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AL KHAWD FAN
GROUNDWATER INVESTIGATION

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PREFACE

This report is not intended as a comprehensive study of the Al Khawd Fan. A number of previous studies have covered the hydrogeology. The foundation for hydrogeological studies in northern Oman was laid by Gibb (1976). Later, MMP (1984) examined in detail the hydrogeology of the various Government Wellfields, Bhatnagar and Ravenscroft's (1985) work for PAWR, especially on the region below the Al Khawd Dam is a principle reference, as is the report of Morgan et al. (MWR, 1994) who provided a much needed update of the overall hydrogeology in the Wadi Samail Rapid Assessment Report.

This study examines aspects of groundwater flow and seawater intrusion into the Al Khawd Fan which have not been covered in depth by these earlier studies. It is a piecemeal study carried out over a number of years, sandwiched between other higher priority works. While contributing a number of new ideas, it nevertheless relies greatly on the earlier works, and to some extent, extends the earlier studies, to a further level of analysis and understanding. It is provided as a comment on the lack of understanding as much as the understanding of a somewhat unusual, albeit important region, which contains many puzzling features not readily explicable by the normal approaches to dealing with seawater intrusion and groundwater flow. While it is probably atypical in many ways to the remainder of the Eastern Batinah, it nonetheless provides additional insight and understanding on groundwater flow processes occurring elsewhere on the Al Batinah coastal plain.

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GROUNDWATER FLOW AND SEAWATER INTRUSION IN AL KHAWD FAN

1 Introduction

The Wadi Samail catchment consists of two distinct regions - an upper catchment (Samail Basin), and a lower catchment occupying the coastal plain (Al Khawd Fan). The two sub-catchments are separated by a gorge cut through ophiolite basement (Fig.1.1). The Samail Basin, has an area of 1635 km², one of the largest catchments of any wadi draining towards the Batinah Region. The Samail Basin. is contained within a perimeter of ophiolite basement rocks. Downstream from Fanjah, the Wadi Samail cuts a deep gorge through the ophiolites, and the wadi re-emerges from the gorge at the village of Al Khawd. By contrast the coastal plain (essentially made up by the Al Khawd Fan) is about one eighth the size of the upper catchment and is one of the smaller coastal plains of Al Batinah. Situated at the eastern limits of the Al Batinah Coastal Plain, The Al Khawd Fan is bounded to the east by the alluvial fan of Wadi Russayl and to the west by the Wadi Taww Fan.

The alluvial aquifer of the Al Khawd Fan provides an important freshwater resource for both domestic and agricultural use. As a consequence, the Fan contains a number of back-up wellfields for the Muscat water supply. However, following the intensive development of the aquifer, there has been a varying degree of seawater intrusion which has been seen as a growing potential threat to water supplies. The toe of the saltwater intrusion extends seven kilometre inland from the coast, almost to the Al Khawd Dam. This threat is highlighted by the shallow depth of the water table on the coastal plain, which is commonly less than 1 m above mean sea level, and often below sea level in the vicinity of the Seeb-Al Khawd wellfields.

Perhaps the least understood feature of the Al Khawd Fan is the means by which the extensive alluvial aquifer system is replenished. Previously it was assumed that the bulk of the groundwater recharge was by flood flow from Wadi Samail whenever major precipitation events occurred in the upper catchment. However, more recent assessment of water balances on the Al Khawd Fan show that it is unlikely that sufficient water passes from the Samail Basin to even accommodate the production from the Government and PDO Wellfields, let alone the extensive agricultural usage put by various authors as lying somewhere between 10 and 20 MCM. In addition, there is a requirement of upto 5 MCM to counter seawater intrusion into the Fan (Macumber, 1992).

From these very rough calculations it is clear that a major additional water source is required. The most likely source of additional recharge, (perhaps by default the only source), is sub-surface transfer from basement aquifers (the ophiolites), linked to the upper Samail Basin catchment area. Here the mechanisms of flow through the ophiolites are still largely conjecture. Whatever this process, further studies on the nature of recharge and groundwater flow in the aquifers of the Al Khawd Fan are required in order to determine the link between groundwater recharge and flow on the one hand and seawater intrusion on the other. Part of such studies requires a review of existing tenets which, while adequate in the past, no longer provide satisfactory and simple explanations for the manner in which the hydrologic system functions on the Al Khawd Fan. This report attempts to better understand the nature of groundwater recharge and flow in the alluvial aquifer and review the seawater intrusion threat.

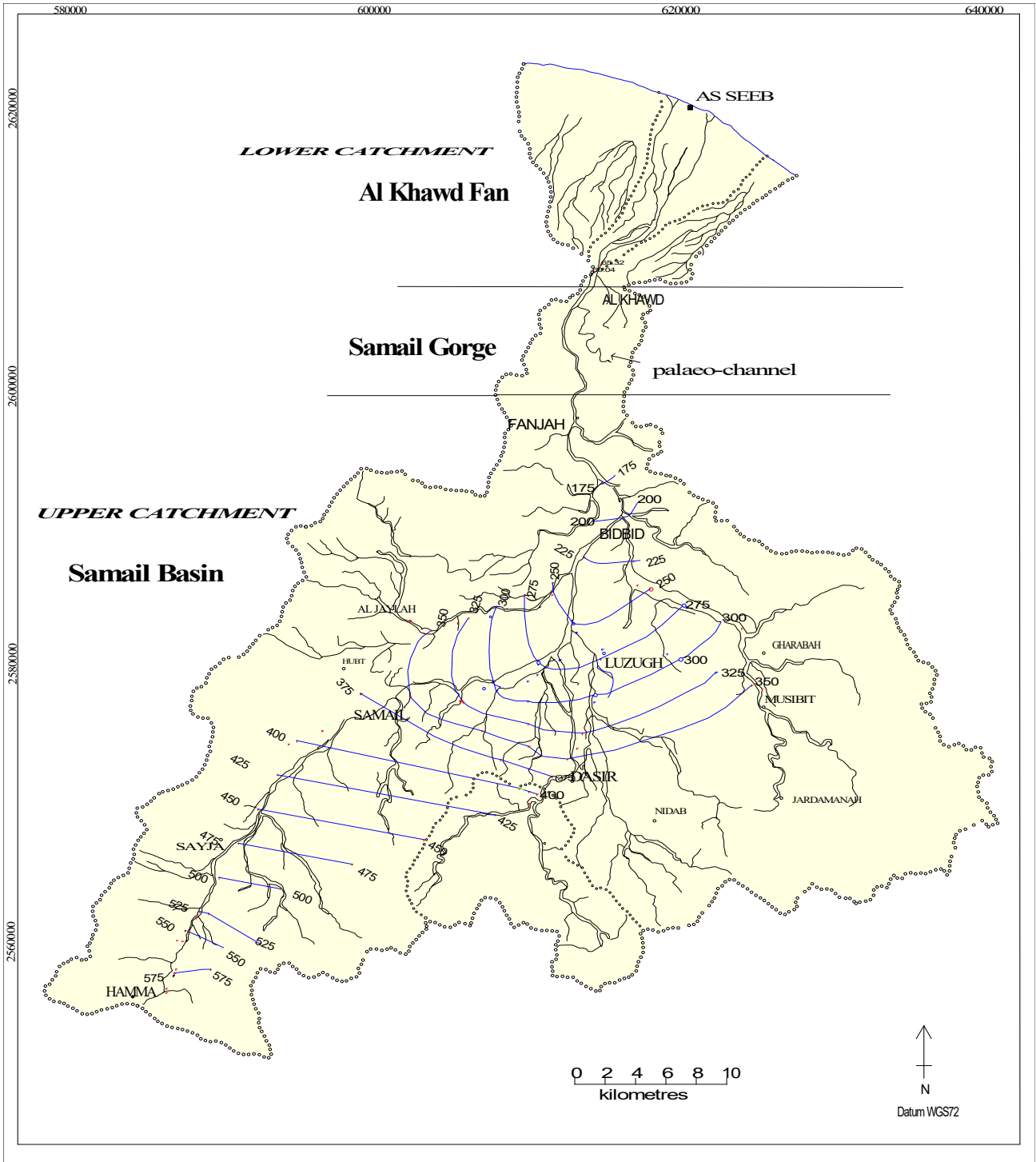


Fig. 1.1 Wadi Samail Catchment and Al Khawd Fan

1. Water table contours are shown for the Samail Basin for June 1996
2. Note the size of the upper catchment (Samail Basin) to lower catchment (Al Khawd Fan).

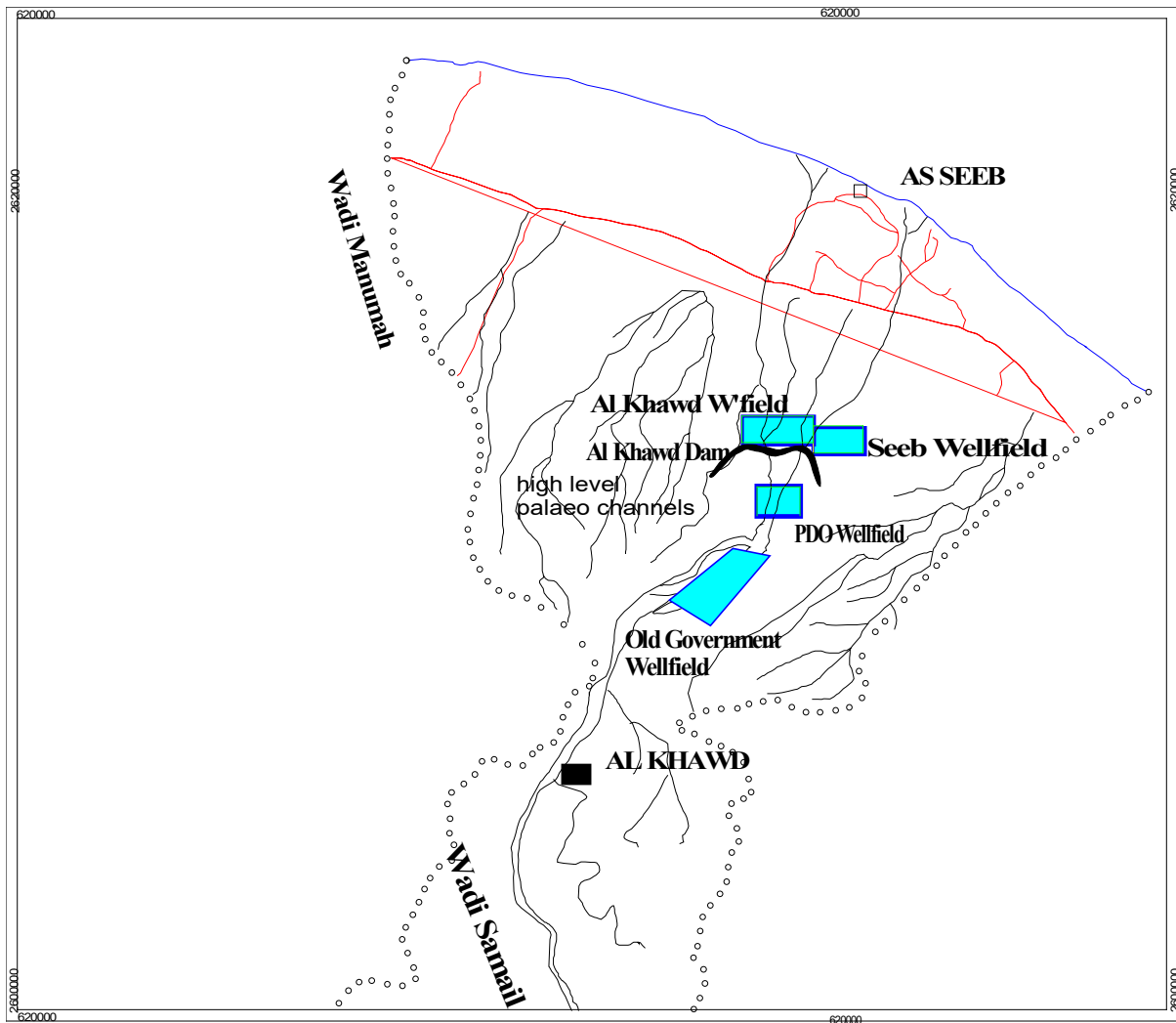


Fig 1.2 Al Khawd Fan Showing Position of Wellfields and Al Khawd Dam

2. GEOLOGY AND GEOMORPHOLOGY OF AL KHAWD FAN

2.1 Geomorphology of the Al Khawd Fan

A number of geologic/geomorphic maps have been produced of the Al Khawd Fan (Gibb, 1976; Hydroconsult, 1978; MMP, 1984; BRGM, 1986). They show the presence of four major depositional units (Figs.2.1 and 2.2) consisting of:

- Terrace 1 - Oldest terrace of strongly cemented gravel and boulders
- Terrace 2 - cemented conglomerate
- Interfluvial areas of braided channel
- Most recent wadi gravel

It is notable that most of the upper and western parts of the Al Khawd Fan consist of either Terrace 1 or Terrace 2 material. Only in the far northeast, on the eastern tributary downstream of the Al Khawd Dam is there significant development of recent wadi gravel.

The Wadi Samail bifurcates at Al Khawd village, with the Wadi Manumah passing along the western flank of the Al Khawd Fan, and Wadi Samail flowing close to the boundary on the east. At Al Khawd, the entrance to the Wadi Manumah channel lies some metres above the channel level of Wadi Samail, and as a consequence only flows during the bigger floods. The large area between the Wadi Manumah and Wadi Samail is considerably higher than the adjacent wadis, especially in the area covered by the older Terrace 1 (Ma'abilah Block), which extends northwards to the Al Khawd Dam. On the Ma'abilah Block, the older Terrace 1 is drained by a number of stream channels, which rise in the upper parts of the terrace, where they are perhaps 50+ m above the adjacent Manumah and Samail channels. The catchment for these channels is confined to the terrace areas on the Fan, and they are therefore fed only by local rainfall. They are not connected with the Wadi Samail surface system. On the older terrace, water tables may be tens of metres below ground level, and it is likely that these channels flow very infrequently, if at all. In essence they are palaeochannels reflecting wetter conditions in the past.

Terrace development is significantly greater on the Wadi Manumah than on Wadi Samail suggesting that in the past, Manumah has been the major distributary, however, now most flow passes down Wadi Samail, where it recharges the alluvium of the middle-lower Fan.

Upstream of the Al Khawd Dam, the channel flows through a shallow gorge incised into the older Terrace 1, but beyond the Dam the wadi spreads out and flows across a broad secondary fan of unconsolidated gravel and boulders which continues to the coast. While the concept of near wadi and far wadi (interfluves), has been used by different authors, the "interfluves", are essentially the terrace areas which make up most of the Fan, especially in the central areas and in the west. The "near wadi" region is largely confined to the main upper channels of the two principle wadis and their distributaries in the lower parts of the plain. These are the respective source areas of intermediate and local flow systems developed on the Al Khawd Fan

Given the differing permeabilities associated with these units, most wadi recharge under flood conditions would normally be in the lower secondary fan area in the northeast, where the recent gravel outcrops between the Al Khawd Recharge Dam and the coast. This is reflected in the spikiness of the local flow system. By contrast, hydrographs of bores beneath the western part of the Al Khawd Fan tend to be more subdued, being away from the influence of the recharge zone situated north of Al Khawd Dam. The lateral effects of the local flow system observed in the spikiness of the hydrographs, reflects the degree of hydraulic connection with the recharge zones, that is, the permeability of the interceding aquifer. One excellent example is the DP-2 bore, situated in the centre of Terrace 1, which shows a strong spikey response, reflecting the influence of the local flow system, despite its presence well away from the active recharge zones.

The distribution of wellfields on the Al Khawd Fan shows that the Old Government Wellfield and the PDO Wellfield are located in zones of strongly cemented gravel and boulders of Terrace 1. The Seeb Wellfield spans an area ranging from cemented conglomerates of Terrace 2 sediments to interfluve channel deposits and recent wadi gravel. The southwestern limit of the Al Khawd Wellfield lies on the margins of Terrace 1 but the bulk of the wellfield lies largely within the braided channel and recent wadi gravel zones.

2.2 Geology of Al Khawd Fan Alluvium.

Tertiary limestone and mudstone outcrop near Al Khawd, and dip northwards beneath the alluvial fan. The Tertiary sequence is unconformably overlain by an alluvial sequence deposited in a fan-delta environment, by ancestral and present day Wadi Samail and Wadi Rusayl systems. This sequence forms the coastal plain. The alluvial fill is over 300 m thick across much of the coastal plain, with the maximum recorded depth of more than 600 m at a site on an alluvial terrace (Gibb, 1997; MMP, 1985). Various depositional phases are recognized in the fan-delta complex, as channel shifting has led to the abandonment of earlier channels and the development of new loci of sedimentation. An example, here, is the Wadi Manumah which is a former course of Wadi Samail. The shift to the east by the present Wadi Samail, and its incision into the earlier Wadi Manumah deposits, means that the latter wadi carries water from the upper catchment during periods of high flow, when the main channel spills to the west. Of special note is the presence of an number of ancient terraces, across which the wadis flow, with the bulk of the more recent deposition occurring only closer to the coast.

Partially as a consequence of the establishment of the Old Government, PDO and Seeb and Al Khawd wellfields in the early-mid 1970's and 1980's, and their significance as supply and back-up systems, there are a large number of bores and much literature written on the Al Khawd Fan. These studies have arisen not only in response to groundwater resource development in the Al Khawd Fan, but also to the threat to this resource from seawater intrusion arising from the development. The basis stratigraphic framework used extensively for hydrogeological studies across the Batinah Coastal Plain comes from Gibb (1976), who provided a tentative threefold division of the coastal plain deposits with depth, as follows:

- a. Upper Gravels - beds of clean gravel and sand with boulders
- b. Clayey Gravel - brown and red coloured marly gravels and clayey sands
- c. Cemented Gravels - grey and white gravelly marls and clays.

2.3 Character of the Alluvium in the Upper Al Khawd Fan

Beds of clean gravel and sand with boulders occur in the upper layers of the alluvium have been termed the '*Upper Gravel* aquifer'. These were seen as being underlain by a clayey unit, the *Clayey Gravels*. The *Clayey Gravels* were postulated to be formed by decomposition of ultrabasic peridotite and gabbroic pebbles by subsurface groundwater/rock reactions to smectite and polygorskite clay minerals, with limestone and chert pebbles remaining unaltered.

Gibb (1976 Appendix 1V p 4) notes - "These clayey gravels have been recorded in many boreholes below gravels and boulders and above grey and white marly gravels, which represent the cemented beds at depth. They appear as brown and red coloured marly gravels and clayey sands. The first appearance of clays and marls are rarely followed by any deeper occurrences of thick beds of clean gravels and this *Clayey Gravel* sequence has frequently been accompanied by significant reductions in groundwater supplies. The occurrence of white marls and clays classified as *Cemented Gravels* have been shown to be the equivalent of the predominantly carbonate horizons of the higher terrace areas".

The Cemented Gravels were thought to represent a further stage of diagenesis from the Clayey Gravels with the clayey material being replaced by dolomite. Here, Gibb (1976, p 4)

notes Glennie's explanation for the origin of the Cemented Gravels as being due to diagenesis associated with a fluctuating water table in which the ultrabasic rock component has been replaced by dolomites. Gibb (1976) notes that this would explain the rapid vertical changes from gravels to carbonates in sequences, which are difficult to explain simply by the alternate formation mechanism provided by variations in primary depositional regimes.

Gibb (1976) also commented that the nature of the Clayey Gravels appears to support the Glennie hypothesis, and he provides the example from the SAG 13 bore, situated downstream of the Al Khawd Dam (Fig. 3). In SAG 13 clay and claystone pellets of decomposed and altered peridotite, referred to by Gibb as the Clayey Gravel unit, occur in a zone above carbonate rich Cemented Gravels. The claystone pellets and other clays consisted of serpentinite, montmorillonite and rare magnesium rich polygorskite minerals. The Clayey Gravels are thus seen in this instance as being an earlier stage of the dolomitization process caused by reactions between magnesium rich gravels and groundwater. In the SAG 13 sequence an uppermost 20 m thick unit of peridotite/gabbro pebbles with subordinate limestone and chert pebbles (Upper Gravel), passes into 6 m thick pebbly carbonate unit overlying the 16 m thick Clayey Gravel. The partially weathered clayey sequence in turn passes into a further 76 m thick pebbly carbonate sequence which lasts until the bottom of the bore at 122 m.

Given the appearance of a distinct pebbly carbonate zone appearing above the weathered peridotite zone, it seems that the main lithologic distinction in SAG-13 lies between the upper Uncemented Gravels and a lower varyingly carbonate rich sequence (Cemented Gravels) within which a clayey weathered unit (Clayey Gravels) occurs. However, the extent that this sequence represents any broader uniform tripartite lithological pattern within the Al Khawd Fan must be strongly questioned.

The most comprehensive study of the upper regions of the Al Khawd Fan were carried out by MMP (1985) during a major well upgrading and construction program. This involved the upgrading of 24 existing wells in the Old Government and Seeb Wellfield and the construction of 17 new wells, together with the construction of the Al Khawd Dam Wellfield comprising 14 new wells (MMP, 1985). In addition a number of monitoring bores were constructed in both the upper and lower parts of the Al Khawd Fan by the PAWR to examine the seawater intrusion problem (Bhatnagar and Ravenscroft, 1986).

In the MMP (1985) report on the upper Al Khawd Fan, the geology, hydrogeology, hydrochemistry and well and wellfield characteristics were examined. Pumping tests were carried out on a number of bores. The lithologic logs of all bores drilled in the Old Government Wellfield situated on the oldest Terrace 1 show conglomeratic dolomitic carbonate sequences occur to the depth drilled in all bores. The total thickness of this unit is unknown but conglomeratic dolomitic carbonate is still present at 220 m in the deepest bores drilled - WD 7A. The conglomeratic dolomitic carbonates were seen by MMP (1985) as representing the Cemented Gravel unit of Gibb (1976). This is in line with the position of the bores on Terrace 1, said by Gibb (1976) to represent outcrop of the Cemented Gravels.

