute substantially to the losses. We have shown in Table 7.8 that direct recharge in the alluvial plains is invariably less than recharge in the wadi channels and piedmont areas largely due to the poor infiltration characteristics of the plains. Nevertheless there is still scope for augmenting recharge in the piedmont; we showed in Chapter 6 that, when storages are heavily depleted in these areas, recharge from runoff did not always make up the deficit in a single storm.

Groundwater from Bedrock Sources

It is evident from the survey of water use that springs issuing from bedrock are extensively utilized by the villages which have grown up around them. However, it is appropriate to consider the potential for further development of new supplies from these sources. The minor springs in the Oman Exotic limestones between Wadi Sayfam and Ibri are the only evidence of groundwater in the Hawasina rocks and we can discount them as a potential source. Ophiolite springs are more frequent and there is clearly groundwater associated with faulting and joint systems in the peridotites of the lower layers of the Sama'il Nappe. We have found no evidence to suggest that large groundwater storages are present although small supplies might be available by drilling through overlying gabbro into peridotite.

The principal hardrock aquifer is the Hajar Super-Group. The evidence from the survey of water use, which located 30 spring sites in the piedmont around the northern and eastern slopes of the Jabal Akhdar-Jabal Nakhl anticline, shows that these limestones are the most important source of water after the alluvial sediments. The springs in the northern basins have a total discharge of 440 l/s, about 14 million m^3/year; at about half the sites the discharge is less than 10 l/s while the largest at Rustaq has an average flow of about 100 l/s. It is clear from the spring hydrographs that open and interconnected fracture systems exist in the otherwise dense and thickly bedded limestones of low porosity. Quite large storages can be shown to exist in these fracture systems. For example at Bawshar in the Wadi Lansab where the absence of tritium shows the water to be over 25 years old a minimum storage of 31 million m^3 must exist to provide the annual discharge. Elsewhere, storages are more difficult to assess since the presence of tritium probably indicates mixed waters of old and of recent origin. Allowing for a ten year residence time, which is not unreasonable in view of the isotopic evidence, storages of 20 and 30 million m^3 must be available to the Nakhl and Rustaq springs.

Although these storages are large, there is little potential for their development without adversely affecting the spring discharges upon which established agriculture already relies. This is evident from a simple consideration of the structure of the spring systems. The fracture zones probably extend from the mountains into the limestone beneath the overlying cover of Hawasina. Abstraction either from above or below the springs would normally lead to a lowering of water levels in the fracture zone resulting in a reduction of water flow. Any leakages of groundwater through the limestones at depth below the Batinah might be a source of additional supply but the geological evidence suggests that the fracture systems to the north of the mountains are closed with the springs representing overspill points above static storage. The Hajar Super-Group is not known to outcrop anywhere in the Gulf of Oman and the detailed studies by Royal Dutch Shell Exploration suggest that to the north the limestones are replaced by fine grained sedimentary rocks of even lower aquifer potential.

However, the question of deep-seated leakage through the Hajar Super-Group is probably of more importance in the southern basins where there are quite extensive karstic features in the mountains but few springs. Recharge should occur to the limestones in the southern flank of the Jabal Akhdar and the geology suggests that deep seated leakages could exist. However, we have no evidence of any groundwater in the limestone exposures south of the mountains; there are no springs for example at Jabal Salakh at the southern boundary of the study area. Nevertheless we are reluctant to dismiss the possibility of groundwater moving south-westwards from the Jabal Akhdar out of the study area.

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

8.1 UNEXPLOITED WATER RESOURCES

The results of our water resources survey of northern Oman have been influenced by two major constraints. Firstly, the study period was one of below average rainfall; rainfall was substantial only during the final 12 months of the study period. Secondly, due to circumstances outside our control, the proposed exploratory drilling programme which was to be undertaken as an integral part of the survey did not proceed. Nevertheless we have been able to acquire a basic understanding of the relationship between rainfall on the jabal, runoff, and recharge to the alluvial aquifers of the northern and southern basins and to make realistic estimates of the availability of water throughout the study area.

Our estimates of the unexploited water resources are given in Table 8.1. They are derived from our estimates of median annual recharge, village water use and surface runoff losses presented in Tables 7.8 and 7.11. The estimates take no account of year to year variability; they represent the long term average. The variability of rainfall is such that severe drought periods are not uncommon, thus the unused resources shown in Table 8.1 are not continuously available and, although some of the additional resources may be developed with advantage in wet years, they will not be available in drought periods unless additional storage can be provided.

Groundwater

In the northern basins the major unexploited groundwater resource could be as much as 15 million m^3/year in the Wadi Sama'il basin. This leakage is reasonably well substantiated by the low groundwater conductivities to the shoreline in parts of the Sib fan. We are not able to confirm the apparent surplus of 4 million m^3/year in the Wadi Far basin because a detailed survey of coastal village water use was not undertaken in this basin. In view of the deficits in the basins of Wadi Ma'awil and Wadi Bani Ghafir and the scarce hydrogeological data in the western region of the survey area, we are not inclined to place too much reliance on the apparent exploitable resources in the Wadi Far and Wadi Bani Kharus basins. The 2 million m^3/year in the Wadi Lansab basin is a resource spread over a broad area involving many minor aquifers. Although probably exploitable locally, no large scale development can be envisaged.

In general terms, therefore, we consider that water use in the northern basins is, at best, in balance with available resources except for one area, namely the coastal zone of the

TABLE 8.1

SUMMARY OF ESTIMATED UNEXPLOITED WATER RESOURCES

(million m³/year)

Basin	Groundwater			Surface Runoff Losses
	Overall Groundwater Availability in Basin	Available for Exploitation Either in Wadi Channel and Piedmont Areas or in Alluvial Plains	Available for Exploitation in Alluvial Plains Only	
NORTHERN BASINS:				
WADI LANSAB	2.1	2.1	—	2.4
WADI RUSAYL	0.8	0.8	—	1.7
WADI SAMA'IL	15.1	15.1	—	20.6
WADI TAWW	(-1.1)[1]	—	—	2.3
WADI MA'AWIL	(-9.4)	—	—	7.0
WADI BANI KHARUS	2.8	2.8	—	27.7
WADI FAR	4.1	4.1	—	13.9
WADI BANI GHAFIR	(-4.2)	—	—	21.2
SOUTHERN BASINS:				
WADI HALFAYN	6.1	5.5	0.6	9.1
WADI MU'AYDIN	(-0.1)	—	—	14.2
WADI NAZWA	5.3	5.3	—	13.2
WADI BAHLA	9.8	8.5	1.3	17.3
WADI SAYFAM	(-1.4)	—	—	12.0

Note: [1] Negative figures in parentheses indicate overall basin deficits between estimated available water resources and current village water use.

Sib fan on the Wadi Sama'il, where as much as 15 million m³ of fresh groundwater is moving out to sea annually. Elsewhere along the Batinah coast zone it is clear that groundwater abstractions are increasing steadily with the consequence that rapidly rising salinities are being reported from hand-dug wells and boreholes alike. This is particularly important in the Rumays area where 70 boreholes have been established comparatively recently along the 16 km wide zone inland from small areas of poor date gardens. These new abstractions intercept small natural groundwater flows to the coastal area and the problems of rising salinities are greater here than anywhere else along the coast.

