GROUNDWATER AND ITS PRESENT DAY USE IN PART OF NORTHERN OMAN

Thesis submitted for the Degree of Doctor of Philosophy, Oxford University,

1978

By

Sally Sutton (Letts)

This thesis was written at a time since which there have been major changes in Oman both socially and economically. It reflects the traditional systems for water abstraction and use, which allowed most of them to survive many hundreds of years of droughts, floods, economic and social pressures. The management systems differed across the country, but the principles remained the same.

Unfortunately it was produced as a document before word processing was much in use and so exists only as a hard copy, which has now been scanned to provide a pdf file of the two volumes.

I would be very grateful for acknowledgment if information and ideas from this thesis are used. Even more gratitude will be given if those using it were to get in touch, as it would be nice to know how things have changed, but also if such a labour from almost 30 years ago still has relevance for anyone else!

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GROUNDWATER AND ITS PRESENT DAY USE IN PART OF NORTHERN OMAN

Sally Sutton (Letts) 1978

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GROUNDWATER AND ITS PRESENT DAY USE IN PART OF NORTHERN OMAN

VOLUME ONE

WATER RESOURCES

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THE WADI SULAYF AND SULAYF VILLAGE

ABSTRACT

GROUNDWATER AND ITS PRESENT DAY USE IN PART OF NORTHERN OMAN

Thesis submitted for the Degree of D. Phil. by
S. E. Letts, St Hugh's College. Hilary Term 1979.

The thesis is concerned with the water resources of a small part of the Middle East, consisting chiefly of four catchments in Northern Oman. It is an area about which very little has been written, being until recently of limited accessibility. Thus almost all the work presented is based on data collected by the author, rather than on literary sources.

Groundwater resources are assessed in the context of the physical environment in the first volume. The second examines the methods by which water is abstracted and distributed to crops (the main consumers of groundwater) and the efficiency with which this is undertaken. The two principle methods considered are the traditional falaj system providing a communal supply to villages, and pump wells, a recent introduction replacing ox-walk wells & capable of much greater rates of abstraction.

The two introductory chapters provide a resumé of existing works on the area studied and on those nearby and similar to it, and outline the approach and methodology employed in the study.

The third chapter examines the geology, geomorphology and hydrochemistry and the ways in which these provide clues to the hydrogeological environment. Particular attention is paid to the evolution of the present landscape and the effect this has had on the main routes of groundwater flow.

Chapter four compares existing and newly collected climatological data to provide an initial indication of water balance. The fifth treats the data collected to provide first approximations of aquifer characteristics and reliability of groundwater resources, using almost all the existing points of water abstraction as sources of information.

Chapters six and seven analyse the physical and socio-economic structures of falajes and wells to assess their suitability and efficiency in the prevailing physical environments and in the fast changing economic and social climate of Oman, now a source of labour for the oil producing areas.

Chapter eight examines the physical efficiency with which irrigation is undertaken by these two systems and the degree to which, in a water balance with only a marginal surplus, savings in water could be made.

The conclusion links these facets of water resources together and identifies those areas in which further research would seem to be most needed.

ACKNOWLEDGEMENTS.

The fieldwork for this thesis was undertaken while the author worked for the Centre of Middle Eastern and Islamic Studies, Durham. To the Director, Professor Bowen-Jones, and to Petroleum Development (Oman) who provided the funds, particular thanks are due.

Back at Oxford I would like to thank Marjorie Sweeting for her long-term support as a supervisor during the time it has taken to prepare this work for presentation as a thesis.

Many people have provided useful discussion which has helped my ideas develop and I would like to give especial thanks to Stace Birks who provided a contrasting(demographic) view-point of the area and shared the perils of crumbling and snake-infested tunnels; and to John Wilkinson who generously provided information and access to his thesis early in the research period.

While in the field, various people in the Oil Company offered back-up facilities in liaison with the Government, provision of medical treatment and vehicle and equipment maintenance, all of which made work in a remote area easier, and to them I am most grateful. Thanks are also due to those providing the same services in Durham, particularly Geoff Wynn and Tom Brett for help with chemical analyses; George Brown, Derek Hudspeth and John Normile for help with maps and diagrams, and to the other members of the team in Durham with whom I worked.

I would also like to acknowledge with gratitude the assistance of Alistair Pitty who has acted as supervisor during Marjorie Sweeting's absence, and Tom Wigley for the use of his Miniwat programme, and the work of Denise Reeves and Frances Glencross for producing a typescript so quickly in the short time before my return to the Middle East.

Lastly, I extend my thanks to the very many Omanis who made the work so enjoyable by giving time, information and unending hospitality with such cheerfulness.

PREFACE

Arabic words are used where no simple English equivalent exists. The first time they are used in the text they are underlined. Comments on transliteration and a list of words appear in the Glossary on page 509.

Maps of settlements and well locations are of the scale marked on Maps 2.3 to 2.10 unless otherwise stated.

All maps were originally drawn by the author, but some have since been re-drawn for publication. Where this has occurred the printed maps are presented.

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VOLUME I

GROUNDWATER

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CHAPTER 1 - INTRODUCTION

I GENERAL CONTEXT

The study of groundwater in any part of the world has much in common with the early popular concepts of the Heavens. These took the sky to be a vast black canopy with a few small holes admitting light from the part beyond. In the same way studies of groundwater rely on a few small holes to shed light on the nature of the 'part beyond', or in this case, the aquifers beneath. The holes are few and provide information on relatively little of the system. Yet the system itself is of major importance, acting as the principal source of water in the arid and semi-arid parts of the world, and a secondary but increasingly significant source for all other parts.

Just as early astronomy was not simply a pursuit of new knowledge but was the basis of navigation and chronometry, so the study of subsurface water resources is principally an applied science. As such the number of disciplines it calls upon is large (1). This is particularly so as more emphasis (2) is put on the importance of considering water supply and water use as integrated systems. Water availability needs to be considered in relation to the costs and available technologies of abstraction, fluctuations in yields with patterns of crop water requirements and water quality in relation to its use.

In the arid environment of the part of Northern Oman studied, all settlements and all crops are, and have been for many centuries, totally dependent on sources originating as groundwater- rain farming practices, as those in South Yemen, being apparently absent. The groundwater exploited by existing methods is of shallow occurrence and is studied in the context of catchments representative of internal drainage basins and systems flowing to the sea. It is of widely varying

quality and is abstracted from aquifers of very different transmissivities. While owing its origin to present climatic conditions, the storage and paths of flow of groundwater owe more to previous climates and in particular to times of greater rainfall.

Methods of abstraction vary from traditional falaj systems which supply water to whole settlements from one source, to wells which supply individual families and their crops and livestock. The falaj system (similar to the Persian qanat) provides 90% of the water of the villages of the Interior and wells only 10%. Conversely on the coastal plain hand-dug wells provide over 95% of water to farms and families and falaj-based settlements are rare. This contrast between water supplies of coast and Interior is referred to throughout the thesis as it reflects prevailing groundwater conditions and affects socio-economic aspects of water abstraction.

The two forms have complemented each other over many centuries, and have evolved with adaptations to suit the hydrological environments in which they lie. The settlements which rely on these supplies indicate by their size and position something of this physical environment, especially the asepcts of water availability and reliability. Conversely the points at which water is still abstracted also reflect not only hydrological considerations but also soil quality and the importance of defensive sites, tribal affiliations and the tenacity of the local inhabitants.

Where water is the principal limiting factor in the development of agriculture and industry, as Simpson points out, the objectives of research cannot be separated from the objectives of water policy (3). If the aim is to describe the aquifer system, its physical properties and the quality and quantity of its contained water, the management of this resource cannot be excluded. The effects of extraction on the natural system, the conflicting interests of water users, the possibilities of expanded exploitation of the resource are all logical extensions and applications of the study.

In Oman this was particularly true in 1972. Here the majority (some 85%) of the population is rural (4) and gains some part of a livelihood from farming. The essential asset common to all is water. Thus when Sultan Qaboos deposed his father in 1970, he was particularly keen to formulate a policy of aid to water supplies to gain the support of the rural population. One of the first moves of the new government was to introduce interest-free loans on pumps. This, and the opening of the country to imports encouraged an increase in extraction from wells and an expansion of cultivation. By 1972 there had been a certain shift to increased well-farming. Inland there was therefore a threat to, and undermining of the stability and dominance of the traditional falaj systems. The desire at local and governmental levels to adopt more modern methods and to increase agricultural production beyond subsistence levels also led to a growth in extraction on the coast. At the same time drought conditions intensified, putting more pressure on existing systems.

A study of water resources at this time thus involved not only research of the physical system, but of extraction methods, water use and adaptations to drought. The suitability of the two existing (and sometimes rival) methods and of drilled wells were examined in the light of hydrogeological conditions and agricultural requirements. This was not in order to suggest the development of one method and the abandonment of another, but to investigate the groundwater system and to see where each method has the greatest advantages. The advantages, however, are not simply in the adaptation to particular aquifer characteristics, but also in the ability of each method to supply the requirements, in terms of water quality and quantity, of the crops which the farmer wishes to grow. At a time of water shortage it is important to consider the possibilities of increasing available water by improving irrigation efficiency rather than by simply increasing extraction, especially if, as was the case, water budget shows reserves to be limited.

At this time, therefore, there was an opportunity to test whether in the Omani context Pereira's (5) view of traditional systems is justified. He holds that the most widespread destructive influence of mankind's water supplies on the hydrological balance is the struggle by increasing human populations to survive by primitive agricultural methods. The thesis therefore examines the hydrology of an arid environment and combines this with a study of the available methods of water use (including both modern and traditional systems) in a water-orientated society.

Thus the approach requires a fusion of physical and human aspects but examines water use primarily in the context of the hydrological rather than the social environment.

II SCOPE OF THE THESIS

A - GENERAL DATA BASE

This thesis is based on primary data obtained by the author in an area of the Middle East (see fig. 1.1) where no such data existed previously. An opportunity was presented to collect information at first hand on water resources and to examine and conduct detailed measurements on systems for its abstraction and use. Living in the field area for an extended period, working on self-help schemes for the improvement of water supplies, having a back-up organisation providing basic instrumentation and having the benefits of working within a multi-disciplinary team* offered a rare degree of accessibility to both physical and human systems in an arid Third World area.

Within the physical sphere, detailed quantitative information was collected on climatology, water quality, aquifers and their characteristics. A qualitative approach was necessarily taken to geology and geomorphology with the facilities available. A high degree of co-operation was exhibited by local people during the fieldwork, especially once the self-help schemes became well-known. Such co-operation also made it possible to gather a large amount of data on both communal and individual water use systems for the examination of the technology, economy and efficiency which they incorporate.

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* While part of a team of five studying other aspects of the area, namely soil, population, agronomy and fishing, the author only presents in this thesis the data, views and hypotheses directly attributable to herself, unless specifically stated otherwise.

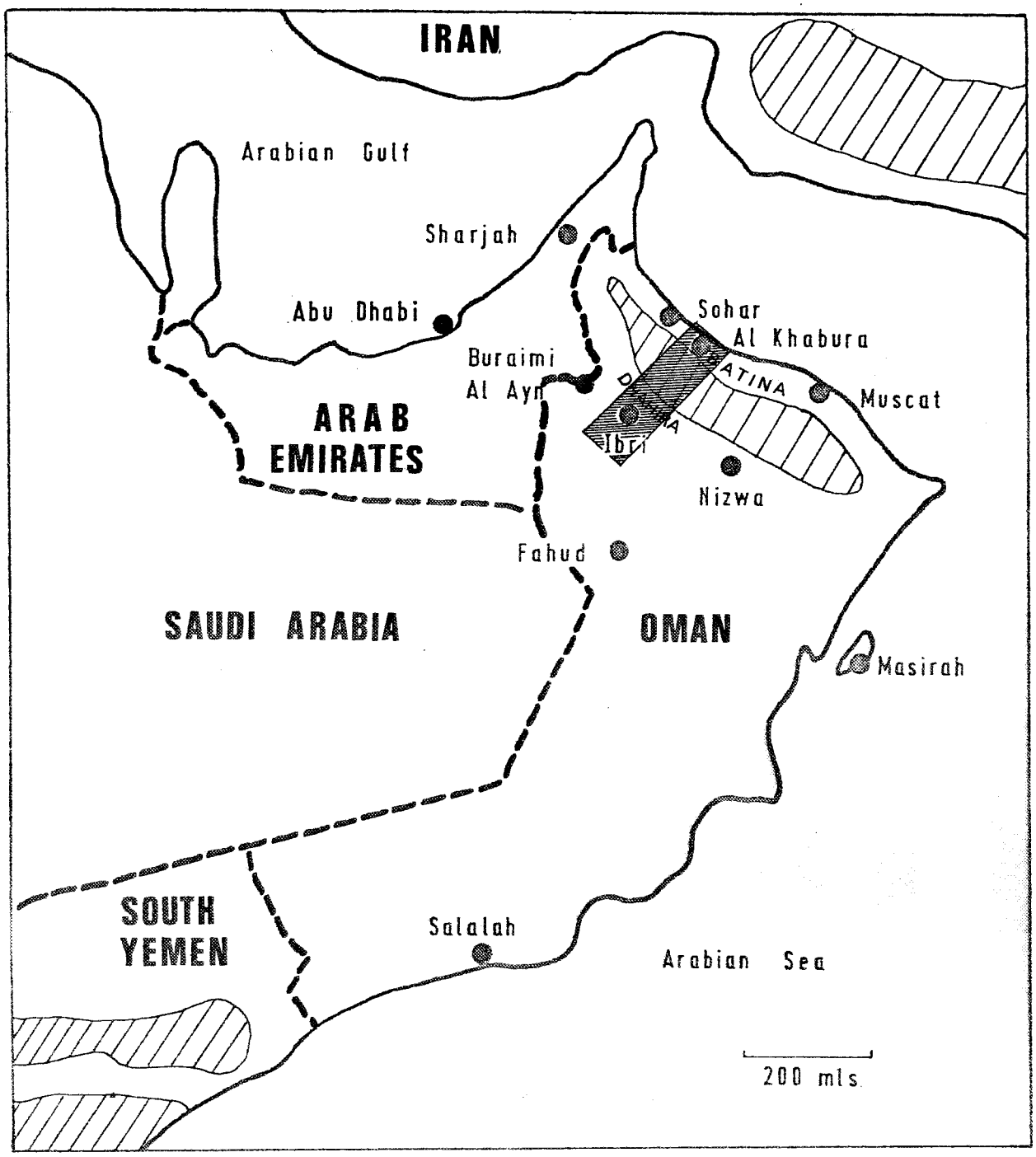
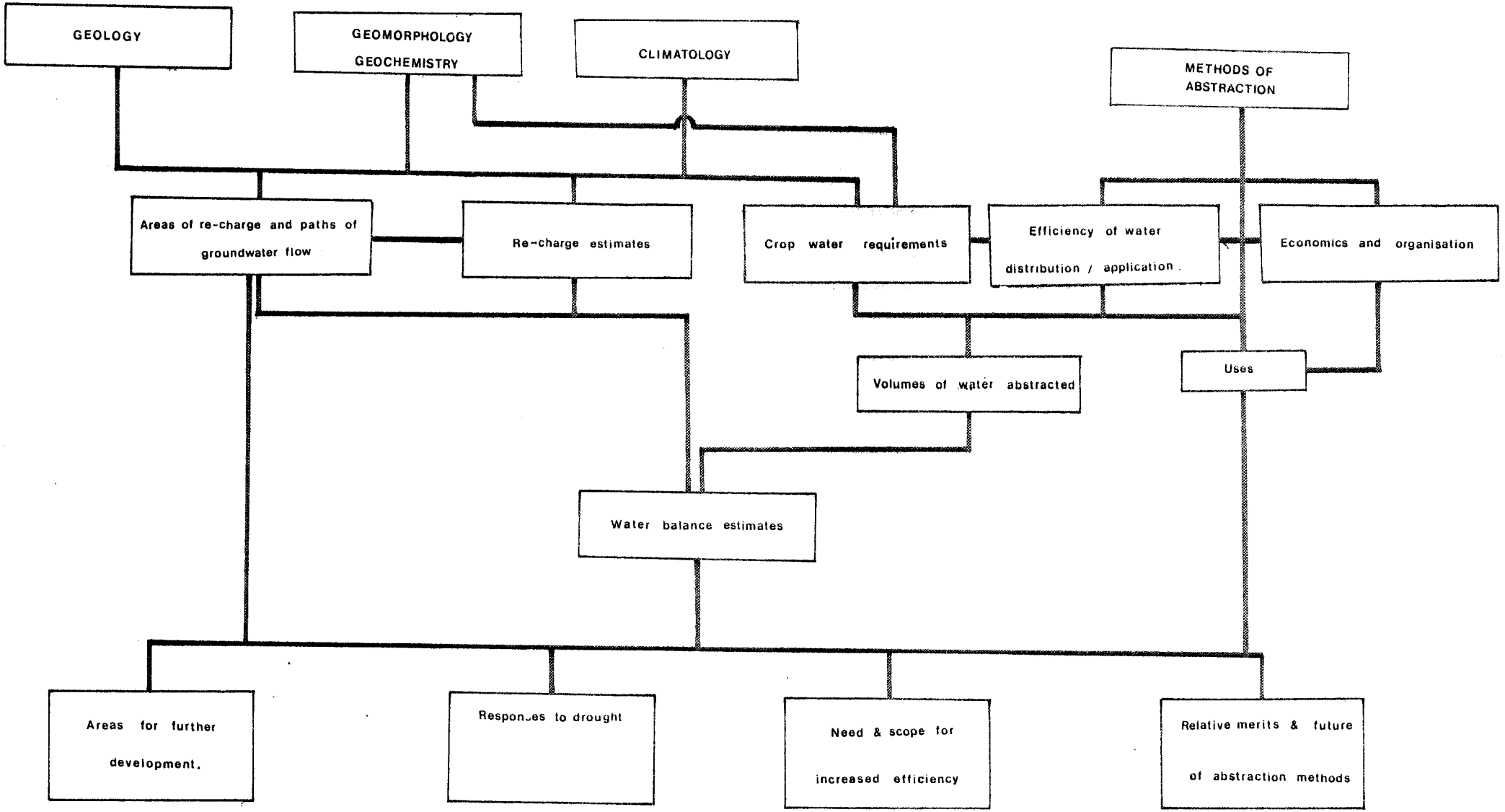


Fig.1.1 THE STUDY AREA.

Fig. 1.2 MAIN FACTORS IN HYDROGEOLOGY & WATER USE.



The resulting sum of information provided an initial data base which, when analysed, yielded a number of conclusion. Many interdependent fields are touched upon. Although each contributed substantially to the focus of the study, each may also be regarded as pointing towards areas where a further stage of data collection and subsequent analysis would be rewarding. The purpose of this thesis is as an introductory study of an erstwhile little-known area, framed around an examination of water resources and their existing and optimal use. This broad assessment has been chosen rather than an examination of one particular facet, which would necessarily have suffered from insufficient background information. The isolation of any one element and its treatment out of context with the existing state of knowledge of the area would be unwise, especially in a field where interrelationships are so important.

B - THE SYSTEMATIC APPROACH - PHYSICAL FACTORS

(i) Introduction

The splitting up of the thesis into systematic sections is not to isolate individual aspects but to examine each and its regional variations and then to relate these to the other aspects discussed. Thus it is aimed to build up pictures of both vertical and horizontal interrelationships of those factors central to the study of hydrology and water use in the area. (see fig. 1.2)

It is necessary to start by defining the physical environment as the people, their way of life and, in particular, their requirements for water are so closely tied to the conditions prevailing. Unlike desert America or Australia, ruralOmanis are not living in 'air-conditioned oases' (6 and 7) yet, but maintain a way of life considerably less changed

by oil than its publicised image might lead one to believe (8 and 9). Thus there has been little attempt to adapt the area to the ideas and practices of more humid climatic environments. Rather practices generally remain those which have evolved for and within an arid area and are still closely related to that environment.

For the purposes of defining that physical environment, the system can be regarded as an organism. The basic framework or skeleton is described first and consists of the solid geology. The infilling of the system is provided by Quaternary erosion and deposition, a function of the geomorphological evolution of the present landscape. Through this courses groundwater, whose quantity is dependent upon the levels of input provided by present climatological conditions. Thus geology and geomorphology are treated first, providing as they do a background to the degree to which rainfall provides effective re-charge. The organism is then examined for its ability to store and provide flow paths (which turn out to resemble veins) for groundwater and for the spatial and temporal variations in this ability. Finally quality of the groundwater is discussed, especially for the degree to which this reflects the paths of flow and to which that quality is suitable for the demands the water is to satisfy. The result is a system whose divers paths can be employed by man, with varying success, to satisfy agricultural and domestic demands.

(ii) Geology, Geomorphology and Hydrochemistry

Geology, geomorphology and hydrochemistry are here regarded as setting the scene for the examination of groundwater conditions. During the initial investigation of these aspects, it soon became apparent

that, especially in such a barren area, there was a feast of landscape features to study. As examples, formation of dipping pavements, the weathering of sandstones, the wind-borne movements of silts and sands all offered obvious lines of research. While they and many other phenomena have not passed unnoticed, they have generally been omitted from the thesis unless felt to be directly relevant to the hydrology of the area.

As a result the geology is mainly considered for its bearing on areas of run-off and infiltration and is the only section to be largely based on existing literature. The history of the landscape, the occurrence of recent and post-Miocene sediments and their significance to groundwater hydrology have not previously been studied. Recent geology and changing patterns of surface water flow have had considerable effects on recharge and paths of groundwater flow, particularly through the differences in development of associated ground and surface water flows. While river or wadi diversions have been remarked on in other areas (10) there seems to have been previously an almost total neglect of their bearing on groundwater resources. In the area studied, however, this phenomenon is a major feature of the surface and subsurface hydrology and has had important consequences for the availability of supplies and geography of water abstraction.

The geomorphology and geology are both reflected in the geochemical patterns observed. Carbonate equilibria and relative saturation levels are particularly important as water mainly comes in contact with dolomitic limestones, calcareous conglomerates and ultrabasic rocks. Examination of these equilibria in present day water also identifies the probable mechanisms by which Pleistocene gravels became cemented

and so preserved as such well-defined terraces and aquifers of marked variability. The passage of water through different rocks causes it to pick up different ions in solution which partly reflect the ratios and solubility of the forms present in the solid phase, and thus may label the source of a particular groundwater flow. Where this 'labelling' is clear, as in the wadi Lusayl, it may be used to check for the occurrence of wadi piracy.

Water quality, while providing information on the groundwater environment, also has direct bearing on the suitability of a given supply for a particular use. This aspect is discussed in the relevant chapters on water use.

(iii) Climatology and Water Balance

The study of the climatology of the area concentrates mainly on those factors which affect water balance, particularly the elements of aquifer re-charge and crop water requirements. Previous to the survey no local data were available so the establishment of one full meterological station at Tan'am and a set of rain gauges provided the first data directly applicable to the area. These have been examined and used for interpolation and to provide information on the predominant meteorological systems. It has also been necessary to look at information outside the area for longer-term records, which may not provide applicable absolute values, but from which relevant probabilities can be calculated. At the same time, the identification of specific drought and flood indicators made it possible to propose an approximate periodicity of extreme events using information which could be obtained from local people. While this

information is of varying reliability, correlation between villages does make it possible to put the observations obtained in the two years of fieldwork within the context of a wider area and of a longer time span. It becomes apparent that those two years did not just seem dry in the eyes of an inhabitant of a temperate clime, but also to the more experienced eyes of local desert dwellers.

While the climatological data collected over this period was found to represent below average rainfall conditions they do provide both the first local figures which can be compared with the nearest longer running stations, and input statistics for the estimation of water balances during this limited time. Longer term water balances, reflecting average conditions, are also required for the buffered groundwater system whose reactions to re-charge and droughts tend to be less extreme that that of surface water systems. As a rule, the larger the aquifer and the further from the re-charge area, the longer the frequency of the moving average which should be used to approximate groundwater response. Thus, while average conditions are something of an enigma in an environment of such extremes, they must be considered. Comparison of local data and longer records provides a first approximation of these conditions and the overall water balance. This balance must be regarded in the light of the very short-term data available and should be continually re-appraised as new information becomes available.

The period of the survey, being one of below average rainfall, offered a particularly good opportunity to study the depletion of aquifers and the reliability of supplies. It did mean, however, that estimates of

run-off and infiltration must be primarily based on other work in similar areas and on the observed geomorphology. Thus the average water balances calculated and the deficiencies noted for the years of 1973 - 1975 will require further refinement. Nevertheless they do point to those areas where abstraction rates in catchments are reaching or over-reaching maximum estimated re-charge; these are obviously the priority areas for further investigations to improve the definition of available resources.

(iv) Groundwater Conditions

After examining the likely total volumes of water available for exploitation, it is important to consider the main routes along which they are conducted and the availability and variability of sources in different areas. Aquifer characteristics could not be measured directly with conventional pumping tests because of the interference of returning irrigation, variable well diameter and intermittent pumping routines. A method was therefore devised to use drawdown and yields from these itermittent pumping routines to provide constant time specific capacities. These specific capacities were found to approximate transmissivities which correlated well with transmissivities calculated from variable time drawdown and yield. The resulting values proved consistent with others found for similar aquifers. Local storage coefficients were obtained from recession curves. These figures are examined with and related to the distribution of the major aquifers.

From the aquifer distributions found, it becomes apparent that inland what appear to be buried alluvial channels provide the key to both water quality and quantity, transmitting large flows of high quality water in the

lower wadis. They also provide a logical reason for the observed alignment of falaj motherwells, a relationship which has not previously been recorded for falaj or qanat systems. Indeed, in the neighbouring Trucial States, where Halcrow (11) found signs of buried channels during drilling, they were not considered to make any significant contribution to the water resources. Nevertheless in the Dhahira, it is apparent that the original falaj builders probably had a good understanding of and/or ability to divine these channels, and that as they provide the major source of groundwater, abstraction has long been closely tied to their occurrence.

The different forms and distributions of aquifers and depths of water affect the degree to which groundwater abstraction can be developed, and the suitability of the methods used. The contrast between coastal and Interior conditions are established, as are spatial variations in the Interior and their influence on water use. Fluctuations in groundwater flow and water levels also vary from system to system depending upon the response of each to drought. These changes offer a measure of the reliability of particular source areas through the use of recession equations and calculated changes in storage. The results from monitoring over the period of fieldwork also show that this method can also suitably be used, with longer periods of data, to obtain better assessments of the proportion of rainfall providing effective re-charge and of the degree to which falaj systems are affected by more than one groundwater regime.

The consideration of the data collected on water balance and groundwater conditions when combined with the broader aspects of geology, geomorphology and water chemistry indicate the areas to which groundwater

abstraction is likely to be confined and how these relate to existing patterns. The degree to which good quality and yields are to be found under existing falaj irrigated areas has particular bearing on the extent to which the falaj system could be replaced, and also the likelihood of farmers extending irrigation locally or establishing well gardens far from the present settlements.

The physical environment has now been defined and some of its limitations pointed out. The way in which its characteristics are made up are discussed in the second half of the thesis.

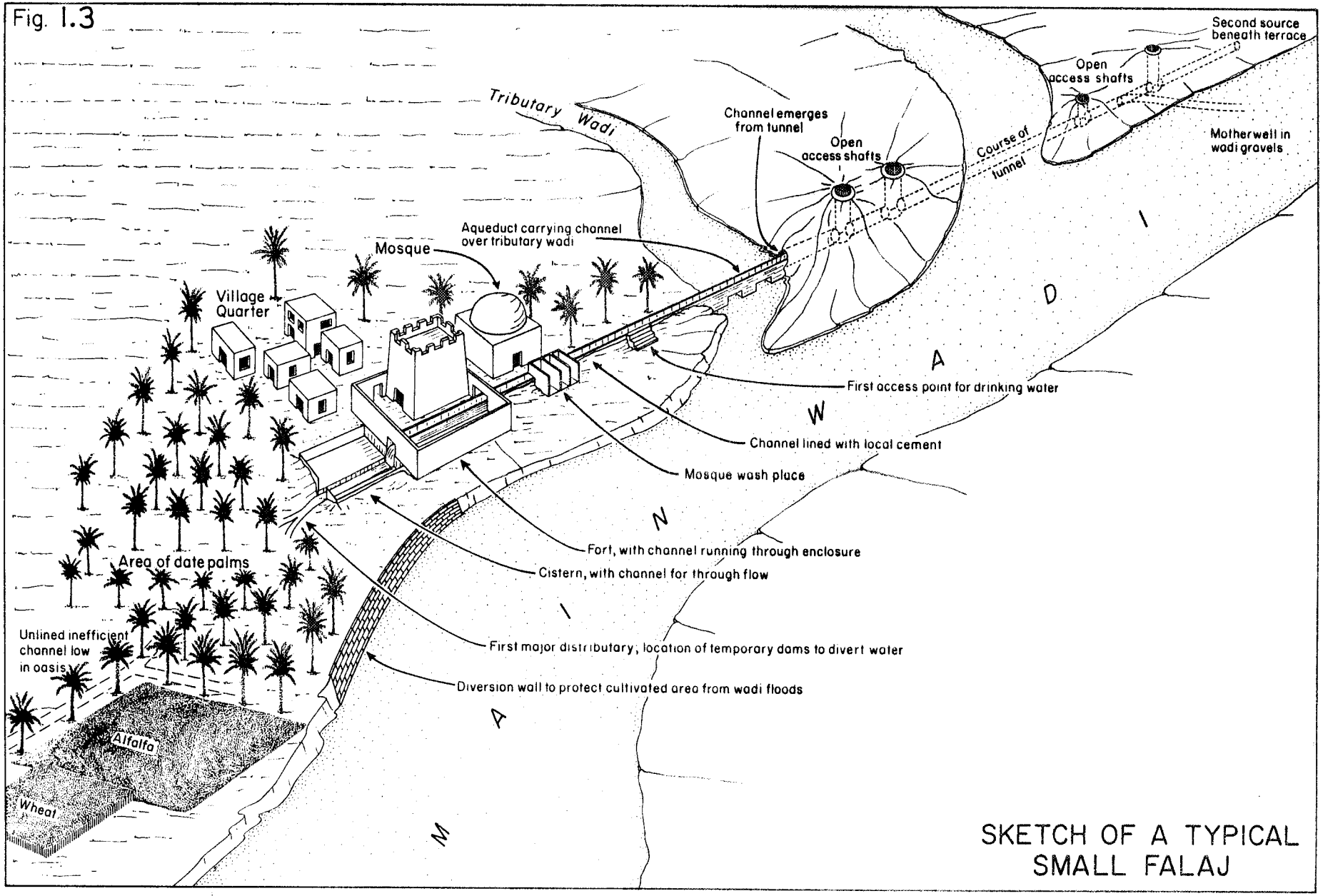
C - WATER ABSTRACTION AND USE

The general view of water use in the less developed countries is of poor management, non-existent control of resources and low efficiency (12). These aspects are examined for two types of water supply, falaj and pump well - the one a system evolved over many centuries and the other a recent development. In particular they are investigated for the efficiency with which they abstract water and carry it to crops, and the degree to which they are, or could be affected by changing economic conditions and modern technology. A measure of efficiency is here taken to be the degree by which abstracted water exceeds the requirements of the crops for which the water is destined.

(i) Falajes

Falaj systems, or more often the qanat systems of Iran, have been surveyed for the fundamental parameters of length, depth to source and flow. The resulting impression is of a set of tunnels and channels constructed a long time ago and little changed in the ensuing years. The

Fig. 1.3


Second source beneath terrace
Open access shafts
Motherwell in wadi gravels
Tributary Wadi
Channel emerges from tunnel
Open access shafts
Course of tunnel
Aqueduct carrying channel over tributary wadi
Mosque
Village Quarter
First access point for drinking water
Channel lined with local cement
Mosque wash place
Fort, with channel running through enclosure
Cistern, with channel for through flow
Area of date palms
Unlined inefficient channel low in oasis
First major distributary; location of temporary dams to divert water
Diversion wall to protect cultivated area from wadi floods
Alfalfa
Wheat
SKETCH OF A TYPICAL SMALL FALAJ

emphasis in this thesis is that the falaj is not a static entity but that both as a physical structure (see fig. 1.3) and a distributor of water it shows a surprising dynamism and flexibility. The routes and sources of the falajes are continually being developed and are closely tied to observed aquifer distributions and the design and fabric of the system reflects a varying degree of concern shown for the efficiency in transmitting water from source to crop.

The only major work on the Omani falaj systems is that by Wilkinson (13) whose approach is principally that of studying a water system from a social and historical, rather than a hydrological or agricultural point of view. The history and general principles of falaj organisation are therefore covered very fully by him and these aspects are not investigated further except in so far as they lead to differences in organisation and water ownership, which reflect on the efficiency of water distribution. Being a communal system,water has to be divided up among a number of consumers and the efficiency and equitability of this devision depend to a great extent upon the abilities of those in the social hierarchy of the falaj organisation. These hierarchies and their effects on individual systems were studied in a large number of villages.

During early work on the underground sections of falajes the author and another member of the Resources Survey carried out repair work and instigated several government-financed self-help schemes. This not only enabled the author to gain familiarity with a large number of falaj systems and examine in detail their design and fabric, and efficiency in conveying water, but also ensured full co-operation from

those in charge of them and from the communities which depended upon them. Thus it was possible also to gain a great deal of information on the practicalities of water division, date palm and water ownership, the economics of falaj water supply, and the effects of water shortage upon the system.

(ii) Wells

Hand-dug wells with medium-lift pumps now offer an alternative method for the abstraction of groundwater. The increasing use of boreholes in the richer oil countries and the risk of pollution in shallow aquifers have meant that hand-dug wells tend to be regarded as the poor man's lot, and it is often assumed that a drilled well is the most suitable type even for very small communities. Yet in Northern Oman in the absence of proven deep aquifers and where shallow gravels and aquifers, in which fissure and pipeflow predominate, are the main sources of groundwater, hand-dug wells may still provide the most suitable type of well. The overall structure of pump wells is fairly uniform whether they are newly excavated or modifications of existing ones. The rock in which they are dug, however, does affect their design and their cost. While geology also has a major bearing on the yields which can be obtained from a well, these yields are further restricted by the types of pump which the farmers install.

Wells have traditionally been complementary to, rather than in competition with, falaj irrigation, but there has been a recent major expansion in pump well irrigation. Not only are wells beginning to compete with falaj settlements for finite water resources, but are also

coming into various sorts of economic competition with them. A restriction on new well development in certain areas may not, however, halt a further increase in volumes of water abstracted, as farmers are shown to use a small proportion of the water available at most wells, and thus even if the number of well units is not increased, pump well abstraction can grow.

While the abstraction of water by falaj or pump involves a number of maintenance and running costs, those for a well are considerably higher, particularly as initial capital costs are seldom yet written off. The costs of water must therefore be weighted against the advantages and disadvantages of a communal or an individual system, the differences in water quality which each supply has to offer and, in the case of irrigation supplies, the requirements of the crops to be grown.

(iii) The efficiency of Water Use

The crops grown are perennial, annual and seasonal, and are arranged in this order outwards from the water source, with date palms providing the spatial, social and economic core of the farm system.

Thus a considerable network of channels is required to carry water to every part of the oasis or well garden. Fundamentally pump well irrigation, having developed after a long history of falaj irrigation, borrows a great deal from it, and so the two systems can be considered together, as many falaj systems have flows no greater than that from a 3" x 3" pump. Whatever the source of the water, the channel networks have evolved by trial and error, or effort and neglect, and it is interesting to see how the resultant structure conforms to

the theoretical ideals which modern designs favour, and to what degree simple changes can improve the system's efficiency. The sources and magnitude of losses within the system are examined in detail.

The water is conveyed along channels to a crop with a certain seasonal water requirement which depends on crop, soil and water quality. Theoretical calculations of these requirements which are included vary from the rule of thumb methods to the greater sophistication of the Meteorological Office Penman Computer programme. The resultant values only take account of evaportranspiration rates and do not allow for leaching requirements which depend on water quality, and they are therefore compared with a large number of observed application rates. Critical application rates can then be identified by observation of crop responses, and it is also possible with the data collected to estimate the demands of different crops and whether they are equally well satisfied by both well and falaj systems. When established crop water demands are combined with the savings which could be made in channel water losses, one arrives at an approximation of how much extra land could be cultivated without the increase in abstraction.

D - CONCLUSION

At the outset of the work on groundwater in Oman, it was intended to study it simply in its physical environment, and to identify the hydro-geological conditions under which it occurred in the most exploitable quantities. Initial water balance estimates, however, underline the limited nature of these groundwater reserves and their enormous

variability. It became, therefore, a logical extension of the work to examine the major agricultural demands upon these reserves, and the efficiency with which existing methods of supply satisfy them. Using detailed case studies it can then be judged whether poor management and low efficiency do occur and whether improvements can be made which would allow an expansion of agriculture without an increase in water abstraction, simply by decreasing wastage. The result is a study of groundwater and its use, following a path from source to crop and looking at methods of abstraction and conveyance on the way.

III SECONDARY DATA BASE

A - AVAILABILITY AND ACCESSIBILITY OF DATA

While the range of knowledge required in considering water resources increases, the availability of that knowledge is still very limited. This is particularly true in the arid parts of the world for which data are very scarce - a fact constantly bemoaned by McGinnies throughout his comprehensive study of the deserts of the world (14) . The scarcity of data is not simply because very little work has been done on these areas, but also because of the lack of communications between the different bodies concerned.

Especially in the Middle East, where the majority of data has been collected by consultants and ministries, reports are often not accessible to members of the public except through the governments of the countries concerned. In other cases, as the F.A.O. Water Use Seminar concludes (15) while countries may have facilities for research, there is a major need for co-ordination and exchange of experience and research findings.

The majority of work has been carried out by consultants and government ministries for several reasons. Primarily it is because arid zone hydrology is a very expensive field of research. Drilling at approximately £300 per metre for a production well with casing, resistivity surveys for small areas at some £8000 plus all the costs of instruments and water analyses mean that comprehensive groundwater surveys cannot be contemplated by small organisations.

Combined with this is the time factor. With very large variations in rainfall from year to year and season to season, a programme for fieldwork of three months, or even of two years, can be of widely varying value. Thus it is more appropriate from an academic point of view for a researcher to select a topic less affected by the extremes of the hydrological cycle. Hence, for instance, out of a listing of 500 research topics registered in America from 1962 to 1976 on Middle Eastern subjects (16) , the majority were on political, economic or agricultural aspects. Only two were on hydrological topics, and yet this remains the basic consideration for man's activity in the area and still the greatest imponderable.

While governments are generally aware of the need for a better understanding of the water reserves of their countries, this is not always sufficient. The governments of most of the arid areas of the world, particularly the Middle East, Africa and South America, sometimes contain few trained scientists and those there are, are seldom in posts where they can make optimum use of their knowledge. Hence planning a resources survey from within may be a problem, particularly a water survey. Water tends to be a resource variously and jointly administered by Ministries of Irrigation and Agriculture, Communications, Fisheries, Housing, Interior Affairs, and Water and Electricity. Seldom does one consult another on what work is being undertaken, what water abstracted and what pollutants discharged. Co-operation and co-ordination is therefore lacking.

In Oman in 1973, when consultants came to work in neighbouring areas, the Government allocated them areas contiguous with the area studied by the author which, in each case, had boundaries running down the

centre line of a wadi, so dividing the catchment in half. This illustrates one of the minor problems encountered in research and planning of surveys - government departments are seldom respecters of hydrological concepts in planning surveys. Nor unfortunately are they necessarily respecters of the results. In Oman a visit was made to a relevant ministry to refer to a consultant's report, the first ever of the particular area, of which ten copies had been delivered the previous week. None were to be found, and neither on any subsequent occasion did any other organisation obtain a copy. All had been lost during house-moving to a new building, but no replacement copies were asked for.

Consultants themselves are generally reluctant to release copies of reports for several years after they have been presented to the clients, particularly if design and implementation stages are likely to follow. Thus many obstacles are set up against one being able to make a comprehensive survey of this type of literature, especially recent works when the aim is to compare results and see how one's own ideas fit in with the existing knowledge on other similar areas.

B - EXISTING LITERATURE ON NORTHERN OMAN AND NEIGHBOURING AREAS

(i) Northern Oman

With a history of tribal unrest, and only a real freedom to travel in the Interior in the last decade, Oman has, with truth, been called the Lost Corner of Arabia. Until contemporaneous work by consultants

in the North, literary allusions to Oman have, as a generalisation, been provided up to the early 1930s chiefly by travelogues and as geological works by those attached to oil companies. Only within the past five years has a third phase, that of more detailed research become apparent.

Previous to 1975, Omani hydrology and related physical topics had been little touched upon in literature. Geology is the only aspect to have been covered in any depth, and this is usually approached on a countrywide scale rather than as studies of smaller areas. Fortunately Lees (17) , who first brought reason and order to the geology of Oman and remarked briefly on geomorphology, used parts of the area studies as type areas for the groups and formations into which he divides the geology. Some of these have inherited local names in their classification to this day (eg. al Wahrah formation, the Hawasina group). His descriptions are, however, purely stratigraphical, and, in common with all subsequent geological works (see Chapter 3 for full appraisal), make no reference to a formation's ability to store water, its characteristic slope development, or other features which have a hydrological or hydrogeological effect. Infilling of geosynclines (18 & 19) and allochthony or autochthony (20) made more popular themes within the geological context. The original Shell commentary to their geological map of the Oman mountains (21) has been used as a stratigraphical basis for the section on geology in combination with the fuller Geology of the Oman Mountains (22) .

The only other physical aspect covered to any significant degree is climatology. Existing literature, which is referred to in Chapter 4, Section 1, identifies the two approaches taken to this subject. One is

regional synpotic analysis generalising over large areas such as Mazumdar (23) , the other is travellers' observations of individual spectacular storms such as that noted in Buraimi by Stevens (24).

Several well-known travellers passed through the area during the first half of the centry, such as Thesiger (25,26) Zwemer (27) Wellsted (28) and Vesey-Fitzgerald (29). They, however, use the landscape principally to set the scene for their observations of tribal politics and social customs with which they were by inclination and of necessity more preoccupied. As Lees (30) himself pointed out, 'social considerations often restricted the studies which could be undertaken as areas of critical importance and friendly tribal country do not always coincide'.

As mentioned previously, shortly after fieldwork commenced consultant firms were brought in to assess water resources in areas contiguous to the Ibri - Khabura area in which this work was carried out. Their brief was somewhat different in that they were required to cover much larger areas and therefore collected information at a much less detailed level. They were later also commissioned to carry out socio-economic and agricultural surveys. These they regarded as secondary in importance to the basic assessment of water and as separate rather than interrelated studies, which were carried out with very little cont act with local communities. The result is a large body of data of slightly different orientation but with which findings in the field area can be compared and contrasted and which became available after the majority of work for this thesis was completed. The Ilaco (31) and Renardet (32) reports became available in 1976 but only limited access was available to the Gibb Report (33).

On the social side the chief work, or set of works, are those by Wilkinson (13, 34, 35) who has made a very detailed study of the successive stages of settlement in Oman and their relation to the falaj organisation of water supply. This comprehensive work is set mainly in the context of economic and social conditions before the advent of oil, and is therefore complementary rather than parallel to the view which is taken of falajes in this thesis. While Wilkinson with his understanding of and familiarity with relevant Arabic literature has had unique recourse to historical sources of information, approach to falajes in this thesis is based upon the observation of specific systems, particularly the smaller, simpler ones for which wide ranging studies could be undertaken. Here a hydrological rather than a sociological viewpoint is taken, and the system is examined, not from an historical or evolutionary point of view, but as a de facto but dynamic entity which was created a long time ago but which is generally well suited to the physical environment in which it is found. A rapidly changing economic climate and the far reaching effects of the introduction of medium lift pumps (which offer farmers for the first time a competitive alternative to the falaj water) make a study of the falaj system, its efficiency and ability to survive particularly relevant at this time. For this, Wilkinson's work provides an extremely valuable foundation.

(ii) Neighbouring Areas

For surrounding areas from Yemen to the Gulf, literary sources are scarcely more numerous than for Oman itself, and consist mainly of consultants' reports and those by Government and international agencies. As such, they tend to suffer the problems of accessibility already

mentioned. As an example, attempts to obtain a copy of a report on South Yemen, through the Ministry of Overseas Development, the Department of Trade F.A.O. and the P.D.Y.R. government all failed. Nevertheless a certain number of reports are referred to and were used to provide background information.

Working from North to South, water resources in Kuwait were studied comprehensively in 1963 (36) , but since this time the establishment of the Groundwater Division of the Ministry of Electricity has meant that apart from publicity articles (37) most work on water resources has been presented as internal reports which are not made available to the public. Thus only general articles in journals (eg. 38) are available. Considerable concern has been shown over the reduction in artesian heads in Bahrein, and as part of Ministry of Overseas Development technical input and consultant reports have been written on groundwater resources and extraction (38 - 41) for this part of the Gulf.

The Trucial States Council which preceded the formation of the United Arab Emirates, commissioned water resources surveys, undertaken by Gibb (42) and Halcrow (43) some five years before those for Oman. These works, in particular, provided a background to the work in Oman, especially when combined with briefer works reported previous to and during these studies (44 - 47). The Emirates were also the source for the only other work found on falaj renovation, the Ministry of Electricity and Water having commissioned Huntings T.S. to do a study of Falaj Dhaid (48).

Literature on Saudi Arabia is also mainly confined to development reports. The area for which the most information is available is probably the Wadi Jiza' (49) . McGinnies' (14) comment on this fact sums up the state of knowledge for all these areas in the remark "Considering the fact that the Wadi Jiza' is probably the most thoroughly studied drainage in Arabia, in terms of hydrologic data that have been gathered, our lack of knowledge is most discouraging". General introductions to Saudi water resources and water use were also consulted (50 - 53) .

Finally attempts were made to obtain reports on Yemen, both the Arab Republic (YAR) and the People's Democratic Republic (PDRY) as these had a certain amount in common with the Omani environment, and put the geology in a broader context. Beydoun in particular provides a useful geological commentary (54, 55) . Certain consultants reports were also obtained (56 - 59).

The degree to which the Arabian Peninsula as a whole has been left behind is evident from the paucity of academic research documents which have been produced on the area in the last three years. In the fields of hydrology and superficial deposits contributions to publications, whether books or journals, are very rare, according to 33 volumes of the Bureau de Recherche Geologique et Minerale 1977 (acknowledged generally as a very comprehensive bibliography). Oman itself receives no attention except in an article on meteorites, while the westward continuation of the geological and geomorphological environment into Yemen also apparently received no attention. Saudi Arabia, a considerably larger area with universities of its own features slightly more in documentary references but is still rarely a subject of study in European and American journals.

It has been possible to find a limited amount of background reading, and places where similar projects to those of the consultants in neighbouring areas had been carried out. This helped to put the work in the field area in context. At the same time it served to emphasise how little information is available and how many aspects, such as rainfall/effective re-charge ratios are still of necessity treated intuitively rather than being based on a range of observed events.

C - THE LEVEL OF AVAILABLE DATA IN THE CONTEXT OF GENERAL HYDROLOGICAL LITERATURE

Not only are the access points to information on groundwater few and far between, in the literal sense, but in the case of the literature available for reference the black canopies of ignorance also cover a larger area than the holes which let in the light.

Thus the level of data on Omani hydrology in the early 1970s put it on a par with Arizona in the 1880s. In terms of records of events and of surveys, the North of the country has no data to call upon. It is a new area which through tribal and larger scale political situations has remained largely unvisited for research purposes. Thus there are few aspects of hydrology in which investigation in the Ibri-Khabūra area would not provide new and original data.

(i) Geomorphology

To some degree the level of data must be looked at in the light of the years before the 1940s. This was the time at which both hydrology and geomorphology rapidly changed course. Before this work was, in the absence of accurate topographic and aerial surveys with good base control and of easily accessible computer facilities, mainly descriptive. With these facilities taken for granted in the present day, it is easy to criticise Davis (60) for his dependence on block diagrams or descriptive terminology, or Penck (61) for his on illustrative diagrams rather than field measurements, but theirs were valuable attempts to try and systematise visual impressions of landscape.

It was not really until after the Second World War that geomorphology moved towards a more analytical and quanititave treatement of data. Horton (62), Strahler (63, 64), Hack (65), Denny (66), Bull (67, 68) and Lustig (69, 70) were all part of the movement which put forward precise quantified descriptions of the development of drainage systems and alluvial fans. These dispelled many theories which had been put forward without adequate attention to minor detail or to the exceptions which proved more frequent than the rules.

While this shift in approach involved a change in philosophy, it was sparked off and made possible by advances in technology. It was the advent of large-scale topographical maps which enabled Denny to reconstruct the former surface of the Appalachian region in 1956 (71). In the following year it was careful fieldwork and mapping of stream channels which made it possible for Hack to propose the

relationships between stream channel, slope, drainage area and bed material (72). In 1956 Leopold & Miller worked on the hydraulic geometry of ephemeral streams in New Mexico, with surveying and sampling.

The theories relating active or past hydrology to certain landforms can be seen to require a certain level of data. It requires maps with contours, or it requires surveying teams, or air photos flown at constant height above land with ground control. Where none of these is available, descriptive methods must still prevail, calling where possible on theories established through detailed investigation in other areas, and on an understanding of the landscape and its history.

(ii) Groundwater Hydrology

Groundwater hydrology took a similar sudden step forward in the 1940s, but one which also requies sophisticated data. Theis (73) and Jacob advanced and clarified analytical methods and were followed in the 1950s by people such as Hantush (75), Watton (76), Boulton (77) who extended the applications of the tests and simplified the methods of analysis. This period of advance was also partly stimulated by technical advances. More reliable test pumping equipment, and more exact level recording was combined with the introduction of computer facilities which enabled the transformation of methods using differential equations into graphical curve-fitting methods.

The parameters quantified by such analyses can be used to build analogue or digital models of groundwater systems, water balance and water management. Partly as a result of the World Hydrological

Decade, the volume of literature on model building has increased enormously. Subsurface hydrology studies are most numerous in temperate climates (particularly Holland, UK, USA, Germany and Israel) and so paradoxically are studies of drought. Thus many techniques which have been developed require a sophisticated level of data generally unobtainable elsewhere. The models which have been built of aquifers (78 - 80) and those employed for water resource management (81, 82) have been devised in and for areas of the world which usually exhibit relatively small climatic varations and ones which can offer considerably more available data. Even the Symposium on the Evaluation of Water Resources with Scarce Data (83) does not consider any areas with less than ten years of records.

These are, however, advances which are not of equal relevance to all. To some degree it can be said that the sparsely populated Third World countries do not fit into this advance and have as yet not benefited greatly from it. As pointed out by Linsley & Franzini (84) hydrological decision-making remains largely intuitive in these areas, until more data are available. In an allied work (85) it is pointed out in the preface "The natural phenomenon with which hydrology is concerned do not lend themselves to such rigorous analyses as are possible in engineering. There is therefore a greater variety of methods, more latitude for judgement and a seeming lack of accuracy in problem solution". Within the existing state of the science, or if the above is accepted, the scientific art, this statement is particularly relevant in the early stages of an examination of water resources. Nevertheless it is important to try and employ methods

which make maximum use of the data which areavailable.

The study of the water resources in Northern Oman provides a contribution to the understanding of hydrology within the Arabian context, by providing information on an area for which data was not previously available- data is also limited for similar neighbouring areas and so it is hoped that the work may also help in increasing the understanding of them. The drawback of working in such an area is that many new methods available to the hydrologist in the European context cannot generally be employed, tested or advanced in such an area. It is important in this case not to analyse the information collected at a higher level than it can bear.

The necessary difference of approach between 'Western' countries and Third World countries can be illustrated by the difference in attitude to test pumping - a fundamental tool in defining groundwater conditions. In England, the Institute of Geological Sciences use a two week constant rate pumping test as standard procedure. In the Middle East few tests exceed a couple of hours since, unless specifically for an exploratory programme, a client is not likely to be interested in or willing to pay for more than the necessary testing to indicate the size of pump required for production. Hence the differentiation which exists between tests which provide information on the aquifer and those which really only provide information on the well itself, and the differences in the levels of data available.

While European hydrology has become an increasingly theoretical discipline, Middle Eastern hydrogeology remains mainly pragmatic. Hence the thesis, while applying theory where possible, and comparing indicated results with those from areas where better data is available, relates observations to the practicalities of groundwater development and use. In particular an attempt is made to employ the most simply collected data to provide indications of the hydrogeological environment and to examine existing methods for its exploitation.

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CHAPTER TWO

INTRODUCTION TO THE AREA AND TO METHODOLOGY OF THE STUDY

I INTRODUCTION TO THE AREA

- A Selection of area for study
- B Physiographic regions
  - i) Mountain range unit
  - ii) Alluvial gravel plain
  - iii) Batina coastal strip
  - iv) Middle wadi unit
  - v) Lower wadi unit
  - vi) Desert foreland

II DESIGN OF RESEARCH PROGRAMME

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- B Availability of assistance
- C Research programme and sampling policy
- D Phases of data collection

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- B Measurements and questionnaires
  - i) Falaj systems
  - ii) Well Gardens
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IV DATA PROCESSING

- A Data and its storage
- B Primary data treatment
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I INTRODUCTION TO THE AREA

A SELECTION OF THE AREA FOR STUDY

The general area chosen (fig. 2.1) was selected by PD(O) management who commissioned the survey of resources. The major factor in its choice was that between Ibri and Khabūra runs one of only three roads to cross the main belt of mountains, the other two being the Wadi Sumail to the East and Wadi Jizzi to the North-west. Thus direct access was possible to both coastal and interior settlements. It is, however, the least developed of the three passes, and at the beginning of the survey there were no tarmac roads in the area, and only one regularly graded road, which ran along the coast. Within the field area therefore communications consisted of rough or non-existent tracks, three transmitter/receivers provided by the oil company and an intermittent postal system provided by the army.

While the area originally indicated was to lie some 50km to either side of the Ibri-Khabūra road, problems of access, and a wish to cover a small area in more detail rather than a more general survey of a large area led to a joint team decision to reduce the survey area to some 1800 km^2. Thus the area within which the survey took place was the product of an outside decision and a joint agreement in which the author took part. Within this area, however, she had complete freedom in selecting the hydrological and water use topics covered and the systems studied in detail.

The resultant area consists of a transect between a coastal plain bordering the Indian Ocean and a desert foreland bordering on the Umm as Samim. The basic division are three fold. From North to South

Fig 2.1

PLACE NAMES & PHYSIOGRAPHIC REGIONS



these are Batina or coastal plain, the Hajar mountain range, and the Dhahira interior lands. While the settlements on the coast are fairly continuous within a narrow shoreline belt, those inland, both present and past, are nucleated and isolated by large areas of mountain or alluvial gravels. While there are ruined villages, water systems and abandoned land indicative of far more widespread (but not necessarily contemporaneous) water use (see fig. 2.2) there are now four major villages of over 3000 inhabitants. These are Khabura and its associated villages along the coast, Ibri, Araqi/Aynayn and Dariz. Some twenty villages and a sprinkling of hamlets and fariqs* (fariq pl. firqan) (individual, isolated households) comprise the remaining settlements. Minor settlements are generally in the smaller mountain wadis with limited culturable areas and unreliable water supplies, or in the Duru' lands of the desert foreland which are historically nomadic areas.

There is one major catchment to the North, the Wadi Hawasina which flows to the sea and three internal drainage basins to the south (the wadis al Aridh/Juffra, al Kabir and al Hijr). Some information was also gathered on the nearby Wadi bani Umr, Wadi Majzi, and the Wadi Quriyat near Bahla.

The watershed dividing the North from the South flowing wadis lies across the Tropic of Cancer. While the mountains form the core of the area, their junction with the plains on either side consists of two very different landscapes. To the North the mountains are abruptly

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*Footnote: Demographic data from J S Birks. Abandoned land map with input from J S Birks.

MAP OF CULTIVATED AND ONCE CULTIVATED LAND (1976) AND FALAJ SYSTEMS

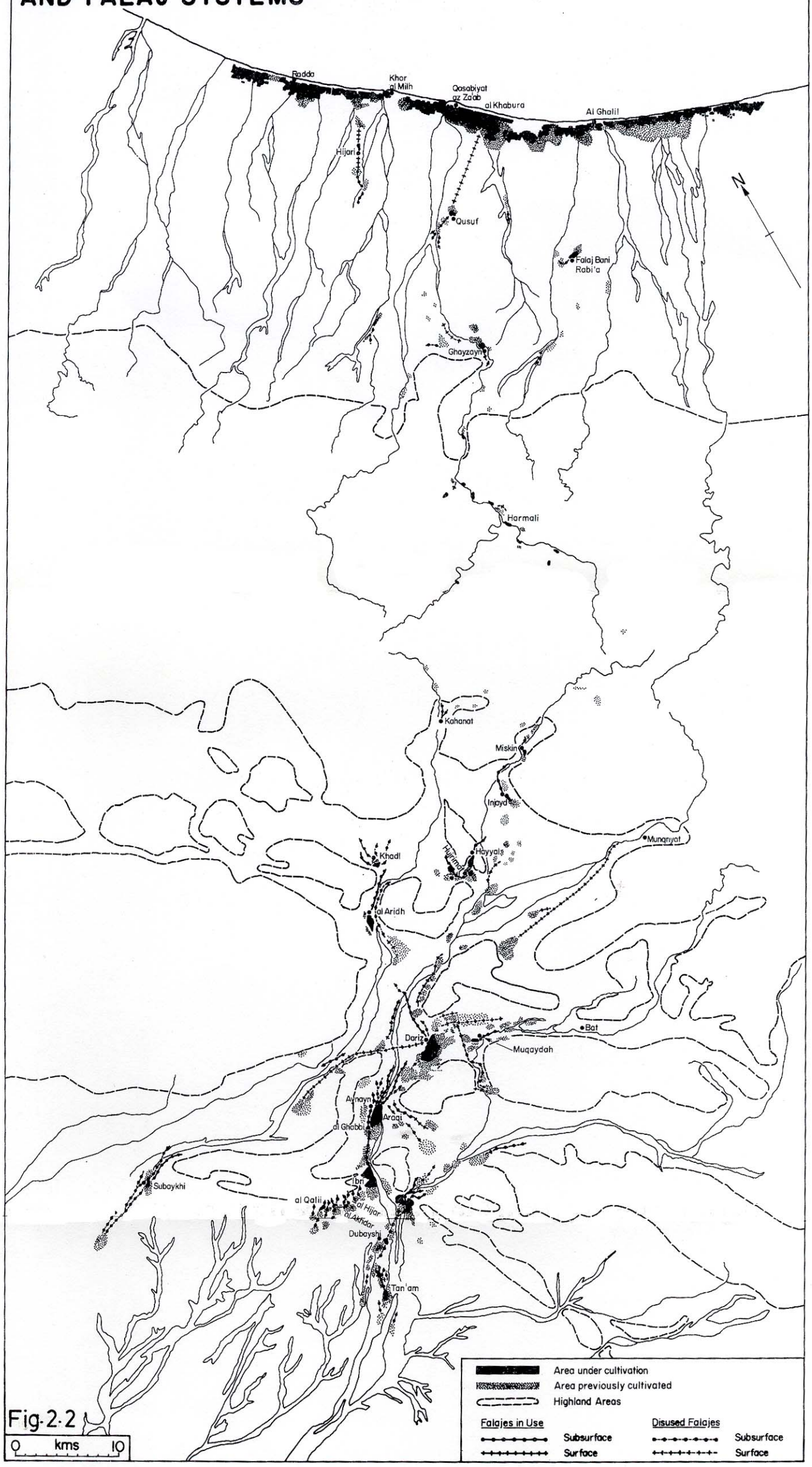


Fig. 2.2

terminated by structural controls. On the southern side, however, the core of volcanic rocks is flanked by a series of softer sedimentary rocks. This basic difference is reflected in the topography and the geomorphology, and affects the occurrence and exploitation of groundwater and thus settlement patterns.

B - PHYSIOGRAPHIC REGIONS

Apart from division into wadi systems, the area can also be divided into six physiographic regions (see fig. 2.1).

(i) Mountain range unit (A)

This is an area of pronounced relief common to the drainage basins flowing both to the North and the South. The mountains rise abruptly from the northern gravel plain (B), reaching a height of 1828m at Jabal Rais, and consistently maintaining a watershed of over 800m. Wadis in this unit are generally confined in gorges less than 200m across. The drainage pattern is dendritic, in some places controlled by structure, such as the fault line of the upper Hawasina, and in some places superimposed. The lateral confinement of flow means that this is an area where perennial surface water may be found (as at the waterfalls of the Wadi Na'am) but cultivable land is scarce, as slopes are steep. Settlements are therefore typically terraced and fed by the diversion of surface or very shallow groundwater. Scoopholes provide water to the small groups of pastoralists (Shawawi) who live on the periphery of villages and in the less accessible wadis.

(ii) Alluvial gravel plain (B)

The main gravel plain is bordered to the North-west by the Batina coastal strip, and to the South-east by the mountains. It is the remnants of the alluvial outwash from the mountains, broken only by a thin ridge of Tertiary limestone. This ridge appears intermittently along the plain's length, and runs parallel to the coast and some 15kms inland.

The general impression is of a featureless plain, with a few low hills, such as the rise on which Qusuf stands. The series of fans reaching out from the wadi mouths and coalescing are incised by the present active wadis forming shallow gorges in poorly cemented sediments, in which flood flows meander and form braided channels.

This area is almost uninhabited because groundwater is difficult to reach, occurring at depths over 25m, and the outwash gravels are generally coarse and not suitable for cultivation. Pastures beyond about seven kilometres from the coast are poor, so although livestock watering wells extend inland beyond pump wells, not even the pastoralists exploit the water and vegetation over the majority of this area.

Only where a Tertiary limestone ridge forces water to within 15m of the surface is water abstraction possible by traditional techniques, and villages have grown up along the gaps in this ridge. (Qusuf, Falaj Bani Rabi'a, Saynah.) On the whole, this area of plain is something of a 'No Man's Land', and as such affords little hydrological information.

(iii) Batina Coastal Strip (C)

This strip of land, approximately 5kms wide is the major area of cultivation on the North side of the mountains. Behind a long storm beach ridge lies a zone of fine sands and silts, with little gradient and almost no relief. It is an area of uplifted shore, with groundwater within 15m of the surface. It forms the main area of pump well development, with an almost continuous belt of gardens inland of the storm beach, with the main living quarters of the town sited on the storm beach itself.

(iv) The Middle Wadi Unit (AD)

This unit is essentially transitional between the mountains (A) and the lower wadi unit (D) which occurs only on the southern side of the watershed. Topographically the area consists of steep slopes, but has a lower amplitude of relief than is found in the central mountain range, and with a greater covering of rock debris. Wadis are not as confined to gorges of bedrock, but tend to continue to flow in unbraided channels. Gravel terraces at the boundary with the mountains form cultivable areas, for falajes with shallow sources, as at Kahanat, Miskin, Injayd and Munqnyat. Well development is limited to natural wadi terraces and low watersheds.

(v) Lower Wadi Unit (D)

This is an area of predominantly alluvial wash, with low hills of much weathered and shattered rock. To the south-west lies an area bordered by a rim of harder crystalline limestone, which extends almost

continuously to the oilfields at Natih and Fahud. This rim funnels most of the flow from the mountain range through three gaps, the Juffra (Ukhwaybīya), Ibri and Sulayf gaps, and is of the same formation as concentrates groundwater on the alluvial gravel plain (B). In contrast with AD, the wadi channels form only a small proportion of the total area covered with wash. Watershed between catchments are hard to identify, suggesting changes in drainage pattern, and both surface and hydraulic gradients are low.

With large areas of fine sediments unthreatened by wadi spates, this region contains the main interior settlements, each, traditionally, with large date groves. These are mainly supplied with water by relatively long falajes with deep sources. Particularly in recent times, an ever-increasing scatter of pump wells has grown up around these settlements, re-colonising land previously watered by falaj. This is the area from which the maximum of information on groundwater can be obtained, and with unit E is the part most likely to be exploited further in the future.

(vi) Desert foreland (E)

The alluvial fans which have built up between the mountains and the gaps are paralleled by those which have been laid down beyond the gaps. These fans have been eroded into low rolling ridges between which lie flat-bottomed wadis. The areas of finer sediments further out into the desert are more featureless, with less relief.

Water remains near the surface far into the desert, but well development is limited. This is less because of water quality (which is generally

suitable for irrigation near the main wadis) than because of political factors. This area has always been part of Duru' territory, and as a Bedu tribe they have until recently been little interested in cultivating land themselves, and have actively discouraged others from establishing wells in their territory. This is, therefore, an area in which possibilities for future development must be considered despite the limited extent of existing well farming.

The area therefore offers a variety of physiographic environments within which to study the occurrence of groundwater and methods of its extraction and use.

II DESIGN OF RESEARCH

A - APPROACH

There are very broadly two aspects of research methodology. One is the descriptive analysis of new empirical data, within which certain themes can be identified and certain conclusions drawn. The second is the use of readily available data (whether existing or to be collected) which allow the proposal, comparison and re-evaluation of hypotheses. The emphasis in the first is on the collection of data, that of the second is on data treatment. Each involves elements of the other, but the emphasis is different because of the state of existing information upon which each can call.

Applying research techniques to an area as little studied as Oman, requires a level of survey and research seldom still necessary in most parts of the world, and one which must mainly employ an approach suitable for the first type of research methodology mentioned above. Research in such an environment presents a very fortunate and privileged situation in that acquisition of even the smallest amount of data provides opportunity both for presenting new theories on the area itself and for comparison with other areas. Thus it can add to the understanding of the area both directly and indirectly.

The level of available data means that fieldwork constituted a major part of the research in terms of time and effort. It was also found that, working within the context of traditional societies, the aspects on which data were required were often very closely tied to and

affected by others which were not previously understood to be significant. In this situation, pre-conceived ideas of the hydrological environment and the themes to be selected are not practical. Comprehensive investigations cannot be planned until familiarity with the area and with the people has been established, when it is possible to see what types of information it is practical to collect, and what themes can be isolated and studied in detail. The themes of this thesis therefore evolved during the preliminary stages of a water resources survey, from the initial observations made of what data collection was possible, and from the information and problems with which the local people presented the author.

B - AVAILABILITY OF ASSISTANCE

A primary consideration in designing a fieldwork programme is the degree to which information and assistance can be provided by other people. In Oman it was found that local people can only provide a limited framework of measurements or data collection. Their educational background is limited to that of traditional Koranic schools. Primary education was only introduced to the area in 1973, and secondary education does not exist. Electricity is not available except to those with private generators, and modern innovations are of very simple levels by European standards; sewing machines, thermoses, medium-lift pumps, taxis and radios having had the most widespread effect.

Despite the level of technical understanding which most local people hold, it is a very good part of the world to try and obtain secondary

information on water. Being a subject so central to the way of life, it is one which almost everyone is interested in and on which they have information to offer. Using measurements of length and breadth expressed in units of a man's height or armspan (see p.408) and of water quality according to fine differentiation of taste and flows of falaj water in terms of numbers of trees watered in a unit of time, a large amount of incidental information can be obtained. Thus, while very little recorded data existed previous to the survey, this does not mean that none was available other than that observed and measured during fieldwork. It was not found possible to use local observers for the regular collection of measurements (mainly because of educational background), but in other ways they provided a wide variety of useful information.

Only in the case of the meteorological station was it possible to enlist aid in regular data collection. An expatriate laboratory technician from the hospital at Tan'am carried out the observations for 26 months with great efficiency, in contrast to the recordings of rainfall by local gauge readers which turned out to be, at best, unreliable.

In other aspects, and especially in the design of monitoring networks and well surveys, work was confined to that possible for a single person. The underground survey of deep falaj systems was the only exception. Here, for safety reasons, it was not possible for one person to work alone, and therefore the demographic member of the team, also a caver, accompanied the author. An arrangement was made for reciprocation of time spent on this work, so that the author in return did household surveys on some 6,000 people. During the early part of the census it therefore became possible to experiment with certain questions peripheral to the demographic data, on water and palm ownership, some of which were subsequently incorporated into the questionnaires used in a number of settlements. These then provided invaluable information on the water distribution system as

* see Appendix Part 2

a whole to complement individual observed examples and to make comparison between settlements possible, particularly those where no previous written records exist.

C - RESEARCH PROGRAMME AND SAMPLING POLICY

Research was undertaken over a period of three years, during which periods of data collection in Oman were interspersed with data analysis in England. In this way progress could be assessed and further fieldwork planned to complement data already collected. The scarcity of available relevant documentation which has already been stressed was of major bearing both on the chosen programme for sampling and for treatment of the information already collected.

The skeleton plan of work on which the study was hung was as follows:-

PHASE ONE	UK	a) desk study of available information
	Oman	b) reconnaissance field survey
	UK	c) assessment and selection of areas for detailed study
PHASE TWO	Oman	d) detailed research and monitoring of time-based variations
	UK	e) assessment of data and identification of areas in which further detail still required
PHASE THREE	Oman	f) final period of fieldwork
	UK	g) analysis of water samples and treatment of data

Any area, but particularly those for which little information is available, offers infinite opportunities for data collection, and in many fields, enormous statistical populations from which to sample. It is therefore necessary to decide upon a sampling policy.

One can sample a small area in detail, cover a large area with intermittent sampling using a grid or random selection method, or try to combine the two. The third alternative, cluster sampling, was selected, and this was made possible by limiting the area to some 1800km^2. Within this all inland wells (over 600), including five large groups of wells, were sampled (see figs. 2.3 - 2.10) and an area of 200 coastal wells intensively studied with one in ten sampling to either side of the main block. Falaj systems were investigated at different levels of detail, partly depending on villagers' knowledge of maintenance and organisation, and also depending on the state of the falaj fabric and the risks in descending the underground sections.

A high proportion of the sample well population was used, because as Stoner points out (1) while a 70% sample provides an acceptable standard error in a population to 3-500 (2%), this only applies if samples are randomly located. To obtain maximum reliability in a biased field where people try to locate wells to obtain maximum water, a higher percentage is used.