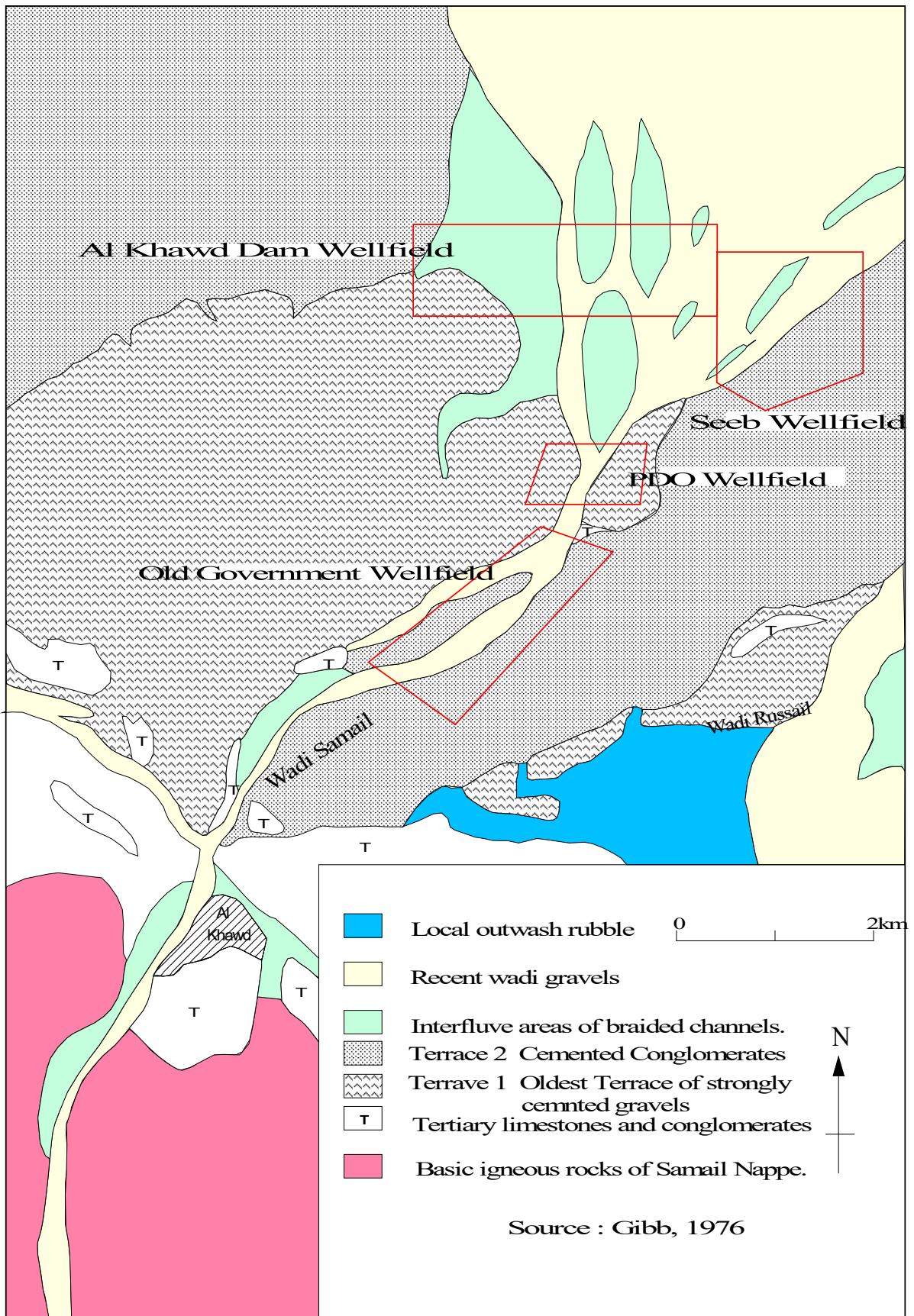


Fig. 2.2 Surficial Geology of the Western Wellfields

The Cemented Gravels were thought to represent a further stage of diagenesis from the Clayey Gravels with the clayey material being replaced by dolomite. Here, Gibb (1976, p 4) notes Glennie's explanation for the origin of the Cemented Gravels as being due to diagenesis associated with a fluctuating water table in which the ultrabasic rock component has been replaced by dolomites. Gibb (1976) notes that this would explain the rapid vertical changes from gravels to carbonates in sequences, which are difficult to explain simply by the alternate formation mechanism provided by variations in primary depositional regimes.

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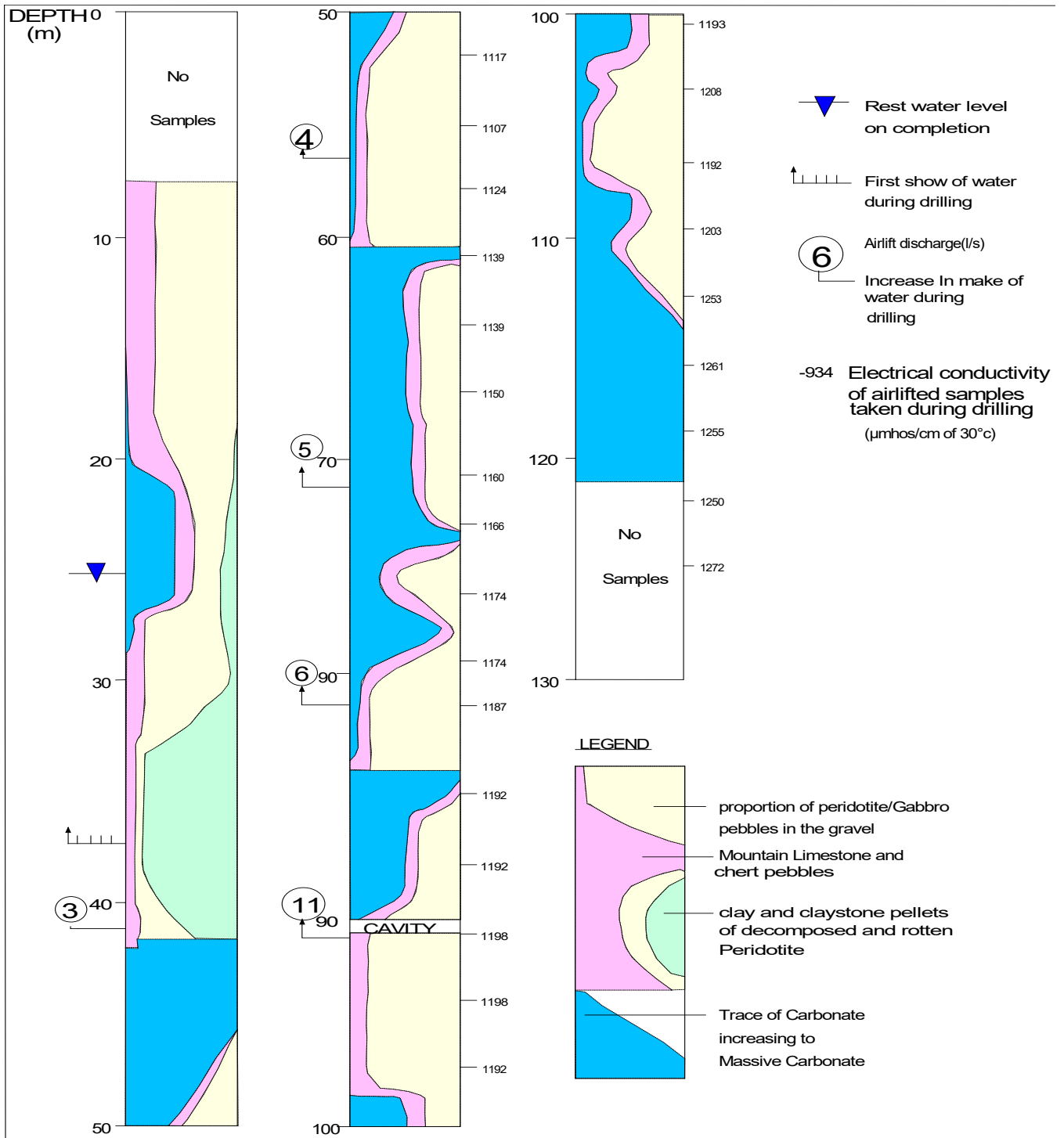


Fig. 2.3 Drilling Log Borehole SAG13 (from Gibb, 1976)

The sequence in borehole WD 13A is given in Table 2.1.

Table 2.1 Lithology of the WD-13A bore in the Old Government Wellfield

Depth (m)	Lithology
0-15	Wadi alluvium - poorly sorted pebbles of igneous rock, limestone and clastics in a silty sandy matrix.
15-19	Soft brown sandy marl
19-47	Conglomeratic carbonate. Brown to creamy white dolomitic carbonate with scattered pebbles of green igneous rock, limestone, quartz and brown clastic material
47-51	As above - but marly
51-89	Conglomeratic carbonate. Buff to brown dolomitic carbonate with pebbles
89-93	Cemented conglomerate
93-174	Conglomeratic carbonate. White / buff / brown dolomites carbonate with scattered pebbles
174-191	Cemented conglomerate. Pebbles of igneous rock and limestone in a buff carbonate cement
191-200	Conglomeratic carbonate

This sequence showing a thin upper unit of wadi gravels overlying a conglomeratic dolomitic carbonate sequence is typical of all bores in the Old Government Wellfield area, drilled during the study. A comprehensive pumping test program on the new wells in the Old Government Wellfield gave transmissivity values ranging from 10 to 450 m³/d/m with an average of 90 m³/d/m. Only in one case was an interval tested solely in the pebbly dolomites, and it gave a transmissivity of 25 m³/d/m.

Significantly higher transmissivities were obtained from the Seeb and Al Khawd Wellfields located in areas having much greater depths of uncemented and partly cemented sand and gravel giving an average T of 1500 m³/d/m and average K of 34 m/d. It was furthermore observed by MMP (1985) that, in the Old Government Wellfield, aquifer yield declined with depth to water table. The explanation was that highest yields were obtained from the upper less cemented parts of the aquifer, and yields declined as static levels declined into the lower less permeable dolomitic horizons, either during pumping or as a consequence of drier years.

The results from the MMP Study of the Old Government Wellfield are clear, however data from elsewhere on the Al Khawd Fan raises questions as to how representative of the Cemented Gravels is the area underlain by the Old Government Wellfield. A further question is raised about the validity of the generalization, that sequences in the older terrace or in the Cemented Gravels have uniformly low permeabilities. This question is important in any consideration of aquifer recharge and the movement of groundwater across the southern Fan.

While no transmissivity data is available, a different picture on yield emerges when examining data from the PDO Wellfield which lies within the older Terrace 1, a little to the north of the Old Government Wellfield. Here three production bores have been in existence for more than a decade. All bores are screened across intervals mostly at depths of between

100 m. and 200 m. - i.e. across the interval deemed to have low productivity in the MMP study (Table 2.2).

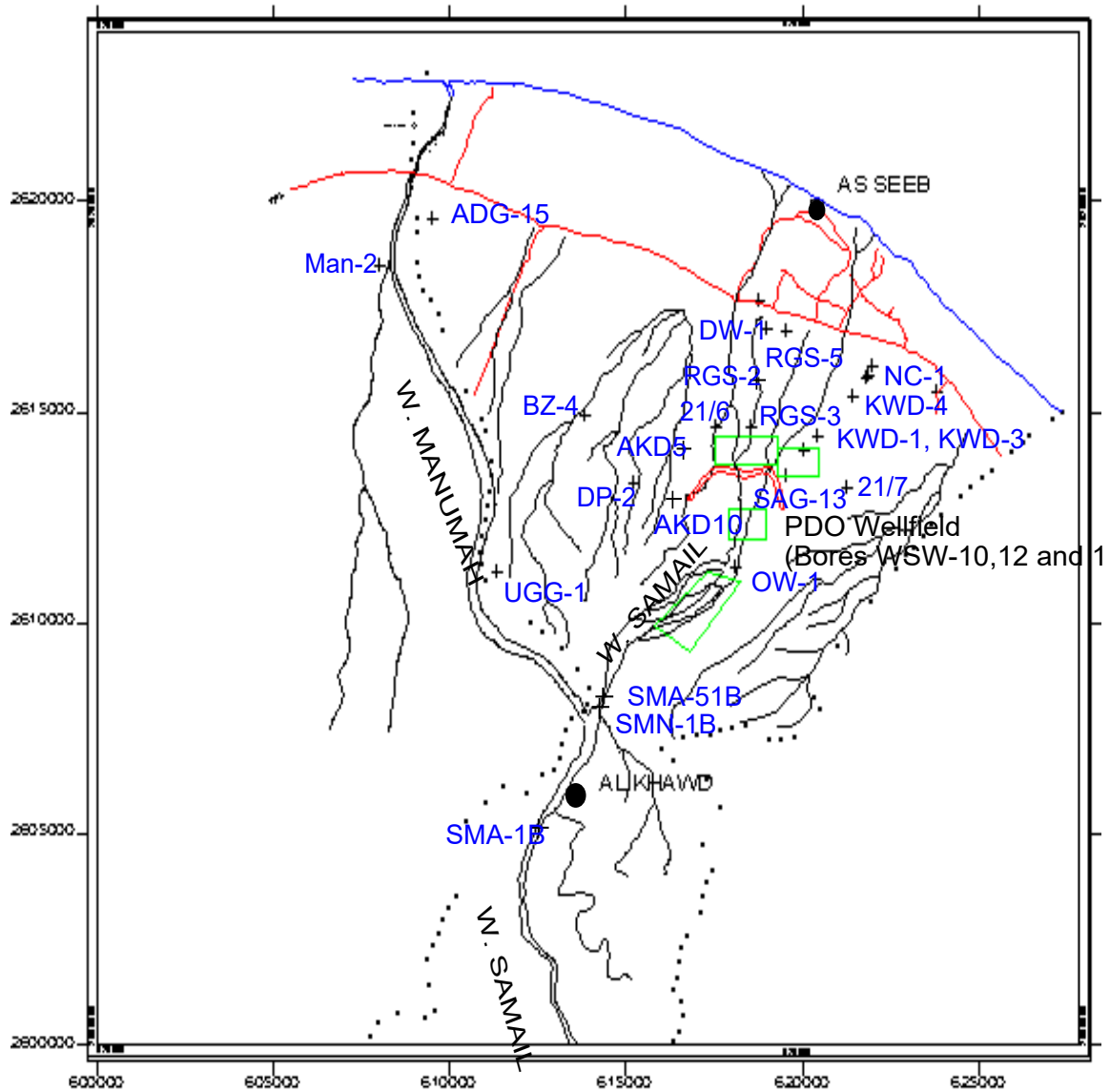


Fig 2.4 Selected Borehole Location on Al Khawd Fan

Table 2.2 Construction details for the PDO bores, Upper Al Khawd Fan (Parker, 1984)

Bore	WSW-10	WSW-12	WSW-13
Depth (m)	220	229	229
Screened Intervals (m)	85 -201	87-95, 105-113, 173-189 199-207	125-137, 150-156, 165-190, 191-229
TDS (mg/l)	800	775	800

Yet pumping rates and long term yields (Tables 2.3 and 2.4) are relatively high and have been

maintained. This is not what might be expected from the MMP study. For instance, over the year 1984, the three PDO bores were pumped consistently and gave average yields ranging from 14.4 l/s to 8.8 l/s (**Table 2.3**)

Table 2.3 Pumping rates from PDO bores during 1984(Parker 1984)

1984	Yield (l/sec)
SIB-WSW-10	8.9
SIB-WSW-12	14.4
SIB-WSW-13	12.8

Annual yields from 1982 to 1984 for the three PDO bores are given in **Table 2.4** (data from Parker, 1985).

Table 2.4 Annual yields from PDO bores, Upper Al Khawd Fan

Year	WSW-10	WSW-12	WSW-13
	m ³	m ³	m ³
1982	188430	167490	166460
1983	204320	197540	157890
1984	183840	184520	248690

The PDO results showing long term yields of 8.9 to 14.4 l/s from the Cemented Gravels are further supported by airlift yields obtained from the SAG-13 bore situated a little further to the north. Here, a steadily increasing airlift yield of from 3 l/s to 11 l/s was obtained during drilling, with an initial yield of 3 l/s coming from near the base of the ‘Clayey Gravel’ unit. The yield increased in the Cemented Gravel unit to be 4l/s at 55 m, 5 l/s at 70 m and 6 l/s at 82 m. The yield almost doubled to 11 l/s at 92 m when a cavity was encountered (**Fig. 2.3**), showing that secondary porosity may play an important role in groundwater flow within the Cemented Gravels. By comparison the average ‘duty’ yields of the three wellfields (**Table 2.5**) are:

Table 2.5 Duty Yields of Government Wellfields (MMP, 1985)

Old Government Wellfield	7.4 l/s
Seeb Wellfield	17.7 l/s
Al Khawd dam Wellfield	14.9 l/s

A picture of higher permeabilities and higher transmissivities within the older Cemented Gravel sequence emerges from the drilling carried out by PWR in the upper Al Khawd Fan (Bhatnagar and Ravenscroft, 1986). Here, pumping tests were carried out on the DP-2 bore

which lies at a high elevation in the centre of the older Terrace 1, and on the UG-1 bore situated west of Wadi Manumah on terrace 2. While DP-2 lies centrally within sequences ‘stratigraphically’ within the Cemented Gravel, The UG-1 bore lies close to the foot (within 20 m) of the dipping Terrace 1, which would have been intersected in the bore at a relatively shallow depth. Details of the two bores are given in **Table 2.6** and pumping test results are given in **Table 2.7**.

Table 2.6 Details of DP-2 and UG-1 bores in the upper Al Khawd Fan

Well No.	Depth (m)	SWL	Screened Interval
DP-2	248	52.5	188-194, 205-217
UG-1	135	40.85	64-70, 82-105

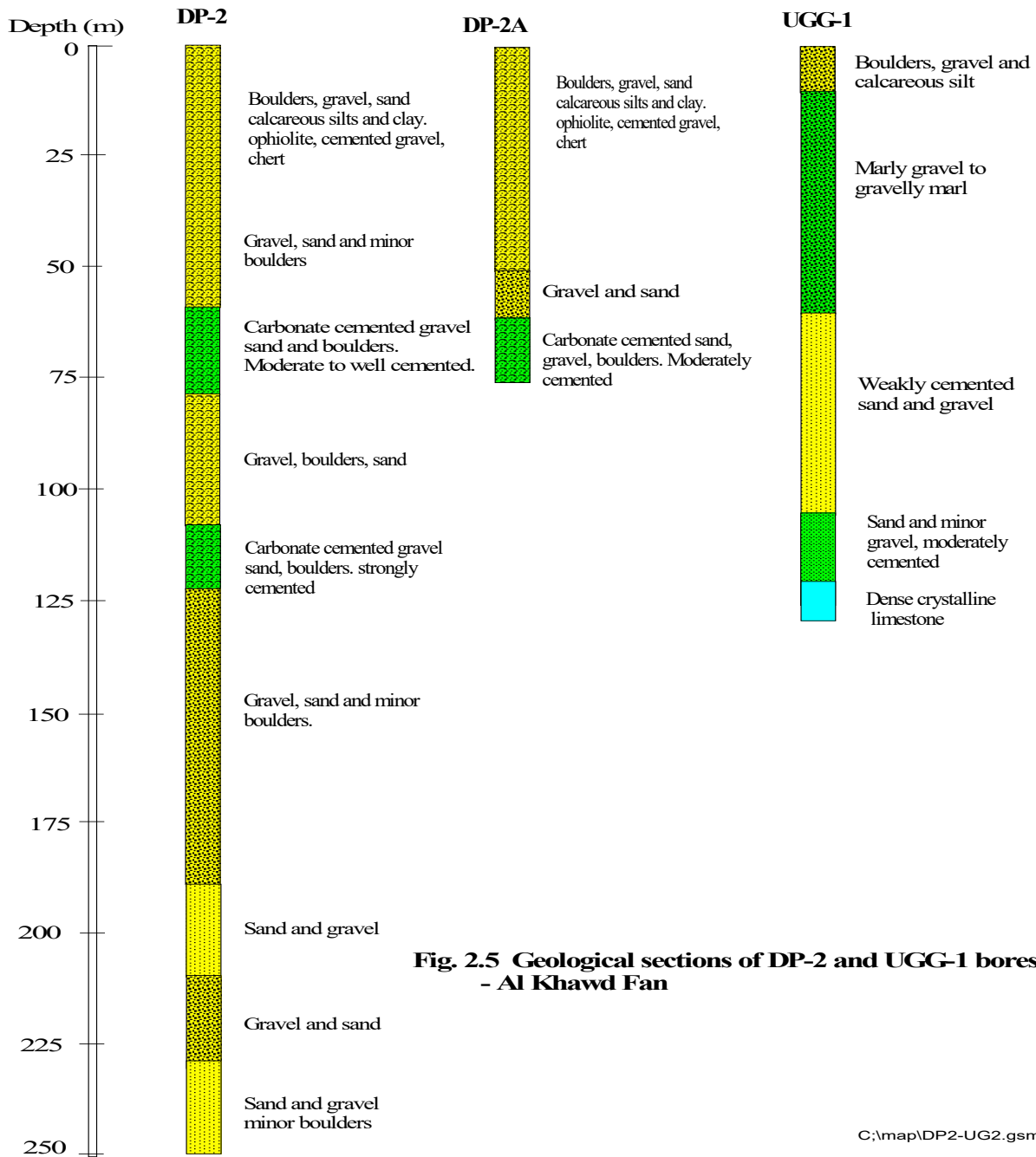
Table 2.7 Pumping test data from DP-2 and UG-1 bores, Upper Al Khawd Fan

Well No.	Transmissivity (m ³ /d/m)	Hydr. Conductivity (m/d)	Storativity
DP-2	650	8.7	.0007
UG-1	1484	35	.036

It is notable that the DP-2 bore is screened across the lowest parts of the aquifer from 188-217 m, deemed to be the low-productive part of the aquifer in the MMP (1985) study. During the pumping test, no evidence of a lateral boundary was present. The transmissivity of DP-2, while not as high as that given for the Seeb/Al Khawd wellfield bores (average 1500 m³/d/m) is significantly higher than any bore tested in the Old Government Wellfield by MMP, being more than 6 times the average of 90 m³/d/m obtained for those bores and 26 times that obtained for the only bore tested solely in the gravelly dolomites (25 m³/d/m)

The UG-1 bore, situated closer to Wadi Manumah towards the head of the Al Khawd Fan has a transmissivity virtually the same as the average for the Seeb/Al Khawd wellfield bores. During drilling airlift yields of 16 l/s were obtained. The UG-1 bore bottomed in crystalline limestone (Tertiary limestone?) and it was speculated that some water might be derived from this source (Bhatnagar and Ravenscroft, 1986).

