SULTANATE OF OMAN

Water resources survey of Northern Oman

ARCHIVE

SUPPLEMENTARY REPORT

OF

INSTITUTE OF HYDROLOGY

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PREFACE

With the completion of the detailed agricultural and soils studies, it is desirable to estimate the limits of the available water resources so that a programme of agricultural development can be defined. It is not easy to provide good estimates at this time; the full programme of the current water resources survey has at least a further twelve months to run and the long period of dry weather without substantial rainfall in the mountains, means that we cannot as yet determine such important factors as the extent of recharge in the alluvial areas.

Nevertheless it is timely to present some form of resources estimate based on the limited data now available so that we can show where further information is required. For the alluvial plain of the Batinah we can now identify the hydrogeological constraints on the availability of groundwater.

We have approached the assessment of available water resources in two ways. Firstly, through estimates of rainfall and runoff from the hard-rock of the mountain limestone and ophiolites, we have estimated the resource at the boundary between the hard-rock and alluvial areas. Some of this runoff will go to recharge the aquifers; some, during floods, will follow the wadi channels and will be lost to the sea in the north or to the desert areas in the south. We have made a preliminary estimate of this division of flow, albeit on circumstantial evidence, in order to determine the order of magnitude of the water resource currently available for agricultural development in the alluvial areas.

Secondly, for the Batinah, we have analysed the hydrogeological information now available in order to determine the physical constraints governing the availability of groundwater. Despite the poor quality of the data currently available concerning aquifer properties, we have carried out a flow net analysis to determine the flow of groundwater towards the coast.

We must stress the tentative nature of these preliminary estimates. They are based on many assumptions. As the survey progresses we shall be able to reduce the level of uncertainty in many areas. During the final stage of our study as better data become available from the exploratory drilling and pumping test programme, we shall develop models of the aquifers. These will enable us to balance recharge and abstractions in a dynamic system whereby we can determine the water resources more accurately and attempt to determine the effects of development of these resources.

1. RAINFALL AND RUNOFF

1.1 Introduction

The major source of water is rainfall on the Jebel Akhdar range giving rise to flows in the wadis and eventually to recharge in the alluvial aquifers. Direct recharge as a consequence of rainfall on the alluvial areas is unlikely to be significant other than from very local and infrequent storms. Experience elsewhere suggests that annual rainfall in excess of 250 mm is required before direct recharge becomes significant. Our preliminary estimates of runoff are therefore confined to the hard-rock areas which comprise the limestones of the Jebel itself together with the surrounding ophiolite hills.

There are no historic data for either rainfall or runoff from these high altitude, hard-rock areas. Neither has there been any widespread rainfall during the period that the network of raingauges has been in operation. Thus our estimates of the rate of increase of rainfall with altitude and of the distribution of rainfall between runoff and losses by evaporation and infiltration must be based largely on experience in similar situations elsewhere. In consequence the estimates are subject to considerable uncertainty. Long periods of record are usually required before reliable estimates of runoff can be derived especially in dry areas.

For the purposes of this analysis, the study area has been divided into ten major basins defined by the wadi systems shown on the 1:100,000 scale maps. Topographic information has been obtained from the 1:250,000 scale maps. Further sub-division of the basins according to geology and drainage pattern was made in order to study the effects of different assumptions concerning rainfall and losses on the estimates of runoff from the major basins.

The two maps, Figures 1.1 and 1.2, show the main features of the topography and the geology on a scale of 1:250,000. Both maps show the boundaries of the major basins and on Figure 1.1 we have indicated the approximate division between hard-rock and alluvial areas used in this analysis.

1.2 Rainfall variation

The seasonal and spatial variation of rainfall would seem to be related because of the two distinct climatic influences affecting the Northern Oman region. During the winter months the air flow is predominantly dry air from the north. This flow is interrupted by depressions moving from the west via the Mediterranean which bring some winter rainfall to the area north of the Jebel Akhdar. Only occasionally is winter rainfall recorded at Nizwa. In the summer months, the Northern Oman region lies in an intermediate zone between the hot dry air flow from the north-west and the relatively moist monsoon air flow from the south west. The high Jebel Akhdar range tends to act as a barrier to the northerly penetration of the monsoon air because the air flow is relatively shallow at this distance inland. Hence north of the Jebel there is little if any summer rain; south of the Jebel summer rainfall can be substantial in some years although it is highly variable both in amount and time of occurrence.

Although these general indications cannot yet be fully illustrated with rainfall data for the high Jebel, the historic rainfall records for Muscat and Nizwa, shown in Tables 1.1 and 1.2, support the seasonal distribution suggested. Thus we can assume that runoff north of the Jebel will tend to be a winter phenomenon, whereas in the Interior,

Table 1.1

MONTHLY RAINFALL AT MUSCAT

(mm)

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

Notes:
1. These data refer to a gauge at the British Embassy, except for the period March 1966 to December 1970 when the data refer to a gauge observed by PD(O) at Mina Al Fahal
2. Missing data are indicated by no entry in the Table
3. Additional data exist covering a period of at least 38 years. At present the monthly or daily records cannot be traced.

Table 1.2

MONTHLY RAINFALL AT NIZWA
(mm)

	J	F	M	A	M	J	J	A	S	O	N	D	Total
1963	0	0	0	4	131	0	28	0	14	0	29	0	206
1964	6	12	7	29	0	0	21	0	0	0	0	7	82
1965	56	0	0	109	0	0	13	9	0	0	0	0	187
1966	0	20	0	0	0	5	48	6	6	26	0	0	111
1967	0	0	15	128	0	47	11	0	0	0	0	0	201
1968	5	157	0	24	0	0	0	0	0	0	0	0	186
1969							0	0	0	0	0	0	
1970							147	132	102				
1971													
1972	64	135	60	235	0	3	89	6	17	0	0		

Notes: 1. The gauge is at the experimental farm Nizwa

2. Missing data are indicated by no entry in the Table.

runoff is more likely to occur in the summer months.

The remaining principal factor affecting the distribution of rainfall is altitude. In the absence of data we must rely on information from areas which could be considered analogous to Northern Oman. As might be expected there are few areas in a similar transition zone between monsoonal and Mediterranean climatic influences and none for which the appropriate records are available. However there are areas subject to one or other of these climatic influences for which analyses of rainfall variation with altitude have been carried out.

The Zagros mountains in western Iran have a rainfall gradient of 300 mm per 1000 m.[1] There the rainfall is confined to the winter months and snow is experienced at higher altitudes. By contrast the rift valley region of Ethiopia has rainfall only in summer and the rate of increase with altitude is about 400 mm per 1000 m.[2] In each case the rainfall gradients hold for a large range of altitude and for a wide geographical area. Data for other areas less similar to the Northern Oman region also suggest values in the range 300-400 mm per 1000 m.

The evidence available suggests that in terms of the average annual rainfall, the variation with altitude is broadly similar despite the major geographical and climatic differences. Thus in the absence of local data, we must assume that the variation of rainfall with altitude is the same on average for the northern and southern slopes of the Jebel. We have assumed a rate of increase of rainfall with altitude of 300 mm per 1000 m from an average annual rainfall at the coast of 100 mm. This can be written as;

$$R \text{ (mm)} = 100 + 0.3\, H \text{ (m)}$$

where R is the average annual rainfall at altitude H.

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1. Sutcliffe J V and Carpenter T G. The assessment of runoff from a mountainous and semi-arid area in western Iran. Proc. General Assembly IASH, 1967.

2. Feasibility study of the Lower Awash valley. Unpublished report, Sir Alexander Gibb & Partners, 1974.

By working in terms of the long-term average annual rainfall we avoid for the time being the problems of variability both in terms of differences from year to year and in terms of rainfall frequency and duration within the year.

The average annual rainfall on each of the major wadi basins was calculated by considering the average rainfall on each sub-basin area within predetermined ranges of altitude. The altitude zones were defined by the 300 m, 600 m, 1200 m, 1800 m and 2100 m contours from the 1:250,000 scale maps. For each altitude band, the average rainfall was determined by a representative altitude, usually the mid-point of the altitude range. The average rainfall in the sub-basins and hence in each of the major basins was calculated by weighting according to the catchment area in each altitude range. These average annual rainfalls are shown in Table 1.3.

1.3 Runoff from rainfall

The major factors affecting the quantity of runoff from a given rainfall input are the losses by evaporation and by infiltration to deep aquifers in the hard-rock area itself, and the intensity of the rainfall.

We have some evidence from the Zagros mountains that in a semi-arid area, the actual evaporation loss tends to be independent of altitude. The effect of a lower potential evaporation at higher altitude is balanced by the increased rainfall giving greater opportunity for evaporation. Thus the actual evaporation loss is fairly constant. This need not be true for Oman where potential evaporation is relatively higher throughout the year and even at the higher altitudes it could always exceed the rainfall.

The intensity and frequency of rainfall is an important factor when there is significant soil storage. Infrequent, intense storms would lead to greater runoff than would occur from the same depth of rainfall spread over a longer period. In the latter case the soil moisture store would sustain prolonged evaporation as the storage would be

Table 1.3

SUMMARY OF TOTAL RUNOFF ESTIMATES FOR THE HARD-ROCK AREAS

Basin	Area km^2	Av. rainfall mm	Runoff volume mcm (20% rainfall)	(rainfall-evaporation)
Northern Basins				
W. Samail	1499	298	90	68
W. Ma'awil	556	300	34	33
W. Bani Kharus	753	408	62	96
W. Far	779	336	49	51
W. Bani Ghafir	617	399	49	76
Total	4204	340[1]	284	324
Southern Basins				
W. Haylayn	264	428	22	35
W. Muaydin	225	584	26	64
W. Nizwa	434	474	42	77
W. Bahla	636	437	55	91
W. Sayfam	252	432	22	34
Total	1811	462[1]	167	301

Note: [1] These values are weighted averages taking account of basin area more frequently replenished.

Substantial infiltration into the limestone does not seem likely as there is a relatively low outflow from springs and much of this is at a high temperature which suggests a deep-seated origin. Infiltration into the ophiolites can be discounted; they are effectively impermeable.