Time-based sampling of a monitoring network was limited by the logistics of being able to sample a number of points regularly, without this taking up a disporportionate amount of time, bearing in mind the problems of access to sites and the time taken simply travelling between them. A network of forty sites was therefore

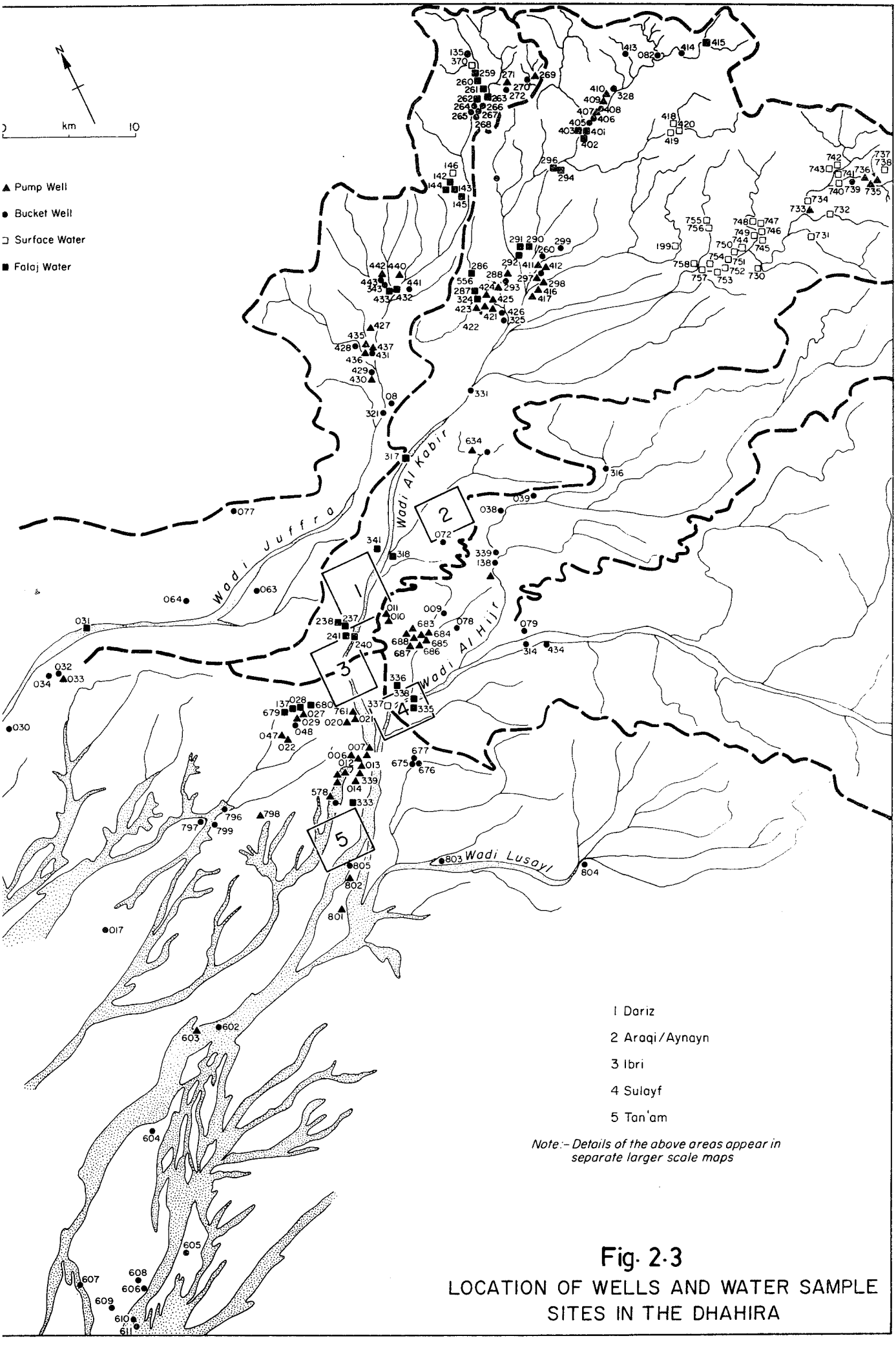
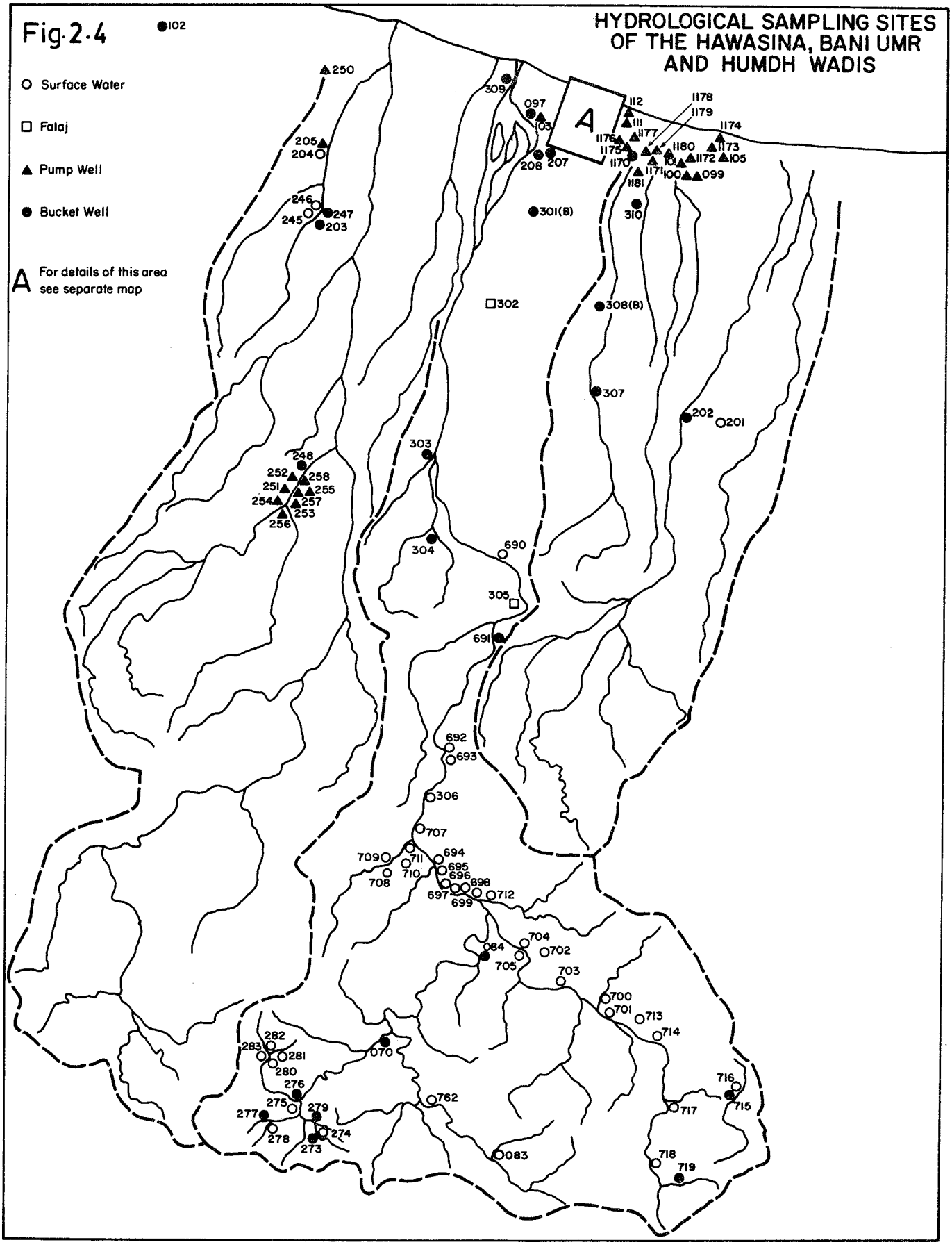
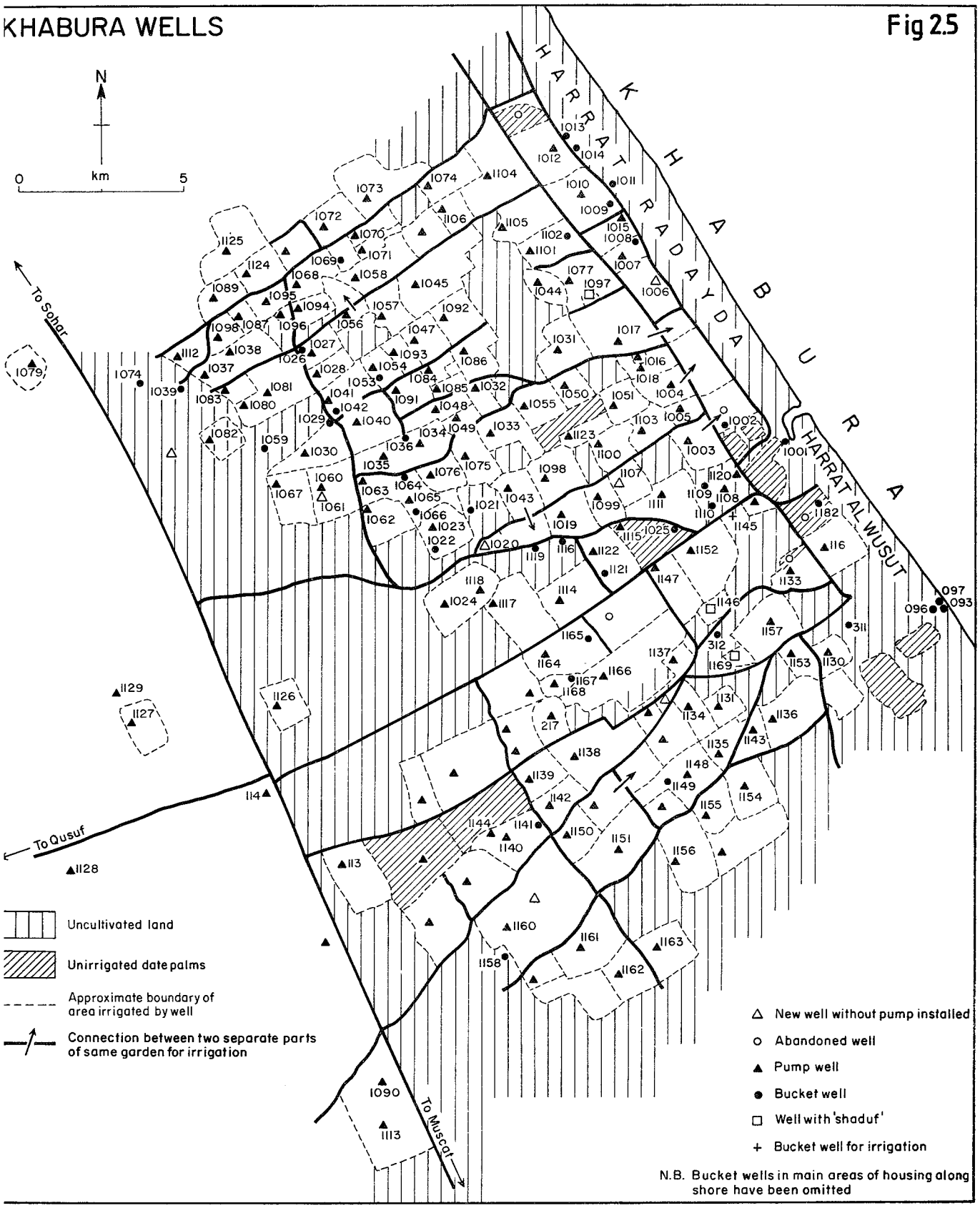


Fig. 2.3

LOCATION OF WELLS AND WATER SAMPLE SITES IN THE DHAHIRA


Fig. 2-4
HYDROLOGICAL SAMPLING SITES OF THE HAWASINA, BANI UMR AND HUMDH WADIS
Surface Water
Falaj
Pump Well
Bucket Well
For details of this area see separate map
A
102
250
309
097
103
112
1178
1179
1174
111
1177
1176
1175
1180
1173
1172
105
104
100
099
1170
1171
1181
208
207
205
204
246
245
247
203
301(B)
310
302
308(B)
307
202
201
303
248
252
258
251
255
254
257
253
256
304
690
305
691
692
693
306
707
709
711
694
710
695
708
696
698
697
699
712
704
084
702
705
703
700
701
713
714
716
715
717
282
283
281
280
070
276
275
279
762
277
278
274
273
083
718
719


KHABURA WELLS
Fig 2.5
N
0
km
5
KHABURA
HARRAT RADAYDA
HARRAT AL WUSUT
To Sohar
To Qusuf
To Muscat
Uncultivated land
Unirrigated date palms
Approximate boundary of area irrigated by well
Connection between two separate parts of same garden for irrigation
New well without pump installed
Abandoned well
Pump well
Bucket well
Well with 'shaduf'
Bucket well for irrigation
N.B. Bucket wells in main areas of housing along shore have been omitted

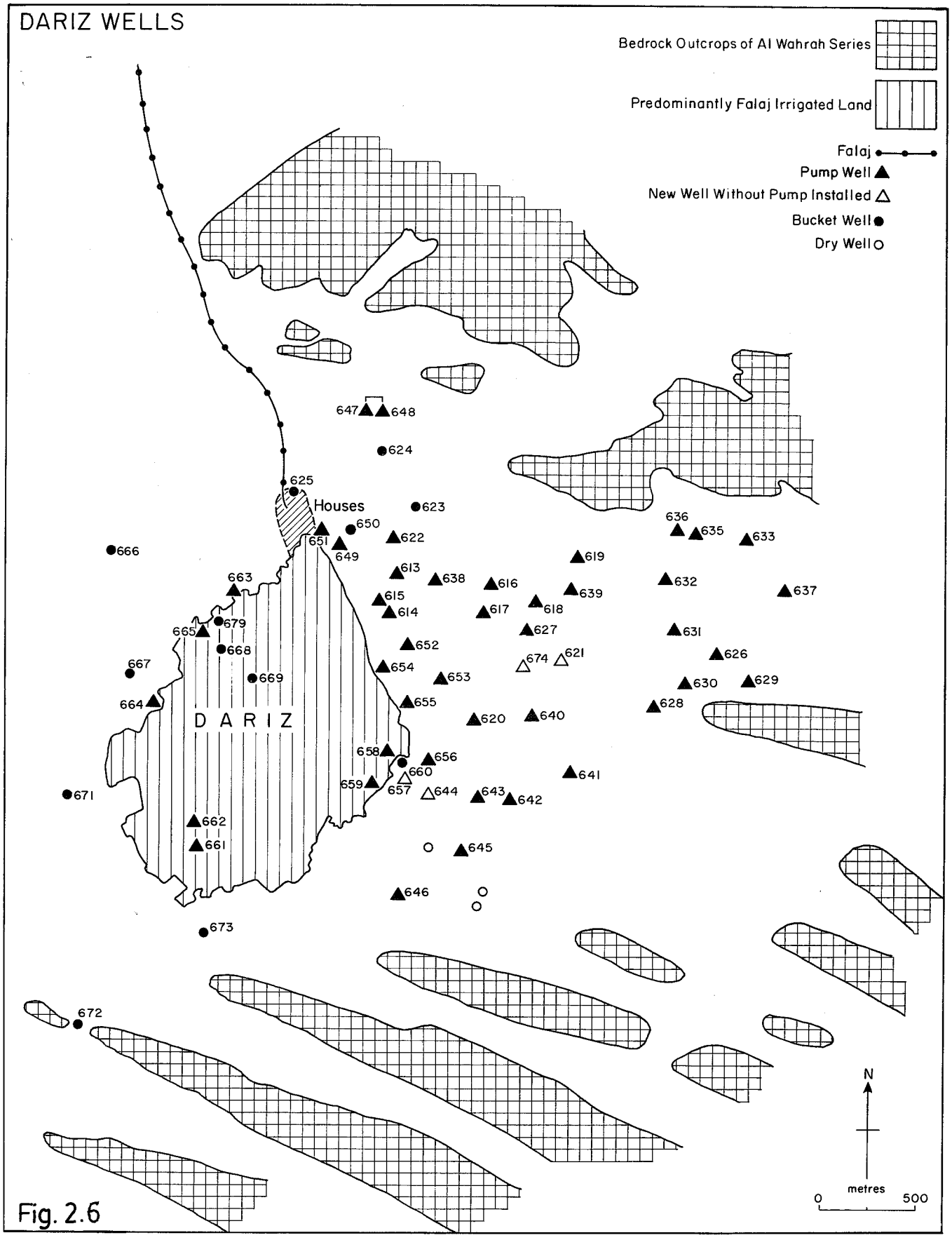

DARIZ WELLS
Bedrock Outcrops of Al Wahrah Series
Predominantly Falaj Irrigated Land
Falaj
Pump Well
New Well Without Pump Installed
Bucket Well
Dry Well
Houses
DARIZ
647
648
624
625
623
650
651
649
622
666
663
679
665
668
667
669
664
652
654
653
655
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672
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633
619
613
638
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632
637
615
614
617
618
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N
metres
0
500

Fig. 2.6

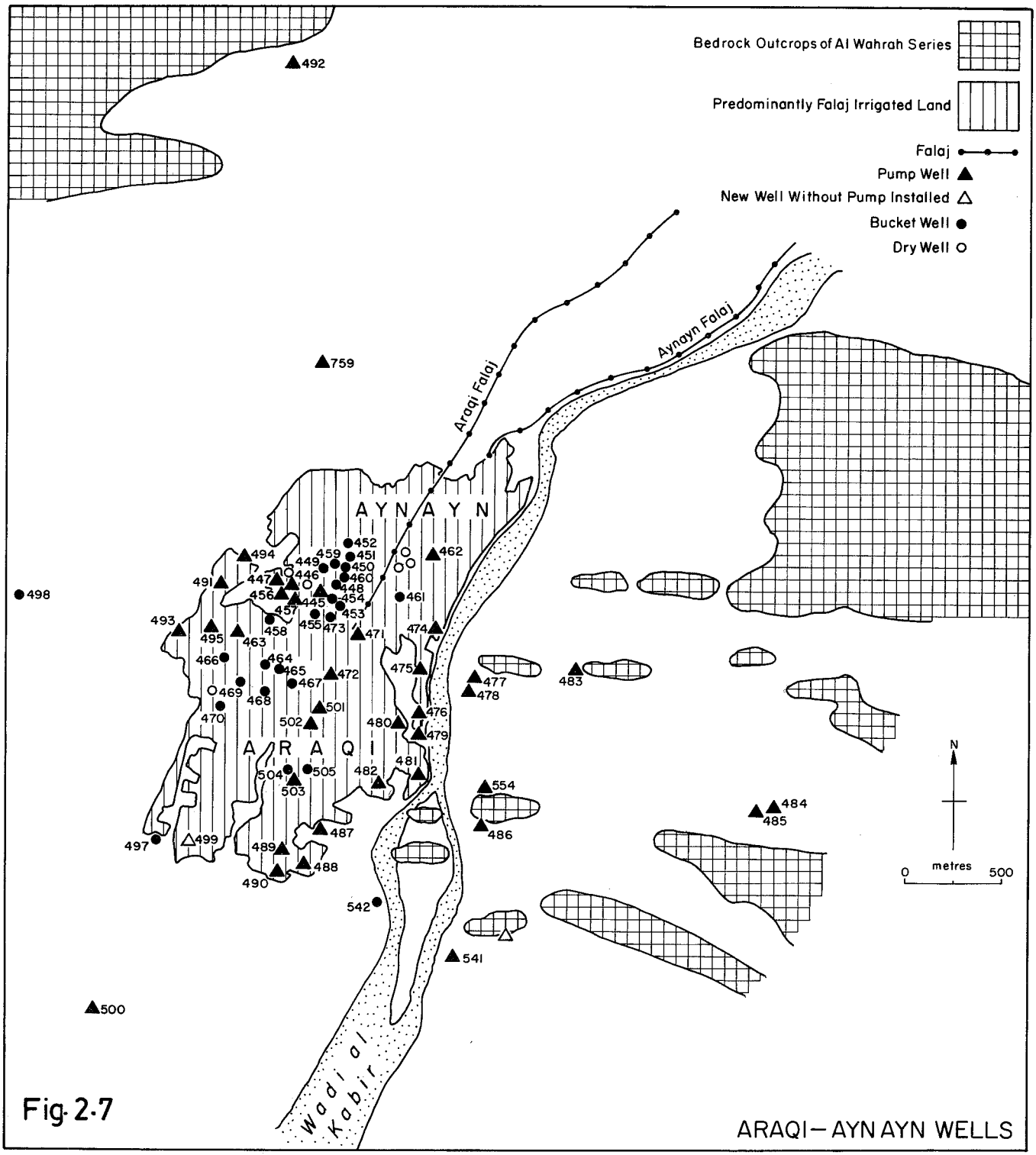
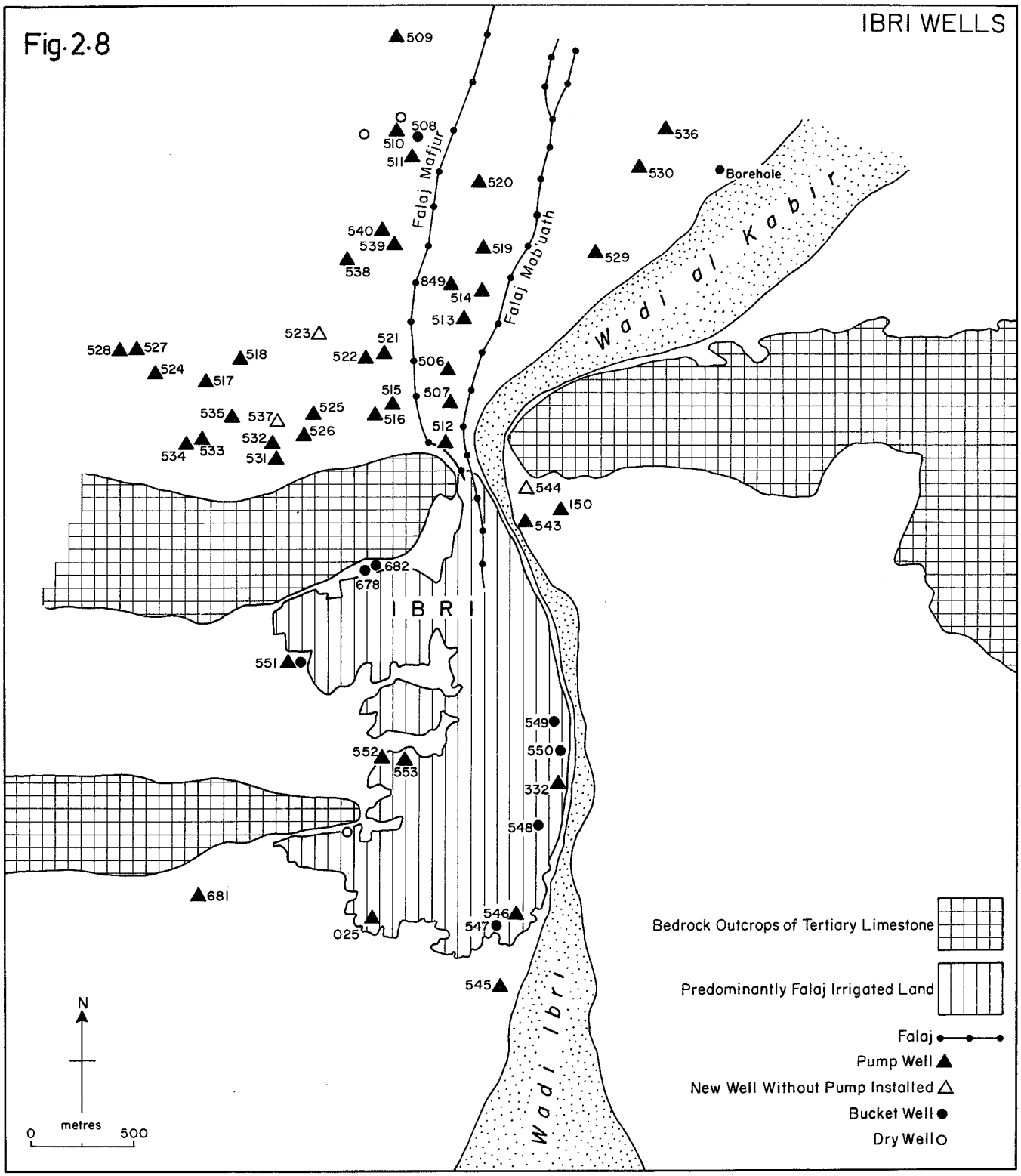
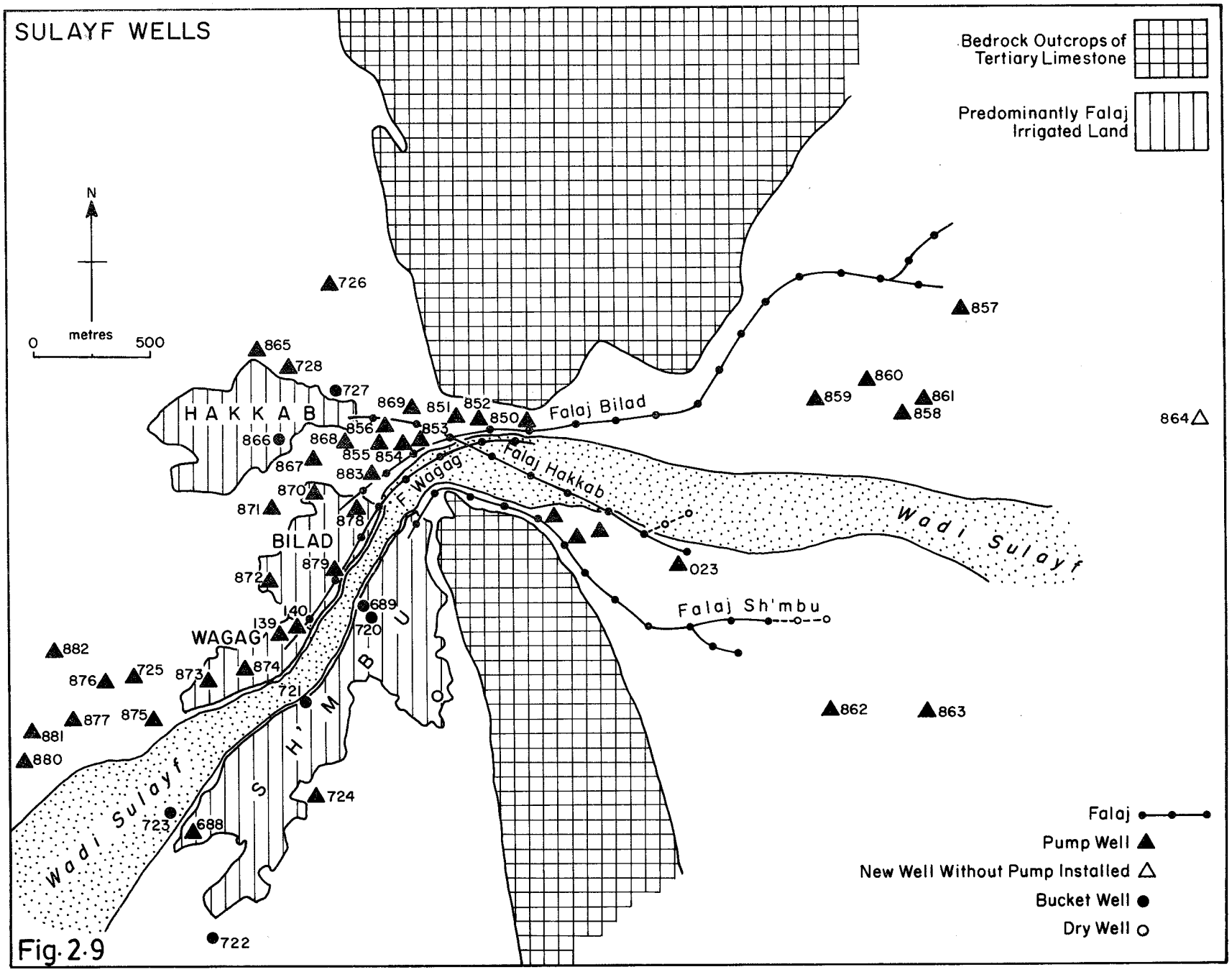
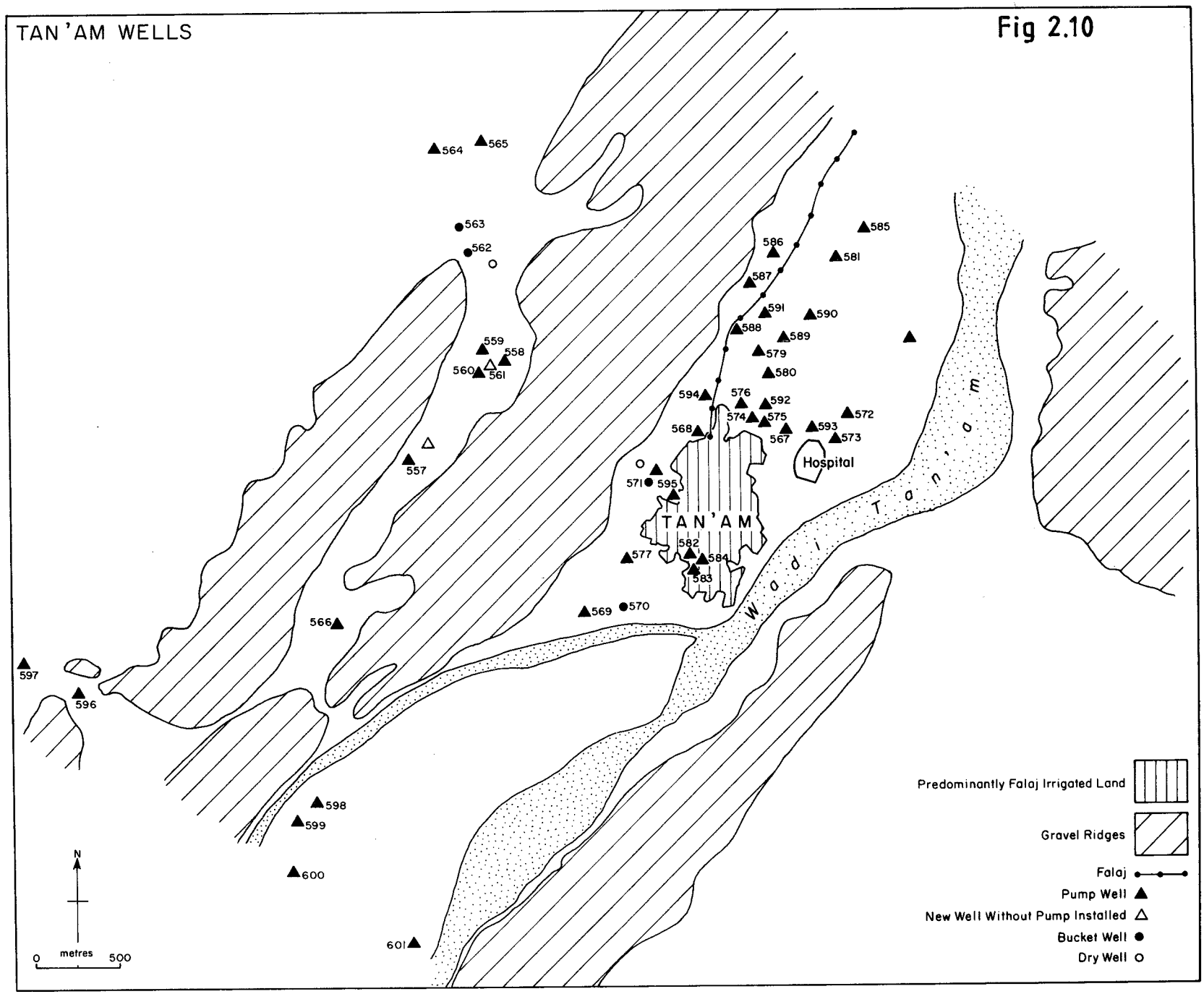


Fig. 2-7

ARAQI – AYN AYN WELLS


Fig.2.8
IBRI WELLS
509
508
510
511
Falaj Mafjur
520
536
530
Borehole
540
539
538
519
529
Falaj Mabuath
849
514
513
Wadi al Kabir
523
521
528
527
524
518
522
506
517
515
507
535
537
525
516
512
526
532
534
533
531
544
150
543
682
678
IBRI
551
549
550
552
553
332
548
681
546
547
025
545
Wadi Ibri
N
0
metres
500
Bedrock Outcrops of Tertiary Limestone
Predominantly Falaj Irrigated Land
Falaj
Pump Well
New Well Without Pump Installed
Bucket Well
Dry Well


SULAYF WELLS
Bedrock Outcrops of Tertiary Limestone
Predominantly Falaj Irrigated Land
N
0 metres 500
HAKKAB
BILAD
WAGAG
SHIMBU
Falaj Bilad
Falaj Hakkab
F. Wagag
Falaj Sh'mbu
Wadi Sulayf
Wadi Sulayf
726
865
728
727
869
851
852
850
856
853
866
868
855
854
867
883
870
871
878
879
872
140
139
689
720
882
876
725
873
874
721
877
875
881
880
724
723
688
722
857
860
859
861
858
864
023
862
863
Falaj
Pump Well
New Well Without Pump Installed
Bucket Well
Dry Well
Fig. 2.9


TAN 'AM WELLS
Fig 2.10
564
565
563
562
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586
581
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579
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558
560
561
580
594
576
592
574
575
572
568
593
573
567
Hospital
557
571
595
TAN'AM
582
577
584
583
Wadi Tan'am
569
570
566
597
596
598
599
600
601
N
0
metres
500
Predominantly Falaj Irrigated Land
Gravel Ridges
Falaj
Pump Well
New Well Without Pump Installed
Bucket Well
Dry Well

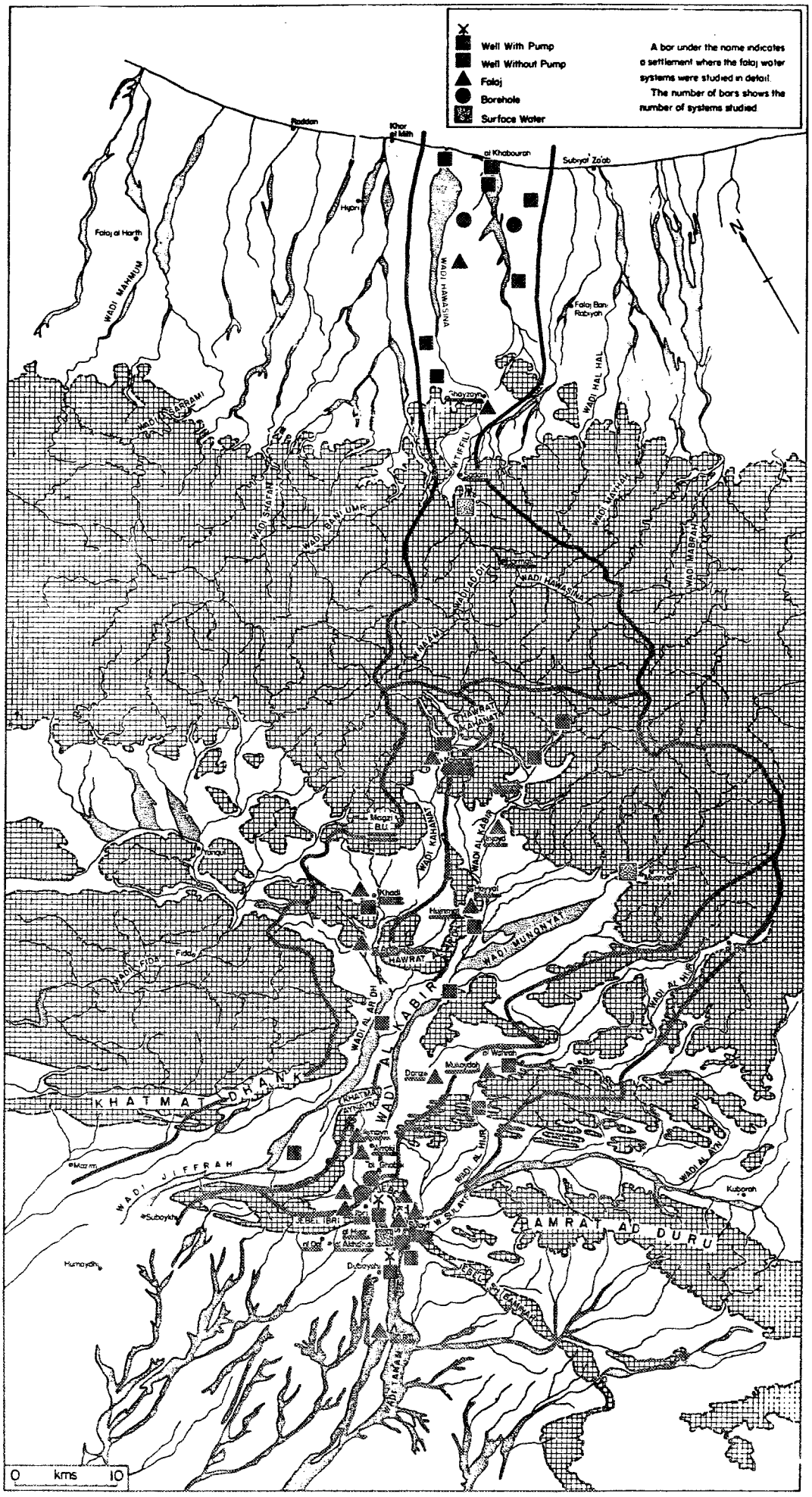
designed (see fig. 2.11). The result is that data are available from sampling both over time and space.

D - PHASES OF DATA COLLECTION

The design of a fieldwork programme generally follows a desk study, and this survey was no exception (2). With little information to call upon, however, this period of the research was restricted to three months, and was also used to order and assemble all the necessary sampling and measuring equipment and to undertake an intensive Arabic course. At this stage an introduction to the area was obtained from map interpretation of the K668 series, to gain an idea of the wadi systems, physiography, geology and the patterns of settlements within the catchments. Air photos were used for more detailed work on cultivated areas, surface hydrology and physical regions, and were later used in the field to make base maps for plotting well and falaj data.

The K668 map series provided a valuable insight into the environment within which the work was to be carried out, but once in the field its limitations became apparent. Being drawn from aerial photographs with very limited ground control it is not surprising that place names are sometimes confused or non-existent, and spot heights only accurate to 30 metres (3). There are no contours and individual wells or falaj systems are only marked in a few isolated instances. It was therefore necessary to design a programme of work which started with the

Fig. 2-11 MONTHLY MONITORING SITES 1973 - 1974 FOR WATER SAMPLING



collection of the most basic data, such as village names, well sites, falaj sources, and the line of watersheds on low ground. In the first phase, therefore, general information was gathered on the area as a whole. Experiments were carried out to find what sorts of relevant information could be most easily collected and what was beyond the available equipment and local technology. It was at this point that, for instance, it became apparent that aquifer storage coefficients could not be reliably ascertained, and that formal test pumping of individual wells was impractical. It was also during this period that local vocabulary on hydrological topics was learnt, and that walis and shaykhs were visited to explain the purpose of the work, and the kind of information required. Water samples were collected throughout the area (spot sampling) to obtain ideas on the general pattern of quality, aquifers and water movement. These data also helped in the planning of the coastal and interior monitoring network, making it possible to assess the convenience of various sampling circuits and the degree to which each site was representative of the system.

This first phase lasted for six months and was followed by examination of the results.

The second phase lasted a year, from October to October, in order that monitoring might cover a year's cycle of hydrological events. During this time all wells and falajes of the Interior were visited and a selection of those on the coast. The 100% sample of Interior wells was decided upon after the initial survey showed very marked differences in well characteristics over very short distances. This

was a period of intensive data collection, with little time for consideration of results. At the end of the year, a return to England made it possible to assess the results of the work and see those aspects or areas not sufficiently covered.

A return to Oman for the third phase of fieldwork followed in January 1975. This was for a shorter period of five months, which was spent partly on a detailed study of 200 coastal wells, and partly on filling the gaps remaining in information gathered during the previous years. On returning to England the first task was some 3,500 water analyses, which had to be done before the data collected could be assessed as a whole.

III DATA COLLECTION PROCEDURES

A - SOCIOLOGICAL ASPECTS

The majority of sampling sites throughout the area are closely tied to particular communities. Thus the procedures involved are not simply those involving the measurement of chosen parameters. Particularly as information was required from villagers and their goodwill was essential, it was necessary to observe the social niceties of the local way of life, and to make considerable efforts to establish a degree of understanding of the purposes of the work. A certain sequence of activities therefore evolved in the study of the physical and social hydrology of an area linked to a particular settlement.

Points of access to water, however far from permanent or temporary habitation, are the province of a tribe and thus are strictly not accessible without permission. Wells are particularly zealously guarded in the desert foreland as recent tribal disputes between the Duru' and Afar had led to the filling in of several wells. At the same time certain falaj systems are also the subject of inter-tribal tension. In particular, Araqi falaj flows under Aynayn fort, a formidable fortress guarded by the Bani Ghafir of Dariz who previously destroyed one of the largest falajes in the area (in the 1870s) which supplied al Ghabbi, a now deserted settlement immediately south of Araqi. The Bani Ghafir are said to have installed an iron sluice gate under the fort, enabling them to shut off the supplies to the people of Araqi (in particular Balush and Abri tribesmen), or at least to threaten so to do. Certainly large support slabs were

glimpsed in the section under the fort, but it was decided to avoid all underground survey of this system because of the political situation.

As is apparent, a hydrological survey must pay attention to other elements of life than water. Tribal areas, affiliations and recent history are all important basic information to be gathered before one moves into an area. Both Lorimer (4) and Wilkinson (5) provide useful information, and local people are generally very willing to explain the situations - especially affairs in settlements other than their own.

After the initial work of establishing the shaykh who lays claim to an area or individual well, there is a hierarchy of visits necessary to explain what is required and why, and to present letters from the government, and obtain local permission to start work. Especially in the early stages, therefore, the pattern of sampling was partly dependent on the time which was available for formalities, which must be balanced against that required for collecting data. In terms of protocol it is necessary to visit the wali of the district first, followed by the shaykh (or shaykhs in order of their importance) and if there are falajes or mosque wells to be investigated, the wakīl and imam (head of the falaj and religious systems respectively). This may take a whole day at each settlement, and although the formalities take so long, much useful information can be gained during them. The people visited for permission are also those generally with the greatest fund of local knowledge. In a country with no tax but the (Waqf) tithe and with a new, more liberal government, respondents

were not unwilling to provide information, and only in one village (Miskin) did checked information show provision of purposefully misleading data.

The lesser tribal awareness on the coast and the paramount importance of the Hawasina shaykh made introductory work less complex in this area. Nevertheless in both areas, formalities at the wilayat and shaykhly levels are not all that is obligatory. Hospitality was also necessarily (and enjoyably) accepted from well-owners and falaj workers while questions were asked about organisation of irrigation, hours of pumping, costs of excavation, etc. If the co-operation of local people is to be assured in such an area, one has to accept a compromise between the speed at which one would work in England and that which is compatible with the Omani way of life.

B - MEASUREMENTS AND QUESTIONNAIRES

(i) Falaj Systems

Within the Interior settlements, the falaj was generally visited before any wells. Being the communal water supply and the main source of drinking water, local interest is focussed on this system. Any work carried out on it attracts this interest and so makes it possible to spread information as to the purpose of the work and the details required to all those who have not heard through the shaykhly grapevine. Fortunately, as a result of early falaj surveys and of

census work by a demographer, it was possible to plan improvements to certain village water supplies and to obtain money from the Diwan (Sultan's purse) for the implementation of those plans. This quickly increased the degree to which the hydrological work was accepted, and the favourable response from local people to it.

After obtaining permission to work and information on the running of the falaj, a survey was made of flows throughout the system. This involved a visit to the motherwell area. Here, the position of the motherwell was ascertained and, with a member of the falaj organisation, or with another member of the research project, the uppermost section of tunnel with air space was entered. The depth to water at this point was generally 10-20 metres, and therefore it was necessary to tether a rope to a Land Rover parked as near the shaft as safely possible. Whenever possible, the major sources and the lesser adits were all visited to investigate differences in water quality and the contributions of water from the different parts of the system.

The velocity of flow was measured with a Braystoke current meter with a 5" (130mm) propeller. The procedure eventually used for all falajes was to take the maximum number of readings without overlapping a radius of 6" from the propeller central axis. Smaller numbers of measurements were tried, including those at the standard 0.2 and 0.8 depths (6). These standards are, however, designed mainly for natural water courses and channels in which channel sides are rough and the width is greater than the depth. In the underground sections especially, falaj channel dimensions are such that depth is

often greater than width (see p.440), and the walls and floor are often relatively smooth. In this case it was found that measurements at standard depths were then less reliable when repeated in the same stretch of water but with different cross-sections, than measurements using a number of readings which varied with the area of the cross-section. This was especially so where measurement sites were near a bend in a channel, or where the channel floor sloped towards one wall. Readings per cross-section varied between 15 and 2. Lowest flows were measured by cistern dimensions and filling times.

Flow measurements are not easy in the confined space of a tunnel. It is necessary to perch above the water during measurements and yet be able to measure channel dimensions in water which may be over a metre deep and travelling at as much as one metre per second. In this case greater inaccuracy was found to occur within the flow calculations from the measurements of channel dimension than were possible from current meter calibration. Nevertheless readings were repeatable to within $\pm$ 5%.

Flow was recorded at a minimum of three or four cross-sections in the underground section, and at as many as fifteen in some of the longer falajes. At the first surface access, at a point of regular channel dimensions, the measurements included duplicate readings at the one or two central points in the channel (one with odd number of points, two with even). The cross-section used was marked and depth to the surface of the water was measured from a datum line. This site was then used for monthly monitoring of variations in flow. To reduce the time necessary for flow recording, except on the largest falajes, only the one or two central points were measured every month

with duplicate readings of a minute. Every third month, or whenever the duplicates varied by more than one r.p.m. the flow was measured with the full procedure, and channel dimensions checked for silting or erosion.

At a time when water was flowing to the furthest gardens the survey from source to first access shaft was continued on to the extremity of the irrigated area. In this way it was possible to identify the parts of the system where water was gained and those where it was lost, and to quantify these credits and debits and so the efficiency of the system as a water carrier. In some cases flows to individual trees were measured, in others the time water flowed to each garden was ascertained and the number of trees or area of field crop established by direct observation.

Information gathered by questionnaire varied from village to village in the Interior falaj settlements*. In some, water rights and tree ownership were recorded for every householder and so it was possible to obtain an average value of water per tree. In others it was only possible to gather information on the ratios of owned and rented water (see p. 328) and more general indications of how the system was run. This was particularly true in those settlements where the falaj was looked upon as the private property of the shaykhly family. In this case the system was less well-defined, and political factors made collection of data less reliable. Whenever possible data obtained from individuals was checked with information provided

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*Footnote: As mentioned previously, detailed information was gathered during the census as part of the house-to-house survey. The author formulated the questions to suit each falaj system, and collected the data from over 40% of the respondents, the demographer collecting the rest as part of the census.

independently by the wakil. In remarkably few cases were significant differences apparent. The same information was collected for the mountain diversion channels with surface water sources.

(ii) Wells

For the well survey the procedure was a little different. Being the property of an individual rather than a community, the number of people from whom information can be collected is far more limited. Thus, while less time is spent on formalities, more has to be spent in searching for respondents. Wells were generally only visited when someone was working the pump, but in the case of some coastal well-gardens this meant visiting every day for a fortnight or three weeks before someone was found to be present. A few wells (less than 5%) were apparently temporarily or permanently abandoned, while the owners or tenants worked abroad, and in these cases information was limited to direct measurement. When the well-owner or user was present questions were asked not only on the physical aspects of the system, but also on costs, type of ownership, place of residence and history of the farm.

The measurements taken depended on whether the pump was working or not. Depth to standing water level could generally be ascertained (90%) and in most cases depth to pumping water level too (70%), using an electrical water level recorder.

Wherever possible (approximately one in eight wells) discharge at working pumping speed was measured using a cistern or oil drum of known dimensions. At other wells discharges were estimated by

eye. This method, after 12 months of observations, became accurate to within 2%, and was used in the majority of cases after this.

Informal questionnaires were employed to obtain information on the approximate fraction of full-speed at which the pump was run, the average number of hours the pump was run per day, or per week, irrigation cycles, and for details of well history including recent maintenance costs, indications of declining yields and problems of pump repair. The ability of respondents to answer these questions accurately varied. In general, since wells cost as much as a hundred times as much as those on the coast to excavate, people inland had an interest and pride in the performance of their wells, and kept some record of how much money had been spent on various operations. They were therefore both able and eager to provide information. This made a striking contrast with coastal wells. Here wells had been longer established and seldom provided more than a cooler house site for the summer months. Well-owners were thus less aware of expenditure and well history, since well gardens changed hands more often, never caused problems of low yield, and were not required to produce a good return for high capital expenditure. Records for inland wells therefore tend to be more complete than for those on the coast.

Irrigation data, comparable with that for falaj crops, was collected wherever possible (some one in ten wells). The lower flows from pumps, however, made it impossible to measure flows and calculate water losses. Either from the well itself, or from the spoil heap

of newly dug or cleaned wells samples of the principle aquifer(s) were taken and the details of colour, texture, degree of cementation, ease of fracture, presence of joints or bedding planes were recorded. Drinking wells with no pump also provided water level and water quality data.

(iii) Water Sampling

In all cases where water samples were taken for analysis the procedure was the same and followed standard practice (7). As far as possible, a representative sample was taken. In channels water that flowed fastest was taken, and well samples were not taken till the pump had been running for five minutes. Where no pump was mounted or where the pump could not be run, a clean bucket kept specifically for the purpose was filled by immersion as deep into the water as possible. pH and temperature were read immediately. pH was measured with an EIL 30C meter and dual (combined) electrode with a 25^{o}C compensator. A resistance thermometer was not used because the difference it made to the value was found to be within the accuracy of the meter. Temperature was read to 0.05^{o}C on a 400mm partial immersion thermometer. Mortality rates for both thermometers and electrodes were high because few local people understood their fragility. This, however, did not affect results because standardisation for pH was carried out with pH 4 & 9 buffers before and after every sample measurement. Unfortunately delivery of electrodes was somewhat erratic, and a number of samples in late 1974 had to be collected without pH readings.

Two 250ml polythene bottles were filled with water at each site. As far as possible air was excluded, and bottles were put in 'Coleman' flasks and kept at constant temperature until arrival at the laboratory. Here, within 24 hours of collection, conductivity and alkalinity were measured. Conductivity was not measured in the field, because it was found that, while temperature compensation is possible for the sample, the meter bucket itself may store so much heat that readings were not reliable. Thus measurement was delayed until all samples were at approximately the same temperature, and the meter kept in an almost constant-temperature environment. Even so, it was found that for maximum repeatability of results it was necessary to employ a KCl standard for every set of samples.

For alkalinity and conductivity measurements a small quantity of water from one bottle was used. After this, the rest of the water from both bottles was filtered. One bottle was then filled with the filtrate plus 0.5ml of acetic acid (glacial) and 0.5ml of phenylmercury acetate (in 1-4 Dioxan) were added to acidify and preserve the sample. The bottle was then closed, sealed airtight, and numbered on base, top and side with the sample number. It was then stored at constant temperature, out of direct sunlight, until despatch to England.

The major part of the analyses, the measurement of stable ions, was carried out in England, as neither time norequipment were available in Oman. Cations measured were calcium magnesium, sodium, potassium, lead, zinc, cadmium, molybdenum and copper.

Initial results showed that aluminium levels were 90% below

detection limits by atomic absorption spectrophotometry, and iron low and unstable because samples could not be filtered immediately upon collection. Boron was only measured on spot samples, and because of the length of the procedure and need for borosilicate-free equipment, these were given to the Ministry of Agriculture, Fisheries and Food's laboratories in Newcastle for analysis. Of the anions measurements of chloride, sulphate and nitrate were undertaken, the first of these by a technician and the other two by the author. Methods were as far as possible kept compatible by maintaining experimental errors within $\pm$ 2%.

Bacterial samples were collected separately, in sterile glass bottles kept in ice. They were taken immediately to the Petroleum Development (Oman) hospital in Mina al Fahal, where they were incubated. Faecal and non-faecal cell counts were made and bacterial type identified for individual colonies.

The above are the procedures used for the collection of specific data where comparability between sites was required. In such cases the procedure needs to be consistent, so that variations found can, with some certainty, be attributed to real differences, rather than to differences in technique. On the other hand, a large amount of data was collected during conversations, reconnaissance visits and unplanned encounters. Questionnaires were not rigidly kept to, but at each site, during conversation the basic details of well or falaj history and present use were elicited. Farmers are happy to talk about water supply: it is, after all, their major concern, and it it is an interest common to interviewer and respondent. Hence direct quick-fire questions and rigid questionnaire format could be avoided.

IV DATA PROCESSING

A - DATA AND ITS STORAGE

The data collected is of varying detail and levels of accuracy, which can be categorised as follows :-

1) the systematic measurement of several parameters at many sites

2) the collection of particular descriptive information at many sites

3) the observation of variations over time

4) the gathering of information of a type specific to a particular site.

The treatment of these data as a whole varies both with its type and the reliability which can be put upon it.

The result is a large amount of information, both numerical and descriptive, some of which forms the basis for the thesis. Details of some 850 wells and 40 falajes are combined with some 13, 000 chemical analyses and over 5000 meteorological observations. The details of well and falaj include both quantitative and qualitative data, while chemical and meteorological data are purely quantitative.

Different methods of storage were therefore chosen for the two types of data.

Meteorological and chemical data were mainly analysed by computer and so were stored on file within the NUMAC system, and also on punch cards. Well and falaj details were card indexed with punch coding for rapid selection of particular categories or parameters.

B - PRIMARY TREATMENT

The quantitative data collected contained many parameters whose chief value is only realised when combined with another data set. For instance, the main application of meteorological data apart from rainfall figures is to synthesise temperature, humidity and run of wind observations into evapotranspiration values. This and other similar calculations require a series of time-consuming and repetitious computations well-suited to the advantages of a computer.

Programmes were used for a variety of purposes. Firstly a copy of the Meteorological Office (Bracknell) Penman programme was obtained and modified by the author for the difference in oasis effect that local conditions required. This then calculated weekly and monthly potential and actual evaporation.

An existing programme was also used to process chemical data and calculate the relative saturation of samples with respect to the principal minerals associated with carbonate equilibria. Wigley's

programme allows for ion-pairing, and with slight modification was capable of treating all of the samples analysed. The calculations involved are even more time-consuming that the Penman one, and it had previously taken the author of the thesis two days to calculate the relative levels of saturation for only four of the simplest minerals.

For isolating types of water, and identifying their suitability for irrigation it was necessary to compute ionic ratios, sodium absorption ratios and bicarbonate hazard. Programmes for the calculation of these parameters were written by the author for use on the NUMAC computer system.

At this first level of data treatment water level information for pumping wells was turned into specific capacity data, pumping times into seasonal abstraction rates and recession curves into changes in storage.

C - SECONDARY DATA TREATMENT

The sample population is limited to those access points already created. On the coast this population is relatively uniform, and closely spaced. Inland, however, groups of wells are isolated, and conditions applying to one group are seldom identical to those in another. Samples, therefore, are often, as in the case of aquifers and their yields, treated in small groups. The maximum number of individuals has been sampled and yet it is still necessary to employ small sampling theories (8). The highest values of well

yields cannot be quantified and samples are not spatially based on random distribution as people wish to site their wells where they are most likely to find water rather than at a point which will provide symmetry for the sampler. Thus generally only non-parametric descriptive statistics can be used (9). It is possible to show, for instance, whether one aquifer provides significantly different yields from another, but it is not possible to establish the mean of the true population or its range. This is also true for rainfall data (see Ch. 4.1) in that the available observations are sufficient to indicate return periods and the length of records necessary to provide a mean value of any statistical significance, but cannot themselves yet provide a mean value in which a high level of confidence can be put.

Some of the information, such as specific capacities, is not absolutely comparable with values obtained from standard pumping tests. Rather the results provide relative values through which it is possible to compare the productivity of all wells. This type of information therefore lends itself well to mapping of values and use of isolines - an old but still valuable tool - where areal distributions are to be portrayed and only broad grouping of values is required. In this study, where much of the data is of comparative rather than absolute values, maps are used frequently in the presentation of data, and visual correlations have still to play a part, until more data become available.

The descriptive element of data treatment is an important stage in the development of theories, and in areas of sparse information

it is a necessary step preceding, not obviating the necessity for more detailed analysis. At an intermediate step, where data are still selective not random, descriptive statistics can be introduced. These are used where data allow, but no higher level of treatment is attempted with figures representing such a small population and a short period in an environment prone to extremes.

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CHAPTER THREE

THE GEOLOGICAL, GEOMORPHOLOGICAL AND HYDROCHEMICAL ENVIRONMENT

I GEOLOGY

A Introduction

B Sequence of Geological Events

C Main formations and their effect on surface and groundwater hydrology

D Conclusion

II GEOMORPHOLOGY

A Introduction

B Previous Geomorphological work on the area

C Sequence of geomorphological events

(i) Phases of erosion and deposition
(ii) Wadi diversion

D The present drainage pattern

(i) Present day catchment characteristics
(ii) Profiles of wadi systems
(iii) Local Profile variations

E Conclusion

III HYDROCHEMISTRY

A Solution and Precipitation

(i) Carbonate Equilibria
(ii) The Salt or Electrolyte effect and the Common Ion effect
(iii) Observed saturation levels
(iv) Processes of solution and precipitation

contd/...

III contd.

B Water Characteristic of Particular Hydrological Systems

(i) Water chemistry and solid geology
(ii) Water in upper wadi reaches
(iii) Water in lower wadi reaches
(iv) Saline or brackish water

C The Effect on the Abstraction and Return of Irrigation Water on Hydrochemical Patterns

(i) Water chemistry and method of abstraction
(ii) The return of irrigation water

D Conclusion

I GEOLOGY

A - INTRODUCTION

The lack of vegetation and soil cover makes the observation of geological features less of a problem in Arabia than in temperate climates. Geology is also the field on which the greatest amount of work relevant to the area has been published. This section is therefore based on a combination of field observation, references dealing with the whole of Oman and one or two which concentrate on Northern Oman in particular. Formation names and sequences are taken from the geological map and notes produced by Koninklijke/Shell (1970).

The area studied was first investigated geologically by Pilgrim in 1908 (1). From this time onwards, geologic commentaries form the major documentary work available on Northern Oman. Lees travelled extensively in the area, and provided the first and only detailed study of the Ibri-Khabūra section of the mountains (2). A field sketch of his covers the whole of the Interior part of the area (see fig. 3.1). Since many of the groups of rocks have retained the names he gave them, the present day classification uses many local place names. The rocks themselves have, however, been studied in more detail in subsequent years in outcrops and boreholes in other areas. Particular attention seems to have been focussed on Musandam and the Trucial States (3, 4, 5) and Dhofar (6).

Literature on the geology of Oman has tended to concentrate on paleontology and stratigraphy (8, 9) and on mineral wealth (4, 5, 10) -

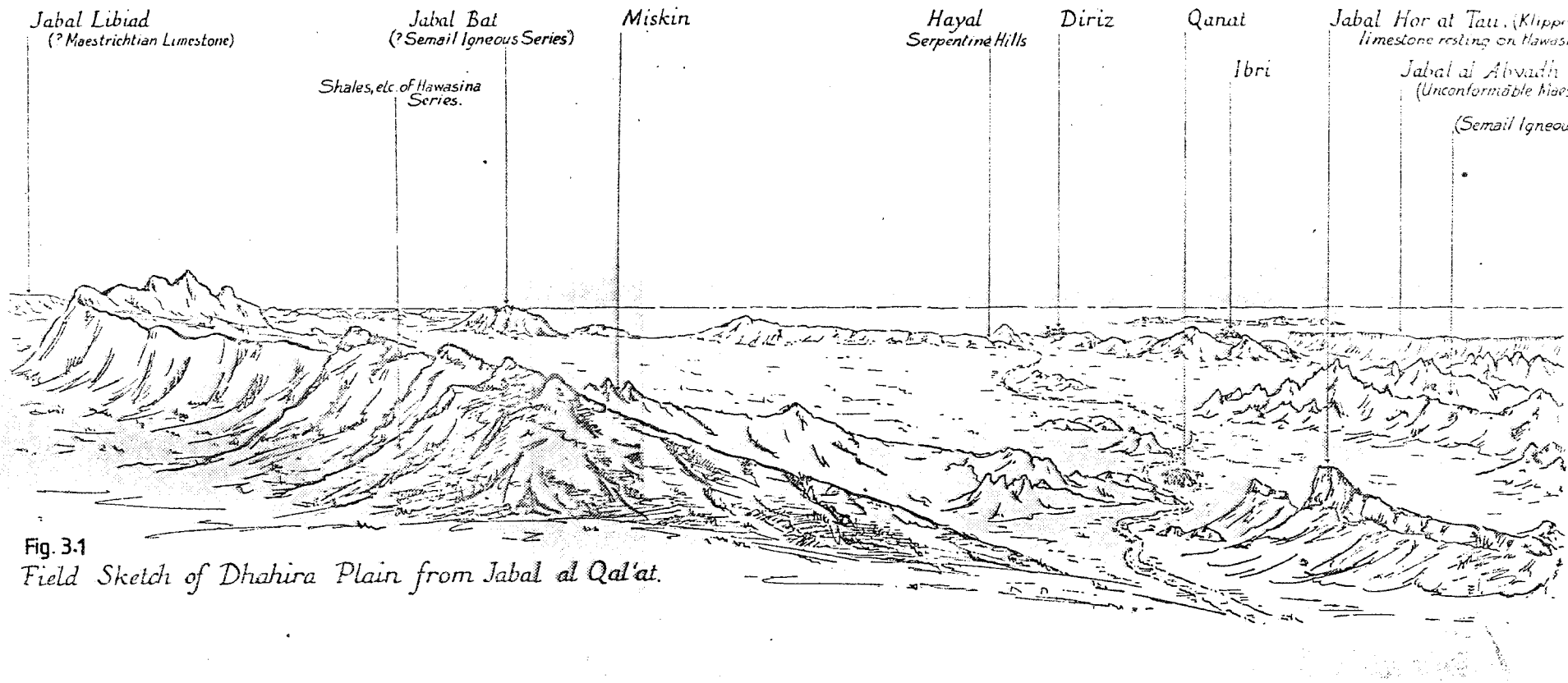


Fig. 3.1
Field Sketch of Dhahira Plain from Jabal al Qal'at.

much of the work being carried out by oil company geologists, Within the series of rocks occurring in the field area, studies have emphasised the degree to which the sequence reflects the stages of oceanic infilling. Interest has been centred on whether the sequence represents autochthony (11, 12, 13)* or allochthony (14, 15, 16). Lithologies have therefore particularly been described in relation to the concept of stages between deep and shallow water environments. No work has previously been undertaken within the field area on the topography and associated geomorphology of these rock types.

B - SEQUENCE OF GEOLOGICAL EVENTS

The area lies to the west of the major outcrop of Palaeozoic rocks in the Jabal Akhdhar region and between the two main area of outcropping Jurassics in the Musandam Peninsula and in the Jabal Kawr/Akhdhar area (see fig. 3.2). It covers an area of sediments and ophiolites ranging in age from Jurassic to lower Tertiary. They are arranged along NW-SE axis at right angles to the axis of the section studied. The majority of the area is covered by rocks which originated either as sediments or extrusions, in an ocean to the North East, associated with the Tethys Sea (18). This ocean was bounded to the West by the Arabian mainland and was

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*Footnote: This theory was put forward by Lees, but all subsequent writers of published articles till 1970 suggested autochthony of these groups. Work by Haremboure and Horstink (17) and by the compilers of the Shell geological map, however, have reverted to the idea that these groups were formed to the North East and later moved to their present site.

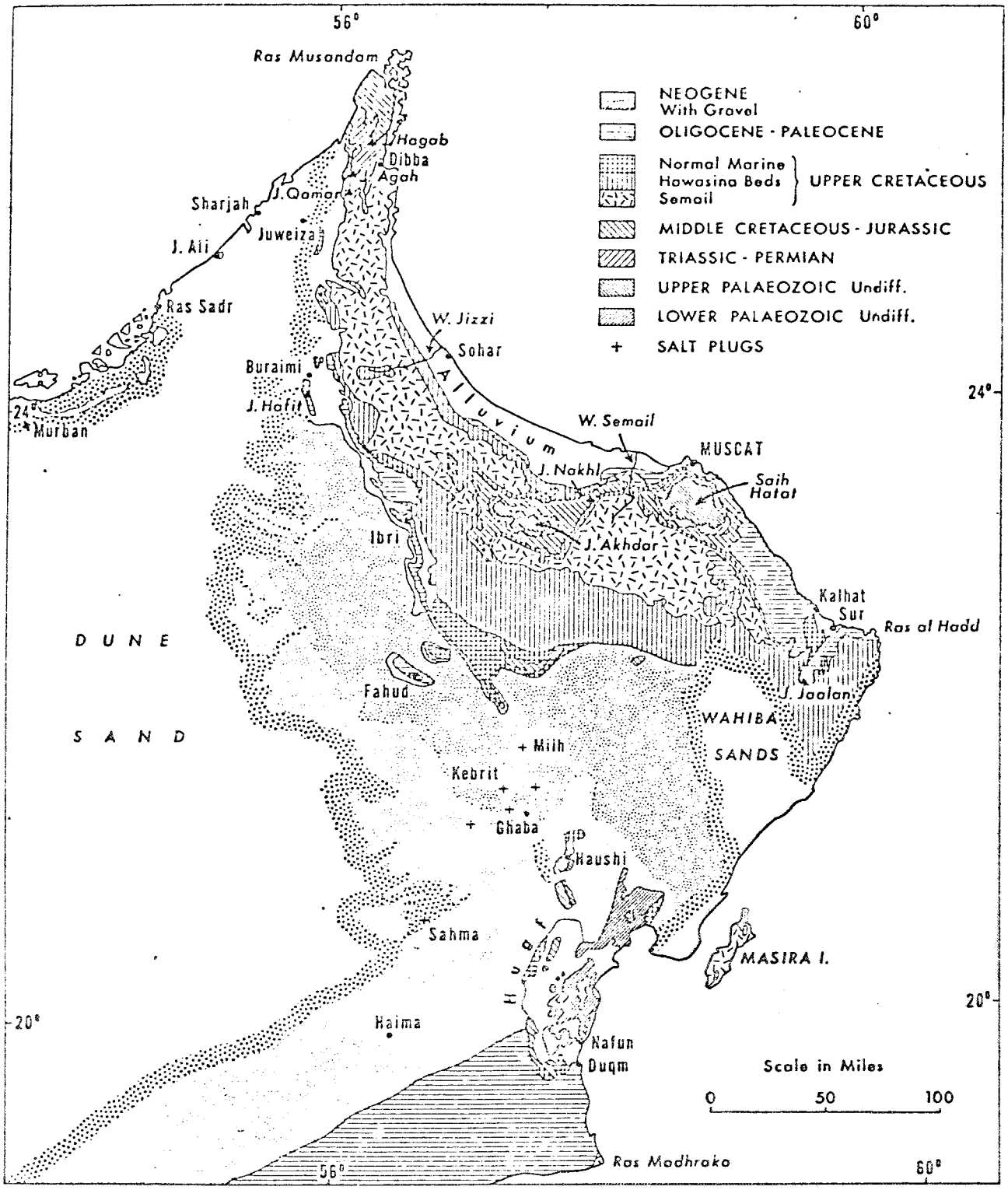


Fig. 3.2 GEOLOGICAL MAP OF OMAN (from Morton 1959 (II)

infilled from mid-Permian to Cenomanian times with shallow water carbonates, radiolarian cherts, mudstones, sandstone and limestone turbidites and conglomerates of the Hawasina series and from Permian to upper Cretaceous times with a large mass of basic and ultrabasic extrusive rocks (the Semail Ophiolites). The Hawasina sedimentary rocks and Semail ophiolites were then overthrust on to the Sumeini group, during the late Campanian to Maastrichtian periods. They were subsequently covered unconformably by shallow marine late Maastrichtian and early Tertiary limestones. The outer area of the Arabian Continent, especially the Oman mountains, was uplifted and much folded during the Oligocene and early Miocene in association with movements in Central Iran but dissociated from it by wrench faulting. Representatives of the Dammam, Rus and Umm er Radhuma Palaeocene-Eocene sequence do not outcrop in the area and were not indicated in shallow wells. They are, however, found further west at Lekhwair, south in Dhofar and north along the Arabian Gulf coast.

The whole of Oman was subject to post-Miocene emergence from shallow seas, at the end of the geosynclinal infilling, but erosion terraces in the mountains suggest differential uplift in stages. Certainly it appears that uplift was not equal on both sides of the mountains, with emerging coastline to the north and infilling of wadis in the south.

C - MAIN FORMATIONS AND THEIR EFFECT ON SURFACE AND GROUNDWATER HYDROLOGY

The oldest rocks of the Mayhah, Muti and Qumayrah formations of Jurassic and Cretaceous periods outcrop to a limited extent in the central part of the mountain range, the Hawasina window (see fig. 3.3). They occur as fine lime-grainstones and mudstones of massive structure, with few bedding planes. The result is that slopes are extremely sheer with a minimum of detrital cover. Run-off is at a maximum, and there is little chance of water sinking in or of storage within this, the highest part of the range.

Overlying this, with a tectonic contact, are the various formations within the oldest rocks of the Hawasina Group. These appear both in the 'window' within the Semail nappe and fringing ridges of Tertiary limestone and comprises the most widespread outcropping rock.

The alignment of cross-section (1) on figure 3.4 gives a false impression of the extent of these rocks to the north east of Jabal Rais, since the line followed zig-zags (see fig. 3.3) and thus misses out the extent of the Semail nappe encountered on the far side of the window.

The lithostratigraphic units into which the Hawasina is divided (see fig. 3.5) reflect a variety of deep and shallow marine environments in which sediments were deposited. They are, however, not a continuous sedimentary sequence, but a series of nappes. While the difference between units is visible in the field, those between

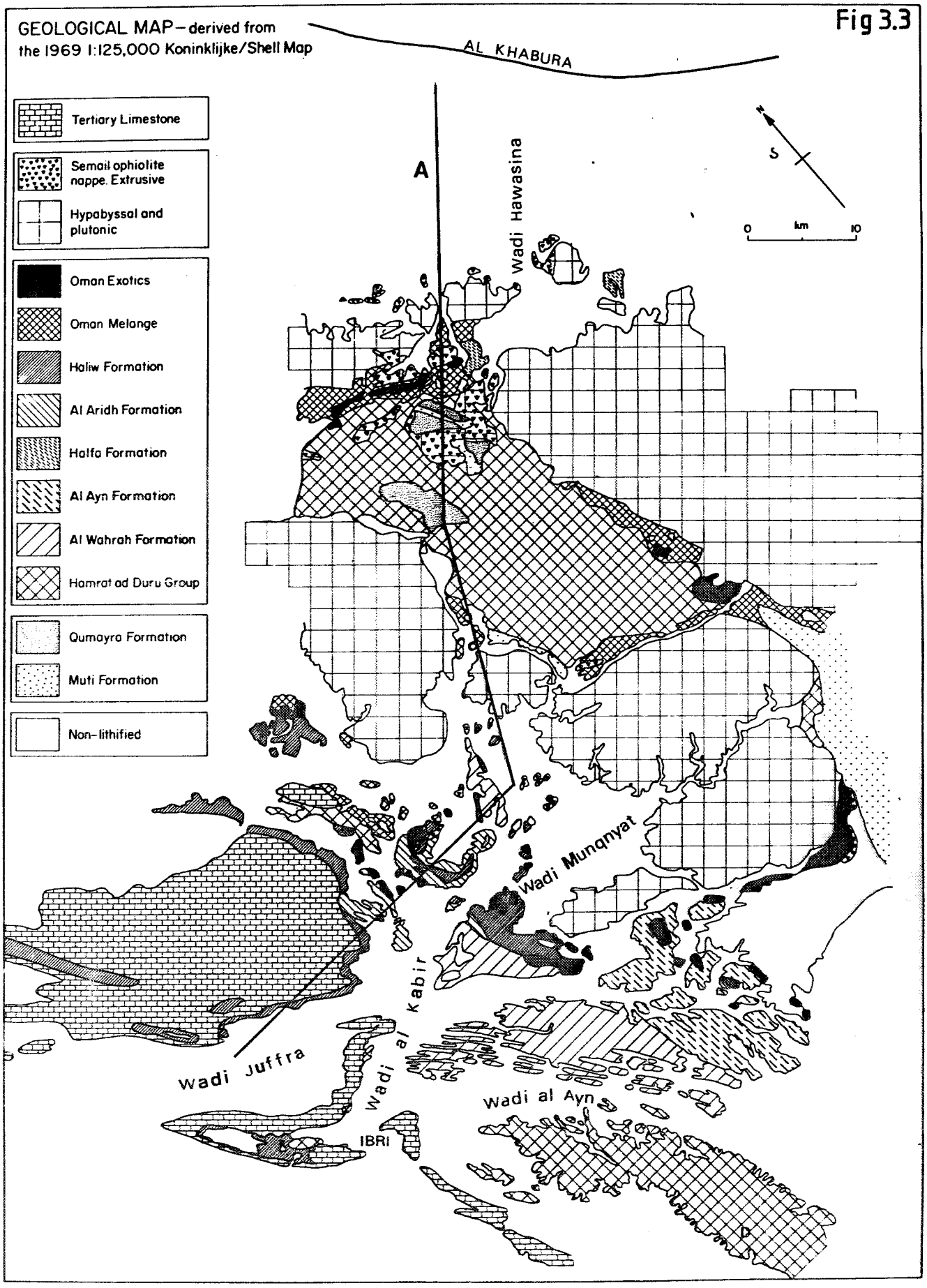
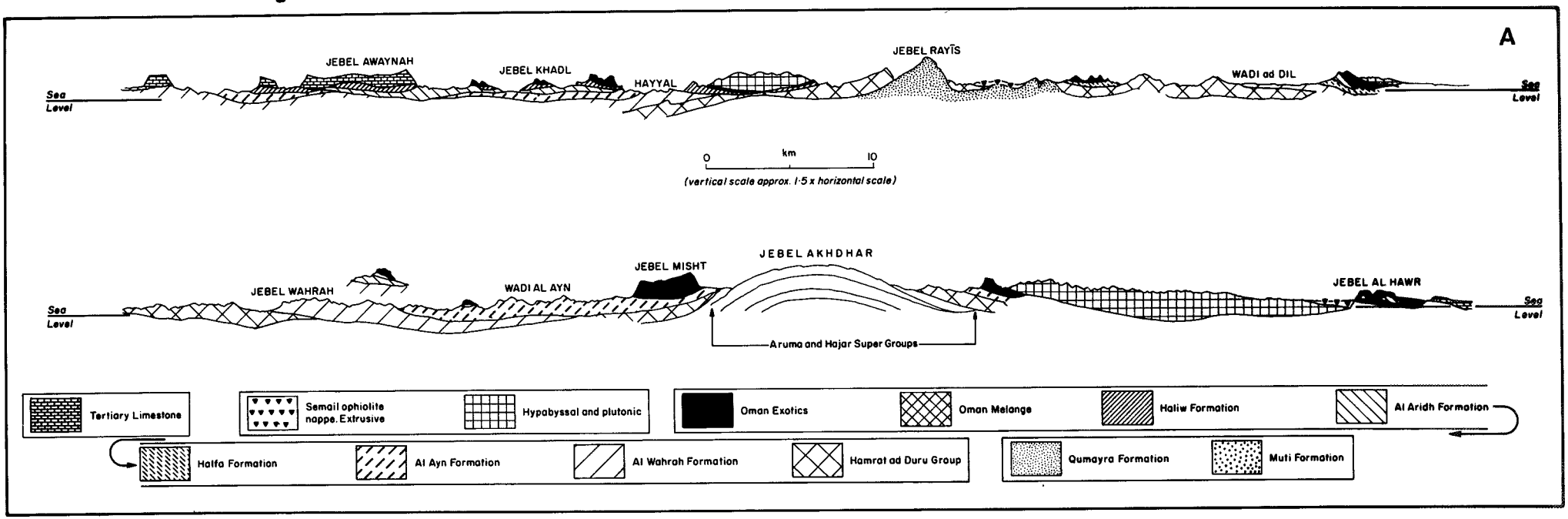

GEOLOGICAL MAP – derived from the 1969 1:125,000 Koninklijke/Shell Map
Fig 3.3
AL KHABURA
A
Wadi Hawasina
Tertiary Limestone
Semail ophiolite nappe. Extrusive
Hypabyssal and plutonic
Oman Exotics
Oman Melange
Haliw Formation
Al Aridh Formation
Halfa Formation
Al Ayn Formation
Al Wahrah Formation
Hamrat ad Duru Group
Qumayra Formation
Muti Formation
Non-lithified
N
S
0
km
10
Wadi Muqnyat
Wadi al Kabir
Wadi Juffra
Wadi al Ayn
IBRI

Fig 3.4 SCHEMATIC GEOLOGICAL SECTIONS REPRESENTATIVE OF THE STUDY AREA (15)



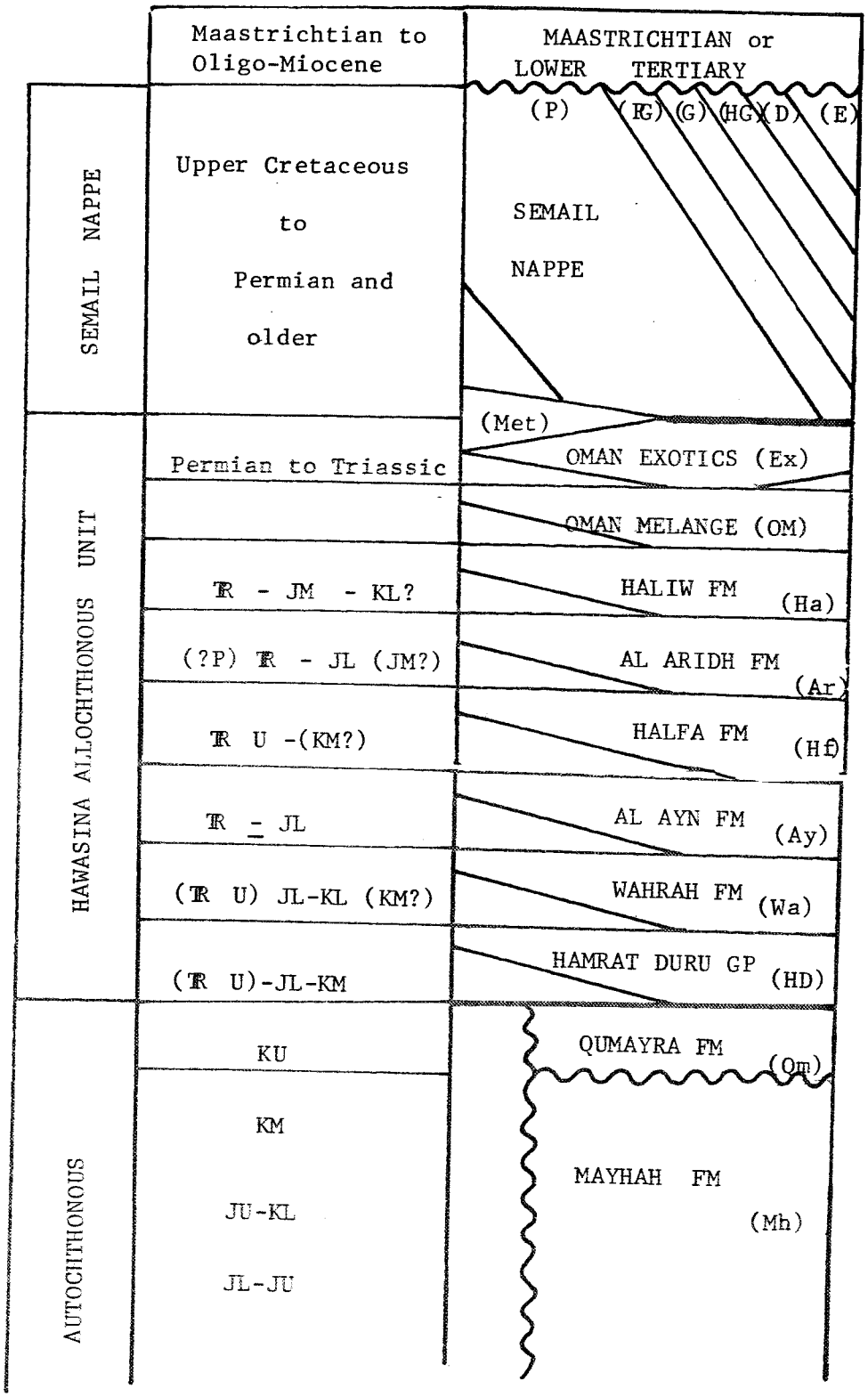


Fig.3.5 **Geological succession in the Field Area.**

individual facies within a unit are not always so easily seen. They are therefore only described where variations between them may be of hydrological significance.