The explanation for the higher yields from the DP-2 bore situated clearly in the middle of the oldest high level Terrace 1, mapped by Gibb (1976) and associated by him with the Cemented Gravels, lies in its different lithology from that occurring in the vicinity of the Old Government Wellfield. The 200+ metre sequence is not heavily carbonate cemented, but instead contains several limited zones where carbonate cement gravel occurs (**Fig. 2.5**) in an otherwise largely uncemented sand, gravel and boulder sequence. Similarly, the UG-1 bore does not contain the thick dolomitic horizons present in the vicinity of the Old Government Wellfield.



It seems therefore that the different permeabilities occurring in the aquifer system in the upper Al Khawd Fan do not correspond to separate aquifer systems developed as discrete time/stratigraphic units. Instead, low permeabilities best reflect zones where dolomitic diagenesis has been strongly active. Thus, in the area of the Old Government Wellfield, dolomite diagenesis has played a strong part in aquifer plugging resulting in lower permeabilities. However, the carbonate plugging of sequences, by itself does not imply low permeabilities or low yields, since a little further downstream in the vicinity of the PDO Wellfield and in the SAG-13 bore, reasonably high yields show that either this process is not so strongly developed, or is less uniformly developed, or secondary porosity is present, or a

combination of these. Similarly, further west in the vicinity of the DW-2 and UG-1 bores, diagenesis is poorly developed and has not significantly effected aquifer permeabilities.

2.4 TDEM Data

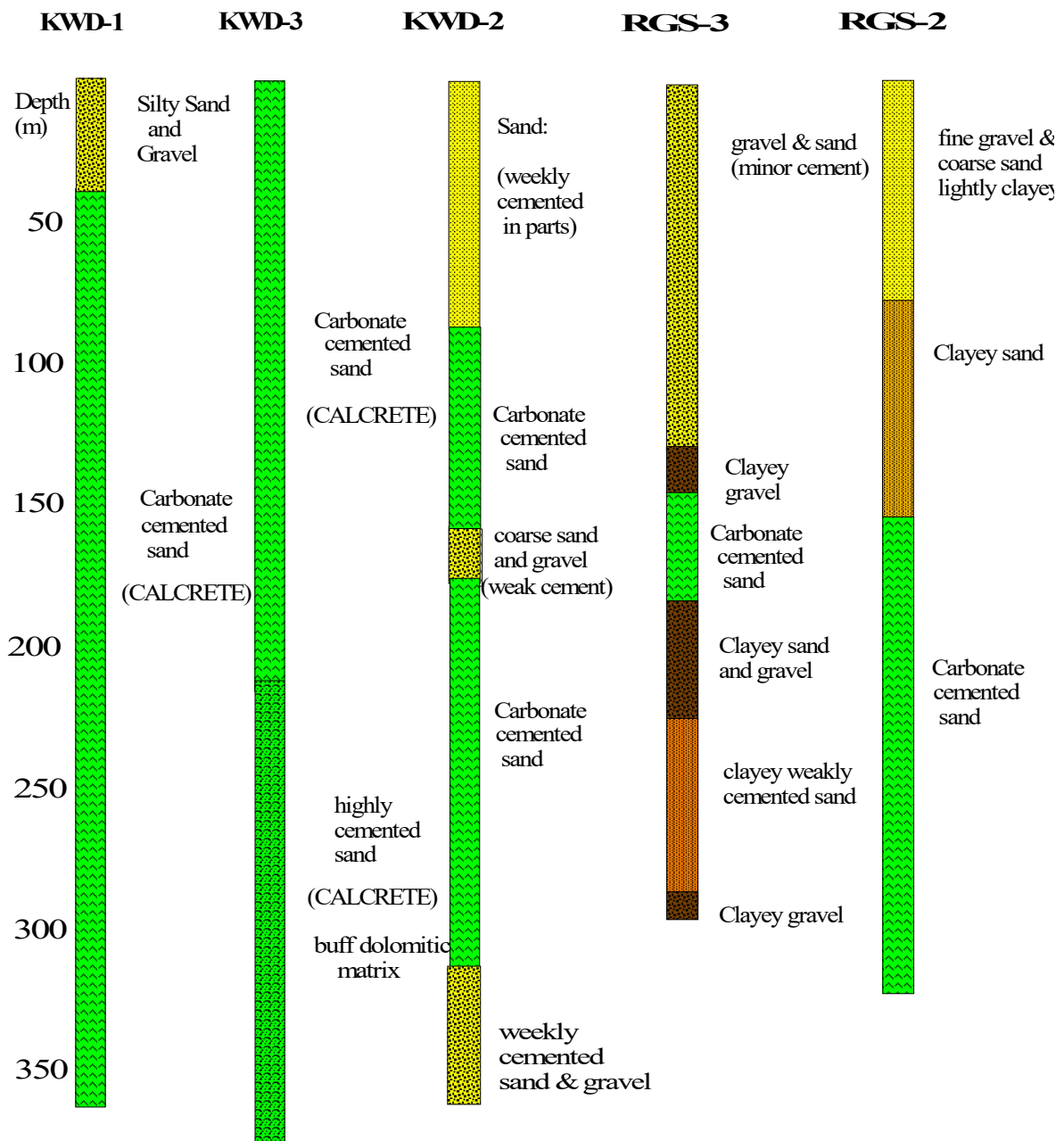
The suggested lithologic variability indicated by the above conclusions are to some degree supported by the TDEM work carried out by Geosystem.SRL for the MWR in the Al Khawd Area (1992) to delineate the seawater intrusion into the Al Khawd Fan. Two profiles were run through the central Al Khawd Fan with Profile PO1 along the RGS piezometer line and Profile PO2 along the KWD piezometer line. Conductivity values of less than about 2.5 ohm.m characterize the seawater intrusion, which comes almost into the vicinity of the Al Khawd Dam. In both lines, zones of intermediate resistivities characterize the aquifer vertically above and below the seawater intrusion with highest resistivities in the upper layers (33 to 96 ohm.m); resistivities are lower, being from 13 to 45 ohm.m in the deeper sequence beneath the KWD-line, and from 7.4 to 45 ohm.m beneath the RGS-line (one value being 109 ohm.m in the north, and a second being 110 in the south near the Al Khawd Dam).

The sequences below 100 m in the uppermost area of the Fan in the case of the KWD-line had low resistivities suggesting “alluvium with argillaceous content or brackish water”, with resistivities from 1.3 ohm.m to 14. ohm.m. Since water quality is known to be similar here to that found to the north, the soundings probably represent clayey sequences, perhaps similar to those in the Old Government Wellfield. By contrast, in uppermost areas of the RGS-line to the south of the Al Khawd Fan, resistivities to a depth of 400 m ranged from 18 to 32 ohm.m, fitting better into the intermediate category seen beneath the seawater intrusion. That is, there is a suggestion that above the Al Khawd Dam, less clayey, higher permeability sequences are found in the east, also, becoming more porous on passing down basin. Whatever the actual values, the TDEM results point to a degree of variability in the upper Al Khawd Fan which agrees with the lithological data.

2.5 Character of the Alluvium in the Middle-Lower Al Khawd Fan

A similar observation on permeability variation was made by Bhatnagar and Ravenscroft (1986) who note that “Superimposed upon these (the original sedimentary facies) are differences which relate to post-depositional effects such as weathering, and cementation by carbonate minerals. The recognition of such deposits is of profound importance to understanding the hydrogeology of the alluvial aquifer system”

Bhatnagar and Ravenscroft (1986) provide a number of lithologic sections through the RGS and KWD well series for the lower Al Khawd Fan. They note that in the KWD section there is a high proportion of well-cemented material in the south which is largely absent to the north of KWD-2 (bores KWD-1, KWD-2 and KWD-3, Fig. 2.6). The RGS series of wells, further west shows generally less evidence of cementation, and only in the latter RGS-series (bores RGS-2 and RGS-3, Fig. 6) is there evidence of a clayey unit which might be correlated with a Clayey Gravel of Gibb (1976), however, in the case of the KWD-series there is no suggestion of this unit.



**Figure 2.6 Geological sections through deep bores in Al Khawd Fan
(Lithologies from Bhatnagar and Ravenscroft, 1986)**

Bathlith3.gsm

In the Bhatnagar and Ravenscroft (1986) report, no sub-division was made on the lower Al Khawd Fan alluvial sequence comparable to the Gibb (1976) tripartite classification of alluvial aquifers. Instead only 2 units were recognized based on the degree of cementation. An upper more permeable sequence with hydraulic conductivities of about 34 m/d which is comparable to the Uncemented Gravel, and a lower low permeability unit with a hydraulic conductivity of about 1 m/d and equivalent to the Cemented Gravel. From a seawater intrusion viewpoint, the

presence of high permeability zone(s) is important given that the movement inland of seawater intrusion is greatest along more permeable strata (Bear 1986).

An attempt at correlation between the southern and northern aquifer sequences of the Al Khawd Fan using the Gibb (1976) tripartite nomenclature, was made by MMP (1985). They produced a section passing from the Old Government Wellfield (WD-1 bore) through the AKD-10 bore at the western end of the Al Khawd Wellfield to the RGS-3 bore and DW-1 bores of the lower Al Khawd Fan (Fig. 2.7).

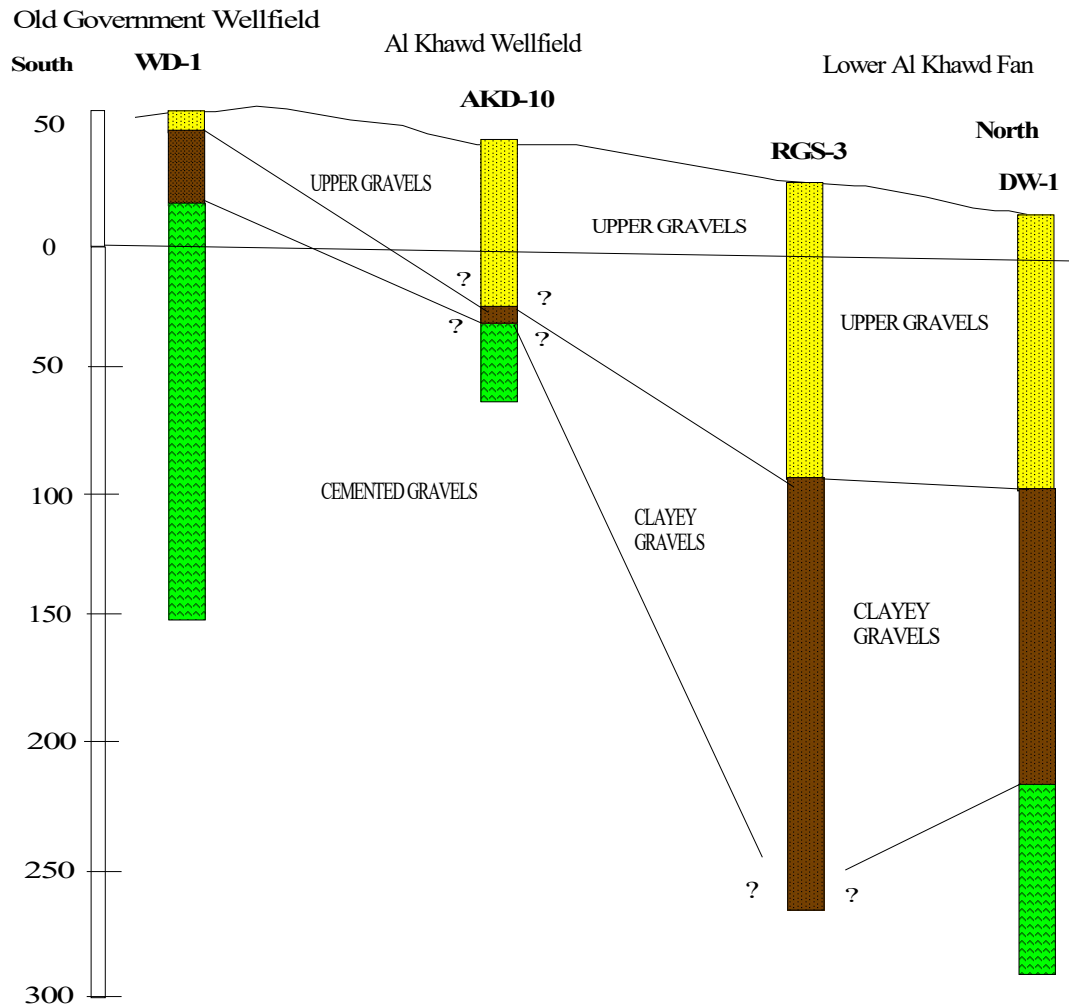


Fig.2.7 - Schematic Geological Section across the Al Khawd Fan (from MMP, 1985)

However from the MMP (1985) section there are clearly some doubts on MMP's behalf (shown by a number of question marks on their diagram) about the correlations in the linking AKD-10 bore. This doubt is well-founded, in that firstly the AKD-10 bore appears to be situated on the older Terrace 1, at the edge of the elevated Ma'abilah Block, not on any more recent gravel sequence and, on this grounds alone, a 50 m thick sequence of Upper Gravels seems most unlikely. Secondly, the original lithologies of AKD-10 (previously unpublished - Fig 2.8) show a very thin gravel unit underlain by a carbonate cemented sequence of sandstones and conglomerates. This does not easily fit the lithologies shown in the MMP (1985) report.

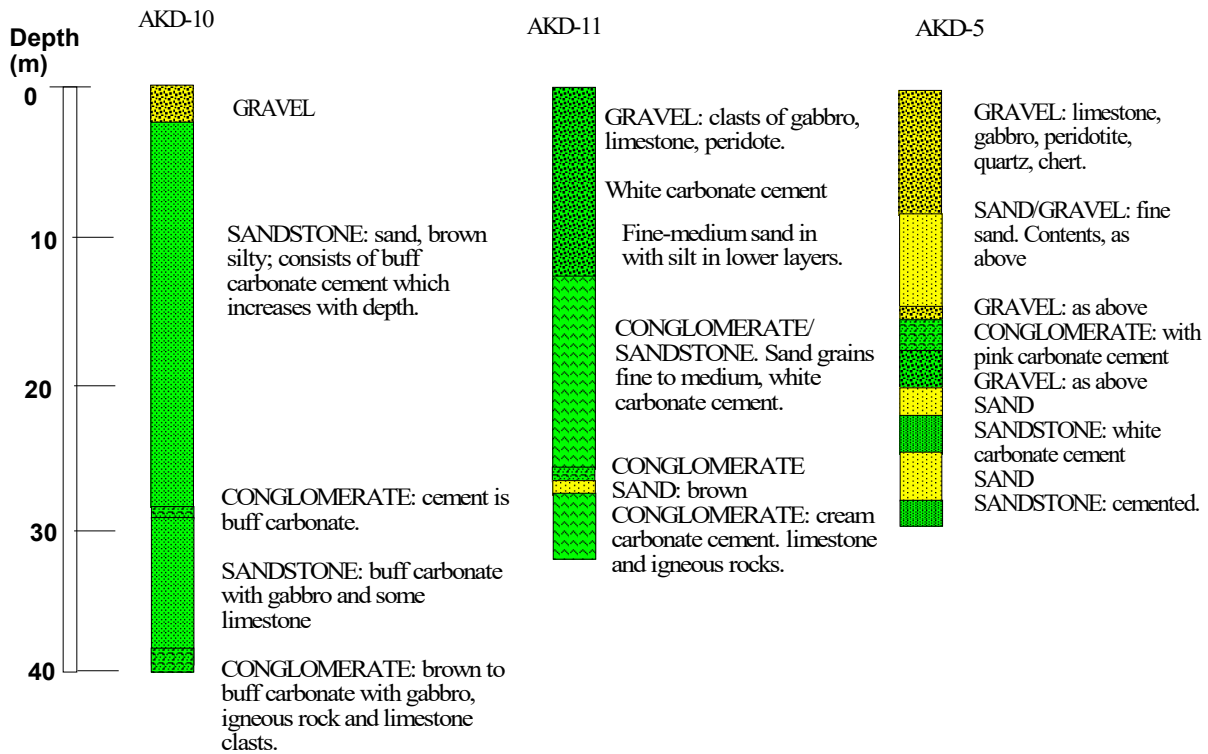


Fig. 2.8 South to north section through AKD-bores - Al Khawd Wellfield

AKDSECT3.gsm

A more complete description of the sequences comes from the recent MWR drilling of the deep 21-Series bores across the Al Batinah plain (MWR, 1995). Two bores (21/6 - 350 m, and 21/7 - 330 m; Fig.2.9) were located on the lower Al Khawd Fan downstream of the Dam. The more westerly of the two bores (21/6) shows a interbedded gravel, cemented gravel and calcrete sequence, with calcrete predominating in the lower part of the section below 230 m.

The more easterly 21/7 bore shows a largely uncemented gravel sequence to 80 m with one interbedded 7 m thick calcrete bed. Beyond 80 m, calcrete predominates with a few thin interbedded sand and gravel bands. While the uppermost unit in both bores was largely gravel, calcrete was interbedded with the gravels and dominant deeper in the sections. Neither bore showed the tripartite division of Gibb (1984).

2.6 Summary of the Lithology of Al Khawd Alluvium

It follows from this brief account of the lithology, that calcreted sequences occur across much of the Al Khawd Fan, perhaps best developed in the eastern areas. Varying thickness of uncemented gravel occurs at the top of alluvium, but are also commonly found elsewhere within the sequences. Their presence therefore does not necessary imply a stratigraphic connotation, or temporal links to only the more recent gravels. Thus, while strongly calcreted/dolomitic sequences occur in the vicinity of the Old Government Wellfield,

elsewhere the pattern of cementation is more random, with strong variations both within single bores and between different areas across the Fan.

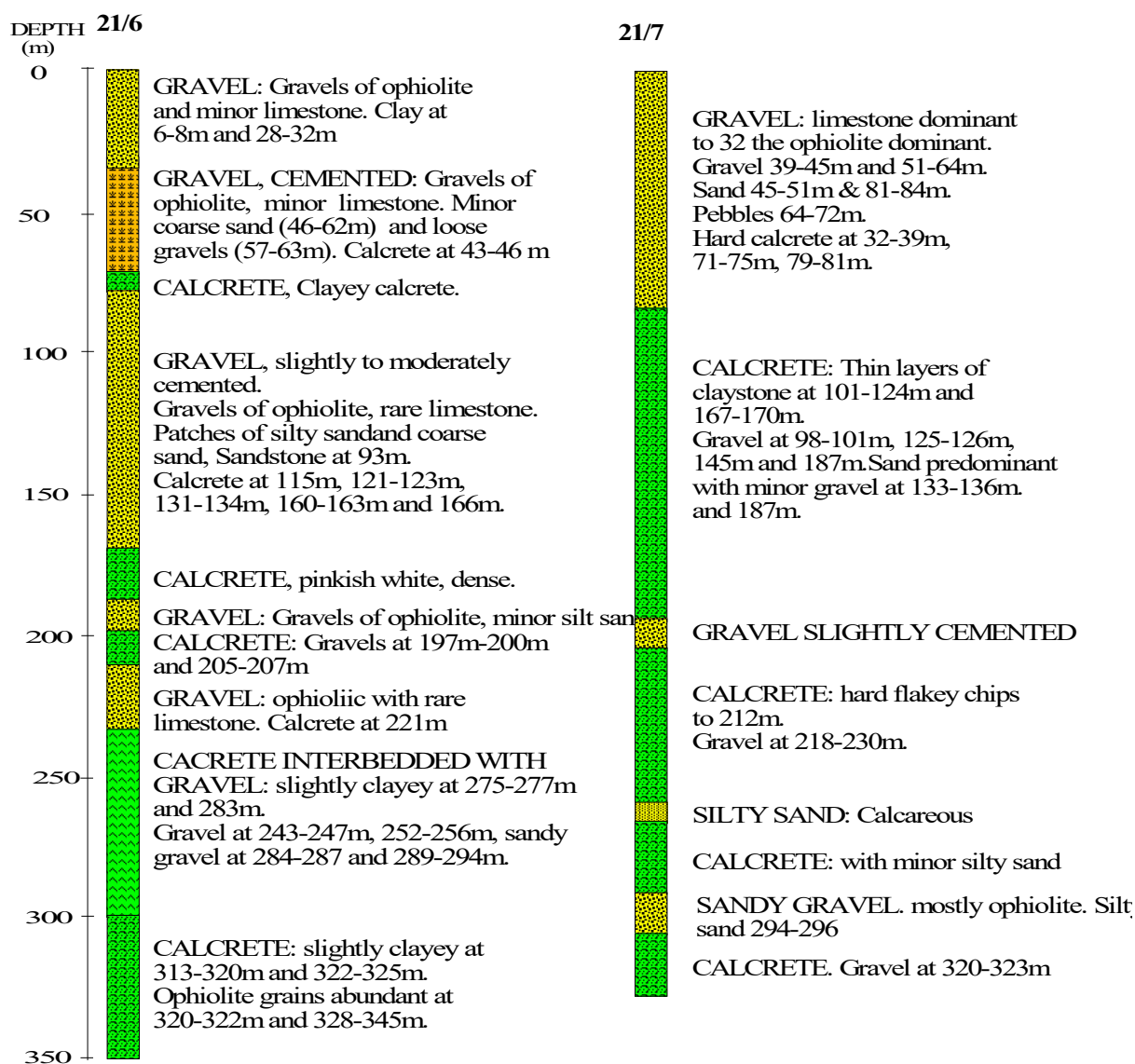


Fig. 2.8 Lithology of 21/6 and 21/7 Bores, Central Al Khawd Fan

21-6DTx.gsm

It follows that, the plugging of discrete intervals by diagenetically instigated dolomitization is not restricted to specific stratigraphic units, but instead represents a widespread process, probably on-going, in which groundwater and ophiolite within the aquifer, interact to produce dolomitic sequences with varying reduced permeabilities.

This process occurs wherever alluvium with a significant ophiolitic component occurs, and is attested to by the ubiquitous presence of dolomitic carbonate cements in soils and sedimentary sequences which are a feature of the geology of alluvium sequences in Oman. The widespread presence of ophiolite gravel diagenesis occurring within the large alluvial fans draining inland

from the Jabal Akhdar, has resulted in the weathered surfaces being given stratigraphic status, and mapped as Barzmanite.

It is important therefore to recognize that hydrogeological studies of thick alluvial sequences such as occur on the Batinah coastal plain, which do not take into account the nature and variable distribution of cementation and aquifer plugging, will inevitably produce oversimplifications which may be very far from the reality of the groundwater flow system.