We have very little evidence yet of the importance of these various factors on the Jebel Akhdar range. Thus our estimates of the quantity of runoff likely from the assumed average annual rainfall are very tentative. We have adopted two alternative assumptions. The first is based on an average evaporation loss of 300 mm per annum suggested by the Zagros study. The second is a runoff coefficient approach whereby runoff is a constant proportion of rainfall alone. The latter approach is less justifiable on physical grounds although it is equivalent to suggesting that actual evaporation increases with altitude as the rainfall increases. A coefficient of 20% has been used and the estimates of annual runoff for the major basins are shown in Table 1.3.

For the northern basins the alternative assumptions lead to a broadly similar result for the five basins taken together. However the relative values for the individual basins show some marked differences. The assumption of runoff being 20% of rainfall leads to a relatively higher runoff from the Wadi Semail which has a large area of its basin in the ophiolites. The assumption of 300 mm evaporation loss leads to a much lower runoff estimate for the ophiolites, but tends to increase the estimate for those basins such as the Wadi Bani Kharus and Wadi Bani Ghafir which have a larger proportion of their area at higher altitude.

The runoff estimates for the southern basins on the basis of either set of assumptions are not as low as the much smaller basin area would suggest. This is because the southern basins have a greater proportion of their area in the higher altitude ranges. This leads to a higher estimate of average rainfall in the southern basins; 460 mm compared to 340 mm for the northern basins. Figure 1.3 shows the percentage of

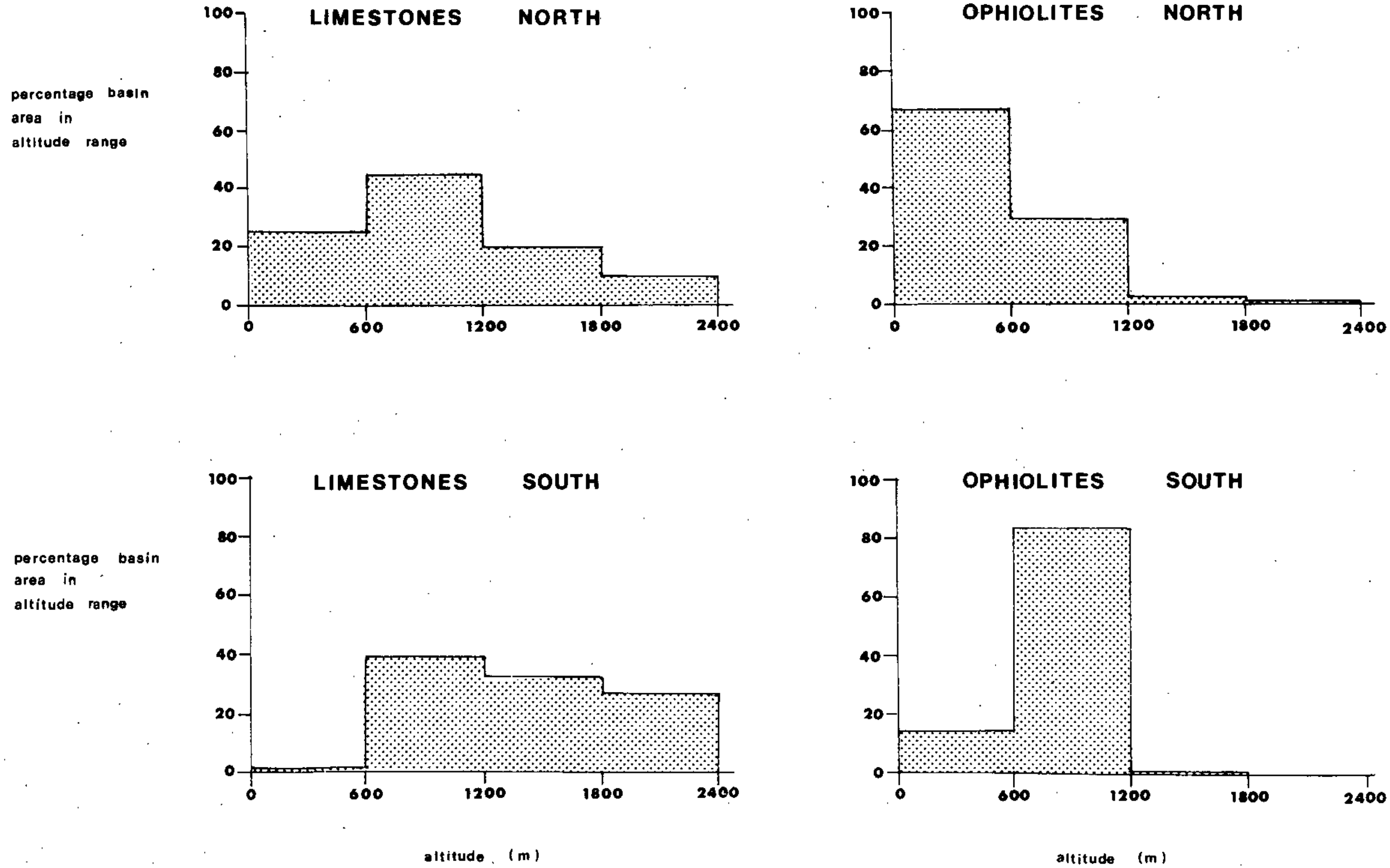

LIMESTONES NORTH
OPHIOLITES NORTH
LIMESTONES SOUTH
OPHIOLITES SOUTH
percentage basin area in altitude range
percentage basin area in altitude range
100
80
60
40
20
0
0
600
1200
1800
2400
altitude (m)
altitude (m)

FIGURE 1.3

the basin area in each altitude range for each of the major rock types in the northern and southern basins. Thus, in summary, our analysis suggests a broadly similar value for the runoff on each side of the main Jebel.

1.4 Assessment of total resources at the hard-rock boundary

The runoff volumes derived in the previous section are estimates of the long-term average runoff. Naturally from year to year there will be considerable variation about the average and there will also be uncertainty as to when, during the year, runoff will occur. Also the estimates are of total runoff. A part will occur as surface flow in the wadis usually during severe storms; part will be base flow from storage in the wadi gravels within the hard-rock areas, and part will result from springs at the limestone alluvium boundary.

We have some evidence of the extent of base flow from the gaugings carried out at Al Khawd on the Wadi Semail by Petroleum Development (Oman) Ltd. They have made measurements of the surface flow once per month from September 1965 to the present although some months were missed and occasionally more than one measurement was made during the month. In Table 1.4 the data are assembled by months without regard to the day of the month when the measurement was made. As such we will assume that they represent a set of monthly average flows. An exception to this approximation would be the five highest flows - underlined in Table 1.4 - which probably relate to floods of a few days duration and, as such, they are unlikely to represent an average base flow.

For the Wadi Semail the average annual base flow is about 15 mcm at Al Khawd for the period of the record. The additional base flow in the wadi gravels at this point will be very small by comparison because the bed rock is close to the surface. However, in order to estimate the proportion of the total runoff which appears as base flow, we should add additional losses to evaporation due to the significant areas of agriculture in the Wadi Semail basin upstream of Al Khawd.

Table 1.4

SURFACE FLOWS AT AL KHAWD
(1000 m^3/day)

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

Source of data: PD(O) Ltd

Table 1.5

ESTIMATES OF THE AVAILABLE RESOURCES

(mcm)

Basin	Total runoff	Base flow	Flood flow	Water use in agricultural areas	Total available resource[1]	
W. Samail	68	25	43	10	19	(21)
W. Ma'awil	33	8	25	3	7	(8)
W. Bani Kharus	96	24	72	0	31	(21)
W. Far	51	13	38	10	7	(6)
W. Bani Ghafir	76	19	57	0	25	(16)
Total	324	93	231	23	93	(72)
W. Halfayn	35	9	26	6	6	(5)
W. Muaydin	64	16	48	3	18	(2)
W. Nizwa	77	19	58	10	15	(7)
W. Bahla	91	23	68	10	20	(11)
W. Sayfam	34	8	26	0	11	(5)
Total	301	75	226	29	70	(30)

Note: [1] the first estimate follows from the use of the total runoff estimate based on the assumption of an actual evaporation loss of 300 mm; the estimate shown in parenthesis is that which follows from an assumption of runoff being 20% of rainfall.

Allowing 3 mcm annually for each square kilometre of agriculture, there is a consumption of base flow of the order of 10 mcm annually. Thus the potential base flow could be about 25 mcm annually. This leaves 40 - 60 mcm annually as flood flow of which a proportion is lost to sea.

It is difficult to extrapolate these figures to the other basins because the Wadi Semail basin contains a much higher proportion of wadi gravels and it could benefit from a greater inflow from springs than any other wadi. Consequently we would expect a lower proportion of the total runoff to appear as base flow in the other wadis. This is supported by the small base flows observed. There are significant flows only in the Wadi Bahla and to a lesser extent the Wadi Bani Kharus. Thus we have assumed a figure of 25% (rather than the value of 40% for the Wadi Semail) for the base flow as a percentage of the total runoff.

Losses to the sea, or to the desert in the south, could be a large proportion of the flood flows because of the poor infiltration characteristics of the alluvial plains. Only the wadi channels themselves are showing reasonably high transmissivity values on the Batinah. There is as yet no reason to believe that the situation is any more favourable for recharge in the south.

In Table 1.5 we have put all the assumptions together to estimate the effective resource at the boundary of the hard-rock areas. These values are essentially the estimated base flow plus 10% of the flood flows which we consider might be recharged under natural conditions, less an allowance for evaporation from those agricultural areas within the general boundary of the hard-rock area shown in Figure 1.2.

2. GROUNDWATER IN THE BATINAH

2.1 Introduction

In this and the following chapter we present our current analysis of the alluvial aquifer system of the Batinah. This first attempt to provide a detailed regional description of the aquifer characteristics is based upon several programmes of field study all of which are still in progress and our interpretations will be reviewed as additional information becomes available.