The Hamrat ad Duru Group, the lowest and most extensive of the Hawasina series, occurs in two main areas. One is the Hawasina window, of which it is the major component. The other is the range of hills after which it takes its name. In the Hawasina window, it occurs in several forms, but particularly as shales and siltstones. At the watershed between the al Kabir and ad Dil wadis (Najd Sharingiban) outcrops are of well-bedded, easily broken up sand/siltstones, which are sometimes shaley. On lower, more gradual slopes there is a good covering of rock debris, mostly recently derived from nearby strata, but also containing large rounded sandstone boulders, from an earlier period of erosion.

Downstream in the Wadi al Kabir, below Tawi Sharingibān, there are thin layers of well-bedded siltstones, often tilted at ca. 10^{o}. Beneath these lie green mudstones and pillow lavas which are more massive and outcrop in the beds of tributary wadis on the left bank. They appear to be more resistant to erosion and are associated with waterfalls and shutes.

In the Wadi Na'am, also, waterfalls and gorge sections are cut in rocks of the Hamrat ad Duru Group. Here a fine-grained

argillaceous grey/blue limestone, with very few bedding planes, forms vertical and overhanging gorge walls over 50m high. Tufa formed along bedding planes suggests old lines of seepage which are no longer active. No springs or signs of seepage are now apparent on this formation. In general, its position high up in the drainage basins reduces the likelihood of its acting as a major aquifer, but even downstream here is no evidence of its acting as a major source of groundwater.

The Hamrat ad Duru range, after which the group is named, outcrops on the inland fringe of the area. It has, therefore, little effect on the hydrology of the area studies. In this Eastern part, nearest Sulayf, it consists of very finely bedded layers of mudstones, tilted almost vertically in places, forming rounded hills covered with fine debris. The hills are generally no more than 50-60 metres high, but rise in the central ridges of the range, eastwards towards Kubāra, to 100-150m (a relative relief).

In the Hayyāl area, and north of Darīz, this formation outcrops in low hills with major accumulations of fine debris in the flat-bottomed valleys between them. In some places (eg. the most south-westerly ridges in the Wadi Lusayl) the bedding is near vertical, but the strata are so thin, and so easily broken, that it is possible to drive a Land Rover over the hills, as if they consisted of gravel.

To the east of the Wadi al Hijr, the rocks form greater relief and are less submerged beneath wadi fill and angular fragments. The beds are thicker but still soft and apparently easily weathered.

Where finger hill topography has been formed, especially west of the Wadi al Hijr, this is mainly due to the interbedding and uptilting of fine lime grainstones of yellow/white colour with red cherty radiolarian mudstones. The former outcrop as beds some 0.5-1.5m thick, and exhibit well developed ripple marks especially to the south east of Araqi. The cherty layers are much finer bedded and form the valleys between the ridges of the coarser rock. Associated mudstones also outcrop in the Wadi floor, near Araqi, and are found in wells around Dariz, Araqi and North Ibri. These commonly break down into unconsolidated clays, especially within the saturated zone and here they merge into shales and cherts and cannot, from well-digging, be easily be differentiated from them.

The formation of consequent valleys of gentle gradient, the low angle of hill slopes, and the layers of fine weathering products all help to slow run-off and thus facilitate infiltration into the bedding plans and joints which are vertically tilted. The fineness of the planes and joints, however, and the breakdown of the rocks into clays and marls, precludes this group from being a particularly productive aquifer. Most flow appears to take place along the lines of coarser bedded, less easily weathered lime grainstones. On the other hand, it is easier to dig in the finer bedded rocks which break up easily on impact. The slow movement of water within this series is also suggested by the poor quality of the water found within it. The high conductivity of the water is also partly due to residual chlorides incorporated in the rock during its formation.

The outcrops of the al Ayn formation within the area are very limited. The only easily identifiable area being east of Bāt, where the topography and lithology is similar to that east of the Wadi al Hijr gorge in the Wahrah group. The relief is, however, a little more accentuated.

Of the higher nappes of the Hawasina (Halfa, Haliw and al Aridh formations), only the al Aridh and Haliw sediments occur over more than a very limited area. The al Aridh group consists characteristically of coarse conglomerates and lithoclastic lime grainstones which tend to be red or pink in colour. As with the Wahrah formation, they contain bands of coarser bedded grainstones of a paler colour. Wherever these series occur without a cap rock, they tend to be much 'rotted', and to form relief of only moderate amplitude, with gradual slopes. Hills such as Jabal Hamra, downstream of al Aridh appear higher because they are surrounded by, and viewed across, expanses of flat wadi and low gravel terrace. Where the Wadi al Aridh breaches the formation near the water hole (well 321) bedrock is not very far beneath the wadi gravels (less than 8m).

Where outcrops of this soft, coarse textured limestone are overlain by the typically hard white re-crystallised limestones of the Oman Exotics, into which they merge, slopes are steeper and relief greater, because of the protection this layer affords. Nevertheless the lower slopes are thickly covered with rock debris. No resurgences were found within this formation.

The al Aridh formation is also capped by Haliw silicified limestone, which protects it in the Hujrimat 'embayment'. Haliw limestones also occur north of Dariz, in association with the al Wahrah formation. Here the limestones are inter-bedded with cherts, and the slopes are 'stained' dark red by the weathering and slipping of the chert beds. Oman Exotics, as at al Aridh, cap some of the more northerly hills, and consequently the hills increase in height in this direction and contrast with the lower, more rolling relief of the al Wahrah formation.

The Haliw formation is also shown to underlie the Semail volcanics, but the contact between these two is hidden under recent conglomerates and uncemented detrital layers. It is therefore not generally possible to observe any effects on groundwater this contact may have. Only north of Bat is the contact visible and here slight seepage from the base of the Semail ophiolites is visible. It is not known whether this is because the Haliw limestone/cherts act as an aqueclude, or because of faulting associated with the emplacement of the Semail nappe.

The Oman Melange which overlies all other Hawasina formations and underlies Oman Exo tics and the Semail nappe, consists of a variety of rocks derived from Oman Exotics and Haliw and Halfa formations. They are mainly a series of Exotic limestones, cherts, basic lavas, and serpentinite which occur in varying proportions. Where, as east of Miskin near well 328, the basic lavas occur on their own in sufficient quantity, they stand out as small mountains of very definitely different topography to the serpentinites and limestones around them. Slopes are steep, rising to conical peaks and the rock is dark with no covering of weathered material.

Covering the majority of the upper al Kabir catchment, and surrounding the Hawasina window is a wide area of Semail ophiolites and peridotites. These, apart from the three windows of the Hawasina, Jabal Akhdhar and Saih Hatat, form also the major part of the whole range of the Northern Oman Mountains, continuing to Muscat and the Sharqiya in the South, and up to Sharjah in the north. Probably extruded from the oceanic ridge in the infilling ocean which formed the Hawasina sediments, they show a sequence of mineralogy and chemistry which suggests a transition from plutonic to volcanic environments (12).

Within the field area outcrops are especially easily visible in the Wadis Munqnyat, Kahanat, upper al Kabir (left bank) and lower Hawasina (right bank). Here they appear as a dark brown massive rock, with much folding, faulting and veining. Outcrops are massive and in the Wadi al 'Oud near Falaj al Hawasina, Lees (2) noted a group some 450-600m thick. On weathered surfaces, the veins stand out and whether originally present or as a result of weathering, vertical outcrops typically contain hollows which tunnel back horizontally like rabbit burrows into the rock. These hollows are up to half a metre in diameter and go back for the same distance. Rock surfaces are seldom covered by much detritus and vegetation is sparse. Run-off therefore tends to be extremely rapid.

Along major faults and junctions with rocks such as pillow lavas there appear to be lines of seepage and deposits of calcite-dolomite. Lines of tufa deposition may be several kilometres long, as in the area of Hayl Shakhut, and Hayl al Laushl south of Kahant. Small

springs, generally discharging less than 0.5 l/s (called hayl pl. huyul), occur throughout the volcanics and are often channelled to feed a small number of palm trees. The density of such occurrences is small so that the total outflow from the rock is negligible when the total collecting area of the rock is considered. Far more groundwater is probably transmitted in the gravels within the wadis which dissect the formation, than moves within the actual rock itself. As an aquifer therefore it is of extremely limited importance, lines of flow appearing to be few and far between and transmissivity low. Water within it is only, at present, exploited where it comes to the surface naturally. Limited transmissivity and the expense of excavating in such a hard rock discourage any attempts to search for further water supplies within it, or to improve those already in existence (as requests for dynamite bear witness).

The most recent limestones and marls within the region are shallow water Maastrichtian and Tertiary limestone which tend to be coarse grained (conglomeritic). Strata with well developed joints and bedding planes around Ibri and Sulayf are some 1-3m thick, and dip at approximately 20^{o} to the north east near the gaps. In some instances, such as at Khatmat Aynayn, they contain bands of pure calcite. Towards the Wadi Juffra from Ibri, they form a breached anticline with a window of Haliw formation limestone. They also occur assimilar thin, tilted ridges on the north side of the mountains.

Karst features have as yet developed little in this limestone and it acts mainly as an aqueclude, funnelling groundwater through the

gaps that have been breached in it (Ukhwaybiyah, Ibri and Sulayf). On the coastal side of the mountains it is mostly submerged under mid-Eocene and more recent deposits, but water quality patterns suggest that the Hawasina water passes on into the sea through a gap similar to those in the Dhahira.

Although karstification is limited in this coarse grained limestone some flow lines have developed, and these have at various times supplied as many as 13 falajes to the west of Ibri. These falajes, of which only four now remain, tap resurgences of water of identical chemical characteristics and of reliable but small flow. There is, therefore, some storage within the rock. Until more work is done on the flow through the gaps, no assessment can be made of the volumes of water flowing in the limestone through the ridges. Ponding of water behind the gaps howerer suggests that the amount of water which by-passes them is probably small. In any case, the structural arrangement of strata is generally not suitable for water to penetrate the rock formation. Synclinal folds and dip slopes facing downstream rarely occur.

On the Bāṭina, however, limestones tend to dip to the north, and here it has been suggested that they either

(a) conduct water deep beneath the Bāṭina Plain, or at least

(b) force it down by their lack of transmissivity. (60)

This may be so for diffuse flow, but concentrated flows appear to be more likely to breach the barrier, and the existence of a line of falaj motherwells immediately to the south of the formation (Qusuf, Falaj Bani Rabiya, Fardha, etc.) suggest that water may be ponded back at this point. Altimetric survey and the construction of piezometric maps would help clarify this.

D - CONCLUSION

The solid geology of the area offers little in the way of aquifers. Those limestones which might develop as aquifers are generally overlain by only slightly permeable Semail ophiolites. They are also nearly always interlayered with thinly bedded shales and siltstones which hinder the development of concentrated flow lines.

It must, however, be pointed out that, because of the hardness of the rocks, little attempt has ever been made to obtain water from them, except where water reaches the surface as seepage or spring. Lithologies suggest generally low permeabilities, except perhaps in the Maastrichtian limestone which may contain some secondary porosity. Drilling may discover good, deeper aquifers, but initial investigations suggest that the likelihood is small.

The main role of the solid geology to groundwater resources is therefore rather a passive one. As relatively impermeable surfaces, the rocks act as a 'water tower', with high levels of run-off which are concentrated and transmitted to areas of higher infiltration capacity, so they themselves store and transmit as groundwater a very small proportion of the rain that falls.

II GEOMORPHOLOGY

A - INTRODUCTION

A brief study of the solid geology has shown its passive role in groundwater hydrology in areas of the Hawasina series and Semail nappes. Storage and transmission of subsurface flows are therefore almost totally confined to Pliocene, Pleistocene and recent sediments. In these efficiency of run-off and recharge and the paths of flow are closely related not only to present day climate and landscapes but also those existing at the times when the coastal plain was emerging and the wadi systems were being infilled. Flanked by the sunken coastline of Musandam and the oyster-covered 400m terraces of Jabal Suneina (27) the area has undoubtedly undergone major changes in base level, during the late Tertiary and possibly Quaternary periods.

The evolution of the present day drainage network has also itself brought about recent base level changes and other far-reaching effects on groundwater resources.

B - PREVIOUS GEOMORPHOLOGICAL WORK ON THE AREA

While desert geomorphology in general has received a great deal of attention, that of the Arabian peninsula in particular has not. Inaccessibility and paucity of data have played their part. There

is also the fact that the Rub'al Khali and its environs cover an enormous area, much of which is relatively featureless compared with the smaller and more varied American deserts. Previous works therefore tend to be limited to the observations of travellers (most of whom recorded journeys further west or north) (19-22) and terrain reports for oil companies, with some other studies, especially on sanddunes.

Despite the greater variety of landscapes in Northern Oman than in neighbouring parts of Saudi and the Emirates, only Lees provides any geomorphological information. Unlike his very detailed and valuable geological survey (26) his geomorphological information, including that on terracing, concentrates on the more spectacular scenery of Jabal Suneini and the Musandam peninsula.

He does, however, suggest a division of Oman into three types of topography; highly dissected limestone country, dissected easily weathered igneous rock and limestone plateau country. Such a classification is certainly possible, but not very useful hydrologically on the basis he puts forward. As typical of many geologists he omits any consideration of those parts of the country which are covered by recent sediments. As these, hydrologically, are the most important elements of the topography, their exclusion makes this approach of little applicability to the study of water resources.

Wilkinson (28) provides a useful background to physical geography on a country-wide scale, emphasising the role of the alluvial fans.

He relates exploitable groundwater to existing drainage patterns, whereas the hypothesis of this section on geomorphology is that aquifers are principally those of Pleistocene and recent deposits, and it is past not existing drainage patterns to which groundwater owes its distribution.

The scarcity of previous work on Oman means that new work can generally only be compared with parallel work in other areas, and data gathered within them. There is, however, a limit to the comparisons which can be made with other work because neighbouring areas of similar climate and topography are equally poorly covered in literature and better studied areas such as arid North America, South Africa and Australia can offer a very much more highly sophisticated level of data, and thus tend to be approached more quantitatively.

The area therefore offers an opportunity for observation little affected by the interpretation of phenomena by previous researchers. Where vegetation is so sparse, the landscape is unhidden and so forms an ideal environment for the study of geological and geomorphological features. Here, only those aspects most relevant to groundwater hydrology are discussed in any detail. In particular factors affecting recharge, the direction of subsurface flows, and the characteristics of the drainage networks are examined.

C - SEQUENCE OF GEOMORPHOLOGICAL EVENTS

(i) Phases of Erosion and Deposition

The present surface drainage of the area on the south side of the Hajar mountains follows the model suggested by Loehnberg (29) for catchments flowing to internal basins. Water is caught by a mountain range and funnelled into a piedmont fringe of coarse alluvial material. Here the lower part is mainly less permeable because of increased cementation rather than from decreasing particle size, but the water follows Loehnberg's model, by eventually emerging in the seepage zone of the Umm as Samim. Thus three catchments are not affected by changes of sea level in relation to land level, but only by changes of local base level brought about by orogenic movement in the mountain range, or the adoption of a new drainage pattern. The fourth catchment, that which flows north, is, however, susceptible to the effects of sea and land level changes as well as to more local movements.

The geomorphology of the area of the Hajar mountain range and the flanking plains shows numerous signs of a series of depositional and erosional phases, forming terraces, gorges and fossil wadi courses, consistent with the formation of alluvial fans in times of changing climatic and base level conditions. While there seem to have been pluvial and drought sequences, neither seems to have been favourable for the development of karst features or discrete paths of flow in the surrounding limestones. These, especially the

Tertiary formations in the South, have well developed bedding planes and joints which are little widened by solution. This is in direct contrast to the strongly karstified Tertiary limestones of the Jabal Qara area of Dhofar Province, Southern Oman, and may be due to differences in the amount of time each has been subject to surface weathering.

Despite the lack of well developed karst features, the geomorphological progression is not only concerned with periods of mechanical erosion and deposition, but also with chemical solution and deposition. Precipitation of calcium carbonate cementing gravels has been common. As karst features are so rare, the source of calcium carbonate in solution is thought to be principally from the alluvial gravels themselves which are, with a high surface-to-volume ratio, a more easily dissolved material than bedrock. Precipitation and cementation may well at times be triggered by the mixing of the calcium-and magnesium-rich gravel water with alkaline water from ultrabasic rocks (see p.127).

A study of pedogenesis in the Trucial States by Stevens (30) suggests the following sequence of Quaternary events:-

1) Deposition of alluvial fans
2) Formation of gypsum crusts - high/fluctuating water table conditions
3) Erosion of fine material spread over Western plains and trenching
4) Aeolian activity, partial uplifting of gullies

5) Limited erosion and infilling

6) Recent aeolian activity plus sheet flow

Although this sequence is also apparent in Oman, its effect is somewhat distorted. In the area close to the mountains, and on the coastal plain caliche replaces gypsum layers, and the pattern is further complicated by a degree of tilting of the whole area, parallel with the mountain watershed. The sequence of events therefore follows more closely that proposed by Halcrow (31) in the Trucial States, which is as follows:-

1) Planation - clay derived from serpentenite formations and gravelly calcareous clays
2) Induration - evaporation of groundwater forming caliche
3) Erosion - possibly accompanied by uplift
4) Deposition of gravel in caliche topography
5) Deposition of sands

From these two sequences and local observations, it is suggested that in Northern Oman two periods of caliche formation also followed an original pluvial. The pluvial is suggested by Stevens, following Butzer's work in Egypt (32) to be that associated with the Würm Early Glacial in Europe. Work by Williams (33), however, which correlates world-wide indications of climatic change, shows that 'there is now firm evidence of late Pleistocene aridity in many parts of the tropics, in contrast to the belief that high latitude glacial periods were coeval with low latitude pluvial periods'. Thus the

original pluvial is likely to have been some 50, 000 years BP, followed by an arid period from around 30, 000 to 15, 000 years BP. A further pluvial, according to information from Lake Chad (34) and Rajastan (33) occurred from around 12, 000 - 5, 000 BP.

The conglomerate terraces of the mountains and the alluvial fans of which the lower wadis and desert foreland are composed may reflect these changing conditions. For instance in the Wadi Hawasina near Sadan, there appear to have been two periods of wadi filling and three of wadi cutting (see fig. 3. 6). While such phases are apparent and can be identified also in the lower wadis (see fig. 3. 7), it is difficult to relate them to specific climatic periods. Lustig (35) links fan-building with periods of heavier than present precipitation and high water levels, and fan trenching with more localised and less frequent rainfall. While this provides a simple guideline for climatic interpretation it should be applied with some reservation to the al Kabir and Hawasina catchments where, under present climatic conditions common to both areas, the former system is fan-building and the latter is fan-trenching. Differential uplift and channel piracy may also play a part, as may the different conditions required for water flow and mud flow deposits (36). Certain of the most cemented conglomerate terraces, especially in the Hawasina and Bilad Shahūm consist of ill-sorted boulders, pebbles and gravels, which suggest mud flow origin (37) and the differential washing out of fines along particular paths may explain the occurrence of pipe flow.

Fig. 3.6 PHASES OF EROSION AND DEPOSITION MOUNTAIN ZONE

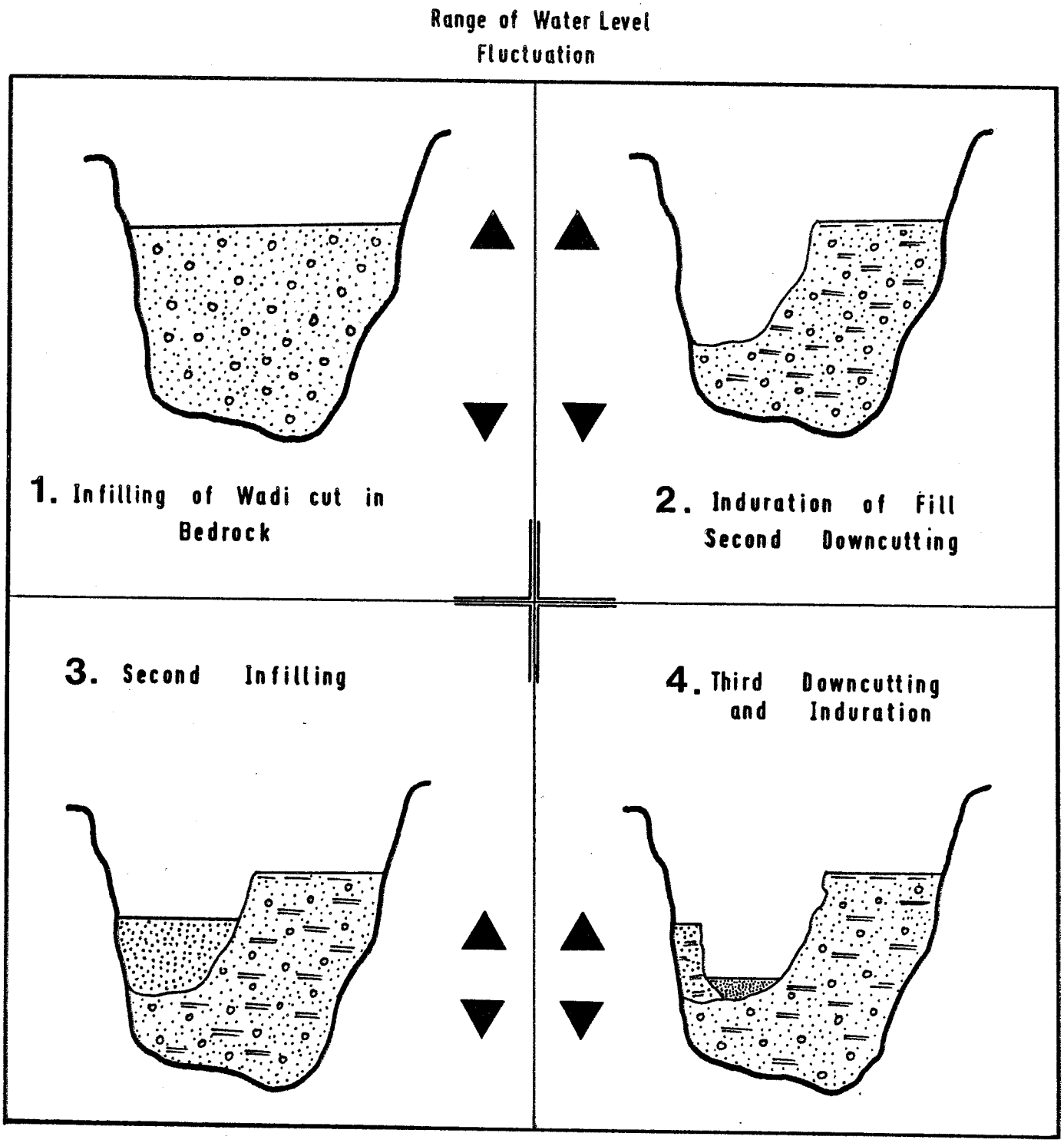
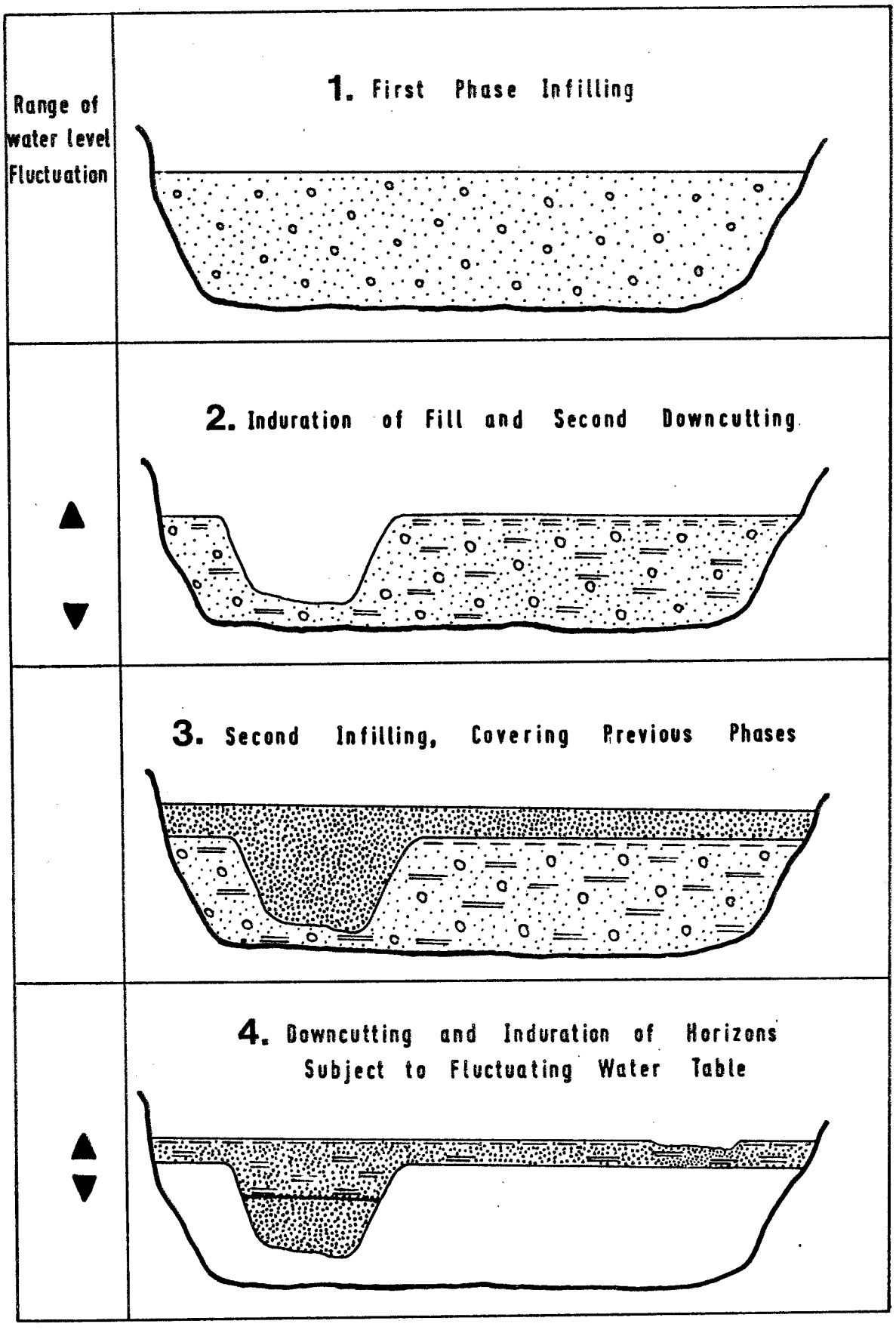


Fig. 3.7 PHASES OF EROSION AND DEPOSITION LOWER WADI ZONE



Within the area studies, therefore, it is suggested that the Quaternary sequence is as follows:-

1) Pre-Pleistocene down-cutting of wadi systems in bedrock, development of large basins.

2) Infilling with gravels.

3) Cementation of gravels with fluctuating and falling water levels. Associated channel cutting as run-off reduced.

4) Second phase of infilling, some aeolian deposition around low watersheds.

5) Channel cutting and cementation of second phase infilling where fluctuations in water level occur.

6) Deposition of sands and windblown silts.

In the mountains this has led to the formation of two terrace systems. The lower one is sometimes not easily seen as the tendency is for channels to develop at the junction of bedrock and fill, so that the most recent channel cutting has sometimes obscured the effects of the previous one. Downstream, the second infilling appears to have covered over the previous one.

In the lower wadis and beyond the gaps there are considerable but discontinuous deposits of red marls and mudstones at depths of

15-20m, probably the products of the late pluvial period. In the deepest boreholes for which information exists, gravel and unoxidised ferruginous clays lie at depths of approximately 36m. These are (probably) the product of planation suggested in phase 1 by Halcrows, and are discussed further in the section on aquifers, as are the other quaternary deposits.

During the pluvial period it appears that considerable layers of gravels were also laid down. These were subsequently cemented with a calcareous matrix. In places this matrix is harder than the pebbles it holds, in others the conglomerate is poorly cemented and pipe flow has developed within it. It can generally be differentiated from later terrace formations, where it outcrops, by the very dark desert varnish which has developed. This varnish is of importance in labelling areas of extensive conglomerate terracing as parts of the drainage system where erosion is no longer very active.

The period of erosion which followed has been equated by Stevens with the Neolithic sub-pluvial, and this appears to have been accompanied by tilting of the land downward in a south westerly direction. Thus the terraces of Pleistocene gravels are deeply dissected in the northern wadis where base level fell, while in the Interior, where downstream wadi gradients were lessened, conglomerates became covered by layers of unconsolidated gravels.

An exception to this pattern is the incised conglomerate terraces of the Bilad Shahūm. These may either owe their origin to a change

in base level through a change in drainage pattern (see following pages) or, being the only major east-west flowing wadi in the system, to the westerly component to the tilting being locally exaggerated.

It is suggested that during this period considerable modification to the drainage pattern occurred. Further caliche horizons (generally called simply conglomerate in this thesis) were formed in the ensuing period, during a second period of low flows and channel cutting. These calcretes are generally of finer texture than those previously laid down. The sequence is particualry important, as it is found that well defined lines of wadi gravels occur within it which are almost totally uncemented and form the major transmitters of groundwater (see Chapter 5). They are not equally well represented everywhere, however, and this is held to be due to differences in the second wadi infilling and induration.

While caliche or calcrete (with a host of other synonyms (38)) is found throughout the area, there is a major contrast between the upper and lower wadi units and the desert foreland. In the upper wadis caliche wadi-fill is widespread and uncemented gravels other than those in present active wadi channels are not found, water being transmitted in pipes developed in the caliche and in the lesser cemented horizons. In the lower wadis, however, uncemented gravels appear within caliche horizons as laterallyconfined channels, and in the desert foreland in similar channels, but with less well-defined boundaries.

It is felt that this progression can be explained in terms of the proposed sequence of Quaternary events. Microscopic evidence suggests that caliche formation is associated with the vadose (unsaturated) zone (39) and only the shallowest saturated layer, being principally the product of downward percolation of calcium-rich waters from the soil zone, and upward capillary action of groundwater saturated with calcite and dolomite (40). Hence caliche formation is almost totally confined to the aerated zone, and the rate of formation is particularly high where water table fluctuations are common. Thus caliche is unlikely to form at levels where alluvium is never saturated, but it is highly probable that it will form during the fluctuations in water level associated with channel cutting in alluvial deposits (especially where these are associated with ultrabasic rocks, see Chapter 3 part III). It appears to be rare during aggradation, recent gravel exhibiting very little induration.

In the upper wadi areas, where groundwater storage is at its smallest (see Chapter 5 Part IV) fluctuation in water level is at its highest, and at the present time groundwater flows may be halved every two or three months in times of no recharge. (See table 5.2). Thus alluvial deposits, once laid down and then cut into during a new phase of downcutting are likely to be subject to fluctuations in water level and cementation over almost all of their depth (see fig. 3.6).

In the lower wadis, however, variations in water level are much less, storage being greater. The second phase of infilling generally

overlies the first, and the present wadi channels are only slightly incised, and generally run between gravel banks of recent alluvium. The present water levels are therefore high, and have not reached as low as the base of the second channel cut, since its infilling with loose gravel. This gravel has therefore never been subject to 'calichification' although alluvial deposits to either side and above and below are cemented; those to the sides and below as a result of the first phase of induration, those above from the second (see fig. 3.7)

In the desert foreland, where alluvial fans have developed outside the confines of bedrock structures, channels are wider, as gradients decline, and consequently the sides of the buried channels are less well defined. Confining cemented layers above the gravels are less common, a cover generally being provided by low gradient deposits of fine sediments. These are generally of sand or finer fractions being deposited by sheet flow whose carrying power is limited. In addition, minor areas of aeolian deposits are found. To the south-west of Darīz and near Bāt, very fine white silt and clay occur. This silt and clay was once cultivated and is now deeply dissected, forming a miniature 'badlands' landscape. Drifted sand is rare and cannot be linked to any one predominant wind direction. Isolated dunes are only found north of Falaj bani Rabīyah (a single line of seif dunes running approximately north-south). Elsewhere, in the Interior, where it occurs, loose sand as sand drifts is always piled against a cliff of bedrock, as at Ukhway biya and on the north slope of the Sulayf gap. It cannot therefore provide

much contribution to the groundwater hydrology even though it is an area of high infiltration because of its very limited extent.

(ii) Wadi Diversions

The sequence of events, related to changes in climate, has brought about a typical arid landscape of wide floored wadis and steep bare-rock slopes, with preservation of previous landforms, by channel burial, abandonment and protection of old surface by formation of caliche, the three processes ennumerated by Warren in the development of alluvial fans (42). Within this generalised picture, however, the same sequence of events has led to important variations to the drainage pattern which have far-reaching effects on the hydrology. As mentioned briefly, it is apparent that the arrangement of wadis has probably changed considerably with the development of the Ibri and Sulayf gaps, and that other wadi diversions have also occured. These are of major significance in two ways:- run-off from the same storm may flow into one catchment as surface water but water which enters the saturated zone may flow into a different catchment- secondly this diversion, whether groundwater and surface water develop similar flow paths or not, leads to the formation of a 'misfit' wadi. In this the remaining groundwater flow will be negligible and therefore at great depth and low gradient.

Such a pattern is identifiable in the Dhāhira, and is likely to occur elsewhere (eg. the Wadi Quriyat/Bahla) on the Interior edge of the

mountain fringe, and was found by Renardet in the Sharqiya where the Wadi al Batha is said to have been captured by the Wadi Bani Khalid. The phenomenon is mentioned briefly by Schoeller (42) but is thoughtby him to be uncommon, while Warren (41) only talks of channel piracy in terms of the meandering and braiding of alluvial fans which leadsto frequent changes in coursesof distributaries. Work on wadi diversion in Mexico by Lopez de Llergo (43) covers similar features but unfortunately treats themin terms of temperate zone river capture. No mention is made of the possibility that groundwater flow might not change direction at the same time as that at the surface.

The evidence for these changes cannot yet be supported by morphometric analysis, but is limited to observations of gradient, sediment size, depth and breadth of gaps in the Tertiary limestone, water quality and aquifer types. A study of the gaps and of low watersheds reveals a pattern which is difficult to explain in relation to the existing wadi system.

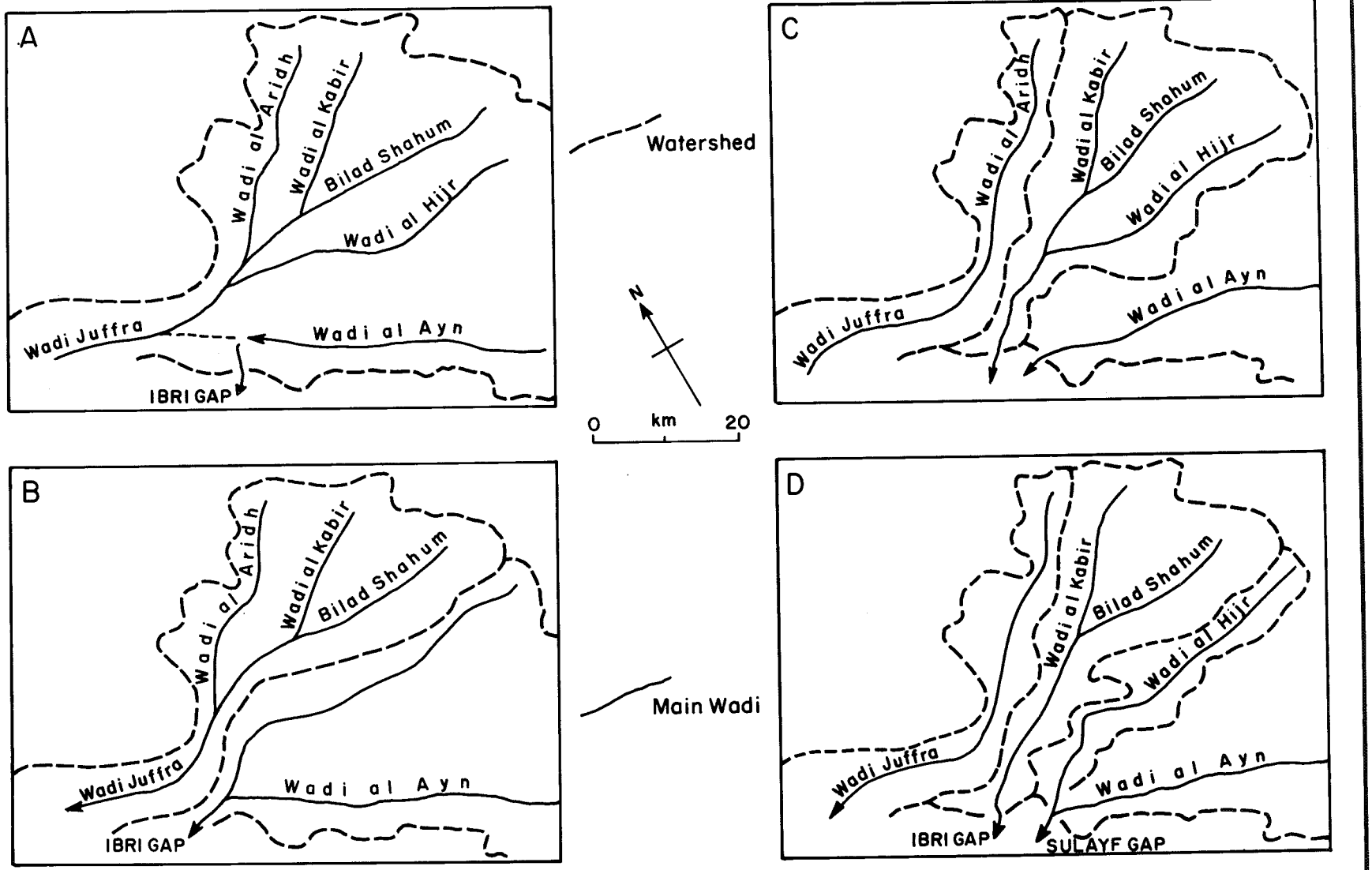
The lower wadi Juffra (sometimes called the Wadi Ukhwaybiya) and its 'debouchement' to the desert foreland is the only structural gap in the Tertiary limestone. Lying to the north of Subaykhi the gap is some 4km wide. Both the active wadi bed and the surrounding areas subject to sheet flow consist of rounded sand-sized particles with silt settled out where water has been pondedbehind obstructions (bushes, fallen trees etc.). The wadi profile is found to be of lesser gradient than that of any of the other systems observed (see fig. 3.9) and water is found in the wadi at some 23m.

The Ibri gap, the next to the East, is narrower, being only about 200m across, and the active wadi bed almost completely fills it. The bed consists of gravel up to about 2cm across, underlain at about 10 metres by conglomerate and with water at about 15m. At Sulayf there is perennial surface water at the gap but not any immediately upstream or more than about 500m downstream. Gravels are well-graded and coarser, up to 5cm across, and thin beds of conglomerate and bedrock outcrop in the channel floor.

The size of the present catchments is such that the largest area drains through the Sulayf gap (some 1500 km^2), a considerably smaller area, almost 1000km^2 through the Ibri gap, and only about half this (530km^2) through the Juffra gap, yet this las t is the best developed and the best graded breaching of the limestone ridge. Low watersheds (less than 10-15m) occur between the Juffra and al Kabir, north of Khatmat Aynayn and near al Aridh, and between the al Kabir and al Ayn wadis north of Jabal Shibamīna .
A fourth low watershed is found to the east of Darīz between the al Kabir and the al Hijr, the latter taking a zig-zag route through the cherts of the al Wahrah hills. Water seldom reaches the surface on this route, but there is no conglomerate and bedrock occurs at depths of no more than a metre. Scoopholes dry up and the ruined al Qabil falaj, which crosses and recrosses the wadi appears to have had its source in the watershed area east of Darīz. The profile of the al Hijr closely resembles that of the al Kabir.

The combined evidence from all these features suggests that there have been a succession of wadi diversions, which will have also caused alterations to the base levels of the systems concerned.

Fig 3.8 SUGGESTED STAGES OF WADI CAPTURE IN THE DHAHIRA



The alignment and gradients of wadis, the depth of gaps and to water, and the size of gravels within them have been used as the main indicators of the succession (see fig. 3.8) but aquifer type and water chemistry (discussed more fully in next section and Chapter 5) provide supporting evidence.

Despite its small catchment the Juffra system has the widest wadi and the deepest groundwater, lying as it does in a synclinal fold. It is therefore suggested that the lower section developed as part of a much larger drainage system, taking in all the water from the al Aridh, al Kabir, Bilad Shahūm, and probably the Wadi al Ayn (see fig. 3.8 Step A). The very low watersheds between the al Aridh, al Kabir, al Hijr and al Ayn consist of recent sediments rather than bed rock, but al Ayn water would have to flow round the north of Khatmat Aynayn. The capture of the al Ayn by the formation of the Ibri gap must therefore have happened early on in the development of the drainage pattern (Step B). The new base level then developed northward, and the al Hijr was diverted south through the Ibri gap. The diversion of the al Kabir and Bilad Shahūm wadis followed, so that at this time (Step C) the Ibri wadi was at its most extensive as a catchment.

The Sulayf gap then developed to divert the wadi al Ayn, and finally the al Hijr 'defected' to the wadi al Ayn to establish the existing pattern (Step D). At present the next wadi east, the Wadi Shuwā'ī, has breached the limestone ridge and reaches 6km through the Hamrat ad Dur range, to within a kilometre of the north east side and the wadi al Ayn, with several right-angle turns

within the finger hills, suggesting a progressive diversion of minor wadis to the north east. Geophysical data and surface and piezometric levelling are needed to confirm this theory, but certainly the diversion postulated as the most recent, the al Hijr, provides additional evidence, as there appears to be a buried wadi connecting the al Hijr and al Kabir at Dariz and a continuity of water quality along the same line (see p. 133). The small quantities of groundwater apparent in the al Hijr as it passes through the Jabal Wahrah, suggest that the majority takes a different route, namely via Dariz to the al Kabir. Thus in this instance, surface and groundwater would seem to be tributary to different systems.

The more recent the change in pattern, especially if occurring since the last major phase of induration/cementation of gravels, the greater the likelihood that groundwater flow lines do not follow those at the surface, but continue to take the same path they took before diversion of surface flow.

Between the Wadis al Ayn and al Kabir, to the East of Ibri, the watershed appears to be better established. Wells near this area tap poor water from aquifers of low yield, which suggests that flow does not still occur between the two, but that the Sulayf gap is sufficiently incised to drain the majority of groundwater as well as surface water which used to flow out of the Ibri gap.

The one area in which uncertainty arises is that north of Khatmat Aynayn. The area has no wells for any evidence to be gathered as to which way water flows. An attempted geo-electric survey was made by Ilaco at this site to clarify the situation as it was the boundary of their area , but results were said to be inconclusive.

The siting of falaj motherwells and water quality in al Ghabbi falaj suggest that al Kabir water passes close to Khatmat Aynayn, but without drilling and mapping of piezometric surface, there is no way to ascertain whether this water flows over into the Juffra, whether it is augmented by flow from it, or whether the two remain unmixed.

At the surface in this area, there is also a degree of uncertainty as to paths of flow. Localised rain falling to the east of the Khatmat Aynayn flows into the Juffra. It appears that in heavy flood, water here flows two ways, so that it is possible the Juffra might recapture the upper al Kabir. In summer 1974 this was very apparent as several flows starting in what was thought of as the al Kabir catchment, in fact moved as sheet flow into the Juffra. Thus instead of augmenting Aynayn and Ibri falajes, the water flowed out beyond Subayhki and was lost.

Minor changes of surface flow pattern may also have occured at three points. The Wadi al Aridh may have flowed round the east side of the Jabal Hamra, and the main route of the al Hijr near al Bānah may have been to the North. Neither of these changes the collecting area of catchments as a whole. The third case, however, may have slightly decreased the al Kabir catchment. The wadi complex in the south of the Munqnyat plain now joins the al Hijr, but appears once to have flowed into the al Kabir near Tawi Qarn Kabsh. In major floods the flow still splits to go either way, suggesting that transition here is not complete.

The changes which have taken place have an important effect in that they make the calculation of water balance with respect to surface catchments very approximate as inter-catchment transfer of groundwater cannot yet be quanitified. They also affect the distribution of aquifers related to previous drainage patterns (conglomerates and uncemented gravels) and so the positioning of falaj motherwells and the yields of pump wells.

D - THE PRESENT DRAINAGE PATTERN

(i) Present Day Catchment Characteristics

While Quaternary deposits act as the major storage reservoirs for groundwater, the configuration of surface catchments, their shape and longitudinal profiles all have considerable effect on the degree to which present day rainfall contributes to these groundwater reserves. In elongate wadis, tributaries are short, and gradient relatively steep, delay between rainfall and run-off to the main wadi is small, and thus floods are violent but generally subside quickly. In a more complex network of wadis, floods from different tributaries are less likely to arrive simultaneously in the main wadi. Here also spates are more often dissipated in the broad stretches of the lower wadi where flows in braided channels of low gradient encourage maximum infiltration. At the same time, those wadis with the greatest proportion of outcropping rock are those which flood most frequently, as run-off is greater from this surface than from gravel or sand-covered areas.

In the area studied the characteristics of the four main catchments are as follows:-

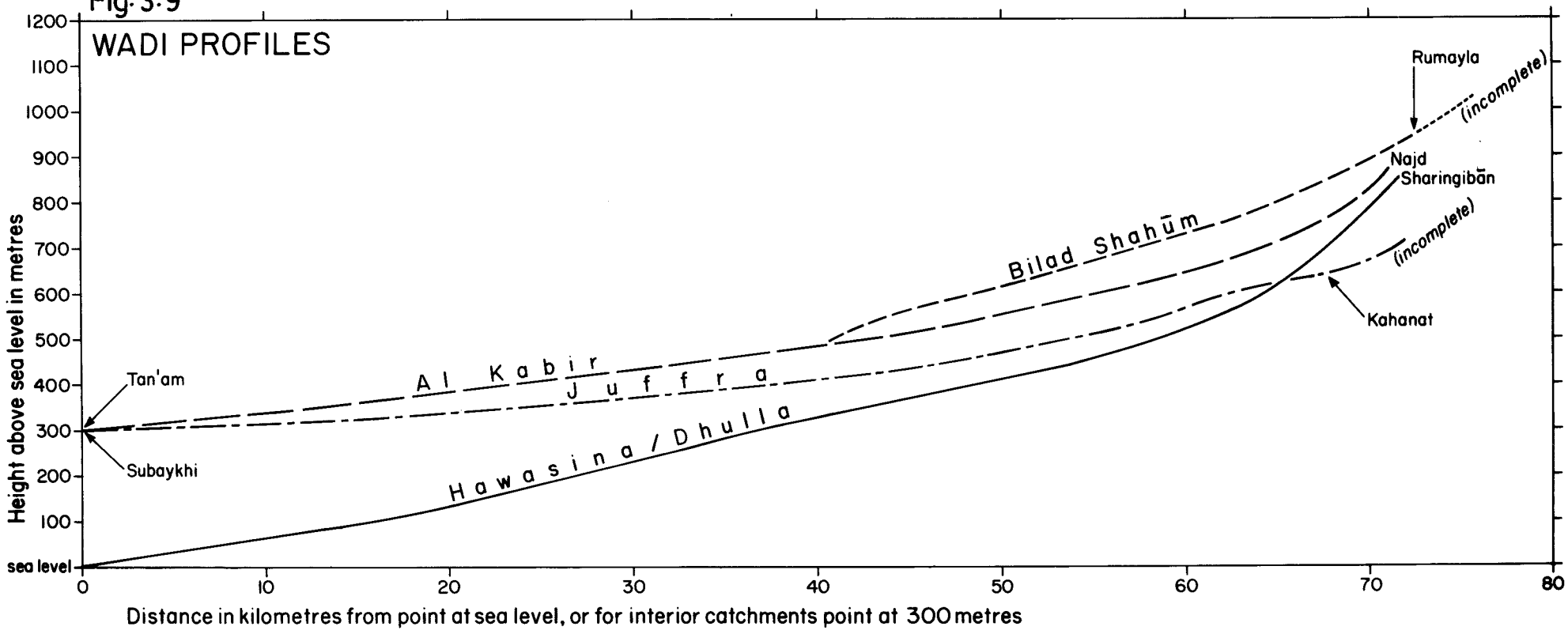
Wadi	Area km^2	Area of solid rock outcrop km^2	Proportion of catchment with rock outcropping	Rf*
Al Kabir	982	575	59%	.292
Juffra	534	171	32%	.126
al Hijr	343	233	68%	.106
Hawasina	640	375	59%	.151

Thus the al Hijr is the most elongated catchment, with the least proportion of recent alluvial deposits. As such it is likely to be the wadi most prone to flash flooding. This view is reinforced by the local people of the wadi and Sulayf, who blame the al Hijr for the greater frequency of wadi flows in the Sulayf gap than at Ibri - two in 1975 whereas the Ibri Wadi remained dry. The Juffra also suffers from relatively frequent flows but these are often found to sink in within the broad 'misfit' wadi above Subaykhi.

While the Hawasina has only 59% of its area as rock outcrops, floods are common in the mountain section. As already mentioned, to the north of the watershed the transition from mountain to plain is abrupt. The southern 60% of the catchment is almost all of outcropping rock, while the northern 40% is all of recent poorly consolidated sediments. Floods are therefore commonly generated in the gorges of the mountains, but seldom reach as far as the sea. This arrangement suggests conditions for maximum infiltration

*Footnote: Horton's form factor (44). The lower the value, the longer the basin in relation to its width. $Rf = \frac{\text{basin area}}{\text{basin length}^2}$

Fig. 3.9


WADI PROFILES
Height above sea level in metres
1200
1100
1000
900
800
700
600
500
400
300
200
100
sea level
0
10
20
30
40
50
60
70
80
Distance in kilometres from point at sea level, or for interior catchments point at 300 metres
Rumayla
(incomplete)
Najd
Sharingibān
(incomplete)
Kahanat
Bilad Shahūm
Al Kabir
Jufra
Hawasina / Dhulla
Tan'am
Subaykhi

(see Water Balance, Chapter 4 Part II), as does that in the al Kabir, where uncemented alluvial deposits occur in greater quantities in the upper wadi reaches.

(ii) Profiles of Wadi Systems

With channel slope often looked upon as only second in importance to drainage area for effect on flood frequency (28) wadi longitudinal profiles indicate certain differences in the response of the wadi systems to rainfall. Topographical information is not sufficient for detailed hypsometric analysis, but general wadi profiles can be constructed using available K668 spot heights, as long as the limits of their accuracy are borne in mind.

From the profiles drawn (see fig. 3.9) it is apparent that the Juffra wadi channel runs at the lowest gradient, especially in the lower reaches. The Hawasina and Bilad Shahūm wadis are the steepest, which is compatible with the idea that these have not been so subject to submerging movements which affected the predominantly north-south flowing al Kabir and Juffra catchments. The lower Juffra has a gradient of 0.2% and the al Kabir at the same altitude runs at twice this slope. On the ground, these slopes were found to remain constant over long distances. The speed of a wadi flow in the Juffra was measured at intervals as it progressed over 15kms, and it was found to remain constant ($\pm$ 5%) over the whole of this distance.

The Hawasina appears to have two separate elements, the upper

section, above Sadan, with a lesser gradient than that downstream. It is at Sadan that there are a series of rock barriers which may act as a local base level for the upstream section. A similar lessening of gradient is apparent in the upper Juffra, above Kahanat, where the Wadi turns to flow approximately east-west.

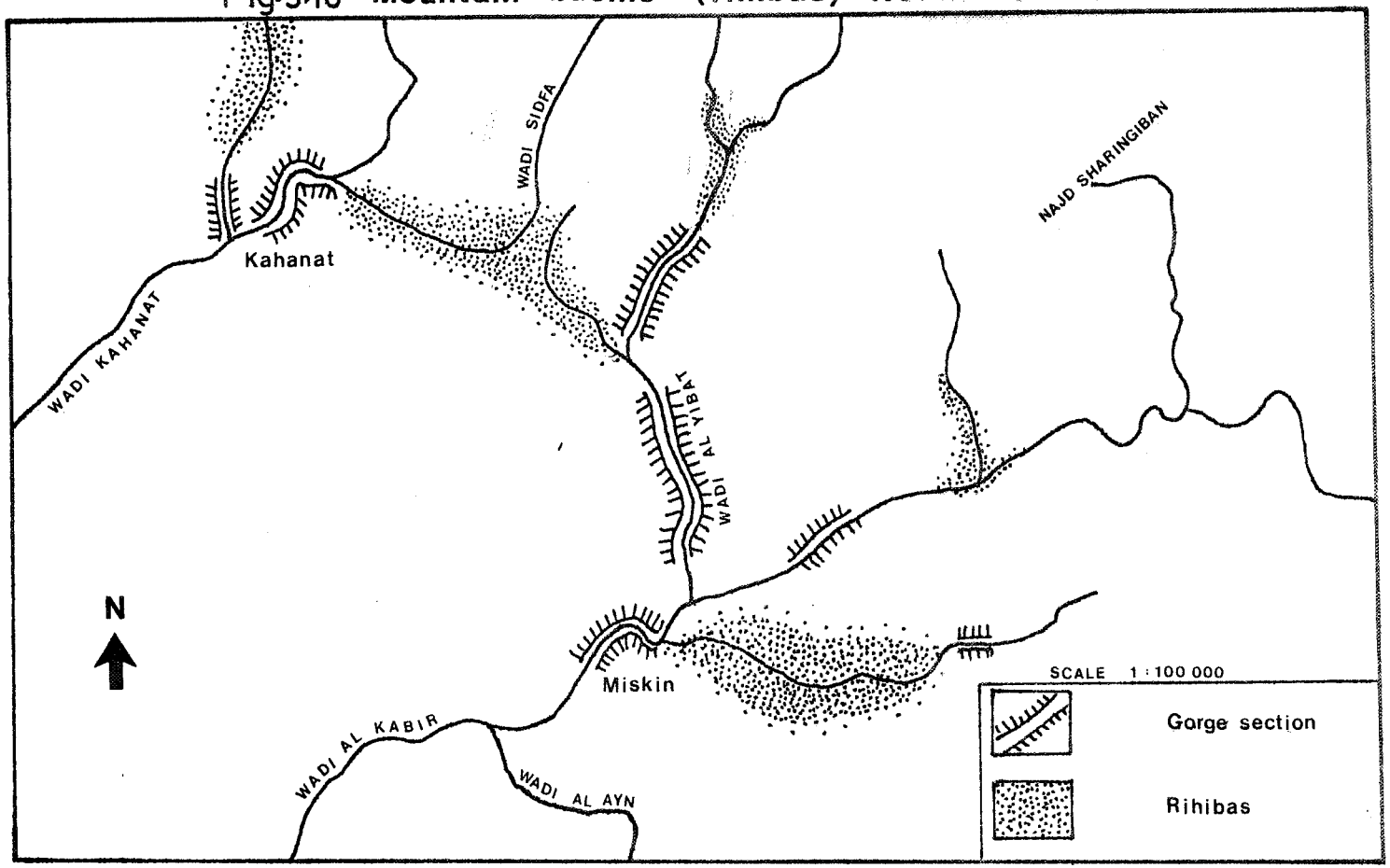
(iii) Local Profile Variations

The existence of wadi beds of lesser gradient in the upstream wadi sections that in the middle sections is a common phenomenon, and one which has a profound effect on the surface and groundwater hydrology.

In the upper reaches of the Wadis Kahanat, al Kabir, al Ayun and Bilad Shahūm, there are a series of valleys with wide upper reaches, then a constriction, and which then open out again into a broader valley (see fig. 3. 10). These features do not appear to be related to lithology, but to changes in base level. Perched valleys are recognised by local people as specific features, and each is called a 'rihiba' (as is a village in one of the best examples on the north side of the mountains).

Rihibas affect both run-off patterns and groundwater flow. The upper wadi valley is wide with gentle slopes covered in rock debris. The basin floor is similarly covered, often underlain

Fig.3.10 Mountain basins (rihibas) North of Miskin.



by rounded gravels. In this section there is therefore opportunity for infiltration and slowing of run-off. Downstream, however, flow is confined to a gorge section, with only very coarse debris. The result is that run-off is funnelled into this section and both that which has penetrated the gravels upstream and flood water must run as surface flow. Wadi spates are therefore common, and despite the gradual gradients of the upstream section, run very powerfully and turbulently, but tail off less abruptly than might be expected in a mountain area with little vegetation.

The existence of such basins near the headwaters of the wadis, means that small perennial groundwater flows occur even this far up the catchments, as there is some storage of water within them. This provides the upper settlements with a small buffer to drought conditions.

(iv) Surface Water

In a high rocky area such as the Oman mountains, run-off might be expected to be at a maximum. The occurrence of basins at a high level slightly reduces this, although the gorges often force water back to the surface. The abrupt changes of gradient at the edge of the basins are also significant in bringing perennial flow to the surface, and so making it easily available for diversion to crops. Mountain settlements are confined to those sites where this water or local seepage from the Semail ophiolites are found.

Settlements extracting surface water from wadis are known as ghayl (pl. ghuyūl) (or sayl pl. suyūl) villages, while those using seepage are called hayl (pl. huyūl) oases. Local place names, some of which are marked on maps, may therefore differentiate between these two features (eg. Ghayl Sarmand Wadi al Hayl in the Bilad Shahūm and Hayl al Lōshl and Hayl Shakhūt in the Wadi Kahanat and Sayl Rihibat al Kabir in the Wadi al Kabir).

The constricted sections vary in depth. In the Wadi al Kabir and Wadi Kahanat, the valleys narrow, but the rock floor does not reach the surface. In the Bilad Shahūm, however, at Suwaydiya, Najd, Rīmay, Bilad Shahūm and Huwaylat, water reaches the surface, after flowing as groundwater in unconsolidated gravels. At these points (as at many in the Wadi Hawasina) it appears that the rock floor of the wadi becomes shallower, and the gravel layer above it therefore thinner. The water in the gravel must either flow faster, or come to the surface. The steepening of gradient which would make the speeding up of flow possible does not occur until downstream of this point. The water is therefore forced to the surface, and it is at these points that settlements have grown up, using diverted water for irrigation. No settlements are found in the more northerly of the south-flowing wadis, where these conditions do not occur.

Not only bedrock forces water to the surface. As Vita-Finzi has shown, the development of caliche affects routes of surface water flow (46) and in Oman it is found also to act in places as

enough of an aqueclude to force groundwater to the surface. On occasions (as at Munqnyat) these layers are so hard that the boulders (up to 20cm in diameter) and pebbles within them may be more easily eroded than the matrix surrounding them. In the mountains conglomerates most commonly occur along the path of waters originating in the Semail ophiolites and so, on the South side of the watershed, are most frequently found in the Bilad Shahūm. Weaker, more permeable conglomerates are found in the Wadi Kahanat below the village of the same name, but here, as above Miskin where they also occur, they do not appear to be efficient enough aquetards to bring water to the surface.

The two main areas in which they appear to affect water flow, in the Bilad Shahūm, are at Bulayda and Munqnyat. At both sites water is ponded back by conglomerate barriers, and then runs over these (and possibly in pipe flow through them) in small waterfalls and pools. Above these barriers are several diversion falaj sources. In the case of Munqnyat, falajes Karūāni, Tasdir and Lamduc all rise within 200m of the appearance of the conglomerate, while at Bulayda, falaj al Bilad and falaj al Halthi rise just upstream of it.

In Bilad Shahūm itself, conglomerates outcrop near the source of one of the diversion channels in the Wadi Rumayla, and at Sidādib too, they bring water to the surface. Similar, but possibly softer conglomerates, also form terraces within the Bilad Shahūm. These rise 15-20m above the present wadi floor, and provide flat areas protected from wadi spates, which

are used both for cultivation and as routes for transport. Local diviners in Magzi Bani Umr (where similar features were observed) suggested that water flows within the conglomerate. Here it contained a falaj source which was being further extended. It therefore appears to be less impermeable, or to support a greater pipe flow, than those denser conglomerates found in the Bilad Shahūm beneath thepresent wadis.

To the north of the main mountain water shed, the occurrence of surface water is spectacular, especially in the Wadi Na'am. The upper wadi forms a wide basin, in which lie three small villages. It appears that this section may at one time have flowed south to join the Wadi Kaha nat/al Aridh. Now, however, it flows through a narrow gorge, in massive limestone (as little as 6m wide and with walls over 50m high) with waterfalls and deep pools. The water comes to the surface from gravels at the upstream entrance to the gorge, and disappears into the gravels of the wadi ad Dil at the downstream end. The upper Wadi Hawasina, except al Ajm, and the ad Dil itself are dry, but surface water commonly flows in the wadi channel between Harmali and Ghayzayn. Here, while gradient changes may have an effect, it is the outcropping of conglomerates with which surface water is most associated. Hence the string of villages diverting the surface water to terraces at Harmali, Shakhbūt, Bidāya, Falaj, Sadan and Na'am.

Flash floods are common in this area, but infiltration capacity

of the gravels is high. Thus even the heavy floods in the ad Dil and Na'am wadis of April 1974 only moved as surface flow in the main wadi for a short distance (less than one kilometre) and then sank beneath the surface.

Since the wadis act as the only points of groundwater recharge, as well as the conductors of surface water, the sections of surface water flow and of conglomerates near the surface are of great significance. Here infiltration is not possible, but flooding is common and destructive. Diversion dams need reconstruction after all except the lightest rainfall, roads are swept away, and communications between settlements temporarily severed.

A point which has much effect on the settlement pattern, is that perennial water provides a particularly suitable habitat for snakes.* Thus while terraces are irrigated from diversion channels, living quarters have to be confined to above the terraces, on rocky slopes well away from surface water.

The speed with which perennial surface water flow issues from the gravels (often at around 8m/min) is an indication of their high permeability. Observations of wadi flow in the gravels near Ibri showed an infiltration capacity of over 7cm/min, and it is apparent that it is flows passing over these gravels which provide the majority of recharge.

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*Footnote:- In the early stages of the field study, wadis with perennial surface water flows were actually identified by consulting the Tan'am hospital outpatients list, for the area of snake bite victims. From this, the Wadi Fida (to the north-west of the area), the Bilad Shahum, and Sulayf were correctly assumed to contain significant areas of surface water.

E - CONCLUSION

Thus the Quaternary deposits in Northern Oman, and in the area extending north to the Musandam peninsula provide the major active unit of the hydrogeology. Infiltration, recharge, storage and flow, all elements of groundwater hydrology poorly developed in the solid geology formations, are represented, if to varying degrees of development, within the post-Miocene deposits. The lower gradients and more permeable structure of the recent sediments prove better, if less homogeneous aquifers and re-charge sites.

It is not, however, sufficient to consider only the effect of the present form of the land surface on the groundwater hydrology. The recent history and evolution of the landscape is of prime importance as the water is mainly flowing and stored in sub-surface paths, which may be associated with the infilling of earlier land surfaces. While surface catchments and lines of flow are relatively simple to follow, those underground have been found not necessarily to follow the same paths. This is a direct result of the Quaternary history of the area.

In terms of assessing groundwater resources, this phenomenon has two principle effects. Firstly it is not possible to assess the degree of inter-catchment transfer. Secondly it hinders the estimation of re-charge to a system, using recession curves. This requires a knowledge of the area contributing to the source, and in the case of all those systems downstream of Injayd in the

Wadi al Kabir, and of Kahanat in the al Aridh/Juffra wadi, it is feasible to propose inter-catchment transfer, but is not possible to quantify it.

Re-charge occurs almost without exception through present wadi beds which, except at points of perennial surface water where they are already saturated, exhibit very high infiltration capacities.

III HYDROCHEMISTRY

A - SOLUTION AND PRECIPITATION

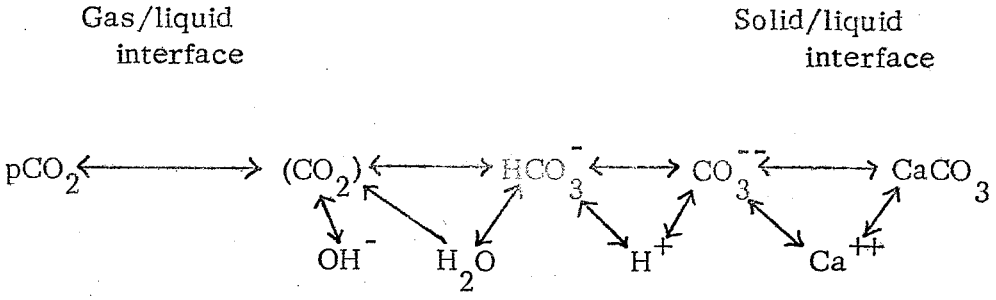
(i) Carbonate Equilibria

From an introductory study of the recent geomorphological history of the area it is apparent that carbonate cementation of alluvial deposits is an important factor in the occurrences of groundwater. Cementation to form calcrete or caliche horizons, reduces vertical permeability and so infiltration, and forces water to the surface in narrow wadis. Layers in which cementation is reduced or non-existent become preferred paths of flow, and it is therefore important to try and define under what conditions cementation occurs and whether existing paths of flow are likely to be subject to widening by solution or diminution by precipitation. This will depend in part upon the hydrological conditions (saturated or unsaturated) and in part upon the chemistry of the water (again saturated or unsaturated). It is therefore necessary to examine the solubility and saturation of water with respect to specific minerals, and the degree to which this is affected by contact with atmospheric conditions.

The chemistry of caliche has been studied in some detail in respect of the minerals of which it is composed (47) but there seems to be less work on the chemical processes by which it reaches a given composition. In other fields, however, carbonate equilibria have been well studied, particularly in soil science (48, 49) . The effects of pCO_2 (partial pressure of carbon dioxide, the negative logarithm of the concentration

in the same way as pH) on carbonate equilibria, and so on soil structure and plant uptake of nutrients, are especially important aspects which have prompted detailed research into the system. Considerable amounts of research have also been undertaken on the solution and precipitation of calcite with reference to karst landforms, particularly caves in the saturated zone, and these have been comprehensively reviewed by Sweeting (50).

The simplest system to consider is that of calcium carbonate itself which occurs mainly in the polymorphic forms of calcite and aragonite. It involves the relationship between gas, liquid and solid phases, the changes which occur within each and at the interfaces between them.



Roques' (51) flow diagram of the system shows that even in its most simplified state most reactions are reversible, particularly in response to changes in pCO_2, and so stability is very seldom reached.

The fundamental equations involve the dissociation of ions in solution. The concentrations which these can reach is related

to dissociation constants of individual ions, and equilibrium constants of the minerals concerned.

There are five simple equations involved where temperature and pressure are kept constant. They are as follows:-

Solid to liquid:

1. $CaCO_{3(S)} \rightleftharpoons Ca^{++}_{(aq)} + CO_3^{-}(aq) = K_{CaCO3} = 10^{-8.3}$

Liquid:

2. $H_2CO_3 \rightleftharpoons H^+ + HCO_3^- = K_{H_2CO_3} = 10^{-6.4}$

$HCO_3^- \rightleftharpoons H^+ + CO_3^- = K_{HCO_3^-} = 10^{-10.3}$

$H_20 \rightleftharpoons H^+ + OH^- = K_{H_20} = 10^{-14.0}$

$H_2CO_3 \rightleftharpoons H_20 + CO_2aq = K_{CO_2} = 10^{-1.47}$

Equilibrium constants (K) are taken from Garrels and Christ (52). The above are expressed as activities and not concentrations, and as

the Debye-Huckel theory shows, activities are lowered by the electrostatic forces of other ions. Therefore, up to a point, solubility of calcium carbonate will increase with higher ionic strength (ie. higher total dissolved solids). The introduction of other ions, however, also has other effects upon the solubility of calcium carbonate, which are relevant to observed water quality in the area.

As mentioned, the majority of the limestones in the area are dolomitic and so the carbonate system cannot be considered without reference to magnesium. This introduces the minerals dolomite $CaMg(CO_3)_2$, magnesite $MgCO_3$, huntite $CaMg_3(CO_3)_4$, brucite $Mg(OH)_2$ and hydromagnesite $Mg_4(CO_3)_3(OH)_2 \cdot 3H_2O$. The stability of these is related to pCO_2 (53) by Carpenter who shows that brucite and hydromagnesite are not stable at atmospheric levels of carbon dioxide (-3.52), while huntite and aragonite are metastable. Time and attendant water percolation through sediments tend to leave only minerals with broad ranges of stability.