3. GROUNDWATER FLOW IN THE AL KHAWD FAN

3.1 The Impact of Upper Catchment Runoff on the Al Khawd Fan

The size difference between upper (Samail Basin) and lower (Al Khawd Fan) catchments of Wadi Samail results in a significantly bigger impact of upcatchment runoff on the groundwater systems in the Al Khawd Fan than is the case with other Batinah catchments, resulting in distinct suites of hydrograph response. During wetter periods large volumes of surface water rising in the upper catchment, pass through the Al Khawd gorge towards Al Khawd where they spread over a relatively smaller plain to recharge the coastal aquifers system. This process is clearly reflected by the large piezometer network across the Al Khawd Fan, and it plays a major part in the very distinct hydrogeologic responses and groundwater interactions within the Al Khawd Fan. The hydrograph pattern on the middle and lower Al Khawd Fan shows very large peaks (Figs. 3.1 - 3.5) during these recharge events. This is a very distinctive response, even in the lowermost regions of the Fan, which is not normally seen in the case other major wadis further west, where, instead, subdued responses in the lower catchment reflect the smaller catchment area to plain area ratios.

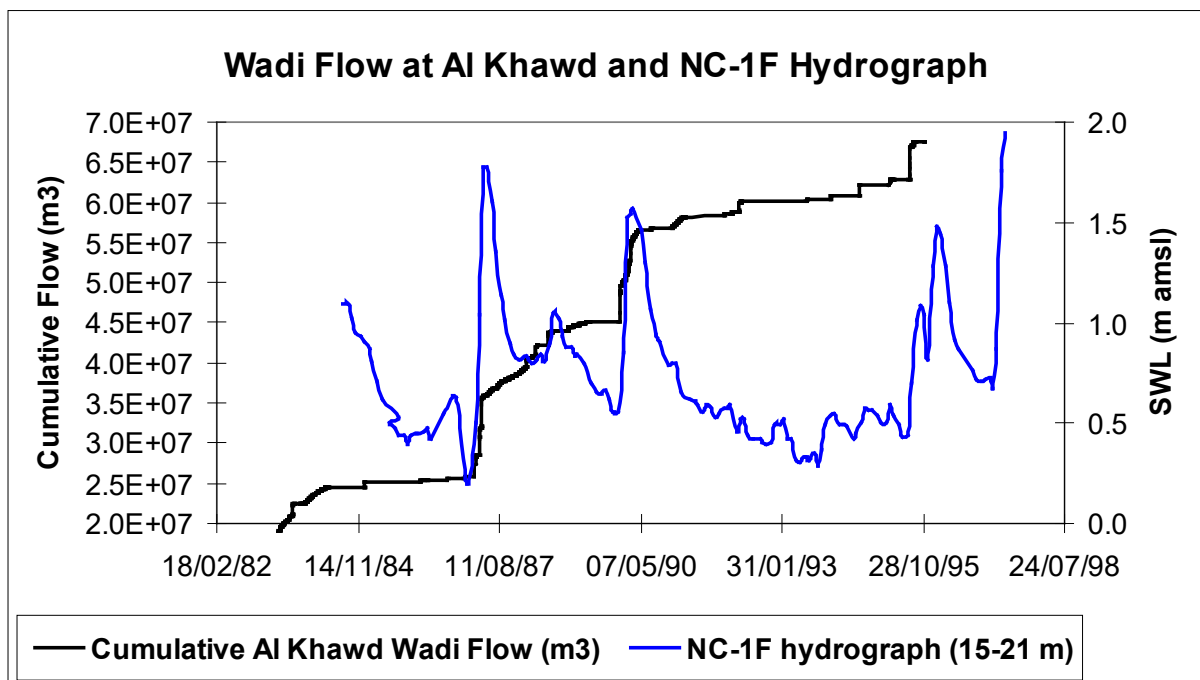


Fig. 3.1 Cumulative wadi flow at Al Khawd and the groundwater response in the NC-1 piezometer

The cumulative flow recorded at Al Khawd gauging station over the 13 year period from December 1982 to October 1995 shows several main phases of wadi flow, such as occurred in 1987, 1990 and 1995 (Fig. 3.1). During these periods the cumulative flow curve rises sharply over a very short time period, before levelling off. Low flow or no flow periods are reflected in small rises or no rise over long time intervals. For instance, following the 1987 wet event, the steep rises represent flood flow while the more gentle rise event is largely base flow.

3.2 Groundwater Response to Wet Events

The groundwater recharge response to major flood flows in the Wadi Samail at Al Khawd during 1987, 1990 and 1995 are clearly seen in the spikes in the hydrographs of the NC-1F and RGS-2L piezometers (Figs. 3.1 and 3.2). The bores represent extremes in depth within the flow system, yet their response to recharge events is similar. The NC-1F bore situated towards the lower end of the Fan, is screened across an interval from 15 to 21 m, while the RGS-2L bore in the central Fan area is screened across an interval from 319 to 325 m. That is, the impact of the extreme wadi flow events, is registered over a 300 m vertical interval in these examples.

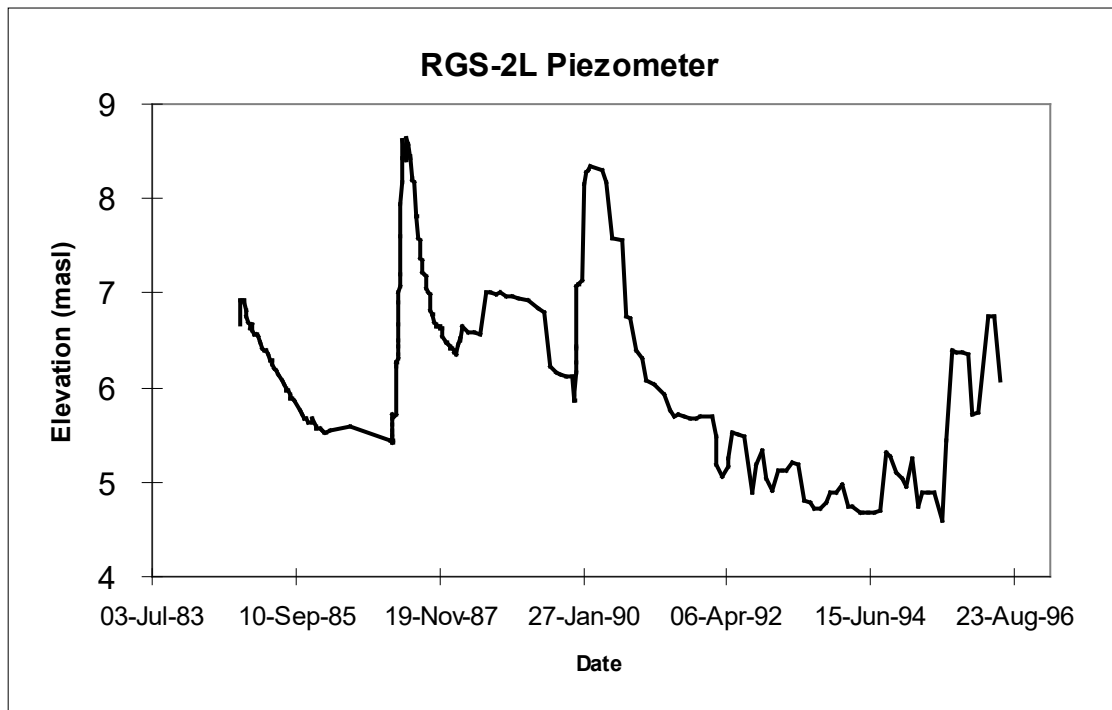


Fig. 3.2 Hydrograph of the RGS-2L deep piezometer, Al Khawd Fan.

3.2.1 “Spike” Effect to Recharge

The pattern of a rapid rise then sharp decline in water tables, is present across the Al Khawd Fan, perhaps best seen in the uniform response of the relatively shallow **WRD-Series** bores monitoring the Al Khawd Recharge Dam (Fig. 3.3). The pattern is essentially that of a local recharge system responding to high flow in Wadi Samail. It is this ‘**spike**’ effect which has come to represent the ‘norm’ for hydrograph response on the Al Khawd Fan, underpinning the importance placed on wadi flow as a principal water source for aquifers on the plains. A similar pattern can be seen for the line of RGS-Series and KWD-Series piezometers (Figs. 3.4 and 3.5) spanning the central and eastern Al Khawd Fan from just north of the Al Khawd Dam to the Seeb-Sohar highway. In these bores major wet events occurring in 1987, 1990, 1995/96 are clearly shown, finishing with the very sharp rise representing the high rainfall/wadi flow during March 1997.

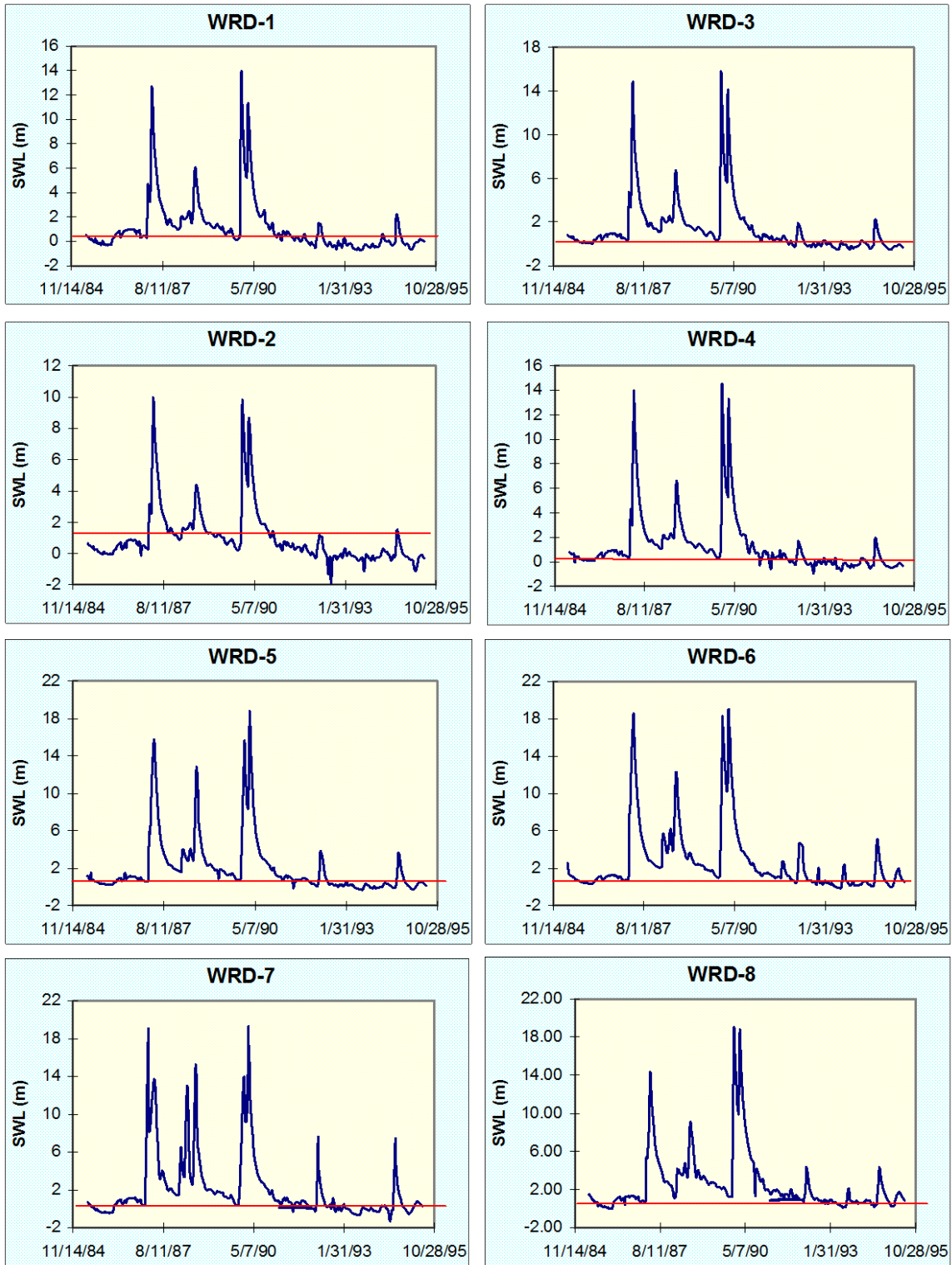


Fig. 3.3 Hydrograph Response of the WRD Piezometers in the Vicinity of the Al Khawd Dam - 1984 to 1995 (the red line marks sea level).

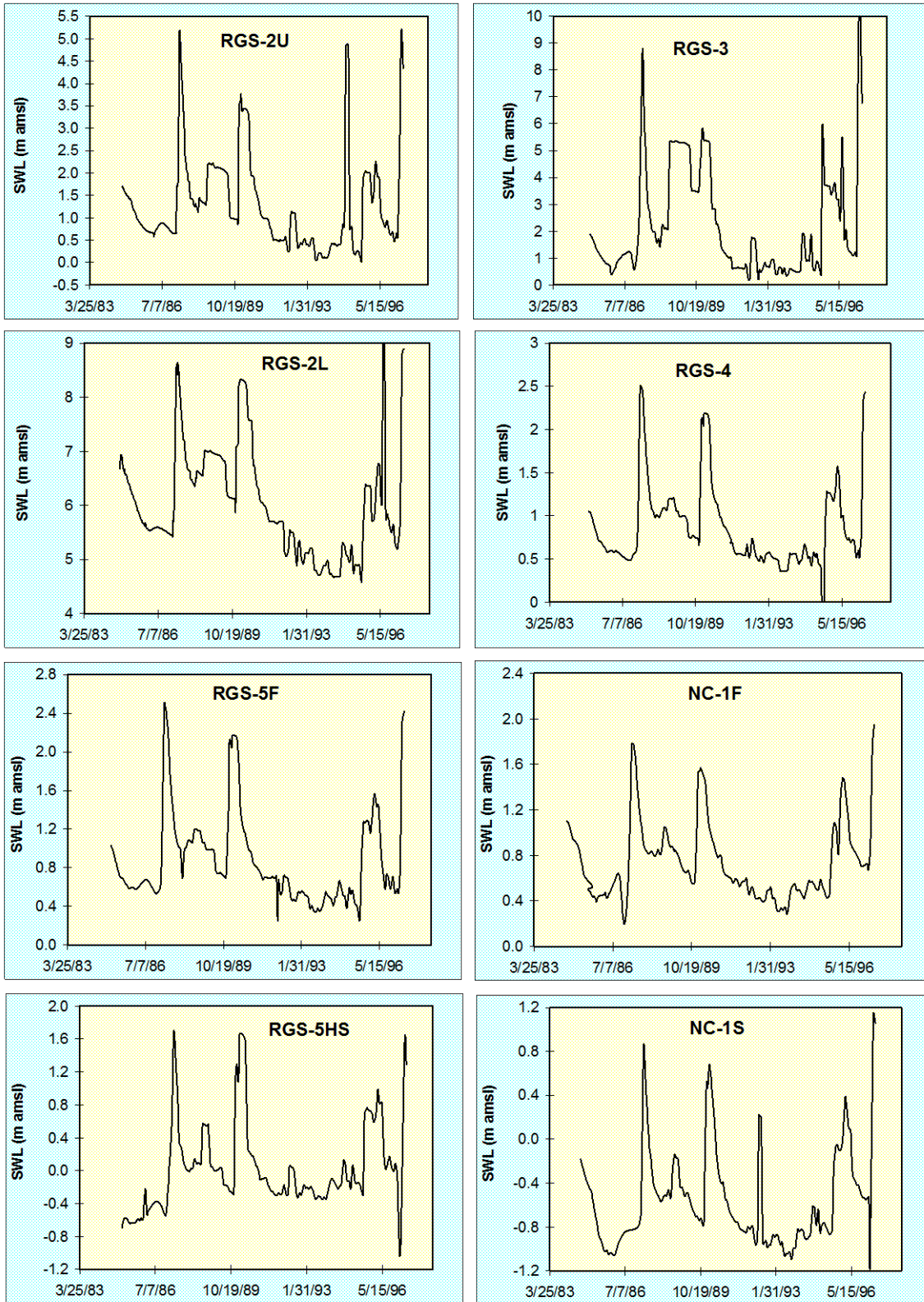


Fig. 3.4 Hydrographs of RGS-Series and NC-1S Observation Bores

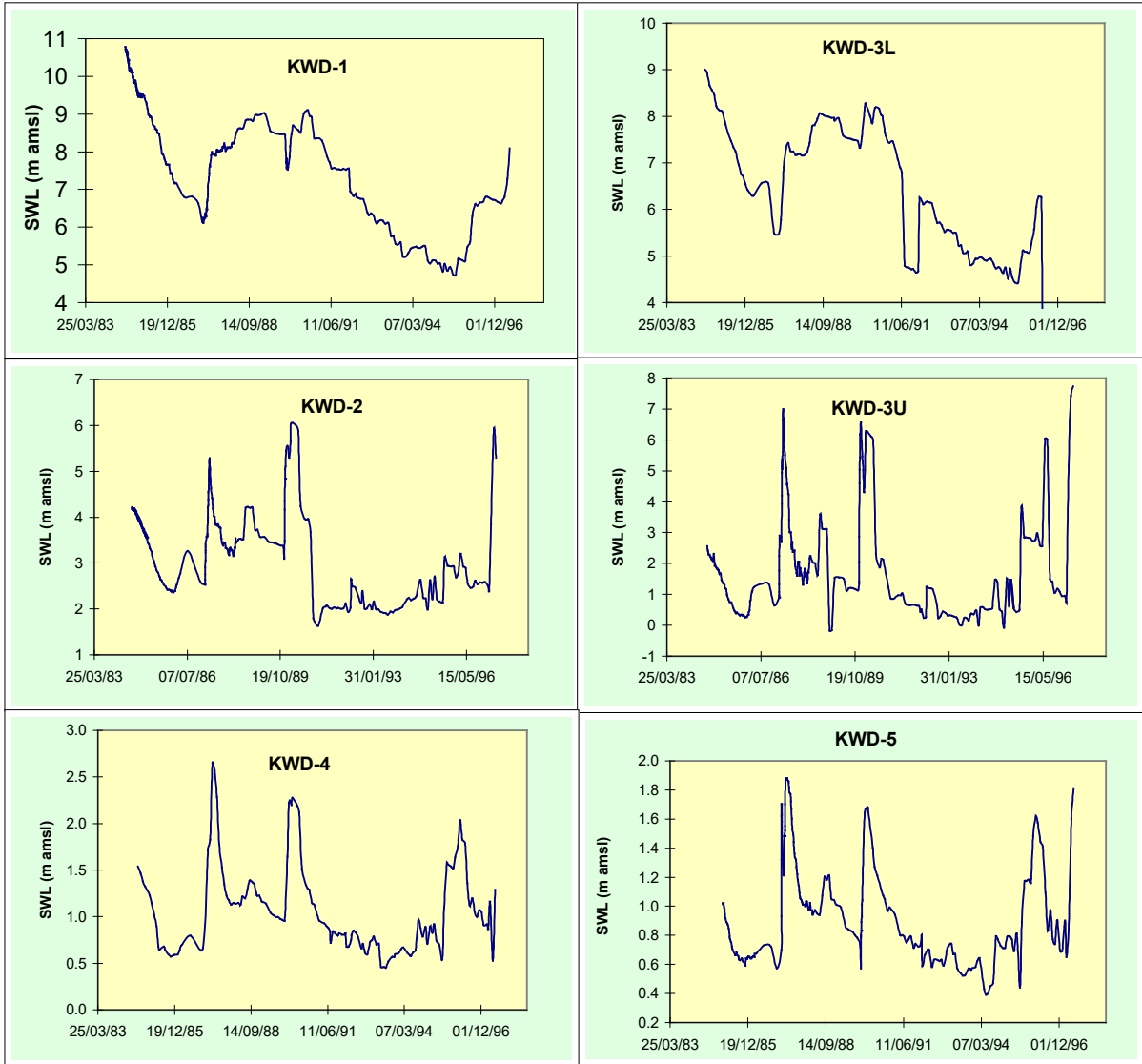


Fig. 3.5 Hydrographs of KWD-Series Bores Situated in the Eastern Region of the Al Khawd Fan.

The Al Khawd series show the 'spikiness' for the shallow bores, and those screened over the upper parts of the aquifer, and the 'saw-tooth' characteristics in the two deep bores screened only in the deep part of the aquifer.