In the southern basins the balance between estimated recharge and water use offers more attractive prospects. Surplus groundwater totalling 6 million m³/year would appear to exist in the Wadi Halfayn basin, 5 million m³/year in the Wadi Nazwa basin and 10 million m³/year in the Wadi Bahla basin. In each case the main resource is available for development in the piedmont areas. Unexploited resources in the alluvial plains are likely to be widely scattered and difficult to recover.

Surface Water

We estimate that surface runoff losses from the study area could average some 95 million m³/year to the sea north of the jabal and 65 million m³/year to the desert south of the jabal. It is these flows which offer the greatest potential for conservation and development identified during the study period. However, surface runoff is of a rapid and violent nature; the duration of peak flood flows rarely exceeds a few hours and in many cases, surface runoff ceases altogether after two or three days. Thus, the control of more than a small proportion of these flows poses major engineering problems.

Bedrock Sources

We have found no direct evidence of a potential for the shallow development of further groundwater from bedrock sources in the study area without adversely affecting existing spring discharges upon which established agriculture already relies. There is no evidence of the existence of freshwater springs in the sea off the Batinah coast. However, the general geology of the southern flank of the jabal suggests that deep-seated bedrock groundwater leakages moving south-westwards from the Jabal Akhdar out of the study area could exist.

8.2 DEMANDS FOR WATER IN THE SURVEY AREA

Non-Agricultural Demand

The only major non-agricultural demand for water from the survey area is that required to meet the domestic and industrial demands of the Capital area. The demand for this area was estimated by Sir Alexander Gibb and Partners in November 1974[1] when the population of the Capital area, estimated to be 60 000, was projected to reach 120 000 by 1980. The 1974 demand for water at source was estimated at 4 million m^3/year of which 1 million m^3/year was obtained from the gravels of Wadi Sama'il and Wadi Rusayl. By 1980 the annual demand at source was expected to be more than 13 million m^3/year. It was hoped to meet part of this by increasing the rate of abstraction of groundwater by 2 million m^3/year, but the remaining demand would have to be met by desalination.

Apart from the Capital area, no towns or villages in the area covered by this water resources survey are provided with a piped water supply nor does it seem probable that any of them will be subject to the same dramatic increase in population currently taking place in the Capital area. An estimate of the distribution of population outside Muscat and Mutrah is given in the April 1975 Soils and Agricultural Studies Report[2]. Taking account of the lack of a piped distribution system it is evident that nowhere in the survey area is the domestic demand likely to be of significance when compared with the agricultural demand. A rough estimate of domestic demand of the Batinah coastal strip from Sib to the western limit of our survey area shows that it is unlikely to exceed one million m^3/year at present. Whenever it is decided to install piped water supply systems to any towns along the Batinah, or inland, with an associated concentrated development of the water resources of the local area—we understand that some schemes of this nature may already be in hand—it would be necessary to investigate the effect of the anticipated additional consumption on the water balance of the area. Such investigations would need to take account of the interdependence of some groups of inland villages as described in Chapter 4.

[1] Final Report on study of "Water Supply to Muscat and Mutrah" dated November 1974, by Sir Alexander Gibb and Partners.
[2] Final Report on Phase 1 Soils and Agricultural Studies, April 1975. Volume V, Figure A2.

Agricultural Demand

We have assessed the current agricultural demand and use of available water in the survey area. The results are summarized in Table 8.2. Inland much of the supply of water is by aflaj, and therefore the extent of agriculture is not susceptible to rapid change. Recent development in agriculture has been due mainly to the introduction of motor-driven pumps, predominantly along the Batinah coastal strip and in some of the piedmont valleys. The indications are that in the northern basins available water resources from natural recharge of the alluvium are, in general terms, fully developed. Short of specific works to increase the availability of water, except possibly in the Sib fan, any new agricultural development is likely therefore to be at the expense of existing agriculture. The recommendation in our April 1975 report on the Soils and Agricultural Studies that present coastal strip agriculture be gradually relocated a few kilometres further inland falls into this category. South of the mountains, we have suggested that there may still be some unexploited groundwater resources locally. None of these is likely to be major. Total unexploited groundwater in the Wadi Bahla basin would be unlikely to support more than an additional 250 ha of irrigated agriculture, whilst unexploited groundwater in the basins of Wadi Nazwa and Wadi Halfayn could support only an additional 150 ha in each basin.

TABLE 8.2

SUMMARY OF WATER USE IN THE SURVEY AREA

(million m³/year)

Basin	Water Use	
	Water Channel and Piedmont Areas	Alluvial Plains
NORTHERN BASINS:		
WADI LANSAB	1.2	1.4
WADI RUSAYL	0.3	2.2
WADI SAMA'IL	15.0	11.1[1]
WADI TAWW	1.0	4.7
WADI MA'AWIL	8.0	15.5
WADI BANI KHARUS	7.0	10.0
WADI FAR	12.0	11.7
WADI BANI GHAFIR	4.8	14.6
SOUTHERN BASINS:		
WADI HALFAYN	5.5	1.2
WADI MU'AYDIN	2.0	5.3
WADI NAZWA	8.2	5.2
WADI BAHLA	12.2	2.1
WADI SAYFAM	2.9	4.5

Note: [1] Includes 1.4 million m³/year abstracted from the government wellfields for domestic and industrial water supply.

8.3 THE EFFICIENCY OF CURRENT WATER USE

The availability of water is fundamental to any proposal for increased agricultural production. It is useful, therefore, to consider whether existing supplies are being properly used or if additional water could be made available for productive use by reduction of waste.

Present Use of Water

In Annex C to the April 1975 Soils and Agricultural Studies Report we estimated that the average efficiency of irrigation in Oman is 45 percent. The 55 percent loss included 5 percent evaporation, 5 percent saline leachate and 45 percent freshwater seepage. Because there is virtually no groundwater loss to the sea (except for Wadi Sama'il), the seepage is not a true loss. Improved efficiency of irrigation therefore would have certain agricultural advantages and would reduce the cost of pumping but would contribute little to the overall availability of water.

Much of the cropping in Oman is perennial—date palms and alfalfa. Annual crops are grown over the winter and have much lower water requirements. It is possible that an increase in the proportion of annual crops might increase productivity per unit volume of water. However, where aflaj are the source of water there would be little advantage because the flow cannot be controlled. Furthermore the palm tree is singularly well adapted to conditions in Oman and the life and social structure of the agricultural community would be seriously impoverished without the palm groves.

In general, any increase in the availability of water by changing the present irrigation or agricultural practices is likely to be relatively small and would take many years to effect. Higher productivity from existing supplies remains the main objective of agricultural development and the foregoing remarks in no way detract from the importance of the drive for improved cropping, methods of cultivation and irrigation.

Aflaj

The traditional falaj is a most efficient means of drawing water from the alluvium of the wadi channels and piedmont areas. Aflaj have the disadvantage that flows are uncontrolled and therefore lead to inefficient use but they are an inexpensive means of exploiting groundwater, inexpensive to operate and they are particularly well integrated with the irrigation reticulation systems. Because the groundwater storage exploited by the aflaj are shallow, modern boreholes do not provide an alternative method of abstraction. The greatest attention should therefore be given to the repair and maintenance of the existing aflaj and to the preservation of the skills of the artisans specialized in this work, albeit utilizing modern techniques where appropriate. Government should continue their assistance in this field by encouragement and grants towards the re-establishment of aflaj which have already lapsed into disrepair.