Magnesium not only increases the forms in which calcium and carbonate ions can be combined in the solid state, but also increases the solubility of calcite itself as ion-pairing increases. Magnesium has been found to inhibit the nucleation of calcite and therefore water may remain supersaturated with respect to calcite over long periods (54).

Sulphate also increases ion-pairing, the occurrence of undissociated molecules which act as thermodynamic entities and are governed by

association constants. Calcium sulphate may therefore exist in solution as $CaSO_4^o$ as well as Ca^{++} and SO_4^{--}, and there will therefore be more calcium in solution than simply that in equilibrium with carbonate solubility products; solubility is therefore increased. As Wigley points out (55) if ion pairing is properly taken into account, many samples otherwise considered as supersaturated turn out to be undersaturated.

Levels of saturation are expressed by comparing the ion activity product aK of the sample with the thermodynamic solubility product at saturation (the equilibrium constant). Where the log of the ion activity product aK exceeds the log of the solubility product then the saturation level is greater than zero. Where the two are equal the saturation index is zero, and in the unsaturated state the index is a minus figure. For the principle minerals - calcite, dolomite and gypsum - the saturation indices are defined by the relations:-

$$SATCAL = \log (a\,Ca^{++}\, a\,HCO_3^{-}\, K_{HCO_3}) - \log (aH^{+} Ks) \;*$$

$$SATDOL = \log (a\,Ca^{++}\, a\,Mg^{++}\, (aHCO_3^{-})^2\, (K_{HCO_3})^2) \;*$$

$$SATGYP = \log (a\,Ca^{++}\, a\,SO_4^{--}) - \log (K_g) \;*$$

and are quite temperature dependent equilibria.

---

*Footnote:- Where a = activity K_d = equilibrium constant for dolomite
K_c = " " calcite
K_g = " " gypsum

(ii) The Salt or Electrolyte Effect and the Common Ion Effect

Water in a bottle is an isolated example of a particular balance between the variety of dissociated and associated ions it contains. It can be examined to see whether it is capable of further solution or is already supersaturated with respect to carbonates, both at the partial pressure of carbon dioxide it is subject to as groundwater and if it were to be exposed to atmospheric levels of carbon dioxide. Such an examination does not, however, define what will happen should this water become mixed with another of differing chemical composition. This is a likely occurrence particularly in a limestone aquifer as water tends to travel in concentrated lines of flow, in fissures, joints and pipes remaining isolated from other flow systems nearby, and so often lacks chemical homogeneity.

The reactions which will occur on such a mixing are very difficult to predict, as artificial recharge projects have found (56) . Apart from the equilibria outlined above, there are two fundamental phenomena which are active in the mixing of two waters, or of a water and a different solid phase to the one with which it was previously in contact. These are the salt, or electrolyte effect, and the common ion effect.

The salt effect leads to an increase in solubilities. It affects the activities of ions, reducing them and so allowing an increase in ionic concentrations to maintain equilibrium.

The common ion effect works in the opposite direction. The thermodynamic solubility product of calcium carbonate in water at 25^{0}C is $10^{-8.3}$. As the ionic strength of the saturated solution is negligible, this is the value of the apparent solubility product, and so long as some undissolved calcium carbonate remains, this (3.2×10^{-4} g. ion/litre) will be the level of calcite in the water (all other conditions such as pCO_2 remaining equal). Calcium sulphate, however, is more soluble with a solubility product of $10^{-4.6}$. If a solution of 10^{-2} Molar calcium sulphate is added there will then be a hundred-fold increase in calcium in the resulting solution. If the thermodynamic solubility product of calcium carbonate is to be kept constant there must, from the equation

$$SATCAL = \log (a\,Ca^{++}\, aHCO_3^{-}\, K_{HCO_3}) - \log (aH^{+} K_s)$$

be a corresponding decrease in bicarbonate ions. The net outcome is the precipitation of a considerable fraction of the previsouly dissolved calcium carbonate.

The mixing of two types of water, with different dominant anions or cations can therefore be seen to have potentially two opposite effects. It may lead to greater solution or increased precipitation, depending on which ions are dominant in each solution and whether saturation levels are being approached or exceeded in either.

(iii) Observed Saturation Levels

The analytical results from over 800 samples were processed to establish the levels of saturation occurring in the hydrogeological environment of Northern Oman. With a slight modification to allow for ultrabasic waters, Wigley's programme Miniwat was used. This allows for ion-pai ring and calculates ionic strength, charge balance error of the analyses, pCO_2 and the saturation indices for calcite, dolomite, gypsum, magnesite, aragonite, huntite, brucite and hydromagnesite. The facility for examining silicate equilibria was not used as silica analyses were not available.

Of all the minerals for which saturation levels are calculated, superaturation is never attained in hydromagnesite and very rarely in gypsum.

Table 3.1 summarises the findings with respect to other minerals. (see over).

Table 3.1 Levels of saturation for coastal and inland waters

INLAND

	CALCITE	ARAGONITE	DOLOMITE	MAGNESITE	HUNTITE	BRUCITE
Under-saturated	10% but generally very near equilibrium	22% Particularly wells east of Dariz	5% All in association with al Ayn limestone	15% Esp. in association with Hamrat ad Duru formation	20% Most under-saturated where pCO_2 lowest.	99%
Over-saturated	90%	78%	95%	85%	80%	1% only seepage from ultra-basic ophiolites
Super-saturated	None with S.1 over 1	None with S.1 over 1	S.1 > 2 10%. Mainly in desert foreland. S.1 > 1 55%	S.1 > 1 6%. Water off ophiolites & into gravel or conglom.	6%. S.1 > 1 Those with very low pCO_2 associated with Semail ophiolites	None
			BATINA			
Under-saturated	9% Wells on inland fringe of cult. area	18%	0.5%	2%	98%	98%
Over-saturated	91%	82%	99.5%	98%		
Super-saturated	10% All with soil fallen in	1%	S.1 > 2 10% S.1 > 1 75%	3% Little or unused wells		

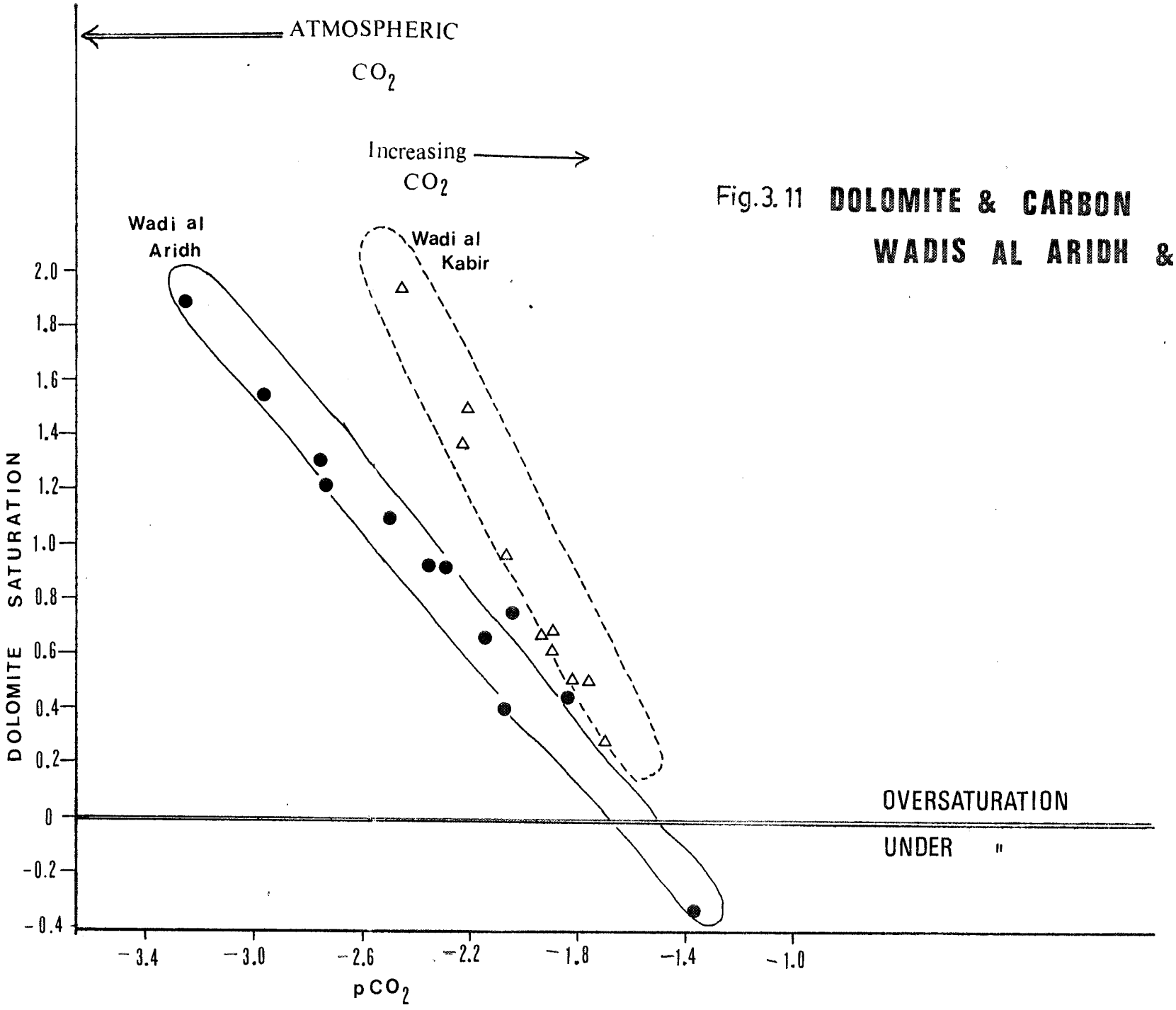


Fig. 3.11 **DOLOMITE & CARBON DIOXIDE LEVELS WADIS AL ARIDH & AL KABIR**

It is apparent that the majority of waters in the area, regardless of origin, are oversaturated with respect to the principle minerals of calcite, aragonite, dolomite and magnesite. Levels of saturation are generally higher than those found in Florida (57), and in direct contrast to the predominantly undersaturated waters found by Thrailkill in Kentucky (58). Waters also contain, almost without exception, above atmospheric levels of CO_2 (see fig. 3.11). Omani waters are particlarly highly saturated with respect to dolomite, and precipitation may easily be instigated, if a stimulus is available. Four main factors are frequently in operation causing changes in saturation level. They are; the addition of small dolomitic and organic particles, changing pCO_2, evaporation and mixing with ultrabasic water.

(iv) Processes of solution and precipitation

In the case of recharging groundwater a considerable amount of silt and clay may on occasions be carried with the water, and this provides readily available exchange sites, organic acids from animal droppings, and an easily soluble form of dolomite (small volume to surface area ratio). If carbon dioxide is of organic origin then it must be obtained from this silt, by the release of H+ ions from exchange sites and acids. Following Roques' diagram there is then a further solution of carbonates and the formation of more bicarbonate ions.

This process is illustrated by a sample of water from a small wadi spate which was unusually heavily laden with silt. Of all the water

samples analysed this was the only one to be oversaturated with gypsum. It was also supersaturated with calcite, dolomite (SATDOL = 2.7, the highest value found), magnesite and aragonite (SI over 1.0 for all species). Despite full contact with air, pCO_2 was 2.7.

Sheet flow carries the finest soil particles and organic matter, and although contact time is generally short, organic acids, ion exchange and small particle size all help to speed up solution (or if picked up after saturation levels are reached may in the case of the last cause deposition). The water infiltrates, carrying the finer particles with it, into the upper layers of alluvium. After the rains pass, evaporation occurs, the water is subject to capillary action and the solution becomes more concentrated. Already supersaturated, and with suitable attendant small silt particles for nucleation, precipitation is almost bound to occur.

Recently infiltrated groundwater is geared to higher than atmospheric pCO_2. Water in the capillary fringe near the surface, particularly where water levels fluctuate markedly, is therefore likely to precipitate carbonates as a response to its own supersaturation with various carbonate species, to a falling pCO_2 and to fluctuations in temperature. Water marks in wadi pools indicate that such deposition occurs, but only the highest mark appears to remain, lower ones often being redissolved. Precipitation and cementation may only therefore be irreversible where falling water tables reduce chances of re-solution.

Groundwater stored for a longer time has even higher levels of CO_2. Except in the case of highly alkaline waters, the observed levels of

carbon dioxide are considerably greater than those encountered under atmospheric conditions, reaching pCO_2 values of as high as 1.4 (cf. atmospheric levels of 3.52 as negative logarithm). Such water is therefore prone to precipitation should it reach the surface or come into contact with any other environment of lower pCO_2. Being also supersaturated with calcite, a water flowing from a predominantly calcitic to a dolomitic area, if already supersaturated with calcite may be subject to calcite precipitation through the common ion effect.

In the area studied a third factor in solution and deposition in addition to silt and pCO_2 is mixing with ultrabasic waters. The water from seepage in the ophiolites is supersaturated with huntite ($Mg(OH)_2$). This is extremely unstable, but can be found in anaerobic conditions. Where such water mixes with water typical of ophiolite gravels or limestones (see p. 129) dolomite is precipitated according to the equation

$$Mg(OH)_2 + 2HCO_3 + Ca^{++} \longrightarrow MgCa(CO_3)_2 + 2H_2O$$

or magnesite $Mg(OH)_2 + 2HCO_3^- + Mg^{++} \longrightarrow 2MgCO_3 + 2H_2O$

A high degree of cementation is therefore found in conglomerate terraces which abut ophiolites from which seepage occurs. In places such as at Sadam the matrix becomes so cemented that the pebbles set within it are more easily eroded than the cement itself. In this situation silicates in solution may also encourage carbonate precipitation (54).

Cementation of beach sands is also common, forming a natural barrier to groundwater movement to the sea, or seawater movement inland. Schmalz and Chave (52) note that seawater is generally supersaturated with carbonates, and the mixing of two supersaturated solutions is very likely to cause precipitation and cementation of sand.

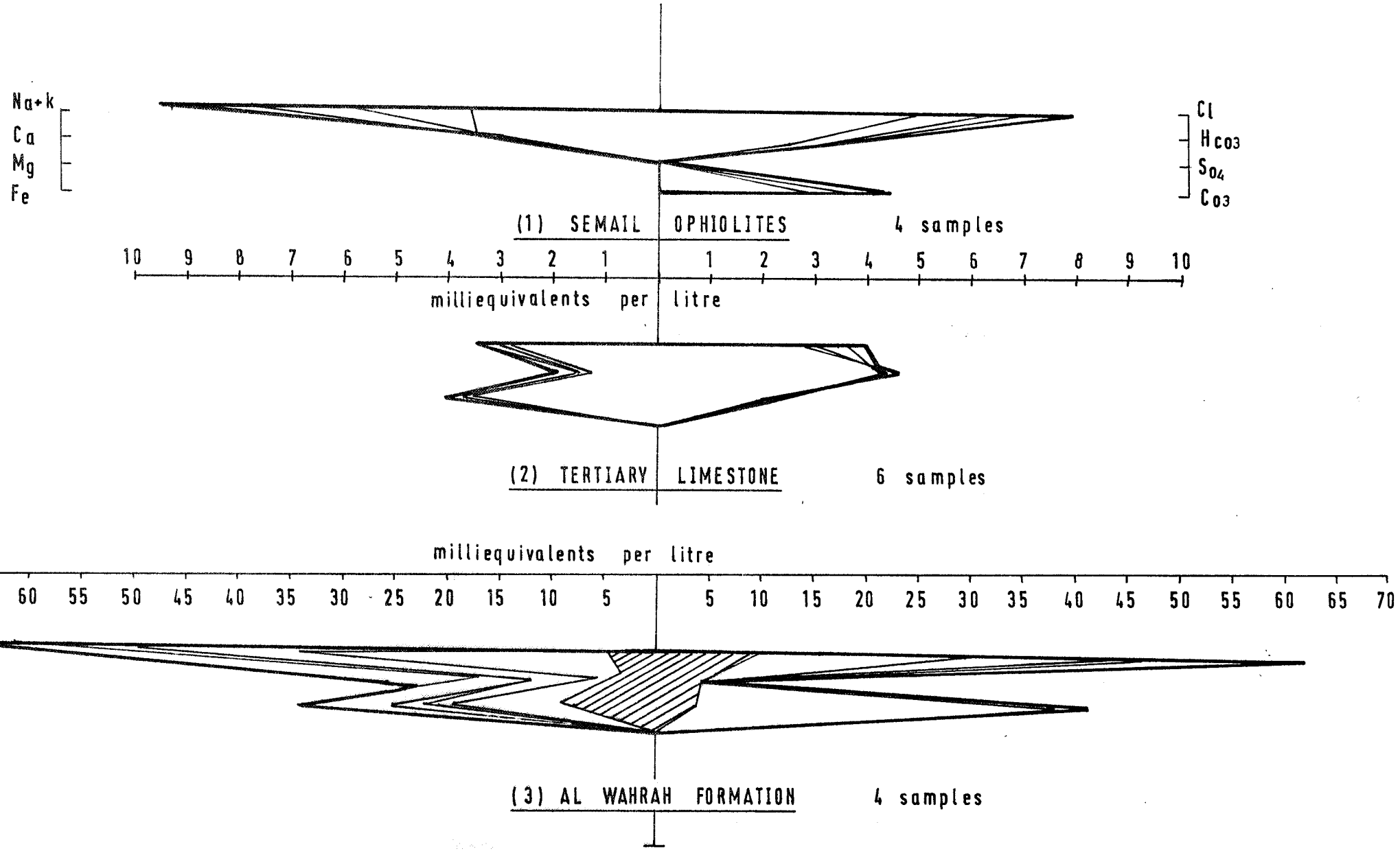
It is apparent that, while the formation of caliche horizons has occurred on at least two previous occasions, the chemistry of present day groundwater lends itself to a further period of precipitation. Most water samples exhibit particularly high levels of saturation with respect to dolomite and this carbonate is the dominant form in the area. Precipitation is especially likely to occur where alluvial deposits may be in contact with silt laden flood water; where water comes in contact with atmospheric pCO_2; where a groundwater moves from one aquifer to another; and lastly where two different types of groundwater mix. It is suggested that these are also the conditions which caused the past cementation of caliche horizons observable in present day terraces, and that the cementation was preserved by falling water tables.

B - WATER CHARACTERISTIC OF PARTICULAR HYDROLOGICAL SYSTEMS

(i) Water Chemistry and Solid Geology

The principle aquifers of the area are calcareous, while the minor ones tend to be saline or ultrabasic. Water in the main paths of flow is therefore predominantly carbonate in character, in accordance with the equilibria discussed above, but locally, in association with poor

Fig.3-12 STIFF PATTERNS OF WATER TYPES ACCORDING TO AQUIFER



aquifers, may be saline or highly alkaline. It is therefore possible to isolate types of water characteristic of particular area. Stiff patterns (59) are used here to facilitate comparison of water types.

While water stored in bedrock as opposed to alluvial fill is only a small proportion of the total, it is usually of very distinctive character. As the water moves away from bedrock storage* it is rapidly diluted by water travelling through the alluvial deposits. Thus at seepage points, resurgences and in some wells close to the source, the origin can easily be identified, but this becomes progressively more difficult to define as the water moves downstream.

The Semail ophiolites, being ultrabasic rocks, are the source area for the most alkaline waters encountered. These waters reach a pH of as high as 11.5, but are also unusual for their lack of magnesium and sulphates (see fig. 3.12(1)), particularly since the rock contains magnesium-rich silicates. As a result of the high alkalinity most of the carbonate appears as carbonate ions rather than bicarbonate ones, which are the dominant form in all other areas, pH being lower. The chemistry of this water and its effects are discussed further in the next section.

Water associated with the Tertiary limestone is more consistent in chemistry thatn any other set of samples collected (see fig. 3.12(2)). Both from point to point and over time the concentration of all the major ions varied little, suggesting that flow out of the limestone is small compared with the volume stored within it, and that the sources

*Footnote:- Water moving from bedrock to alluvium undergoes such rapid and major changes that mapping of water quality for the area as a whole has not proved possible.

may be interconnected at depth. It tends to contain almost equivalent quantities of sodium and calcium with about half as much magnesium. As in most areas bicarbonate is the dominant anion.

The al Wahrah formation is the only truly saline aquifer. The cherts and mudstones of which it is mainly composed contain chlorides probably left at the time of the rock's formation, reflecting its marine origin. Thus sodium and chloride ions are commonest, with magnesium and sulphate ions second in importance. It is however in direct contrast to the very constant quality of the Tertiary limestone. In fig. 3.12(3) the shaded sample and the outermost one (with electrical conductivities of 1590 and 3250 micromhos respectively) come from springs less than a metre apart within the same well, illustrating the wide variation in quality found over short distances.

(ii) Water in Upper Wadi Reaches

In contrast to the water from bedrock, that travelling in the more transmissive alluvial deposits is generally lower in total dissolved solids and may be of different character to water flowing in the parent rock. This arises from the longer residence time of water in the bedrock and the lesser contact with atmospheric conditions. Gravels in wadi beds are of sufficient volume to provide short-term storage and perennial surface flows of relatively recent storm run-off, within a short distance of the watershed.

The gravels tend to originate from the Hawasina limestones and Semail ultrabasic rocks. On the coast the ratio is about one part of the former

to three of the latter (60) but in the Interior, especially in the lower wadis the limestone fraction is a higher proportion (probably up to 60-70%) of the whole, reflecting the relative areas of outcropping rock types in each catchment and their resistance to erosion.

In the upper wadi reaches the quality of the water tends to reflect the proportion of the catchment which consists of calcareous/dolomitic or ultrabasic rocks. The water which passes through gravels derived from the ultrabasic rocks, however, is not of the same type as that which issues from the bedrock itself, as this is very unstable under atmospheric conditions. Thus the Bilad Shahūm, almost totally enclosed by ultrabasic surfaces, contains groundwater which is characteristically low in sodium, calcium, chloride and sulphate (see fig. 3.13), almost a reversal of the chemistry of the seepage from the same rock. This pattern is also identifiable in the Wadi Kahanat/al Aridh, but increasing levels of sodium and to a lesser extent of other ions are found as water moves down the catchment.

The Wadi Hawasina, which mainly consists of the Hamrat ad Duru formation, exhibits a pattern typical of water draining a limestone catchment, resembling the water type observed in the Tertiary limestones (cp. fig. 3.12(2) and 3.12(3)).

The upper Wadi al Kabir above its junction with the Bilad Shahūm contains water whose composite nature (see fig. 3.13(4)) reflects the fact that the left bank is of Hamrat ad Duru limestones and the right of Semail ophiolites.

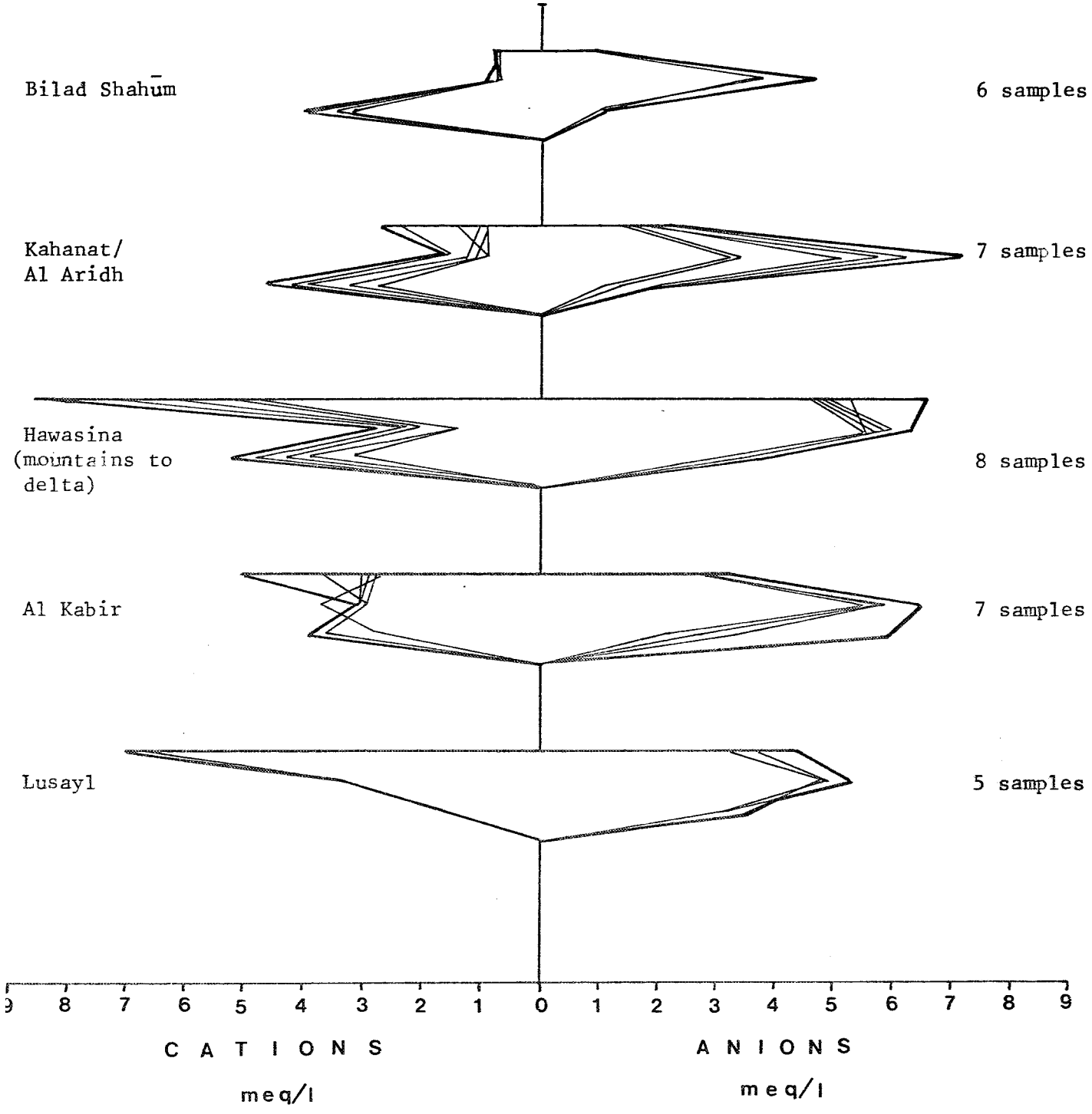


FIG. 3.13 STIFF DIAGRAMS OF WATER TYPE IN UPPER WADI SECTIONS, AND LOWER WADI LUSAYL

All the above catchments reflect the dominance of dolomites and magnesium-rich silicates, 97% of water samples containing magnesium in excess of calcium. The Wadi Lusayl is the only system in which groundwater, while exhibiting the normal balance of anionic concentrations, contains considerably higher levels of calcium than magnesium (see fig. 3.13(5)). It is also the only system in which a major proportion of the catchment is made up of al Ayn formation and Oman exotics, and tends to suggest that these are more calcitic than dolomitic, in contrast to the other limestones encountered in the area.

(iii) Water in the lower Wadi Reaches

While it is possible to isolate types of water in specific rocks and near watersheds, this becomes increasingly difficult as one moves down the system, except in the Wadi Hawasina where changes are small over its whole length. Inflow from tributary systems, the varying quality of water moving from the alluvial deposits near wadi walls, and the increase in solution and precipitation processes as residence time underground increases, all help to lessen the differences between the waters from different hydrological systems in the Interior. If one is to be able to identify water any distance from the source area then it is necessary to look at the most concentrated flows, as these will change least in chemical character. Here, falaj sources are therefore generally used as the basis for most comparisons, being found to tap discrete spring flows (see p. 293).

Within the Al Kabir, the system for which most information has been collected, the character of groundwater changes even between Miskin and Injayd. Water appears to flow in from the ophiolites and gravels derived from them in the Wadis al Ayn and Yibat, so that at Injayd the water becomes indistinguishable from that found in the adjacent system of Kahanatand al Aridh. This is also true for almost identical water at Hujrimat, which could come from either catchment, and at al Hayyal (though here magnesium levels seem to be subdued by local occurrence of the al Ayn limestone and of gravels derived from it).

By the time one reaches the major systems of Dariz, Araqi and Ibri Majjur it is apparent that the water contributing to them could come from all or any one of the three wadis of the Bilad Shahum, al Kabir or Kahanat/al Aridh, but that the water is characteristic of water from ophiolite gravels. The falajes of Aynayn and Ibri Mab`uath show the influence of small amounts of water flowing in from the East which are of higher electrical condictivity. This may be from the al Wahrah formation, but al Wahrah water is generally of low bicarbonate and high chloride and sulphate levels (see fig. 3.14(3)), whilst the observed samples require water of high bicarbonate content, such as that found in the al Hijr (see fig. 3.14).

The influx of al Hijr water to the al Kabir has already been suggested on geomorphological grounds. Water chemistry supports this idea, in two different ways. Firstly the overall pattern of electrical conductivity follows a pattern indicating the junction of two systems (see fig. 3.15). These are the low conductivity (about 460 micro-mhos) water of the al Kabir and of infiltrating falaj water to the west

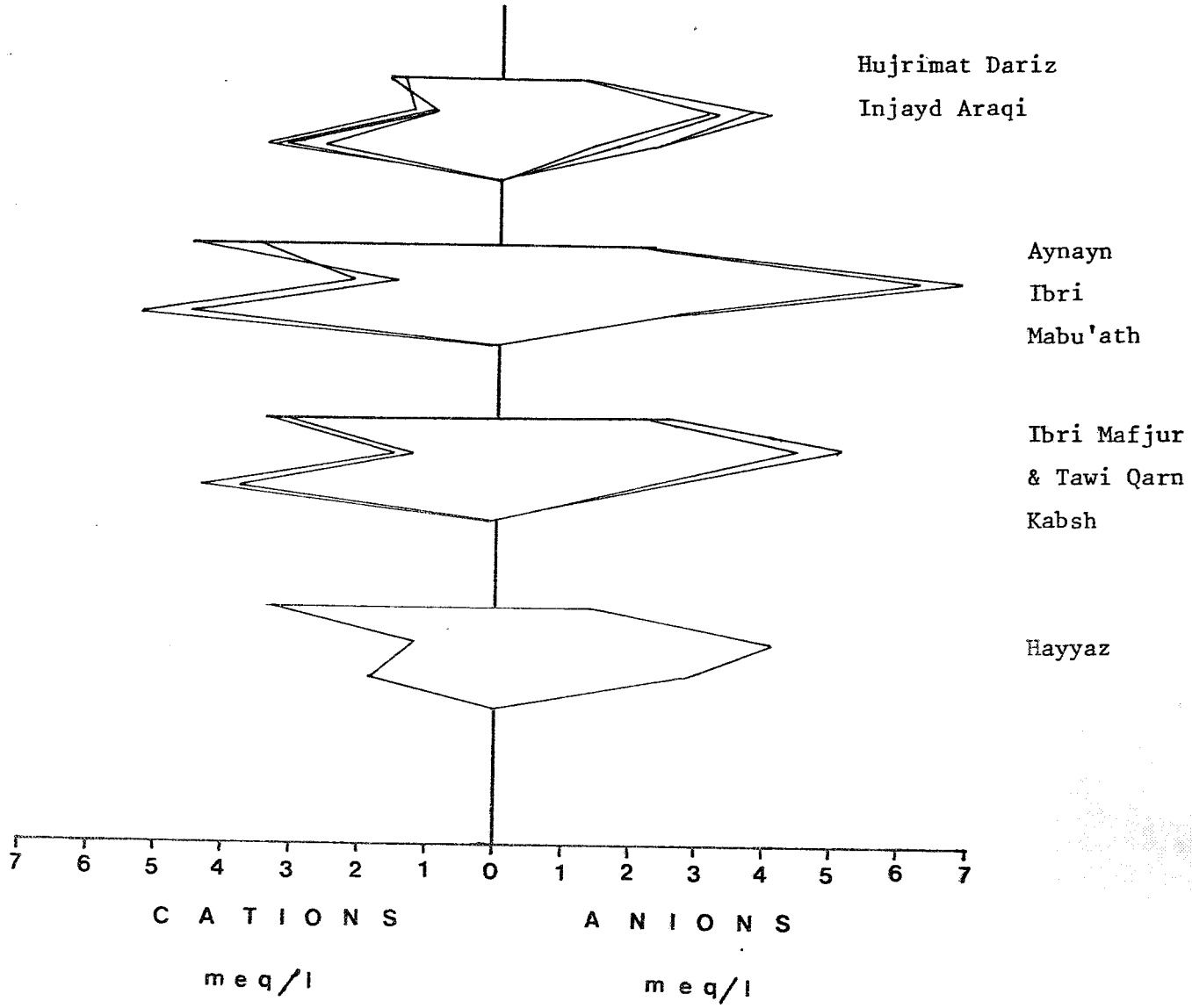


FIG. 3.14 STIFF DIAGRAMS OF WATER TYPE IN LARGER FALAJES AND IN TAWI QARN KABSH

ELECTRIC CONDUCTIVITY

DARIZ WELLS

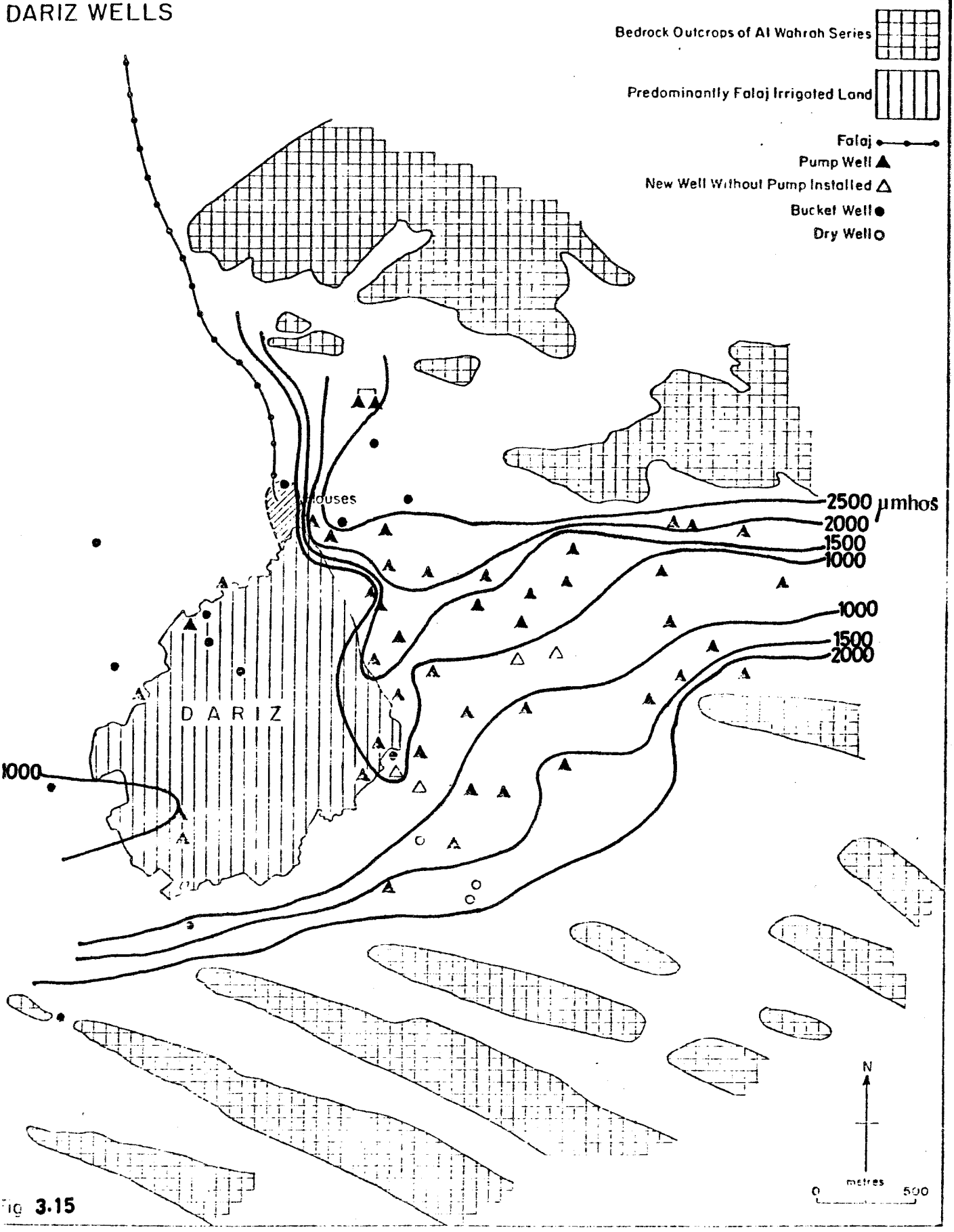


Fig 3.15

and a distinctive linear distribution of water of about 900 micromhos found to the south and east of Dariz. Quality declines away from these two areas of good water, as the effects of the al Wahrah formation (its high chloride and sulphate content) become apparent.

Secondly, taking fuller analyses of the water to the south and east of Dariz shows it to be of very different quality to the al Kabir water of the falaj and wadi al Kabir (see fig. 3.14), but of similar character to that of the few samples of al Hijr water available (see fig. 3.16).

It is not possible to investigate other proposed drainage pattern changes on the grounds of water chemistry because of the increasing similarity of the water of adjacent systems as one moves downstream. One negative result can be recorded as the Wadi Lusayl is the one system which maintains its character of a low magnesium to calcium ratio, and no such water is found in the lower wadi al Kabir, from the Ibri gap southwards. Groundwater from the system from the East would therefore appear not to cross the low watershed to the north of Jabal Shibamina.

While the main flows of groundwater lose their distinctive character, there appears to be little mixing with and contribution from the poorer aquifers. Water quality towards the Ibri gap (see fig. 3.17) presents a picture of a major stream of groundwater flow with poorer water and slower flows to either side. The main flows in the al Kabir are of very high quality and change little between Injayd and Ibri, some 35km distant (see fig. 3.14), despite the indications of water of higher conductivity in all the areas peripheral to them. This has an important

Fig 3.16 Stiff diagrams of assorted types of water.

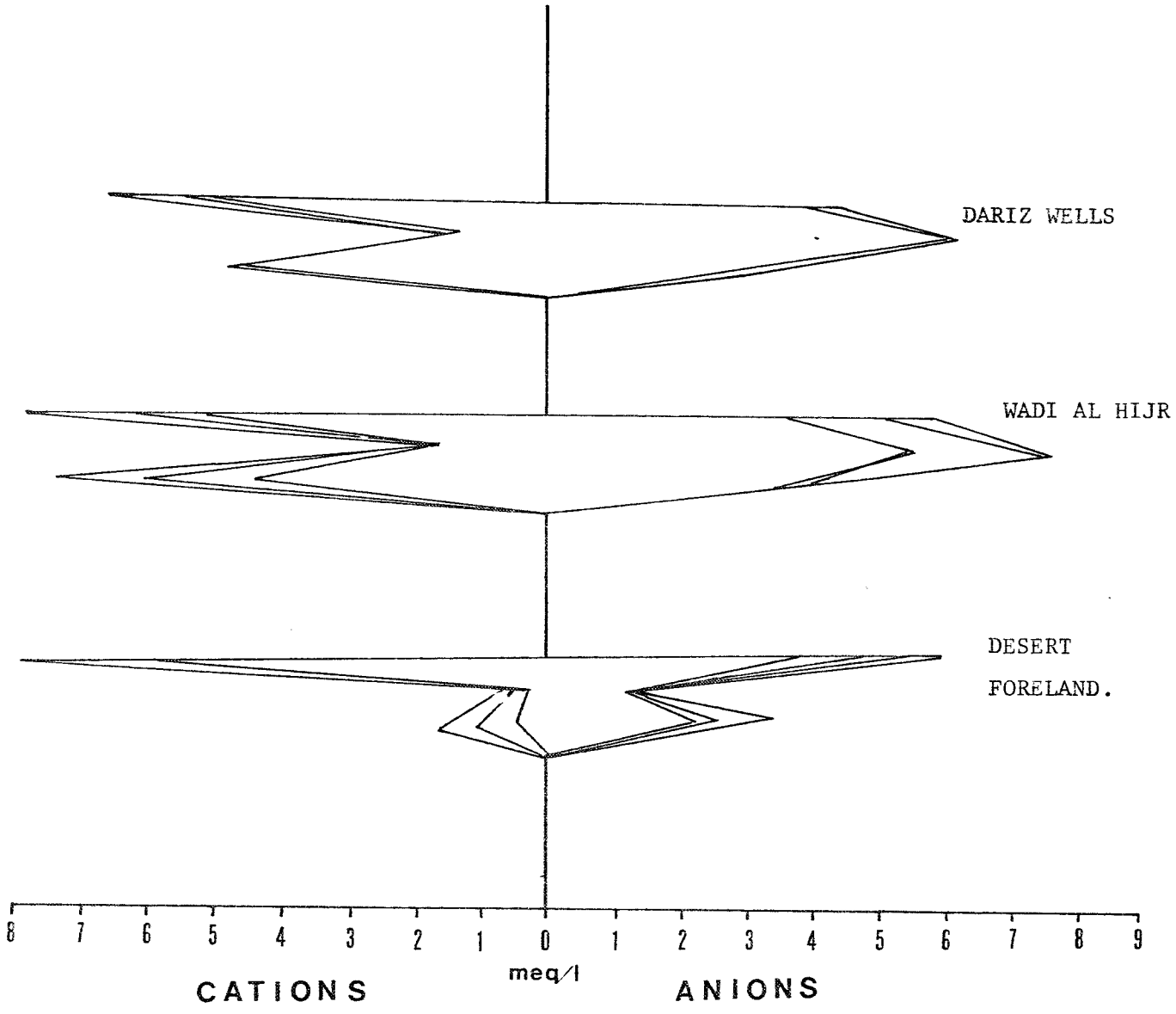
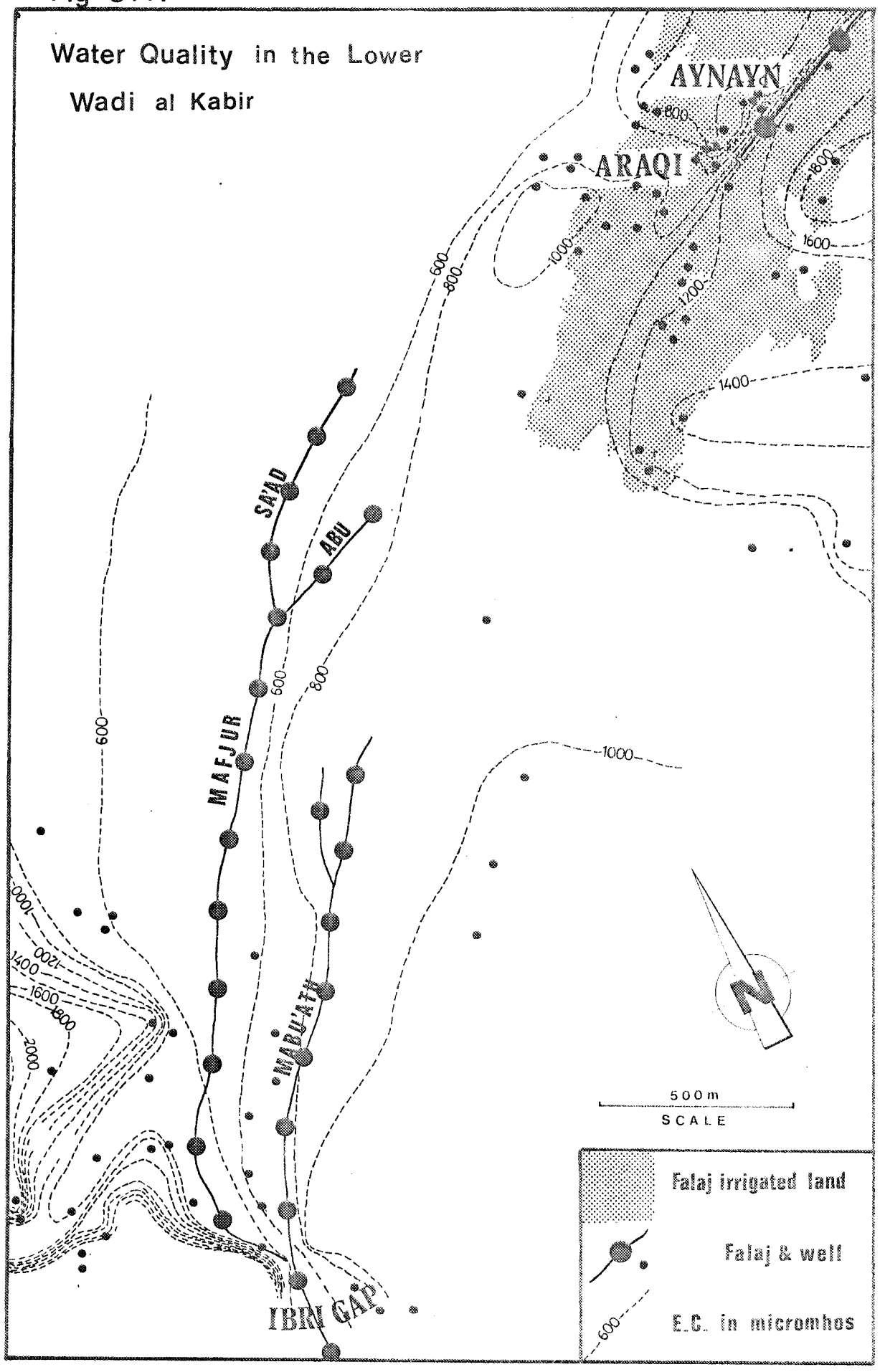


Fig. 3.17


Water Quality in the Lower
Wadi al Kabir
AYNAYN
ARAQI
SA'AD
ABU
MAFJUR
MABU'ATH
IBRI GAP
600
800
1000
1200
1400
1600
1800
2000
500m
SCALE
Falaj irrigated land
Falaj & well
E.C. in micromhos

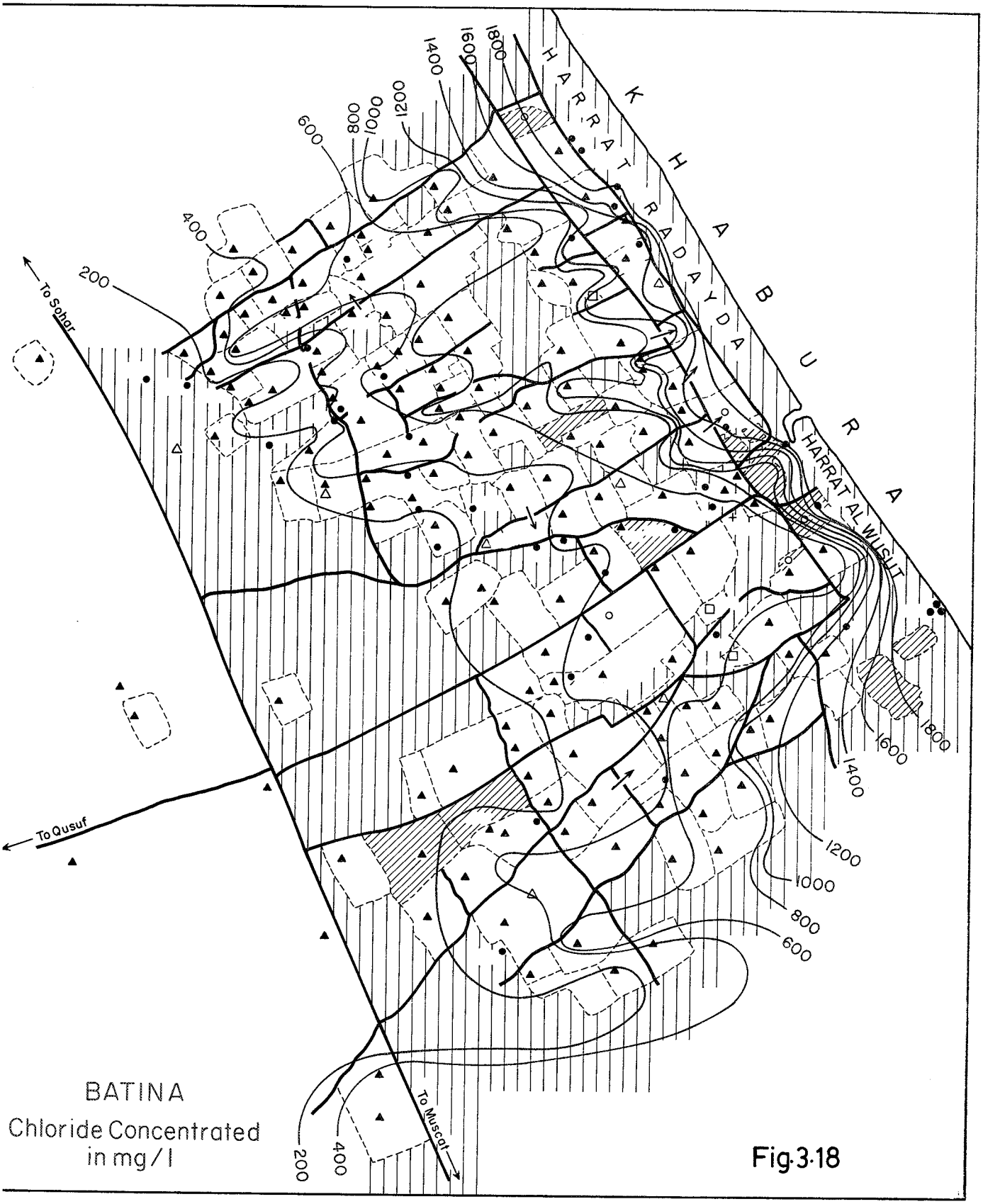
bearing on the differing quality of well and falaj water discussed later (see p. 140), and shows that the water tends to travel along particular paths of concentrated flow rather than dispersed throughout all the alluvial deposits.

(iv) Saline or Brackish Waters

There are three principle sources of chloride waters in the area, and they are generally the only ones to provide water which is too poor to drink (see Appendix Part Two) or which may cause problems to crops (see Ch. 8). These are the al Wahrah formation already mentioned, the brackish waters of the saline-fresh water interface on the coast, and the concentration of chlorides through evaporation from shallow water tables.

Although evaporation has been proposed for groundwater as much as 50 metres below the surface (62) it is generally of a very low rate, perhaps 0. 02 $l/sec/km^2$, and 5 metres is a more generally accepted depth from which evaporation can be expected. Water is found near the surface out into the desert, particularly in association with wadi beds. Fifty kilometres south of Ibri water is found less than a metre below the surface at Fariq, as it is in the Umm as Samim.

While chlorides increase from around 200 mg/l at Dubayshi to 1000 mg/l at Fariq Hamid and 17, 310 mg/l in the Umm as Samim, it is not a regular progression. This is because poorer water away from wadis and local recharge alter the pattern, and sampling points are few and far between. Good water is said to be found over a hundred kilometres



BATINA

Chloride Concentrated in mg/l

Fig.3.18

away from the Ibri gap. Signs of evaporation and concentration can be seen at al Ghuwayl, south east of Sulayf. Here water lies 1.5m below ground level, and there is a surface salt crust and salt heave of silty soils around the clumps of stunted date palms. In the surrounding area the soil is stained dark, with an oily appearance from capillary action on brackish water. Such sabkha areas are rare, however, in the area studied. The chloride waters of the desert are different from those originating in the al Wahrah formation, in that, whilst sodium and chloride ions are commonest in both, levels of calcium, magnesium and sulphate are lower in the desert foreland waters (see fig. 3.16), probably as a result of the common ion effect, with dolomite and calcite precipitating out in favour of equivalent sulphates and chlorides.

Inland only 13% of water samples had electrical conductivites of over 2000μmhos, but on the coast the proportion rises to 67%. The water passing from the mountains to the coast lies more than 20 metres below the surface in most areas, so the chloride is more likely to reflect the interface between sea water and fresh water only, and evaporation of groundwater is not thought to be an important contributory effect.

In the area of wells studied in detail, it is apparent that chloride levels increase with proximity to the coast (see figs. 3.18) and with depth. It appears from the pattern of water quality at Khabūra that there is a central core of better water (roughly bisected by the main road into the village) (see fig. 3.19), and areas to either side in which poorer water reaches further back from the sea. This may be due to saline intrusion through higher pumping rates to either side, or to a major line of groundwater flow



BATINA
Specific Conductivity

Fig. 3.19

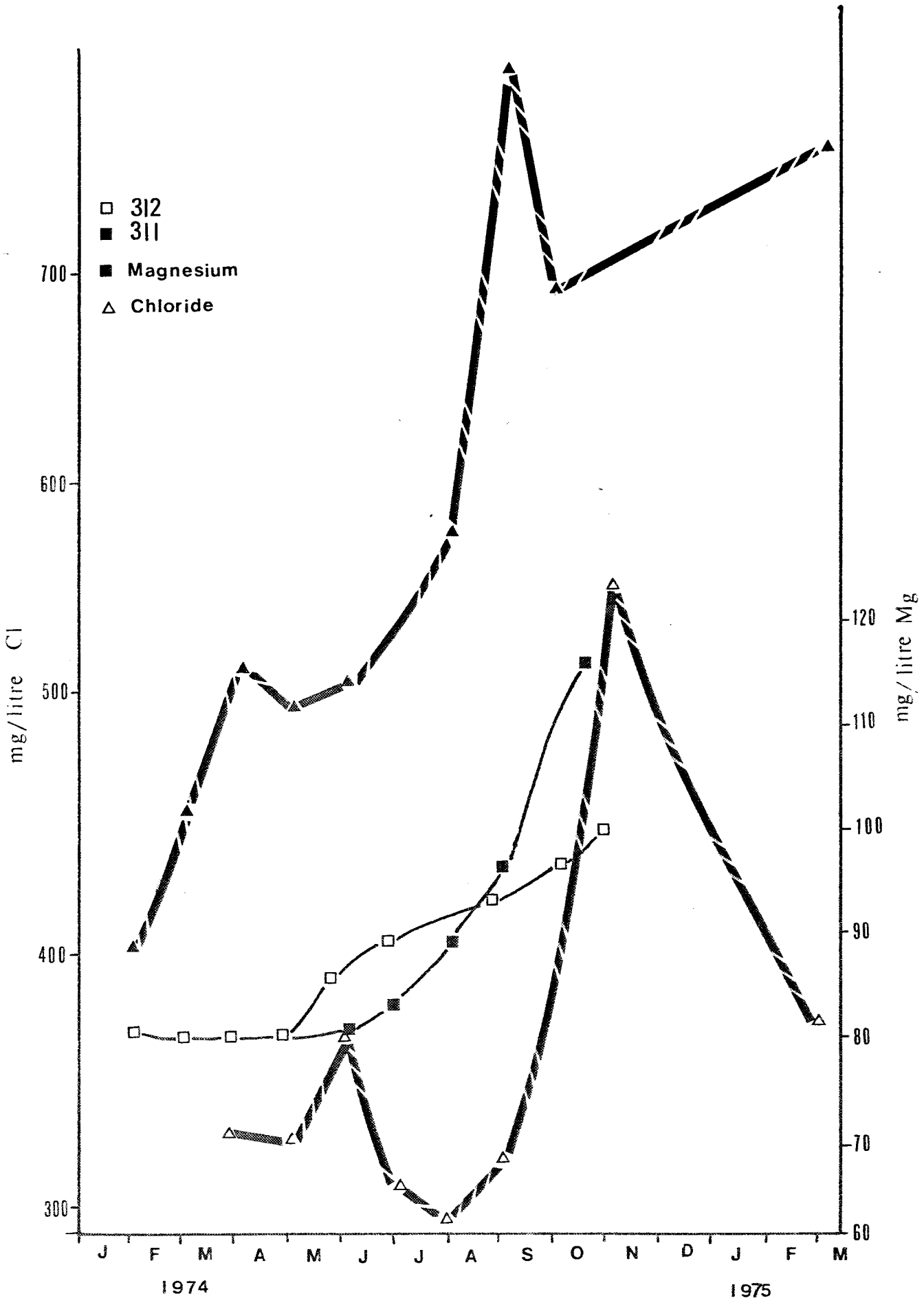


Fig.3.20 **Changes in water quality at two coastal wells.**

reaching the sea in the central area. While the effect of both would be the same it is important to identify which situation is in operation as the latter implies a system which is probably in equilibrium, while the former indicates over-extraction of water and a dynamic and deteriorating system.

The introduction of pumps to the coastal area has led to an increase in the volumes of water abstracted (see Ch. 7), and in the rates at which it is withdrawn. Both changes are likely to cause a shift in the previous balance between brackish and freshwater, as reduced head of water leads to upwelling and inland movement of saline water, within the freshwater wedge (approximately according to the Ghyben-Herzberg principle).

Monitoring and questionnaires indicate that a change in salinity levels is taking place, but while a trend can be identified it varies in degree throughout the area. Seven well owners in the northern-most part of the area sampled (around wells 1095 and 1087) noted increases in salinity following the installation of pumps, but neighbouring farmers and users of adjacent drinking water wells noted no such change.

During the period of the survey, the sampling of wells on the monthly monitoring network, and the occasional (approximately every 4 months) re-sampling of a set of eight pump wells provided a limited amount of information on variations over time in the area of wells

inland at Harrat al Wusut. In all the wells the concentrations of ions, especially of sodium and chloride, do not necessarily follow the pattern of specific conductivities, and in most wells sodium and chloride levels rose.

Of the wells without pumps, 311 showed a steady increase in magnesium, sodium and chloride (see fig. 3.20), 312 suffered an erratic increase in chloride, and a gradual increase in magnesium and sodium. In both cases, calcium and sulphate levels were not steady, but showed an overall decrease, while chloride increased the most (percentage increase) and sodium the least.

Of the eight pump wells, two (1183 and 1139) maintained approximately the same levels of sodium and chloride and other ions over the eighteen months. Of the other six, five showed increases of around 48% (sodium), 54% (chloride). The garden with the greatest deterioration in water quality was the one with the greatest extraction of water, the garden itself being a vegetable production unit for the Muscat market (well 1090, whose owner had already dug a second well 1113, to reduce extraction from the first). In the first two years of use, however, 1090 suffered a 108% increase (ie. a doubling) in sodium, chloride and sulphate levels, and lesser increases in calcium, bicarbonate and potassium. This despite the well being one of the farthest inland from the sea.

Site	Time	HCO_3	Ca	Mg	Na	K	Cl	SO_4	Specific Conductivity
1090	April 1973	201.0	42.0	69.0	171.0	5.6	250.0	233.5	1695
	April 1975	219.0	57.0	105.0	356.0	6.6	520.0	480.0	2397

(concentrations in mg/l, conductivity in micromhos)

At the other extreme, 1130, the nearest to the sea, experienced only a 10% increase in sodium, and a 14% increase in chlorine. It therefore appears that increases of dissolved solids in water for irrigation is not necessarily related to an overall advance inland of the salt water/fresh water interface. Increasing salinity may be confined to individual wells drawing up greater quantites from deeper, more brackish levels. Conductivity alone does not give a true indication of the problem, as sodium and chloride concentrations may increase by a greater proportion than other ions, especially as waters tend to be supersaturated with calcium and magnesium carbonates, which are less harmful to crops (eg. 1080 where sodium and chloride increased by 108% for a 41% increase in conductivity and 1144, a 30% increase in conduc tivity accompanied 69% sodium, and 87% chloride increases).

A low density sampling of wells over time suggest that coastal changes in water chemistry may arise as a result not simply of increasing groundwater abstraction, but in particular as a result of the rate of which it is removed. A wider sampling network, a longer time period, and depth profiles of salinity are required for a better study of the saline-freshwater interface. Initial indications are, however, that conditions are not now static (and may never have been), and care should therefore be taken in identifying the changes now taking place on the coast, and the reasons for them. Such a study would also be relevant to abstraction taking place in the Interior where this may equally be subject to declining water quality from inflowing saline water, if in somewhat smaller quantities.

C - THE EFFECT OF THE ABSTRACTION AND RETURN OF IRRIGATION WATER ON HYDROCHEMICAL PATTERNS

Irrigated agriculture has been carried out in the area for at least one thousand years, giving ample time for man's activities to have a marked effect on the basic pattern of water chemistry. He looks for the best quality water and selectively abstracts it, he overwaters and causes a return of leaching water to groundwater reserves, and he can now, with pumps, overabstract water to cause an inward or upward movement of water of a different quality.

The type of the water abstracted affects both the chemistry of the returning water and the amounts which the farmer withdraws. It is therefore necessary to see how selective man has been in abstracting the best water as this both by its removal and by its return alters the local chemistry of groundwater. For this purpose falaj and well water quality are compared.

(i) Water Chemistry and method of abstraction

Falajes, the providers of 90% of Interior water supplies, draw water from sources of concentrated flow, whether they be resurgences in fissured limestone, pipe flow in conglomerates or buried wadi gravels with little cementation. Falaj systems tapping diffuse seepage are extremely rare, but wells tend to exploit more minor groundwater flows. As such, the water moving to wells may generally be expected to have remained in contact with rock for longer than that found in falajes, for two reasons. Firstly,

the more diffuse the flow the slower it tends to travel and the more frequently water molecules come in contact with rock. Secondly, falajes divert groundwater into a channel which transmits it rapidly from source to settlement while well water travels all the way from the point of recharge to that of extraction within aquifers, thus further increasing the residence time of the water in the ground. There should therefore be a contrast in the water quality of the two systems.

This theory is borne out by the water samples analysed. From these it is apparent that water quality is generally higher in falajes than in wells in the same settlement, and that the contrast may be very marked. Of the middle and upper wadi villages, only Al Aridh, Khadil,Hujrimat, Kahanat and Miskin have several wells in addition to the falaj source. Of these, in the first four settlements, with eighteen wells to the four falajes, only one well approaches the quality of falaj water. The average well water contains almost twice as many dissolved solids as the associated falaj. Only at Miskin are well and falaj waters almost indistinguishable, and this is because the wells (at Tawiān) are near the falaj source, not its outlet in the village.

In the main areas downstream the pattern is much the same and is summarised in Table 3.2 overleaf.

Table 3.2 Falaj and Well Water Quality

FALAJ SYSTEM	FALAJ WATER QUALITY * in micromhos	AVERAGE WELL WATER QUALITY in micromhos	NO. OF WELLS	PROPORTION OF WELLS WITH WATER BETTER THAN FALAJ
Dariz	460	1760	60	0%
Araqi	450	1294	58	0%
Aynayn	850			7%
Tan'am	1050	1968	44	0%
Sulayf Shimbu) Hakkab) Wagag)	1050	1950	42	6%
Bilad	1900	1950	42	40%
Ibri Mafjur	690	1334	48	30%
Mabu'ath	890			54%

* For water type, see fig. 3.14

Only at Ibri and Sulayf Bilad is the pattern noticeably different. Sulayf Bilad is the only falaj in the area with water of low quality and is not even used as a drinking water supply.

Statistical testing of the difference between well and falaj water is not possible, as at each settlement there are only one or two falajes, but many wells, thus giving only one or no degrees of freedom. Samples of each type from different settlements cannot be lumped

together as the water quality regimes differ at each, so that the best quality at one may be the worst at another. The consistency of comparative results in many cases, however, suggests the higher quality of falaj water is a common occurrence where both sources of water occur in the same neighbourhood. The lower total dissolved solids in the falaj water suggests that it has travelled more rapidly, with less time in contact with rock surfaces than the water found in wells, and the poorer well water reflects the aquifers underlying the settlements.

Statistical comparison is, however, possible between water quality in wells with and without pumps, particularly in Araqi, where the latter are unusually numerous. Here there is a significant difference at 99% confidence levels in the electrical conductivity of water from the two sources, using a sample of 35 pump wells and 23 points where water is drawn by hand. Samples from the former average one and a half times as much dissolved solids as the latter both because of well siting and extraction rates.

The traditional methods of water extraction, the falaj and lifting water by hand can be seen to select higher quality water than the modern development of pump wells, where these offer an alternative method. The present observed patterns of water chemistry are therefore likely to have been affected by the abstraction of higher proportions of low conductivity water than of the poorer quality sources, which may have led to a movement of poorer water into some originally good areas. On the other hand it means that the irrigation water which percolates back to the water table has been initially of the best quality available, since falaj systems were introduced. Thus salinity problems have been

minimised and falaj systems may in some instances, particularly in Araqi - Aynayn have actually caused an improvement in local groundwater conditions.

(ii) The return of irrigation water

Except where roots can obtain minerals direct from exchange sites, plant nutrients in the soil must be in solution for uptake to occur. The soil solution often contains very high concentrations of such nutrients (48) particularly where evaporation and evapo-transpiration causes their concentration. Where water is applied to the soil in sufficient quantity to displace that already in the soil, or itself to be carried on below the soil layers, the dissolved solids it contains may increase markedly. Ayers and Branson (62) assume a three-fold increase in salinity as irrigation water becomes soil water. Observations in Northern Oman, however, suggest that at the rates of application used, such an increase in dissolved solids is an overestimation.

Direct samples of returning irrigation were mostly taken in the upper wadi reaches, where the soil is coarsest but the source of water can be identified with some certainty. Six Kahanat and Bilad Shahum systems are used as examples, all being of similar chemistry and of low initial conductivity 380-420 micromhos. The irrigation water is typical of water flowing in ophiolite gravels (see fig. 3.13) and is undersaturated with calcite and oversaturated with dolomite. Returning water contains 30-40% higher levels of the major ions, with

magnesium sulphate and carbonate as the main additions, but nitrate levels remaining constant. Saturation indices show a shift towards greater supersaturation, the calcite index becoming just positive and dolomite rising from about 0.3 to 1.0 despite the rise in pCO_2 as the water passes through the soil.

Sodium concentrations do not increase more than the divalent cations suggesting little build-up of salt in the soil. Nitrate levels remain almost constant, and although the soil water contains nitrate in similar quantities to those found in water from well-developed soils in England (63) the nitrate all originates from irrigation water and is not added to during passage through the soil. The changes observed are small and are therefore very much those to be expected of water percolating through a poorly developed sandy mountain soil. They do not, in the upper parts of the systemappear likely to cause problems for downstream settlements, should the returning water be re-used.

Downstream soils are finer and better developed, but it appears from water quality patterns under settlement that a proportion of falaj water finds its way back to below the water table. At Aynayn-Araqi the pattern can be studied most easily because of the large number of wells in the cultivated area. Two large falajes run parallel down the centre line of the oasis, the lower one the Araqi system splitting into distributaries half-way down the cultivated area. The Araqi falaj is of 450 micromhos, while the majority of surrounding water is of around 1000 micromhos. Along the line of the major distributaries, however, local groundwater is of 600 micromhos or less (see fig. 3.17). This might be due to an incursion of al Kabir water from the west, but the distribution of higher quality water in the centre of the oasis than at the edges suggests that leakage from falaj channels is the origin, and such leakage has been identified in the system (see Ch 8 pt II). Dariz

shows a similar pattern (see fig. 3.15) but al Kabir water, the source for the falaj, reaches as far as the oasis, making it difficult to isolate the effect of the falaj alone.

Recharge may also occur from over-irrigation of crops. The degree to which recharge occurs cannot be estimated from quality data alone, particularly since falaj-type water occurs under parts of both settlements in association with the major wadi systems. Water quality is generally high under the palm groves and the levels of change suggest that leaching rates allow little build-up of nitrates through nitrification or of salts through capillary action and evapo ration. Leaching therefore probably exceeds the levels of 7-10% estimated by the University of California Extension Services (62) as necessary to maintain low soil leachate concentrations with good quality irrigation water.

The level of leaching which occurs also tends to mean that in most falaj settlements there is no ruinous decline in quality as water returns to aquifers. A water which was of good quality before, contains more dissolved solids after percolation, but is still basically likely to be good quality irrigation water and may even displace poorer quality water. Well water, however, applied at lower rates (see Chapter 8) and often initially not of good quality, is more likely to suffer major deterioration when leached through to the water table.

D - CONCLUSION

Hydrochemistry, while reflecting geological and geomorphological conditions more than any other aspect of the study incorporates all aspects of water resources assessment. Observations suggest

processes active at present and mechanisms which have been operative in the past.

Factors now operative include:-

Geology	Initial water type before infiltration
Geomorphology	Alluvial deposits provide the solid medium with which water remains longest in contact
Geochemistry	Ionic concentrations and changes as water passes from one environment to the next
Climatology	Temperature changes and fluctuating water levels
Hydrogeology	Rate of solution. The speed with which water is transmitted through an aquifer and so the time any one water modecule is in contact with a solid
Water Use	Preferential abstraction of water of lowest conductivity, and its return to groundwater at a different point

These have all played a part in the observed patterns of water chemistry.

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CHAPTER FOUR

CLIMATOLOGY AND WATER BALANCE

I CLIMATOLOGY

A Introduction

(i) Research literature on synoptic conditions and individual events
(ii) Data from existing meteorological stations
(iii) Data from newly established meteorological stations

B Synoptic Situations

C Rainfall

(i) Showers, storms and their measurement
(ii) Rainfall observations 1973-1975
(iii) Periodicity of droughts

D Factors in the Assessment of Evapotranspiration

(i) Temperature and humidity
(ii) Wind
(iii) Insolation
(iv) Resultant patterns of evapotranspiration

E Conclusion

II WATER BALANCE

A Introduction

B Average conditions and those in 1973-1974

(i) Rainfall
(ii) Proportion of rainfall as run-off and re-charge
(iii) Water balance estimates.

I CLIMATOLOGY

A - INTRODUCTION

Oman lies at the north western edge of the Indian Ocean, and at the Eastern edge of the African-Arabian bloc. The mountains form a ridge parallel to the Persian Highland, and divided from it by the Arabian Gulf and the Gulf of Oman. The field area itself lies across the Tropic of Cancer.

Under Meigs' (1) classification (one of the most suitable systems as it is specifically tailored to the limited data available for most of the desert areas of the world) the Interior of the area falls in the class Aa24 and the coast Ac24. This suggests that climatically at least, the majority of the area has much in common with the North Thar desert, Kuwait, the Western shores of the Persian Gulf, Baja California and the Gibson desert. It is an area for which little information has been collected, but over which, on the basis of altitude differences alone, isolines have been projected. Particularly in the case of Meigs' and Thornwaites' (2) and Griffiths (3) work, the effect of the mountain range apart from the Jabal Akhdhar itself would seem to be overestimated.

Within the area studied arid conditions prevail even over the Hajar mountains and on the coast. As with most arid and semi-arid areas of the world, Oman can boast neither numerous meteorological stations nor a continuity of observations over many years. At the same time conditions on the coast are so different from those in the Interior, that observed patterns cannot be projected over large areas without great care. To study the climatology, it is therefore necessary to examine a variety of data.

(i) Research Literature Available

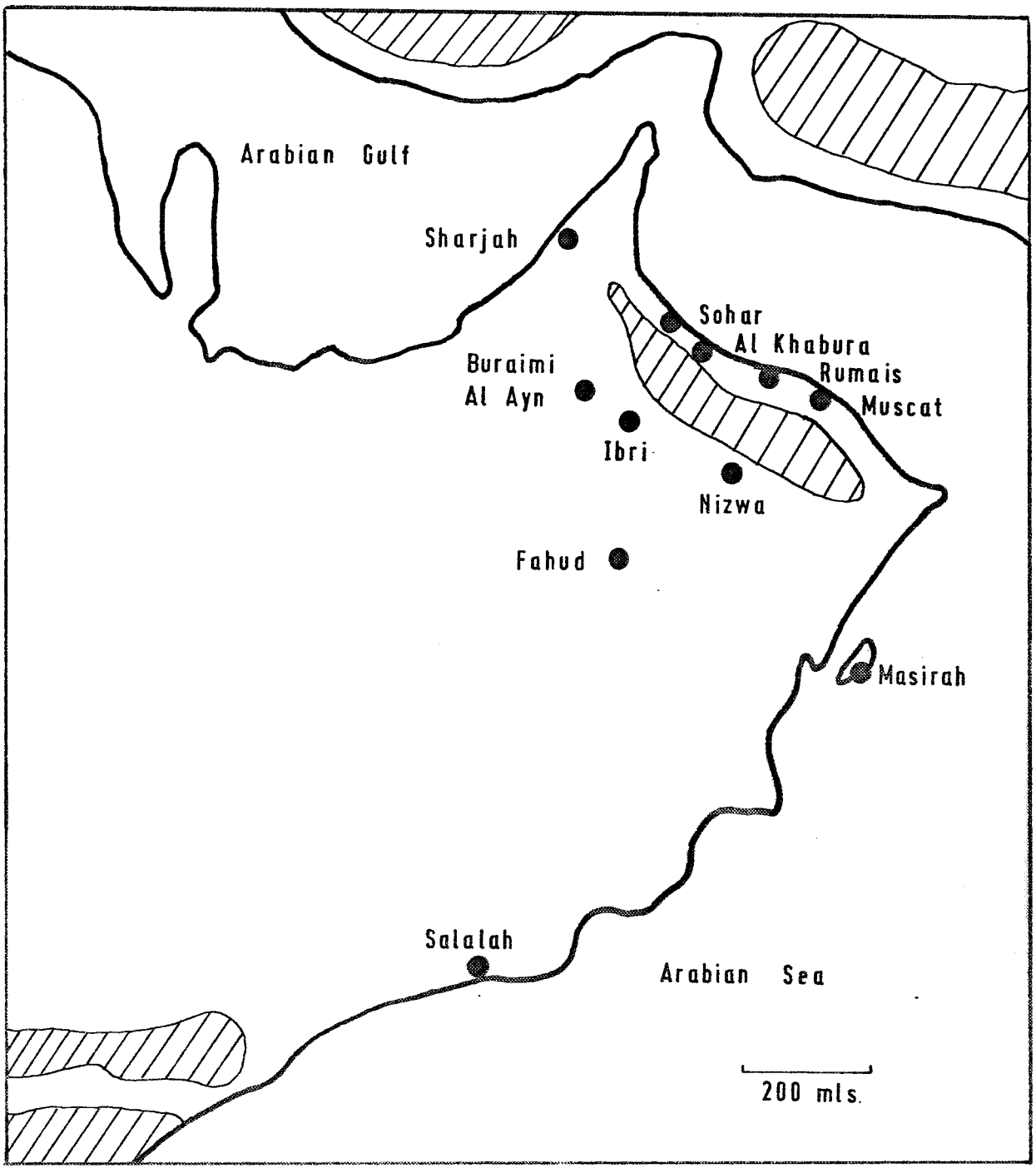
Of existing literature, references to the synoptic situation are most common, generally covering a large area of southern Arabia (4-9). These refer to the large scale systems affecting the area, with little in the way of measurements. At the other extreme are the details of individual events, with impressions and some measurements, generally described by a traveller passing through (10-16). These especially tend to cover spasmodic storm situations, and, being observed on brief visits, can give little idea of how typical or frequent such events are. They are, however, or particular value in showing the effect of certain synoptic situations.