3.2.2 Shallow Water Tables

It is notable that the static water levels in many of the bores lie close to sea level, often falling below sea level, as clearly seen in the WRD-1 bore (Fig. 3.3). This reflects the low level of the water table across much of the Al Khawd Fan, and, in the case of bores, such as the WRD-Series situated immediately to the north of the Al Khawd Dam, is exacerbated by the effects of pumping from the Al Khawd and Seeb Wellfields. A water table map for the Al Khawd Fan for January 1995 is shown in Figure 3.6

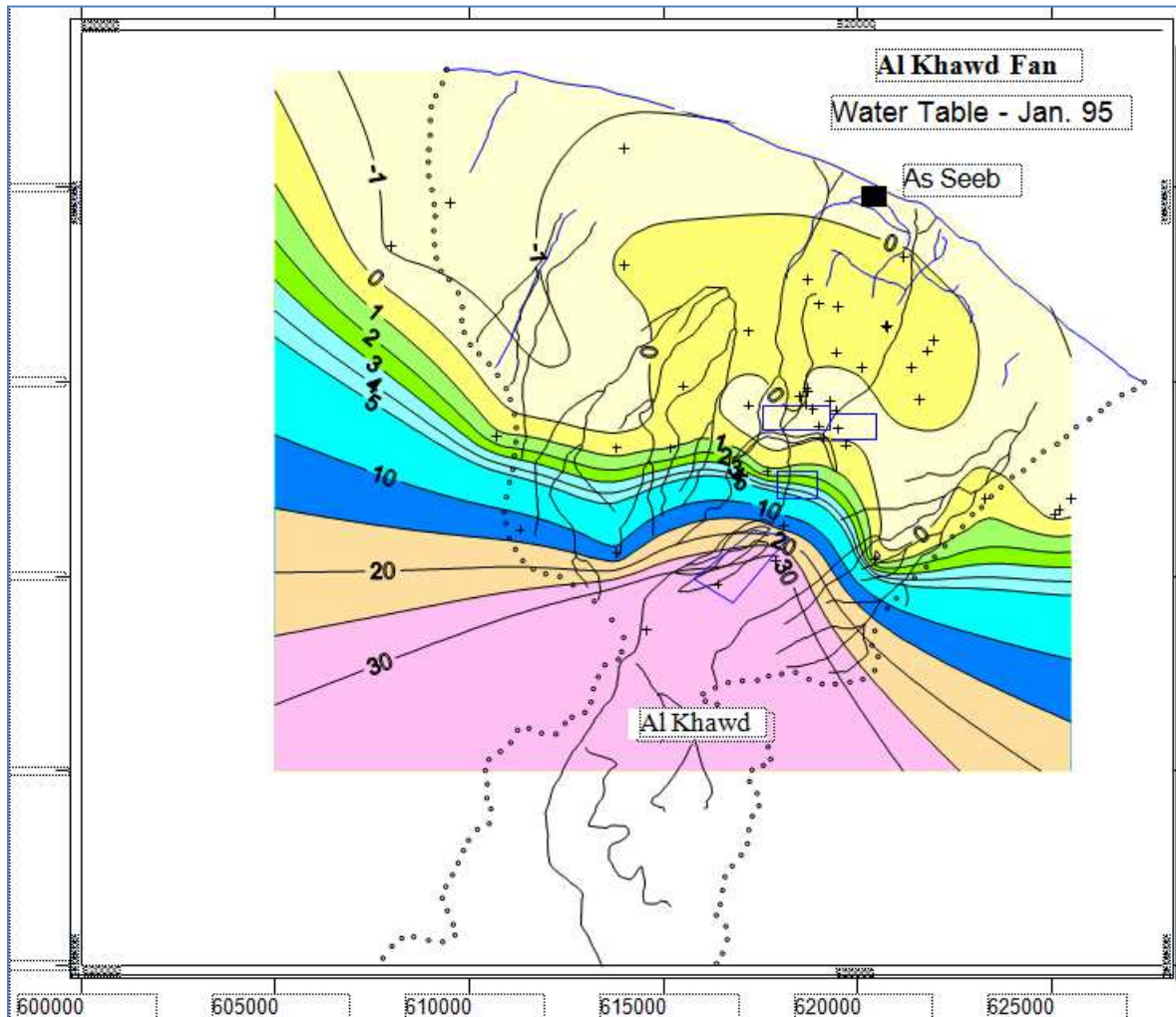


Fig. 3.6 Water Table Map of the Al Khawd Fan - January 1995
(contours are relative to mean sea level)

This map shows the zero water table contour well inland in the western (Wadi Manumah) and eastern parts of the Al Khawd Fan, while a shallow plume lying between the zero and 1 m contour extends northwards towards Seeb. The zero water table contour extends from the east, into the area of the Al Khawd and Seeb Wellfields.

This map shows the zero water table contour well inland in the western (Wadi Manumah) and eastern parts of the Al Khawd Fan, while a shallow plume lying between the zero and 1 m contour extends northwards towards Seeb. The zero water table contour extends from the

east, into the area of the Al Khawd and Seeb Wellfields. On passing southwards, the water table rises rapidly towards the village of Al Khawd, and the Old Government Wellfield (OGW) lies 30 m or more above sea level.

3.2.3 Vertical Upwards Hydraulic Gradients of the Coastal Groundwater Discharge System

By contrast, to the above situation where static water levels are only slightly above sea level (apart from during times of recharge), the static level of the deep RGS-2L piezometer (319 m - 325 m) is some 5 m higher than for the adjacent RGS-2U piezometer. The RGS-2L and RGS-2U bores form a piezometer nest (Fig. 3.4). The high static levels in the RGS-2L bore reflect high groundwater pressures which exist deeper in the alluvial aquifer, resulting in strong upwards directed hydraulic gradients, which are an important feature of the alluvial aquifer system on the Al Khawd Fan. This reflects the presence of a regional groundwater discharge system developed in the central and lower parts of the Fan. Such gradients are a common feature of coastal groundwater flow systems.

Of the examples given in Figure 3.3 and 3.4, only in the case of the RGS-3 piezometer are static water levels well above 2 m for any length of time. The reason for this, lies in the wide interval screened by the RGS-3 bore (24 m to 294 m) which spans both upper and lower parts of the aquifer. The resulting static water level is essentially a composite of water levels found across the screened interval. In such instances static water level information must be used cautiously, especially if used to construct water table maps.

It should be noted that, where strong vertical gradients exist, the displacement effect on vertical salinity profiles in widely screened bores may also be significant. In cases where such bores are used to monitor a freshwater-saltwater interface, the strong upwards gradients would tend to cause such interfaces to migrate higher in the bore than actually occurs in the aquifer. This process was seen in the case of the Cable Tool bore C-2 on the eastern Batinah where the displaced interface in the bore was some 30 m higher than actually occurred in the surrounding aquifer.

3.2.4 Sympathetic Response in Saline Zone

Finally it can be seen that the rapid response of the shallow bores to recharge events is also present in the saline zone beneath the freshwater-saltwater interface. This occurs, for example, in NC-1S bore (Fig. 3.4), a piezometer screened in saline water (52500 $\mu\text{S}/\text{cm}$), which monitors an interval beneath the interface at 116 m to 122 m.

Further examples (Fig. 3.4) are those of the RGS-5HS screened from 180 to 186 m, with an EC of 71920 $\mu\text{S}/\text{cm}$, and the widely screened RGS-2U which had a pumped salinity of 58000 $\mu\text{S}/\text{cm}$. The pressure response seen within the saline intrusion to recharge events is important, in that it negates the basic tenet used for Ghyben-Herzberg interface calculations of the effects of recharge events, that there be no pressure change in the saline water (see later) as water tables fluctuate in response to wetting and drying.

It is important to stress that, while the freshwater system may be treated as being separate

from the saltwater system for conceptual and modelling purposes, pressure changes are not affected greatly by the implied barrier between the two flow systems. The examples show clearly that pressure changes occurring in the freshwater in response to recharge events are readily transmitted to the saltwater system. As will be seen later, this transmission can significantly effect the freshwater/saltwater interface.

3.2.5 KWD-Series Piezometers

The same patterns that occur in the WRD-Series and the RGS-Series are also present in the KWD-Series of bores drilled in a N-S line passing from the eastern end of the Al Khawd Dam northwards towards the highway (Fig. 3.5). The impact of the local flow system is seen in the spikes of 1987, 1990, 1995/96 and 1997 occurring in the KWD-2, 3U, 4 and 5 bores. Of great significance is the fact that the two bores, KWD-1 and KWD-3L, do not show the spikiness of the local recharge system, normally present in bores across the Fan. These two bores are deep bores, screened across intervals ranging from 321m to 366 m, and 216m to 366m respectively. They are seen as being influenced by both a regional flow system and an intermediate flow system, the latter recharged at the head of the Al Khawd Fan (see later). Both piezometers have high hydraulic heads with the implied strong vertical upwards gradients observed in the deep RGS-2L bore. All KWD bores lie within the coastal plain region groundwater discharge zone.

The extent of the upwards hydraulic gradient, is best seen in the KWD-3L / KWD-3U piezometer nest. The KWD-3L bore (216 m to 366 m) is screened across the deeper part of the aquifer and KWD-3U spans the upper parts of the aquifer from 22 to 200 m. The head difference between the piezometers is about 5m. In the same area, from 1987 to 1995, the KWD-1 bore had static water levels ranging between 9 m and 4.5 m (amsl), yet the water table was within only 1 m of sea level. Vertical head differences therefore ranged from 3.5 m to 8 m over this period.

As was the case with the RGS-3 bore in the RGS-Series, the KWD-2 bore has a somewhat higher static level than other locally recharged bores of this sub-set. This again reflects a long screened interval from 106 m to 353 m spanning deep (high head) and shallow (low head) intervals. In addition, a somewhat less prominent spikiness also suggests a combination of different characteristics of the deep and shallow systems. This apparent mixture of waters is also reflected in the stable isotope composition of KWD-2.

3.2.6 Saw-Tooth Response

The 'spike' response to recharge events, although widespread, is not present in a number of bores on Al Khawd, which, instead, show a more subdued response to wadi flow events. The response of these bores is clearly visible in the freshwater KWD-1 piezometer (Figs. 3.6 and 3.7), and the KWD-3L piezometer (Fig. 3.5), as noted above. Here, a strong saw-tooth effect occurs, in which the initial recharge events cause a rapid rise in groundwater pressures, but the decline occurs over a long period, up until a later major recharge event. In the case of the KWD-1, the rise in 1987 levels off with only a small impact in 1990, and then water levels gradually decline until the major recharge event in 1995/96

It should be noted however that while the KWD-1 and KWD-3 are deep piezometers, not all

deep bores, for example RGS-2L have a saw tooth character. This difference stems from lithological differences within the alluvial aquifer system and is reflected in differing stable isotopic composition (see later).

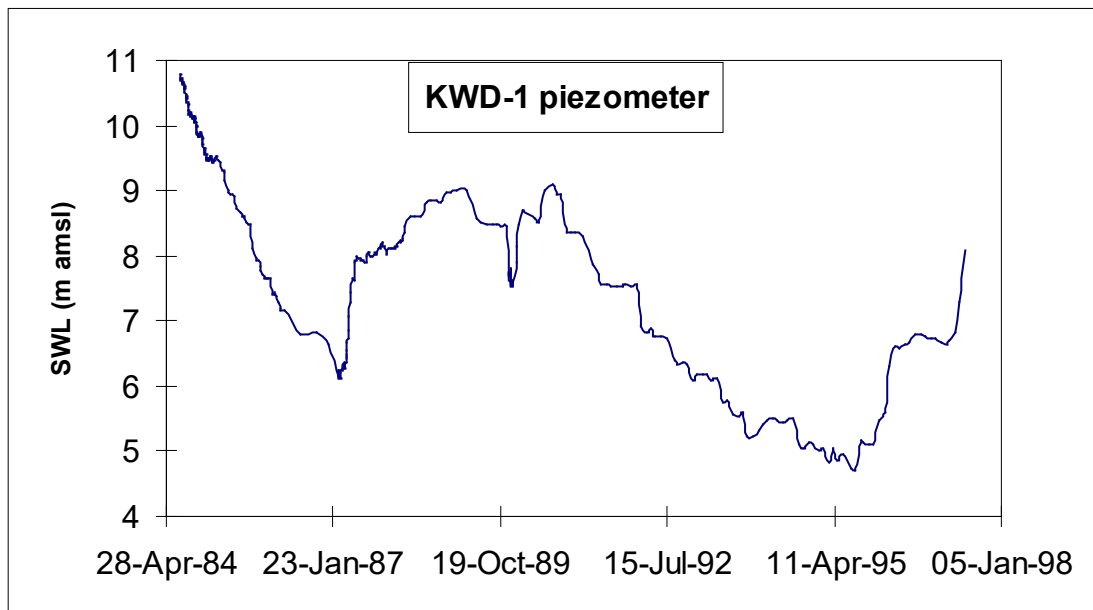


Fig. 3.7 Hydrograph of the KWD-1 Piezometer from 1984 until 1997

The hydrograph response observed in the deeper KWD-1 and KWD-3L bores in the central Al Khawd Fan echo similar fluctuations observed in the OW-1 and UG-1 bores (Fig. 3.8) on the terraces of the upper Al Khawd Fan. The UG-1 bore lies closer to the Wadi Manumah.

The OW-1 bore is an originally PDO monitoring bore which lies within the Old Government Wellfield. It monitors an interval in the Cemented Gravel unit of Terrace 1 and has one of the longest hydrographic records of any bore on the Al Khawd Fan. The similarities between the hydrographs are clear. All four bores were at low levels prior to 1987, following an earlier dry phase. The static water levels all climb steeply in response to the 1987 wet period but they do not show the rapid return to previous levels, seen in the spikey response of the majority of bores on the Fan. The hydrographs do have some individuality, seen clearly in the low levels reached in early 1992 in the KWD-3L bore, however this may be in response to groundwater pumping at the adjacent Seeb/Al Khawd wellfields. In all bores there is a peak in 1990, however this is subdued compared to the sharp spikes of bores most strongly influenced by the local recharge system. The simplest explanation for the saw-tooth hydrographs is that they represent an intermediate flow system component originating in the upper areas of the Al Khawd Fan above the Al Khawd Dam.

3.2.7 Recharge Processes in the Upper Al Khawd Fan

The amplitude over which the water levels fluctuate in the bores is about 4 m to 5 m, except in the case of the OW-1 bore, where it is between 25 m to 40 m. The OW-1 bore lies on the oldest terrace (Terrace 1) close to the main outflow channel of wadi Samail, where it experiences all significant wadi-flow events. The wadi is deeply incised into the oldest terrace,

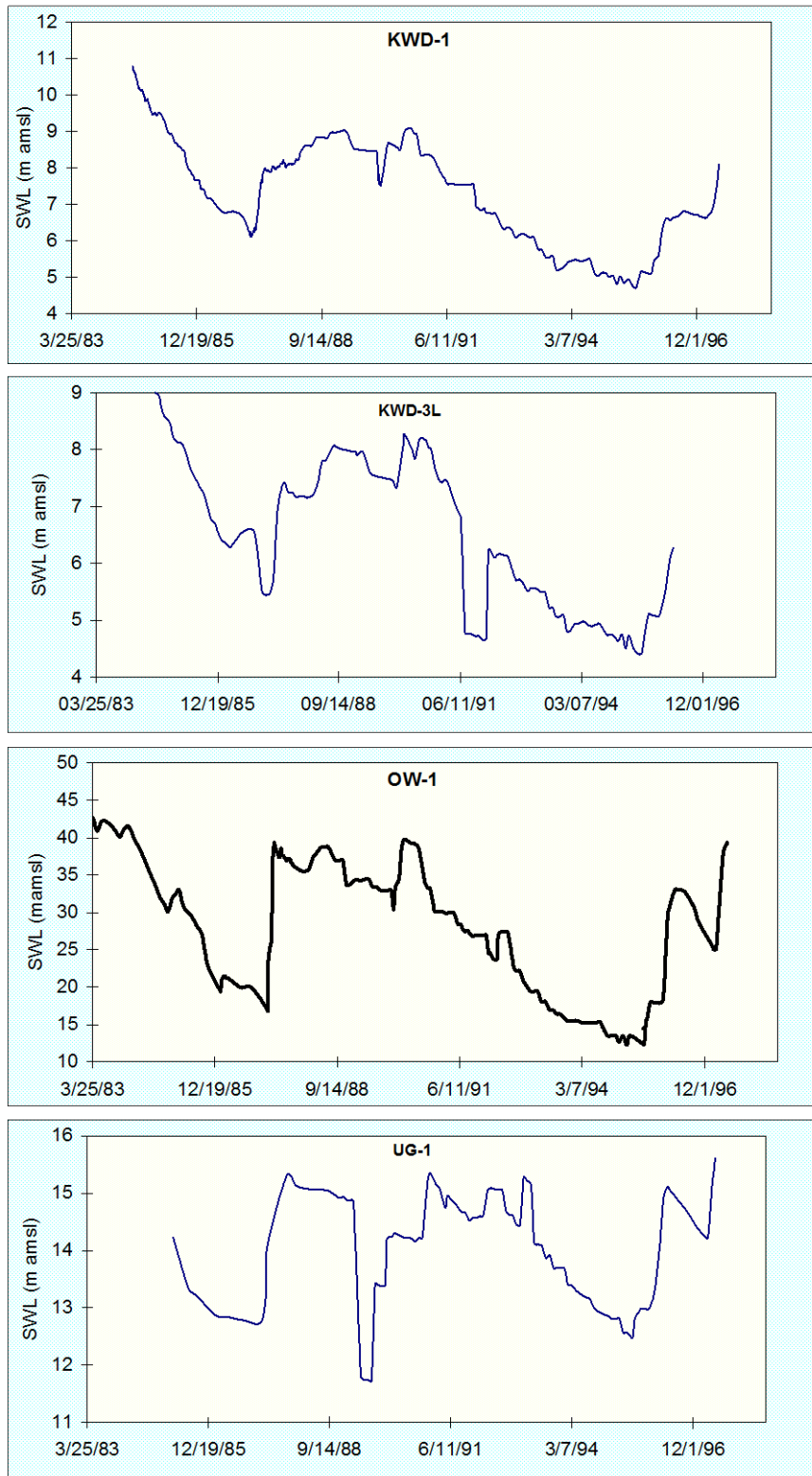


Fig. 3.8 Saw-Tooth Hydrographs from Al Khawd Fan

and the wadi floor consists in part of heavily cemented gravelly pebbles. The wadi is a line-source of recharge under very wet conditions. When the wadi is active, flow and hence recharge is limited, mainly occurring through thin discontinuous gravel sequences in the incised wadi channel which are, in turn, underlain by relatively impermeable carbonated cemented pebbly units. By contrast, downstream from the Al Khawd Dam, the wadi leaves the terraces and spreads out across the flood plain. Here, the various anastomosing channels, together with the surrounding flood plain, consist of loose gravel, pebbles and boulders. Recharge is greatly enhanced both on account of the wide area flooded, and the high permeability of the flood plain floor. Most spikey piezometer responses occur in this area.

Recharge in the vicinity of the Old Government Wellfield, is concentrated along the main wadi channel where recharge mounds develop during phases of high wadi flow, as occurred in 1982 (MMP, 1985) following a prolonged dry period commencing in about 1977 (Fig. 3.9). The elongated mound had largely disappeared by 1985 (Fig 3.9b, Fig. 3.10), as the water table fell. However while line recharge is clearly shown in the ridged counters of 1983, water levels in general were some 10 m to 16 m higher in 1983, than in 1985. That is, the water table across a wide area adjacent to the wadi had also risen significantly during the flood event of 1982. Thus, the contours not only show a ridged line source of recharge, but also a wide lateral dispersion of the higher pressures generated at the time. This results in a steepening of the down basin gradient.

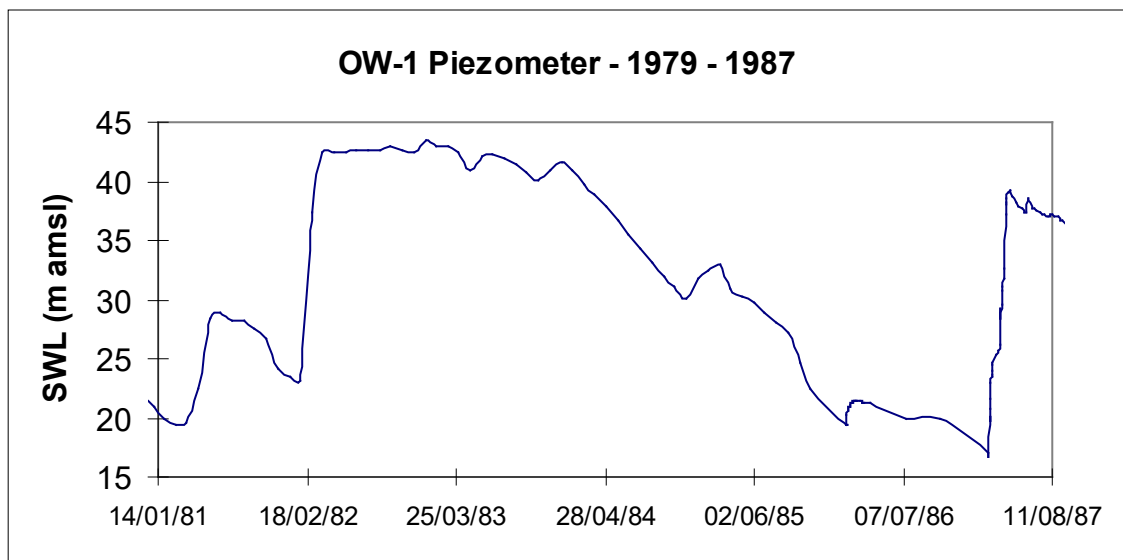
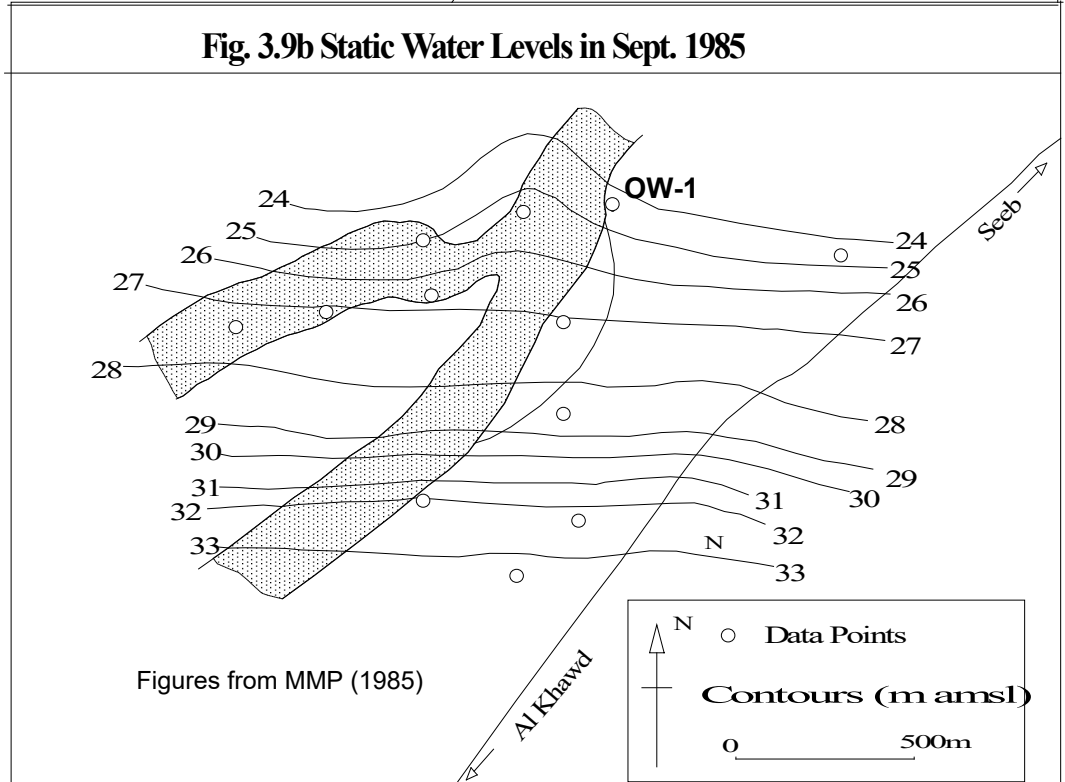
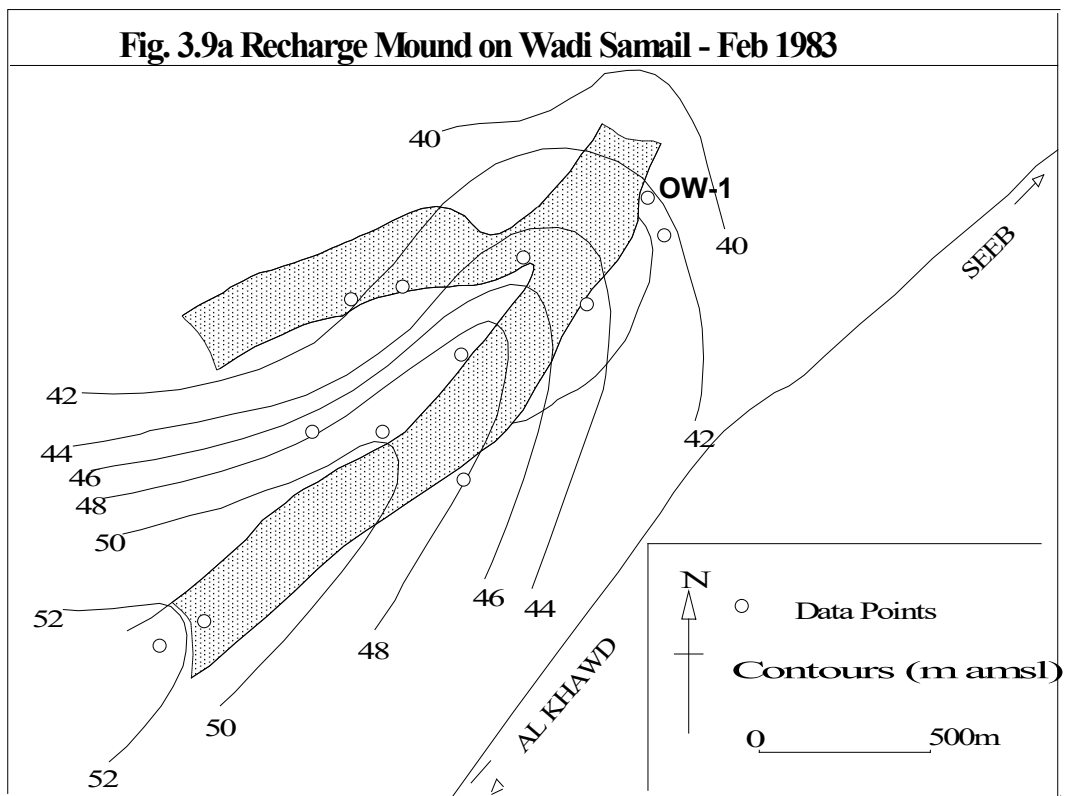


Fig. 3.10 Hydrograph of OW-1 Bore, 1979 to 1987

The rise and fall in water tables between 1982-1985 (Fig. 3.9), and from 1987-1995 (Fig. 3.7) represent only two of a number of similar recharge cycles occurring in the Al Khawd Fan.