8.4 INCREASING WATER AVAILABILITY

Exploiting Surplus Groundwater

There are three possible strategies for exploiting the apparently available groundwater resources in the basins of the Wadis Sama'il, Halfayn, Nazwa and Bahla:—

(i) In the piedmont areas,
(ii) at the exit from the piedmont areas onto the alluvial plains,
(iii) in the alluvial plains.

There are problems with each strategy. In the piedmont, new groundwater abstractions will be bound to affect water use in downstream villages detrimentally, by causing more rapid aflaj recessions and therefore more frequent low flow conditions. We do not recommend this approach unless compensating water can be made available from another source.

At the exit from piedmont areas the most attractive development possibilities are at Al Khawd and Bahla where rock bars provide nominal surface sources. The possibility of sub-surface leakage at the rock bars is a disadvantage to effective abstraction since the resource can only be partly utilized. Conjunctive development with downstream alluvial storage, where it exists, could allow the development of a continuous additional supply.

Recovery of groundwater in the alluvial plains is difficult; it is widely dispersed and not readily exploitable in significant quantities. Fortuitously, the Sib fan, which has perhaps the largest unexploited groundwater resource, up to 15 million m^3/year, is the basin with the largest development of good aquifer. Borehole abstractions in this area are therefore possible; elsewhere, surplus groundwater should be intercepted before it reaches the alluvial plains. There is a clear economic case for reserving surplus groundwater in the Sib fan for urban supplies to Muscat and Matrah. Any alternative strategy would imply the use of expensive desalinated water for agriculture. In future there could be a case for reducing agriculture at the coast in order to provide further supplies of groundwater to the Capital area but this has social implications which are beyond the scope of this study.

The existing loss of groundwater to sea in the Sib area has allowed agriculture to become established up to the shore. However, any new groundwater development, particularly exportation out of the Wadi Sama'il basin, will have some detrimental effect on water quality in these seaward areas. Saline encroachment will accompany new abstractions until the patterns of groundwater quality and agriculture are similar to those presently seen in other basins on the Batinah. These effects can be minimized by siting boreholes away from the coast between the existing wellfields and the coastal gardens. This is the only major exception to our general recommendation that exploitable groundwater should be developed at the exits to the piedmont areas.

Surface Storage

Long term surface storage in the mountains is unpromising. Costs would be high, the wadis are steep and narrow, flows are erratic and unpredictable, and evaporation losses over a period of time would be high. The short term use of surface storage is a different matter. We have emphasized in Chapter 6 that recharge of the aquifers of the alluvial plains is dependent on the duration of runoff. Any storage, therefore, which can attenuate the storm runoff from the wadis, even if only for a matter of hours, should do much to increase recharge locally by reducing the estimated median surface runoff losses in the north of 95 million m³/year and in the south of 65 million m³/year. In such cases evaporation losses would be unimportant although the problem of sedimentation would remain. A series of low elemental storage structures strategically sited throughout the piedmont areas of a wadi basin would be necessary to cause sufficient attenuation of flood flows. We must emphasize that we do not consider that these low barrages would conserve large quantities of surface runoff. Their advantage would be felt locally by villages but over a large area.

Subsurface Storage

We demonstrated in Chapter 6 that storm flows can be of such short duration that the storages of the wadi gravels and piedmont alluvium are not always filled. It is from these gravels that the aflaj draw their supplies. We have also shown that in 1974 the areas of perennial crops were generally related to minimum observed flows in the aflaj supplying them. It would be possible to reduce the likelihood of such aflaj flows in the piedmont areas during times of drought by ensuring that recharge of these gravels can be made more effective. This has already been attempted many centuries ago by means of a low barrage on Wadi Nazwa. The barrage prevents leakage flow downstream through the gravel and therefore serves to maintain the water level in the wadi gravels. Also, the gravels which have now built up to crest level at the Nazwa barrage provide an effective additional subsurface storage area which, after recharge, is slowly depleted either through the adjacent aflaj or by downstream base flows in the Wadi Nazwa. The effectiveness of this type of barrage could be readily assessed by constructing a pilot scheme barrage across the intake area of an existing gauged falaj and measuring the difference in flow resulting from it. Such aflaj exist, for example, near Al Hamra, Al Ghafat, Rustaq and Awabi.

Recharge on the Alluvial Plains

Our data suggests that the groundwater in the mid-Batinah is old and that movement through the aquifer is very slow. Recharge should therefore occur close to the coastal gardens. The maintenance of recharge basins or channel systems in the wadi beds would be prohibitively expensive, but relatively low-cost spreading devices such as low gabion barrages should be tried. In general the wadi beds are wide but flood flows presently follow a few braided channels in the bed; if the water can be spread out from these channels by a series of inexpensive line obstacles, the potential for recharge would be enhanced. If these works can be co-ordinated with flood attenuation measures further upstream, their effectiveness would be increased.

Precipitation

Methods of directly increasing precipitation by "cloud seeding" from aircraft have been attempted in various parts of the world. The effectiveness of these methods is highly controversial; clearly it is almost impossible to set up a "control" situation against which to compare the operations. We would not recommend that serious consideration be given to what must be an extremely costly process of very doubtful efficacy in the particular climatological conditions of Northern Oman.

Desalination

Desalination has been proposed to help meet domestic demand in the Capital area. Fresh water produced by this process is far too expensive to consider for agriculture.

8.5 DEVELOPMENT OPPORTUNITIES

Our April 1975 Soils and Agricultural Studies report established that, from soils considerations, the major potential for agricultural development in the survey area is confined to the Batinah. Elsewhere, except for Quryat in the Wadi Sayfam, soils suitable for irrigated agriculture are of limited extent and widely scattered.

The major agricultural development potential in the Batinah cannot be realized unless adequate water resources are available. We have shown that in general terms groundwater is fully utilized in the northern basins. Agricultural development in the Batinah will be dependent to a large extent, therefore, on the effectiveness of measures which can be designed to conserve the estimated 95 million m^3/year surface runoff losses to sea.

A particular situation exists on the Wadi Sama'il near Al Khawd. Here the present course of the wadi as it emerges onto the alluvial plain is separated at the rock bar from a deeply incised older course of the wadi. Consideration should be given to the construction of a low barrage at Al Khawd to divert surface flood flows into the old wadi channel for temporary storage and slow release into the alluvial aquifer west of Sib. The attractions of additional recharge in this area are twofold; firstly less reliance would need to be placed on desalination as a source of water supply for the Capital area but also the possibility arises to alleviate deteriorating groundwater quality at Rumays.

In the southern basins, from soils considerations, the only major potential for agricultural development appears to be adjacent to the existing Quryat development in the Wadi Sayfam basin. Here there are some 10 million m^3/year surface runoff losses which might still be available after rectifying the apparent groundwater deficit of 1.4 million m^3/year. Some of these losses might be made available by induced recharge in the wadi bed. Elsewhere, a small irrigated agricultural development of about 150 ha could also be supported by additional abstractions of groundwater by boreholes near Jabrin in the Wadi Bahla basin.