Our description of the aquifer system is presented in the form of a classification of the alluvium into three major hydrogeological units. Where possible we have illustrated the regional characteristics by means of 1:250,000 scale maps of the Batinah coastal area. This scale is compatible with the general nature of the regional study; larger scale presentation would imply a more detailed and intimate understanding than is possible at this time.

Some aspects of the study are not being reported at present. For example it is premature to review the hydrochemical data even though large numbers of water samples have been collected during our routine field work. We consider that insufficient subsurface information is yet available to identify the detailed flow processes within the aquifer and hence to understand the hydrochemical identity of many of the water samples. We are providing borehole logging facilities including depth sampling equipment in order to advance this aspect of the study. Similarly our survey of current water use is still in progress and is based on detailed field mapping and recording of existing sources of supply. Analysis of this work will be carried out during 1975 after the completion of this programme of field work.

2.2 Description of the Batinah

The aquifer system of the Batinah is composed of alluvial materials derived from the Jebel Akhdar and deposited in a series of coalescent fans emanating from the points where the wadis discharge from the hard-rock areas. These sediments have built up to form the present gently dipping coastal plain up to 30 km in width. The part of the system studied in sufficient detail to allow a preliminary estimate of the resources extends westwards from Sib over a distance of about 100 km.

The surface distribution of the alluvium is shown in Figure 2.1; it has an area of about 2,425 km^2 and can be divided into distinct areas which we have described by the names of the major wadis associated with them.

		Area (km^2)
Wadi Bani Ghafir		280
Wadi Far		710
Wadi Bani Kharus		400
Wadi Nakhl	Wadi Ma'awil	385
Wadi Al Ajal	Wadi Ma'awil	155
Wadi Taww	Wadi Ma'awil	70
Wadi Halban	Wadi Ma'awil	140
Wadi Semail		190
Wadi Rusayl		95
Total Area		2425

Near the mountains the topographic divides between these wadis are fairly distinct but when traced northeast towards the coast they become relatively obscure and the most recent sediments may overlie older material from adjacent wadis. In Figure 2.1 we show the position of the main wadi gravels based upon the 1968 aerial photography. Analysis of these photographs has formed the basis for defining the boundaries between the areas listed above.

The location of the principal wells and boreholes and their current reference numbers are shown in Figure 2.1. A catalogue of the borehole construction details and pumping test information is given in Appendix B. This catalogue, which provides a summary of the results of the recent drilling programme, also contains records of some older boreholes and others outside the boundaries of the map. The boreholes shown on Figure 2.1 are those which have provided the records used in this analysis.

2.3 Geology

A review of the general geological conditions and of the hydrogeological potential of the area was given in our Post Reconnaissance Report of July 1973. Since then we have confined our main investigations to the alluvial sediments of the coastal plain and in places to the underlying limestones.

Glennie[1] describes the area as follows: " .... Maastrichtian and Lower Tertiary strata are represented by shallow water, partly conglomeritic limestones and deeper-water marls desposited on a Mesozoic carbonate platform upon which the Hawasina and Semail Nappes had been emplaced. Marine carbonate sedimentation probably ceased during the Oligocene or early Miocene due to uplift which formed the present Oman Mountain Range. The products of erosion of the mountain range were desposited in a marine environment in the Gulf of Oman."

The products of erosion comprise gravels, marly and silty gravels, sands and sandy silts, with boulders occurring throughout. The alluvium may be cemented and in places boulder conglomerates occur. Fine grained material is more common in the coastal area particularly where the coastal plain is widest. Since the main purpose of this immediate study is concerned with an evaluation of the water bearing potential of the sediments, we have attempted to classify the deposits according to their aquifer potential rather than by precise geological identity. The results indicate that the alluvium can be described as an aquifer system composed of three units:

1 Glennie K W *et al.* Notes to accompany the Geological Map of the Oman Mountains. Koninklijke Shell, 1970.

Upper Gravels

These are clean gravels with small quantities of sand, a little marl, clay and carbonate cement. They comprise the near surface deposits of the Batinah which when water bearing form a major aquifer. Thicknesses of up to 120 m have been recorded. However in many areas part or the whole of these gravels are above the water table.

Clayey Gravels

The *Upper Gravels* are underlain by much greater thicknesses of gravel which typically exhibit poor aquifer characteristics. Geological samples collected from rotary mud-flush drilling appear as "marly" or "clayey" gravels, and as marls and clays with fine gravel and sand. Carbonate cement can sometimes be identified in hand samples and there must be some doubt as to whether the frequently recorded marls and clays are in fact always a primary constituent. They could at times be a reconstituted carbonate cement broken down by the action of drilling. Up to 600 m of these gravels have been encountered. The beds form poor aquifers although they appear to contain at least one major gravel lens of promising aquifer potential.

Cemented Gravels

At outcrop, and at depth in various boreholes, it is possible to identify coarse clastic material heavily cemented with carbonate material resulting in a virtually impermeable formation. These are normally the older gravels; the most heavily cemented beds being found in the vicinity of the Lower Tertiary Limestone outcrops. The cemented gravels are not easily distinguished from the underlying limestone conglomerates and marls of Lower Tertiary age. We are carrying out a computer analysis of the lithological, drilling and strata penetration data in order to provide a more objective classification than we are able to report at this stage. However since the *Cemented Gravels* and the Tertiary limestones and marls appear to be impermeable, we have not attempted to separate them at depth.

The lithological logs from four representative boreholes are shown in Figure 2.2. Beds of clean gravel and sand with traces of clay or marl are typical of the surface layers and appear to be readily identifiable throughout the area. The presence of silts and clays in the *Upper Gravels* of DW3 is a local coastal feature of the Wadi Bani Kharus area. The *Clayey Gravel* sequence is marked by the first extensive appearance of brown clays or marls which are rarely followed by any deeper occurrence of clean gravel. The grey sands at depth in borehole WD1 are somewhat exceptional although in some areas a thin clean gravel horizon occurs at the base of the *Clayey Gravels*. The underlying *Cemented Gravels* have been identified on the basis of the appearance of white marls and clays.

The strata logs for boreholes DW1 and DW3 demonstrate that at some sites drilling samples indicate gradual changes between the conditions identified as clayey and semi-permeable gravel, and cemented, impermeable conglomerate. The introduction of caliper logging should enable us to locate more precisely the upper limit of the *Cemented Gravels* in future boreholes. Also we are introducing temperature, conductivity and flow velocity logging equipment to confirm the apparent semi-permeable or impermeable nature of these strata in existing boreholes. Our present identifications are based upon yield characteristics, pumping test results and inspection of the various records given in Appendix C to this report.

Borehole records do not readily allow a separation of the *Cemented Gravels* from the underlying Tertiary Limestones. Thus we have taken the base of the *Clayey Gravels* as the most useful indicator of the structural geometry of the higher alluvial beds. Figure 2.3 shows the contours of the base of the *Clayey Gravels* together with the geographical position of the Tertiary Limestone outcrops and the older bedrock areas.

The Limestones, exposed at the surface between the bedrock of the mountains and the main alluvial plain, dip northwards below the Batinah and could be related to the outcrops which form the offshore islands.

The structure contours suggest that two basins exist separated by a ridge of limestones or cemented material. This ridge underlies the Wadi Bani Kharus. The basin to the west is associated with the Wadi Far and Wadi Bani Ghafir; and to the east with the Wadi Nakhl and Wadi Semail.

The combined thickness of the *Clayey Gravels* and *Upper Gravels* is shown numerically on Figure 2.3. There is only some 50 m of uncemented material overlying the ridge whereas thicknesses of over 140 m are encountered in the western basin and over 220 m in the eastern basin although PD(O) drilling indicates some 600 m of uncemented material in the Wadi Semail.

In Figure 2.4 we show the thickness of the *Upper Gravels* alone. A slightly different picture emerges in that there are three basins containing these most recent sediments. Again the ridge in the Wadi Bani Kharus separates a single western basin from the Wadi Nakhl basin. However in the *Upper Gravels*, the Wadi Semail basin is seen as a separate feature. At the coast there is a thinning of the *Upper Gravels* in the western Batinah where they tend to be replaced by sands and silty sands.

The distribution shown in Figure 2.4 seems to reflect the fairly recent erosional history of the area with the greatest thicknesses of gravel occurring in the three major wadis. It does not however reflect the present day situation since river capture has now diverted part of the headwaters of the Wadi Far and the Wadi Nakhl into the Wadi Bani Kharus.

2.4 Hydrogeology

When traced northwards from the mountains the depth from surface to water level increase from about 20 m to over 60 m in the vicinity of the Tertiary Limestone inliers. It is not certain whether groundwater is present at all locations along this outcrop area. Some dry boreholes have been constructed while others have slowly made water over periods of several months. However water is found below the base of the *Upper Gravels* in the areas between the main wadi channels. Figure 2.5 shows the distribution of depth to water table based upon the assumption that hydraulic continuity exists between the limestones and the various sub-divisions of the alluvium. Between the limestone outcrop and the coast the depth to groundwater gradually decreases, and in the vicinity of the coastal agriculture, groundwater is to be found within 10 m of the surface.

Detailed analysis of water level fluctuations in the Batinah is not possible at present. The full network of observation boreholes has not yet been operational for a complete year and there has been no widespread recharge since our study began. Generally it is apparent that water levels are falling only slowly throughout the area despite the prolonged dry period. Along the coast in June 1974 water levels were between 0.01 m and 0.25 m lower than in the previous June. In the Wadi Semail, the Wadi Bani Ghafir and at one site in the Wadi Far water levels were between 1 m and 4 m below the June 1973 level. These changes are shown in Figure 2.6. The confused pattern in the central Batinah area, where water levels at some sites in June 1974 were higher than in 1973, demonstrate the complexity of the early network data. Some wells show rising stages which are due to slow recovery in water level following test pumping several months previously. Other wells show some recovery in water levels possibly associated with a reduction in the quantities of water diverted for irrigation from the wadi gravels of the foothill areas during the winter months.