Parts of five cycles can be observed in the OW-1 piezometer extending over the period 1972 to 1997 (Fig. 3.11). While these are distinct cycles, the periodicity varies markedly, ranging from

5.2 years during the earliest of the three cycles show to 10.4 years for the most recent cycle.



Figs. 3.9a and 3.9b Line Recharge Mound Development in the Vicinity of the Old Government Wellfield, Feb. 1983 and its Dissipation by 1985.

That is, there is no set value for cyclic periodicity in the intermediate flow system of the upper Al Khawd Fan.

The second feature of the OW-1 curve is that there is a steady decline in the base level reached after each cycle, showing a gradual, decline from 22 m to 13 m in the ‘drought level’ water storage over this period. The upper level shown in the piezometer was about 42 m to 43 m in the early period falling to about 38 m in the last cycle (1987 to 1995). One likely explanation is that this level lies close to the level of the adjacent wadi bed, and may be regarded as the uppermost level of saturation via line recharge from the wadi. If this is the case, there is a finite limit to the levels which may be reached as a consequence of this recharge process acting on the intermediate flow system at the head of the Fan. The small impact of the 1990 recharge event could then be explained in terms of prior conditions in which, under the high head conditions, remaining from the 1987 event, there was only a limited amount of unsaturated aquifer available. This explanation, however does not account for the lesser levels reached during the 1987-1995 cycle. The data for the remainder of 1997 will show whether or not there is also a fall in levels reached during the recharge events to match the falling levels occurring at the end of each dry cycle.

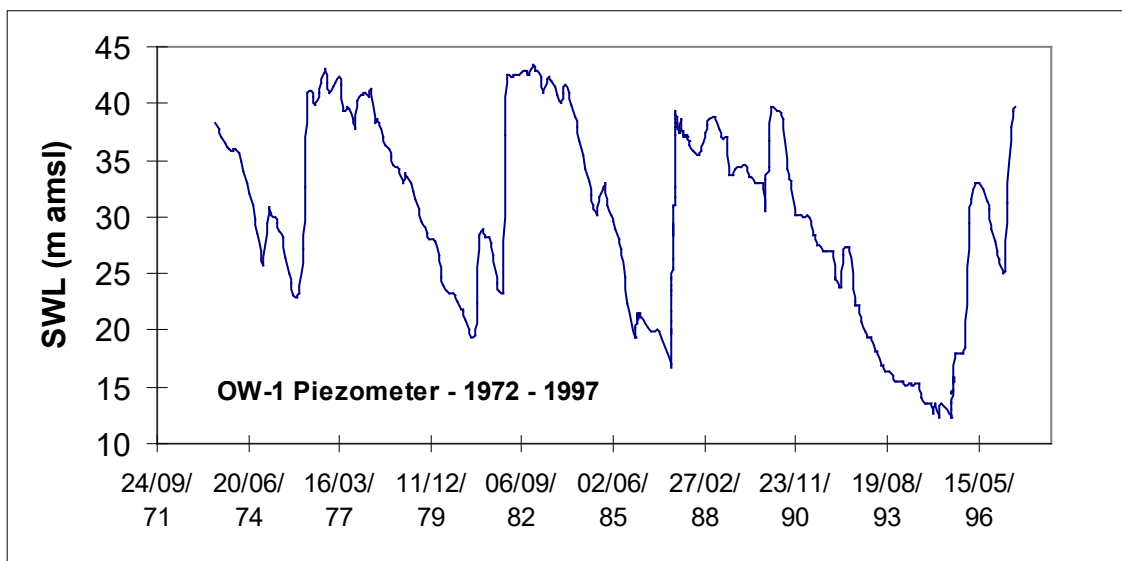


Fig. 3.11 Cyclic water level response in OW-1 piezometer from 1972 to 1997.

The cycles occurring within the OW-1 piezometer are repeated in the DW-1 bore situated in the lower Al Khawd Fan, close to the highway (Fig. 3.12).

Here, however the static water level is always within a few metres of sea level and the fluctuation amplitude is about 2 m, but with the addition of the spikes previously associated with the local flow system.

It is considered that similar generalized rises in groundwater pressures in the upper areas of the Al Khawd Fan during major recharge events provide loading pressures which are transmitted down, and laterally across, the Fan via the alluvial aquifer system. The sympathetic longer term

responses in the DW-1 piezometer, with the latter part of the record also present in the KWD-1 and KWD-3L bores, are attributed to this process. It is notable that there is no significant travel-time lag between pressure rises generated from the upper Al Khawd Fan, and the response in the aquifer system of the central and lower Fan.

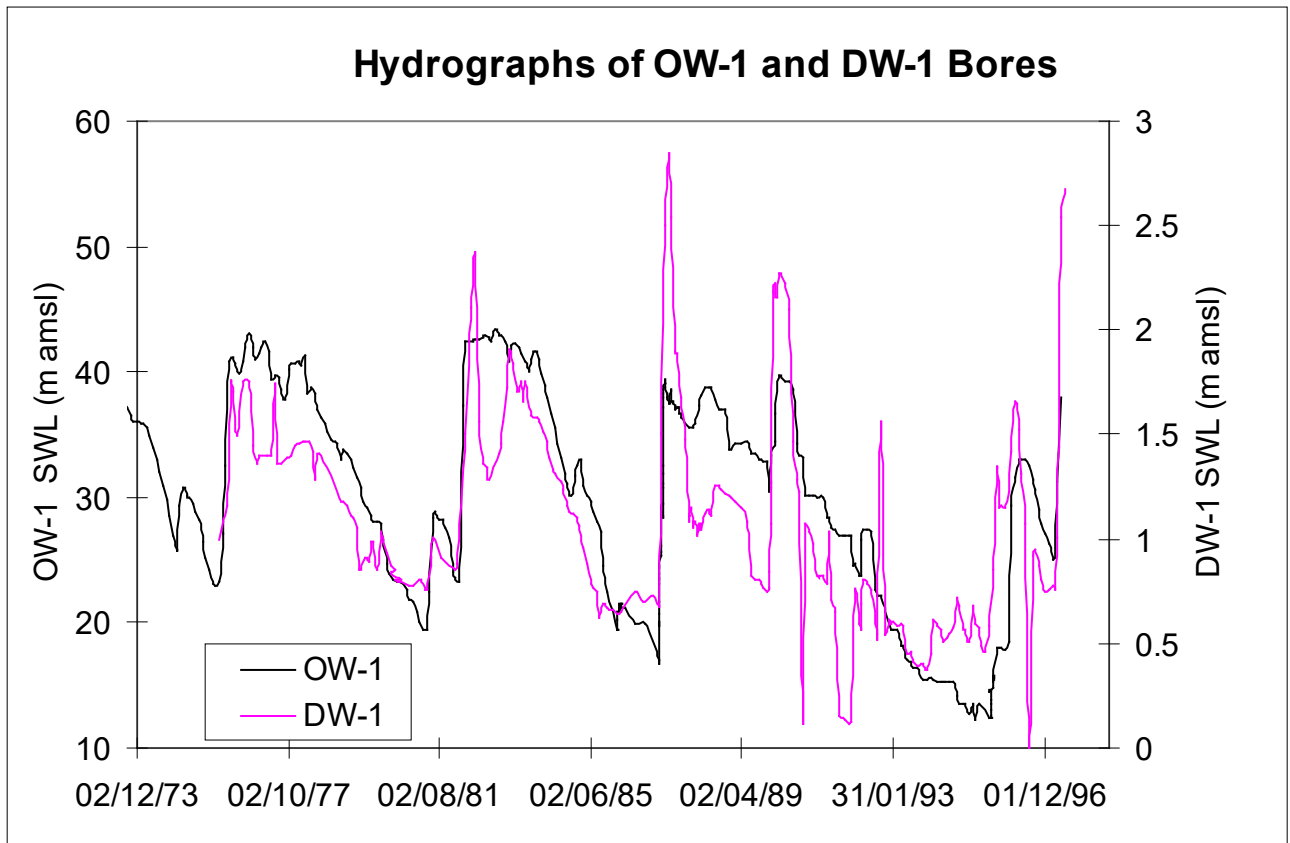


Fig. 3.12 Hydrographs of OW-1 and DW-1 Piezometers - 1974 to 1979

3.2.8 The Influence of the Intermediate Flow System in Al Khawd Hydrographs

The impact of hydrostatic head changes (transmitted as pressure effects) in the intermediate flow system generated by recharge at the head of the Al Khawd Fan is clearly visible in the KWD-1 and KWD-3 bores, it is also discernible in virtually all other bores on the Al Khawd Fan. It is clearly seen in the case of the DP-2 bore (Fig. 3.13). Here the spikeness of the local flow system can be shown to be superimposed on an underlying base, representing the influence of an intermediate flow system, in a manner similar to that observed in the DW-1 bore. That is, all hydrograph responses are a composite of pressures generated by the intermediate and local flow systems.

A similar pattern can be seen in the RGS-2L and NC-1F piezometers (Figs 3.2 and 3.1), and a further example is that of the RGS-5F piezometer (Fig 3.14), screened across a shallow interval from 17 m to 23 m, and situated close to the lower end of the Fan. . Here the static water level is within 1 m of mean sea level, and given the shallowness of the piezometer, may be regarded as the level of the water table.

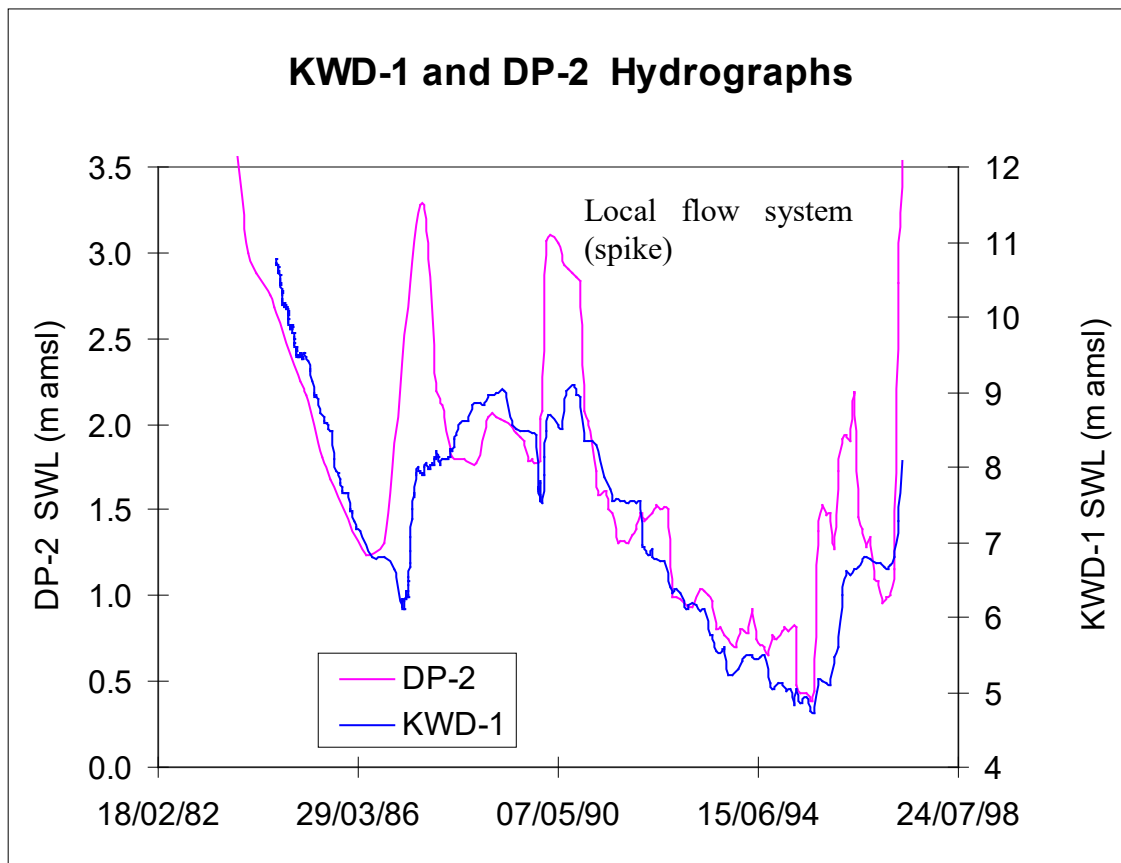


Fig. 3.13 Hydrographs of KWD-1 and DP-2 Piezometers

In all these hydrographs, it can be seen that whenever a recharge spike occurs, the base to which it returns will be determined by the the pressure levels within the intermediate flow system. That is, the spike of 1987, coincides with a period of increased hydraulic heads within the aquifer system, and the return levels are significantly higher than those occurring immediately prior to the initial rise. Conversely, after the 1990 recharge spike, heads within the intermediate system are falling and the static levels within the local system return to lower levels than previously experienced.

Water tables across the fan behaved similarly, and while they rose slightly in places after the 1987 recharge event, following the 1990 event, they rose only briefly but quickly instead returned to their pre-recharge levels (or lower in the case of DP-2), and then slowly declined until 1994 when a number of small recharge events occurred. However the water table decline continued until the major 1995 event.

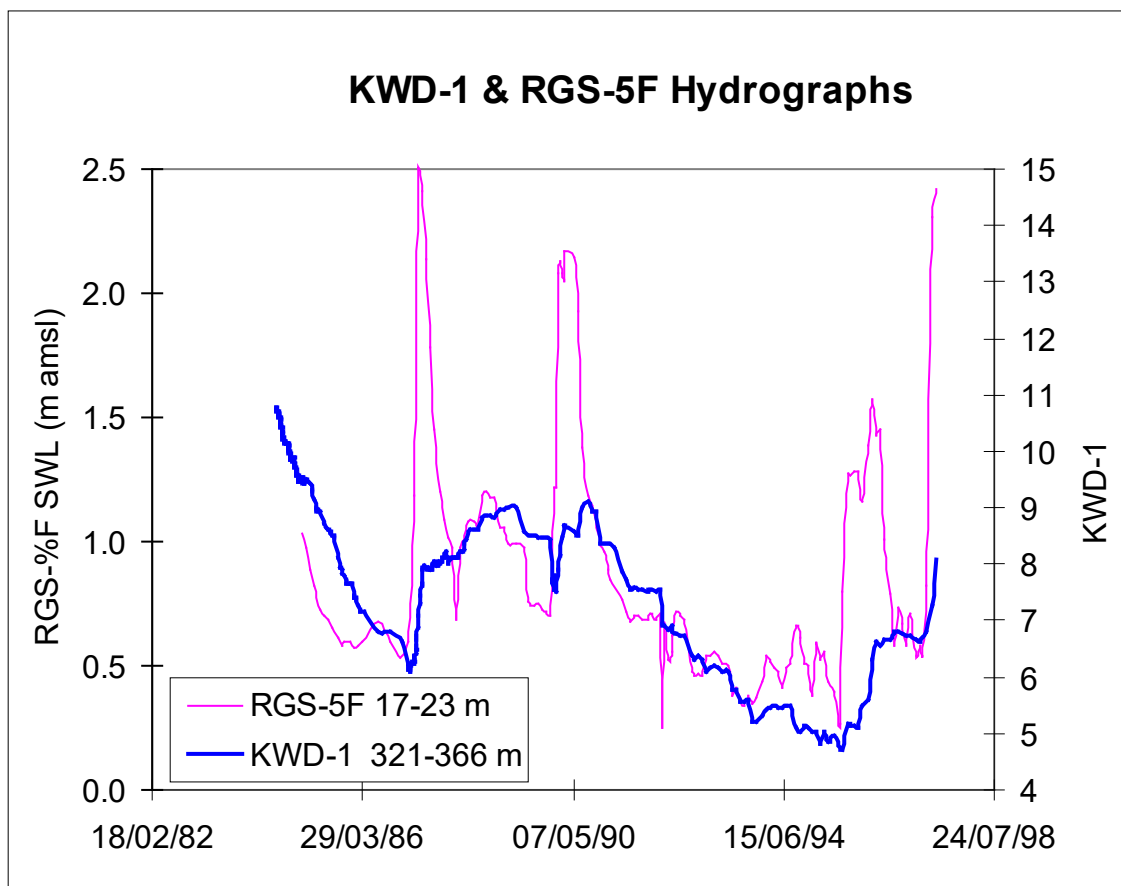


Fig. 3.14 Hydrographs of KWD-1 and RGS-5F Piezometers

3.3 The Regional Groundwater System

While the influence of the intermediate flow system on groundwater pressure levels in the Al Khawd Fan is clearly visible, it is largely unclear to what extent the intermediate flow system is, in turn, influenced by the regional flow system. However very little is known about the regional system which is generated from further upbasin within the ophiolite aquifer. Groundwater balances on the Al Khawd Fan indicate that the local and intermediate flow systems, activated only by flood flows down the Wadi Samail (average ca. 5 MCM), are grossly inadequate to account for the annual water usage on the Al Khawd Fan (25-30+ MCM). The only other available water source capable of providing this input is the regional groundwater system emanating from the upper catchment area of Wadi Samail including the Samail Basin and surrounding Jabal Akhdar. This is a basement rock aquifer component.

The effect on hydrographs of the regional groundwater flow system is difficult to identify. However, any pressure impact is likely to be subdued, and perhaps underpin the intermediate flow system in a manner similar to that to which the intermediate flow system underpins the local flow system. That is, all hydrographs may have components of the three systems, with each successive underpinning more muted. The superimposition of the local, intermediate and regional flow systems is normal in a regional groundwater discharge system, such as occur in the Al Khawd coastal plain. However, as a consequence of the arid climate and irregular rainfall/recharge, the influences of the various flow systems wax and wane, and in the case of the local system virtually disappear for long periods.