Overall, exploitable and usable water resources therefore appear to reduce to:—

Northern basins:

Wadi Sama'il	—groundwater from Sib fan for the Capital area. —surface water in the old channel north of Al Khawd as an additional resource for Rumays area.
Wadi Ma'awil Wadi Far	—Surface water retained by barrages for piedmont villages
Elsewhere	—water spreading in wadi gravels of the alluvial plains.

Southern basins:

Wadi Halfayn	—piedmont groundwater for local development
Wadi Nazwa	—piedmont groundwater for local development
Wadi Bahla	—piedmont groundwater for development at Jabrin
Wadi Sayfam	—induced recharge of surface water losses for Quryat area.

8.6 FURTHER STUDIES

Observations

In the course of this survey, networks of instruments including five meteorological stations have been established throughout the 14 500 km^2 of the study area. Regular observations have been made of rainfall and other climatological data, wadi flows, falaj flows, groundwater levels, and surface and groundwater quality. We consider that it is of utmost importance that the established networks should be regularly maintained and monitored, and extended to provide better coverage. The continued collection of hydrological records to confirm and improve estimates of median resources and the variability of surface and groundwater flows is essential if the full potential of the water resources of the survey area is to be realized. In this we would particularly emphasize the essential requirement for regular monitoring of the high jabal rain gauges, runoff and recharge estimates at existing stations and basins through a period of wet years to confirm the general conclusions of this survey. Continuous monitoring of groundwater levels and of groundwater quality particularly along the Batinah coast is also important.

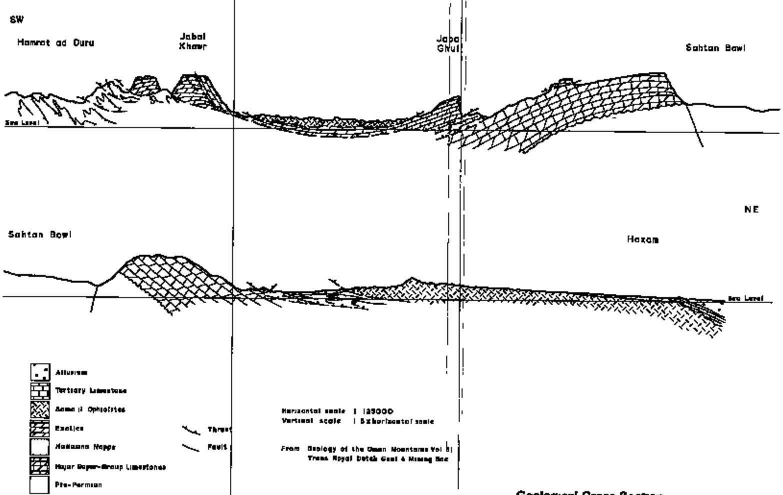
Exploratory Drilling

The programme of exploratory drilling proposed for this survey, but not implemented, was intended to give a wide coverage of subsurface conditions in keeping with the broad approach of the terms of reference for the survey. Further drilling is undoubtedly required, particularly south of the mountains and further pumping tests are needed to evaluate aquifer characteristics. However as this general survey has now ended, the most useful results from exploratory drilling would not be obtained by following the proposed programme. Other consultants are reporting on water resources surveys in areas adjacent to our area in central northern Oman and future exploratory drilling requirements should be assessed on the basis of an objective evaluation of the results of the three water resources surveys. In the area covered by this survey our general view is that further drilling programmes should be associated with the specific developments outlined in Sections 8.4 and 8.5 and specific problems. For example, we feel that the piedmont areas require exploring more fully to obtain a better understanding of the groundwater recharge processes, base flow transfers and the long term availability of groundwater in the alluvium, particularly in those basins offering scope for development.

Surveys

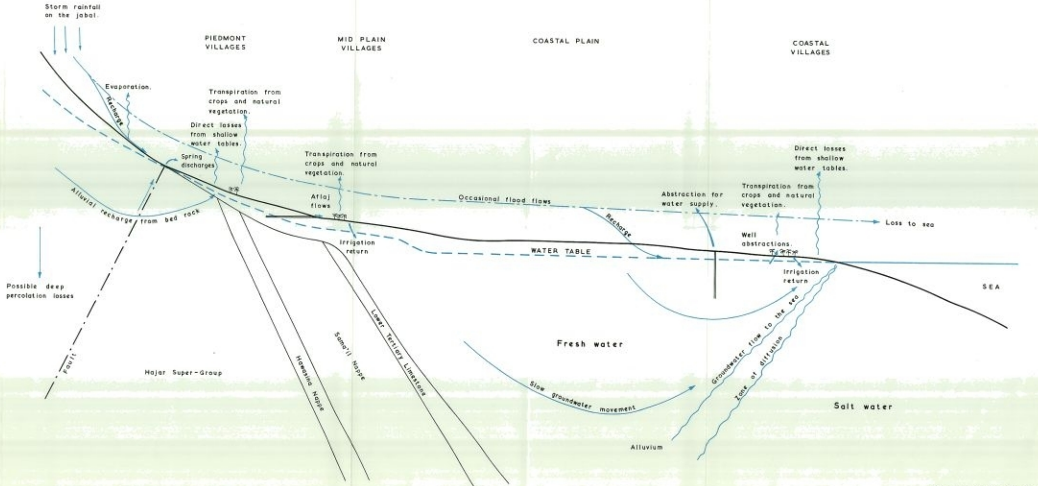
This water resources survey, although broad in scope, was undertaken in detail in the representative basins of Wadi Bani Kharus in the north and Wadi Bahla in the south, and in the Wadi Sama'il, a basin of more special significance in view of its role as a principal source of groundwater supply to the Capital area. It would be of value to extend the village water use studies along the whole Batinah coastal strip to determine if there are any additional groundwater losses to the sea. Additionally, if the accuracy of our estimates of water resources availability is to be improved, in those basins where development is possible the studies of this survey should be continued and extended. In this, we would emphasize the importance of confirming the extent to which potentially exploitable water resources, estimated in this report on the basis of median rainfall figures, are capable of being utilized by practical measures.

We would also recommend studies of ephemeral surface flows in the study area. Throughout most of our study period surface flows had dried up and we were unable to reach any conclusions concerning ephemeral flows. The studies should be incorporated into the regular falaj and spring discharge observations. We would suggest that gaugings be undertaken at Al Khawd, Labijah, Hawqayn, Bahla, Nazwa and Firq.