Falling groundwater levels in the Government and PD(O) well fields are an obvious feature in Figure 2.6. Water levels were some 4 m below the 1973 levels in the observation boreholes. Since June 1974 more rapid changes have occurred and, in some boreholes, levels have been falling at a rate of over 1 m per month. In others water levels have stopped falling due to local recovery when pumping has stopped.

The water table contour map shown in Figure 2.7 is based on the March 1974 water levels. For the few boreholes not observed in March, levels on the nearest date to March 1974 were used. The shape of the piezometric surface indicates low recharge mounds below the beds of the Wadi Semail and Wadi Nakhl, and over the ridge of cemented material beneath the Wadi Bani Kharus. However lack of water level data in the Jammah area prevents contouring of the groundwater surface, and difficulty of access hampers further investigation in that area.

The contours also suggest that there might be recharge along the bedrock boundary with the alluvium. In particular the apparent recharge mound beneath the Wadi Halban warrants comment since there is no major mountain wadi system to provide dry weather inflow to sustain such a piezometric surface. However taken with the anomalous mound on the ridge in the Wadi Bani Kharus, these two features correspond with the thinning of the *Upper Gravels* shown by Figure 2.4. Thus it is possible that these apparent recharge mounds could result from subsurface drainage to the adjacent deeper gravel basins and they need not necessarily be indicative of recharge. However the changes in water level observed to date are relatively small and it is therefore too early in the study to draw any general inferences concerning the pattern of groundwater movement.

Over much of the Batinah it can be shown that groundwater levels are below the base of the *Upper Gravels* which are water bearing only in a fairly narrow coastal zone. In Figure 2.8 we show the saturated thickness of the *Upper Gravels* in the form of a contour map. To the south of the zero contour, the *Upper Gravels* are generally unsaturated except probably beneath the main wadi channels.

Along the coastal area the fresh water-bearing gravels have direct contact with sea water and intrusion of sea water does occur. According to the Ghyben/Herzberg principle, salt water can be expected at depths below sea level of about forty times the height of the fresh groundwater level above sea level. The shallow water table and the very slight gradient to the coast illustrated in Figure 2.7 indicate that extensive intrusion is possible. Brackish water has been encountered at depths of several kilometres inland from the coast but the origin of this water is not yet proved.

Electrical conductivity profiles of groundwater in the four 300 m deep observation boreholes are shown in Figure 2.9. Saline interfaces are present in each borehole at slightly greater depths than indicated by the Ghyben /Herzberg principle. These boreholes were sited immediately inland from the main agricultural area of the coast. Boreholes DW1 and DW2 are in the Sib area and demonstrate that only some 30 m of the *Upper Gravel* contains fresh water despite a total thickness of over 100 m.

Boreholes DW3 and DW4 in the Wadi Bani Kharus have a higher water table elevation and hence a deeper interface. The *Upper Gravels* are relatively thin in this area and the saline interface lies within the *Cemented Gravels or Clayey Gravels*. The boreholes are 5 km and 7 km respectively from the coast and are located between the Wadi Far basin and the Wadi Nakhl basin.

In DW4 the saline interface is particularly sharp by comparison with the interface in the *Upper Gravels* of boreholes DW1 and DW2 where fairly thick zones of mixed fresh and saline water are apparent. The profile in DW3 indicates a thick zone of brackish water between a thin fresh water layer and the main saline interface at about 100 m. Further study is needed to confirm this pattern which was obtained shortly after completion of drilling and might be a condition caused by contamination during well development.

Our investigation of saline intrusion is not sufficiently far advanced to report in any further detail at present. We have collected enough evidence to suggest that saline groundwater is present at depth beneath the date gardens along the whole coastal zone of our study area. The fresh water flowing through the alluvial sediments towards the coast can be expected to be only 82 m in thickness below the + 2 m water level contour.

A summary of our interpretation of the hydrogeological conditions in the Batinah is given by Figure 2.10a and 2.10b. Four cross-sections from the coast to the foothills of the mountains illustrate the main features of the aquifer system. The locations of these cross-sections are shown in Figure 2.1.

Section 1 has been drawn through the Wadi Bani Kharus while Section 2 is some 8 km to the east through the edge of the Wadi Nakhl basin. These sections show the shallow occurrence of the *Cemented Gravels* and/or Lower Tertiary Limestones. The relatively thin beds of the *Upper Gravels* are above the water table throughout much of the area. In section 1, less than 15 m of saturated *Upper Gravels* are shown to occur although the water bearing thickness increases on either side of the ridge. Section 2 shows up to 30 m of saturated *Upper Gravels* in the Wadi Nakhl basin. A major feature of our interpretation is the considerable thickening of the *Clayey Gravels* when traced eastwards from the Wadi Bani Kharus compared with the small increase in the thickness of *Upper Gravels*.

The aquifer potential of the *Clayey Gravels* is poor by comparison with the overlying gravels but several boreholes have shown the presence of a clean gravel horizon at the base of the *Clayey Gravels*. This is shown in sections 1 and 2 where it could be fairly extensive in area and is worth further exploration.

In section 1 the water bearing *Upper Gravels* are not affected by saline intrusion to any great extent; the intrusion appears to be contained mainly within the sandy and silty coastal beds or within the *Clayey and Cemented Gravels*. However in section 2, saline water in the area to the east of the ridge appears to have access to the gravel lens at the base of the *Clayey Gravels*.

Sections 3 and 4 are taken across the Wadi Semail. Section 4 shows selected boreholes in the Government and PD(O) well fields. By comparison with sections 1 and 2, the greater apparent thickness of the *Clayey Gravels* could reflect the difficulty of assessing the amount of carbonate material in the alluvium.

The intrusion of the saline interface into the *Upper Gravels* is clearly shown in both sections. Despite the thickness of these beds, the zone with fresh water is relatively thin for some distance from the coast. It would appear that the wedge of *Upper Gravels* containing fresh water is only about 30 per cent of the total volume of the beds. The screens in the boreholes of the PD(O) and Government well fields, shown in section 4, are below the main aquifer and on the basis of our interpretation, they are set deep in the semi-permeable *Clayey Gravels*.

2.5 Aquifer Conditions

A feature of many alluvial fans is that groundwater becomes confined in the down slope direction. Water table conditions in the gravels high up on the fan become replaced down-slope by water bearing layers or lenses separated by clayey beds, producing confined aquifers with the possibility of artesian conditions in the lower areas furthest from the sediment source. In the Batinah this simple hydrogeological pattern has been complicated by the carbonate cement deposited in the void spaces of the gravels of the older sediments. This has led to the occurrence of semi-permeable and impermeable beds high up on the fans where the best aquifer conditions would normally be expected. Furthermore the carbonate cement is present at depth in the alluvium some distance down-slope thus further reducing the aquifer potential of the normally poorer finer grained sediments.

The main productive aquifer, the *Upper Gravels*, probably comprises a heterogeneous collection of clastic materials characterised mainly by the absence of secondary carbonate cement. As far as the primary sedimentary history of the area is concerned the *Upper Gravels* are undoubtedly of very mixed origin. In the Wadi Semail, where the coastal plain is narrow, the aquifer is formed from coarse sediments deposited in the head and upper areas of the fan. In the Wadi Nahkl and Wadi Far basins, the productive aquifer is low down on the fan but inland from the present coastline. The aquifer unit can thus be expected to comprise smaller gravels mixed with finer sediments derived from either terrestrial or marine sources.

Simple water table or artesian aquifer conditions are not expected to occur. The analysis of pumping test data suggest more complicated aquifers with vertical movement of groundwater impeded by the cemented beds of low permeability. This situation produces conditions around a discharging well whereby groundwater is obtained by leakage through the semi-permeable horizons or by slow dewatering of the cone of depression. Both situations, termed leaky artesian aquifer and delayed yield water table aquifer, can reasonably be expected to occur in the Batinah.

3. GROUNDWATER RESOURCES OF THE BATINAH

3.1 Introduction

Recharge to the aquifer system probably occurs following major surface flows across the Batinah, and by base flow and sub-surface inflow from the wadi alluvium and bed-rock areas at the southern boundary of the plain. Direct infiltration from rainfall is unlikely to be a major source of recharge except locally after exceptionally heavy rainfall. As yet we have no data following a major recharge event. Consequently there is insufficient hydrogeological information to enable us to determine the groundwater resource from a study of the inputs to the aquifer.

At the coast the major loss from the aquifer is by abstraction for irrigation of the agricultural areas. There will also be some direct evaporation loss from the shallow water table and transpiration losses from the natural vegetation. Direct losses to sea cannot be estimated at present; we require more detailed information concerning the movement of water in the aquifer in the zone near the saline interface.

Until we have the additional information to enable us to develop a model of the aquifer system as a whole we must adopt a more simple approach to the estimation of the groundwater resource. A form of flow net analysis is appropriate whereby we can calculate the quantity of groundwater flowing towards the coast across some arbitrarily defined section of the aquifer. This method requires estimates of the transmissivity of the water bearing layers together with data concerning the width and thickness of the aquifer and of the hydraulic gradients within it. We have taken advantage of the known saline interface to define the thickness of the aquifer as 82 m at the + 2 m groundwater contour. The choice of a section defined by this contour, which is inland of the cultivated area, avoids the problems associated with the abstractions further seaward. For comparison we have calculated the groundwater flow across a further section defined by the 10 m groundwater contour.

3.2 Estimation of transmissivity

Data from the programme of well yield tests have been used to provide first estimates of the transmissivity and hence of the hydraulic conductivity of the aquifer. These tests were not designed to provide detailed data for precise evaluation of aquifer properties because the drawdown was measured in the pumped well and not in observation wells. We have reviewed the results from over a hundred of these tests and have adopted the following approach to provide estimates:

1. Determination of aquifer transmissivity by analysis of water level data collected during the first stage of step-drawdown testing. Only tests yielding the best data were used.

2. Estimation of transmissivity for all boreholes using specific capacity data (yield in m^3/day divided by drawdown in metres).