(ii) Existing Meteorological Stations

Data from meteorological stations are not always easy to trace, as at Rumais experimental farm where five out of six years' rainfall data were unobtainable. There is no published academic research work on available data, but some consultants' reports refer to stations nearest to the area in which they were carrying out surveys (17, 18). Raw data, particularly on Sharjah and Masirah are available, and were obtained from the Meteorological Office Bracknell. Records for Fahud, Muscat (Mina al Fahal) and 'travelling' observations by rig crews are available from PD(O).

The result is that data have been found for seve ral stations as follows:- (see fig. 4.1)

Fig 4.1 LOCATION OF METEOROLOGICAL STATIONS



Station	No. of years Recorded	Distance to Tan'am
Fahud	10 years*	140 km.
Nizwa	7 years*	110 km.
Buraimi	5 years*	80 km.
Al Ayn	6 years	80 km.
Sharjah	36 years*	230 km.
Masirah	23 & 12 years*	400 km.
Muscat	24 years*	220 km.

* Records not continuous.

(iii) Newly Established Meteorological Stations

In the area of study, new data were provided when a metoerological station was established by the author, as were rain gauges in the mountains and on the coast. The meteorological station was set up at Tan'am hospital. This station ran for 26 months, from April 1973 to May 1975, and is the longest running of the standard meteorological stations established in the last four years. The following observations were taken at 9 o'clock each morning:-

	INSTRUMENT
Maximum daily temperature	Casella thermometer
Minimum daily temperature	" "
Wet and dry bulb temperature	" thermometers
Run of wind at 2m	Casella anemometer
Incoming solar radiation April 1974-May 1975	Gunn Bellani Solarimeter
Rainfall	5" standard gauge

and continuous recordings were made of relative humidity and temperature on a weekly (with standby monthly) thermohygrograph (see fig. 4.2, and Appendix for observation results).

No similar station was sited by Durham on the coast as consultants, Ilaco to the West and Gibb to the East, finally established stations at Sohar and Rumais respectively. The Gibb data are not available and 1974 is the only year for which Tan'am can be compared with Sohar. Further rain gauges were, however, set up in the pass between the wadis Hawasina and al Kabir (Najd Sharingiban), at Khabura, and in Ibri. These remote rain gauges contained small quantities of oil to reduce evapration and were visited at weekly intervals (more frequently when rain storms were reported by local people). Additional gauges at Kahanat, Munqnyat and Injayd recorded no rain before their eventual removal by local children.

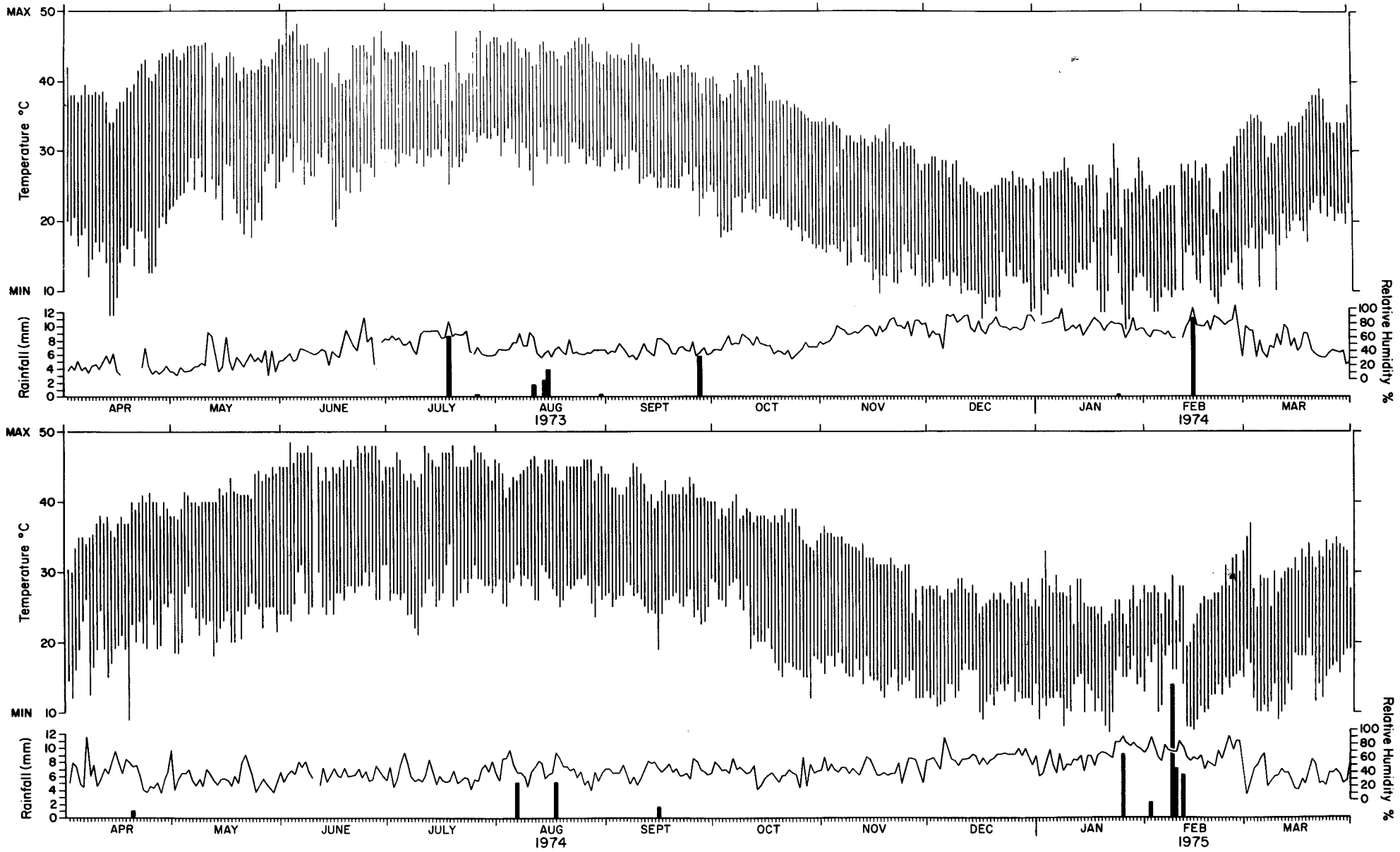


Fig. 4.2 TANAM – DAILY READINGS of TEMPERATURE, RAINFALL and RELATIVE HUMIDITY from APRIL 1973 to MARCH 1975

B - SYNOPTIC SITUATION

Despite the many simple concepts of the reasons for aridity, such as rain shadows and high altitude air circulation, factors in aridity for any particular area are generally difficult to analyse. This is partly because of the limited amount of detailed information, particularly on the upper air conditions, but also because a variety of factors all play a part at this point. They include orography, thermal low pressure, coastal upwelling and the influence of the Indian monsoon.

The area is one in which trade winds are diverted by major topographic features. At the same time seasonal shifting and continuous oscillation of the inter-tropical convergence may bring disturbances in summer, and polar air may bring frontal pressure waves in winter. In combination with this overall pattern, local topography affects the climate. In particular the parallel lines of coast and mountain range accentuate differences between coastal and interior conditions. The overall patterns ascribed to air mass distribution and monsoon activity are discussed in detail in various articles (4-9) and are not expanded here beyond an outline of major features.

The year is divided into the two main seasons of summer and winter with very short transition periods. In the summer, pressures are low (Muscat 989mb, August average) in a continuation of the deep depression over North-West India and the Gulf. South easterly winds are diverted into this depression and so winds become predominantly south westerly (see fig. 4.3). Within the field area, these winds tend to be hot and dry, having passed over Somalia and Saudi Arabia.

JANUARY

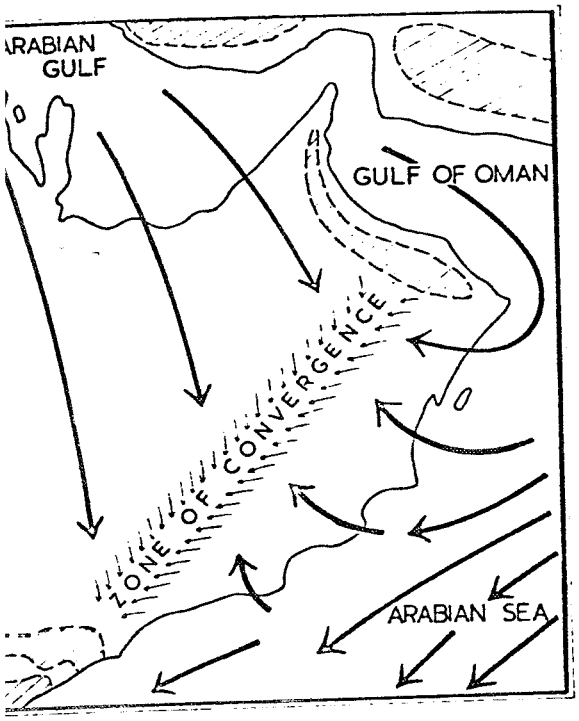


Fig 4.3

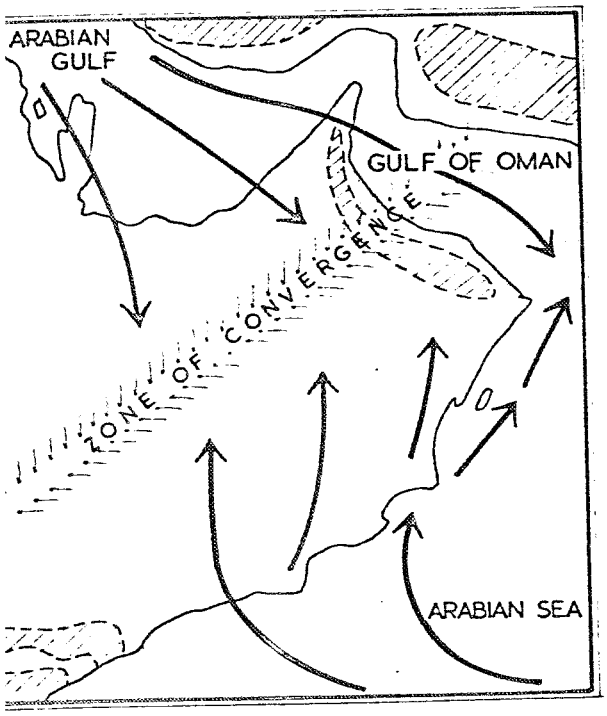
AIR CIRCULATION IN THE LOWER SURFACE LAYERS OVER OMAN

From E. Pedgley

Land over 1000m

Direction of prevailing wind

APRIL



JULY

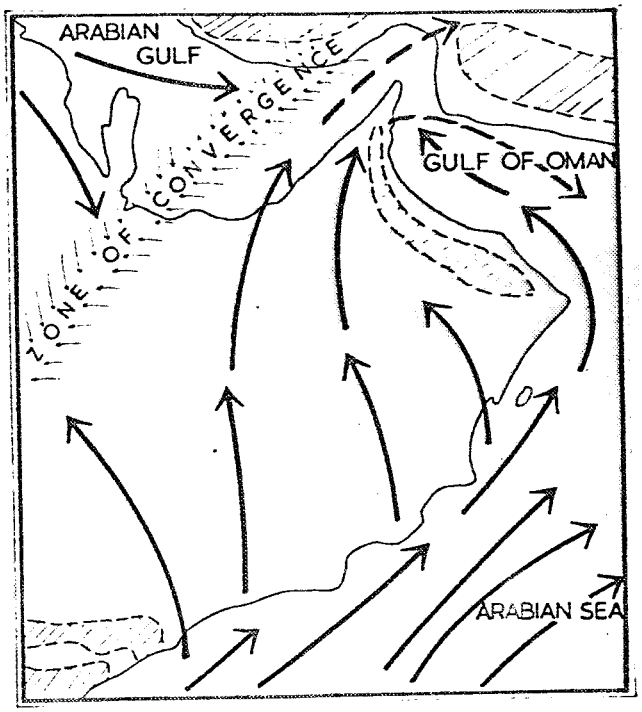
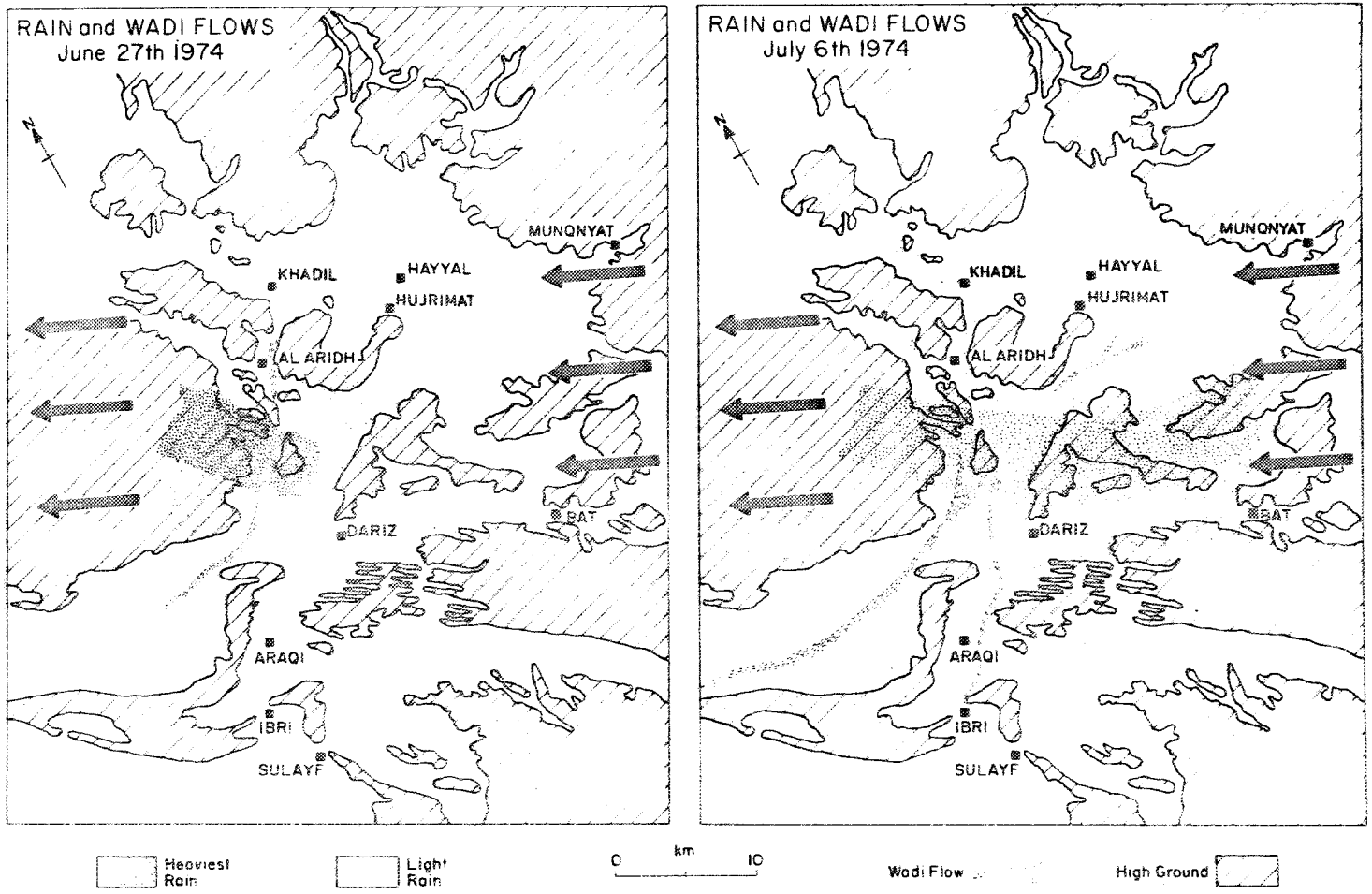


Fig.4.4

SUMMER RAINSTORMS
(Examples of their limited extent)



On the coast, however, local on-shore breezes are dominant and lead to much higher humidities and slightly lower temperatures. In winter, Asiatic anticyclones predominate, winds from the north east are therefore common, but they are also diverted round the southern tip of the mountains, returning from the south east. There is therefore a local zone of convergence in Interior Oman at this time of year (see fig. 4. 3). When the Asiatic anticyclone temporarily moves north, cold north-westerlies sometimes reach Oman, with associated depressions.

The inter-tropical convergence zone (ITCZ) at this point does not seem very active, and Pedgley(19) suggests that the shallowness of the monsoon is the probable reason for the rarity of summer rain in Oman. The variations in weather both from season to season and from year to year depend to a large extent on fluctuations in the intensity of monsoon development and the northernmost limit of the shifting of the inter-tropical convergence zone. Thus the climate is less than characteristic of monsoon areas, for, being at the limit of such influences, other peripheral factors cause considerable modification of the basic climatic pattern.

C - RAINFALL

(i) Showers and Storms and their Measurement

There are several rain producing situations which occur in the area, but most of them tend to lead to very localised rain. The two major circumstances are:-

(a) In winter the southward movement of cold air from the North, forming cold front conditions, as the cold air lifts the warmer air above it.

(b) Orographic rain, sometimes connected with cyclonic conditions along the coast. Littoral rain is rare in this area, because coastal relief is low. Similarly rain attributed to the inter-tropical convergence is uncommon, as the winds are weak during the season the ITCZ lies over the area, and cold air rides over the warmer air leading to stable weather conditions.

In local weather lore, wind directions are named as follows: North = shamāl, South = Kaws, East = Sharqi, West = Gharbi. In the winter, if the wind blows constantly from the south, south-east or east, rain is expected. Hence 'kaws' is the name of the rain-bearing winds. When the wind moves round as far as north or north west it is said that the clouds are blown away and no more rain is expected. This pattern fits very well with the winter cold front situation, as described by Pedgley (19): "North west winds develop in the rear of disturbances moving across the area, and their leading edge is often marked by a cold front, ahead of which winds usually blow from between south and east."

The heavy rains of February 1975 were of the above type, and it was during these rains that the traditional 'weather forecasting'system was explained. It suggests that in winter this situation is that which is most likely to produce rain in the Ibri area, where the information was gathered.

In the summer, conditions of uplift occur rarely in relation to main wind systems as wind speeds are at their lowest. It seems that localised

thermal convections, especially in relation to the Jabal Akhdhar, provide the most suitable combination of factors for rainfall. Intense and powerful local convections are set up, and appear to follow specific, or at least narrow, paths out from the highest mountains of the range.

Local storms such as these, originating to the east of the area, were observed in the Interior in July, August and September 1974. During these months 'dust devils' ascending 100-200 metres were also frequently observed in the gravel plains of the lower wadis of the Interior. The paths of these small whirlwinds are sometimes marked by the trail of uprooted acacia trees left in their wake. Eighty such trees were counted in a 2km stretch of the wadi Lusayl. Acacia trees are particularly prone because of their 'mushroom' shape which gives the wind considerable leverage.

The larger storms originating in the Jabal Akhdhar/Jabal Kawr to the east tend to follow the al Ayn or al Hijr valleys, across the middle al Kabir and on to the wadi Fida (see fig. 4.4). A second route lies near the crest of the ridge, bringing rain to the Upper Bilad Shahūm, al Aridh and Dhank wadis. These disturbances were usually limited in the area of their effects, causing very intense rain along a narrow path. The preferential east/west path of storms, favours those wadis running in this direction. The Bilad Shahūm, al Hijr and al Ayn wadis are all similarly orientated and so receive rain over a larger proportion of their area and for a longer period than the al Kabir and al Aridh at right angles to the path of the storms.

Rain in winter and summer being seldom evenly spread over a large area is difficult to measure accurately. While winter rain may be caused by a widespread disturbance and may bring rain to several parts of Oman at the same time, on the occasions observed, the intensity of rain varied enormously from place to place. In summer the disturbances are generally smaller if equally intense. This feature of rainfall within the area causes problems in estimating total input to a catchment, and the measurement of rainfall from individual disturbances is very difficult. Clearly in an area with under $\frac{1}{2}$km of maintained road (graded or with tarmac) per 10 sq. km no great density of gauges could be established. The density recommended by the Institute of Water Engineers (20) for hilly country (see table 4.1) is clearly unsuitable in such conditions, as is the density of 2.5 - 5 gauges per 10km^2 recommended by Fiddes (21).

Table 4.1 Density of Rain Gauges (20)

Catchment Area Sq. Mls.	No. of Rain Gauges
4	6
20	10
80	20
160	30

If monitoring of rainfall is not going to be the sole objective (and in 1973-4 this would have been particularly fruitless) then the ideal arrangement must be modified to form a more practical compromise. Gauges were therefore established at sites which also coincided with

the route taken for groundwater monitoring, and where a degree of security could be achieved, and people notified of the purpose of the gauges.

There were therefore four permanent rain gauging points, at those sites most frequently visited. These were at the two houses used as bases, at Tan'am hospital, and on the only route between the coast and Interior.

(ii) Rainfall Observations 1973-1975

During the period of observations, rainfall was limited, and in January to April 1973 preceding the establishment of the Tan'am rain gauge, no rain fell. There appear to be two main periods of rain, one in January and February, and another in July to September (winter and summer rains). In the two and a half years January 1973-May 1975, no rain fell in the months of June, October, November, December or March (see fig.4.2).

The intensity of rainfall was on several occasions high. On 9th February 1975 at 4am 15.9mm fell in Ibri in 40 minutes, while 19.42 fell at Tan'am in approximately the same period of time. On those days when most rain fell, storms were of short duration and rainfall heavy. No examples of prolonged rain were observed, except on 9th February 1975 when rain of varying intensity continued after the main storm, until 6pm.

Total rainfall at Tan'am in years April-April 1973/4 and 1974/5 was 34.26mm and 60.28mm respectively. The difference between the two

years was almost totally made up from the heavier February rains in 1975.

With a low density of gauges (one per 350km^2) several significant local storms were not measured (see table 4.2). Their occurrence was, however, noted, so that time (delay) if not quantitative correlations with groundwater response could be established, and changes in falaj flows be identified as response to climatic conditions or human interference.

Table 4.2 Un-measured Rainfall

During the period of fieldwork, rain was also noted to fall over limited areas in quantities to cause local run-offs (probably over 10mm) on several occasions. The incidents were so localised, however, that no rain was recorded in gauges, and in some instances the sky remained cloudless in Ibri. On 6th July 1974 rain fell from al Aridh to Dariz, but skies at Injaydand Ibri to North and South were clear.

The following incidents were noted from observations after the event, or using local information in 1974.

1974	April 27	Wadi Munqnyat, al Aridh to Hujrimat, but missing Khadl. Injayd showers but no rain at watersheds.
	May 21	Wadi Kahanatand Wadi al Aridh. Wadi Sulayf.
	June 27	Tawi Qarn Kabsh to Dariz, wadis al Aridh and Kahanat
	June 30	Wadi Kahanat
	July 6	al Aridh to Dariz, lower al Hijr, al Aridh, right bank tributary only.
	July 7	Wadi Munqnyat, small part of al Kabir near Araqi

Gauges at both Ibri and Tan'am, separated by some 12kms of flat alluvial plain, were used to observe variations found over a short distance with no topographical barrier (table 4.3).

Table 4.3 Recorded Rainfall in mm

Date	Tan'am	Ibri	Najd Sharingiban	Khabura
1973				
July	8.56	NO OBSERVATIONS		
	0.08			
August	1.65			
	2.41			
	3.83			
	0.21			
	5.92			
1974				
Jan 24	0.23	T	No rain	No rain
Feb 14	11.37	5.3	) 7.6	16.3
Feb 18	No rain	4.2	)	3.2
Mar 12	No rain	No rain	1.2	No rain
April 1	1.03	No rain	No rain	No rain
April 19	1.59	No rain	No rain	No rain
April 27	No rain	No rain	No rain	20.1
May 21	No rain	7.5	No rain	No rain
May 27	No rain	No rain	20.1	No rain
Aug 6/7	5.05	10.6	No rain	No rain
Aug 17	5.84	No rain	No rain	No rain
Sept 15	1.58	No rain	No rain	No rain
Oct 2	No rain	No rain	No rain	2.0
Oct 3	No rain	No rain	No rain	7.8
1975				
Jan 25	8.92	2.8	) 1.5	
Jan 26	No rain	2.24	)	
Jan 28	No rain	No rain	No rain	4.4
Feb 2	2.13	2.2	7.8	No rain
Feb 7	No rain	No rain	No rain 0	0.2
Feb 8	19.42	15.1	) 41.75	2.2
Feb 9	7.1	7.8	)	10.1
Feb 10	No rain	No rain	)	43.3
Feb 11	7.7	0.6	No rain	
Apr 21	0.40	14.5	No rain	No observation
Total since Jan 1974	72.35	72.84	79.95	109.6

The resultant levels of rainfall at the two sites were found to vary enormously in individual events. In May 1974 Tan'am had no rainfall, while Ibri had 7.5mm, in April 1975 Tan'am had 0.4mm and Ibri 14.5mm (see table 4.3). Despite the 44% of occasions in which only one or other site had rain and the total variation of 70mm between the two sites, the total rainfall at each station over 18 months varied by less than 0.8%. This suggests that while estimates of total rainfall in one event are made very difficult by variations in intensity over short distances, totals over more extended periods of time may suffer no such disadvantage.

The above conclusion was supported by the mountain rain measurements at the Najd Sharingiban.. Rainfall events were fewer within the same period but when rain did fall, the depth of water tended to be greater than that measured at the lower gauges inland. The total therefore turned out to be slightly more (9%) than at Tan'am, for a 500m increase in height.

Ilaco, with a raingauge at Magzi al Hawasina, observed higher levels of rainfall - 136.8mm in the year March 1974-February 1975 (cf. Najd Sharingiban 90.1mm) on the northern side of the mountains. This difference was particularly due to the heavy rain of October 1974 which fell in the Hawasina but did not reach over the watershed.

On the coast, in the period of observations, it appears that the winter storms were morepowerful than those in the Interior, but that summer rain associated with orographic features did not occur. Summer rain, though generally lighter than winter storms, is said to fall, possibly

in relation to localised thermal convections, when the gradient between the sea and land temperatures is at its greatest.

While Tan'am data are only available for a short period and other stations provide records over an even shorter time, certain basic patterns are apparent. Monthly frequency distribution (see fig. 4.5) shows that at this time there is only a one in three chance of more than 2mm of rain falling during a month. Both in fact and in effect this means that almost no rain falls in eight months of the year. While the records are short for extending observed distrubitions over a longer time, Sharjah data over the previous ten years show a similar pattern. In June and August over 29 years, no rain has fallen in Sharjah, while averages for May, July, September, October are below 5mm. Tan'am also experienced no rain in June in 1973 and 1974 (see fig. 4.1) in August, however, disturbances from the Jabal Akhdhar, and the southward return of the ITCZ coincide, so that rain is likely to be commoner than at Sharjah. Conditions stabilise by October, and this and the following two months were rainfree during the period of observations.

Contrary to expectations, in 1973-5 rainfall on the coast was higher than at the mountain water shed, and this in turn was only marginally higher than levels observed in the Interior. Whether this pattern is representative of average conditions is unknown, but it is suggested that it is not, and that rainfall observed was below average in quantity.

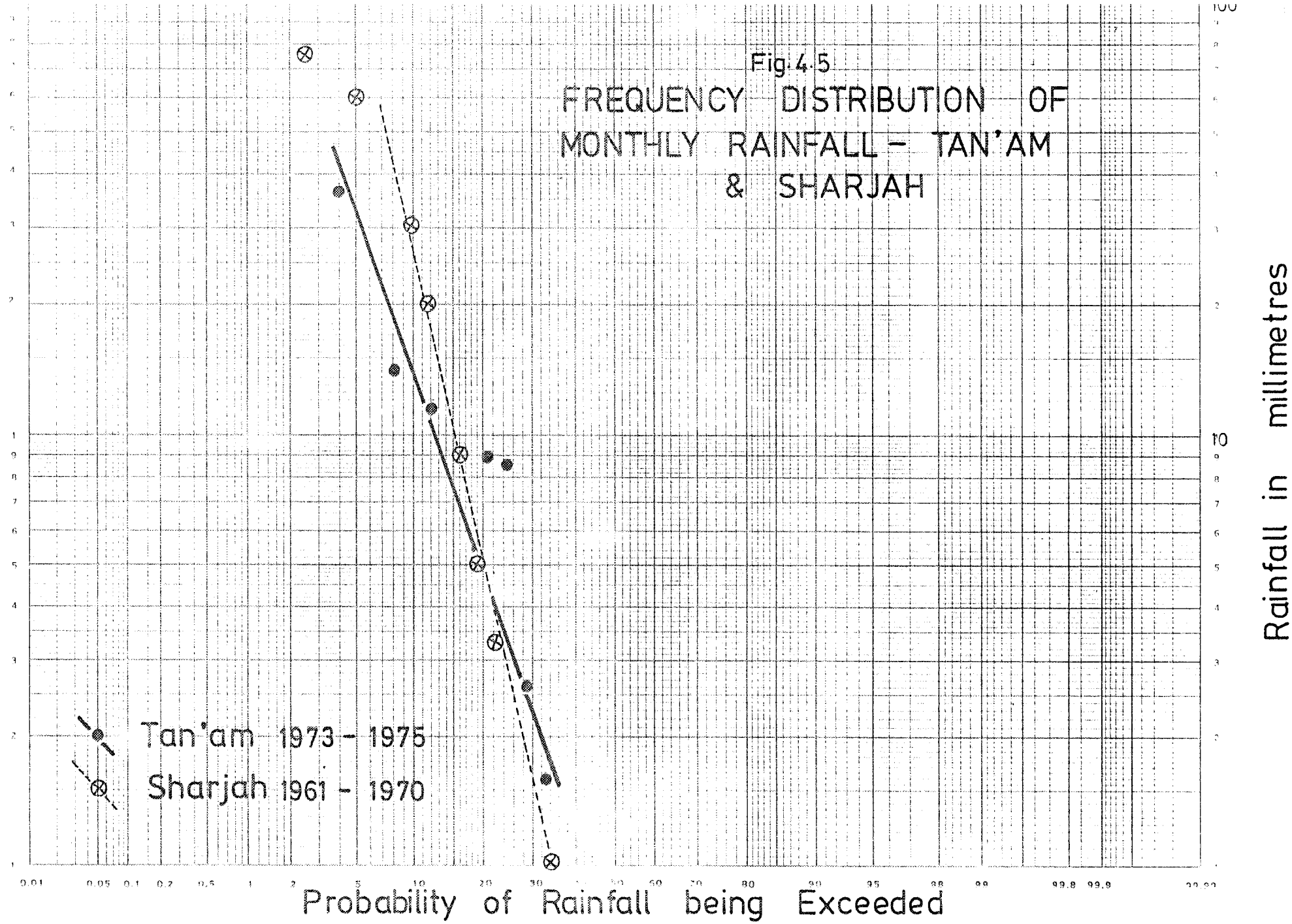
In a semi-arid area such as this, 'average' rainfall is a very difficult value to reach and because of the enormous variations from it, is not particularly significant on its own. Two years' observations

can give no indication of average conditions. Indeed McDonald (22) working on the far more complete records of the American South West concluded that 50 years of data are necessary to establish means that are even within 10% of the population mean at a 95% confidence level.

Using available data at Sharjah and Muscat, it would seem that for Oman 120-200 years data are needed for the same level of accuracy in estimating the mean. Muscat, with lesser variation in annual rainfall (s = 56) requires less years of data than Sharjah (s= 74. 4).

The problem is that while rainfall is the most significant climatological factor as far as hydrology is concerned, it is also the factor with the greatest variability. For instance, at Sharjah, mean annual temperature varied by a maximum of only 6% in 30 years, while annual rainfall varied by 250% in the same period. This fact is also reflected in the UNESCO/FAO recommendations (23) that for precipitation and temperature, satisfactory means can be produced in less extreme climates from 25 and 10 year records respectively. Thus rainfall, while a most vital factor, requires data over a far longer period to produce reliable conclusions as to its average value. Long and continuous records are also necessary to investigate its variability, and in particular, the probablility of drought and exceptional rainfall.

In order that some measure of water budget may be made, an estimate of average rainfall is required. The Tan'am data can provide no indication of this in isolation, but must be combined with values from surrounding, longer-running stations. Sharjah, a station within 250 kms, has run discontinuous ly for 36 years, but was unfortunately abandoned in 1973, the year in which Tan'am was established. There is therefore no period over which the two stations can be compared, and comparisons of individual


Fig. 4.5
FREQUENCY DISTRIBUTION OF MONTHLY RAINFALL – TAN'AM & SHARJAH
Tan'am 1973 - 1975
Sharjah 1961 - 1970
Probability of Rainfall being Exceeded
Rainfall in millimetres
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
50
60
70
80
90
95
98
99
99.8
99.9
100
10

events and averages can only be made via other stations (see table 4. 4) which were running both during times when Sharjah was in operation, and later when Tan'am observations were being taken. On a monthly basis, however, using the last ten years of Sharjah monthly data, and all the available Tan'am data, the pattern of rainfall probability is very similar (see fig. 4. 5). Thus, while individual events or monthly totals may not be comparable, it appears that levels of precipitation overall follow the same patterns. In order to see whether a more widespread comparison of probabilities is possible, Muscat and Sharjah records, being the longest available, can be compared using logarithmic normal probability paper. These show that on an annual basis the frequency distributions are very similar (se fig. 4. 6), and are approximately normal, but with highly positive skew. Thus both areas are subject more commonly to serious deficiencies in rainfall, and average values (97mm Sharjah, 112mm Muscat) contain a large element due to rare very heavy storms. Frequency distribution shows that while around 100mm is an average value, there is only a 40% chance of this value being exceeded. Tan'am may be expected on the basis of existing monthly data, to follow the same pattern.

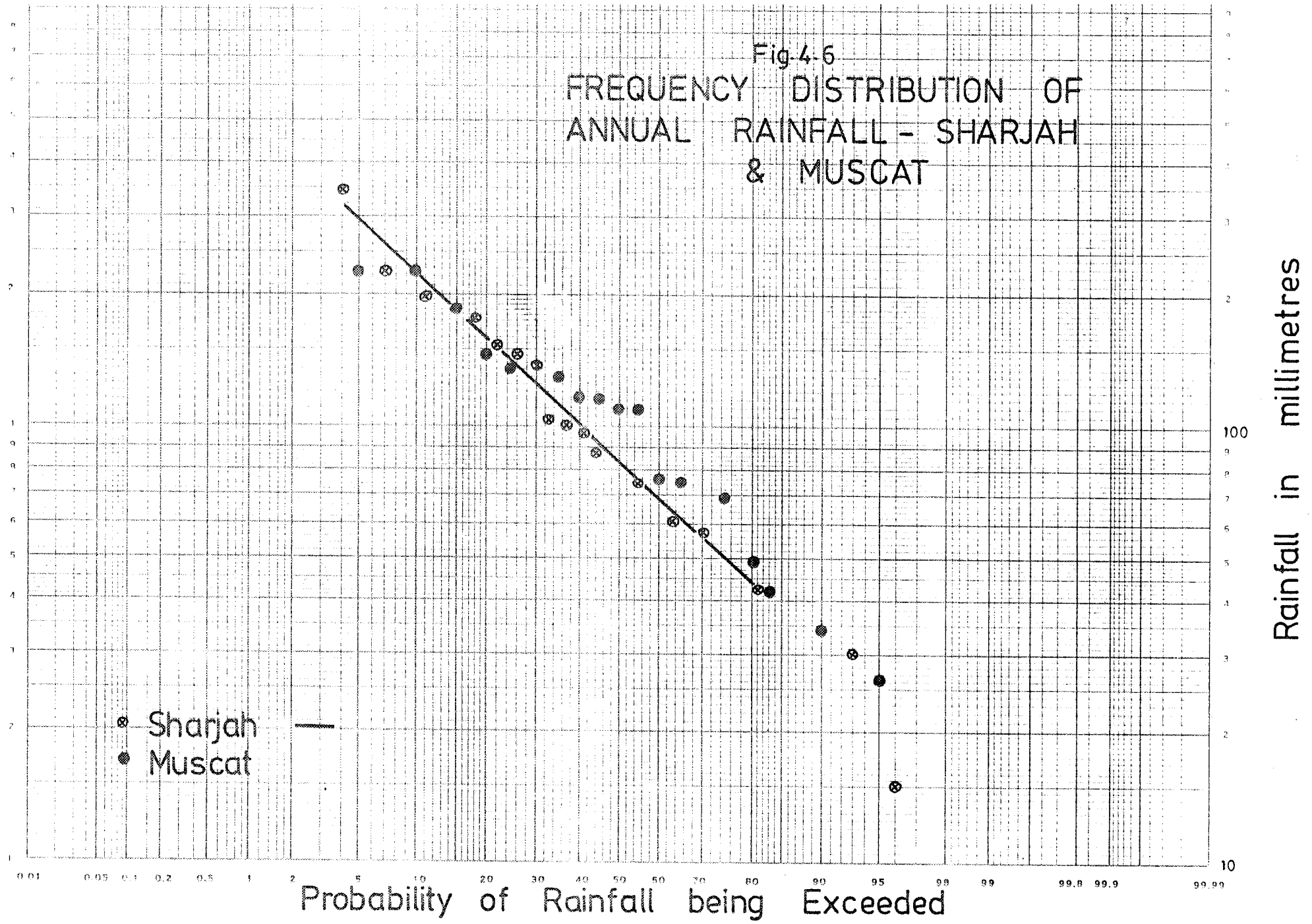
Buraimi, al Ayn, Nizwa and Fahud provide some data during the required period, but their records are not continuous (table 4 . 4)

Table 4. 4 Rainfall Averages for Neighbouring Stations

Station	Length of Record	Annual Average	Range
Fahud		33. 5mm	0-131mm
Nizwa		161. 0mm	82-654mm
Buraimi		44. 0mm	14. 8-77. 3mm
al Ayn		85. 4mm	2. 1-331mm
Sharjah		100. 6mm	0. 3-258mm

Fig 4.6

FREQUENCY DISTRIBUTION OF ANNUAL RAINFALL - SHARJAH & MUSCAT



Of the stations in Table 4.4, neither Fahud nor Buraimi had data for 1971-2, which was the wettest year recorded at Nizwa and al Ayn, and the wettest during the same period of records for Sharjah. Of these other stations, al Ayn/Buraimi is the most similar to Tan'am in situation, and also the nearest. In individual months, or years, the two recorded very different amounts of rain. As with the two gauges only 13km apart, the longer the period considered, the nearer the totals approached each other. Taking the maximumavailable period of parallel readings, from February 1973 to February 1975, the totals become almost identical (94.93mm Tan'am, 94.9mm al Ayn).

In the six years for which data are available for both al Ayn and Sharjah, mean rainfalls are approximately equal. (85.4mm and 81.96mm respectively) These values, however, are obtained in a period containing the lowest consecutive four years of rainfall in Sharjah's records. The 36 year old average is some 23% higher at 100.6mm.

It therefore appears that over the six years of records the calculation of annual mean precipitation at al Ayn/Buraimi may also be below the mean for a longer period, by approximately 20%. Bearing this in mind, it is suggested that the long-term mean annual rainfall for Tan'am may be around 100mm. The period of observations was therefore one of below average conditions, especially in 1973-4 when monitoring of wells/falajes was also undertaken.

This overall below average situation was also the impression gained from local people. As mentioned in the section on changes in water level (see p. 261), indications were of constantly declining water levels over the past ten years.

On the coast, rainfall appears also to have been below average. Khabura is the longest running of the new rain gauge sites on the coast with records over 18 months, and with a single year's rainfall of 73mm. This compares with an 18 year average of 111.9mm per annum at Muscat (British Embassy) 130km away to the south east.

(iii) Periodicity of Droughts

The average alone, however, is of little relevance without any idea of how often exceptional conditions, whether below or above average, occur. Probability analysis of data defines the chance of a given rainfall occurring, and calculation of return periods express the probability that a given level of rainfall will occur again within a given number of years. What neither establishes is the probability of a series of below or above average years running concurrently. The data from Sharjah are not long enough to work this out. However, in England 250 years of data proved too little in the summer of 1976 to predict the succession of dry months witnessed. Sharjah's or Muscat's length of record cannot be used to calculate design droughts or floods. Indeed it is calculated from existing records that 200-120 years records respectively are required to obtain standard deviations within 10% of true values at 95% confidence limits. For the probability of successive years of drought, local information can provide useful indicators of drought frequency in the past. Observation in 1973-4 (see table 4.5) showed that in dry years indicators include falaj motherwells having to be extended, pump motors lowered, and palm trunks becoming narrowed by successive years of reduced water supply. In wet years, flood damage is common and extra large areas of seasonal crops are grown.

Obviously the more recent the event the more reliable the information, but an approximate 10-12 periodicity of drought was indicated. This fits well with the periodicity of rainfall noted by Halcrows for Trucial States observations (17) and the results of work by Cochrane and Willett (24, 25).

Table 4.5 Drought & Flood Events from Local History

Approx. Date	Drought or Flood	Elapsed Time	Event
1974	D	0	Injayd, Miskin, Khadil, Ibri, Tan'am, Araqi, cleaning and extending falajes. al Wagag collected water from sunken source.
1961-62	D	12-13 yrs.	al Aridh extended Sa'ad. Miskin made a cistern.
1953	D	21 yrs.	Khadil Safil re-started.
1951-53	D	22-23 yrs.	Injayd regraded falaj after palms died. al Wagag (Sulayf) last collected water underneath wadi gravels. Dubayshi died. Khadil Ahli drought and most recent servicing.
1950	F	24 yrs.	Hakkab (Sulafy) flood damage.
1945	F	29 yrs.	Dubayshi falaj flooded.
1930	D	34 yrs.	Hujrimat re-started.
1929	D	35 yrs.	Hayyal drought killed most trees.
1914	D	60 yrs.	al Aridh Sa'ad dug.

Both sets of work suggest an 11 year periodicity of droughts, and Willett, using the 80 year sun spot cycle, suggested that 1960 to 1980 would be a below average set of years.

The last major drought, remembered as the 'Mahal al Kabir' is a long time ago. Its date is not known, but only people over about sixty years old recall it, others only have hearsay evidence of it. Almost every falaj dried up except al Qal'ai and al Hijar. It is said that it consisted of seven years with almost no rain, and that many people were forced out of the area by it and little livestock survived. Only at the major settlements, where date irrigation in normal times is generally more generous and an oasis micro-climate is better established, did date palms survive. In other settlements, the trees all post-date this drought.

Within any period of years the range of annual rainfall may be very large, and on rare occasions more rain may fall in one day than falls in the whole of another year. For falaj supplies, which tap specific springs, the lack of rain in a single year has little effect. It is the occurrence of a succession of several years without significant recharge events which causes major declines in these water supplies. The higher up the catchment, the less the number of successive 'below average' years needs to be, before water supplies are affected. See p 259

The return period of individual annual rainfall totals is therefore less important than the probability that one poor year will follow another. So far theories of sunspot activity (24, 25) coincide most closely with hearsay evidence on drought frequency collected in the field area. This is, however, a controversial theory that is not always accepted, and does not fit equally well with observations in all parts of the world. To test its validity requires many more years' data, as the pattern is of 11, 22, and 80-100 year cycles.

Whatever the causes of the periodicity of droughts and their intensity, the maintenance of reliable rain gauge stations supplying uninterrupted information is of vital importance in water resource planning. The closure of Sharjah, the longest running station in the southern Gulf, is extremely unfortunate from this point of view.

D - FACTORS IN THE ASSESSMENT OF EVAPOTRANSPIRATION

(i) Temperature & Humidity

The overall annual pattern of temperatures is of a group of summer months in which mean maximum temperatures remain roughly constant at well above 40°C while night temperatures seldom fall below 25°C (see fig. 4.1). In winter minimum temperatures are generally above 10°C except for brief periods, especially when cold front conditions prevail. These average, during the four winter months December, January, February and March, less than one day per fortnight. The highest shade temperature recorded is 48.5°C (3.6.74), the lowest 4.5°C (7.12.74). Out of the shade, as at most Dhahira well gardens, where shade giving tree crops are rare, temperatures reached 56-60°C*.

In the Interior, warmest conditions prevail during the period of southerly and south westerly winds which have travelled across stretches of the Empty Quarter, in May, June, July and August. The highest mean maximum temperatures were recorded in June

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*FOOTNOTE: This in itself, without consideration of the high evaporation rates, is sufficient discouragement to farmers to mid-day irrigation.

1974, at 45.9°C. On the coast, temperatures are kept lower by onshore breezes. At Sohar in 1974 the hottest mean maximum was recorded in July with 41.2°C (see table 4.6). The onset of summer appears to occur later on the coast, and the season of highest temperatures to be of shorter duration. Only June and July have mean maximum temperatures of over 40°C, and the coast remains cooler than the Interiorthroughout the year.

Table 4.6 Temperatures Monthly Means 1974

		J	F	M	A	M	J	J	A	S	O	N	D
MAX.	Tan'am	25.8	26.2	34.2	37.2	41.4	45.9	45.5	44.6	41.7	37.5	31.7	26.9
	Sohar	24.4	23.9	30.6	33.1	38.1	40.4	41.2	37.1	36.4	33.8	29.6	25.6
MIN.	Tan'am	11.5	11.7	18.9	19.5	23.3	27.0	27.1	27.7	25.2	20.5	15.0	12.9
	Sohar	12.1	12.8	17.3	18.6	23.0	25.2	26.2	26.9	24.6	16.8	14.0	12.9
MEAN	Tan'am	18.6	19.0	26.6	28.3	32.3	36.4	36.3	36.1	33.5	29.0	23.3	19.9
	Sohar	17.0	17.3	23.1	25.4	30.3	33.3	33.1	31.7	30.4	24.5	20.9	18.7

In winter, the effect of the sea is to reduce the range of temperatures on the coast, so that in December, January and February, the minimum temperatures equal or exceed those in the Interior, while in the warmer months, Interior minimum temperatures are higher.

In the intermdeiate months, and in April in particular, the oscillations of the convergence zone may cause considerable and rapid variations in temperature.

In terms of comfortfor living and of evapotranspiration, the pattern of relative humidity in relation to temperature is important. As with temperature the influence of the sea is significant. Humidities are higher throughout the year on the coast than in the Interior, and fluctuations smaller. What makes the coast so much less pleasant a place to live, and reduces irrigation requirements, is that here

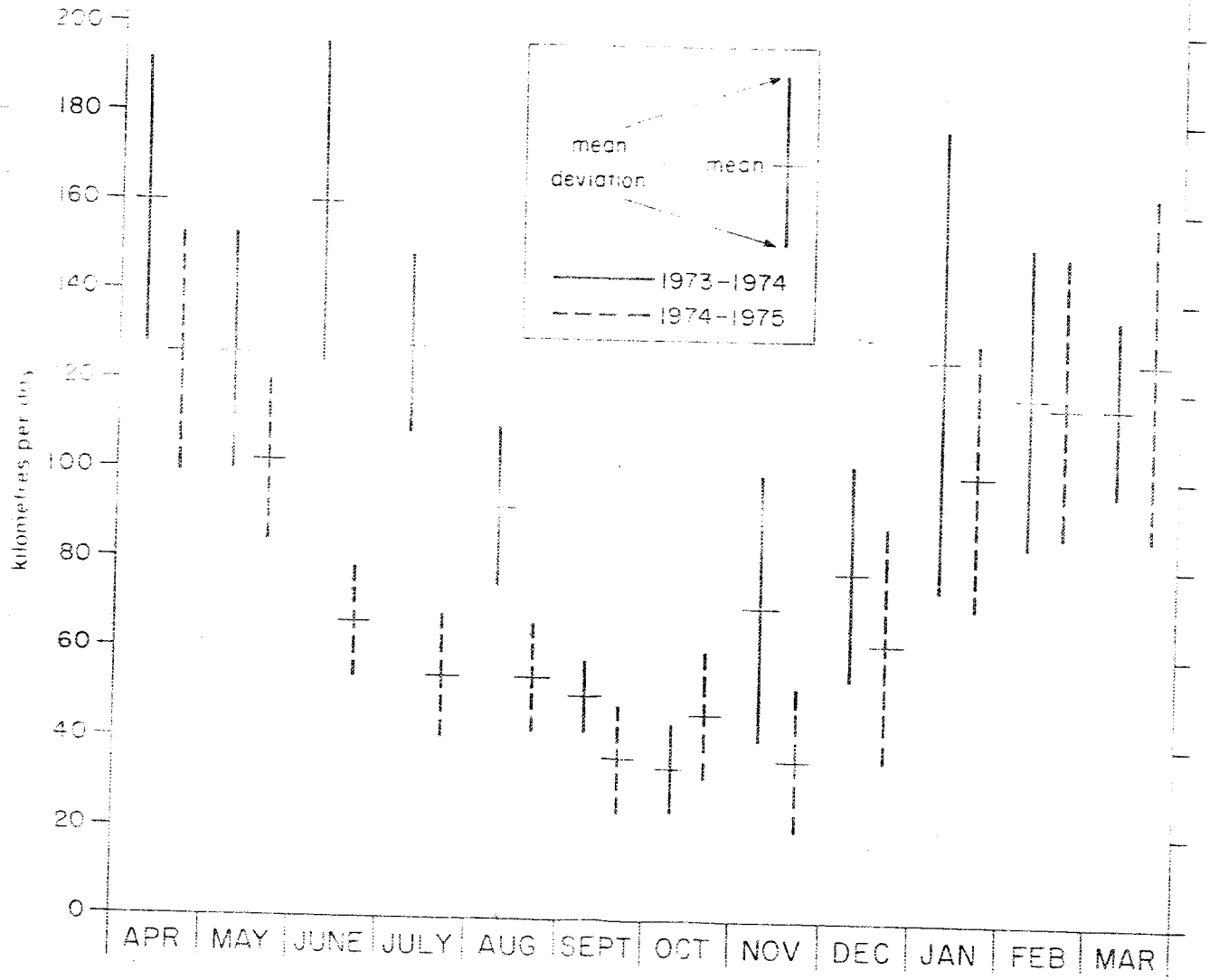
highest humidities coincide with the hottest temperatures. In the Interior relative humidities are highest at night and in the season when temperatures are lower and crop demand for water at its lowest.

Inland humidities often vary within a day, by as much as 50% as lower temperatures at night increase the relative humidity of even slightly moist air. Humidities over 90% are seldom reached except in association with rain, but during the day-time dry winds off the Empty Quarter may bring extremely dry air, which is recorded on the zero baseline of the hygrograph. These very extreme values caused problems in calibration of the thermohygrograph (where 9o'clock readings varied by more than $^{+}$- 5% from calculated values recordings are not included and months are marked with an asterisk in Table 4.7 On the coast, on the other hand, humidities never fell below 9% and readings of 100% were recorded every month except January. (see table 4.7). The influx of moist sea air was apparently an almost unbroken daily event.

Table 4.7 Relative Humidity, Coastal and Interior

1974	Tan'am	Sohar	Tan'am	Sohar	Tan'am	Sohar
	MAXIMUM		MINIMUM		MINIMUM	
Jan	80	99	49	74	0	28
Feb	86	100		75	16	24
March	95	100	37	70	3	17
April	*	100	*	69	*	21
May	*	100	*	58	*	12
June	*	100	*	59	*	9
July	88	100	26	66	0	11
Aug	90	100	40	79	6	16
Sept	78	100	33	76	0	25
Oct	*	100	*	67	*	15
Nov	*	100	*	73	*	14
Dec	78	100	45	75	4	25

Fig.4.7. RUN OF WIND AND ITS VARIATION AT TAN'AM, April 1973 to April 1975



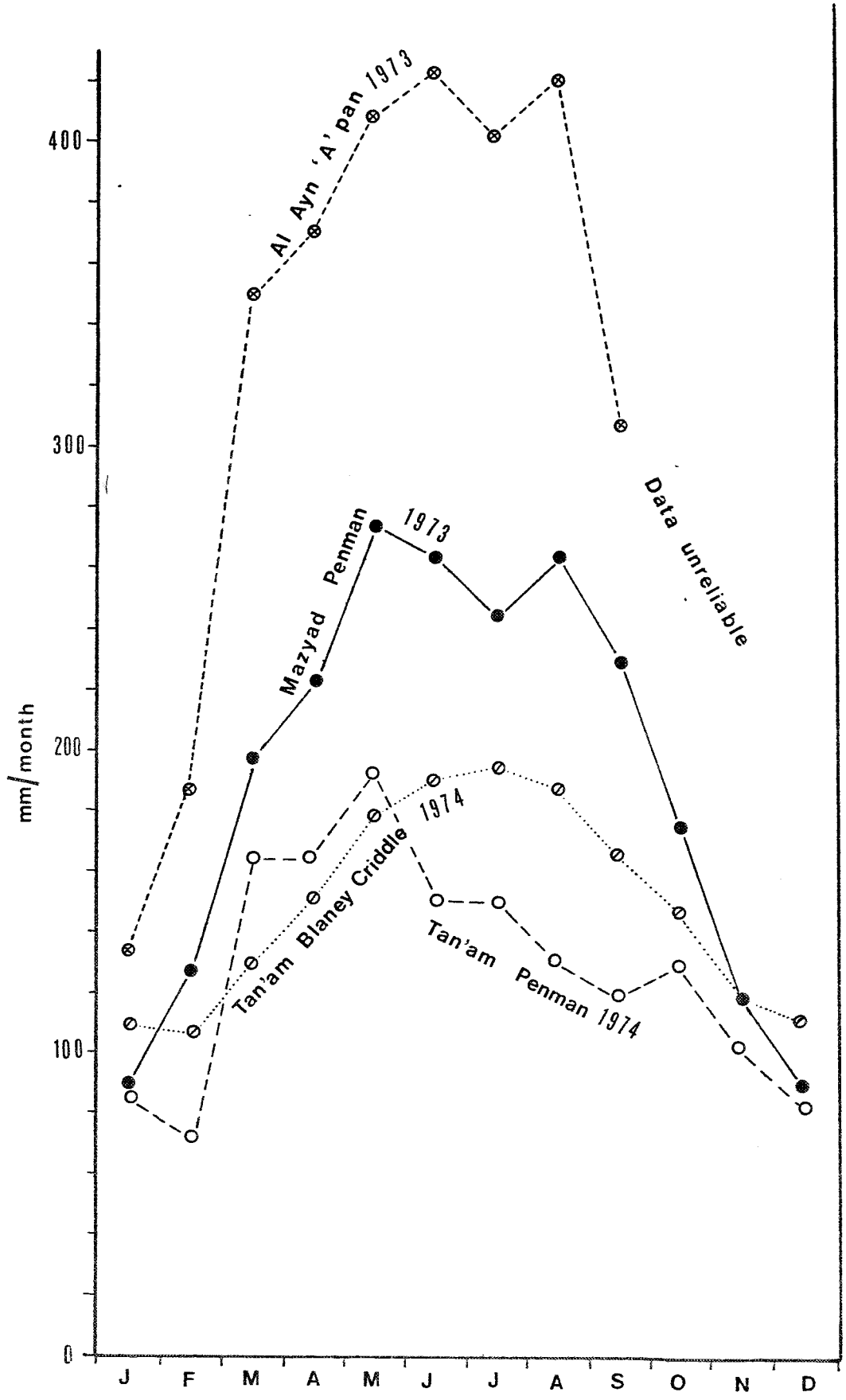
(ii) Wind

At Tan'am, and also apparently at Sohar, while run of wind records were kept, wind direction was not observed. In the Interior, wind speeds were lowest in August-October and highest in March-June, but in the two years of observations the pattern was found to be very variable (see fig. 4.7). Run of wind varied from 0.8km/day (21.11.74) to 541.6km/day (5.12.73). Run of wind was most changeable during the winter months; summer winds were less powerful and also less variable.

In association with winds, rainfall generally fell during a series of days with below-average winds. Only where disturbed conditions brought rain on several successive days were wind speeds higher and more variable. The isolated local cyclonic conditions of 12th December 1973 were an exception to this, but rainfall was very low.

On the coast wind speeds were far more constant, throughout the year, and varied less from day to day (see table 4.8). Lowest run of wind occurred in November and December. At Khabura it was noted that in winter (Nov-Mar) the air was still from before dawn until ca. 7.30 am. On-shore breezes then developed and continued till dusk. It appeared that the air remained still until dawn. As summer drew near, however, the lower humidities and cooler air inland appeared to reach nearer the shore at night. In high summer, however, it seemed, from the positioning of summer sleeping platforms, that on-shore breezes predominated at night. During the day, weak off-shore breezes were said to be common. This pattern is observable up and

Fig. 4.8 Evaporation in the Interior.



down the coast, and is noted by Flohn (26) in Sharjah.

Table 4.8 Daily Run of Wind (in km) 1974

	MAX		MEAN		MIN	
	Tan'am	Sohar	Tan'am	Sohar	Tan'am	Sohar
Jan	541.6	141.7	126.4	69.1	8.6	41.5
Feb	481.0	133.0	117.8	75.2	24.7	47.5
Mar	276.4	114.0	116.0	68.2	38.3	37.1
Apr	204.9	200.4	126.5	85.5	34.2	55.3
May	198.7	125.3	101.7	92.4	34.5	67.4
Jun	145.3	168.5	64.8	93.3	9.5	63.1
July	213.2	146.0	54.3	82.1	6.3	63.1
Aug	142.9	122.7	52.8	92.4	2.2	70.8
Sept	166.8	102.8	34.9	79.5	4.4	59.6
Oct	179.4	99.3	44.7	57.0	3.4	32.0
Nov	197.1	90.7	33.0	48.4	0.8	33.7
Dec	233.9	82.1	61.4	43.2	3.1	17.3
Average	248.3	127.2	81.8	73.9	14.2	49.0
s	128.8	33.8	35.9	17.3	14.0	16.8

(iii) Insolation

Insolation was measured as total radiation with a Gunn-Bellani solarimeter. No record of sunshine hours was undertaken. Unfortunately only 14 months of readings could be taken because of slow delivery of the instrument. The pattern of monthly averages resembles that observed in Sharjah in 1966 (with a correlation coefficient of 0.93) but results at Tan'am were considerably higher. It is not known whether this is due to differing calibration of the two instruments, or whether the more humid conditions at Sharjah cause a real difference.

The highest averages were recorded in June and July, as was the highest value of 30 mls. Very low values are not accurately measured by the

instrument, as liquid sometimes tends to run into the column when the globe is fitted back into the collar. This water (which amounts to less than .3ml) is then read as equivalent sunshine next day. The lowest recorded reading was 5.5 ml on a rainy day in January 1975.

Table 4.9 Gunn-Bellani Solar Radiation Readings, Monthly Means

Month	Sharjah 1966 Values	Tan'am 1974-75
April	18.6	22.46
May	21.9	22.83
June	22.1	23.02
July	20.8	23.21
August	19.1	22.12
September	18.2	21.63
October	15.0	18.2
November	10.7	16.1
December	9.4	12.49
January	7.9	12.67
Februaryy	12.0	13.02
March	16.4	17.93
April	18.6	17.95
May	21.9	21.60

(iv) Evapotranspiration

From the hydrologist's point of view, observations of temperature, relative humidity, run of wind and insolation are of little significance on their own. Their main relevance is to provide information on potential evaporation where no direct measurements can be taken. In

Oman neither time nor finance allowed the installation of a lysimeter, nor equipment to monitor the turbulent diffusion of water vapour.

At the same time, high winds, frequent dust storms, children and thirsty goats all militated against the direct measurement of evaporation using the pan method. It was therefore necessary to employ an empirical method which required only climatological data which was recorded at the stations. The conclusions of Stanhill's work (27) were that for an arid climate Penman's equation compared well with pan evaporation and was highly correlated with actual avapotranspiration measured from lysimeters. His comparisons with Thornthwaite's method (28) showed the Penman formula to approximate observed values more closely. The Penman method was also noted in Iraq (29) to be in agreement with observed water use in irrigation.

While it is acknowledged that this particular method is not equally well suited for use in all climates, it was first selected here as being particularly useful in arid cond tions. It is also the method used by the Meteorological Office (Bracknell) in the treatment of the data they receive. Despite its apparent suitability it appears likely it underestimated evapotranspiration at Tan'am. In this study, a modified version of the Meteorological Office Penman computer programme was used and produced a pattern found also at Aynayn and Mazyad (Abu Dhabi) (see fig 4.8) with an abrupt change in March, and a peak in May. This differed from the coastal pattern which peaked in June and July at Sohar. (see table 4.10)

Comparing actual values is difficult, both because some stations use 'A' pan readings (al Ayn) and others calculated values, and also because

those using calculated values do not all use the same formula. Even where, as in the case of Sohar and Tan'am (see table 4.10) the same method is used, comparison is of doubtful validity. Sohar uses the Penman formula but with sunshine hours rather than total radiation, and there is no mention of whether any allowance is made for the oasis effect.

Table 4.10 Evapotranspiration 1974/5

Month	Tan'am Penman	Sohar Penman	Tan'am Blaney Criddle	Sohar Blaney Criddle
April	165.5	172	153.4	143.6
May	192.1	222	179.6	172.2
June	152.9	239	191.6	180.6
July	152.8	241	196.0	184.3
Aug	132.3	216	188.5	173.1
Sept	119.8	192	165.5	155.5
Oct	129.5	143	147.5	133.3
Nov	102.5	102	119.6	112.5
Dec	83.0	82	110.9	107.3
Jan 75	90.2	79	110.6	104.5
Feb	74.3	90	107.0	101.3
Mar	165.2	147	132.3	127.8
	1560mm p.a.	1925mm p.a.	1802mm p.a.	1696mm p.a.

Annual values calculated for Tan'am (potential evaporation) totalling 1560mm per annum are arrived at using 0.59 rather than 0.35 (30) as the constant in the aerodynamic term. This is because the grassland radius used by Penman (31) is assumed as ten miles in all directions, whilst a tenth of a mile is nearer the size of the oasis at

Tan'am. However, the low annual total and the pattern of monthly totals suggest that this may not be sufficient compensation.

As the inputs to the calculations of evapotranspiration differ at Tan'am and Sohar it is impossible to state whether the differences are real or simply a product of the data type used. Sohar Et is calculated as higher than Tan'am by approximately 25%, which is in direct contrast to observed water use practice. Crop water application rates were found to be over 60% higher inland than on the coast (see p.490). It is, however, the same pattern as the water balance maps produced for the area by Thornthwaite, Mather and Carter (2). These too suggest that both water balance deficit and potential evapotranspiration are greater near the coast.

Only the Blaney-Criddle formula can be used in exactly the same way for Tan'am and Sohar data, as this is the only method for which the necessary data are available at both sites. This reverses the pattern to one compatible with observed irrigation practice, with higher deficits inland (see table 4.10). The Blaney-Criddle formula does not include windspeeds, which are higher inland than on the coast. It would therefore be expected that incorporation of this factor also into calculations would increase the contrast between the two areas, making calculated evaporation rates even higher in the Interior than on the Batina. This suggests that the Penman formula may have been used differently for Sohar data, or that the difference may be due to the employment of sunshine hours, not radiation intensity.

Mazyad data is equally difficult to compare because of there being no details of how the values were calculated, and the original (discontinuous) climatic data could not be obtained. Only at al Ayn were observations of evaporation undertaken. From the levels recorded, it is presumed that the 'A' pan method was used, and this is very likely to lead to overestimations without correction (31). Certainly levels recorded at this station were far higher than the calculated levels at Tan'am. Some doubt is thrown on the al Ayn observations as five months' data are not available, the results having been too unrealistic to be circulated. It is likely that the true values of potential evapotranspiration fall somewhere between the two extremes of the Penman method and the 'A'pan observations.

These water use values are discussed further in relation to observed crop irrigation practice in Chapter 8 .

E - CONCLUSION

Climatology in Oman as a field of study and data collection is only just beginning to become established. The longest running stations have no continuous observations, records being interrupted by holidays or even whole years, when no army or oil personnel were directed to take readings. Those set up since 1973 have run for too short a time to give any idea of averages or variations on their own. With the closing of the Sharjah base, the running down of Masirah, and the abandonment of the country's hydrological programme, hopes are few for better data in the near future.

At present, therfore, it would be misleading to undertake detailed statistical treatment of the data using methods designed for reliable and continuous data available in more developed countries. There are, however, sufficient data to provide values for use, with extreme caution, in work on water balance and crop water requirements.

II WATER BALANCE IN THE FIELD AREA

A - INTRODUCTION

Water balance even with a plethora of data is difficult to calculate with a high degree of reliability. The field area suffers from a shortage of data on a regional basis and on a temporal one. Nevertheless, with abstraction systems which suffer from even relatively minor fluctuations in water table it is especially relevant to examine the degree to which water balance is achieved in observed years and under average conditions.

With respect to rainfall alone, (see p. 111), 'average' conditions are difficult to define, and are of little relevance, in that deviations from the mean are so great that the average is attained very rarely. 'Average' recharge is, however, more realistic for the storage and slow passage of water through aquifers means that at least in the areas of lower wadi and desert foreland seasonal and annual variations are smoothed out. Resultant water levels and yields relate not to the recharge of a single year, but from evidence of response to drought reflect the events of several years. The higher up a wadi, the less the available storage for groundwater and so the quicker the response to flood or drought (see Ch. 5 Section IV) and the less the relevance of the average condition.

The degree to which a balance between extracted and available water is met therefore depends not only on how much the events of a year or a succession of years approaches the average, but also what

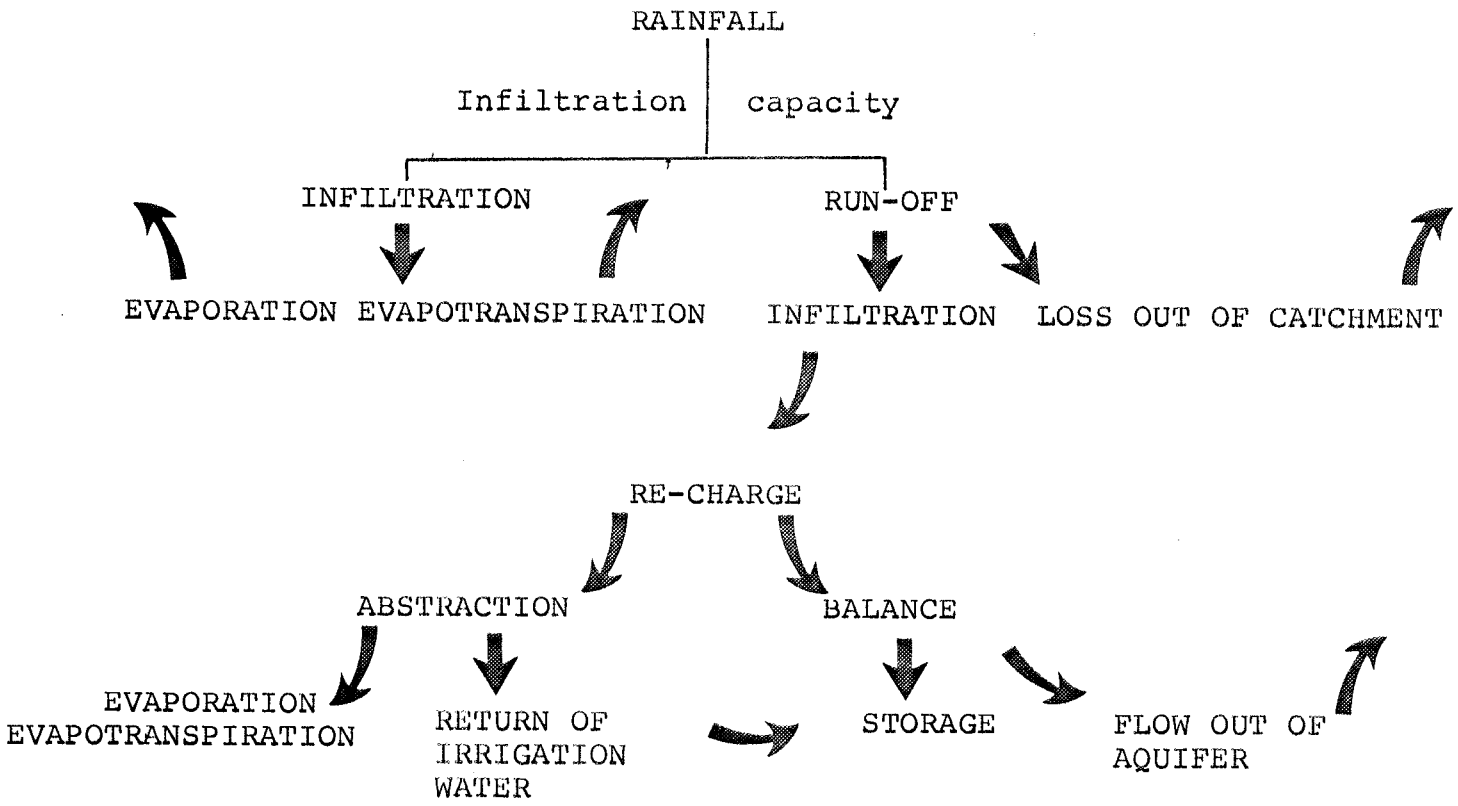
point in a catchment or aquifer is being considered. This is particularly so in the situation encountered in Northern Oman, where exploited aquifers are discontinuous and tend to resemble the network of a river rather than a widespread continuous aquifer such as the great extent of the Umm er Radhuma, which is relatively independent of surface catchment patterns.

Three main catchments are considered, these being the al Kabir, Juffra, and al Hijr , all of which flow to an inland basin, the Umm as Samim. The Hawasina is not considered because of the problems of delimiting the lower catchment and which of the wells are on the coastal strip and which tap water originating in the Wadi Hawasina. Balances are calculated for the al Kabir at the Ibri gap, the al Hijr above its diversion at Muqaydah, the Juffra above Subaykhi. Thus if a surplus of water is identified it refers specifically to the area downstream of these points.

The elements of water balance are well-known, and the 'hydrological cycle' tends to form an introductory chapter to every hydrology textbook (eg.32) . Nevertheless, certain features need to be emphasised, especially since the spectacular nature of wadi spates may lead to false ideas of very high proportions of run-off. The elements may be summarised by a flow diagram (see fig. 4. 9). From this it can be seen that the number of elements which contribute to water loss (here meaning water which does not provide aquifer recharge) outnumber those which cause recharge.

In desert conditions with poorly developed karst, no water which does not form a concentrated stream of run-off will contribute to

Fig.4.9. FLOW DIAGRAM OF RE-CHARGE FACTORS AND WATER BALANCE.



groundwater storage, and recharge is principally through the gravels of wadi beds. Simiarly, of water which does run off a proportion will flow out of the area considered, a proportion will evaporate, and a proportion sink in sufficiently to give rise to a significant recharge event. The quantifying of these different elements and of the initial input of rainfall itself cannot be estimated with a high degree of accuracy only from measurements within Oman itself as these are few and far between. By analogy with results in other similar areas, however, a first approximation can be made

B - AVERAGE CONDITIONS

The consideration of average conditions requires the temporal extension of observed radings in the area which only cover 18 months, and also a lateral extension over the area to allow for differences in aspect and altitude. In discussion of rainfall at established meteorological stations (see p. 170) it was suggested that average rainfall at Tan'am should be taken as around 100mm pa. Similar figures are established by Ilaco for the coastal area, using Sohar data.