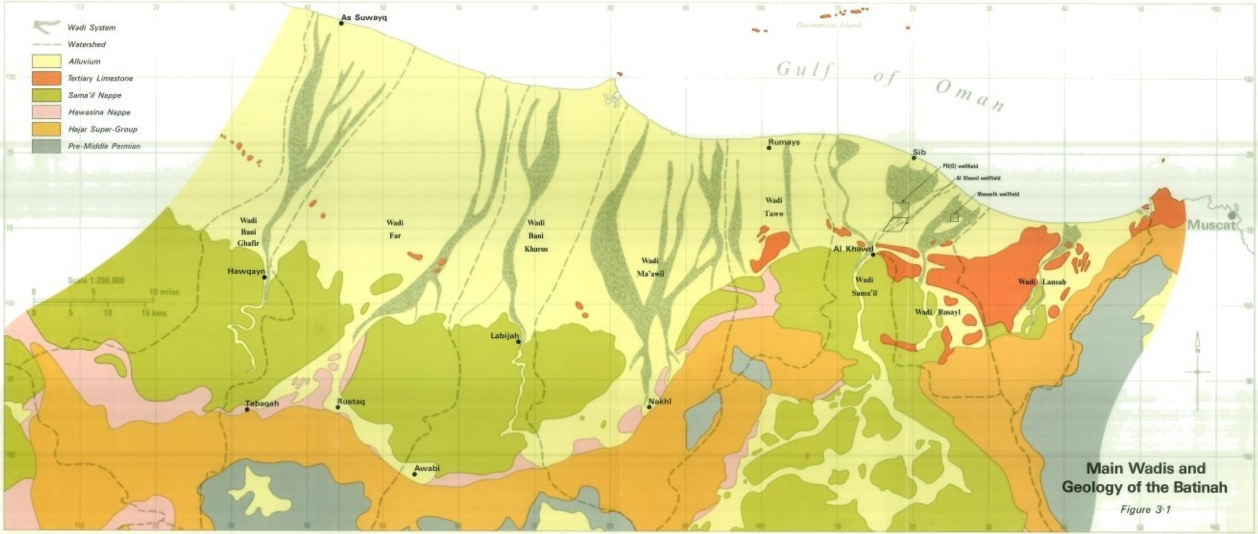
Geological Cross Section

Figure 1 3



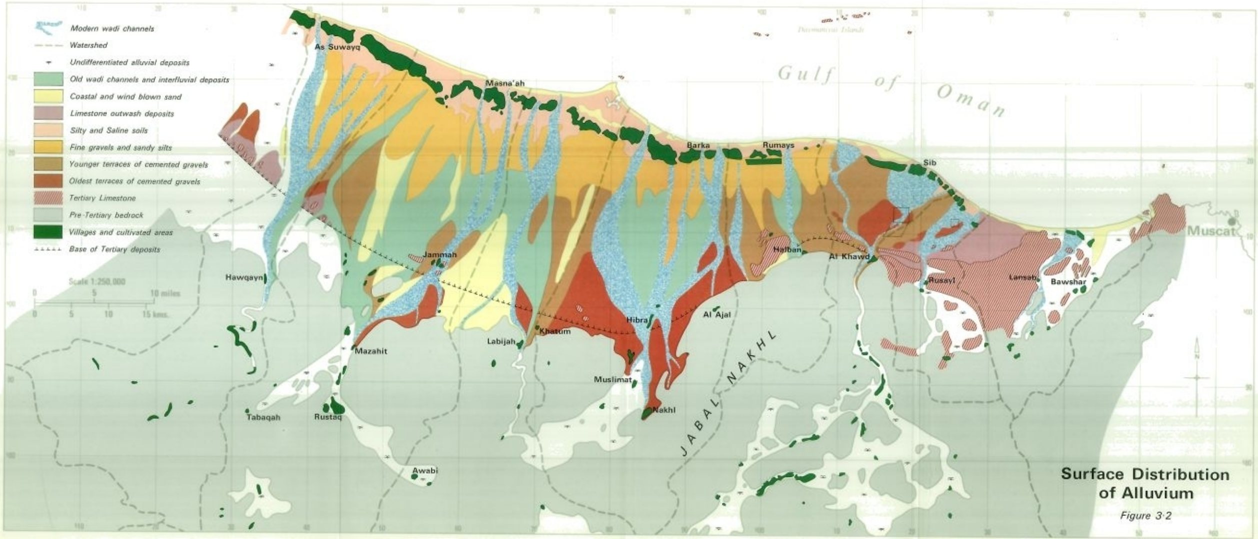
The Hydrological Cycle

Figure 2·1



Main Wadis and Geology of the Batinah

Figure 3·1

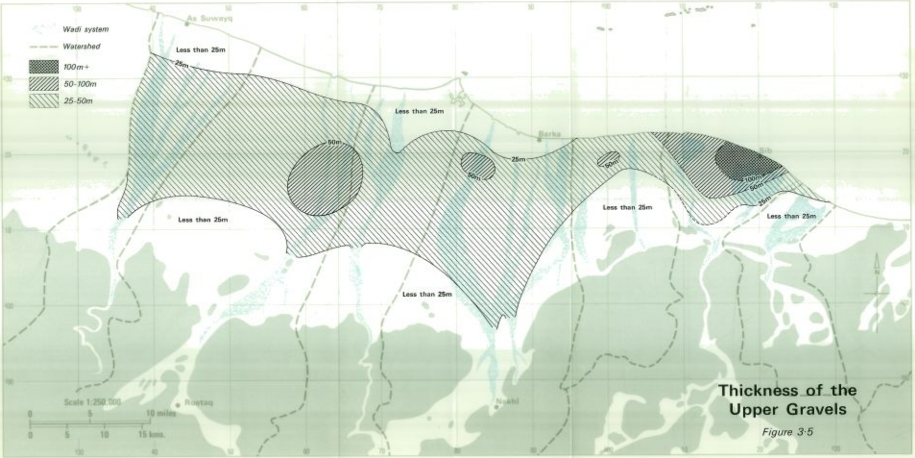


Surface Distribution of Alluvium

Figure 3·2

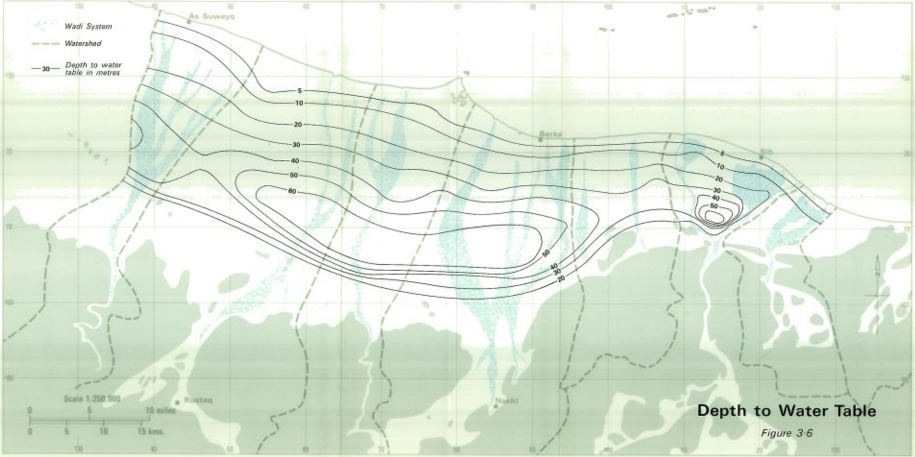
Wells and Boreholes of the Northern Basins