3. Determination of hydraulic conductivity on the basis of the position and length of the screened section of the pumped borehole. The transmissivity in m^2/day divided by screen length in metres yielded the hydraulic conductivity, k, in m/day.

The results of this analysis together with a discussion of the validity of the methods of analysis of the pumping tests are set out in detail in Appendix A of this report. In summary we have shown that the transmissivity values are low even in the *Upper Gravels*. The major cause of uncertainty in the current estimates of transmissivity lies in the interpretation of the response of the aquifer to pumping. We believe that the aquifers exhibit leaky artesian conditions and as such have transmissivities some two or three times lower than values obtained assuming non-leaky conditions. The full scale pumping tests will enable us to eliminate much of this present uncertainty.

3.3 Flow Net Analysis

The method of calculation is based on Darcy's Law whereby;

$$Q = k\ m\ i\ w$$

where: Q = groundwater flow in m^3/day
k = hydraulic conductivity in m/day
m = aquifer thickness in m
i = hydraulic gradient
w = width of aquifer in m

Hydraulic conductivity values for individual segments of the flow net have been obtained from the specific capacity data. Where flow segments in the vicinity of the + 2 m and + 10 m contours have not contained test results a mean value has been obtained from nearby sites. The hydraulic gradients and the flow segment widths were derived by measurement from the groundwater contour maps using the flow net geometry and the contour spacings between the + 2 m and 5 m contours, and the + 5 m and + 10 m contours. The aquifer thickness has been taken to be 82 m beneath the + 2 m contour (Ghyben/Herzberg relationship) and the same thickness beneath the 10 m contour on the grounds that the saturated thickness of the *Upper and Clayey Gravels* is of this order.

The individual discharges for each basin are shown in Table 3.1 and details of the flow net analysis are shown in Tables 3.2 and 3.3.

The results indicate a total seaward groundwater flow of about 51 mcm/annum beneath the + 2 m contour compared with 81 mcm/annum beneath the + 10 m contour. Large groundwater flows are given by both sets of data for the Wadi Semail basins. Those basins to the west of the Wadi Semail are shown to have small, relatively insignificant resources although larger values are obtained at the + 10 m contour. The progressive decrease in hydraulic gradient and hydraulic conductivity from east to west accounts for the relatively small estimates of groundwater flow at the + 2 m contour in western wadis. By comparison the hydraulic conductivity values beneath the + 10 m contour, and a less marked westward decrease in the hydraulic gradient, produce larger and perhaps more realistic estimates for

Table 3.1

GROUNDWATER FLOW TOWARD THE BATINAH COAST

(mcm/year)

	Flow across the + 2 m contour	Flow across the + 10 m contour
W. Bani Ghafir	0.93	6.85
W. Far	2.34	16.38
W. Bani Kharus	1.93	2.10
W. Nakhl	3.77	2.07
W. Al Ajal	0.57	1.25
W. Taww	0.38	0.32
W. Halban	5.96	2.02
W. Semail	27.81	37.15
W. Rusayl	7.66	13.34
	51.35	81.48

Table 3.2

FLOW NET ANALYSIS - GROUNDWATER FLOW ACROSS THE 2 m CONTOUR

Flow segment	Width (km)	Hydraulic Conductivity (m/day)	Distance between +2 m and +5 m contour (km)	Flow (mcm/year)	
W. Bani Ghafir					
1	3.8	1.9	6.3	0.10	
2	4.5	7.7	6.7	0.45	
3	3.8	7.7	6.7	0.38	0.93
W. Far					
4	3.8	9.4	6.6	0.47	
5	3.8	8.2	7.2	0.38	
6	3.8	8.5	6.0	0.47	
7	4.5	8.5	3.3	1.02	2.34
W. Bani Kharus					
8	3.8	4.6	3.2	0.48	
9	2.8	5.2	3.5	0.36	
10	3.8	7.8	4.0	0.65	
11	3.0	8.7	5.2	0.44	1.93
W. Nakhl					
12	3.8	11.6	4.5	0.86	
13	3.8	14.5	3.7	1.30	
14	3.8	9.7	3.0	1.08	
15	2.5	8.0	3.3	0.53	3.77
W. Al Ajal					
16	1.2	8.0	4.0	0.21	
17	1.8	8.0	3.5	0.36	0.57
W. Taww					
18	2.5	6.2	3.6	0.38	0.38
W. Halban					
19	3.8	14.3	3.8	1.25	
20	3.8	22.3	2.4	3.09	
21	3.8	11.2	2.3	1.62	5.96
W. Semail					
22	3.8	11.4	1.7	2.23	
23	2.5	29.4	1.5	4.29	
24	0.8	29.4	1.5	1.37	
25	3.8	16.7	1.4	3.97	
26	2.5	13.8	1.3	2.32	
27	1.4	40.7	1.0	4.99	
28	1.8	49.3	0.9	8.64	27.81
W. Rusayl					
29	1.5	44.0	0.8	7.23	
30	1.5	5.0	1.6	0.41	
31	1.7	0.3	2.0	0.02	7.66

Table 3.3

FLOW NET ANALYSIS - GROUNDWATER FLOW ACROSS THE + 10 m CONTOUR

Flow segment	Width (km)	Hydraulic Conductivity (m/day)	Distance between + 5 m and + 10 m contour (km)	Flow (mcm/year)	
W. Bani Ghafir					
1	2.5	18.0	4.4	1.49	
2	3.8	18.0	4.2	2.38	
3	3.5	20.4	3.5	2.98	6.85
W. Far					
4	4.3	16.8	2.8	3.77	
5	6.8	13.5	2.0	6.70	
6	6.0	13.5	3.0	3.94	
7	4.5	13.5	4.5	1.97	16.38
W. Bani Kharus					
8	2.7	7.3	5.0	0.58	
9	0.4	7.3	5.5	0.08	
10	1.0	6.2	5.0	0.18	
11	5.8	6.7	4.5	1.26	2.10
W. Nakhl					
12	4.4	2.3	2.5	0.59	
13	4.1	1.6	1.8	0.53	
14	4.0	1.6	1.4	0.67	
15	3.4	0.8	1.4	0.28	2.07
W. Al Ajal					
16	3.4	2.0	1.7	0.58	
17	4.1	2.0	1.8	0.67	1.25
W. Taww					
18	2.0	2.0	1.8	0.32	0.32
W. Halban					
19	2.3	3.0	2.0	0.50	
20	3.4	3.0	1.7	0.88	
21	2.2	3.0	1.5	0.64	2.02
W. Semail					
22	2.5	9.5	1.6	2.17	
23	2.8	9.5	1.2	3.24	
24	1.8	9.5	1.3	1.92	
25	5.0	9.5	1.1	6.30	
26	1.7	10.9	0.9	3.01	
27	1.1	40.7	0.8	8.17	
28	1.2	49.3	0.7	12.34	37.15
W. Rusayl					
29	1.8	44.0	1.0	11.56	
30	2.8	5.0	1.2	1.70	
31	2.1	0.3	1.0	0.08	13.34

the Wadi Bani Ghafir and the Wadi Far areas. Groundwater availability in the central areas of the Batinah is shown to be small by both sets of results.

3.4 Preliminary estimates of abstraction at the coast

As part of our survey of existing patterns of water use, we have estimated the rate of abstraction of groundwater in the coastal area of the Wadi Semail and the Wadi Bani Kharus basins. Detailed mapping of these areas is complete; the majority of the wells have been located and an assessment of their pumping capability has been made. However we do not yet have full information concerning the seasonal variation in abstraction rates. Consequently the estimated annual rates presented here must be regarded as tentative.

The results of the Wadi Semail survey were given in our Interim Report. Current abstractions were estimated to be about 25 mcm/annum and we drew attention to numerous reports of progressive increases in groundwater salinity. The survey data also suggested that little groundwater reached the sea except at the eastern edge of the area. The flow net analysis gives significantly large flows for the same area, flow segments 27, 28 and 29 in Table 3.2.

About 1000 wells were located in the coastal area of the Wadi Bani Kharus basin where over 600 pumps are now installed. Although the general pattern of groundwater quality was similar to that found in the Wadi Semail there were no reports of increasing salinities in the Wadi Bani Kharus. However an estimate of well abstractions indicates a possible yield of about 11 mcm/annum.

The estimates are based entirely upon the type and capacity of pump, and local information regarding pumping operations; they do not take into account the excess irrigation water which will return to the aquifer by percolation. Therefore these estimates of abstraction could exceed the rate of flow of groundwater towards the coast if there is an insignificant flow of groundwater directly to the sea.

4. DISCUSSION OF THE RESOURCES ESTIMATES

4.1 Introduction

In this present analysis we have divided the study area into a hard-rock zone comprising the mountain limestones and ophiolites, and an alluvial zone which includes the Lower Tertiary Limestones. The higher altitude hard-rock zone has a higher rainfall than the alluvial plains giving rise to runoff which becomes the major source of recharge to the alluvial aquifers. Until we have evidence to the contrary we must assume that the rainfall in the alluvial areas is insufficient to cause recharge and that it is lost by evaporation directly or through transpiration by the natural vegetation.

Owing to the weather conditions during our survey, we have no direct measurements of surface flows as yet, other than the record of base flow at Al Khawd. However we have estimated the surface water resources of the hard-rock areas by analogy with similar areas elsewhere. These estimates are presented in Chapter 1. It is readily apparent that the major uncertainty is the proportion of the surface flows which are recharged to the alluvium. The large surface floods which are known to occur are of short duration and much of this water is known to be lost to sea in the north or to the desert in the south. Thus the available water is the base flow, derived from storage in the wadi gravels upstream from the main alluvial plains or from springs in the mountain limestones, together with a proportion of the flood flow which is recharged as the floods cross the plains.

Our field programme is organised to provide the data to improve these estimates. Unfortunately the past year has been very dry. However the analysis of the aquifer properties for the Batinah suggests that we should be conservative in our estimate of the recharge from flood flows. As such we have used a value of 10%. This is in direct contrast with the value of 90% adopted by Burden[1] although our estimates of the

1. Burden D. J. Technical Notes on the Water Resources of the Sultanate of Oman. FAO December 1972.

total runoff from the hard-rock areas are in broad agreement for the northern basins of the Jebel Akhdar.