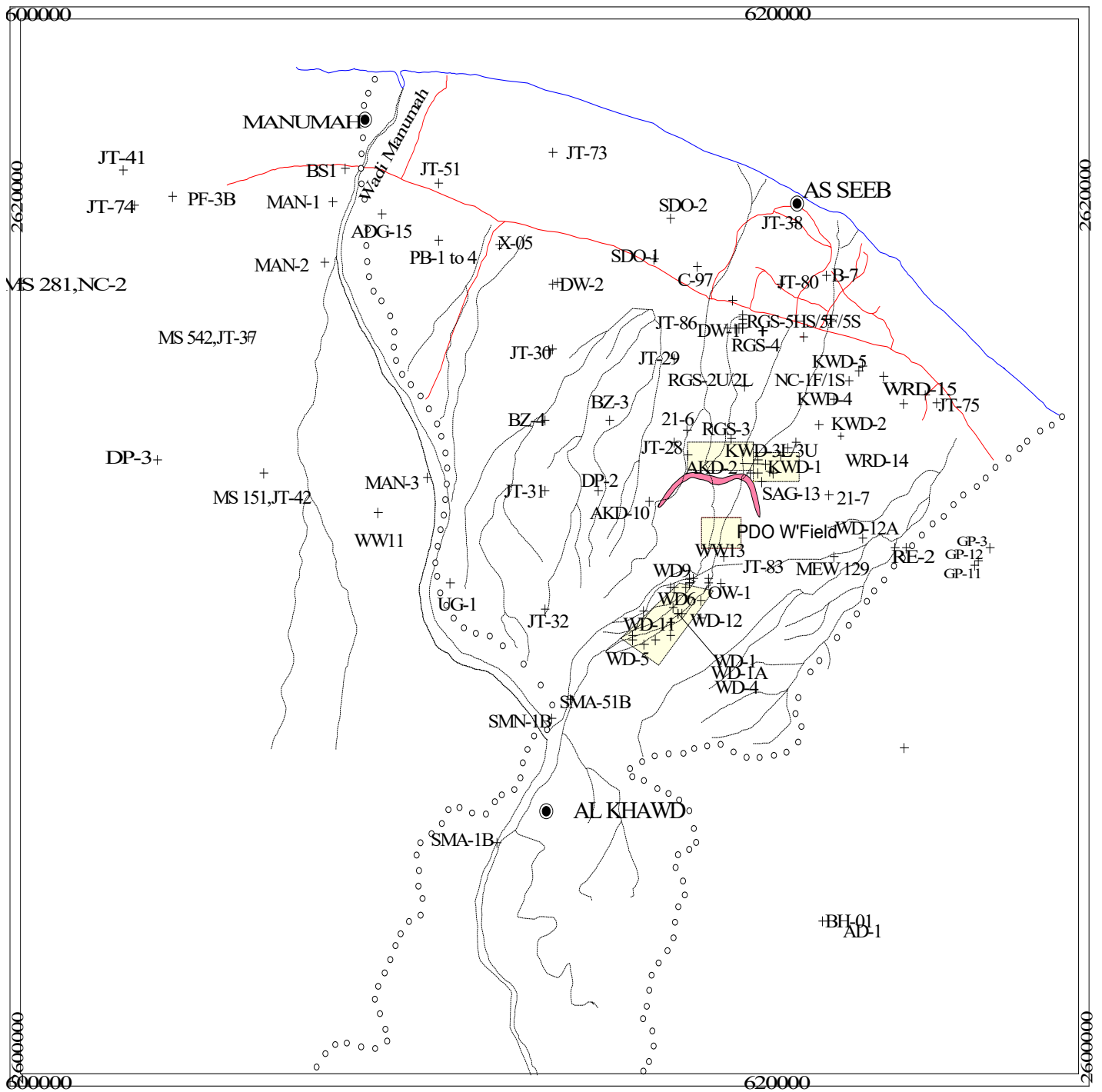


Figure 3.15 Major Borehole Locations on the Al Khawd Fan.

The figure shows the wide distribution and high density of boreholes across the Al Khawd Fan, a number of which are cited in this Report. The bores shown are only part of the very large number drilled on the Fan over the last three decades. The close interest in the Fan clearly follows from the presence of the various wellfields and the threat posed by seawater intrusion to both the domestic irrigation users and the wellfields (Chapter 4).

3.3.1 Old Groundwater in the Al Khawd Fan

Groundwater with considerably longer residence times, and an isotopic composition more readily associated with ‘fossil’ water, occurs in some of the bores screened in the deeper parts of the aquifer. For instance the KWD-1 and KWD-3 bores, shown earlier to have a strong response to pressures generated by the intermediate flow system. Radiocarbon dating on groundwater from these bores has given ages of between 2000 to 5000 years, and 8000 to 12000 years old respectively.

A further bore with a sub-fossil carbon date is that of the BZ-4 bore, with an age of ca. 3000 years (PAWR 86-7). This bore is situated on Terrace 2 in the western area of the Al Khawd Fan. It is a 100 m deep bore, developed over 2 intervals. The first interval from 98 m to 100 m intersects the transition zone between fresh water and seawater, and has an EC of 11,500 $\mu\text{S}/\text{cm}$. The second interval is from 49 to 72 m and has an EC of 1340 $\mu\text{S}/\text{cm}$ (about 800 mg/l). The hydrograph of the BZ-4 bore is incomplete, however it appears to have a similar saw-tooth character to those of the other sub-fossil groundwaters (**Fig. 3.16**).

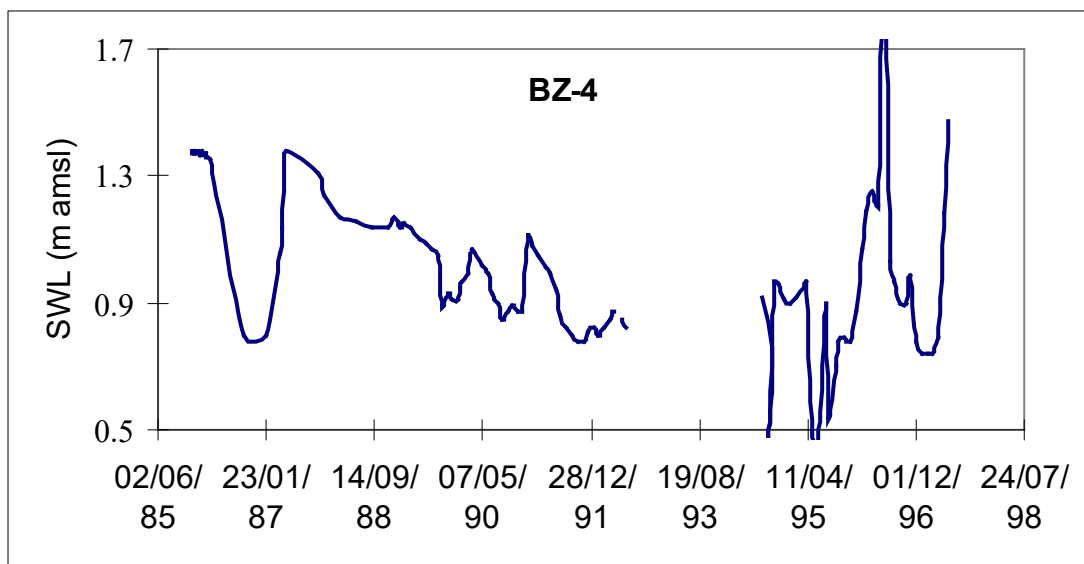


Fig. 3.16 Hydrograph of BZ-4 Piezometer, 1985 to 1997.

The presence of the seawater intrusion at depth beneath the fresher upper part of the aquifer is important, in that it shows that the upper groundwater is part of the active flow system within the discharge zone, where groundwater moves up the freshwater-saltwater interface towards the surface. Although having an old age, the stable isotope signature from the bore, does not show the same distinctive character as that occurring in the deeper KWD-1 and KWD-3L bores (see below)

Given the high vertical hydraulic gradients, and the clear hydrographic responses to modern recharge events, it seems unlikely that the old groundwater, at depth in the KWD-1 and KWD-3 bores, and in the BZ-4 bore overlying the saltwater interface, is stagnant ‘trapped’

groundwater, isolated from the 'active' system. The alternative explanation, is that it is older regional groundwater recharged further upbasin, and having a significantly longer flow path. It has retained its character by being separated from the more recent groundwater by the hydraulic boundary that normally exists between different order flow systems.

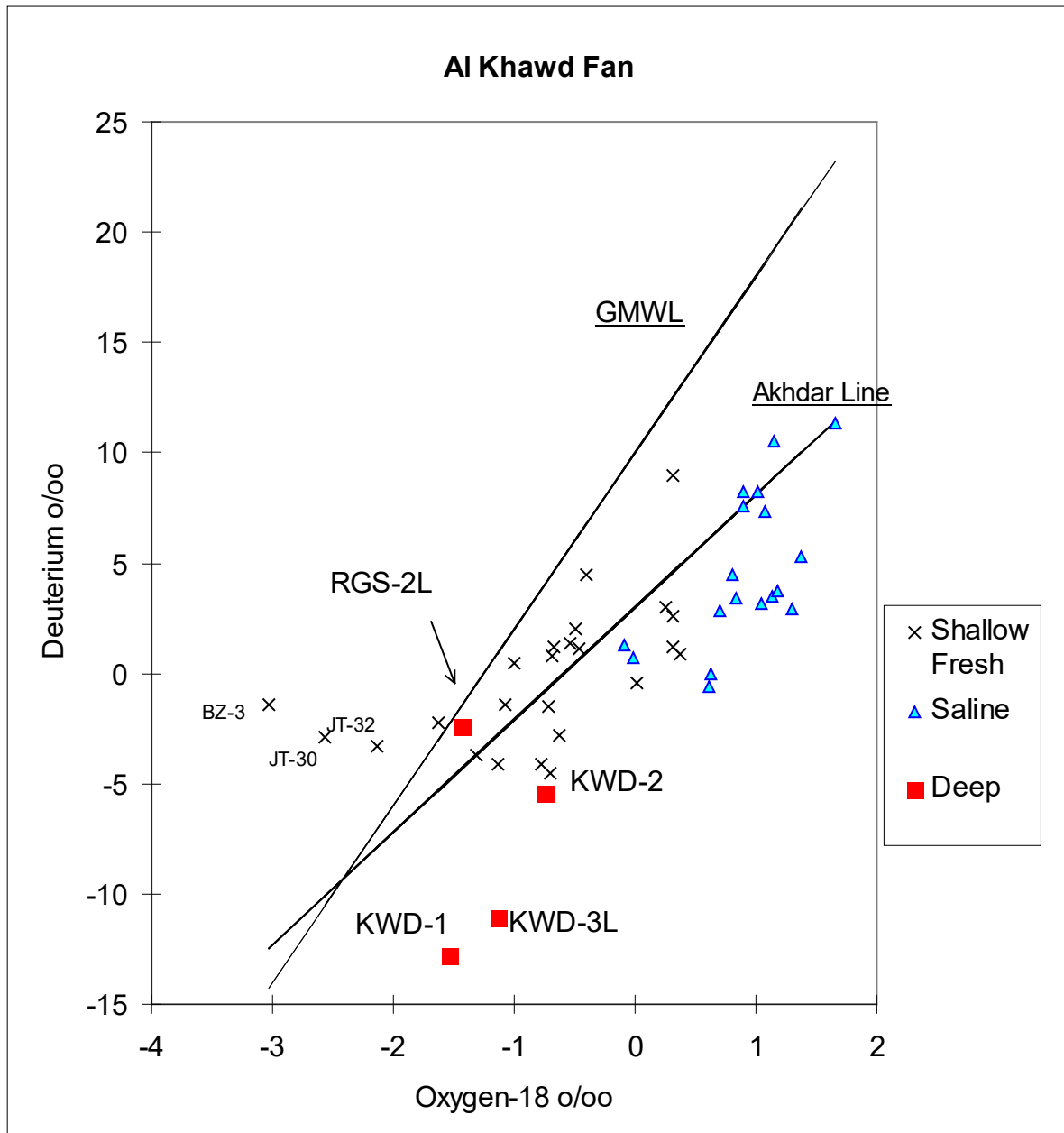


Figure 3.17 Deuterium v oOxygen-18 for Groundwater from the Al Khawd Fan

3.3.2 Stable Isotopes

Stable isotopes (deuterium and oxygen-18) from bores on the Al Khawd Fan show that the majority of groundwaters plot roughly along the Akhdar Line (Fig. 3.17), the line derived from groundwater samples collected on the Jabal Akhdar at the upper end of the regional groundwater flow system. $-\delta D = 5.1 \delta^{18}O + 3.0$ (Macumber et al., 1997). This line

characterizes the relationship between deuterium and oxygen-18 for modern day groundwater falling on the catchments of the Jabal Akhdar.

However, the two older groundwater in the KWD-1 and KWD-3L bores lie well to the right of this line in a field normally occupied by fossil groundwater (Macumber, 1995). In terms of deuterium, the deep bores are significantly more depleted than the rest of the groundwater, however no comparable depletion occurs in the oxygen-18. An explanation for this difference, is provided in the PAWR (86-7) Isotope Report where it is stated that *"The deep fresh groundwater (in the al Khawd Fan) appears to have been recharged at a relatively high altitude..., although a strong positive ¹⁸O shift, possibly from evaporation, has altered the stable isotopes"*. This would be in line with a long flow path source associated with a regional groundwater flow system.

By contrast, the deep RGS-2L bore, screened from 319 m to 325 m, despite having similarly high static water levels to those of the deep KWD-1 and KWD-3L bores, has a stable isotope composition similar to that of modern groundwater. Furthermore, unlike the KWD-1 and KWD-3 bores, it shows the strong spiked pulse generated by modern local recharge and lacks the sodium enrichment of the KWD bores, which is a feature of the Old Government Wellfield bores (see below). The RGS-2L bore, although at the same depth as the KWD-1 and KWD-3L bores appears to represent a different flow regime. The likely explanation is that the aquifer in the vicinity of the RGS-2L bore, is significantly more permeable, and therefore has a stronger connection to flow processes occurring in the upper parts of the aquifer, than in the case of the KWD-1 and KWD-3 bores. It is also possible that the bores are separated by hydraulic boundaries between different order flow systems. A very simplistic section that would account for the different responses is given in Figure 3.18.

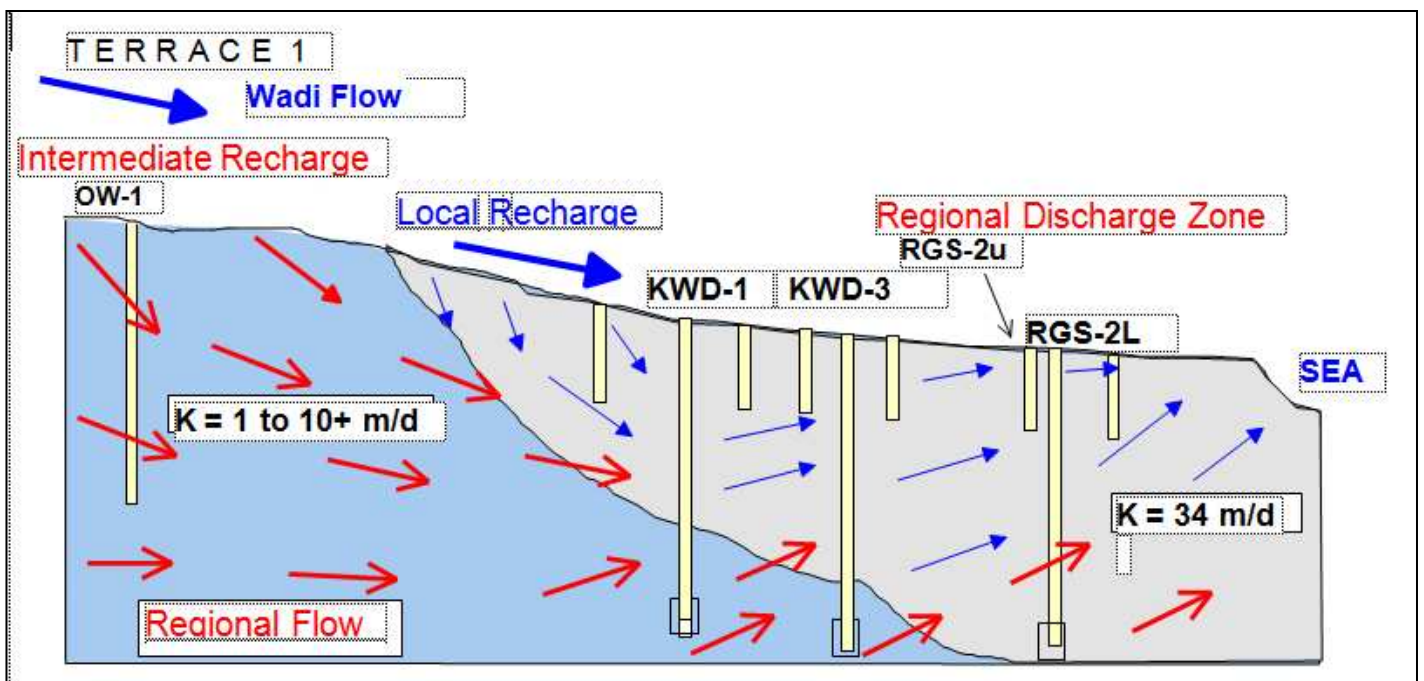


Fig. 3.18 Diagrammatic Section Showing Groundwater Flow Pattern in Al Khawd Fan

The section is a simplistic groundwater flow diagram. It ignores the seawater intrusion (which is dealt with in Chapter 4) and does not include the hydraulic boundaries which normally exist between different order flow systems. However in the latter case, such boundaries will be varyingly transient, especially in arid settings where wadi flow and recharge is in the form of discrete isolated events, often separated by considerable time periods. For instance the boundary between the local flow system and the intermediate flow system will be strongly developed during the course of the recharge events (the spikes) but will largely or fully disappear as the short lived recharge mound dissipates and the dependent local flow system declines. Here hydrology, not geomorphology dictates the nature of the local flow system. By contrast, the presence of old groundwaters in the KWD-1, KWD-3L and BZ-4 bores indicates that in these instances, a hydraulic boundary between regional and lesser order flow systems is maintained in those parts of the aquifer.

To reach the Al Khawd Fan, groundwater must pass via the ophiolite aquifer from the Samail Basin. In the Samail Basin, it has been shown that while the alluvial aquifer system is important for the supply of towns and villages, the major aquifer for downbasin flow is the ophiolite aquifer. During the very dry period upto 1995, the alluvial sequences had been largely dewatered as water tables had fallen, leaving the ophiolites as the main conduit for flow. In the ophiolites, groundwater movement is by secondary porosity via joint, faults, lineaments etc. However, there is still much to be learned about groundwater flow in the ophiolites. A further obstacle to be overcome, is the suggested low permeabilities of the Tertiary limestone at the head of the Al Khawd Fan. However, elsewhere on the Batinah, e.g. at Landsab and at Muaskar Al Murtafaa (where karstification strongly influenced groundwater yields), the Tertiary limestones are an important aquifer supporting wellfields. There is no good reason why they should be seen as a major barrier to flow at Al Khawd.

In the OW-1 bore, the saw-tooth pattern of static water levels has an amplitude of almost 30 m, which arises from wadi-induced groundwater recharge, responsible for the intermediate flow system. This is shown by high tritium values (11 T.U.) obtained in early 1986 by PAWR from bores from the Old Government Wellfield. The depth to which the intermediate flow system persists is unknown, however it is likely that any hydraulic boundary between it and the underlying regional flow system will rise and fall with the cyclicity of the major recharge events, being at its shallowest after prolonged dry periods.

In the upper Al Khawd Fan therefore, regional downbasin flow will be best represented during the dry periods in OW-1. If the hydraulic boundary is sufficiently shallow at these times, groundwater samples, especially from the deeper bores, may provide the best clue to the chemical signature of the regional system entering the upper Fan from the ophiolites.

3.3.3 Sodium Enrichment in Groundwater from Old Government Wellfield

The chemistry of the groundwater from the Old Government Wellfield plots in distinct field on a Durov diagram to that of the locally recharged Seeb and Al Khawd Wellfields (MMP, 1985). It has significantly higher sodium levels than waters from the latter wellfields. The explanation for the higher sodium is ion-exchange arising from longer residence time in the aquifer. By contrast, during the recharge period in 1983, the water chemistry in the Old Government Wellfield was more like that arising from recent recharge (MMP, 1985). The composition of the groundwaters from the various wellfields is given in Table 3.1.

Bhatnagar and Ravenscroft (1986) note the MMP (1985) observation that the Old Government

Wellfield almost always shows enrichment in sodium, whereas this is rarely observed in the Seeb and Al Khawd Dam Wellfields. However they also observe that "with the exception of RGS-2L, the deep fresh groundwater (i.e. KWD-1 and KWD-3L bores) is enriched in sodium". This data, linking groundwater from the Old Government Wellfield and the deep fossil groundwater further downbasin, is in line with the similar hydrograph responses, showing an absence of any local recharge component in the two deep bores.

Table 3.1. Chemical Composition from Wellfield Groundwater

Average Well Water Quality (mg/l)		
	Old Govt. Wellfield	Seeb and Al Khawd
EC	1330	1135
TDS	742	662
pH	8.19	8.07
Ca	32	29
Mg	59	58
Na	155	110
K	5.1	4.3
HCO ₃	238	181
SO ₄	142	139
Cl	214	189
NO ₃	3.7	4.3

A second feature of the deeper fossil groundwater, noted by Bhatnagar and Ravenscroft (1986) is the presence of a high Cl/Br ratio. This is shown in Table 3.2. It is notable that the three highest Cl/Br ratios in the table all correspond to the three bores shown in Figure 3.8 as having a saw-tooth character. However, additional sampling is required.

High Cl/Br ratios have been observed previously in Oman groundwater. Macumber (1995a; 1995b) and Macumber et al. (1997 - in Press), show a strong bimodality for Cl/Br in groundwater from central Oman, with higher values mostly ranging from 700 to 3000, and the lower values commonly being from less than 500 to 100. By comparison, seawater has a Cl/Br ratio of about 290-300. The explanation given by Macumber et al., (1997) is that the high chloride is derived by deflation of sabkha, occurring throughout large regional groundwater discharge zones occurring in inland and coastal areas of Oman. This results in the addition of halite to the soils and sediments, which is in turn leached down into the groundwater. One example of this is that from the Wadi Rawnab Gorge in Central Oman, where very fresh groundwater salinities are from 300 mg/l to 150 mg/l, but Cl/Br ratios range from between 700 and 3000, mostly being above 1000.

The widespread occurrence of aeolian derived chloride in Oman groundwater must be taken

into account whenever recharge estimates based on chloride balances are carried out. In cases where higher Cl/Br ratios are present, the calculated recharge will be less than actual recharge.

Table 3.2 Chloride to Bromide ratios in Bores from Al Khawd Fan

Bore	TDS (mg/l)	Cl/Br*
UG-1	1050	3550
KWD-3L	856	2090
KWD-1	656	1840
C-50	802	1000
KWD-2	1046	797
RGS-5f	594	729
RGS-2l	1958	637
BZ-4	844	589
NC-1f	590	580
DW-2	1324	568
WD-6A	838	565
WD-90	528	467
BZ-3	966	443

* Cl/Br ratios based on mg/l chloride and bromide.

Given the high Cl/Br ratios in certain of the groundwater, then the addition of aeolian sourced NaCl, is a further factor which must be considered to that of ion exchange, in any explanation for the high sodium content of the groundwater from the Old Government Wellfield.

The high sodium values were obtained mainly during 1985, when the static water levels in the Old Government Wellfield were at their lowest. That is, when a regional groundwater component would be most strongly represented. A change in chemical character after wetting up was observed by MMP (1985), who suggested that the character had been modified by recharge from the wadi.

It is stressed however, that the identification of different flow systems in the Al Khawd Fan using chemical and isotopic data is still in its infancy, and much work is required to refine the very tentative and somewhat speculative relationships suggested above. Even so, it seems that the identification of the regional groundwater component, will be most readily made on the basis of hydrochemical properties rather than hydrographic response. However, the hydrochemical (and isotopic) data is both scattered and patchy, and there is clearly much scope for further work on the Al Khawd Fan, to help further elucidate the the various hydrochemical relationships, as well as demonstrate their use in the separation of the flow systems.