Figure 3·3



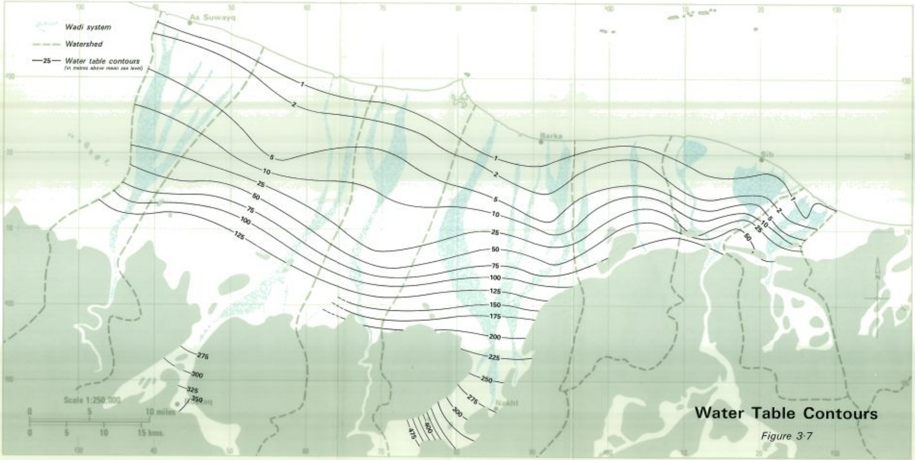
Thickness of the Upper Gravels

Figure 3·5



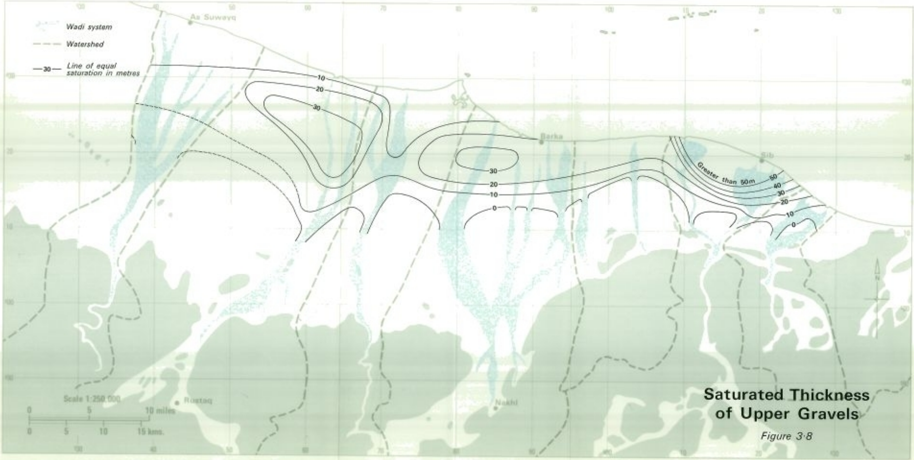
Depth to Water Table

Figure 3·6



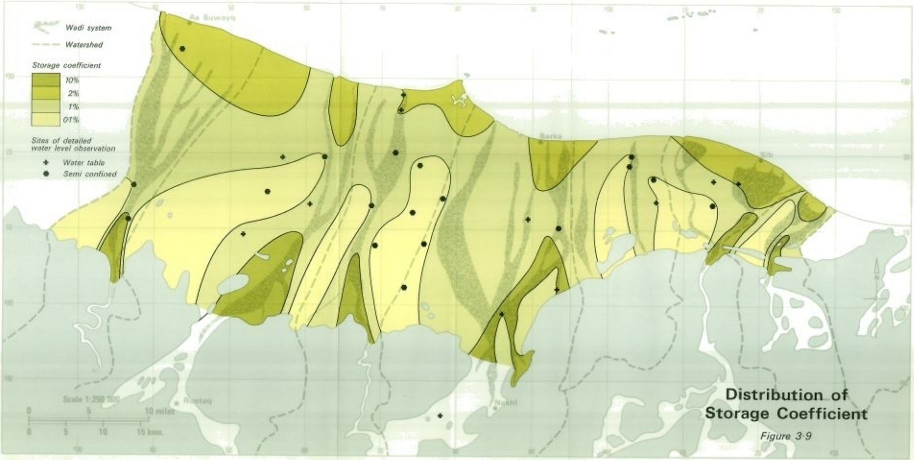
Water Table Contours

Figure 3·7



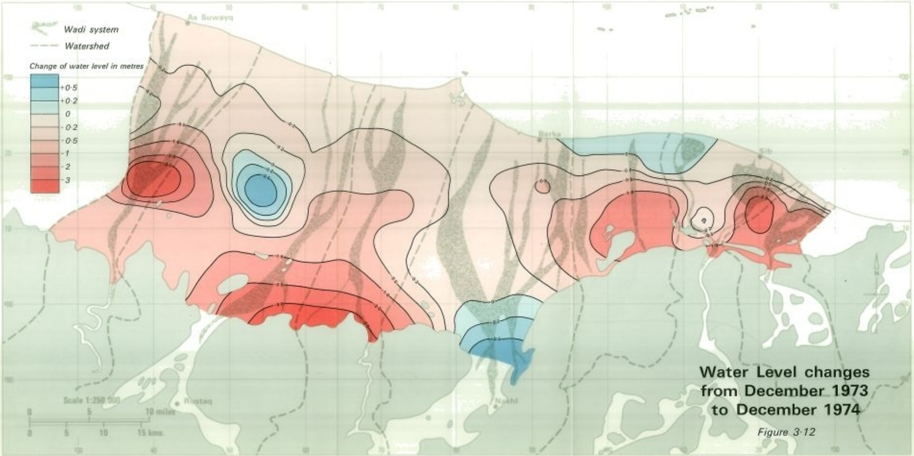
Saturated Thickness of Upper Gravels

Figure 3·8