Our second estimate of the available water resource follows from an analysis of the hydrogeology of the Batinah alluvial plain and is presented in chapters 2 and 3. As a measure of the resource to the north of the Jebel we have calculated the groundwater flow across sections defined by the 2 m and 10 m contours using a flow net analysis. Unfortunately we have insufficient data at the present time to carry out a similar analysis for the southern basins.

The major cause of uncertainty in this groundwater flow estimate is in the calculation of aquifer permeability. The data have been collected during a drilling programme, established prior to this survey, which did not include provision for the detailed study of aquifer properties. Further exploratory drilling with full-scale pumping tests of the main aquifer units will enable us to improve our estimates of the aquifer properties and to improve our knowledge of the lithology and groundwater configuration in the Wadi Far and Wadi Bani Ghafir areas where the present coverage is inadequate.

The flow net form of analysis is preliminary to the full model study which we shall undertake when the improved estimates of aquifer properties are available. While it is clear that some of the results from the flow net analysis appear to be much too low, we have presented them without adjustment for direct comparison with the estimates derived from considerations of rainfall and runoff, and with the evidence available concerning the extent of abstractions from the wells in the coastal agricultural areas.

4.2 Comparison of the resources estimates for the Batinah

In Table 4.1 all the estimates of the available water resources for the Batinah coastal plain are shown together with some evidence of the extent of abstraction from wells in the coastal villages. The only

Table 4.1

A COMPARISON OF THE WATER RESOURCES ESTIMATES FOR THE BATINAH

(mcm/year)

Basin	Available resources from surface water analysis[1]		Groundwater flow to the coast from flow net analysis[2]		Coastal village abstractions[3] (estimated)
	1	2	1	2	
W. RUSAYL	(1)	(3)	7.7	13.5	7
W. SAMAIL	19	21	27.8	37.2	25
W.MA'AWIL	7	8	10.8	5.7	
W. BANI KHARUS	31	21	1.9	2.1	11
W. FAR	7	6	2.3	16.4	
W. BANI GHAFIR	25	16	0.9	6.9	

..OTES :

1 the first estimate is based on the total runoff being rainfall less 300 mm evaporation; the second on total runoff being 20% of rainfall. In both cases allowance has been made for water use within the general boundary of the hard-rock area. See Table 1.5 for the derivation of these figures.

2 the first estimate refers to flow across the 2 m groundwater contour; the second to flow across the 10 m contour. See Table 3.2 and 3.3 for the derivation of these figures.

3 these figures refer to total abstractions derived from data collected during our survey of coastal villages.

other new figures in Table 4.1 are estimates of the resource in the Wadi Rusayl derived from the surface water analysis. They were not included in Table 1.5 in Chapter 1 because the Wadi Rusayl basin is not similar to the other major basins; it is entirely in the ophiolites and it reaches an altitude of only 1200 m. Consequently there is a greater uncertainty in the validity of the assumptions in this case.

The estimates of total annual abstraction from the wells in the coastal agricultural areas are difficult to interpret precisely in terms of the net loss of water from the aquifer. As yet we cannot adjust the figures completely to allow for the seasonal variation; data are still being collected. Also the gross abstraction figure must include a substantial proportion of recycled water; excess irrigation is returned directly to the shallow water table. Although it is probable that the date palms draw some of their water directly from the water table, we would estimate that net abstraction from the aquifer is substantially lower than the gross figure shown in Table 4.1.

With a few exceptions the figures show a reasonable measure of agreement considering the broad assumptions we have had to make at this time. In total they suggest that there is some 50 - 90 mcm per year available to support agriculture in the coastal area. The main uncertainty is over the figures for the western wadis. We have already drawn attention to the particular problem of determining permeabilities in the western wadis because of the relatively sparse coverage of boreholes and the fact that many of them do not tap the very shallow productive part of the aquifer. Certainly a figure of 2 mcm/year derived from the flow net analysis of the Wadi Bani Kharus is too low on the evidence of coastal abstractions alone. However the hydrogeological evidence for a ridge of cemented material below the Wadi Bani Kharus suggests that our assumptions about recharge could be optimistic in this case. We would suggest that it would be prudent to assume that no more than 10 - 15 mcm per year is available in this basin. The same might be true of the Wadi Bani Ghafir but we have no evidence on which to make a judgement. Thus our regional estimate would be a total of 50 - 75 mcm per year available for agriculture or other purposes at the coast.

4.3 The Southern Basins

Since we have insufficient data for a groundwater flow net analysis, we must rely at this stage on those estimates derived from recharge of the surface water resources. We have used the same assumptions in deriving these figures as we used for the northern basins. However in estimating the proportion of these resources which can be considered as available we face the same need to make assumptions about the effective recharge of flood flows and of the proportion of base flow storage.

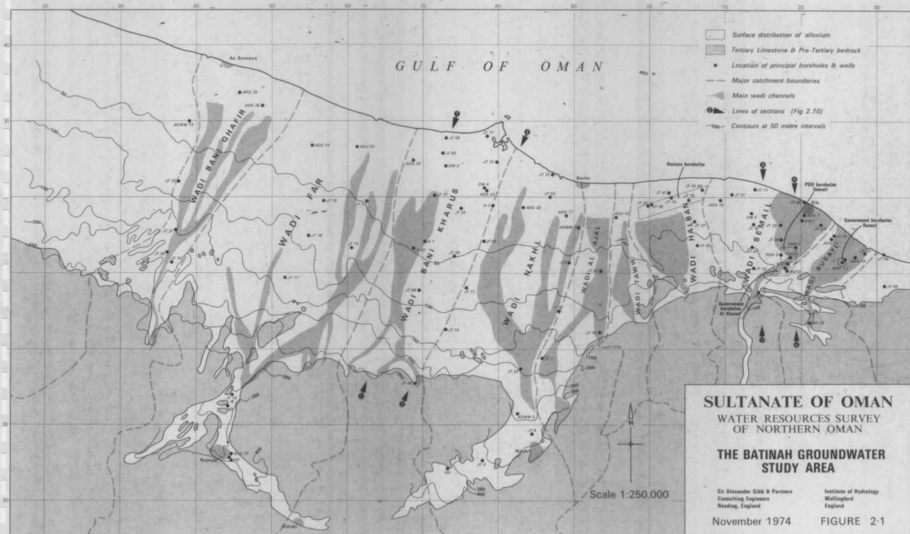
The southern basins do have marked differences from the northern basins in terms of the distribution of alluvium. There are fairly extensive piedmont areas upstream of Bahla and Nizwa which could hold substantial base flow storage. On the other hand the relatively sparse development of agriculture south of Bahla and Nizwa suggests that the good aquifers may well be thinner than in the Batinah with poorer infiltration characteristics. However these are qualitative considerations and in the absence of data we do not feel justified in using different assumptions concerning base flow and recharge from those used for the north. The lack of a basis for comparison must necessarily result in a greater uncertainty in the estimates for the south. We would suggest that the total of 70 mcm/year be regarded as an upper limit to the water currently available in the five southern basins.

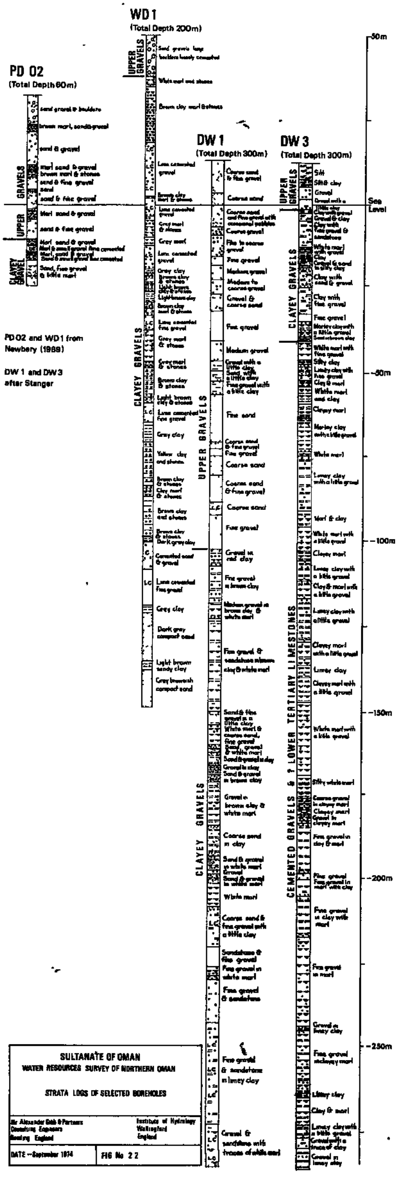
4.4 Other factors affecting development

The major factor affecting the utility of the groundwater resources is quality, principally salinity but also the presence of boron ions could be limiting to some crops. We have not reported on water quality at this time; our field programme of sampling is continuing and we have not yet obtained sufficient data from depth in the alluvium of the Batinah to form a coherent picture of the pattern of water quality and how this might change with recharge and subsequent decline of water table levels. We are monitoring the changes in quality at Rumais where there is increasing abstraction for agricultural development and there are clear indications of the need for careful management of abstraction to avoid encroachment of saline water.

We have discussed already the difficulty of determining the proportion of flood flows which are recharged naturally into the alluvial aquifers. If the true recharge is as low as we fear then there is scope for a programme of artificial recharge to augment the groundwater resources hence utilising water that would otherwise be lost. Our field programme includes studies of the nature of the gravels beneath the main wadi fans as an essential preliminary to any estimates of the potential for artificial recharge.

The only other natural source of water is the aquifer formed by the mountain limestones of the Jebel. Although the detailed study of the potential of the hard-rock aquifers is regarded as being outside the scope of this present survey, we are carrying out a survey of the Jebel foot villages in order to determine the extent to which water from this source is currently being used. Monitoring the chemistry of the base flows in the wadis will enable us to determine the origin of these waters and particularly to assess the importance of the mountain limestone as a base flow storage.