100mm pa is, however, the average for the lowest point in each catchment studied, and cannot be projected over the whole area. Observed rainfall atNajd Sharingiban and Magzi al Hawasina give no indication of increased precipitation with greater altitude during the short period of measurement. The reasons for this may be two-fold. Firstly the number of events measured is small (less than fifteen) and falls are below average and may therefore not reflect the situation during storms which provide the long-term majority of rainfall. Studies in Kenya and Uganda (34) found that for rainfall run-off correlations

measurements on approximately 50 large storms were needed in an area with considerably less rainfall variation. Secondly it has been shown (see p. 161) that the rainfall in 1973-5 originated from very localdisturbances. These in summer are generated over the Jabal Akhdhar and move westwards along apparently well-defined paths in the mountain fringe. There may therefore be little local correlation between altitude and rainfall if the majority of rain does not come from more widespread disturbances. Rain gauges within the storm belt will then tend to exaggerate the effect of altitude and those outside to underestimate it. Such disturbances are, however, associated with orographic effects and therefore as a whole the mountains are expected to receive more rain than the coastal plain or desert foreland.

In the absence of local indications of altitude/rainfall relations, it is necessary to adopt ratios from a neighbouring area of similar topographic and climatic conditions. The mountains of south west Saudi Arabia , although a larger barrier to coastal influence, are similarly affected by shifts in the ITCZ. Here in the Jidda-Taif area using data quoted by Blehed from meteorological stations (35) gives a relationship of 11% increase in rainfall per 100m altitude. The watershed area of the OmaniHajar mountains in the north averages 1200m and the highland average rainfall is therefore taken as 170mm, based on Tan'am data at 300m.

If the relief of individual catchments is taken into account, the average input rates per annum are as follows:-

Catchment	Rate	Volume
al Kabir	141mm	$138m^3 \times 10^6$
Juffra	122mm	$65m^3 \times 10^6$
al Hijr	148mm	$51m^3 \times 10^6$

(ii) Proportion of Rainfall as Run-off and Recharge

Of these levels of input to wadi systems, the degree of recharge depends mainly on the amount which runs off. Light rains may cause no run-off at all, while in heavy rains the majority of water contributes to wadi spates. Locally it was observed that the formation of run-off followed the pattern observed by Joly in the Sahara (36) in that puddles formed quite quickly, and then coalesced to form local run-off as sheet flow. The progress of such water to a major wadi bed, however, tended to take much longer, especially on the low gradients of the desert foreland and lower wadis. Flows from storms of under 7.5mm did not cause run-off over more than 100-200m (cf. the Sahara where Dubief (37) observed that 5mm of rain caused no run-off). Small flows in minor wadis were found to cause little or no response in the main wadis, and it is therefore suggested that significant recharge may not take place until rainfall exceeds 10mm overall, although from rock areas local run-off may occur at lesser intensities than on gravel.

Thus the proportion of total rainfall from events of under approximately 10mm may be discounted in terms of contribution to recharge

of the lower wadis as may the first 10mm of rain which exceeds this value. It is acknowledged that the validity of this figure will depend on antecedent moisture content (from previous rain), but while this is an important factor in wetter climates it is less so for deserts where rain events are generally so infrequent that each can be treated as an isolated occurrence.

From observations at Tan'am in 1973-5 it is apparent that during this period 90% of rainfall was ineffective in replenishing groundwater reserves. This is supported by the fact that almost all falajes and wells in the lower wadi area exhibited steady or continuously falling water levels or declines in yield (see fig 5.25). Only in the upper parts of catchments, or immediately beside wadi beds subjected to local flows did water levels recover during this period, until the rains of February 1975. At this time recovery was observed throughout the majority of the area, establishing this as the first occasion on which major recharge occurred during the period of study. At Ibri, however, with almost 24mm of rain in two days, run-off remained local and did not lead to flow in the main wadi. 10mm may therefore be slightly low as a figure for initiating major run-off on low gradients with high infiltration capacity. It is, however, high for steep rocky slopes and should therefore provide an approximate mean for each complete catchment.

It is expected that long narrow wadis such as the al Hijr and upper al Aridh, with a high proportion of outcropping rock (70%) will experience greater loss from run-off than those wadis with alluvial basins, such as the al Kabir and Juffra. While estimates remain at such an approximate stage, however, no differentiation is made on this basis.

In an average year Tan'am would expect three times as much rain as in the year for which water levels were recorded. From Sharjah data this leads to approximately a doubling in the number of rainfall events and the proportion of these not exceeding 10mm then falls to some 55% of total rainfall, leaving 45% to reach wadis and run-off into the sea or the Empty Quarter, or to sink in, in an average year.

Confusion arises in comparing run-off infiltration data, as there is sometimes little differentiation between pre-run-off and run-off infiltration, or quantification of infiltration of the latter as a proportion of total run-off. This means that the element giving rise to desert aquifer recharge is often poorly defined. A reason for its neglect may be that in more humid areas it is infiltration before run-off which leads to most recharge, while conversely run-off is regarded as an element of water loss. For instance in a study of the Salton Sea Area, Colorado (USA) (38) rainfall varied by a factor of ten. In the areas of low rainfall, run-off was relatively insignificant compared with those areas of higher rainfall and perennial flows. It was therefore neglected as a measured factor in the programme, and was assumed to be zero, which is unfortunate in one of the best instrumented semi-arid areas of the world.

The researchers in this study, however, point out the problems of measuring desert flows when they say " Conventional records of desert stream flow are extremely expensive relative to the small quantities of water involved, are difficult to obtain and are difficult to evaluate because of the absorption of stream flow. " While this is true, it neglects the major point, which is that it is vital to

Table 4.11 Estimated recharge parameters in neighbouring or similar semi-arid Areas

Area	% Rainfall Running off	% Run-off Sinking in	% Rainfall Recharging
N.N.Oman (33)	16-20%	70%	15%
Central N.Oman (39)	16-20%	70%	15%
S.N.Oman (18)	60% mountains 70% plain	38%	23% 27%
Qatar (40)	20%	70%	14%
Colorado Mt.	40%	-	-
Salton Sea (38) Dry Range	2%	-	-
Albuquerque (41)	0.8-9.3%	-	-
Catchments draining to Interior Iran (42)	53%	-	-
Arizona, Pinal County (41)	-	50%	-
Trucial States	-	-	14%
S.Yemen (43) Wadi Tuban	-	50%	10-15%

obtain measurements of the absorption of stream flow to assess the amounts of water replenishing aquifers where no perennial surface water is available.

Assessment of this factor is a major problem in Oman, although some catchments have been instrumented to provide information on infiltration along wadi floors. A difficulty here is that while it is possible to measure what flows into an area, and what flows out, it is only if there is no input between these two points that valid figures of infiltration are obtained.

Wadi floors are the only major source of re-charge in the systems observed, and infiltration capaciti es can be very high. In the Ibri Wadi in July 1974 infiltration rates of over 7cm/min were observed by the author. In small floods, therefore, 90% of run-off can be expected to sink in before leaving the catchment. On medium floods into the wadis Jizi and Ahin, Ilaco (33) (Annex A p31) measured 84% and 73% infiltration of run-off between the mountains and the sea, while in the Hawasina the only observation of a more major disturbance suggested 19% infiltration.

To cover the wettest years which have a longer return period but which have a large effect on long-term averages, a modified infiltration rate of 70% is suggested, giving an overall recharge figure of 32% of rainfall. This is rather higher than estimates by consultants and researchers (see Table 4.11) working in neighbouring areas during the same or other recent periods of below average rainfall. Their estimates are somewhat lower at around 15-20%, but appear to be poorly related to longer-term rainfall distributions.

The final proportions of rainfall to recharge adopted for the two southern regions of North Oman appears to arise from very different assumptions. Gibb adopted a rainfall/run-off relationship a quarter of that used by Renardet in the Sharqiyah, but the proportion of run-off which sinks in is taken to be twice as high as that suggested by Renardet. Work in Qatar has provided the same level of post run-off infiltration as used in this thesis and by Gibb, and although gradients and areas of outcropping rock are less in Qatar, this is counterbalanced by catchments being smaller, leaving less opportunity for infiltration of run-off before reaching the sea. Qatari rainfall/run-off levels may be expected to be lower than those in Oman for the reasons expressed above. It is interesting to note that MacDonald (44) after a year's observation of wetter conditions in Oman is using a general rainfall/recharge figure of 35%.

(iii) Water balance estimates

Adopting, therefore, 32% of rainfall as average recharge, gives the following volumes per catchment per annum:-

al Kabir	$44.1 m^3 \times 10^6$
Juffra	$20.8 m^3 \times 10^6$
al Hijr	$16.3 m^3 \times 10^6$

Of this a proportion is already extracted. As the period during which systems were examined was one of declining flows, the

earliest falaj flows have been regarded as approximating 'average' ones.

Total abstraction:-

	Falajes	Wells	Total
al Kabir	$32.0m^3 \times 10^6$	$3.4m^3 \times 10^6$	$35.4m^3 \times 10^6$
Juffra	$2.5m^3 \times 10^6$	$0.25m^3 \times 10^6$	$2.75m^3 \times 10^6$
al Hijr	$3.6m^3 \times 10^6 +$	$0.25m^3 \times 10^6 +$	$3.85m^3 \times 10^6$

Without allowing for returning irrigation water or flow between catchments, the balance becomes:-

al Kabir	$8.7m^3 \times 10^6$
Juffra	$18.0m^3 \times 10^6$
al Hijr	$> 12.4m^3 \times 10^6$

Returning irrigation, however, forms a major recharge to downstream aquifers though less so in years of water shortage. The rise in water levels under oases suggests this as do seasonal water level fluctuations and patterns of water quality (see p. 144). Water losses even from distribution channels in falaj systems vary from around 20-80% and water quality indicates leaching rates in (Table 8.2) excess of 10%. Return irrigation water as a proportion of that abstracted has been assessed at a wide variety of values for various similar areas.

Table 4.12 Proportion of Irrigation Water Returned to Groundwater Reserves

Wadi Tuban Yemen (45)	30%
North (Haco) area of Oman (33)	25%
South-east (Gibb) area of Oman	45%
Wadi Hadramaut	20%
Trucial States	10%

NB: all are estimates. None are based on observations.

The overall balance would therefore be as follows, if a 25% return is assumed (the average of the above estimates).

al Kabir	$17.5 m^3 \times 10^6$
Juffra	$18.7 m^3 \times 10^6$
al Hijr	$13.3 m^3 \times 10^6$

In 1973-4 however, recharge was considerably below average and a deficit was therefore obtained.

	Max. Recharge	Deficit	No. average years needed to replenish
al Kabir	7.9	-18.6	1.06
Juffra	7.4	+4.6	-
al Hijr	2.7	-0.25	0.02

However, if 15% is a more realistic estimate of effective rainfall, then the Wadi al Kabir is under a permanent deficit of about $6m^3 \times 10^6$ per year, allowing for returning irrigation. This is unlikely to be so, as the deficit would be a third of estimated recharge leading to very large declines in flow and in water levels. Higher rates of recharge, or a very high proportion of water flowing in from other catchments must therefore be assumed.

A certain amount of inter-catchment groundwater flow has been postulated but cannot yet be quantified. This first approximation of water balance does, however, show the great contrast between the scope for further abstraction in the Wadi al Kabir compared with the other two wadis examined on the south side of the mountains. Existing rates of abstraction are two-thirds of average recharge. Using Sharjah rainfall data and probability curves (see fig. 4.6) it is apparent that in this case a deficit can be expected on average every other year, and that in the last 36 years falaj extraction alone has caused an overall deficit in four successive years on three occasions.

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CHAPTER FIVE

HYDROGEOLOGY

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I. INTRODUCTION TO AQUIFER PROPERTIES.

In the previous section, it was possible to identify water balance and areas of re-charge. In order to study the potential for water resource development, it is also necessary to identify the major paths along which water is transmitted and the quality and reliability of supply. The potential for increased extraction has already been shown to be limited, and it is, therefore, of special importance to identify areas where increased extraction would not cause problems and where different extraction methods may or may not be expected to interfere with each other. Ground water conditions are also examined in relation to their suitability for exploitation by existing and available methods of extraction.

The parameters examined are those most relevant to shallow well or falaj development. Deep aquifer data is confined to very limited information from existing boreholes, but this and economic considerations combine to make drilling a less significant alternative in the small scale private enterprise which predominates at present.

For the shallow aquifers, it has been possible to identify the different types and to map their extent in the major areas of well farming. No information existed on either the well or aquifer characteristics in the area before the work for this thesis and, therefore, various methods have been used to quantify these characteristics. It is emphasised, however, that these methods provide first approximations whose validity can only really be tested by pumping test analyses. The parameters which have been quantified, are those relevant to both well and falaj development, and were most closely applicable to the locating of further sites for abstraction and resolving the future of traditional falaj water abstraction in areas of well development.

There are three aspects of the study of ground water conditions. These are:-

a) The identification of specific aquifers and their distribution.

b) Analysis of well+falaj data to provide estimates of aquifer characteristics.

c) Examination of the reliability of supply as indicated by the monitoring programme.

Each type of information available does not generally provide conclusive evidence of hydrogeological conditions in isolation. It is the sum of all the information which has helped the author to come to the conclusions drawn of regional and local conditions. Hence maps of aquifer distribution should be compared with specific capacity, pumping depths and water chemistry data to provide a comprehensive picture of conditions.

The properties of water bearing rocks which require closest examination, are their ability to transmit water and their ability to store it. For precise planning, especially when the availability of further ground water is limited, these two parameters need careful quantification, and yet in both, even with ideal data it is difficult to establish values with more accuracy than an order of magnitude. In the absence of long term pumping tests, estimates must be used from the data collected from wells by the author. The resulting figures are regarded as first approximations and are, perhaps, particularly useful in identifying the relative quality of the different aquifers. They can also, with certain reservations, be used to suggest degrees of well interference and the siting and spacing of new ones, but mainly should be regarded as indicators of those areas in which further investigations should be concentrated.

Permeability or hydraulic conductivity which exerts the chief control on the flow of water through rock has not been measured on its own, either by field or laboratory techniques. It is, however, mainly used in combination with the thickness of an aquifer to give values of transmissivity, the amount of water that passes through a given cross-section of the aquifer in a day. Permeability alone, is only used in this work, as an unquantified basis for classifying water-bearing rocks as aquifers (high permeability) aquitards (lower permeability) aquicludes (lowest permeability). This is possible for, as can be seen, these terms are relative not absolute so that accurate quantification is not essential.

Transmissivity values, to be derived from permeability, require information on aquifer thickness and this could not be obtained. Transmissivity is, therefore, estimated by indirect means.

Transmissivities are inversely related to the amount of drawdown there will be at a given rate of water extraction. The higher the transmissivity, the smaller the drawdown, but the greater the cone of influence. Thus, with high transmissivities, large amounts of water can be withdrawn from a single well with little drawdown, but the effect is spread over a large area. This effect is cumulative, so that if there are several wells in the area, the drawdown in any one is equal to the combined influence of all of them. Thus, transmissivity directly effects the economics of water extraction, the spacing of the wells and the amount of water it is possible to abstract with available technology. In boreholes it will also affect the design and construction of the well.

The storativity (the amount of water held in a rock which is available for abstraction) is particularly significant in the consideration of the reliability of supplies. The smaller the system, the more frequently re-charge to storage is required to avoid drying-up of supplies. Hence, the largest settlements requiring high flows and little fluctuation, require the greatest storage of water to supply them and so are bound to be situated at the lowest point in a system, with maximum upstream storage.

Storage co-efficients depend on the type of rock, the pore and grain sizes, but are particularly dependent on whether the water occurs under water table conditions or is confined by overlying less permeable layers. In the latter case, water is only released by the elasticity of the aquifer which remains saturated even when water is withdrawn, and thus storage is much lower than in water table conditions. The difference is generally taken to be some two orders of magnitude. The aquifers encountered in the field study are generally taken to be un- or semi- confined from geological evidence, and this is supported by storage co-efficients estimated from recession curve and catchment volume data.

II. METHODS OF ESTIMATING AQUIFER PROPERTIES.

A. Transmissivities.

i). Degree to which conditions conform to general assumption.

The wadi fill aquifers with which present water abstraction is principally concerned are, from the analytical point of view, far from ideal. They do not cover large areas and are generally not of great thickness. They can more realistically be viewed as normal branching river systems in which the water instead of being free flowing, runs in a narrow passage through a variety of sedimentary layers of differing permeability. These aquifers are laterally arranged with a central core of high permeability, and then reduced permeability towards the edges until a bed rock is reached, which is seldom more permeable than the wadi fill itself. Thus, to treat any one aquifer as a system for the analysis of its characteristics is difficult, both because of the small areal extent of each,and so the limited number of samples available, and also because so few of the basic assumptions relevant to hydraulic property equations (e.g. Theis (1) Jacob (2) are fulfilled. Homogeneity, constant thickness and lateral extent, isotropic nature, instantaneous discharge with decline in head, are but four parts of the eight assumptions on which solutions of aquifer characteristics are based, which the observed conditions do not satisfy. Nevertheless, as no aquifer conforms to the ideal, it is possible to use available data to approximate hydraulic and well properties where the aquifer responds in an ideal fashion even if the limitations are not all satisfied.

The grouping of wells, their large number, and the inconsistency of diameters, make normal pumping tests invalid. Interference between wells cannot be avoided and it was found that the narrowing of well shafts with depth and the development of collecting chambers has a marked effect on drawdown curves, and so suggested aquifer boundaries where none existed. Despite these problems, it was necessary to select a characteristic which could be ascertained for a maximum number of wells, without lengthy measuring, in order to compare the potential of different aquifers.

ii). Specific Capacity.

Specific capacity is a well characteristic rather than an aquifer characteristic which expresses the amount of water which can be abstracted for a given drawdown.

After preliminary investigations, it was found most practicable to use well yield and specific capacity as the basis for comparisons. These being the parameters most easily obtained and ones which can be used to estimate hydraulic properties. Highest specific capacities are, however, difficult to quantify as drawdown is small and so accurate information is often difficult to acquire.

Two specific capacities were calculated. One is that for whatever pumping time the well yield and pump capacity allowed. The second is specific capacity over constant time, allowing for variable discharges and recovery times. A simple formula is proposed to include these variables:-

$$\frac{\frac{24}{P+R} \times P \times Q}{s} \quad m^3/day/m\ (m^2/day)$$

where P = pumping time in hours
R = recovery time in hours
Q = rate of pumping in m^3/hr.
s = drawdown in metres.

Where the terms are not divided by drawdown, one then also has the advantage of a value for well yield on a 24-hour basis, which can easily be compared with continuous falaj flows.

The variables which make up the above formula are easily measured, but are also of advantage for three other reasons. They are parameters which the well owner understands and on which he can usually provide information, as they are extremely important to him, affecting the cost of well excavation and the area of crops which can be irrigated. At the same time, they are factors which make it possible to compare a large number of wells regardless of pump types and outputs and of whether they can provide water for 24 hours or only for three or four minutes a day.

The third advantage is that the yields observed are the product of the usage required by the farmers concerned, and have mostly evolved from several years' pumping. They are, therefore, an expression of well performance very relevant to existing practices and of those likely to be adopted by the majority of farmers for the forseeable future.

There are two principal limitations to this approach. Firstly, the highest specific capacities could not be accurately determined. As visits to wells were of limited duration, drawdown data was generally obtained by ascertaining the length of time a well could be pumped before the pumping water level fell to the pump intake. On wells of highest yield, this level was never reached and where drawdown was still declining markedly or pumping could not be observed, depth to pump intake was used to provide a minimum specific capacity. Where this has occurred, mapped values of specific capacity have

plus sign after them to show that the true value is greater than that recorded,(that is, that yield was divided by depth to intake, but drawdown did not, according to the farmer, reach this far.)

Secondly, the data express well performance rather than aquifer characteristics. Transmissivity values calulated are approximate, and because the rate of change over time could not be recorded without interference, storativity could not be ascertained. While specific capacity data does not provide exact values of transmissivity, the two are closely related. High specific capacities signify high transmissivity.

iii). Transmissivity from Specific Capacity, Time Dependent Method.

Transmissivity (T) calculated by two methods using the data collected, produced comparable results which suggest that specific capacity, while being primarily a well characteristic can, in this instance, be regarded as a direct indication of transmissivity. The methods used were Walton's method and Logan's modification of the Dupuit equation (4). These are based on different aspects of observed well performance.

Walton, allows for the time dependence of specific capacity, Logan assumes steady state has been achieved.

Walton (3) uses the equation:-

$$\frac{Q}{s} = \frac{T}{264 \log \left(\frac{Tt}{2693 r_w^2 S}\right) - 65.5}$$

where $\frac{Q}{s}$ = specific capacity in gpm/ft.

T = transmissivity (US gpd/ft.)
t = time since pumping started in minutes.
r_w = radius of well in feet.
S = storativity here assumed as 0.2 representing water table conditions.

which in consistent units may be written $\frac{Q}{s} = \frac{4\pi T}{2.303 \log \left(\frac{4Tt}{r_w^2 S}\right) - 65.5}$

The equation, therefore, includes pumping time but, in the case of intermittent pumping when the well is dried up and needs time to refill, does not include a correction for the water stored in the well. This has been corrected here by making Q in the equation proportional to $\frac{\text{the volume pumped - the volume standing in the well}}{\text{the total volume pumped.}}$

Although a correction has been made, it is not of high accuracy in the poorer wells, where recovery times are much larger than pumping times.

While storativity is an unknown value, it is a logarithmic term within the Walton equation&a doubling in the value only increases estimates of T by less than 10%. This equation assumes the production well penetrates the total saturated thickness of the aquifer, well loss is negligible, and that the effective radius of the production well has not been affected by its excavation and development and is equal to the nominal radius of the production well. While the second of these assumptions is fulfilled, the third is not in those wells with varying radius, especially if collecting chambers are included. Such wells have, therefore, not been considered in attempting to quantify the transmissivities of a given aquifer. Neither is the first assumption usually met, so that the calculated transmissivities are generally

likely to be an under-estimate of the real condition.

In some instances, a well passes through more than one aquifer, although each must be of very small vertical extent for this to be possible. It is more common for a well to pass only through layers of varying permeability within one aquifer, except at the lateral extremeties, where beds thin out and interdigitate. Wells where this occurs, are not included in assessing the quality of individual aquifers, as the yields are the product of more than one aquifer and the effects of each could not be separated.

The advantage of the Walton method, is that it allows for the fact that specific capacity decreases with time, as the cone of influence of the well expands. Here, therefore, specific capacity is not a twenty-four hour yield, but purely the amount of water which can be abstracting during one pumping and allowing nominally for well storage. The advantage is that, unlike methods such as Turcan's (5), it does not require steady state - a condition which would seldom be fulfilled for water table conditions by the spasmodic daily pumping regimes of the farmers visited. (it is common practice to assume 2 - 14 days continuous pumping at constant discharge to reach equilibrium under unconfined conditions).

iv). Transmissivity from Specific Capacity Using the Steady State Method.

The resulting values were compared with transmissivity obtained by the Logan method (4) from the Dupuit-Thiem formula. This is based on the equation:-

$$Q = \frac{2\pi T s_w^1}{2.303 \log_{10} (R/rw)}$$

$$\text{so that} \quad T = \frac{Q \times 2.303 \log_{10} (R/rw)}{2\pi s_w^1}$$

in consistent units.

This can generally be simplified to $T = 1.22Q/ s_w$ without much loss of accuracy.

Where Q = yield

T = transmissivity

r_w = radius of the production well.

s_w^1 = corrected drawdown.

The correction for drawdown in unconfined aquifers, is

$s_w - s_w^2/2D$ where D = thickness of the saturated part of the aquifer.

as s_w in specific capacity terms equals unity and the aquifer is generally taken to be 10 - 30 metres thick, the correction will make 10% difference at the most. Kruseman and de Ridder (6) point out that this method of estimation may yield results which are erroneous by as much as 50%, and so the correction is not felt to be justified within the accuracy of the method (especially since D is unknown). Hence simple s_w as for a confined aquifer is used, and is likely to cause slight under-estimates of T, especially in the thinnest aquifers.

The major advantage of this method, is that where r_w nominally equals one metre (as is a reasonable assumption for hand-dug wells) R = 500 metres, (Muskat's (6) suggested value)and s_w is 1 metre , Q is expressed as specific capacity in m^3/day. It then follows that specific capacity and transmissivity are approximately equal values, since

$$T = \frac{Q \times 2.303 \log_{10}(500/1)}{2 \times 3.14 \times 1} = \frac{Q \times 6.22}{6.28} - 1$$

Thus, the figures of specific capacity can then be regarded as transmissivities as long as the assumptions in calculating a constant time (24 hour) specific capacity, hold true. There are two assumptions made when comparing wells using the constant time specific capacity formula proposed. One is that a well which has no perceptible drawdown at the end of eight hours pumping, will continue to exhibit the same behaviour if pumped at the same rate for a full day. The other is in the case of a well pumped dry and allowed to recover to the previous static water level. The well is then pumped dry again, forming a series of cycles lasting anything from half an hour to twenty-four hours. It is assumed this cycle or sequence of cycles can be repeated indefinitely within 24 hours if full recovery is allowed between each pumping. This does not, however, mean that the well has reached steady state and it is, therefore, important to see time dependent and steady rate derivations of transmissivity from specific capacity compare.

v). Comparison of Methods.

When the Logan constant time specific capacity method is used for calculating T, correlation is high, with those values calculated from Walton's method. The Araqi wells are chosen as an example, because of the virtual absence of collecting chambers and the wide range of values they exhibit (4 - 600 m^2/day). The mean of the two sets of data is identical at 93 m^2/day and the correlation co-efficient $r = 0.8$. While Walton's equation allows for changes in specific capacity with

time, an additional correction had to be made for well storage, as this particularly affected the lower transmissivities. The correction is, however, an arbitrary one, assuming constant well radius, but this problem is avoided in the second method by using a constant time specific capacity. This is because it takes account of water draining into the well over twenty-four hours, including recovery times, and so reduces the effect of the initial volume of water stored at the commencement of pumping. The high degree of correlation between the two methods, suggests that the assumptions of the simpler (constant time) method are no less valid than those for the Walton equation and may, therefore, equally well be used as a direct indication of transmissivities for this study. Maps of yield per day per metre drawdown are, therefore, presented to demonstrate variations between and within aquifers and may be regarded as an expression of transmissivity (figs. 5,3,7,11,15,19).

It should, however, be borne in mind , that the transmissivity values are likely to be under-estimated at the upper end of the range (over 1000 m^3/day/m) and over-estimated at the lower end (less than 20 m^3/day/m). Higher values are difficult to quantify accurately, as in highly transmissive aquifers, flow may commonly be turbulent, thus increasing head loss and so decreasing apparent transmissivity values even in conventional pumping tests. Flow net analysis is likely to give higher values. At the lower end, drawdown may still be on the steepest part of the curve and is not easily corrected accurately for well storage. Thus, drawdown may be under-estimated.

While specific capacities can be looked upon as an expression of a physical characteristic of the aquifer, they are also in practical terms an expression of well yield. Specific capacity, when combined with

well depth below standing water level, gives a measure of the maximum of water which can be extracted from the well and so of the amount of water the farmer has at his disposal.

B. Storage Co-efficients.

Storage co-efficients are less easily estimated. For calculation from pumping test data, it is necessary to be able to include changes in the rate of drawdown with time. Data is not locally available for this, and could not be obtained with sufficient reliability to exclude the effects of interference from other pumping wells and from returning irrigation water over a long enough period of time.

Another method of calculation is to take changes in volumes of water stored, obtained from falaj recession curves (8). This is compared with the volume of aquifer drained, obtained from aquifer surface area multiplied by the fall in water level observed within it. The ratio gives a value of storativity. While this was tried for several systems, it was found that the high frequency with which falaj sources are adjacent to low water sheds and points at which ground water divides are difficult to define, caused estimates of the volume of aquifer drained to be insufficiently accurate in most cases.

Within this thesis, the major application of storage co-efficients would be to calculate storage volumes and so to indicate the reliability of supplies. This can as effectively be done by the simple use of recession constants exhibited by free-flowing falaj systems, which obviates the need for including the terms of aquifer surface area and the change in overall water level which proved unsatisfactory. Study of

recession curves not only gives a measure of system reliability, but also may make it possible to quantify re-charge events, and to identify the contribution of individual tributaries where falajes tap more than one source. Falajes generally conform to the pattern exhibited by a shallow-entrenched stream only partially penetrating the aquifer, and thus, are found to follow an exponential decline which can be represented by a straight-line on semi-logarithmic paper.

III. MAJOR AQUIFERS AND THEIR DISTRIBUTION AND TRANSMISSIVITIES.

A. Lithologies and Depth to Water Table.

The vast majority of water is extracted from Quaternary and recent sediments of varying degrees of cementation and permeability. Both wells and falaj sources tend not to reach more than about 25 metres below ground level, or more than three or four metres below standing water level. Information is, therefore, mainly restricted to these levels, and data on deeper strata is extremely limited.

Four main aquifer types were observed to be particularly common within the area studied. These are, in order of decreasing transmissivity, uncemented or poorly cemented wadi gravels, hard calcareous conglomerates, recent sandy limestones, and silts or marls.

The pattern over the southward-draining wadi at Kabir is for the wadis of the mountain and middle wadi region (A and AD fig. 2.1) to be underlain by conglomerate, and for the water bearing formations only to diversify downstream towards the lower wadi region. It has been suggested that through chemical weathering, in association with outcropping peridotite, conglomerate may break down into a dense clay, but those clay and silt formations found in the Dhahira were mainly associated with weathering of the al Wahrah series, found chiefly in the lower wadi areas.

The most important aquifer, appears to be coarse, uncemented or poorly cemented gravels. These appear as clearly defined narrow lines, bordered by well cemented conglomerates and, as such, appear to fill relict wadi systems within the conglomerates. These lines are now buried under 10 - 15 metres of more recent fluvial deposits, and so cannot be identified from the surface or from the air. Never-

theless, they appear to be the major line for the transmission of ground water, acting as a submerged natural pipe network.

While similar buried channels have been found in a glacial landscape (11, 12), studies of alluvial fans, even those as detailed as Lustig (13), tend to provide little or no information on their occurrence in desert environments.

Within Oman, suitable conditions for their formation occur all along the southern edge of the Hajar mountains. To the North, Halcrows (14) found that in the Trucial States, despite evidence of their existence, they did not appear to have any effect on ground water reserves and, despite higher water quality, were not thought worthy of exploitation.

In Northern Oman, however, the submerged wadi gravels are of primary importance to existing water sources and have not previously been identified. They do not necessarily underlie the present active wadi, and only occur in the areas where the present wadis do not cover the whole floor of the basins and where the surface wadi appears to have changed course in the past within one valley, or moved to drain into an adjacent basin. (see p. 99). The alignment of these deposits has had a marked effect on water extraction, and would appear to have been recognised by early falaj builders and water diviners.

Falaj mother wells for all the largest systems, reach in the direction of these sub-surface gravels, as do the collecting chambers of many of the more recently excavated wells (see fig. 5.1). The yields to

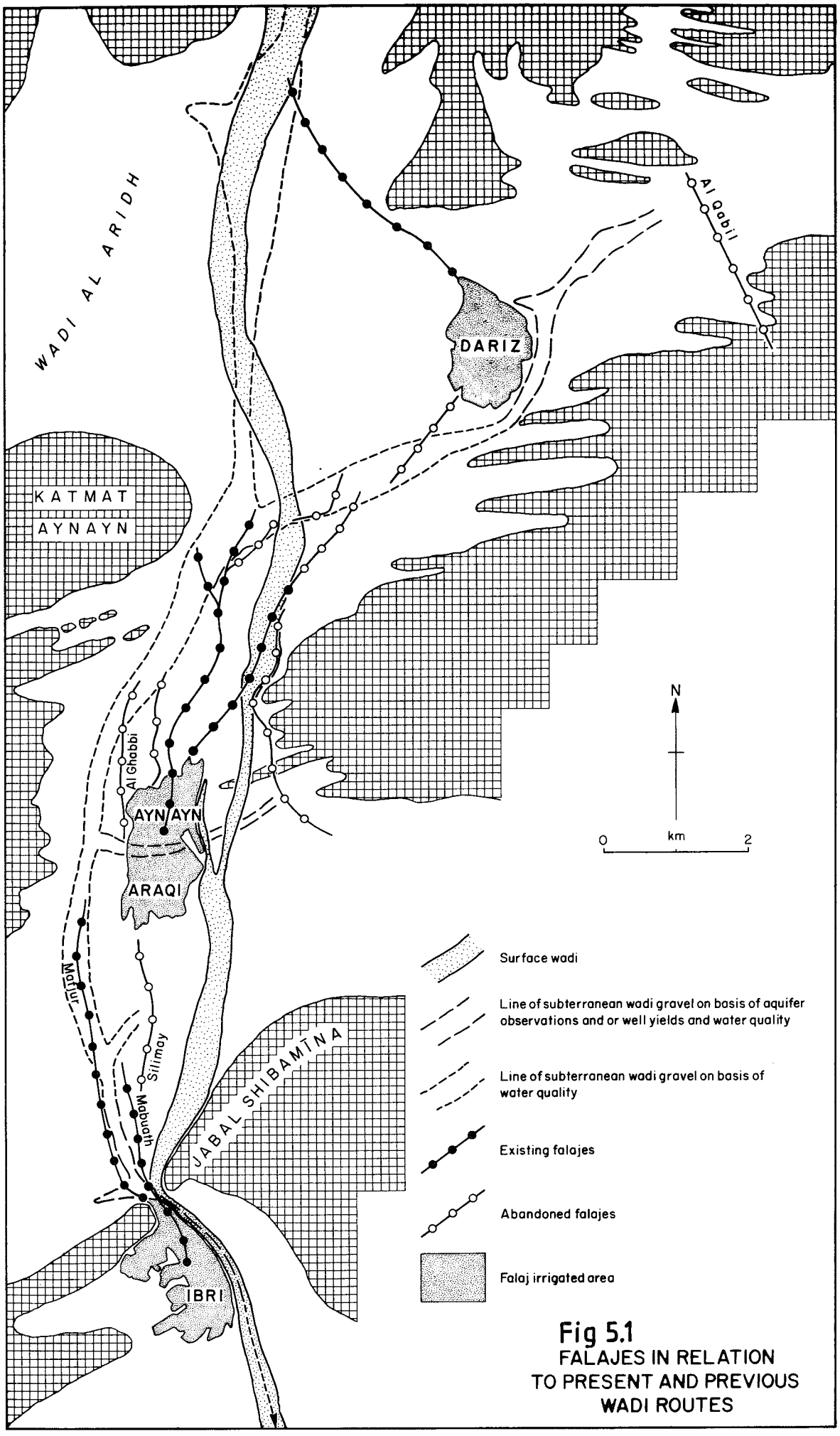


Fig 5.1
FALAJES IN RELATION TO PRESENT AND PREVIOUS WADI ROUTES

be expected from this aquifer, are high. Indeed, any well which penetrated more than about half a metre into it, obtains a supply that exceeds the pumping capacity of the 3" x 3" pumps used (1200 m^3/d.). At falaj mother wells, individual springs produce as much as 12000 m^3/d. No other aquifer in the area was found to produce such a yield. Similar gravels, but with more frequent cemented bands, provide a more widespread aquifer, which underlies all the Batina well gardens and provides them with a reliable supply.

In association with the uncemented gravels, are conglomerates of varying hardness and permeability. Characteristically, they are at their most conductive near the uncemented layers, though whether this is due to interdigitation of the two, or to associated development of pipe flow, could not be ascertained. There is, however, chemical evidence to suggest that cementation is now potentially active (see p.124). Conglomerate, the product of Pleistocene pluvials (page 95), underlines the unconsolidated deposits on the surface of present wadi systems back up into the mountains, and out into the desert foreland. Particle size in this aquifer is similar to that for the unconsolidated gravels at 0.2 cm. - 2cm., but permeability is reduced by the presence of carbonate cementing matrix.

Larger pebbles are found in the mountain conglomerates, reaching diameters of 15 cm. or more and here the matrix is in some cases harder than the pebbles contained in it.

It is the most widespread water bearing bed but varies in character and is often also found above the present water level. Flow within it is associated with development of pipes and less cemented layers as preferred paths of flow. Thus, two adjacent wells of differing depths, may have very different specific capacities, and collecting chambers are common. The horizontal layers of varying cementation, cause vertical permeabilities to be lower than lateral ones, so reducing infiltration rates throughout the area.

While the gravels exhibit consistently good yields, the red marls and siltstones always provide little water, and what there is, is generally of poor quality. While outcrops show numerous rock cleavage planes, and fractures, when wetted the rock tends to swell and break down, suggesting that below standing water level these paths of flow are likely to be compressed and so of low efficiency. This characteristic makes it difficult at times to differentiate whether a well shaft reaches shales and cherts or less cemented . While wells have been dug to tap water from this formation, it can scarcely be regarded as an aquifer, and wells such as 022 and 042 have been abandoned for lack of sufficient water, while four owners of wells in red marl north of Ibri have dug second wells to try and improve supplies to their gardens.

More limited in extent, are the recent sandy limestones. These are generally coarse; the pure white deposits being slightly less good aquifers than the pink layers, discoloured from association with red mudstones. Despite the high porosity found in the sandstones, the degree of recent, brittle cementation is sufficient to reduce permeability and the result is that they generally only exhibit well yields intermediate between the conglomerates and marls.

The gravels and marls retain their contrasting abilities to transmit water wherever they are found. The conglomerates and sandy limestones, however, vary in quality as aquifers in the different areas where they have been tapped.

The extent of these different deposits is examined in some detail because it has particular bearing on the future of methods of extraction.

Few settlements are at present sited with regard to the aquifers immediately underlying them, but owe their positon among other factors, to the gradient of land from a falaj source which is some distance from the centre of demand, so that the water has sufficient length of channel to be brought to the surface. The disposition of aquifers under existing settlements, therefore, has important bearing on the degree to which the communal falaj system can be replaced by individual sources on the property of garden and householders, and to the degree to which the cultivated area can be extended by well farming.

Depth to water itself imposes some limitations to abstraction. As shown in Chapter 7, pump outputs are related to depth to water and, in particular, to suction distance. This distance is, to some extent, dictated by fluctuations in static water level, and by the specific capacity reflected in the difference between static water level and the deepest level at which pumping occurs. Medium lift centrifugal pumps obviously cannot be sited lower than the highest level to which the water reaches after pumping.

Similarly, the logistics of falaj building as practised in this area, appear to require source water at no greater depth than about 20 metres. While much deeper mother wells are found in Iran, the Dhahira systems have never been driven so steep, even though tunnelling is commoner than the shallow trenching methods used in falaj building in the wadi Quriyat. Both falaj and well excavation costs increase with depth (see Chapter 7, Section III) as with hardness of rock encountered. Thus, depth to and nature of the aquifer and overlying layers are important factors in the economics of water abstraction.

B. Aquifer Distribution and Depth to Exploitable Water.

Areas for which a high density of information has been collected from wells, are the coastal strip and the areas associated with existing falaj irrigation, but where land elevation does not permit water from remaining falajes to reach. The latter have previously been watered by falajes which are now inoperative. In other parts of the Interior studied, the density of wells is lower, and although all wells were visited, the greater distance between points of information makes the extension of generalisations from particular sites less valid. Thus, information from the areas of high density have been mapped to show the distributions of characteristics investigated, while the low density information is discussed without recourse to maps.

i). Upper and Middle wadi Units.

In the mountains and upper wadi reaches, there are only isolated wells to indicate the large lateral and vertical variation in aquifer properties. 90%. of wells, numbering some 30, tap conglomerates. The remainder tap bedrock. In this part of the area surveyed, transmissivities vary enormously, but are mainly low seldom exceeding $100m^3/day/m$, and often being as small as $10m^3/day/m$. This, while partly reflecting the generally low hydraulic conductivity of the conglomerates, is partly due to shallow wells because of the small cultivable areas available. A farmer will not develop a well further than is necessary to provide him with enough water to irrigate his land. The data for this upper area may, therefore, not be strictly comparable with the downstream well-fields, and may give a slightly pessimistic impression of potential. Certain falaj mother wells, Magzi Bani Umar and Rīmay in particular, have conglomerate sources which provide a baseflow which is augmented at times by the

less reliable flows within the surface wadi gravels. While the Bilad Shahūm and wadi Bani Umar conglomerates seem to have pipe flow developed within them, the al Kabir cemented pebble beds are less permeable and specific capacities seldom exceed 50 m^3/day/m.

Since rocks other than Pleistocene and recent deposits tend to be aquecludes, or at best aquetards, the water table tends to be at its shallowest where older rocks reach nearest to the surface, but are overlain by gravels, which allow infiltration and so a certain storage of ground water. In the upper parts of the catchments, perennial surface water is common except in the Upper wadi al Kabir and wadi Kahanat. Here the gravel appears to be deeper and shallow without underlying cemented layers. This means that water cannot be pumped from the surface as it can be at Magzi Bani Umar or Sidādib and Rumayla in the Bilad Shahūm. Neither can it be diverted into ghayls such as those which supply the settlements above Ghayzayn in the wadi Hawasina, and the majority of those in the wadi Munqnyat. In this mountain area, all villages obtain their water from the surface and shallow gravels or from minor seepages and springs in the Semail rocks or along the unconformities between these and the Pleistocene conglomerates.

While, in the upper and middle wadis, wells mainly tap conglomerates this provides a misleading picture of homogeneity. Yields may vary according to the density of the conglomerate and the degree to which sand grains give way to silt and clay. Permeabilities vary over very small vertical and horizontal distances, and concentrated lines of flow (pipes) and more permeable horizons are a characteristic feature especially in the upper wadis. Thus, minor deepening of a well or tunnelling back of a spring may improve a well enormously. An exceptional example of this is well 435 at al Aridh. For three

years this tapped the upper part of a conglomeritic aquifer, with a specific capacity of some 74m^3/day/m. Deepening the well a further metre brought it to a level of pipe flow. The total yield of the well then increased from 354m^3/day to over 1050m^3/day. Yield was approximately tripled by only a 30% increase in depth. A diviner called into well 437 in the same area and with a specific capacity of 14m^3/day/m, predicted a similar layer 4.4 m. below the present well floor.

In the Hujrimat area, the conglomerate forms a particularly poor aquifer. Here the main wadi is associated with a small tributary in which Hayyal is situated and which consists mainly of a shale bedrock. The main bands and lenses within the conglomerate of the Hujrimat area may well be the product of weathering of these formations, and the nearest wells exhibit specific capacities of only 9 to 12 m^3/day/m.

Wells in the upper and middle wadis are not as numerous as those downstream, and are distributed over a wider area. Thus, the density is very low and the poor yields observed may purely be the result of a random and very thin distribution. Falaj sources prove that concentrated flows are to be found, but whether they are the result of siting nearer active wadis or of skilful divining in an area where few such sources occur, cannot be established with available information.

ii). Lower Wadi Units - Introduction.

Downstream, more land is available for cultivation and well farming by those in falaj settlements is on the increase (see Chapter 7 pt. II).

Wells are more common and tend to be in groups rather than as isolated individuals. In the neighbourhood of such groups, it is possible to obtain a wealth of detail enabling one to note the continuity of aquifers with a higher degree of reliability, and to compare the yields available from them. On the other hand, it means that little information exists on those areas where well farming has not developed. In general, these are the areas of low watersheds between catchments where ground water movement is likely to be slow, and the indications are of poor fine-grained sediments. Boreholes in the Ibri-Sulayf and al Aridh-al Kabir watersheds, indicate the poor potential of most of their area. It is possible, however, that relict buried wadis of limited lateral extent may still be found crossing these watersheds.

The other areas of poor information are those where depth to water exceeds the lifting capabilities of the pump types used at present. This applies particularly to the wadi Juffra, where water is only reached at 23 metres and therefore even the smallest drawdown would put the water beyond the reach of the 3" x 3" centrifugal medium lift pumps (see p371) Other areas where water is too deep include the gravel plain between the mountains and about 5 km of the coast, and possibly to lower wadi Munqnyat.

There are five areas for which detail has been obtained. Two, Dariz and Araqi are lower wadi settlements where tributary buried wadis are postulated as providing an additional local source of ground water. Two, Ibri and Sulayf, are typical gap settlements with wells both upstream and downstream of the gaps. These exhibit characteristics which are a combination of the effects of the gaps in the Tertiary limestone barrier, and of the aquifers which have been laid down in association with them.

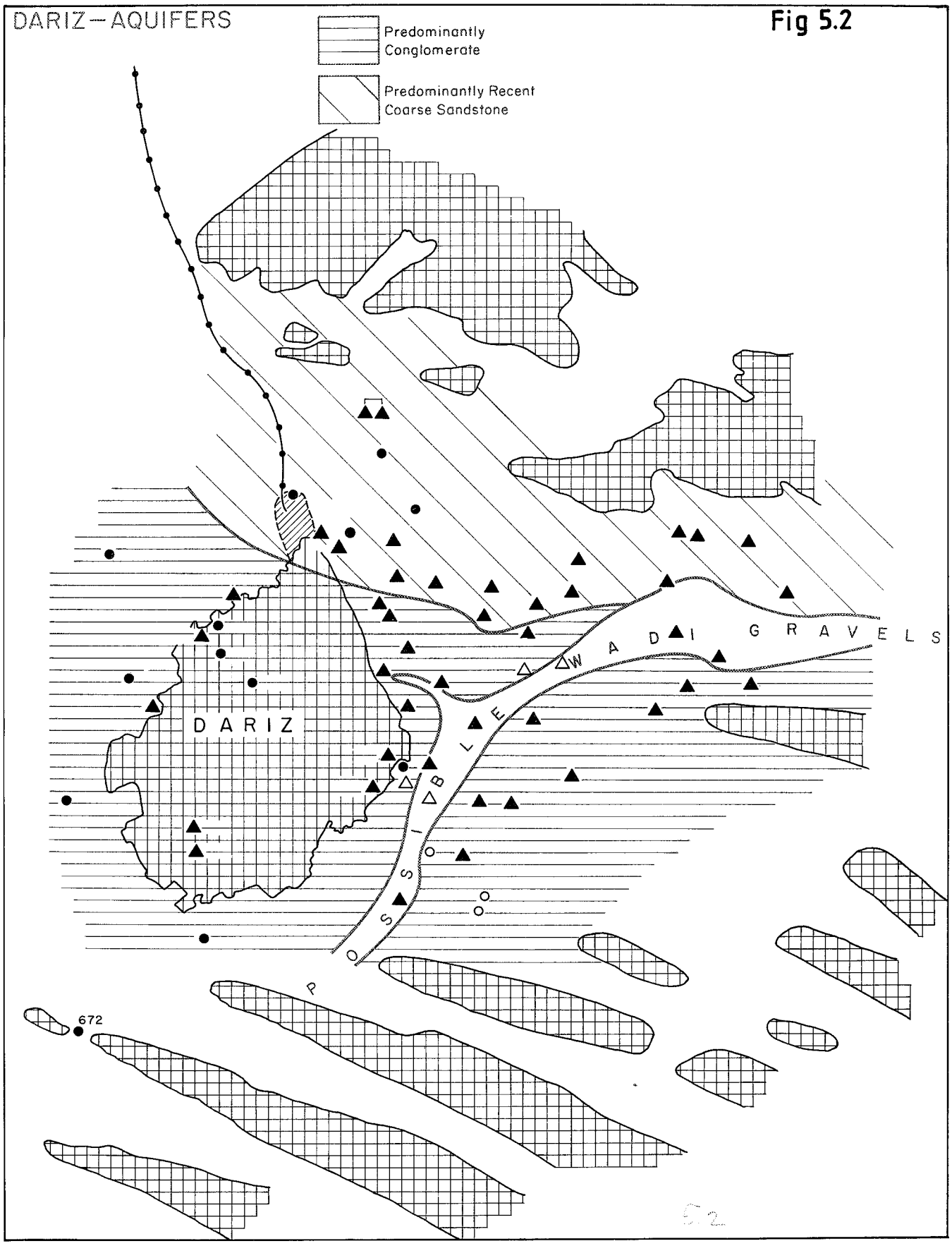
One, Tan'am, is an example of a well-field developed in the desert foreland. Each consists of more than fourty wells, which surround and, in some cases, penetrate falaj-watered date groves.

Darīz and Arāqi both lie on the east bank of the wadi al Kabir, and in both the falajes tap the main North-South groundwater flow of this wadi, postulated as a continuance of the submerged wadi gravels at Ibri. The wells, however, except in the western-most parts of both settlements, tap different sources, most of which appear to originate from other areas and to exhibit mainly an east-west component of flow.

C. Detailed Study of Local Areas.

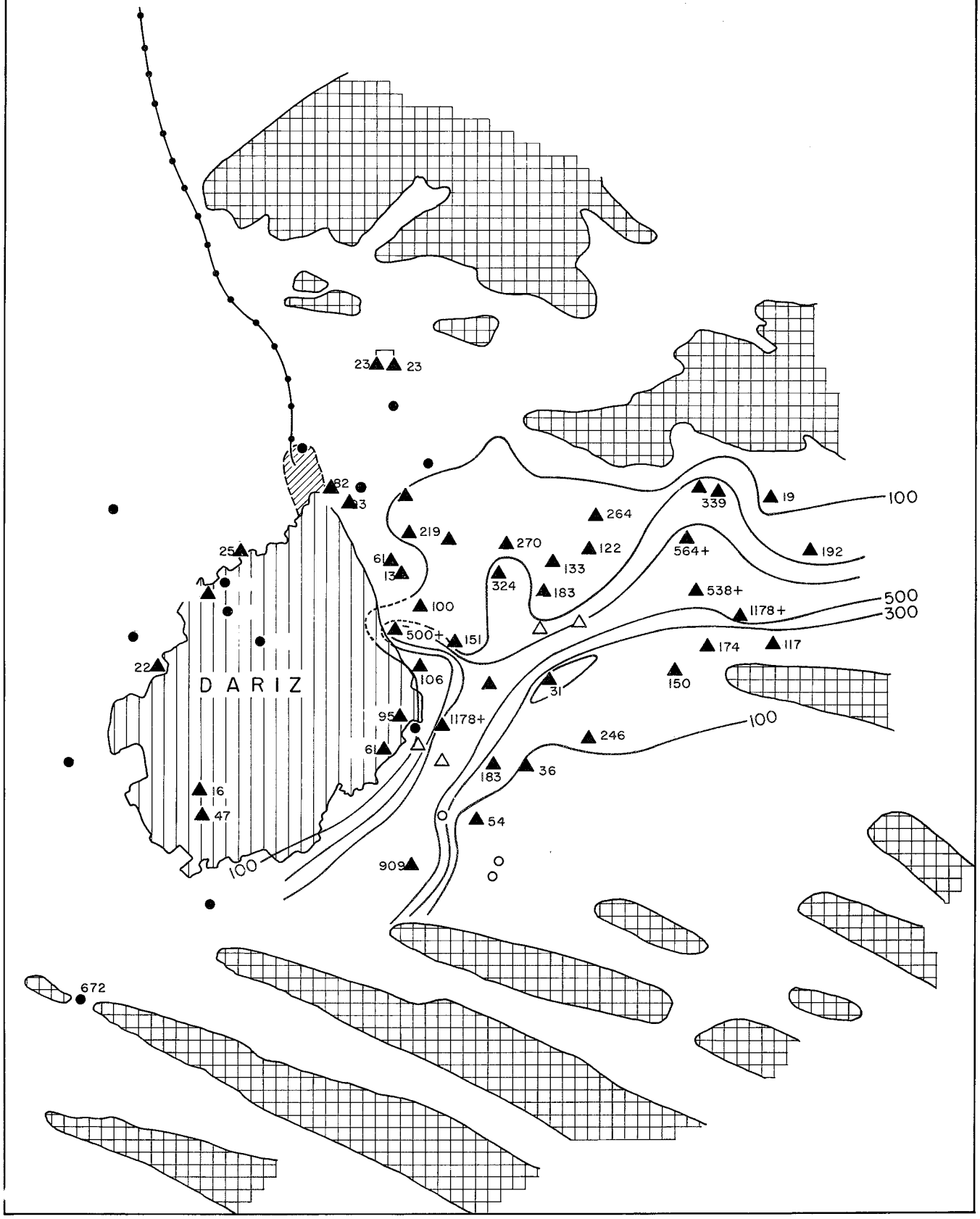
i). Darīz.

Darīz lies at what appears to be the site of the original junction of the wadi al Hijr and the wadi al Kabir (see p.103). Surface water has been naturally diverted through the al Wahrah hills but the information gained from the Darīz wells, suggests that a high proportion of al Hijr ground water may still find its way to the al Kabir. Conglomerate predominates to the South of an east-west line, which passes through the settlement just south of the main quarter. (see fig. 5.2). Around this line, the conglomerate is made up of increasingly fine particles and passes Northward into a brittle recent sandstone with large pores. Pump wells in this area are mostly adaptions of pre-existing zāgira wells (see p.365), so that the aquifer could not always be ascertained. There is a line of wells, two of which were known to have reached uncemented wadi gravels and all of which do not dry even at maximum pumping speeds (see fig. 5.3). The other wells in the line have never been cleaned down to bedrock in the lifetime of the present farmers and so the source of the water is not definitely known. There is, however,


DARIZ—AQUIFERS
Fig 5.2
Predominantly Conglomerate
Predominantly Recent Coarse Sandstone
DARIZ
WADI GRAVELS
SABLE
672

DARIZ – MAXIMUM YIELD PER METRE DRAWDOWN (in m^3 per day)

Fig 5.3



no other aquifer in the Dhahira, other than uncemented gravels, which has been found consistently to provide such a supply of water. It is therefore suggested that a band of these gravels may run down the East side of Dariz, joining the wadi al Kabir to the South of the settlement. This may be associated with a former route of the wadi al Hijr (see p. 103). It also, incidentally, appears to run from the area in which al Qabil falaj rose and towards the source areas of Mushaqasa and Aynayn falajes.

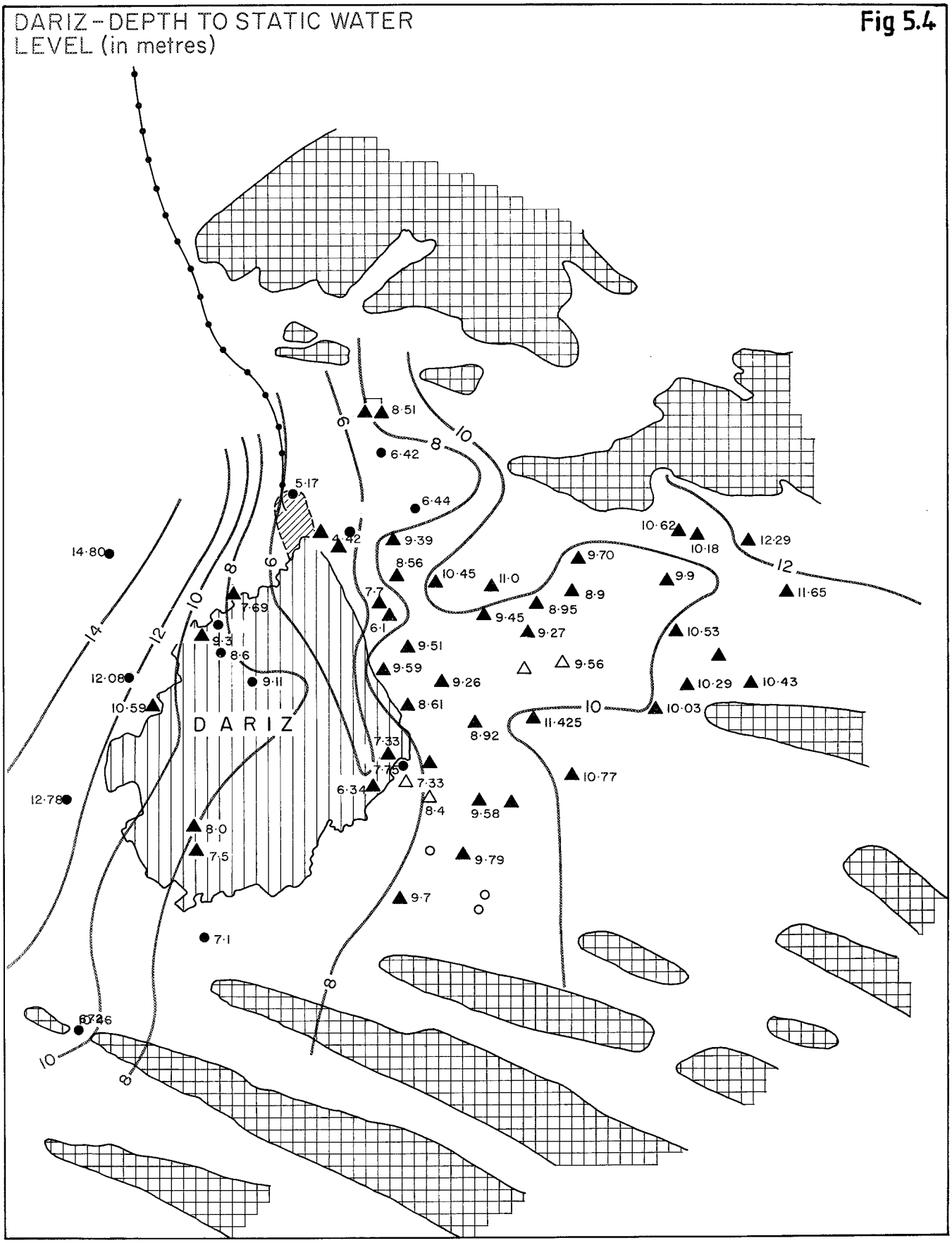
Except in the Northern area where the recent white sandstones merge into pink sandstones associated with the al Wahrah formation, the majority of wells tap a conglomeritic aquifer, the quality of which falls away in all directions from the line of maximum specific capacity. In places the conglomerate is associated with well cemented sandstone lenses (as at 626, 640, 629).

Around Dariz, the patterns of estimated transmissivity (see fig. 5.3) do not seem to be particularly affected by position within either conglomerate or sandstone. Analysis of variance (one-way) indicates no significant difference between the two groups at the .01 level. Most of the wells not on the line of highest specific capacity, lie in the range of 100 - 300 m^3/day/m, to the East of Dariz. This area is bordered to the North, West and South-East by wells with values of less than 100 m^3/day/m. In one case (447, 448), two wells each produced such poor amounts of water individually that they were joined by a tunnel and are now used as one well. Even in combination they can only produce 23 m^3/day/m, exhibiting the fact that even a doubling in well radius only increases yield by less than 10% (see equation p.214).

Water reaches to within 4.5 m. of the surface at Dariz (see fig. 5.4). To East and West of the settlement, distances to water increases, with

DARIZ – DEPTH TO STATIC WATER LEVEL (in metres)

Fig 5.4



isolines running approximately North-South, except in the North-West where possible interference from the wadi al Hijr occurs. Although altimetry readings do not exist and therefore exact figures cannot be given, the land must fall away in all directions to the South of the quarter along the North-South axis of Dariz, in order that the falaj may irrigate the fields. It is interesting to note that, in contrast to this trend in the land surface, the water table is at its nearest point along this axis. There must, therefore, be an up-coning in the water table along this line, and this would appear to be associated with the return of the falaj irrigation water to ground water reserves.

In terms of distance to maximum pumping level, the gradients and patterns apparent in depth to standing water level are not in evidence (see fig. 5.5). The majority of wells pump from 11 - 13 m. Those wells which have had to do the least digging below SWL are those on the line of maximum specific capacity, postulated as a line of submerged wadi gravels. Conversely, the wells in the palms which tap a conglomerate of poor transmissibility, although in an area where the water table is nearer, have to pump from just as deep because of the lower specific capacities. They have been excavated as much as 5 or 6 m. below SWL to obtain sufficient water for irrigation requirements. What on first appraisal seems a good area for wells with water close and conglomerate beneath, turns out to be a very expensive choice and unsuitable for irrigation wells except, as in this case, where irrigation is limited to a small area of land, and replaces costly falaj water.

Without accurate surveying of ground level and well datum points, the pattern of water levels cannot provide information on directions of ground water flow, but the patterns of aquifer characteristics support the theory of the junction of two wadi systems (see p.103), despite the diversion of surface water. This is further indicated by water quality patterns

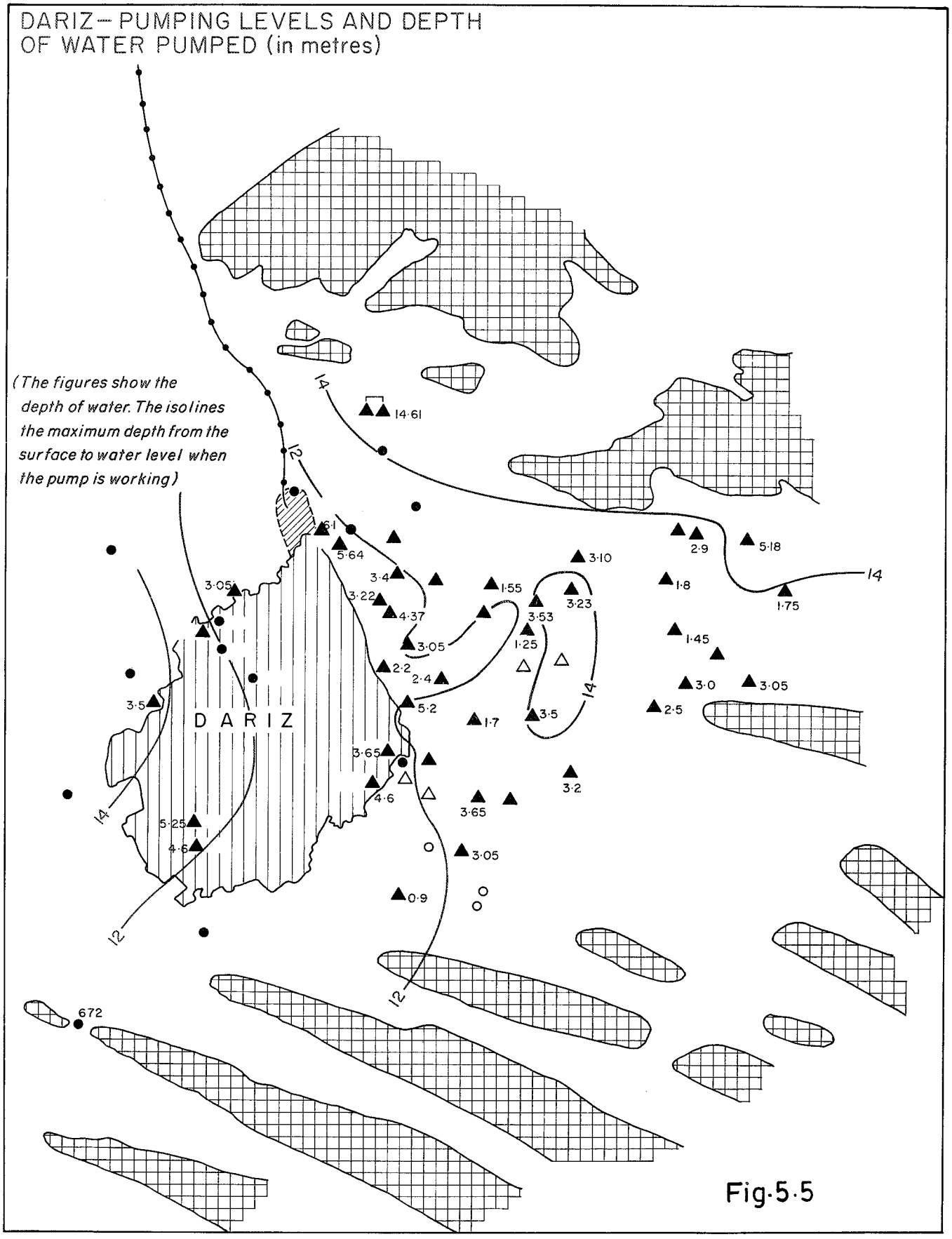

DARIZ – PUMPING LEVELS AND DEPTH OF WATER PUMPED (in metres)
(The figures show the depth of water. The isolines the maximum depth from the surface to water level when the pump is working)
DARIZ
14
12
14.61
5.64
3.4
3.22
4.37
3.05
2.2
2.4
5.2
3.65
4.6
3.05
0.9
1.55
3.53
1.25
3.23
3.10
1.7
3.5
3.2
3.65
2.9
5.18
1.8
1.75
1.45
3.0
3.05
2.5
3.5
5.25
4.6
672

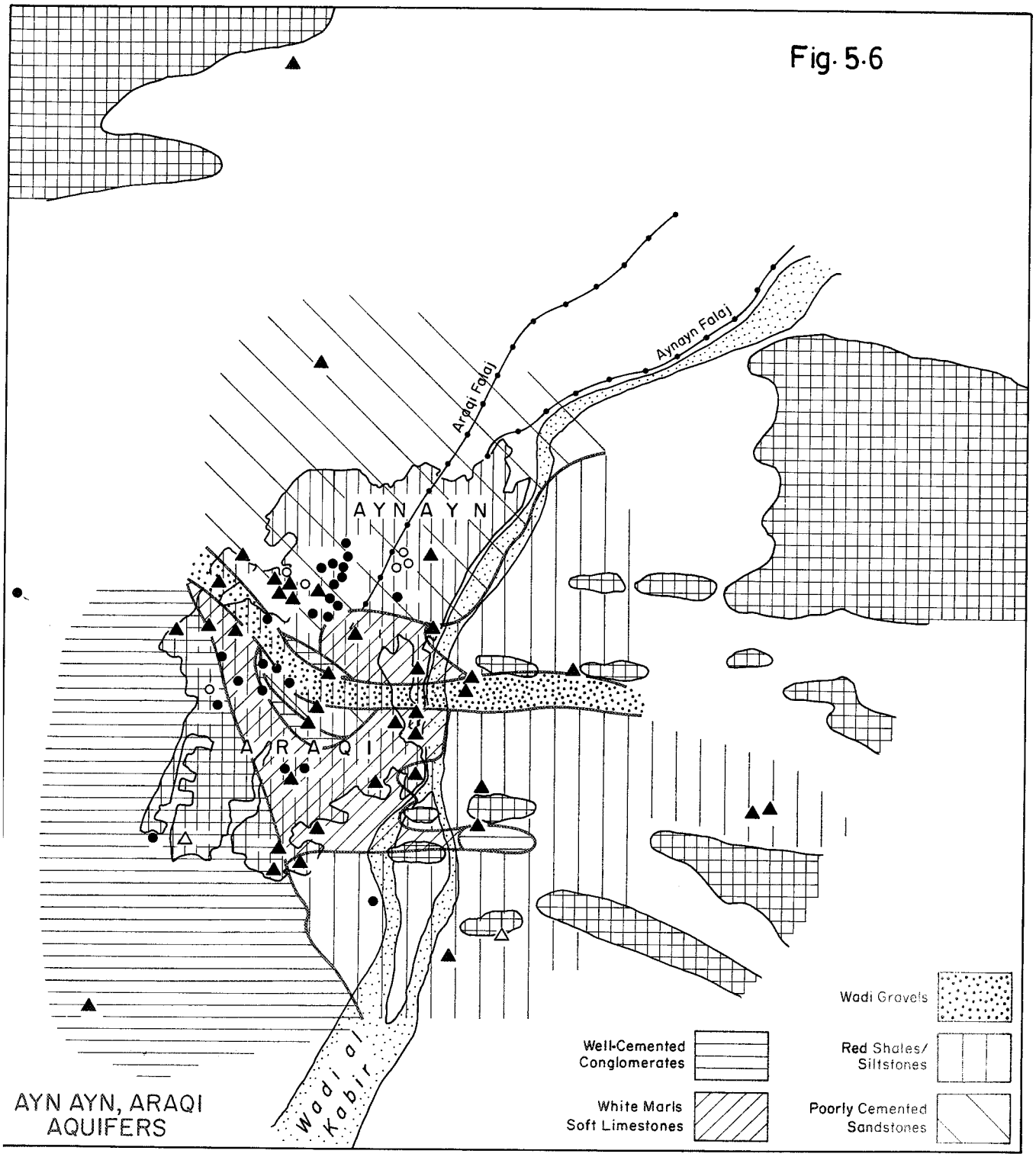
Fig.5.5

(see fig. 3.15). The use of high transmissivity indicated running to the East of the village, appears to be a relict of the original surface wadi system. It is of special importance, as estimated transmissivity falls off away from this line, so that beneath the falaj-irrigated land, which lies on the wedge shaped watershed between the ancient confluence of the al Kabir and al Hijr, well yields are very much lower, discouraging the replacement of falaj water by wells in the date gardens.

ii). Arāqi - Aynayn.

Similar conglomerates to those at Darīz are found to be west of Arāqi-Aynayn and continue on down towards Ibri in an ever-narrowing band. While Arāqi/Aynayn has some 31 pump wells, the number of aquifers tapped is greater than at Darīz (see fig. 5.6) and several wells tap more than one aquifer. Thus, the characteristicsof each can only be indicated at the very lowest level, as there are so few representative samples of any one category. Even using small sampling theory, no statistical significance can be attached to the observed results. For aquifer distribution, however, domestic wells provide additional information but cannot contribute data on their characteristics.

As in Dariz, a narrow belt of submerged gravels is an important feature, providing the only unrestricted source of water using existing pumps. The gravels bisect the falaj-irrigated area and run approximately East-West. Unlike Darīz, they are identifiable in every well on this line, including two without pumps. Originally, all the wells for irrigation had unlimited pumping, with specific capacities of 700 m^3/day/m or more. In 1974, however, the yield of one well (491) was considerably reduced, so that instead of unlimited extraction at 13 l/s, the pump could only be run for 4 hours at this rate, and then had to wait 15 minutes


Fig. 5.6
Arqat Falaj
Aynayn Falaj
AYNAYN
ARAQI
Wadi al Kabir
Wadi Gravels
Well-Cemented Conglomerates
Red Shales/ Siltstones
White Marls Soft Limestones
Poorly Cemented Sandstones
AYN AYN, ARAQI AQUIFERS

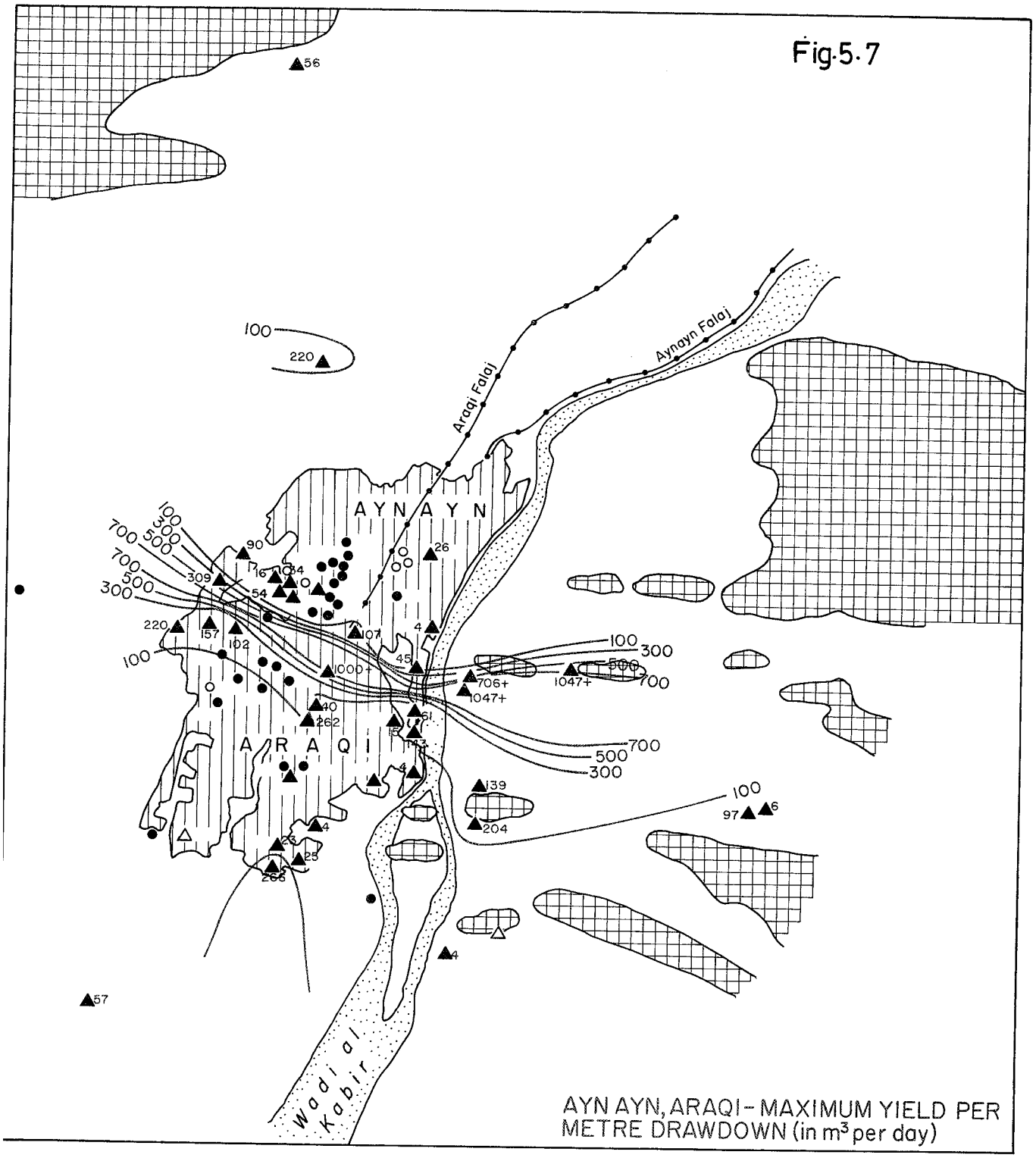
for recovery. This represents a 50% change in specific capacity and reflects a decline in transmissivity from de-watering with a fall standing water level of 2.4 m. As the other wells tapping the gravels have suffered no reduction in yield, this suggests that 491 may be on the edge of the belt of the most productive aquifer.