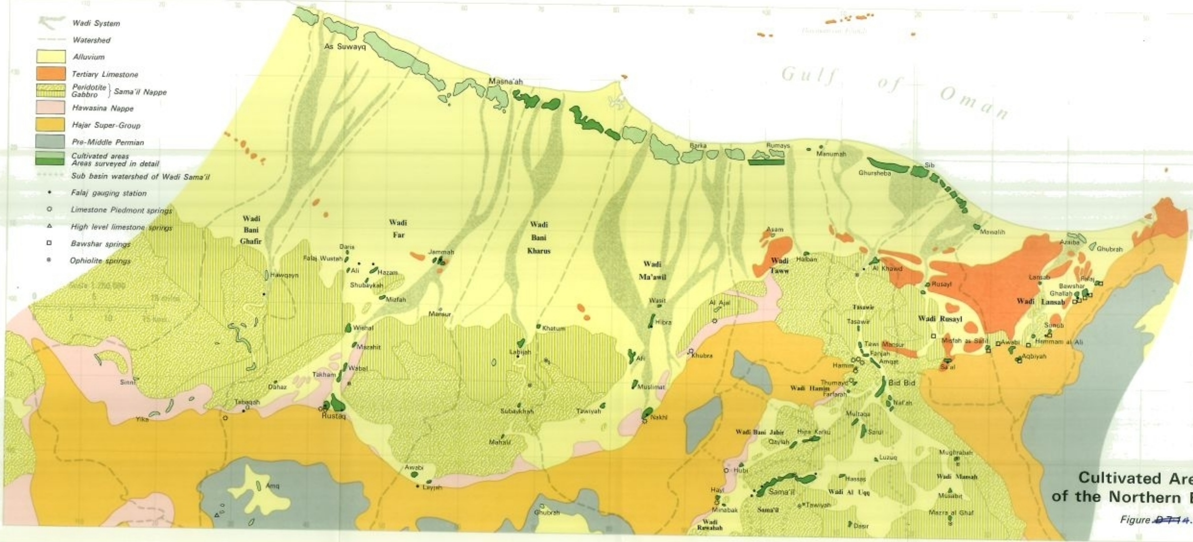
Distribution of Storage Coefficient

Figure 3·9



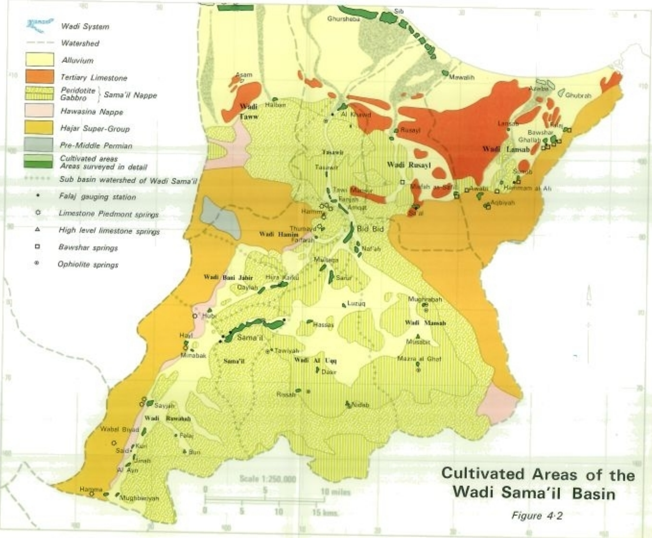
Water Level changes from December 1973 to December 1974

Figure 3·12



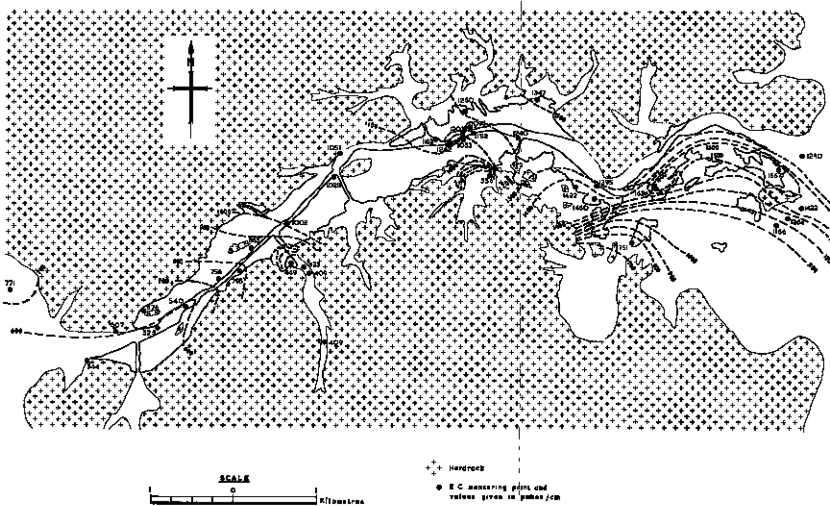
Cultivated Areas of the Northern Basins

Figure D714.1



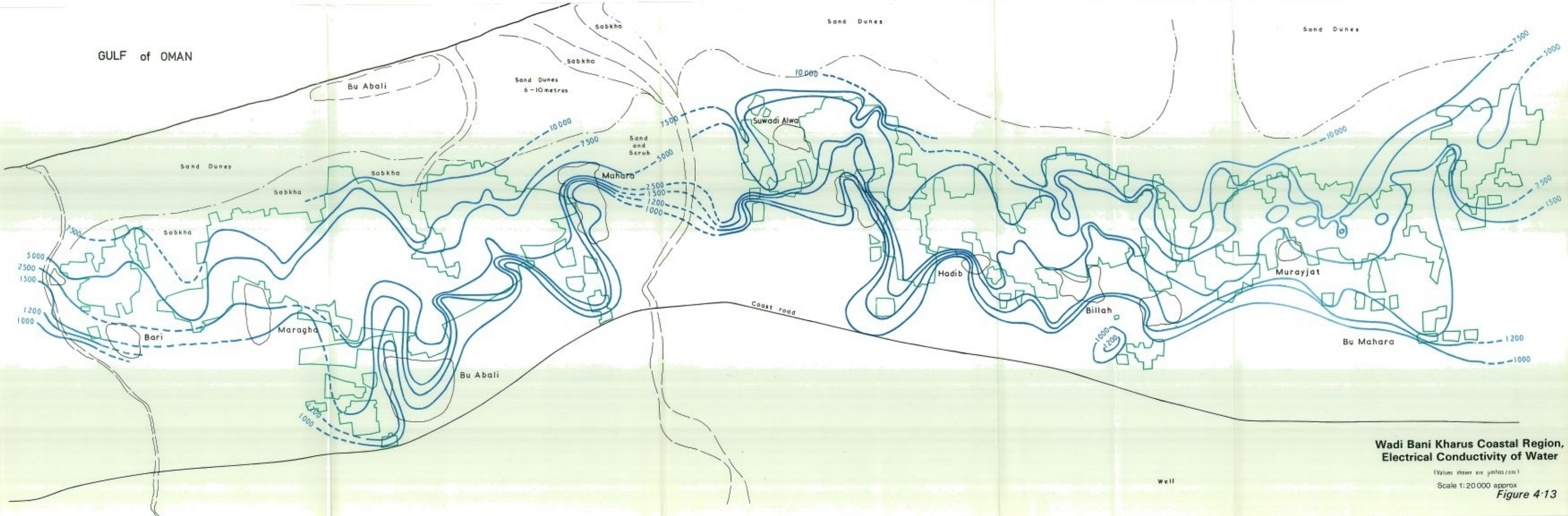
Cultivated Areas of the Wadi Sama'il Basin