GULF OF OMAN
Surface distribution of alluvium
Tertiary Limestone & Pre-Tertiary bedrock
Location of principal boreholes & wells
Major catchment boundaries
Main wadi channels
Lines of sections (Fig 2.10)
Contours at 50 metre intervals
As Buwayq
Barka
Sib
Rustaq
Nakhl
Awabi
WADI BANI GHAFIR
WADI FAR
WADI BANI KHARUS
WADI NAKHL
WADI AL AJAL
WADI TAWW
WADI HALBAN
WADI SEMAIL
WADI RUSAYL
Rumais boreholes
PDO boreholes Semail
Government boreholes Rusayl
Government boreholes Al Khawd
Scale 1:250,000
N
SULTANATE OF OMAN
WATER RESOURCES SURVEY OF NORTHERN OMAN
THE BATINAH GROUNDWATER STUDY AREA
Sir Alexander Gibb & Partners
Consulting Engineers
Reading, England
Institute of Hydrology
Wallingford
England
November 1974
FIGURE 2·1

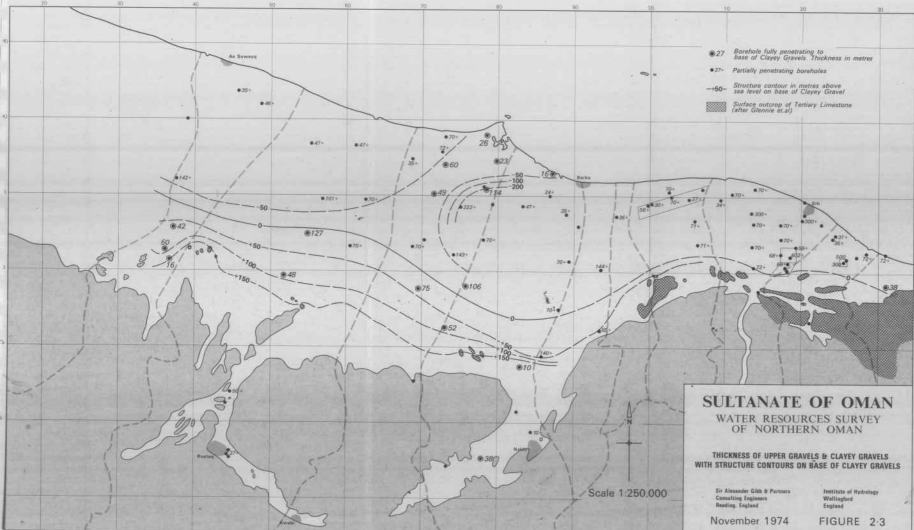


SULTANATE OF OMAN

WATER RESOURCES SURVEY OF NORTHERN OMAN

STRATA LOGS OF SELECTED BOREHOLES

Sir Alexander Gibb & Partners Consulting Engineers Reading England	Institute of Hydrology Wallingford England
DATE – September 1974	FIG No 22



SULTANATE OF OMAN

WATER RESOURCES SURVEY OF NORTHERN OMAN

THICKNESS OF UPPER GRAVELS & CLAYEY GRAVELS WITH STRUCTURE CONTOURS ON BASE OF CLAYEY GRAVELS

Sir Alexander Gibb & Partners
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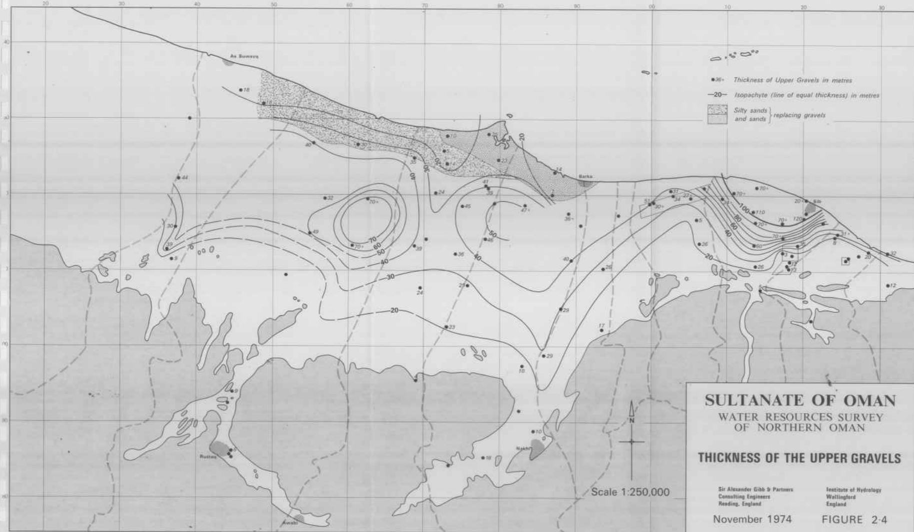
Reading, England

Institute of Hydrology
Wallingford
England

November 1974

FIGURE 2·3



SULTANATE OF OMAN

WATER RESOURCES SURVEY OF NORTHERN OMAN

THICKNESS OF THE UPPER GRAVELS

Sir Alexander Gibb & Partners
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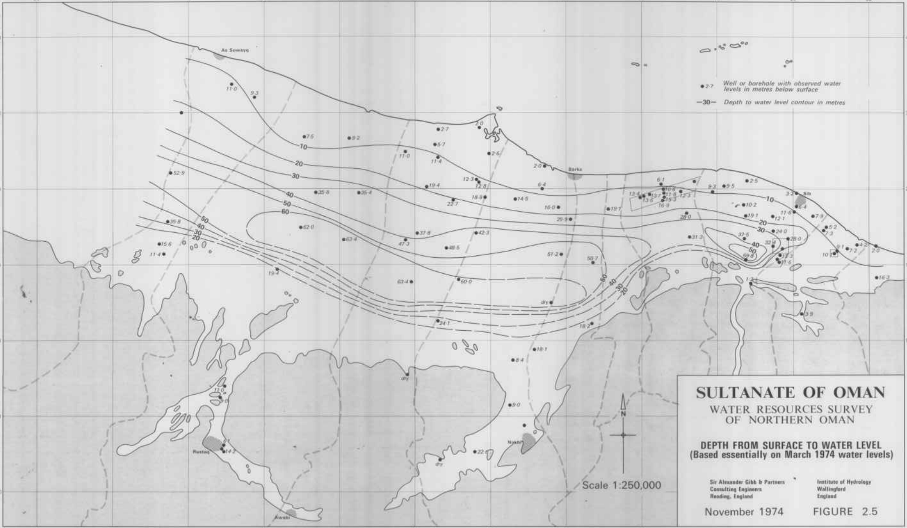
Reading, England

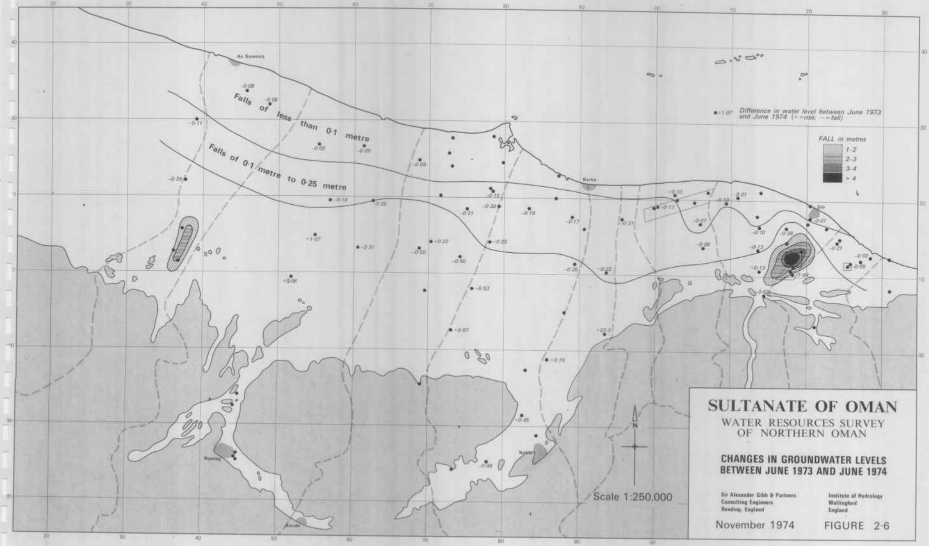
Institute of Hydrology
Wallingford
England

November 1974

FIGURE 2·4



Well or borehole with observed water levels in metres below surface
—30— Depth to water level contour in metres
As Suwayq
Barka
Sib
Rustaq
Nakhl
Awabi
Scale 1:250,000
N
SULTANATE OF OMAN
WATER RESOURCES SURVEY OF NORTHERN OMAN
DEPTH FROM SURFACE TO WATER LEVEL
(Based essentially on March 1974 water levels)
Sir Alexander Gibb & Partners
Consulting Engineers
Reading, England
Institute of Hydrology
Wallingford
England
November 1974
FIGURE 2.5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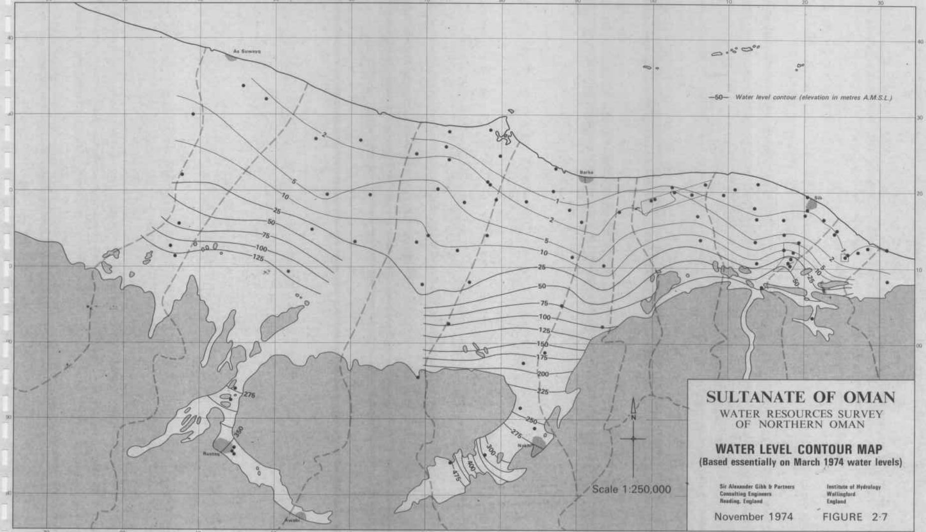
WATER RESOURCES SURVEY
OF NORTHERN OMAN
CHANGES IN GROUNDWATER LEVELS
BETWEEN JUNE 1973 AND JUNE 1974
Sir Alexander Gibb & Partners
Consulting Engineers
Reading, England
Institute of Hydrology
Wallingford
England
November 1974
FIGURE 2·6
Scale 1:250,000
N
Difference in water level between June 1973 and June 1974 (+ = rise, − = fall)
FALL in metres
1-2
2-3
3-4
> 4
Falls of less than 0·1 metre
Falls of 0·1 metre to 0·25 metre
As Suwayq
Barka
Sib
Rustaq
Nakhl
Awabi