As in the upstream wells of Dariz, conglomerates appear to be less conductive towards the West (see fig. 5.7). An extreme example is that of a drinking well on the edge of the palms near al Ghabbi fort, which has been deepened several times but still dries in summer if even only three or four households collect water from it. A pump well nearby has been abandoned because of its poor yield.

At its edge, the layer of conglomerates is underlain by white marls and soft limestones, so that some shallow wells, though in the area where these strata occur, may not reach through to them, as sufficient water is obtained from the conglomerates. Others, such as wells 489 and 495, tap both levels. Average specific capacity is 140 m^3/day/m within the conglomerates.

When average extraction rates are combined with the observed transmissivity values, it appears that the theoretical effect of each well in the conglomerates reaches a radius of 36 metres after two hours pumping, when drawdown at the well will have reached 3.2 metres. The well is then usually allowed to recover before further pumping. There is, therefore, little interference between wells. There is, however, constant recharge to this area from returning irrigation falaj water, so that actual drawdown and extent of the cone of influence may be reduced.

Fig.5.7


56
100
220
Araqi Falaj
Aynayn Falaj
AYNAYN
ARAQI
Wadi al Kabir
57
AYN AYN, ARAQI - MAXIMUM YIELD PER METRE DRAWDOWN (in m³ per day)

To the North of the settlement, in the area watered by Aynayn falaj, lie poorly cemented sandstone and siltstones, similar in lithology to those found at Dariz. They are not, however, as conductive as those to the North, and specific capacity nowhere exceeds 100 m^3/day/m (averaging 43 m^3/day/m) within the area near the groves. Wells tapping the white marls and limestones to the South of this group are equally poor, with an average specific capacity of 42 m^3/day/m.

To the East of the settlement, mudstones and shales derived from the al Wahrah formation underlie the gravel terraces which flank the present wadi. The shales are red, easily fractured and are tilted almost vertically, as are the bedded mud and siltstones. These latter strata are up to a metre thick, with yellow and brown staining. It is these bands of more thickly-bedded rock which transmit the most water, although neither are very productive aquifers. Estimated transmissivities are as small as 4 m^3/day/m in the low-lying shales between the ridges of vertically bedded mudstones. In the latter, forming low longitudinal hills, maximum yields rise to around 100 m^3/day/m.

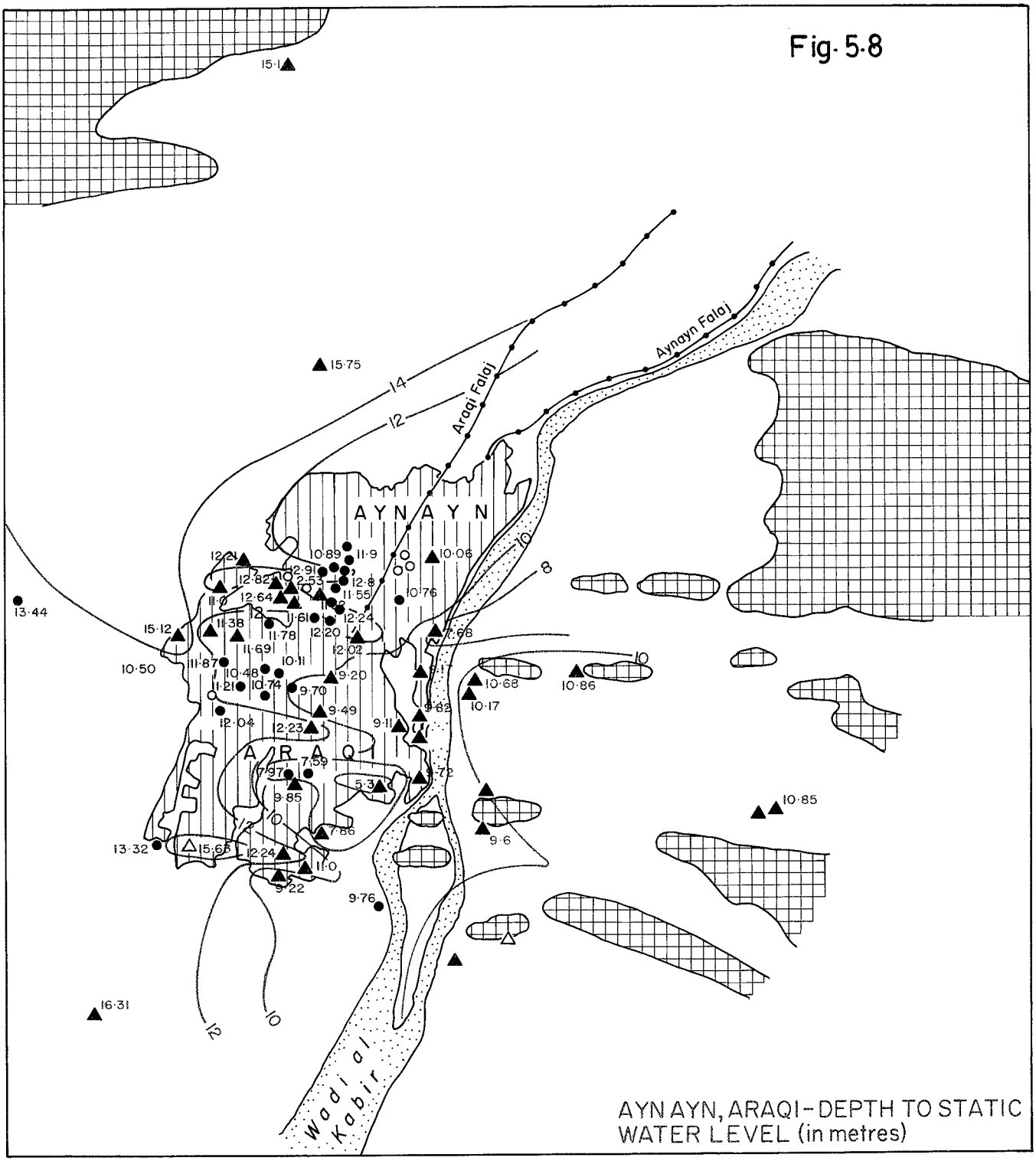
A borehole to the East of Araqi (near well 611) was drilled for 58 metres, and produced 63 m^3/day/m for an unrecorded drawdown. For the greater part of its depth, the hole was drilled through red shales, and finally reached a green, poorly consolidated mixture of marls, sand and gravel in which very little water was found. It appears, therefore, that at least at this point, no better aquifer immediately underlies the red shales derived from the al Wahrah formation. At Araqi, the siltstones and the uncolsolidated gravels are at opposite ends of

the scale for potential well development. Between these two, lie the other aquifers identified, whose yields vary greatly but within the same range so that they may be classed together. While the wadi al Kabir's North-South flow dominates the western part of the settlement, East-West flow appears to be more important to the East. Local people themselves suggested this was so, and the pattern of aquifers tends to confirm that ground water from the longitudinal hills to the East (possibly an old line of the wadi al Ayn) flow westwards, beneath the present wadi and the groves turning South.

North-South trend to isolines of depth to SWL is apparent (see fig. 5.8), but here this trend is also complicated, apparently by an East-West factor. This is parallel to the finger hills which flank Araqi to the West. In contrast to Dariz, the falaj appears to have no visible effect on the SWL, the topography around the present wadi being a more significant factor. In general,depth to the water table increases to the west and to the south of the settlement.

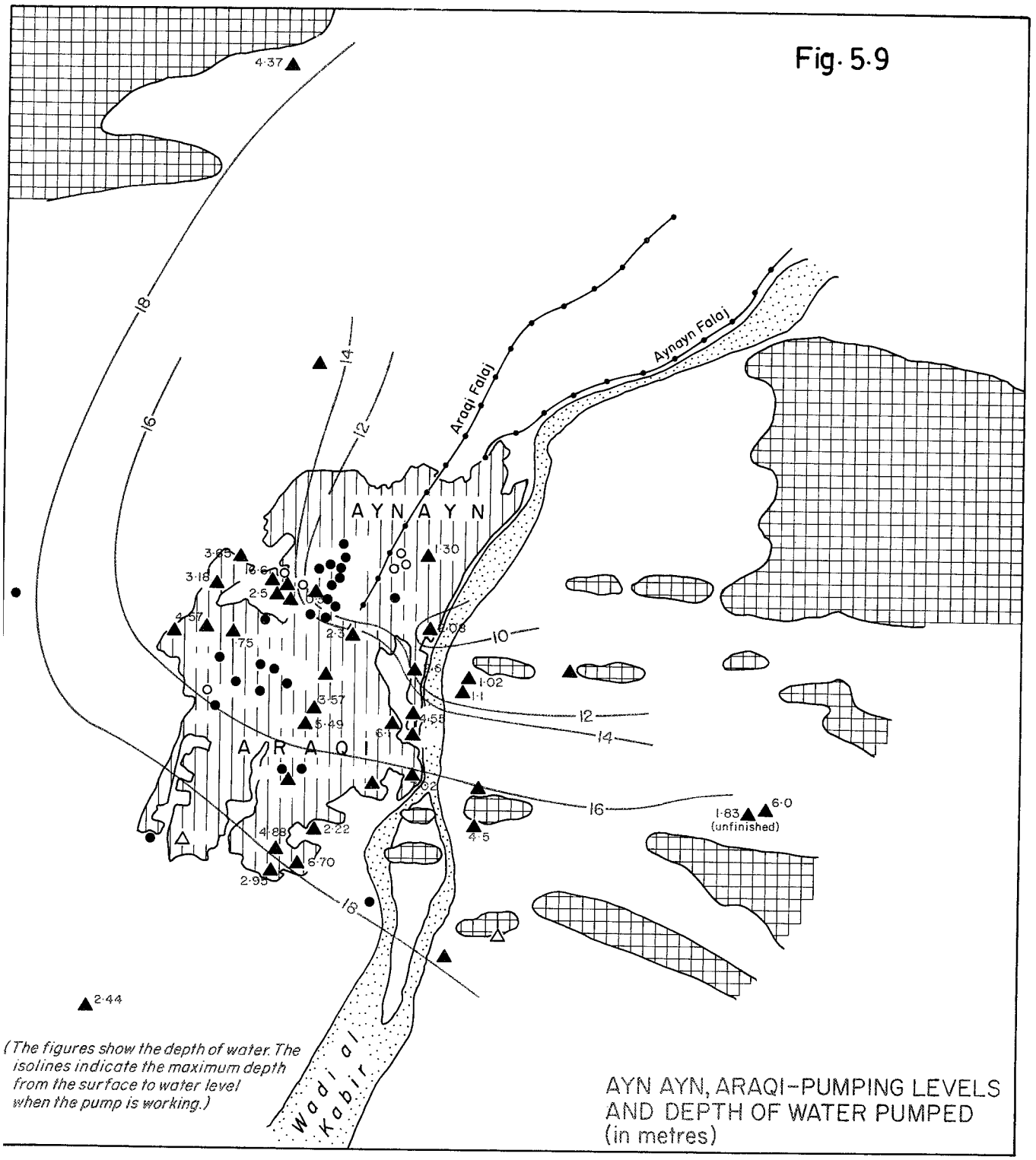
As in Dariz, the excavation to maximum pumping depth, changes the trend of isolines to an East-West one. The sample number is less, so that the pattern is somewhat simplified but, in general, the depth to the well floor from the surface increases as one moves South (see fig. 5.9). As this is also moving into the area of conglomerates, well development in this area would be expensive - apart from the more political drawbacks of this area. As pumping levels to the West and South exceed 18 m., extraction in this area is limited to less than 60 gpm (4.6 l/s) using present pump types even before considering aquifer characteristics.

Fig. 5.8



AYN AYN, ARAQI – DEPTH TO STATIC WATER LEVEL (in metres)

Fig. 5.9



(The figures show the depth of water. The isolines indicate the maximum depth from the surface to water level when the pump is working.)

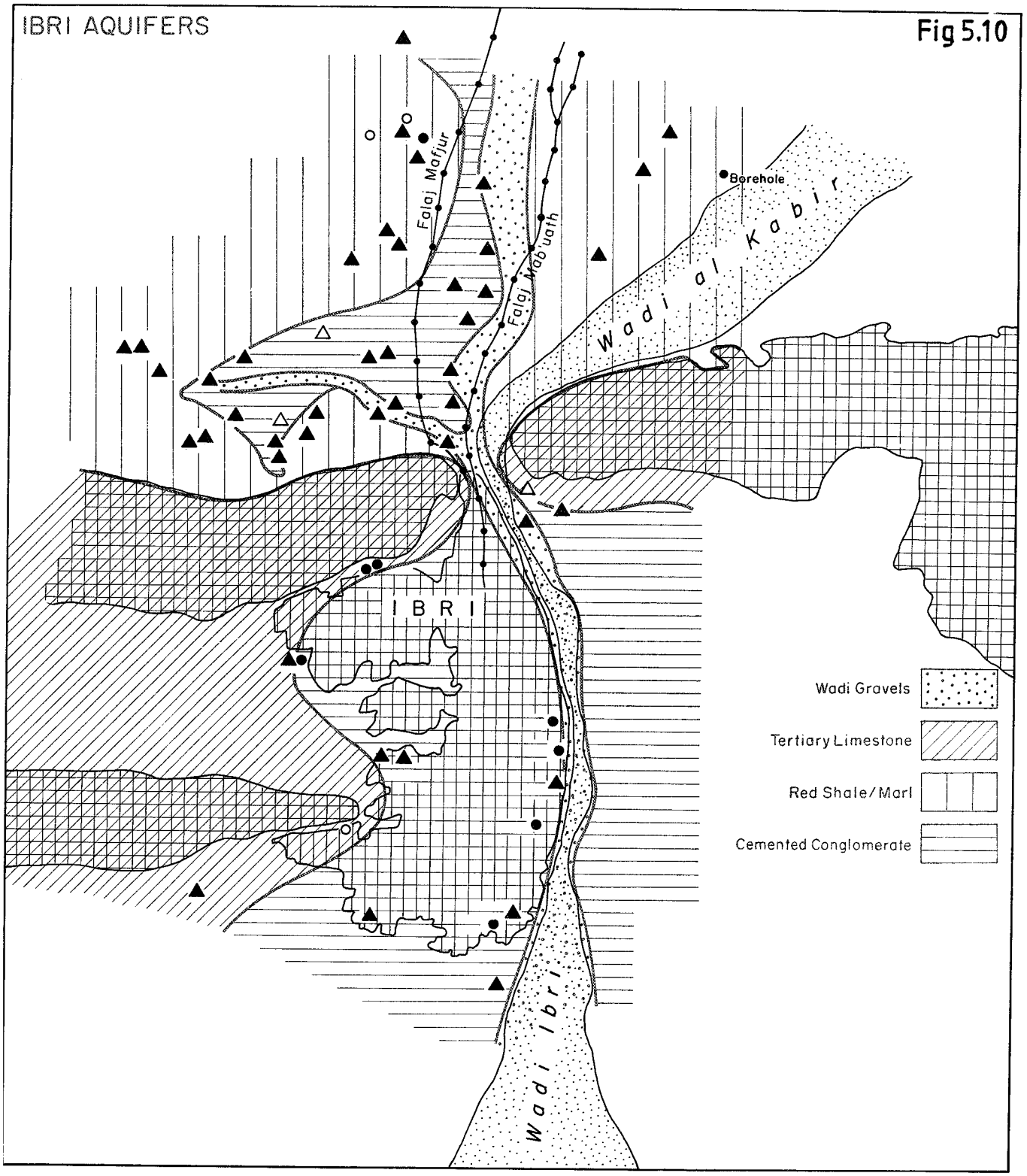
AYN AYN, ARAQI–PUMPING LEVELS AND DEPTH OF WATER PUMPED (in metres)

Downstream of Araqi, the two gap areas differ markedly. The gap postulated as being the most recent, is that at Sulayf and here recent deposits are confined to gravels which are cemented to varying degrees.

iii). Ibri.

At Ibri, on the other hand, the variety is greater (see fig. 5.10) and the submerged wadi gravels found at Dariz and Araqi, are clearly defined. They are flanked by conglomerates and then mudstones and marls derived from the al Wahrah formation which, in turn, lie against tertiary limestone bedrock. Such a contrast with Sulayf suggests a different set of climatological and base-level conditions during the formation of each. The gravels are again the best aquifer, providing yields which exceed the pump capacities. Red shales and marls are consistently poor transmitters of ground water. The conglomerates exhibit values intermediate to the two types and, despite a wide range of yields (from 4-500 m^3/day/m) differ significantly from both the marls and shales and the gravels at the 0.1 level on the basis of a two-tailed test.

The buried wadi gravels run North between the two Ibri falajes and from the direction in which the gravels and Mafjur run and the patterns of water quality (see p. 134), it would seem that this aquifer is probably the source of Mafjur water. Dariz and Araqi falajes also cross the wadi al Kabir to gain water from the western side, which suggests that the gravels continue up this side of the wadi. The estimated transmissivities range from 750 to 1500 m^3/day/m for this aquifer.


IBRI AQUIFERS
Fig 5.10
Falaj Mafjur
Falaj Mabuath
Wadi al Kabir
Borehole
IBRI
Wadi Ibri
Wadi Gravels
Tertiary Limestone
Red Shale/Marl
Cemented Conglomerate

Unlike the other areas of submerged gravels, in the Ibri area, it is possible to identify two separate wadi deposits. One is the major North-South line which runs parallel to the falajes, and the other is a West-East branch. The latter has pink gravels which are associated with the tributary wadi to the west. The conglomerates can similarly be divided into those from the same two origins. West of falaj Mafjur the rock contains rock fragments traceable to the mesa formation in the western tributary through which runs the road to the wadi Juffra and Dhank. This variation seems to have little overall effect on specific capacities, but in the loose gravel aquifer, the values on the main wadi are higher than from those on the tributary.

The conglomerate North of the gap is of variable quality as an aquifer, but is in general better than the conglomerates found further upstream in the catchment. Specific capacity averages 285 m^3/day/m (S.D. = 132) with the highest values being found nearest to the buried wadis. South of the gap the aquifer is only tapped by 4 wells, 3 of which are near the present wadi. Especially at well 332, the conglomerate has large well-connected pores and, at some levels, appears to be more like a breccia with very crystalline cementation. Specific capacities are higher at 380 m^3/day/m, but this gives perhaps a too optimistic view of the aquifer in this area, as well 025 has been abandoned since the springs which provided it with approximately 4 m^3/day/m dried up after being temporarily plugged with cement.

The isoline for 100 m^3/day/m, is very nearly the same as the boundary to the red shales and marls which border the gap to East and West (see fig. 5.11). This is an extremely poor aquifer, with an

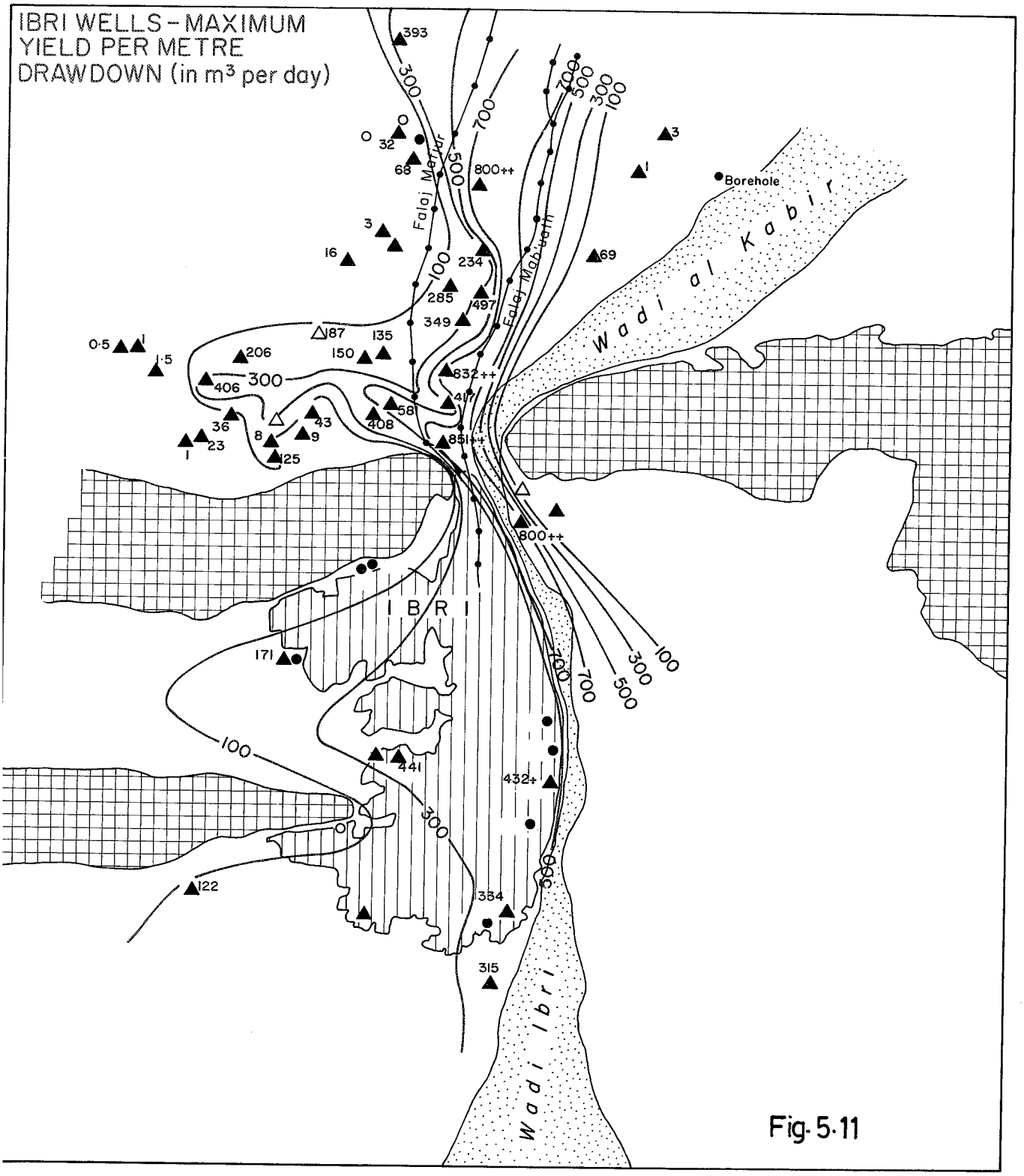

IBRI WELLS – MAXIMUM YIELD PER METRE DRAWDOWN (in m³ per day)
Falaj Mettar
Falaj Mabkhah
Wadi al Kabir
Wadi Ibri
IBRI
Borehole
393
300
700
500
300
100
0
32
68
800++
3
1
69
16
234
285
497
349
87
135
150
206
406
832++
417
58
408
36
43
8
9
23
1
25
851++
0·5
1·5
800++
171
100
441
432+
122
384
315

Fig. 5.11

average specific capacity for the 14 wells observed, of 19 m^3/day/m. The borehold drilled by Arab Development at 536, is 54 m. deep with 36 m. of water, but even this only has a maximum yield of 108 m^3/day.

Drawdown is not known. With indications of this poor aquifer extending well beyond the depth suitable for medium lift pumps, it is apparent that deepening of wells tapping this stratum, is unlikely to give much return for efforts expended, beyond increasing well storage.

There are only two wells dug in the tertiary limestones, of which the barriers to the gap are composed. Both have yields of over 100 $m.^3$, but the expense of digging in this extremely hard, crystalline rock, discourages well-development in this area, and further improvement of existing wells. Excavation involves 'burning' the rock to open up cracks and make rock brittle and is a skilled and expensive job.

The gap itself has a marked effect on the area to the North, and its formation would seem to precede the establishment of the pattern of gravel and conglomerate aquifers. Water levels are also much affected (see fig. 5.12). If it is taken that the wadi flows through the lowest part of the gap, and is bound to have a downwards gradient in the direction of flow (southwards) there appears to be a ponding back of water behind the gap, the orientation of which is not particularly related to the alignment of the present wadi, but seems to be associated with the conglomerate and gravel beds. In contrast to Darīz and Arāqi, depth to water increases in the less transmissible shales, which surround the gap, as the land rises and distance for the structure of the gap increase and its effects decrease. As surface relief is so much more pronounced in this area than in the wadi areas to the North, this appears to over-ride any effects of underground variation in rocks, except for that of an apparent barrier in the gap itself, and a rapid fall-away of the water table to the South of the gap.

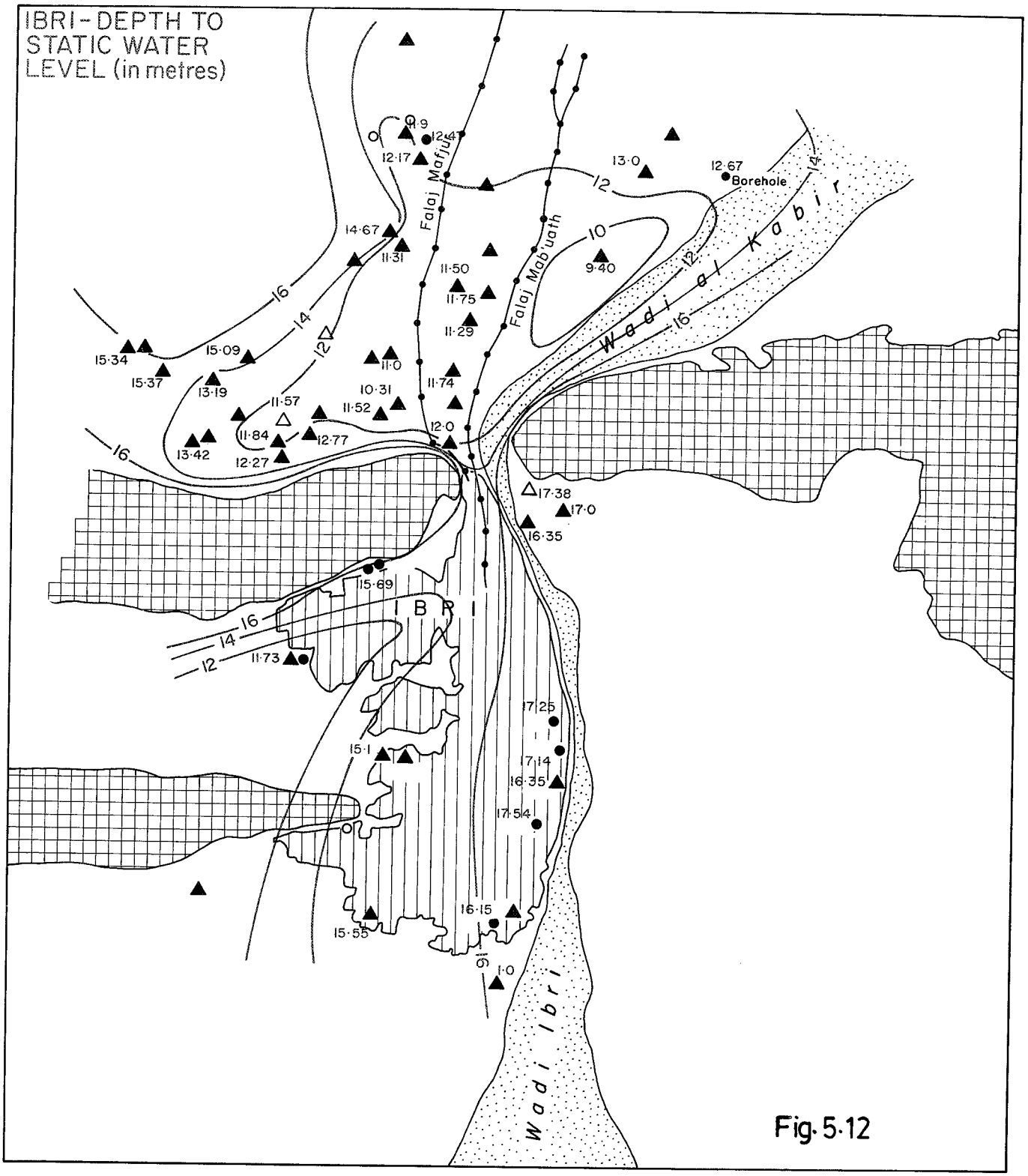

IBRI - DEPTH TO STATIC WATER LEVEL (in metres)
Falaj Mafjur
Falaj Mabuath
Wadi al Kabir
Wadi Ibri
IBRI
Borehole
12·9
12·47
12·17
13·0
12·67
14·67
11·31
11·50
11·75
11·29
9·40
15·34
15·37
15·09
13·19
11·0
11·74
10·31
11·52
11·57
11·84
12·77
12·27
13·42
12·0
17·38
17·0
16·35
15·69
11·73
17·25
17·14
16·35
17·54
15·1
16·15
15·55
1·0
16
14
12
10

Fig. 5·12

Pumping levels follow much the same pattern but with a wider range of depths (fig. 5.13). The shallowest wells are those in the conglomerates and wadi gravels North of the gap, but none have a great depth of water except for 540 and 527 in the red shales. South of the gap, depths of water are small. In this area, the wells dug so far, bar 025, have all found sufficient supplies of ground water, within a short distance of the water table. This is fortunate, as depth to water is generally over 14 m. in hard conglomerate or limestone, so that considerable expenses are incurred even before water is reached.

The effect of aquifer type on well development around the Ibri gap, is examined in more detail than at Dariz and Araqi, as the number of types and the range in transmissivities of each, is smaller. The main effects are on well yield and spacing depth of well below rest water level, and pumping routines. Average estimated transmissivities for the three principal aquifers, are as follows:-

Conglomerate	285 m^2/day.
Gravels	970 m^2/day.
Red Shales and Marls	19 m^2/day.

The depth of well below standing water level in each of these aquifers seldom exceeds 2 metres, 3 metres and 5 metres, respectively (see fig. 5.13).

Rates of extraction which cause greater drawdown than these levels, within an average six hour working day, will require intermittent pumping allowing a degree of recovery between workings.

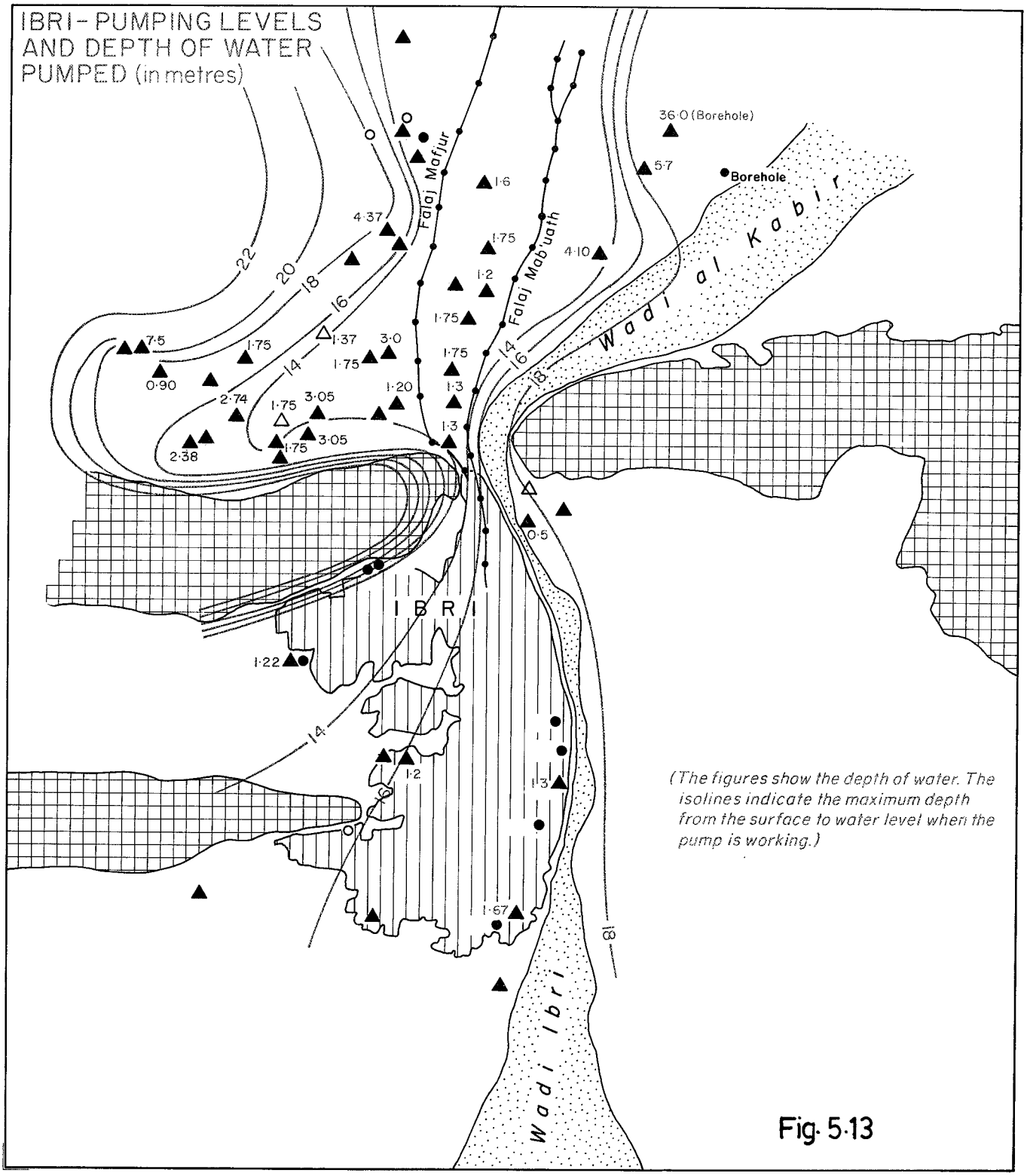

IBRI - PUMPING LEVELS AND DEPTH OF WATER PUMPED (in metres)
Falaj Mafjur
Falaj Mabuath
Wadi al Kabir
Wadi Ibri
IBRI
Borehole
36·0 (Borehole)
5·7
4·37
1·6
1·75
4·10
1·2
1·75
1·37
3·0
1·75
1·75
7·5
1·75
0·90
2·74
1·20
1·3
1·75
3·05
1·3
1·75
3·05
2·38
0·5
1·22
1·2
1·3
1·67
22
20
18
16
14
14
16
18
14
16
18
(The figures show the depth of water. The isolines indicate the maximum depth from the surface to water level when the pump is working.)

Fig. 5.13

Using the equation $$s = \frac{2.303 \times Q}{12.6 \times T} \times \log_{10} \frac{(2.25 \times T \times t)}{(r^2 S)}$$

derived by Jacob (15) from the Theis equation (1)

where
- s = drawdown in 100% efficient well
- Q = discharge
- T = transmissivity
- t = time since start of pumping
- S = storativity
- r = distance from pumping well

the case of interference can be roughly calculated, as can drawdown in the well. Taking average pumping rates of 8.2 l/s (see Chapter 7), it appears that while drawdown in a well tapping conglomerate if of average transmissivity is some 1.5 metres in the first hour, a further seven hours abstraction at the same rate produces a drawdown which is still less than 2 metres (1.97 m.) This means that few wells in Ibri conglomerates pump dry during a normal working day and thus practices tend to incorporate constant pumping routines, in contrast with Araqi conglomerates where intermittent pumping is commoner - average T being approximately half that at Ibri.

Based on a six hour working day, the radius of the cone of influence is approximately 130 metres (see fig. 5.14) with less than 10 cm. drawdown at 100 metres. While this drawdown will be increased proportionally at higher than average pumping rates, the cone of influence will be of the same lateral extent after the same time. Where the cones of depression overlap, their effect is cumulative, but in general, distances between wells or well and falaj still exceed this distance.

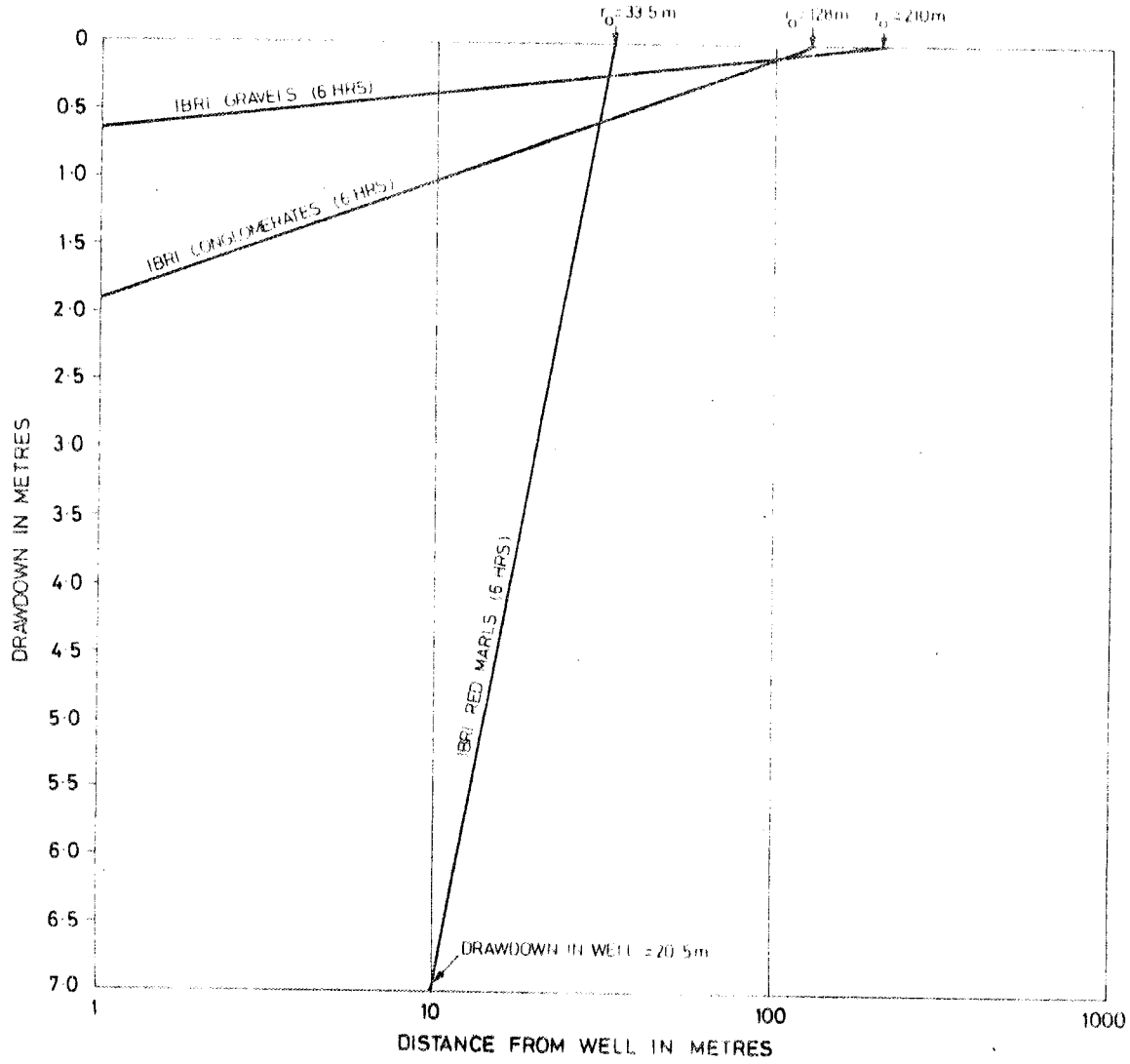


FIG. 5.14

CALCULATED PUMPING WELL DRAWDOWN AND CONE OF INFLUENCE FOR IBRI AQUIFERS

NOTE

DRAWDOWN AT 1 M = DRAWDOWN IN WELL WHERE r = 1 METRE

In the gravels, T values are estimated to be at least three times as high as in the conglomerates, although boundary effects will more commonly interfere with long-term well yields, lateral extent of the aquifer being less. The higher transmissivities mean that even with a year's full-time pumping, drawdown in a 100% efficient well will only marginally exceed 1 metre and in the time of an average working day, is calculated to equal 0.63 metres. (It should perhaps here be pointed out that 100% efficiency has not been established. There are indications that well yields continue to develop after completion, sometimes for several years, since wells dug before pumps were introduced in some cases can now be pumped at the highest rate (13.5 l/s) without drawdown to within depths which make the bottom of the well accessible for digging. Wells are uncased and unscreened and have often been in use for several years and are, therefore, likely to be of high efficiency).

Being of higher transmissivity, the cone of influence is broader in the gravels than in the conglomerates (210 metres) but, as drawdown in the well itself is less, depression of water levels at 100 metres is approximately the same as that calculated for cones in the previous aquifer, at some 0.098 metres.

The values for the uncemented and poorly cemented wadi gravels fit well with those estimated for alluvial fans in Ras al Khaimah, although the latter at 600 - 2400 m^3/day/m would appear to contain few bands of conglomerate or marl (16).

In contrast to the above aquifers, the red marls which fringe the gap on the North side exhibit very much greater drawdown, but over much shorter distances. Pumping at average rates for one hour would give rise to a drawdown of over 15 metres, and even 10 minutes pumping is cal-

culated to cause a depression in water level of 10 metres at the production well. This depression in water levels, where standing water level is already over 20 metres below ground level, exceeds the depth from which medium lift pumps can reach, both in terms of suction lift and discharge head. It is, therefore, apparent that wells in this rock are only operable over very short periods of time and that water pumped from them is predominantly that which has been stored rather than in-flowing water. Thus, short periods of pumping must be followed by long periods of recovery. Wells can however, be spaced at relatively short distances of less than 50 m. without interference but, since recovery generally takes as much as 24 hours, a permanent cone of depression some 0.7 m. deep at the well, is formed.

Using Ibri as an example, it can be seen that the ideal spacing of wells on the grounds of interference is not the major factor in existing patterns. Interference between wells will be least in the worst aquifer, but it is in the areas of better aquifers where the demand for wells will obviously be highest, as returns are better. As cones of influence will overlap, especially in the wadi gravels, a widespread depression of water levels may occur within the aquifer, with effects which include an increase in the loss of water from any falaj channel running through the area (see p.450), as the slope of the piezometric surface away from the channel will be steepened. Leakage of poorer quality water from bordering aquetards under reduced head may also occur.

iv). Sulayf.

At Sulayf, while the same variety of aquifers are not encountered, the pattern of aquifer quality is similar. Water is almost completely

abstracted from wells in conglomerates, only well 140 nearest the wadi passing on into uncemented sands and silts, but more uncemented gravels may well be found, as in the falajes, in association with existing wadi channels. Of the group to the North (in the area of al K·rain - named after the falaj that used to water it) all reach conglomeritic deposits except that nearest the source of falaj Bilad, which taps uncemented gravels.

The conglomerates in this area vary enormously in their ability to transmit water (see fig. 5.15). The best are those near the present wadi and along a line from the wadi to Sulayf Hakkab (at which point lies the remains of one of Dubayshi falaj's three mother wells). These wells have a specific capacity rising to 600 m^3/day/m, but more commonly in the range 100 - 300 m^3/day/m. The aquifers surrounding the lands of falaj Bilad are the least promising, with transmissivities as low as 1 m^3/day/m (well 872), mainly due to increasing proportion of fines in the conglomerate matrix and the higher degree of cementation. The well with the lowest specific capacity has not improved, even with excavation 11.4 metres below standing water level. A neighbouring well (725) contains such a hard well-cemented conglomerate that it took a week to excavate each 0.2 metres of the 1.6 metres below SWL, and the digger broke eight cold chisels in one day. Maximum yield remained below 10 m^3/day. Paradoxically, despite low yields, changes in water level are rapidly transmitted laterally, and water levels rose over two metres in a day following a flood in the wadi Sulayf. It is not known whether yields increased, as the well owner, having spent six months lowering the pump, arrived the day after the flood to find the engine under a metre of water. It is suggested the contrast between response to re-charge and well yield is due to higher lateral permeabilities than vertical ones.

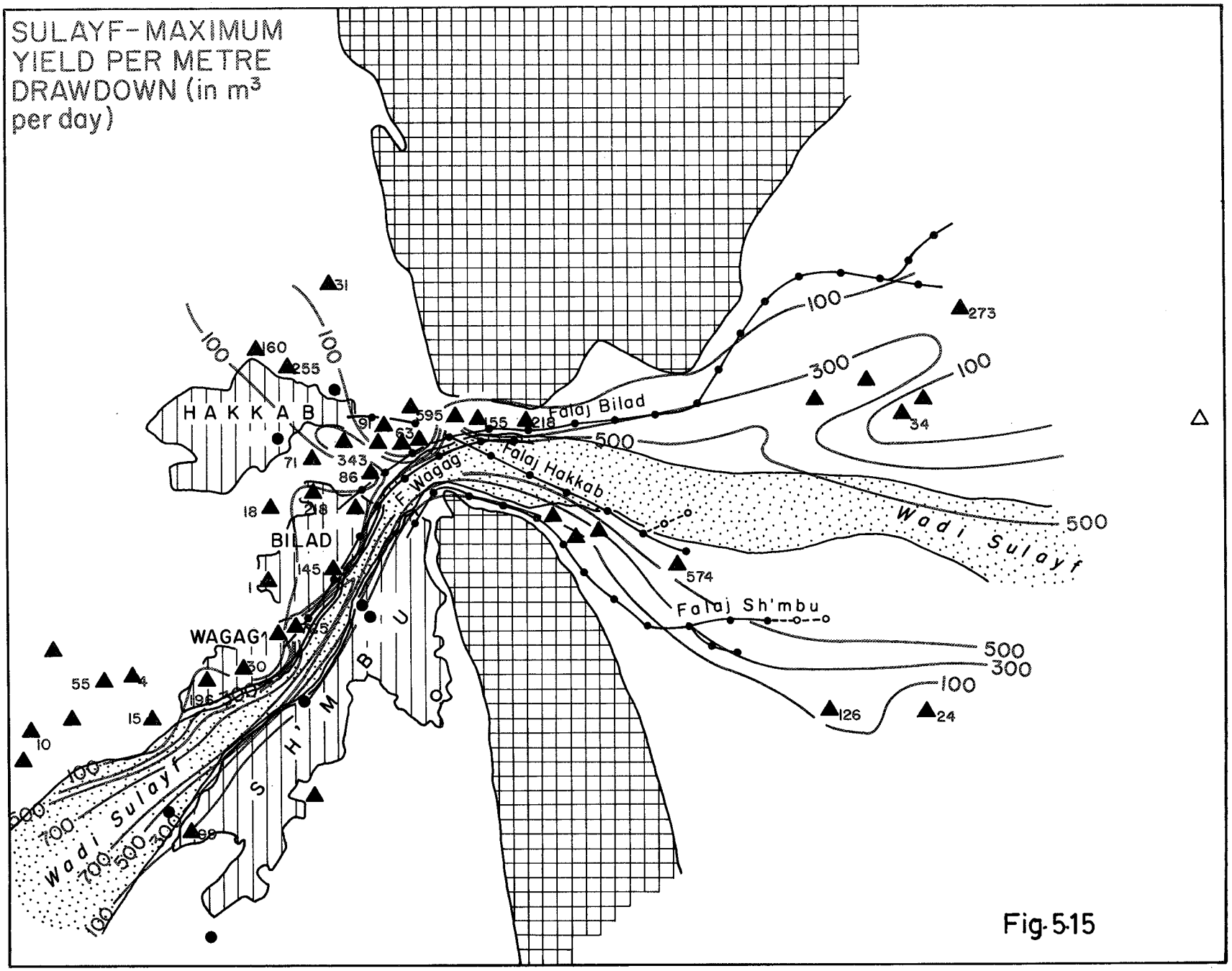
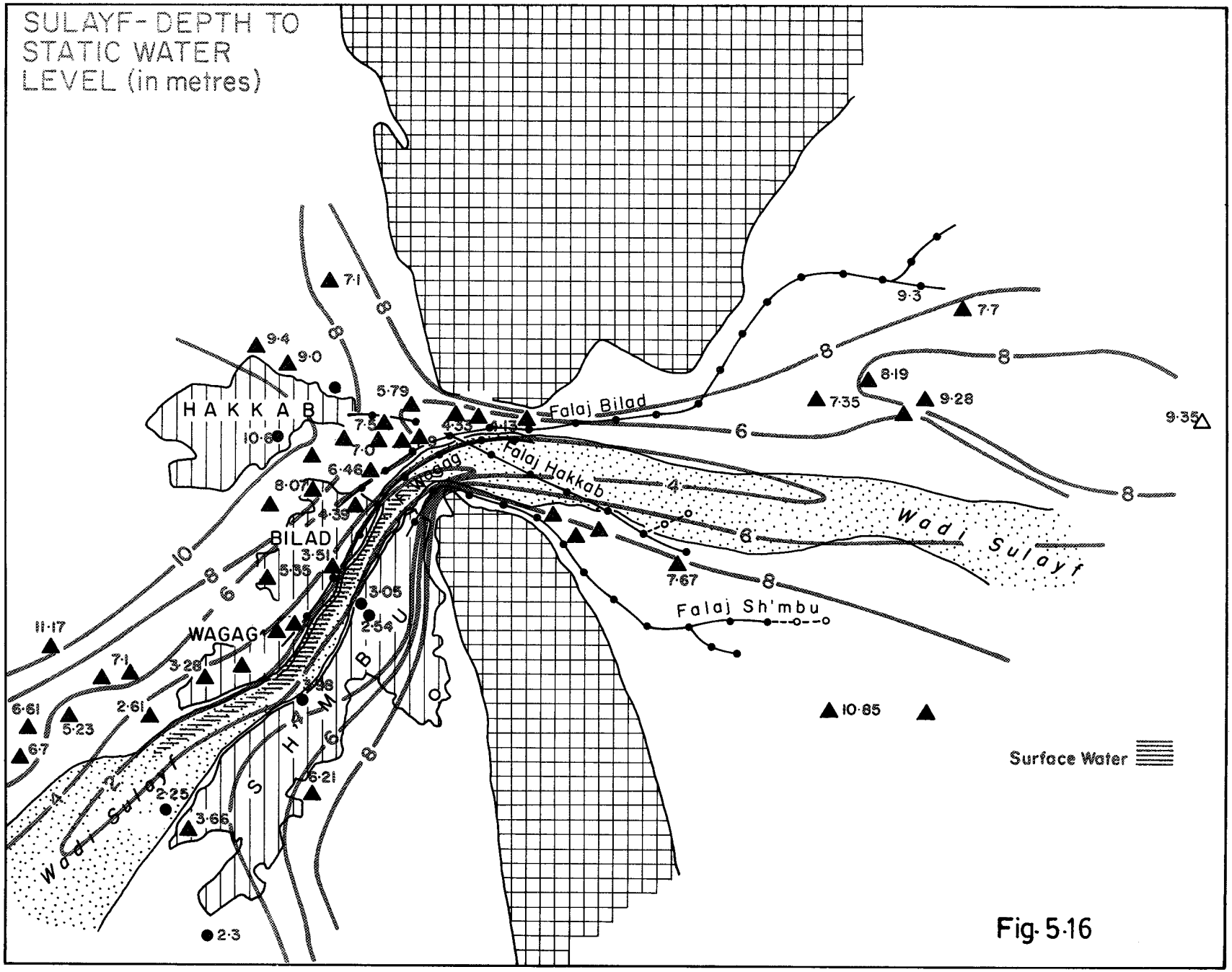

SULAYF - MAXIMUM YIELD PER METRE DRAWDOWN (in m³ per day)
HAKKAB
BILAD
WAGAG
SHIMBU
Falaj Bilad
Falaj Hakkab
F. Wagag
Falaj Sh'mbu
Wadi Sulayf
Wadi Sulayf
100
300
500
700
31
160
255
595
155
218
273
34
91
63
343
71
86
18
145
574
55
4
15
10
196
30
126
24
98

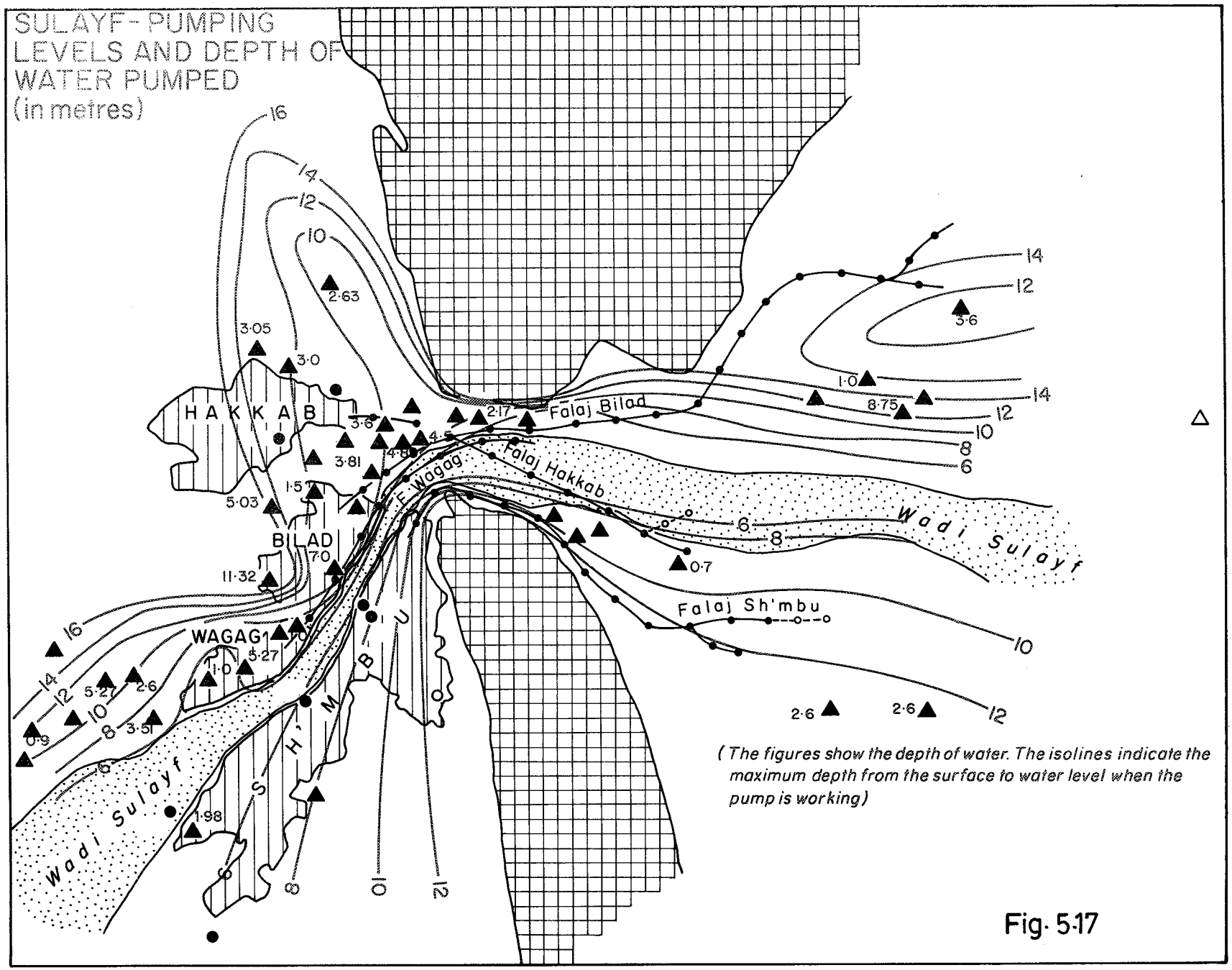
Fig. 5.15

In the Sulayf gap, water is shallow (see fig. 5.16), reaching the surface in parts of the present wadi, where limestone bedrock reaches near to the surface, or in association with conglomerates which are found in the wadi bed. Surface water is perennial, providing water for falaj Wagag - the only diversion channel falaj outside the mountain area. To the sides of the wadi, SWL is still below four metres, only rising to more than ten metres inland of the palms. The majority of wells are in an area of water less than eight metres from the surface.

Depth of water (see fig. 5.17) in contrast, is generally as deep or deeper than for any other area of wells (average 3.7 m., compared with 2.7 m. at Tan'am, 3.4 m. at Darīz, 2.1 m. at Ibri, 3.6 m. at Arāqi). Sulayf has the well with the deepest water observed (11.32 m.) In the other areas, the averages are generally a product of the proportion of wells on wadi gravel aquifers, and conglomerates of high conductance. In Sulayf, the depth of water is high in almost all wells, in a search for springs within the very variable layers of conglomerate where collecting chambers are less popular than at Tan'am. Deepening has generally been carried out over a long period, as wells here have been used all year round since before the introduction of pumps.

Outside the main settlement, declining transmissivities, combined with increasing depth to water, makes the area between Ibri and Sulayf unsuitable for well development. One abandoned well was excavated to 25 m. without finding water. In contrast, to the South-east of Sulayf, in an area known as al Ghuwayl, water reaches the surface. Here it is not fast flowing water as in the gap, but as the


SULAYF - DEPTH TO STATIC WATER LEVEL (in metres)
HAKKAB
BILAD
WAGAG
SHAMBU
Falaj Bilad
Falaj Hakkab
Falaj Sh'mbu
Wadi Sulayf
Wadi Sulayf
Surface Water
7·1
9·4
9·0
10·6
5·79
7·5
7·0
4·55
4·13
6·46
8·07
4·39
3·51
5·55
3·05
2·54
11·17
7·1
3·28
3·98
6·61
5·23
6·7
2·61
2·25
3·66
5·21
2·3
9·3
7·7
8·19
7·35
9·28
9·35
7·67
10·85
Fig. 5.16



(The figures show the depth of water. The isolines indicate the maximum depth from the surface to water level when the pump is working)

Fig. 5.17

only example of sabkha found in the field area. It is slow moving water of high conductivity ponded behind low gaps, and is shallow enough for the cultivation of dates without irrigation after the first two years. Well development has, therefore, been limited to the digging of scoopholes for temporary irrigation. These are now seldom used, even in summer.

v). Desert Foreland - Tan'am.

Further along the foot of the ridge to the North-West, wells hit a soft marl which produces very little water. Possibilities for well development in this area immediately South of the gaps, are few, and those existing are generally not very successful until the group at Dubayshi are reached. The Awāmr who divine for water, say that this area of foreland is a very poor area for wells, and are reluctant to accept commissions to divine and/or dig wells here. In the area beyond the gaps, there is a variety of layers of weathered material, especially clays and marls, brought down from higher up the catchment and deposited in a fan beyond the gap. These deposits are interlayered in beds of less vertical extent than upstream, but occurring over wider areas, and their sequence is, therefore, complicated. Detailed levelling is necessary to define their succession, but the occurrence of conglomerate above or below the water table is a major factor in well yields in the area, as it provides the main source of water. At well 020, the main springs are at the base of the conglomerate where it overlies a recent sandstone. As this source is very near to standing water level, the well is very susceptible to failure if this level falls by as little as a metre.

Specific capacities increase towards Dubayshi, particularly around the area previously watered by Dubayshi lower falaj, where specific capacities reach 500 m^3/day/m. The interbedding of different layers continues down to Tan'am, and in the neighbouring wadi Mukhtābiya. To the north west of Tan'am and to the South-west as far as 602, unconsolidated wadi gravels are found, but the position of the connecting line between them is not certain. Here, the buried wadi, like the surface wadi, appears to be wider than upstream. It is also thinner in vertical extent, with hard conglomerates overlying it and some interlayering with pink sandstones, and some mixing with clays (see fig. 5.18). Its specific capacity (see fig. 5.19) is somewhat lower than for the other gravels found further North, both because of its impurity and because, being a thin layer, its effect is reduced when averages for the whole well are used. It does, however, cover a much wider area, so that a larger proportion of wells in the area have high yields (see p.274) than in the other main well concentrations.

The interlayering of loose gravels here, with poorer aquifers, is an ideal situation for the digging of collecting chambers (sal. pl. salūl) . Where a line of small springs is found and followed back, it may well lead to a thicker part of the gravel band. Here the chamber is not dug simply to increase the storage capacity of the well, but to try to improve the pumping characteristics of the well. Very marked improvements have been made in this way. At 568, pumping time was increased from 10 minutes to more than 10 hours, when 4 sals were driven along spring lines through coarse pink sandstone and finally reaching old wadi deposits. 580 was also improved in this way and the sals which increased the yield of 581, appear also to have reached them.

To the East of these gravel layers, conglomerates predominate. These lie over marls (red and white layers) which act as aquetards. 574

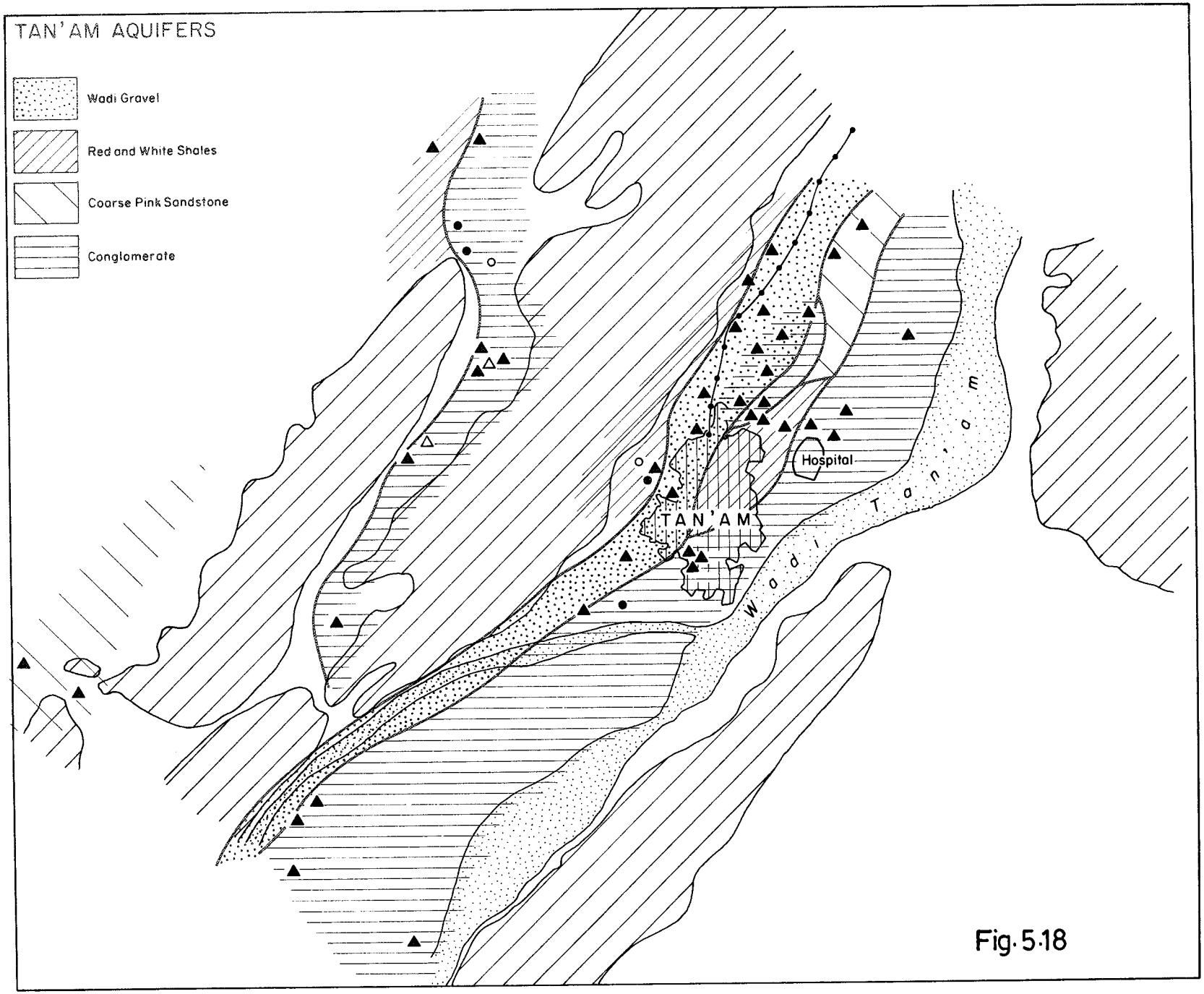

TAN'AM AQUIFERS
Wadi Gravel
Red and White Shales
Coarse Pink Sandstone
Conglomerate
Hospital
TAN'AM
Wadi Tanoe

Fig. 5.18

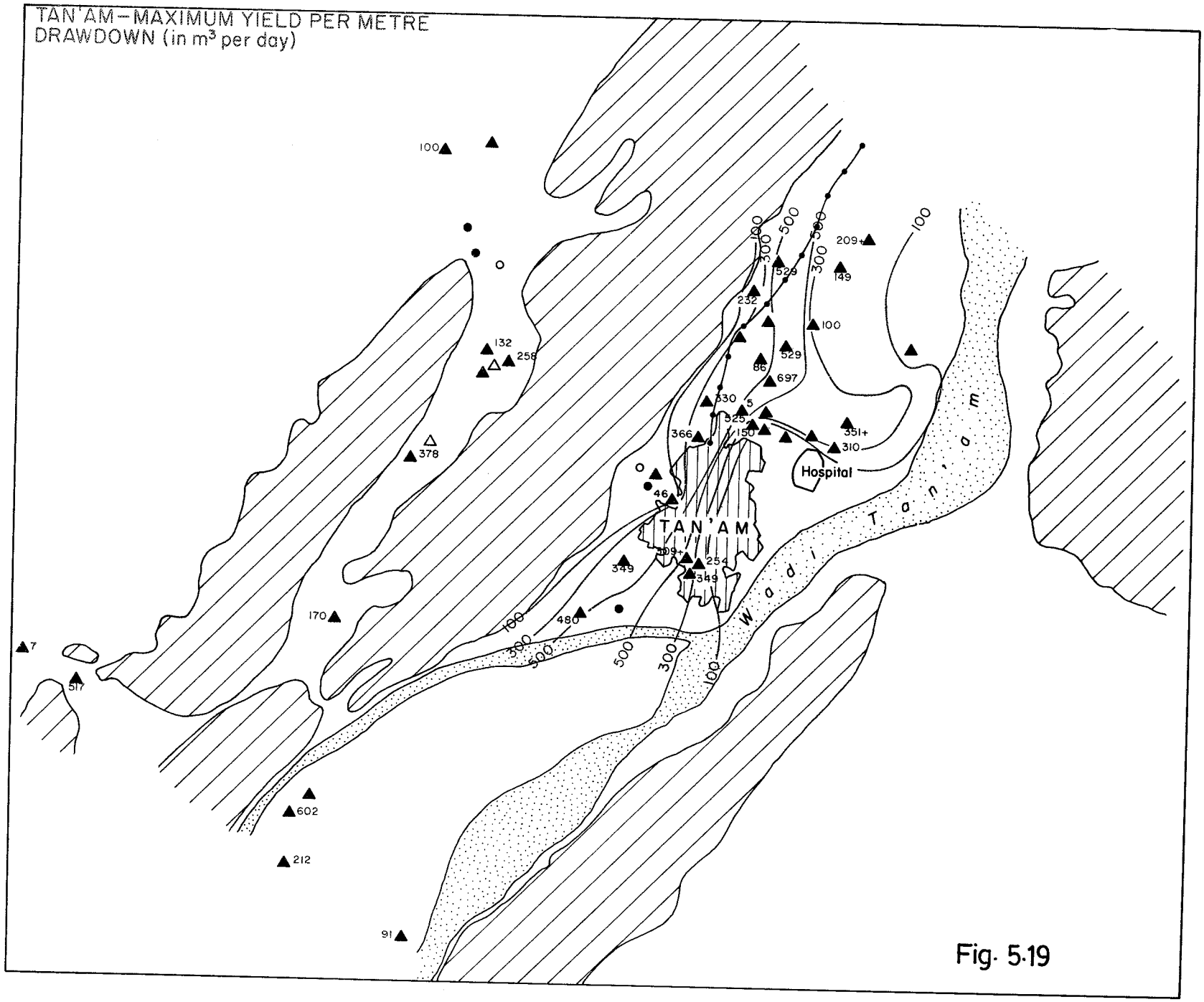

TAN'AM – MAXIMUM YIELD PER METRE
DRAWDOWN (in m³ per day)
TAN'AM
Hospital
Wadi Tan'a E
100
132
256
378
46
170
7
517
602
212
91
480
349
254
366
330
325
150
310
351+
209+
149
232
529
86
697
5
100
300
500

Fig. 5.19

passes through the conglomerate and on into the marls with a resultant yield of 150 m^3/day/m. At neighbouring 575, the conglomerate layer is almost non-existent, so that the well is almost completely in red marls such as those found North of the Ibri gap, and with similarly low transmissivity at some 7 m^3/day/m. Beyond the marly area, the conglomerate becomes thicker and more transmissive (over 300 m^3/day/m). With interdigitation with gravels, it is not possible to find a statistical significance between yields within the conglomerate at Tan'am and Ibri or Sulayf. This is because wells with collecting chambers have to be discounted and there are then not a sufficient number of wells for a statistically significant (at .01 level) difference to be established.

Beyond Tan'am, wells are spaced too far apart to attempt the delineation of boundaries between aquifers. The depth to water in Tan'am and out into the desert, is small (see fig. 5.20) and only at one well (601) are depths approaching the limit for the pump installed.

The depth of water in wells is generally small, increasing away from the right bank of the wadi Tan'am where it was suggested there lay a submerged wadi. Shallow water in wells occurs frequently because of well-owners preference here for the digging of collecting chambers as a lateral extension rather than for deepening the shaft. Depths are greater in the shales and siltstones (see fig. 5.21).

While the Tan'am area contains more widespread uncemented gravels than the other well areas of the Interior, they are still not nearly as broad in extent as the alluvial gravels of the lower coastal plain, which are tapped by the coastal wells.