Figure 4·2



Sama'il Village, Complex Electrical Conductivity

Figure 4 9

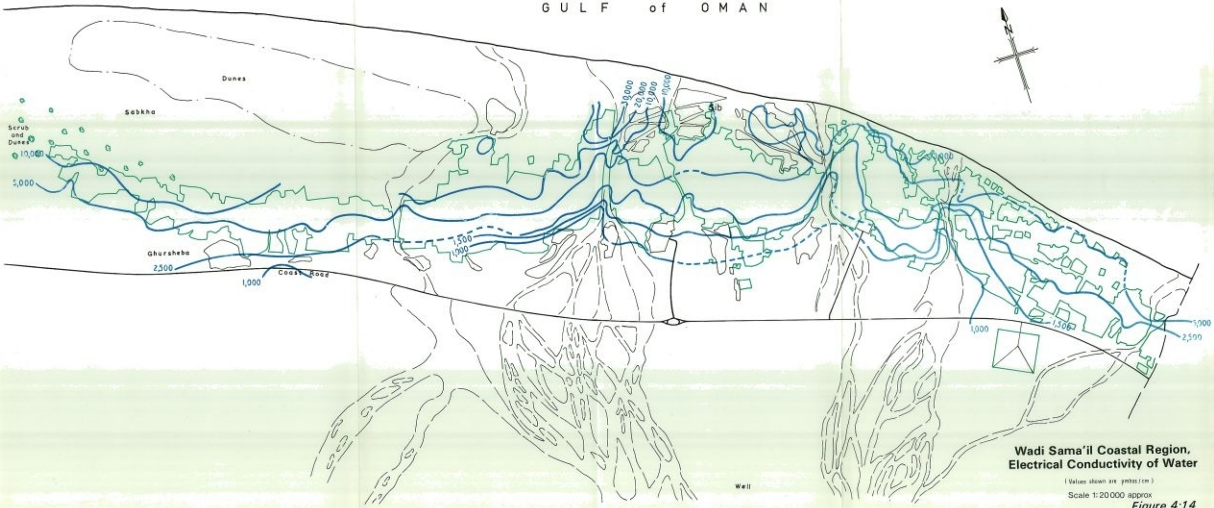


Wadi Bani Kharus Coastal Region, Electrical Conductivity of Water

(Values shown are μmhos/cm)

Scale 1:20 000 approx

Figure 4·13

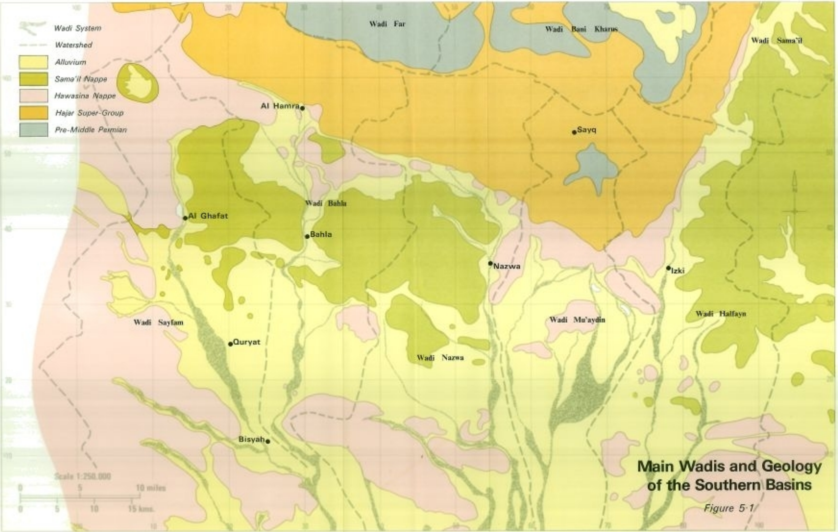


Wadi Sama'il Coastal Region, Electrical Conductivity of Water

(Values shown are μmhos/cm)

Scale 1:20 000 approx

Figure 4·14

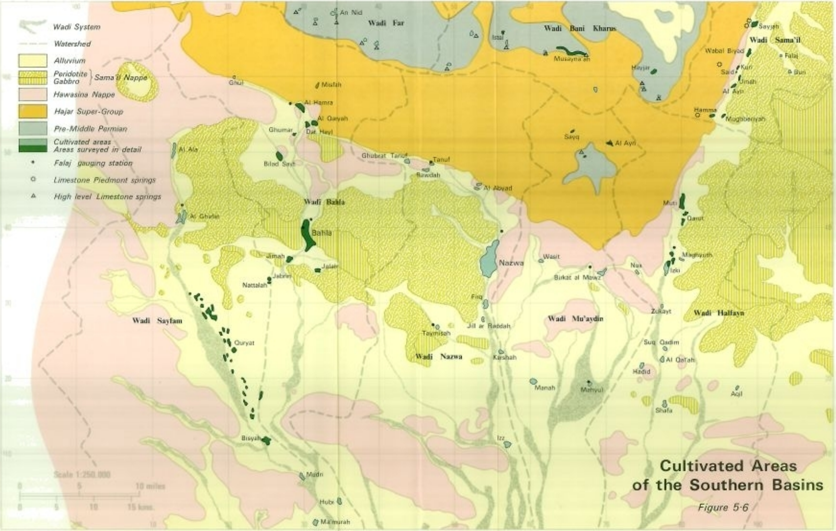


Main Wadis and Geology of the Southern Basins

Figure 5·1

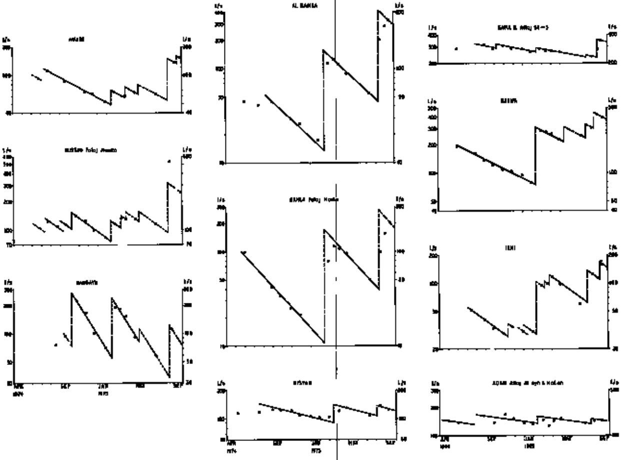
Wells, Boreholes and Water Table Contours of the Southern Basins

Figure 5·5



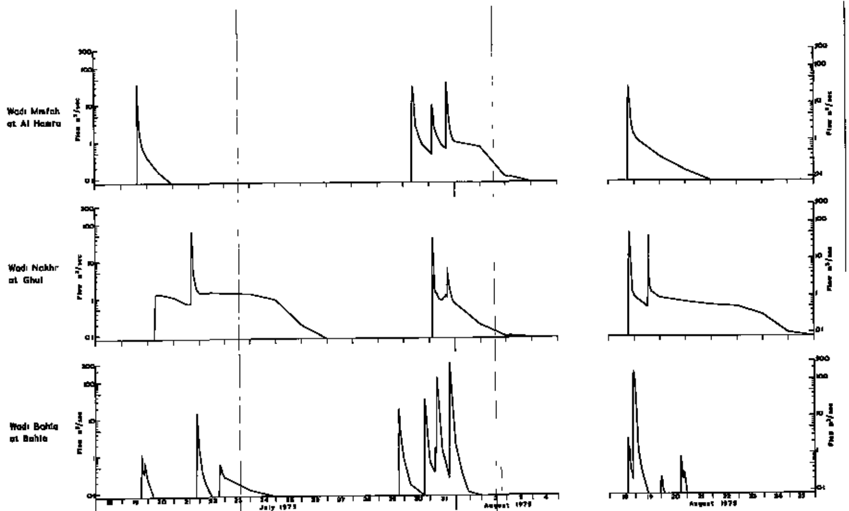
Cultivated Areas of the Southern Basins

Figure 5·6



Selected Falaj Hydrographs

Figure 6 10



Surface Flows in the Wadi Bahla Basin in July and August 1975

Figure 6 13

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The Institute of Hydrology is a component establishment of the Natural Environment Research Council