SULTANATE OF OMAN
WATER RESOURCES SURVEY OF NORTHERN OMAN
WATER LEVEL CONTOUR MAP
(Based essentially on March 1974 water levels)
Sir Alexander Gibb & Partners
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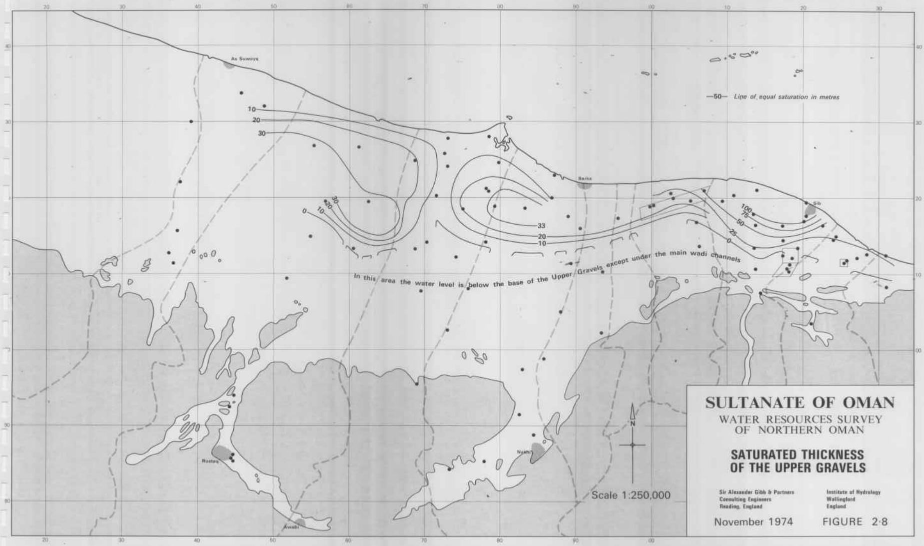
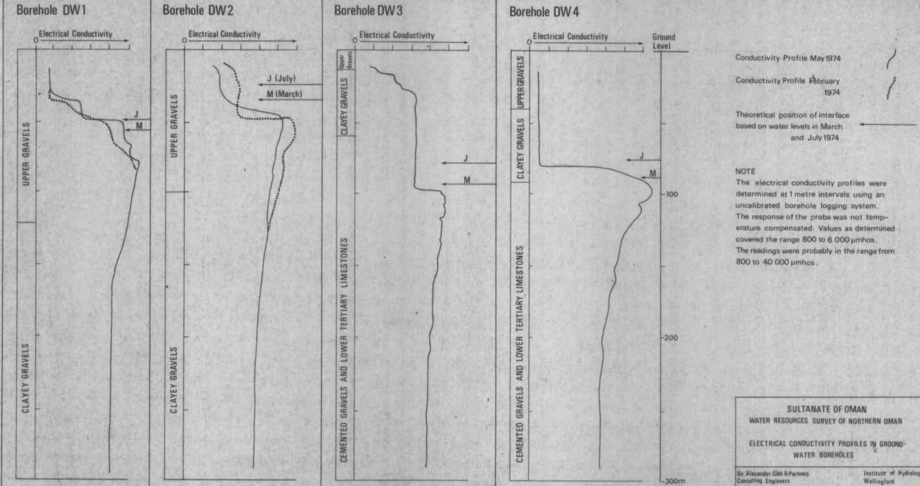
Institute of Hydrology
Wallingford
England
November 1974
FIGURE 2·7
Scale 1:250,000
N
—50— Water level contour (elevation in metres A.M.S.L.)
As Suwayq
Barka
Sib
Rustaq
Nakhl
Awabi


As Suwayq
Barka
Sib
Rustaq
Nakhl
Awabi
—50— Line of equal saturation in metres
In this area the water level is below the base of the Upper Gravels except under the main wadi channels
Scale 1:250,000
N
SULTANATE OF OMAN
WATER RESOURCES SURVEY
OF NORTHERN OMAN
SATURATED THICKNESS
OF THE UPPER GRAVELS
Sir Alexander Gibb & Partners
Consulting Engineers
Reading, England
Institute of Hydrology
Wallingford
England
November 1974
FIGURE 2·8



NOTE

The electrical conductivity profiles were determined at 1 metre intervals using an uncalibrated borehole logging system. The response of the probe was not temperature compensated. Values as determined covered the range 800 to 6 000 µmhos. The readings were probably in the range from 800 to 40 000 µmhos.

SULTANATE OF OMAN

WATER RESOURCES SURVEY OF NORTHERN OMAN

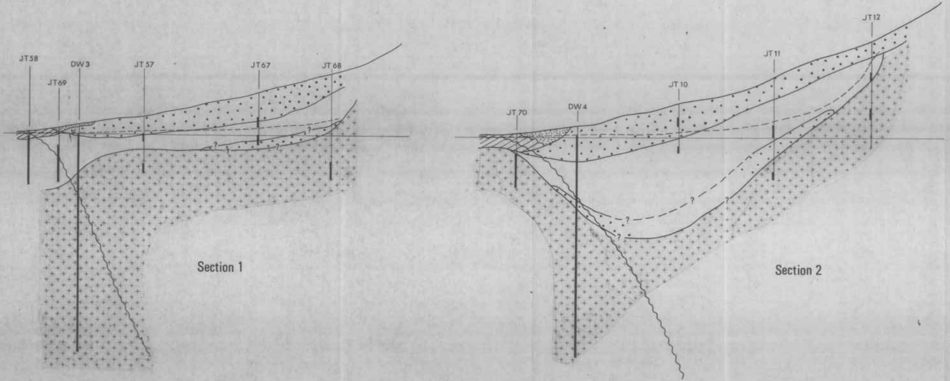
ELECTRICAL CONDUCTIVITY PROFILES IN GROUND-WATER BOREHOLES

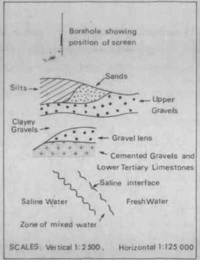
Sir Alexander Gibb & Partners, Consulting Engineers, Reading, England

Institute of Hydrology, Wallingford, England

DATE – November 1974

FIG No 2.9

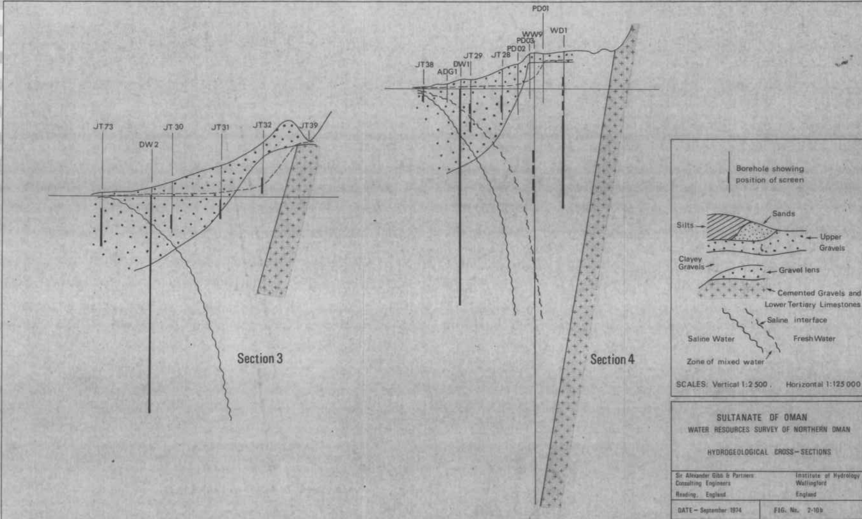




SULTANATE OF OMAN
WATER RESOURCES SURVEY OF NORTHERN OMAN

HYDROGEOLOGICAL CROSS–SECTIONS

Sir Alexander Gibb & Partners Consulting Engineers Reading, England	Institute of Hydrology Wallingford England
DATE – September 1974	FIG. No. 2-10a


JT73
DW2
JT 30
JT31
JT32
JT39
Section 3
PD01
WW9
WD1
PD03
PD02
JT29
JT28
JT38
ADG1
DW1
Section 4
Borehole showing position of screen
Sands
Silts
Upper Gravels
Clayey Gravels
Gravel lens
Cemented Gravels and Lower Tertiary Limestones
Saline interface
Saline Water
Fresh Water
Zone of mixed water
SCALES: Vertical 1:2 500. Horizontal 1:125 000
SULTANATE OF OMAN
WATER RESOURCES SURVEY OF NORTHERN OMAN
HYDROGEOLOGICAL CROSS-SECTIONS
Sir Alexander Gibb & Partners
Consulting Engineers
Reading, England
Institute of Hydrology
Wallingford
England
DATE – September 1974
FIG. No. 2-10b