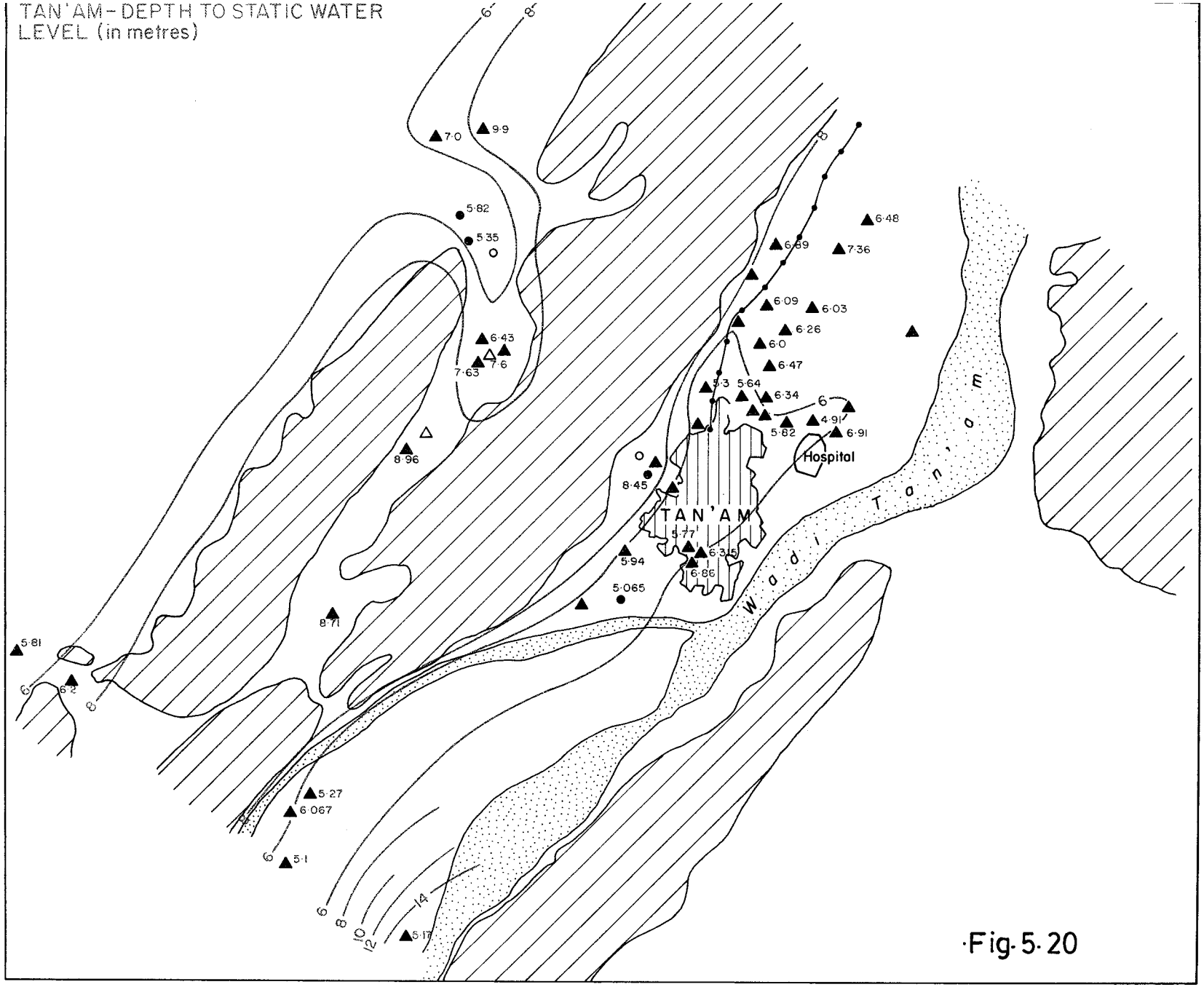

TAN'AM - DEPTH TO STATIC WATER LEVEL (in metres)
TAN'AM
Hospital
Wadi Tan'am
7·0
9·9
5·82
5·35
6·43
7·6
7·63
8·96
8·45
5·77
6·35
6·86
5·94
5·065
8·71
5·81
6·2
5·27
6·067
5·1
5·17
6·48
6·89
7·36
6·09
6·03
6·26
6·0
6·47
5·3
5·64
6·34
4·91
5·82
6·91

Fig. 5.20

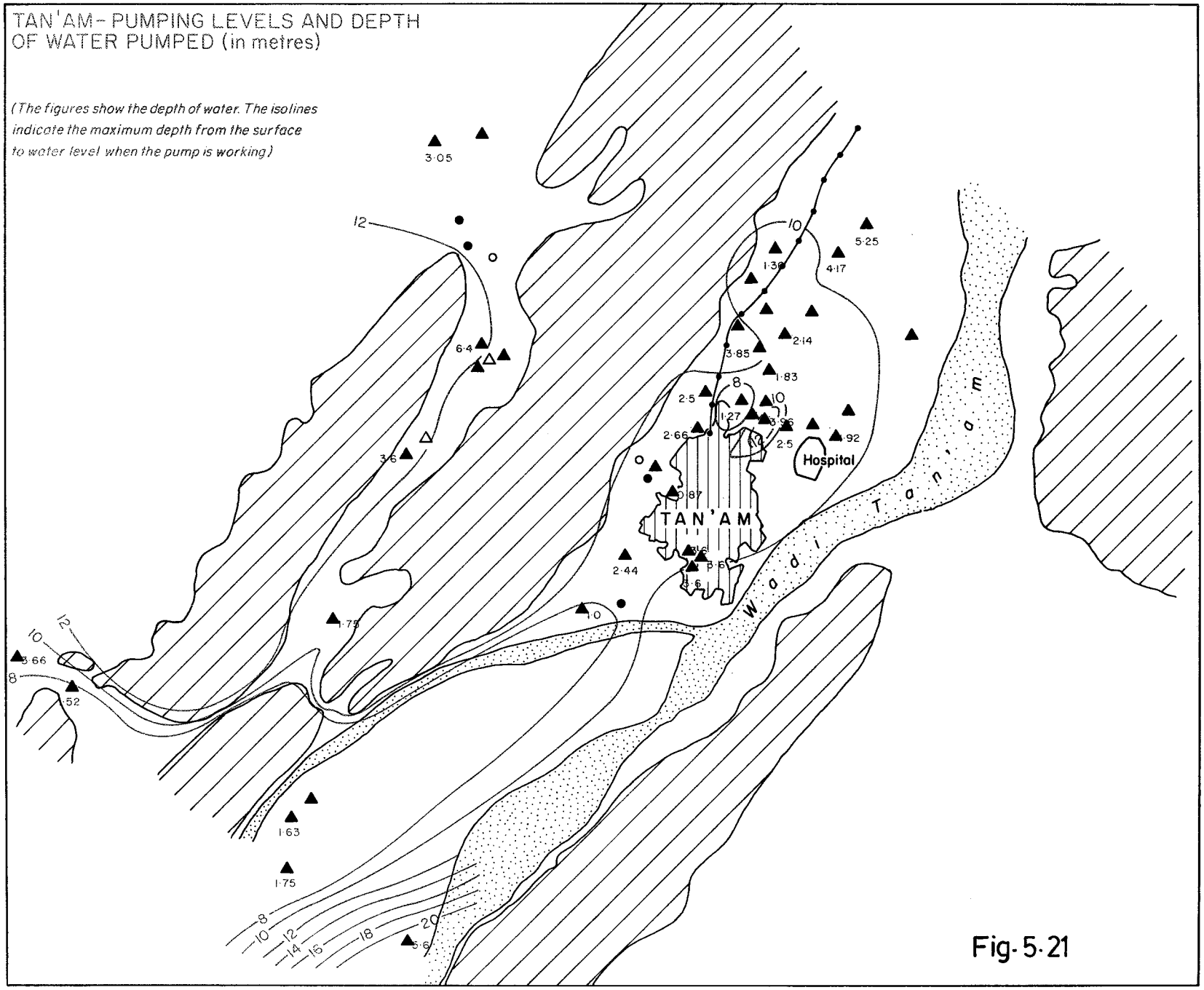

TAN'AM – PUMPING LEVELS AND DEPTH OF WATER PUMPED (in metres)
(The figures show the depth of water. The isolines indicate the maximum depth from the surface to water level when the pump is working)
TAN'AM
Hospital
Wadi Tan'o E
3·05
5·25
4·17
1·30
2·14
3·85
1·83
6·4
3·6
2·5
1·27
2·66
2·5
·92
·87
2·44
·75
·66
·52
1·63
1·75
5·6
12
10
8
14
15
18
20

Fig. 5·21

vi). Bāṭina.

The coastal aquifer at present exploited, is mainly a gravel mixed with sand and with marl bands and lenses in some parts. It tends to be encountered at approximately the same depth below ground level, about 8 metres, over a major part of the coastal strip (see fig. 5.22). Although not of identical quality throughout and with varying amounts of cementation, it appears to be far more homogeneous and widespread than the aquifers of the Interior.

Specific capacity data could not be obtained as easily or accurately on the coast, but values generally vary from 100 - 1000 or more m^3/day/m, but in no case fall below 100 m^3/day/m, averaging some 380 m^3/day/m with standard deviation of 255. This is in direct contrast with the Interior, where four out of ten wells exhibit estimated transmissivities below 100 m^3/day/m. The patchy distribution of wells on the coast, does not therefore seem to be associated with the poorest of aquifer conditions, but is more likely to be related to soil and water quality, problems of land-holding or other factors.

Depth to standing water level predictably increases inland (see fig. 5.22). Beyond about 6 km from the shore, it has reached over 20 metres beneath the surface, and cannot therefore be tapped by the medium-lift pumps at present most commonly employed. In the area of the majority of wells, depth to water seldom exceeds 6.5m. Those wells which lift water from a greater depth than this are those most recently established, and without a previous history of zāgira extraction.


KHABURA DEPTH TO STATIC WATER LEVEL (in metres)
KHABURA
HARRAT RADAYDA
HARRAT AL WUSUT
To Sohar
To Qusuf
To Muscat
10
10·0
8
6
4
8·95
8·86
8·03
7·35
8·85
6·72
5·08
4·57
2·56
2·91
4·35
6·43
5·03
6·55
5·9
5·6
5·8
5·5
5·68
5·75
5·05
4·99
6·8
6·6
6·5
7·3
8·4
7·0
7·11
6·5
4·2
4·1
4·3
4·0
5·0
4·13
5·2
5·7
2·89
3·25
3·65
3·37
3·29
3·05
3·01
2·45
3·4
3·3
3·7
4·4
5·14
4·74
4·73
3·0
2·4
2·7
2·0
1·9
3·3
3·2
4·5
5·5
4·5
4·1
3·7
4·0
7·4
6·7
6·3
5·3
5·9
4·2
4·1
4·0
4·3
5·0
3·7
3·3
2·7
2·5
2·0
1·9
1·2

Fig 5.22

Nearer the shore, within 200 metres, depth to water is slightly greater than a little further inland, as the land surface rises, forming a storm beach ridge. This ridge is breached by a small inlet, near the sūq. It appears that this was once of greater extent, turning back North-westwards to form a lagoon behind the storm beach. Local people say that at one time it stretched along at least as far as well 1106. The isolines for depth to water support this idea.

The depth to which wells are driven appears to be fairly constant within the main concentration of wells (see fig. 5.23). Most are 7 - 9 metres deep, even when they are within 300 metres of the sea (e.g. 1111, 1133). Only the first line of wells is shallower. It appears that the wells are all sunk to a particular level which provides sufficient water. Deepening beyond this point is neither necessary nor possible, (since the well cannot be pumped dry) while shallower wells do not provide enough water without deepening. As already mentioned, this layer is mainly of uncemented gravels (though bands of cemented gravels are also found) and appears to slope at only a slightly lesser gradient than the present land surface. The relatively constant depth to pumping level means that within the present area of greatest well density, variations in pump outputs are not dictated by lift, and no one area has an advantage over another. Only near and inland of the new coastal road is extraction rate affected by the distance the water is lifted.

vii). Conclusion.

An examination of the distribution and transmissivity of aquifers, and depth to standing and pumping water levels emphasised three particular points of the characteristics of the ground water environment of the area.

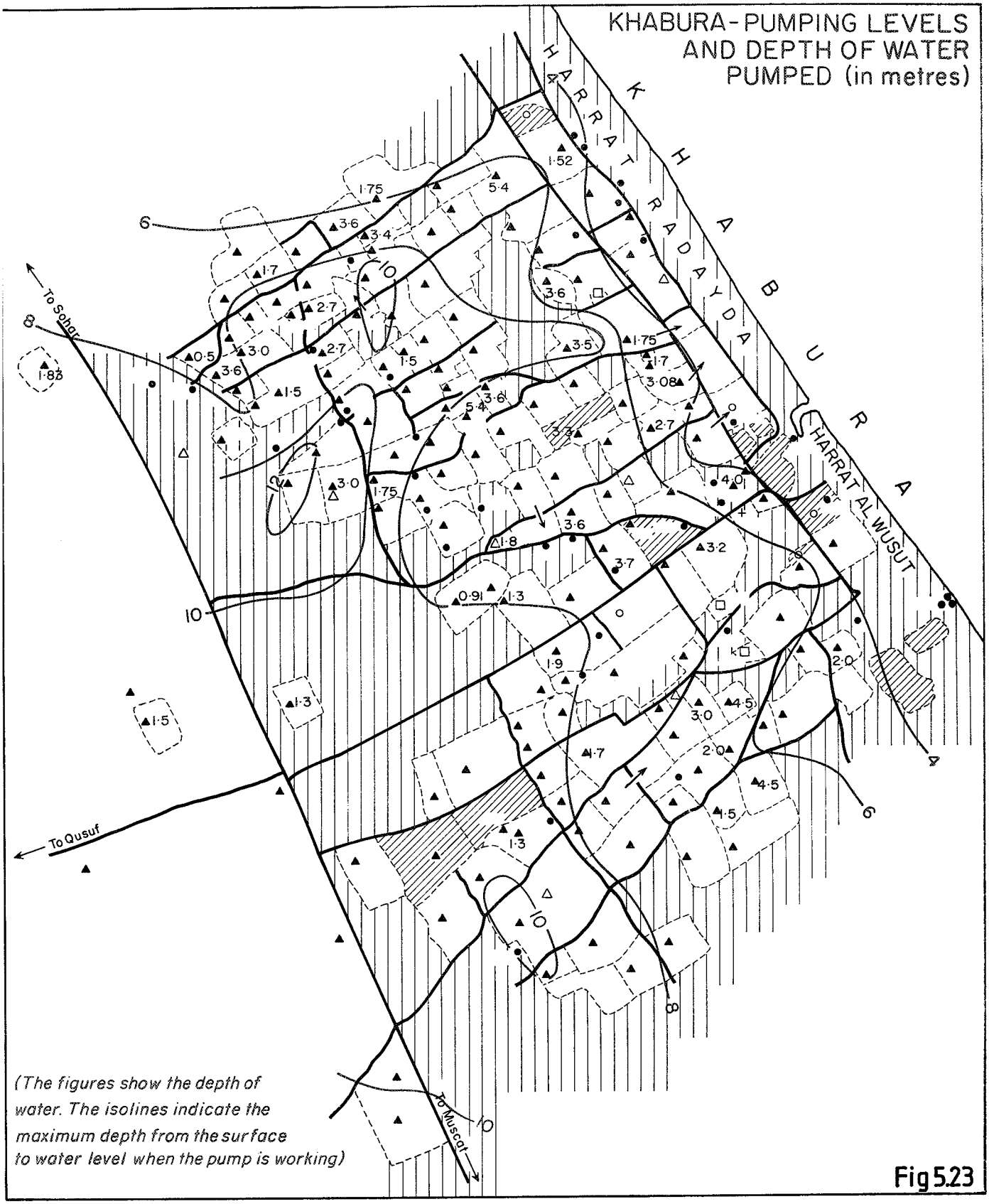

KHABURA - PUMPING LEVELS AND DEPTH OF WATER PUMPED (in metres)
KHABURA
HARRAT RADAYDA
HARRAT AL WUSUT
To Sohar
To Qusuf
To Muscat
(The figures show the depth of water. The isolines indicate the maximum depth from the surface to water level when the pump is working)

Fig 5.23

Firstly, in the Interior, the linear development of uncemented gravels - probably as infill to an old wadi channel, but not necessarily on the line of the present channel - is of primary importance.

While the overall transmissivities of gravels estimated fall within the same range of values as those established by test pumping in the alluvial fans of the Hamraniya area of the Trucial States (16), 600 - 2,000 m^3/day/m, they are of very limited lateral extent. Gibb uses a similar range of T values to calculate flow in surface wadi gravels (17) and it would appear that the buried gravels transmit the majority of ground water, in a similar way to a gravel packed field drain. Falaj sources in particular tap this aquifer.

Secondly, although unquantified, it would seem that surface and ground water catchments do not necessarily coincide, so that from one storm surface water may flow in one direction and infiltrated water in another, as in some karst landscapes. If this dichotomy is still developing, it may lead to lesser re-charge to some falaj storage areas, particularly the lower al Kabir ones, where more surface water appears to be being diverted into the wadi Juffra. It is this feature of the landscape which makes water balance estimates for individual catchments very difficult but also explains the siting of falaj mother wells, such as al Qabil, and the concentration of wells East of Dariz. The author found similar features in the wadi Quriyat, and there are probable sites of wadi capture or diversion all down the inland edge of the Hajar mountains.

Thirdly, there are few large areas where depth to water alone precludes well development. Only the wadi Juffra, mid-coastal plain and lower wadi Munqnyat would seem to be unsuitable for pump wells or falaj

sources. Pumping levels remain fairly constant within the Interior for, although there are wide variations in depth to water and in transmissivities, the aquifers with water nearest the ground surface tend to be of the lowest transmissivity. Except near the Ibri and Sulayf gaps, greater distance to water generally coincides with higher transmissivities, so wells of deep water are generally counter-balanced by those of greater depth to water.

IV). STORAGE AND RELIABILITY OF SUPPLY.

A. Introduction.

Falaj flows and well yields are seldom constant. Changes in head and in storage affect both systems, and a measure of the reliability of supply can be obtained from observed changes in water levels and from changes in storage calculated from falaj recession curves. The period from 1973 - 1975 was well suited to the study of recession, as re-charge events were few and so interfered little with rates of base-flow change.

Falaj flow measurements are, however, complicated by the interference effect of human activities upon them, especially in times of low flow. As the water shortage intensifies, more villages set about increasing the efficiency of falajes, taking out roots and silt, extending the mother well, removing collapses, lining channels, etc. (see Chapter 6). The result is that some increases in flow are not responses to climatic factors. Similarly, as the flow of falajes declines and water tables fall (see p.447) water losses as a proportion of flow, increase. Thus, decreases in flow are not simply a response to changing ground water conditions, but are also a function of changes in the efficiency of the falaj as a carrier of water.

Table 5.1 shows base-flow recession curve equations for those systems where curves could be identified and re-charge or repairs and maintenance had not continuously affected flows and so altered the rate of decline. This rate can be expressed exponentially by the equation $Q_t = Q_o e^{-kt}$, a simplification of his original non-linear equation which Boussinesq made as long ago as 1877 (18). The plot on semi-

Table 5.1. Recession Constants for Falaj Systems.

Category.	System	Recession equation.	Stored Water available Nov.'73 (in m^3)
North-draining catchment.	Wadi Hawasina	$Qt = 66e^{-t/110}$	6.3×10^5
	Ghayzayn I	$Qt = 96e^{-t/123}$	1.0×10^6
	Ghayzayn II	$Qt = 500e^{-t/59}$	2.5×10^6
	Qusuf	$Qt = 27e^{-t/201}$	4.7×10^5
Upper wadis south side of mountains.	Injayd I	$Qt = 29.5e^{-t/1253}$	3.2×10^6
	Injayd II	$Qt = 140e^{-t/85}$	1.0×10^6
	Injayd III	$Qt = 13.6e^{-t/992}$	1.2×10^6
	Khadil I	$Qt = 14.7e^{-t/1058}$	1.3×10^6
	Khadil II	$Qt = 35e^{-t/253}$	7.6×10^5
	Hujrimat I	$Qt = 14.2e^{-t/345}$	4.2×10^5
	Hujrimat II	$Qt = 60e^{-t/167}$	8.7×10^5
	Al Aridh	$Qt = 38e^{-t/1536}$	5.0×10^6
Lower wadis	Ibri Mafjur	$Qt = 172e^{-t/1253}$	1.86×10^7
	Sulayf Shimbu	$Qt = 100e^{-t/934}$	8.1×10^6
	Bilad	$Qt = 24.5e^{-t/1190}$	2.5×10^6
	Hakkab	$Qt = 20e^{-t/3307}$	5.7×10^6
	Araqi	$Qt = 182e^{-t/671}$	1.0×10^7
	Aynayn	$Qt = 105e^{-t/2164}$	1.96×10^7

logarithmic paper is a straight line of slope - k loge, and the value of the zero intercept is Q_o. Q_t is the discharge at time interval t after a given discharge Q_o and k is a recession constant. (see fig.5.24)

The volume of water in storage (St) is given by,

$$St = \frac{Q_o e^{-kt}}{k} = \frac{Qt}{k}$$

From this equation it is possible to calculate both the time required for a given decrease in flow from the flow at time zero (here taken as November 1st, 1973) and to calculate the maximum potential drainage loss (19) (equivalent to available storage) at this time by using the value of the zero intercept divided by the reciprocal of the slope as a value of storage.

B. Catchment Storage Characteristics.

i). Storativity.

Ideally, volumes of storage and their fluctuations should be related to inputs calculated in water balance estimates, and should, with recharge events, be employed to provide values of storativity. Water level fluctuations can then also be used to indicate storage losses and to quantify losses in well yield. Two major disadvantages are inherent in the systems observed. The first of these is the partial penetration of the aquifer which means that the value of Q_o is not equivalent to the total flow through the aquifer. The second is the movement of ground water between independent surface water catchments, which makes it very difficult to establish, without contours of the

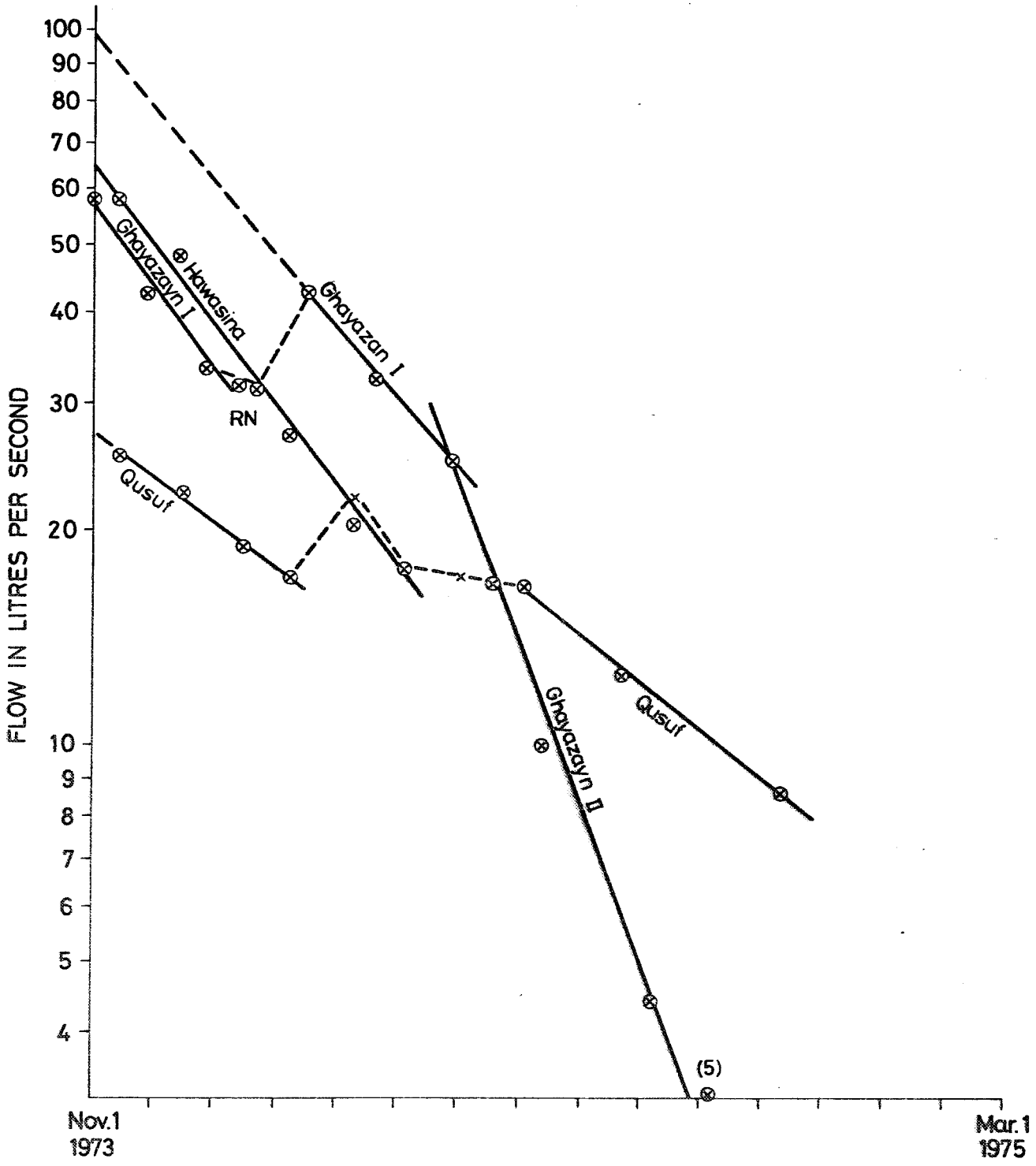


Fig.5.24 RECESSION LINES FOR HAWASINA SYSTEM

piezometric surface, the surface area of the ground water reservoir.

Storage fluctuations can, however, be used to quantify regional values of storativity and certain re-charge events. (5). Using Injayd first stage recession curve, (taken to be the product of combined al Ayn and al Kabir storages) and water level changes observed in the area, S (storage co-efficient) for upper al Kabir gravels and conglomerates can be estimated, by dividing the storage loss by the volume of rock drained.

During the 135 days the recession line was observed, 3.5×10^5 m^3 of stored water was removed. In the same period, an average 1.3 metres fall in water level occurred within the 75×10^5 m^2 area of wadi fill, so that 97.5×10^5 m^3 of rock was drained. Storage was, therefore, approximately equal to .036, a value compatible with the assumption that the aquifer is unconfined. The storage co-efficient for the Khadil area, worked out on the same basis, appears to be around .007, indicating semi-confined conditions. The value calculated, however, probably illustrates more the consequences of a poorly defined ground water catchment in a low watershed area, where the whole area may not contribute to the same system.

The above examples show that, while recession curves have potential for giving a value of S for quite a large area, such values for accuracy, require the refinement of piezometric contours, so that the volume of rock drained can be better established. It is, however, apparent that, at least in the upper wadis, the assumption that unconfined to semi-confined conditions prevail, is valid. (Since S is for most purposes here only required to be correct to an order of magnitude (see p. 212) the confirmation of this provides sufficient accuracy for the present.)

ii). Storage Volumes of Observed Systems.

The storage available to most of the observed systems (see table 5.1) is that in upstream gravels and conglomerates of an approximately fan-shaped area where the head of water is higher than that of the mother well source. The rate of decline is highest in those systems with small upstream storage because, a) they are high up in the catchment, or b) the wadi concerned has a very narrow upstream section and a small number of tributaries of similar morphology, so that even those falajes far from the watershed have only limited upstream storage in wadi gravels and conglomerates. This is particularly true for those systems which abstract wadi Hawasina water (see fig. 5.24). These show the steepest recession curves of all the flows monitored and reflect the narrowness of the catchment and small number of major tributaries. The flows at the wadi Hawasina narrows, drained 80% of their potential storage in six months in 1974, underlining the dependence of upper wadi systems on frequent recharge and the large variations in water available within them.

In contrast, the system of the lower wadis on the south side of the mountains, have the maximum potential volume of storage (see table 5.1) and so exhibit the most gradual decline in flow (see fig. 5.25). These systems, being generally downstream of, or at the junction of major wadis, benefit not only from a larger storage area, (generally 10^6 or 10^7 cubic metres as opposed to the mountain systems' 10^5 cubic metres), but also a larger probability of re-charge from local disturbances which are the commonest contributors of rainfall. Thus, while the majority of upstream falajes show marked recession lines (see fig. 5.25 and 5.26) some of the downstream ones, especially Dariz and Aynayn, show little marked decline during the period of monitoring and recession lines cannot be identified. This is probably as a result of re-charge in the major tributary, the Bilad Shahum and also possibly

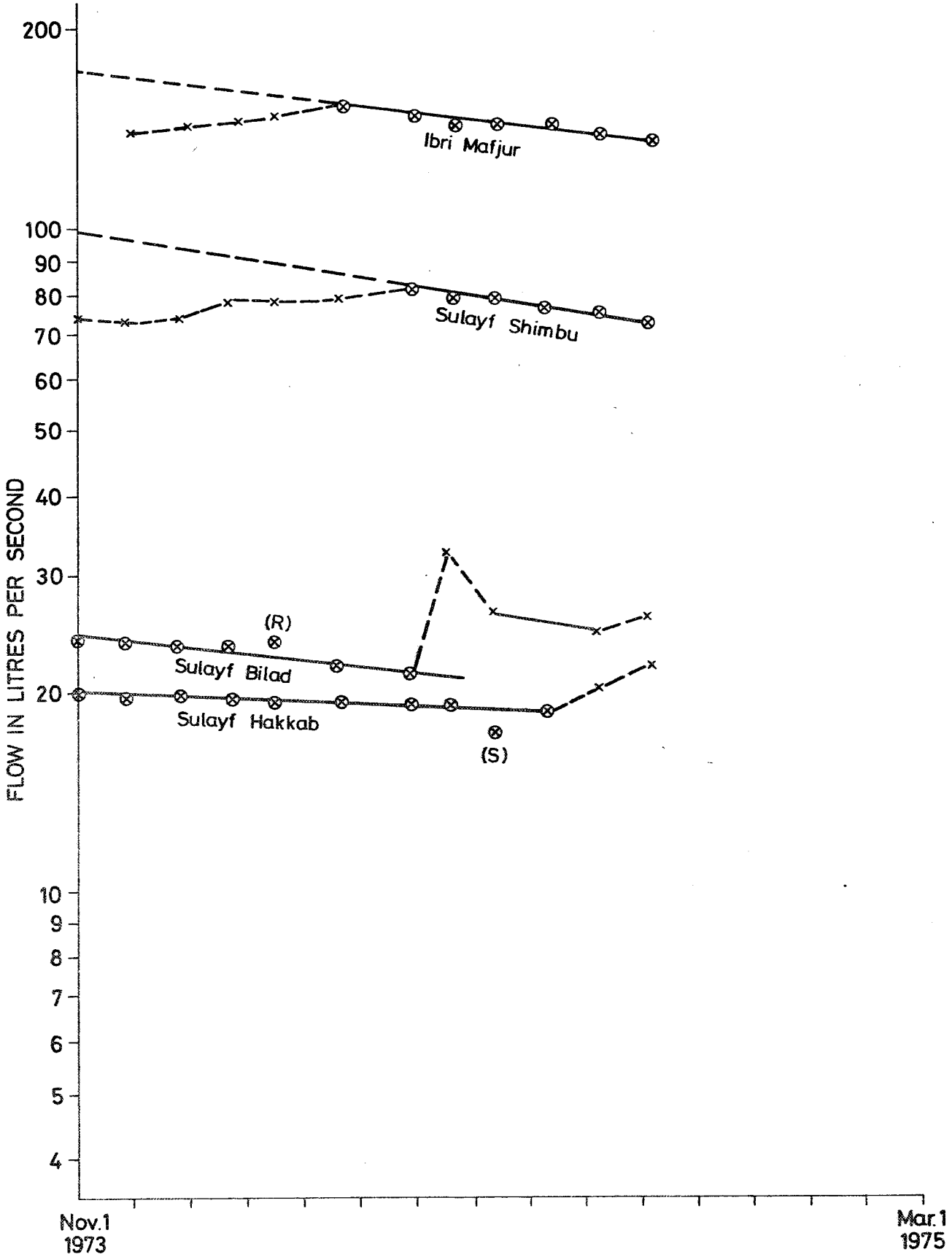
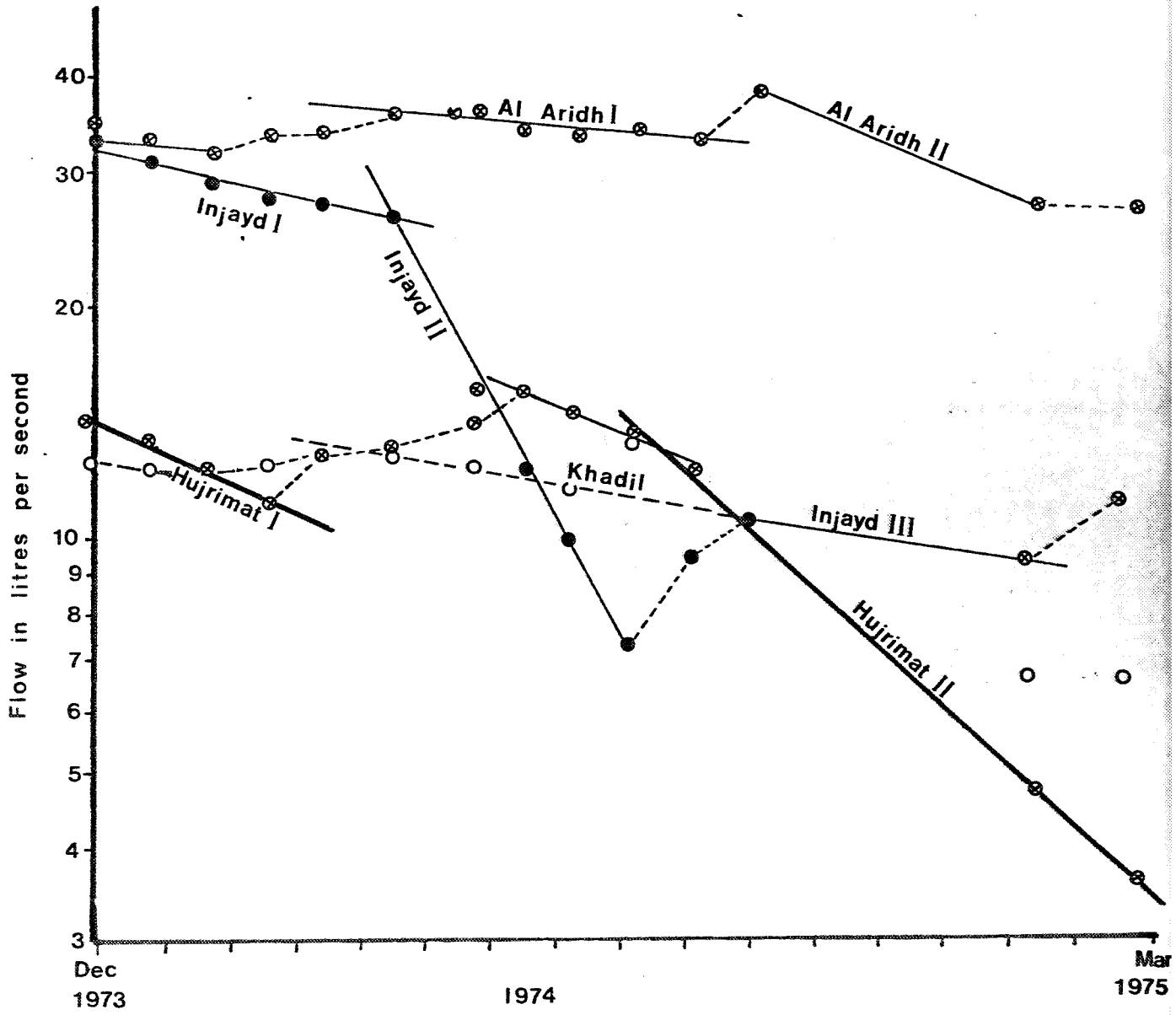


Fig 5.25 RECESSION LINES FOR LOWER CATCHMENTS
(SOUTH SIDE HAJAR MTS)

Fig. 5.26 Recession lines for upper wadis

(South side Hajar mountains)



the al Hijr, which lie on the path of disturbances moving from the Jabal Akhdhar.

iii). Response of Dual Source Systems.

While the recession constant is related to general position within and morphology of the catchment, it is apparent from the recession curves with more than one component, that several falajes obtain water from more than one ground water system. This is particularly true for Ghayzayn, Injayd, Khadil Safil, Hujrimat, and al Aridh. The change in rate of decline suggests that in these cases a source abruptly stops contributing to the system and it is postulated that the water level has dropped below that of the falaj intake. This can be illustrated by the succession of events at Injayd.

During the period of the survey, Injayd falaj declined rapidly, but it can be seen that the rate of recession is split into two parallel lines (Injayd I and III) separated by a period of more rapid decline (Injayd II). The falaj gains water from two separate sources, the wadi al Kabir and a tributary the wadi al Ayn. The wadi al Kabir source was initially perched 3.35 metres above the al Ayn intake, and in mid-April 1974, it dried up. The rate of decline then increased rapidly, and outside aid was then called in to deepen the al Kabir source. This work appears to have led to a re-establishment of the earlier lesser rate of recession which may be taken to be a composite rate of the combined al Ayn and al Kabir systems.

A similar response can be seen in the flows of Ghayzayn falaj, which collects water from the wadi Tiffili and the wadi Hawasina itself.

See Appendix, Section 3 for Monitoring data.

Here the two segments of recession rates (Ghayzayn I and II) may reflect the fall of the Hawasina source below the intake zone, and the smaller available storage of the Tiffili, giving rise to a more rapid rate of decline.

As an experiment with type curves, these recessions were plotted on log/log paper and were found to conform perfectly to Boulton's water table aquifer curves (20). The curves represent different r/d values, which are a function of transmissivity, storativity and rate of de-watering, and thus, similar curves may be expected to indicate drainage of similar or the same aquifers (r/d = drainage factor).

Injayd I and III both fit a curve for r/d value of 0.6, while Injayd II follows an r/d = 1.5 type curve, suggesting a common source for I and III and a different one for the intermediate section of recession. A sequence of events corroborated by observations at the source.

For Ghayzayn falaj, however, while the two segments of the recession curve exhibit very different slopes, zero intercepts and maximum storage, they both fit the same Boulton-type curve with an r/d of 1.1. In this case, it would seem that the interpretation of the semi-logarithmic plot as indicating two different sources, should be reconsidered. It seems from comparison with the log - log plot, that both segments represent the same catchment, but that in the second segment it is subject perhaps to increasing evapo-transpiration losses.

While there remain too many unknowns for it to be possible to solve the equations to obtain values of Tor S from r/d, it is suggested that use of the curves may help categorise the curves obtained from monitoring data and so provide additional information on ground water catch-

ment area. In general, the larger the storage area, the smaller the r/d value for the type-curve which fits the data.

The poor definitions of ground water catchments can partly be improved by surveys of water and ground levels, but the pattern of falaj flows and water levels over time, also gives some clues. For instance, although Hujrimat is near the wadi al Kabir, and the scoophole south of the village (343) conforms to the al Kabir pattern of a steadily declining water table, the falaj itself shows greater similarity to al Aridh and Khadil falaj flows and wells, suggesting it imports water across the catchment boundary (middle wadi falajes). (see fig.5.26). The storage on which a falaj depends may not, therefore, always be that of the catchment in which the falaj settlement lies. Evidence of this phenomenon can be also found from the ruined 'Sheba's channel' which once took water from the wadi al Kabir to Ukhwaybiyah in the wadi Juffra. Thus, while change in storage volume can quite easily be ascertained, the area to which such change applies may be more difficult to establish.

iv). System Reliability.

Injayd and Ghayzayn show that, as where boundary conditions are encountered in test pumping, conclusions drawn on a hydrogeological system after insufficient time, can give a very misleading impression of future yields. Unfortunately, as in the calculation of t_{s1} (5), the time necessary for observation of the components of the true curve is only apparent at the end of the period of data collection and, in the case of monitored flows, more features become apparent the longer the period for which information is available - especially in an area

where re-charge events vary so much from year to year. Thus, while the examination of recession curves allows attempts at predictions of future base-flows in the absence of re-charge, their use with respect to partially penetrating and dual sources, should particularly be regarded with caution until several years' data are available, as $-k \log e$, may not remain constant. A further limit of the method is that, while storage and flows can be predicted in a future without recharge events, the curve cannot be projected backwards over time with any certainty. There must be a finite capacity to the storage of the system, beyond which surface run-off occurs, but the volume of this storage is not known. Some small catchments with very steep recession lines may initially appear to have greater storage than a larger catchment where projections are made too far back in time. There must be, in fact, a point at which each system no longer follows its type-curve.

Table 5.2 TIME TAKEN FOR 50% DECLINE IN FLOW.

	Months.
Wadi Hawasina	2.6
Ghayzayn I	2.9
Ghayzayn II	1.3
Qusuf	4.8
Injayd I	16.8
" II	1.9
" III	25.0
Khadil I	19.5
" II	5.0
Hujrimat I	7.6
" II	3.8
Al Aridh	34.8
Ibri Mafjur	30.0
Sulayf Shimbu	17.4
Bilad	25.2
Hakkab	135
Araqi	21.4
Aynayn	49.0

While bearing the above provisos in mind, it is apparent from the available period of data monitored by the author 1973 - 1975, that only at al Aridh of the upper and middle wadi falajes, do flows consistently decline by less than 50% in six months. Of the lower wadi systems, however, none suffer a 50% decrease in flows in less than seventeen months. This measure of reliability (see table 5.2) underlines the contrast between the upper and lower wadi systems, but also explains to some degree, why falajes are less suitable on the North side of the mountains, where catchments are generally smaller and flows therefore very much more erratic.

Most of the lower falaj systems take two to four years to decline by more than half of any given flow. (The eleven year value for Hakkab suggests that the prolonged servicing the system underwent, may have had more effect than at first thought). While any one point may expect four consecutive dry years (below 75% of average) in every ten to fifteen, the local nature of storms in the area makes it likely that (see p.197) some tributary area will be subject to re-charge events during this period. Thus, the lower down the system one moves, the less the likelihood of a total absence of re-charge and therefore of the predicted rate of decline.

v). Change In Storage as an Indicator of re-charge.

To be of real value, the quantification of re-charge events should be combined with rainfall data, as proportion of rainfall infiltrating *\ this, particularly as the re-charge events in the field area during 1973 - 1975 were too local to be registered accurately by the established density of rain gauges. Using Qusuf and Ghayzayn flows, however, it is possible both to ascertain that they responded equally

*\ Omission ... can then be ascertained. At present rainfall data are insufficient for

to the same re-charge event (and so confirm that they tap the same ground water system) and to establish the delay period. After 105 days from t zero, Ghayzayn falaj system experienced a re-charge of approximately 1.9×10^5 m^3. While no rain fell downstream of Ghayzayn or upstream of the Hawasina narrows, after 130 days Qusuf falaj responded to a recharge of around 1.8×10^5 m^3. Qusuf falaj shows a lesser initial storage than Ghayzayn, which threw doubt on whether it really tapped the same wadi Hawasina system. The similarity in response of the two falajes suggests that the Hawasina system is common to them both and that the difference in initial storage is probably due to a lesser degree of penetration at the much neglected Qusuf source.

While the period of monitoring was near ideal for the study of recession curves, longer records are necessary before full use can be made of ground water flow observations. However, analysis of information to date shows that falaj flow data are suitable for the interpretation of storage characteristics, re-charge events and the interrelationship of different ground water systems, as well as giving simply a measure of reliability.

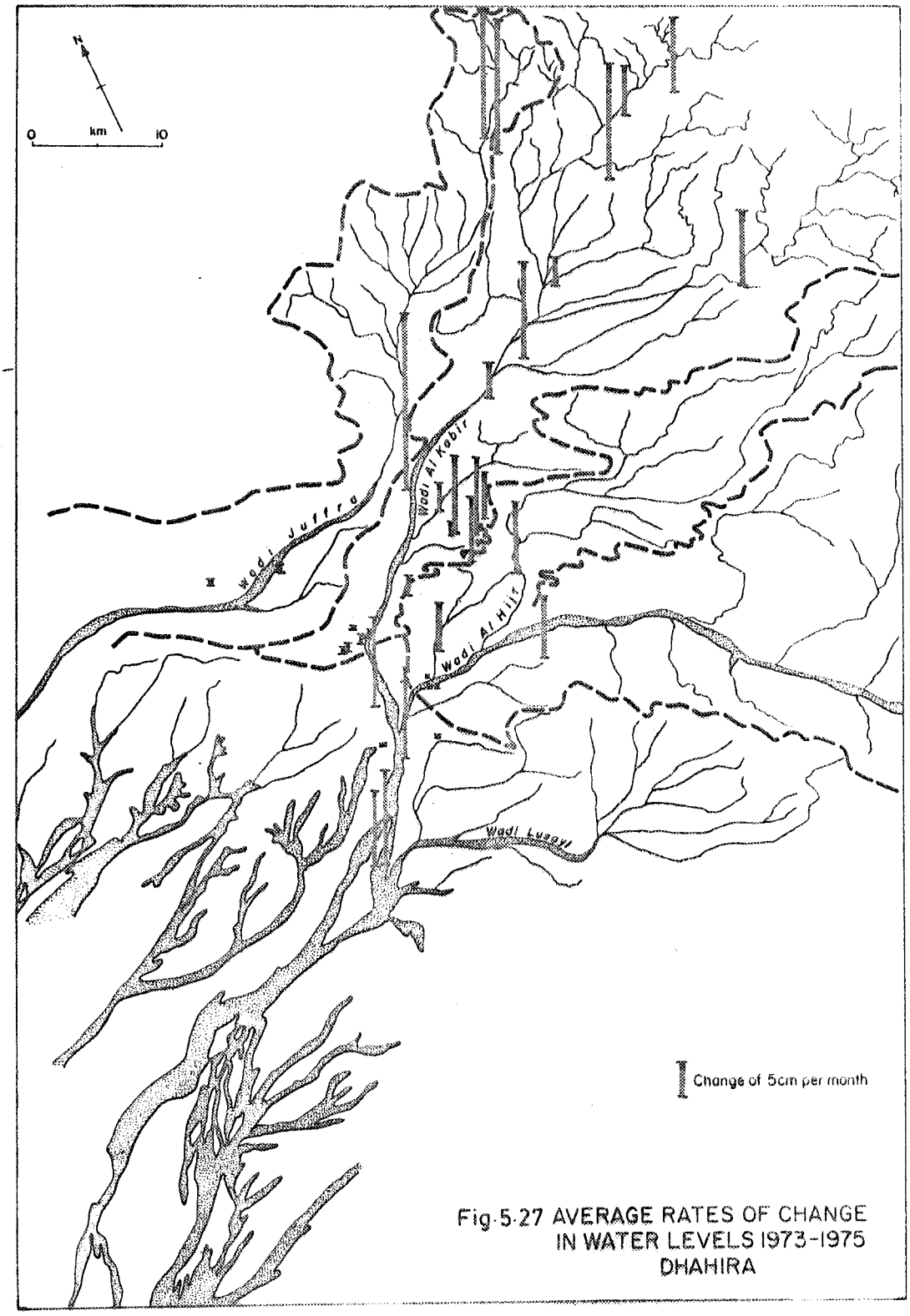
C. Water Level Fluctuations.

i). Their effect.

Change in storage can be identified, however, not only from falaj flows, but also from fluctuations in water levels, particularly where values of storativity are known. A fall in the water table reduces transmissivity by decreasing the saturated thickness of the aquifer

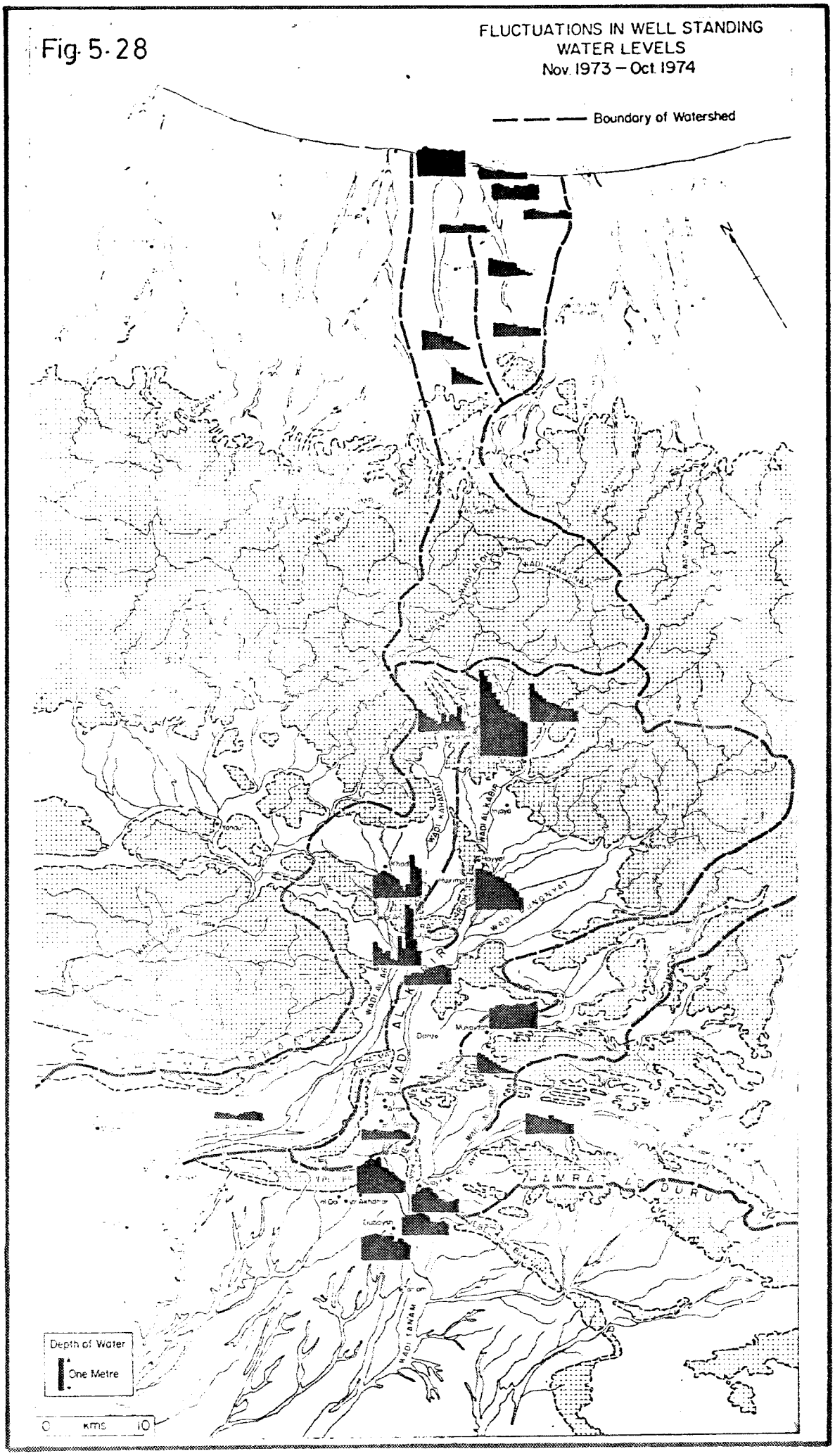
(transmissivity being the product of permeability and aquifer thickness). The largest changes in water levels occur where hydraulic gradients are steepest (see figs. 5.27 and 28). Thus, a fall in water level also decreases the gradient of the piezometric surface. As flow through the aquifer is directly related to transmissivity, hydraulic gradient and width of the aquifer and two of these terms are reduced by a lowering of water levels, through-flow obviously also decreases as a result of water level declines. This affects wells yields as much, if not more than falaj supplies.

Wells are affected in two ways. Firstly, the flow into the well, as the flow into a falaj mother well, is reduced. Levels take longer to recover and therefore those wells pumped intermittently have to stand longer between pump workings and, at others, the rate of pumping may have to be reduced. Secondly, the efficiency and discharge of the pump itself, is affected considerably by changing pumping water levels (see fig. 8 , Chapter 7). This is particularly true for medium lift pumps whose output is much affected even by small changes in suction head. Thus, a 3" x 3" pump with engine working at half speed from 10 metres, a fall in water level of 2.5 metres, means a drop in output from around ten litres/second (130 gpm) to six l/s (80 gpm). and from fig. 7.4 , a four metre increase in suction head caused a reduction of discharge from 13 l/s (175 gpm) to 4 l/s (550 gpm). To keep pumps working efficiently, farmers try to keep pumps as near pumping water level as possible, thus with increasing acuteness of drought and falling water levels, pumps and engines are lowered.



Fig·5·27 AVERAGE RATES OF CHANGE IN WATER LEVELS 1973-1975 DHAHIRA

Fig. 5-28


FLUCTUATIONS IN WELL STANDING WATER LEVELS
Nov. 1973 – Oct. 1974
Boundary of Watershed
N
WADI AL AIN
WADI AL KABIR
WADI LINGWAT
WADI TANAM
Depth of Water
One Metre
0 kms 10

ii). Changes Prior to the Period of Monitoring.

While monitoring has only been carried out for some sixteen months, evidence was collected on longer term fluctuations to put this short period of observations in a longer term context, and to give some idea of the overall trends in the past ten years. Indicators used included the recent history of wells since pump installation, the need to lower the pump platform, declining yields, and recent well deepening. Rings of calcium carbonate deposited on pump pipes and even the number of additional lengths of rope added to scoophole buckets, helped to give an indication of increasing depths to water. Questions of changing yield were only made to farmers with pump wells more than two years old. On younger wells, changes have usually not had time to be very marked, and are complicated by the improving of the well or adjusting to initial increases in crop areas. In falaj settlements, information on falaj extension, previous crop acreages, changes in water costs and time taken to fill cisterns, was collected. It appears that, despite frequent and vague claims of declining falaj flows, no real evidence could be produced of such declines between some twelve and four years ago.

At Tan'am and Dariz in particular, evidence of falling water levels is common, partly because these two areas have the oldest pump wells, and therefore have seen the greatest range in levels. A ten year-old pump well at Tan'am has a ring of precipitate 3 m. above SWL. A mark was found 1.8 m. above SWL on a five-year old well, while a well three years' old had a mark one metre up. Such a sequence suggests a regular and progressive decline in water level of some 33 cm./year over the last decade, which is similar to the 36 cm/year observed in a bucket well in the area in 1973 - 75. Evidence of falling levels also come from the siting of new auxiliary pumps at lower levels than the original pumps.

Apart from change in level, lesser amounts of available water were also noted at Tan'am. Of 23 farmers, 12 had noticed marked decreases in well yield, while 6 estimated that yields had not changed. Data was difficult to obtain on this as, where wells had changed hands recently or were irrigated by bīdar at some stage, or extracted only a very small amount of water, information was not available (as for 5 wells in Tan'am). 'Don't know' answers, therefore in this case do not mean a greater likelihood of no change. Where no improvements had been carried out, it was possible to get some measure of the change in yield from the lengths of time the pump had been able to work during the first year after installation, and at the present time. Usually, however, improvements had since been made where yields had fallen and so the fact could only be recorded without an estimate of its magnitude.

At Sulayf, pump owners were perplexed as to the procedure for raising the pumps and building a higher platform after the inundation of pump sets following wadi flows of February 1975. This perplexity suggested that, since pumps were installed, seasonal fluctuations in water level had never led to any action other than further lowering of the pumps. There was, at this time, no history nor experience of pumps needing raising in response to a marked rise in water-level. This suggests that in Spring 1975, pump sets which had been moved since their original installation, had reached a lower level than at any time in the last 10 - 15 years (since they were apparently not engulfed by the wadi flows of 1972). Of the farmers, 2 claimed that yields had not decreased, 14 registered some degree of decrease and 9 did not know.

At Ibri, few signs of a marked fall in water level were observed. The well (526) which had had a pump longest (25 years) has an old collec-

ting chamber approximately 1.2 m. above the present SWL, but others provided no evidence of a major change in level. On the other hand, ten well-owners mentioned declining yields on wells more than two years old. Only five had no indication of lesser water available, while eight could provide no reliable information.

At Arāqi, only two wells had noticed a marked fall in water-level, but no change in yield. Six had had to reduce the working rate of the pump and two had carried out improvements. The majority of the wells are less than two years old.

At Darīz, there are signs that levels have been falling previous to the study period. Eight wells have lowered pumps - three of them three times since installation six to seven years ago. Only one well, 640, mentioned declining yield but, of the remaining 22 wells three years old or more, for which data is available, 13 have carried out improvements since those undertaken when the pump was originally installed. Nine have registered no change.

Upstream of Darīz, wells generally irrigated lesser areas of crops, so that any loss of pumping efficiency was seldom critical to the supply and so was not easily apparent. Another factor is that the re-development of mountain zagira wells is a more recent phenomenon than downstream - the average age of these as pump wells is under two years (1.8 years), so that pumps have mostly been installed allowing for the lower levels of the water. Problems will arise here, as they did in Sulayf, when re-charge leads to a sudden rise in water level. Even when used with ox-lifts, however, it seems that levels fluctuated considerably. Depths of wells being converted to pumps, depths below standing water levels in 1973, were generally greater than those

necessary to provide required yields (around 3 l/s) of ox-lifts, suggesting that since their original excavation the wells had suffered periods of lower yield. On the Bātina, no decline in yield was noted, nor were marked changes in standing water level.

In the five major groups of wells in the Interior, information exists for just over 75% of the wells over two years old. Of these, 70% have been noticeably affected by increasing water shortage. This is approximately one in two of all the wells in the Interior part of the field area. Of the 30% (28) who have not been noticeably affected by change, 20 were wells with unlimited pumping at the rate they preferred. For these, the decline may have been in a range above that of the capacity of their pumps, and has, therefore, not yet fallen to a level where the change may be registered. Degree of decline, or presence or absence of evidence of it, appeared to be independent of lower extraction rates. Thus, previous to the period of fieldwork and continuing on into it, there appears to be a general trend towards falling water tables and declining well yields, and calculated storage, and specific capacities should be regarded in this light.

iii). Changes Recorded During the Period of Monitoring.

Data collected during the period of monitoring are presented graphically in the Appendix, Section III. Flow variations have already been mentioned, and similar patterns can be identified for water level changes (see fig.5.28).

Differences are apparent between catchment systems, primarily because of the aspects of varying morphology and re-charge events. Thus, in

the Interior, the wadi Juffra wells show a very erratic rise and fall in conjunction with the April to July run-off events, while the al Kabir wells show a steady decline above Tawi Qarn Kabsh and below the Ibri gap, as do those catchments to the North of the mountains. Those wells at Tawi Qarn Kabsh and Muqaydha/Bāt with the East-West flowing Bilād Shahum and al Hijr systems, however, show a gradual rise, which is not noticeable during the time span studied, south of Aynayn and Araqi. This suggests a considerable delay in the transmission of response to re-charge events which occur in a limited area of the catchment. This is supported by the apparent delay of two months between a rise in water level at Qarn Kabsh and an increase in flow at Aynayn mother well, 15 Km downstream. In contrast, response of a rise of 1.5 metres in water level was observed at Dubayshi within 12 hours of a wadi spate two kilometres away. Types of ground water response and variations in delay, obviously need further investigation but it is not possible to undertake statistical correlation on a varying time base, using the collected data, as some rainfall events directly effect several monitoring points, while in others, any response to recharge is only via pressure waves through the aquifer, from a site subject to direct recharge to one where no rail fell and no wadi flows reached. It has not been found possible with the systems examined over such a short period of sixteen months to separate these different effects, without too large a measure of subjective interpretation as to which responses should be discounted. It is felt that a much closer network of rain gauges and monitoring sites is necessary and so perhaps concentration on one system over an extended period of time to make this possible.

While differences in overall catchment responses are apparent during the period studied, variations can also be categorised within catch-

ments, according to distance from the watershed. Maximum drop in static water-level occurred in the mountain region, where deep gravels of limited lateral extent overlie an aqueclude. Falls in level of 2.5 metres in 12 months were encountered in several places on both sides of the mountains. On the north side, possible measuring points were limited, as most settlements and fariqs obtain water from points at which supplies occur at or very near the surface. At these points, aquecludes force water to the surface and so form major irregularities in the hydraulic gradient. Fluctuations in level were, therefore, small, and it was speed of flow which varied more in response to drought. (see site 306, Appendix, Section III & fig 5.28).

Once on to the alluvial fans North of the mountains, however, levels varied by as much as 3.5 m. in 12 months. This led to the abandonment of three drinking wells and the movement of those who had used them to other wells, and so to concentration of flocks, and problems of over-grazed pasture. As hydraulic gradients and transmissivities lessened, so did the rates of decline. By approximately May 1974, the fall in standing water level had begun to level off in all the upper catchments. In the wadi Juffra, ground water reserves were at this point augmented by rain in Kahanat-Khadil area, so that neither the wells nor the falajes of this catchment experienced declines in yield of the same order as those in the other wadis.

On the inland side of the mountains, the fall in levels decreased as the gaps were reached. In the gaps, the change was less than 20 cm/pa, and beyond them increased to around 35 cm/pa. The larger declines here may be related to increasing water use upstream and within the Tan'am area itself.

D. Conclusion.

i). Effect of Fluctuations in Yield on Exploitation of Ground water.

Changes in storage and water levels are greatest at the upper end of catchments. It might be expected that wells offered more flexibility than falajes in this situation, but in fact it appears that it is these fluctuations which are a major factor in keeping down the number of pump wells in the area. Rapid response to rainfall means that pumps lowered to be near standing water level at periods of water shortage, may easily become inundated and are then extremely difficult to recover and repair. Mountain falaj systems, however, are geared to low flow and often allow enormous wastage of water to avoid over-filling and damaging channels within the palm groves during periods of more plentiful water. In such an environment, however, the best solution is to have submersible pumps or belt-driven centrifugal pumps, which mean that only the pump has to be raised or lowered and the prime mover can remain at the surface. While Kirloskar pumps were found to be keen to introduce such belt-driven units, no farmers in the area had installed one.

Reliability of supply increases with storage volume and thus the settlements in the lower catchment zone, and those at the junction of major wadi systems, have most dependable supplies. Both falajes and wells can rely on far smaller changes in yield than upstream systems. Thus, the areas of perennial crops, relying on year-round - and in the case of palms at least twenty years of consistent supplies - can here be greater and it is here that the major settlements are established. The desert foreland offers equally good conditions for wells, but low gradients and so long tunnel section for falajes make it a less suitable

area for falaj development. It is, however, the area where further development of water abstraction can do little harm to existing sources, water is near the surface and fluctuations in water level are relatively small. It is possible, however, that over extraction may lead to a decline in water quality.

ii). Importance of Recession Curves.

In terms of what can be deduced from falaj recession curves, the existing data really only indicates the possibilties and shows the areas where further research may be particularly rewarding. If resistivity or seismic surveys can be used to give a better idea of the volumes of wadi fill, both cemented and uncemented, study of recession curves will help fill in on where the collecting area of a falaj is, how the ground water flow is affected by wadi diversion, and what proportion of rainfall acts as effective recharge. These are all basic questions, but ones of great importance in the provision of greater accuracy to water resource assessments of the area, and a better understanding of the interrelationships of the different ground water elements involved. To reduce the time necessary for monitoring to provide answers to these questions, a greater density of observation points is necessary, particularly of wells near falaj sources.

V. SOME CONSEQUENCES OF AQUIFER DISTRIBUTION ON WELL AND FALAJ DEVELOPMENT.

i). Spacing of Points of Abstraction.

The distribution and transmissivities of the aquifers observed already affect the working routine, irrigable area and demand for land within the area. In addition, it is suggested that, as pressure on land increases, they should also be used as a basis to reduce risks of interference between users, particularly well and falaj systems.

It has been shown that in the normal working regime of wells within the two main aquifers, from which most water is abstracted, drawdown is reduced to around ten centimetres 100 metres from the pumping well. Such a reduction in head will cause little additional decline in yield (except in the shallowest of aquifers), to that caused by dewatering at the pumping well itself. Thus, 100 metres may be taken to be a safe distance for relatively interference-free wells within both conglomerate and less cemented gravels. A lesser distance is permissible in the shales but here permanent depression of the water table is likely and the general poor quality of the aquifer and its water, coupled with high costs of excavation suggest that there will never be sufficient demand for wells tapping this rock to justify close well spacing.

Wells in conglomerate and gravel are at present sited considerably closer than 100 metres from falaj channels where these are still underground - particularly at Sulayf and Ibri. While the channels at the points concerned flow above the water table, ridges of saturated ground have formed underneath them and may, as at Dariz, fan out over a large area. A depression of the water table at these points will increase seepage rates from the channels and it is therefore suggested that such channels should be lined or operating wells be kept

out of a zone 100 metres broad, extending each side of the falaj.

It is unfortunate that transmissivity/specific capacity values are at their least reliable within the wadi gravels, for a value combined with aquifer width and hydraulic gradient, would give a flow through value for the main path of ground water flow in each wadi. Until such values are available, there must be considerable grounds for restricting the development of pump wells in competition with falaj sources. If the falaj takes a major proportion of the flow in the gravel, then particularly in Western Araqi and South Dariz, well development will need to be limited to protect the Ibri and Aynayn falajes. Should it appear that the falajes only use a small proportion of the total flow, then controlled well development could be envisaged, but is still likely to encounter stiff local opposition. Already in 1975, all Araqi and Aynayn wells to the West had been ordered to stop pumping for a trial week at the order of the wali of Ibri, to see the effect on the falajes.

ii). Relative Success of Well Development, Judged by Well Yields.

If specific capacities are combined with depth of well in the saturated zone, or rather the depth at which the pump intake is set within this, the maximum operating yield of each well can be calculated. If this is considered, some measure of the success of wells can be obtained both with regard to aquifer and siting, without consideration of actual abstraction routines and any other constraints.

In terms of well development in any one area, results vary from one group of wells to the next. 'Success' is here categorised as being at a maximum where a well has a yield of more than 750 m^3/day of

water (or around 200 m^3 in six hours). This is equivalent to being able to pump at a minimum of approximately 110 gpm (8.4 l/s) - the average pumping rate for wells in the Dhahira for over six consecutive hours.

At the other extreme, very poor wells are considered to be those which have a yield of under 100 m^3/day, and which at an output of 110 gpm (8.4 l/s) can pump for less than three-quarters of an hour in a 6-hour working day. Intermediate to these two extremes, wells are divided into moderate and mediocre. The former being those of 750 m^3 - 425 m^3/day, which therefore can supply a minimum of three and a half hours work in a six-hour period at 110 gpm, but do not have unlimited pumping at this speed.

In the area studied, there appear to be three common aquifers which are found at a variety of places, but which are fairly similar in lithology at these different points. These are the unconsolidated wadi gravels, the well-cemented conglomerates, and the shales and siltstones. Other aquifers which are found, appeared to be typical of and confined to a certain area.

Of these three, the wadi gravels provide the most successful wells (see Table 5.3) and, in the cases of falajes from the same source, springs of up to 12,000 m^3/day exist within this aquifer. Those which tap conglomerates have an almost equal chance of being successful or unsuccessful, while those in shales have little or no chance of medium or high yields.

Table 5.3. Success of Wells in Different Aquifers.

(Dhahira) Aquifers,	Good over 750m³/day	Moderate 750-425m³	Mediocre 425-100 m³	Poor 100-0 m³	No. of Wells.
Wadi gravel	86	14	0	0	22
Conglomerates	22	21	35	22	81
Red Shales	0	0	25	75	24

In terms of the success of wells in different areas, the distribution of aquifers mean that of the coastal wells, 100% are truly successful, while in the Interior only a quarter come into this category, (see Table 5.4).

Table 5.4. Success of Wells by Area (expressed in percentages).

Area	750m³+	425-750m³	100-425m³	0-100	No. of Wells
Darīz	22	22	39	17	40
Tan'am	44	18	23	15	34
Arāqi	26	6	39	29	31
Ibri	14	24	25	37	43
Sulayf	21	16	39	24	38
Mountains	21	14	29	36	14
TOTAL:	26	19	35	20	200

Taking the Interior groups individually, the best results are to be found at Tan'am. Here, almost two-thirds of the wells are successful or moderately so, with almost half in the top category. This is ascribed to the availability of funds for well improvement among the Duru' and to the widening of the line of deep wadi gravels at this end of the catchment, both of which increase the chances of a successful well.

Dariz wells are next in quality, with approximately one in six wells of very poor quality - these mostly peripheral to the main area of wells. It appears that further well development would be most successful East of the present wells, following the line of major yields back up towards the present course of the al Hijr, near Muqaydah. This land is part of the awabi of Bat falaj and parts of it are still sometimes used for falaj irrigated winter wheat.

At Araqi, a quarter of the wells are very successful, but few are moderately so, so that over two-thirds (68%) are of low productivity. This is partly because of the presence of only a very narrow band of wadi gravels, and the contrasting broad extent of the red shales and vertically bedded mudstones, which cover the area to the East of the oasis. Those wells in marls and poorly cemented calcareous sandstones have been no more fortunate than those on the shales.

The probable area best for well development at Araqi is to the West, in the area of the wheat awabi of Aynayn, and further North towards Khatmat Aynan. It is suggested that the main stream of ground water in the Wadi al Kabir runs in this area, and this is supported by water quality evidence (see p. 134). It is, however, unlikely that this area will be exploited for pump well irrigation in the foreseeable future. The main reason is that this is the area in which Ibri's main falaj, falaj Mafjur, rises. At least until considerably more is known about the volumes of water flowing along these lines of submerged wadi gravels, any possibilities of increasing already bitter conflict between well and falaj interests should be avoided.

At Ibri, the best wells are those nearest to the falaj, and here again public feeling has generally been a factor in limiting well development,

especially in the area of 520. To the East of Mabu'ath, results are anyway poor, as they are in the fringe areas to the West, where the red shales again are the only aquifer. Because of the limited area available for well-farming here, wells have spread onto the fringe areas and consequently a high proportion (almost 40%) of wells are failures, and several have actually been abandoned.

Ibri cannot, therefore, offer many new areas for wells, except filling in the gaps between existing wells North of the gap, and out to the South, towards Wells 021, and 022, where prospects are not good. Ibri people who wish to set up well farms are, therefore, looking further afield for land, towards Tan'am, into the Wadi Tayyib, and around Sulayf.

Sulayf itself has very limited areas for well development south of the gap. The majority of the one in four 'failure' wells found here, are to the South and West of falaj Hakkab and Bilad lands. Near the wadi where the best wells are found, available areas are limited by falaj irrigated land and existing well farms. On the Shimbu side of the wadi, gravel ridges confine the irrigable area, so that there is little room for well-farming. Those who wish to dig wells, are forced more and more into the poor areas where the conglomerates appear to be of very low transmissibility, or to move out of the area near their houses to land North of the gap (al Krain). This offers a greater chance of success.

Upstream of these five areas, well development is still mostly limited to the renovation of zagira (see p.365) wells. The results are often mediocre to poor (65%) but volumes to irrigate extensive areas are seldom required. In the recent drought, however, the decline in falaj

flows, especially at Injayd and Miskin, caused several falaj garden-owners to dig wells. The nearest area of potential was Hawmaniya, which originally had some 40 zajira wells. Most of these have since become filled in, but the area is becoming increasingly popular for well-farming by mountain villagers of the upper al Kabir and Bilad Shahūm. The results are moderately successful, with larger areas available for irrigation than on mountain terraces and smaller fluctuations in water level than further upstream.

In the area as a whole, the tendency until recently has been to dig wells as near to existing settlements as possible, both on the Bātina and inland. In both areas, the opportunities are getting fewer. There is now a movement to site wells away from existing areas of irrigation. On the coast, this has led to the setting-up of farms of a very different character, towards the new coast road, without palms as the major crop.

In the Interior the move is small, but should continue as it is realised that the areas surrounding the present groups of wells, especially at Ibri and Arāqi, suffer from disadvantages of poor chances of success, or else of interference with existing falaj supplies.

The major areas of potential in terms of aquifers would appear to be, a) East of the Darīz wells, b) North of Sulayf, up to the Wadi Tayyib, and c) between Dubayshi and Tan'am and, on to the South, d) an area around the junction of the wadi Bilad Shahūm (Munqnyat) and al Kabir. Of these, the last area has the best quality water, and Tan'am and Darīz the poorest, but it is not generally poor enough to be an obstacle to well irrigation. (See Chapter 8, pt. III, B).

Finally, the use of drilling rigs is unlikely to become common on behalf of individuals. Production bores cost in the region of £300/ metre each in 1977, and few can afford such an outlay, especially with results unlikely to be much more successful than for hand-dug wells. In 1975, Wimpey were drilling for water supplies for road making, requiring a yield of around 325 m^3/day. They were successful with less than 40% of their trials. Hand-dug wells are, therefore, likely to be the only suppliers of water other than falajes in the near future, and are better suited than drilled wells; with their larger diameter there is more chance of their reaching a pipe or fissure flow.

iii). <u>The Suitability of Single Point (falaj) or Multipoint (well) Systems in the Local Hydrogeological Environment.</u>

While observed aquifer yields are important in an assessment of areas where further development is possible, they are also a major factor in considering the future of falaj systems and the degree to which pump wells might replace them as the major source of irrigation water.

Of the aquifers studied in over 400 wells, on the coast and in the Interior, maximum pumping capacity at irrigation wells was found, without exception, to be associated with poorly cemented alluvial gravels. In the space they occupy, the gravels of the buried valleys are of very limited extent, comprising less than 5% of recent wadi floor sediments in the Interior. In terms of water supplied, however, they produce some 80% of all Dhahira water extracted. Thus, in an analogy with water supply pipe systems, they can be regarded as a supply main, carrying the major flow of water. This supply main is tapped by a set

of distribution mains, the falajes, which lead water off to areas of soil suitable for irrigation and cultivation.

The supply main (buried wadi gravel) seldom passes directly under a settlement and this is of significance to well development, for it means that replacing falaj flows by wells in the date groves could not provide comparable amounts of water on a permanent basis. Both quality and yields of most wells in falaj irrigated lands are low, and the wells are very expensive to dig in the well-consolidated rocks which underlie them. Yields are so poor that few of the wells so far excavated within the existing date groves have spare water to offer to other adjoining gardens, but wells in every garden would be very expensive (see p. 411) and would cause problems of a permanent and widespread lowering of the water table. In Arāqi, the only settlement with pump wells spread throughout the date groves, some 150 wells would be needed to replace the flows of the two falajes. In Ibri and Darīz, even more wells would be required, with a sacrifice of water quality (see p. 140).

To abandon the supply main/distribution main pattern described and to adopt wells at the points where water is required, is to ignore the advantages that the aquifer system contains, and to use it inefficiently. To obtain the best water at lowest cost, requires extraction from the gravels and transport of water to the areas of demand. Falaj water extraction is very well adapted to this situation. It would also be possible to extract water by pump and to conduct it by pipe to the settlements. In either case, the characteristics of the aquifers and their distribution are such that the future of water supply to the existing Interior villages would appear to continue to lie in communal systems, not individual sources for each garden owner, if the most efficient use of available water is to be made.

The more widespread occurrence of highly conductive aquifer within the coastal strip, is well-suited to the establishment of a high density of wells, in preference to the single or dual point source of a falaj. It would appear from abandoned channels that falajes with sources over 10 km away did, at one time, water crops near the coast (as they did at Sohar). They have, however, been replaced by wells which allow greater flexibility and individuality of operation (see Chapter 7) and are well suited to the relatively homogeneous ground water conditions.

Examination of the hydrogeological environment indicates those areas where further development of water abstraction may take place with a reasonable chance of success. The suitability of existing methods for lifting water has been assessed in principle, but without yet looking in detail at the practices. At the same time, water balance calculations and the constant falls in water-level noted in 1973 - 1975, suggest that no great increase in abstraction may take place, either on the coast or in the Interior, without affecting those sources of supply already established. It is, therefore, necessary to consider the existing systems of water abstraction and use, to see how well in practice, they are adapted to present physical, social, economic and agricultural conditions. If agriculture is to expand without an increase in water abstraction, it is also necessary to examine the efficiency of the systems and the degree to which wastage of water can be reduced, before there can be any real control and management of water resources in the area.

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