3.3.4 Movement of Groundwater from the Ophiolites

There is little data between the bores of the Old Government Wellfield and those of the Samail Basin, except for three bores, which provide data on the Tertiary limestone and ophiolite aquifers. These are the SMN-1B and SMA-51B bores in the Tertiary limestone, and the SMA-1B bore situated further upstream in the ophiolites (Fig. 3.16). All bores lie within the lower gorge of Wadi Samail, downstream from the village of Al Khawd.

In this area, the Wadi Samail is deeply incised into the surrounding sequences and base flow normally occurs within the wadi. The three bores were only constructed in 1993, however they reflect the period spanning the dry phase prior to 1995, and the subsequent wet periods of 1995, 1996 and 1997. Hydrographs from the bores are shown in Figure 3.19

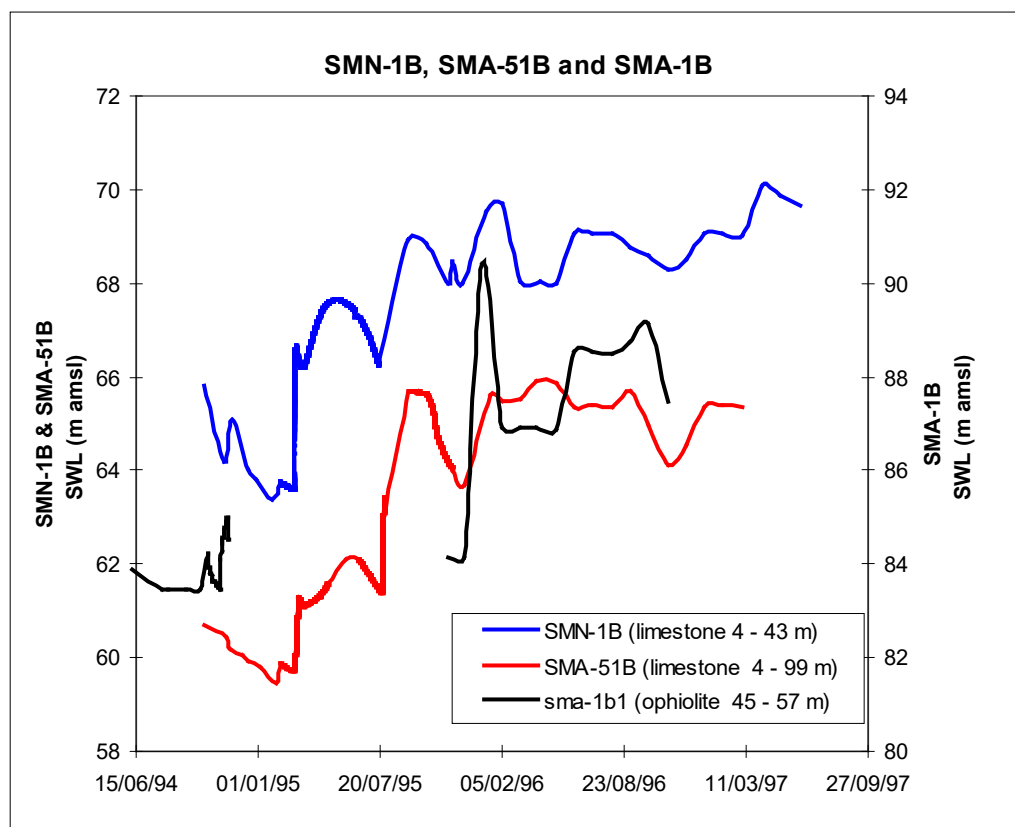


Fig. 3.15 Hydrographs of bores in the vicinity of Al Khawd

The hydrographs of the limestone bores that are screened from a shallow depth reflect water tables, which lie close to the ground surface. The ophiolite bore (SMA 1b1) is however screened from 45 m to 57 m, reflecting heads deeper in the aquifer. During drilling, very little water was obtained from the limestone, giving rise to the contention that the limestone in this area had a very low permeability. Much of the data from SMA1b1 prior to January 1996 is missing, however the 1996 'spiked' response of the ophiolite piezometer suggests a strong

connection to the water table, as might be expected in the fractured rock aquifer. The steady rise in the limestone bores over the period from 1995 until 1997 suggests a gradual topping up of the aquifer. The static water levels show a fairly steep hydraulic gradient which is maintained downstream into the area of the Old Government Wellfield where the OW-1 bore has static levels ranging from 13 m to 43 m above sea level; by comparison, these latter bores rose 27 m in 1997. There is no comparable rise in hydrographs upbasin, and on this basis, groundwater flow from upbasin into the Al Khawd Fan would probably be greater during dry years when the hydraulic gradients are at their steepest, and fall off after wet events as hydraulic gradients again flattened.

Further upbasin, within the Samail Basin proper, long-term hydrographs are limited to a small number of wells and private bores, which were used for observation purposes up to the completion of the bores by MWR into the ophiolites in the early 1990's. Hydrographs from the observation bores show a similar response to those on the Al Khawd Fan, with some having spikey character and others a saw-tooth pattern. Figure 3.20 shows the water table response in 4 wells over the period from 1984 to 1994. However, in this instance there is no clear distinction between an intermediate and regional flow pattern and the saw-tooth pattern is deemed to represent a regional response of the ophiolite aquifer to long term wetting and drying. The upper catchment hydrograph pattern has the same periodicity as that of the intermediate system in the Al Khawd Fan. In these examples, the static water level is relative to a local datum(s) and not to mean sea level.

The catchment wide hydrograph response showing the long term cyclic pattern is shown in Fig. 3.21

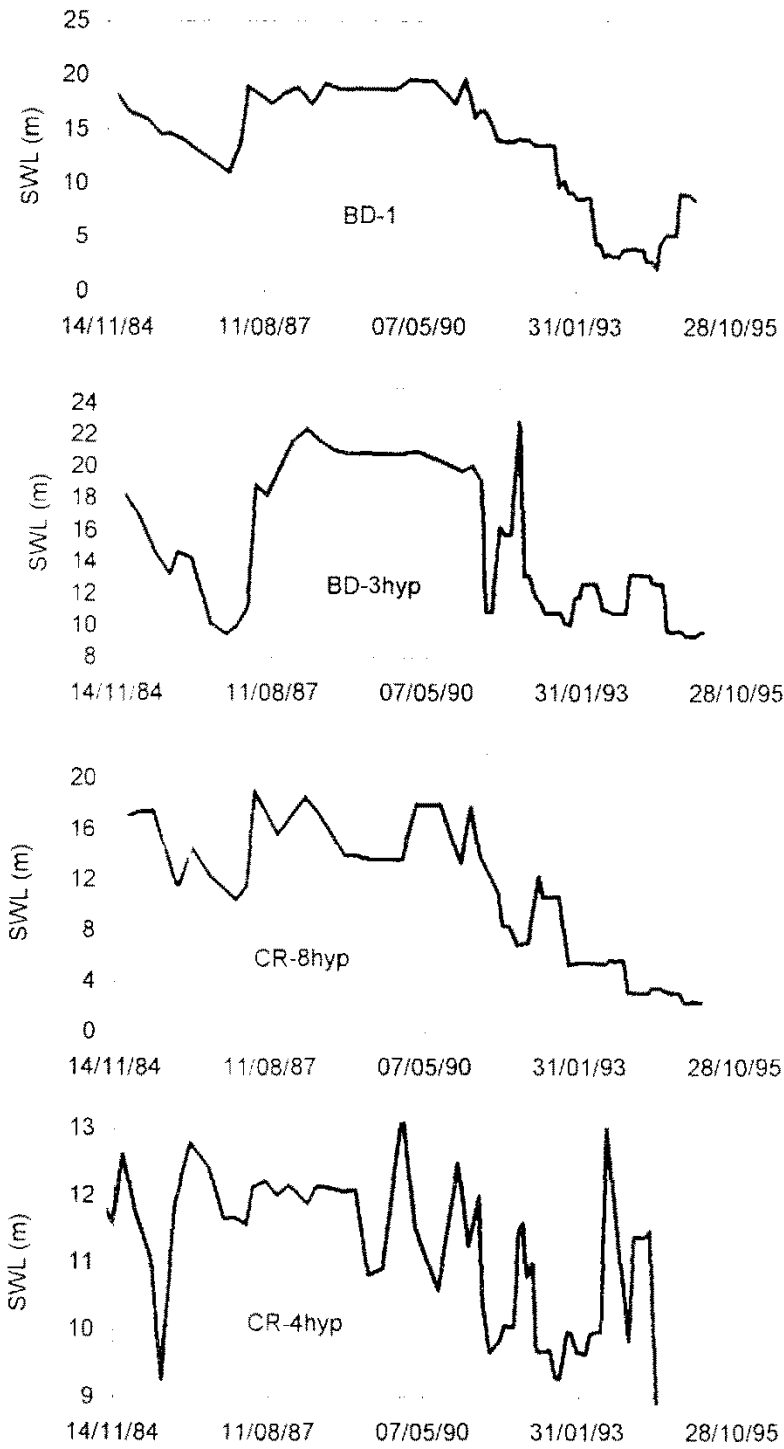
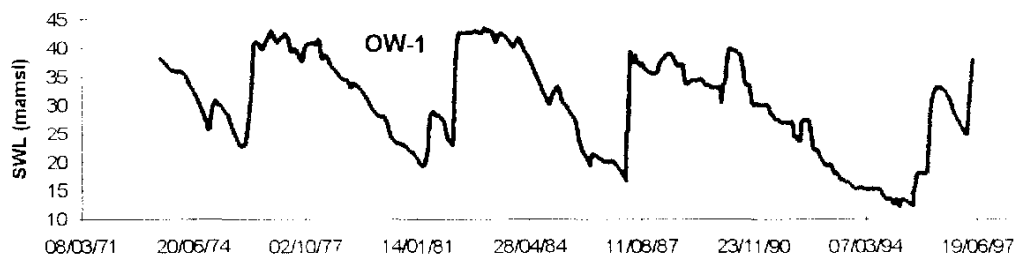
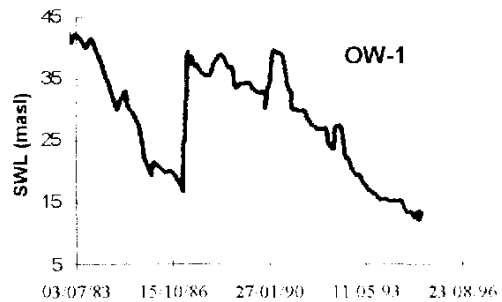
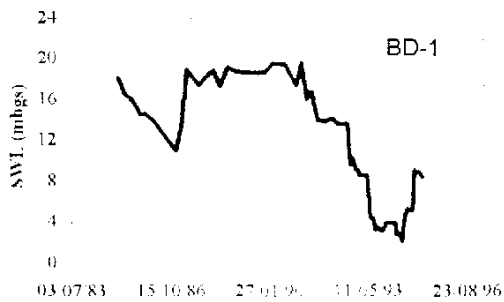


Fig. 3.20 Saw-Tooth Hydrograph Response in Upper Catchment (Samail Basin)

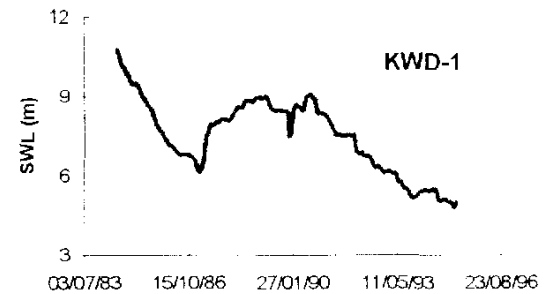
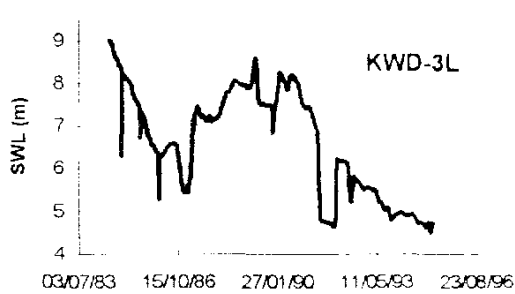


Cyclicality in the Intermediate (and Regional) Flow System of the Al Khawd Fan

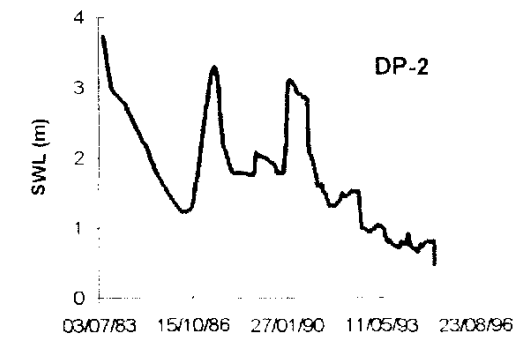
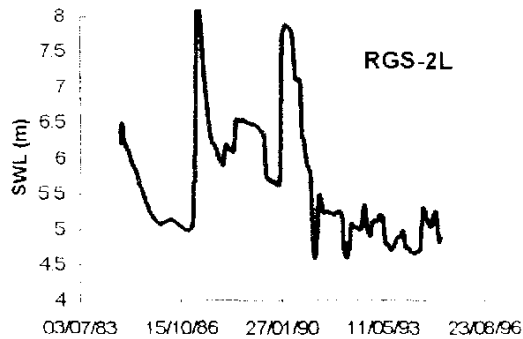


Upper Catchment - Samail Basin

Upper Fan - Intermediate and regional flow system



Middle Al Khawd Fan (deep) - intermediate to regional with no local recharge



Middle Al Khawd Fan - local recharge over intermediate and regional trend

Fig. 3.21 Catchment-wide Responses of Hydrographs to Cyclic Climatic Events.

4. Seawater Intrusion into the Al Khawd Fan.

4.1 Introduction

At the coast, freshwater is naturally underlain by a wedge of seawater, which extends inland to varying distances. With the exploitation of coastal aquifers for irrigation and domestic purposes, the seawater wedge moves further inland, the extent depending upon the amount of groundwater extracted. As it extends inland, the seawater replaces freshwater in the aquifer, leading to the salinization of coastal wells.

Significant groundwater extraction occurs from the alluvial aquifers of the Al Khawd Fan, both privately to irrigate the date palm plantations on the Batinah, nearer the coast, and to provide additional backup to the Muscat municipal water supply. Estimates by Gibb (1974) based on village surveys, were that about 13 MCM/ yr. of groundwater were being extracted from the Al Khawd Fan, from over 400 pumped wells alone, near Seeb.

As a consequence of the increased extractions, the saltwater wedge has progressively migrated inland to a point where it is now as much as 7 kilometre into the alluvial aquifer system of the Al Khawd Fan. It is now found at a depth of about 160 m in the 21/6 bore, situated in the Al Khawd Dam Wellfield, just to the north of the Al Khawd Recharge Dam. There is a varyingly wide transition zone, both lateral to the wedge and in advance of the wedge at its inland limits. While mostly within the range of normal seawater, the hydraulic conductivity reaches levels of 72,000 $\mu\text{S}/\text{cm}$, somewhat higher than that occurring in the average Gulf of Oman seawater ($\sim 55,000$ $\mu\text{S}/\text{cm}$). However, a important feature of the seawater intrusion is the presence at depth beneath the wedge, of fresh water, recorded in a number of boreholes (Figs. 4.1 and 4.2).

4.2 Shape of the Saltwater Wedge and Origin of the Underlying Freshwater Zone

The inland extent of a saltwater wedge dictated by the aquifer properties such as thickness and hydraulic conductivity. In the most simplistic case, the lower boundary of the saltwater wedge is a low permeability aquitard marking the base of the aquifer. The wedge advances inland over the impermeable layer. In a multilayered aquifer system containing high and low permeability units, the intrusion advances in the permeable, albeit varyingly confined, layers creating a number of discrete wedges, stacked on top of each other and each with an aquitard base. An example from a recent study in California is shown in Fig. 4.2. Here, a number of saline wedges intrudes into the coastal aquifer, each wedge having the characteristic shape, but underlain by a corresponding freshwater layer. The similarity between the geometry of this situation and that occurring in the Al Khawd Fan is clear. A feature of the cable tool drilling program carried out further east along the Batinah coast was discrete saline layers intruding along permeable beds with interceding freshwater layers..

The presence at depth of lower permeability units, is in itself an explanation for the shape of the Al Khawd wedge, with its underlying freshwater, and this shape alone might support the argument for a deeper low permeability unit, such as is shown in Fig. 3.14. However, the lower unit in this case is not an aquitard, but a varyingly less permeable part of the alluvial aquifer. The extent to which the shape of the wedge is influenced by permeability zones within the Al Khawd alluvial aquifer can be roughly gauged using different values of hydraulic conductivity to produce a suite of theoretical wedges (Fig. 4.3).

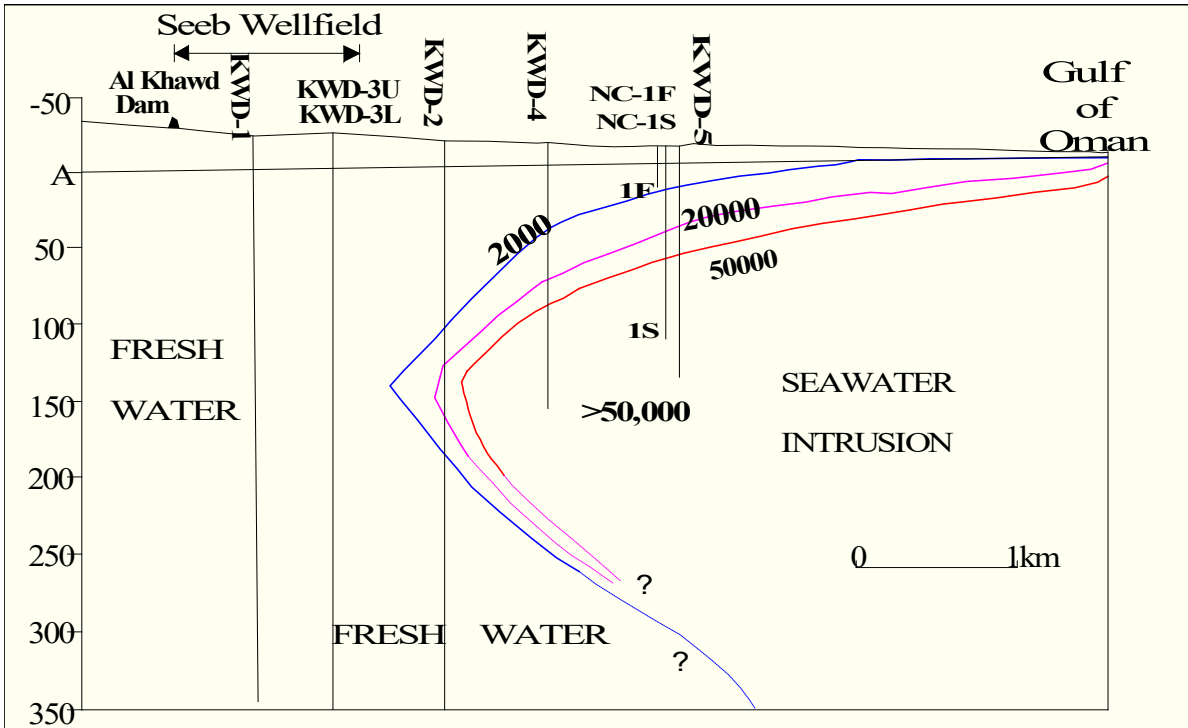


Figure 4.1a Saline Intrusion in the KWD Wells.

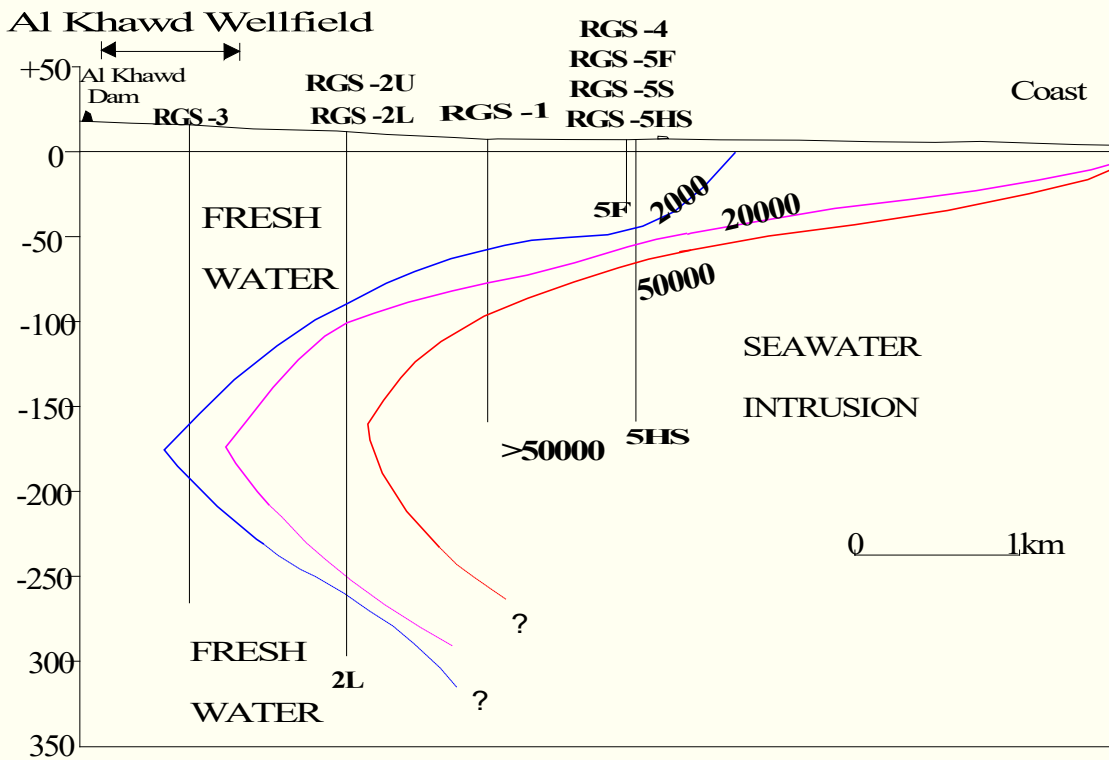
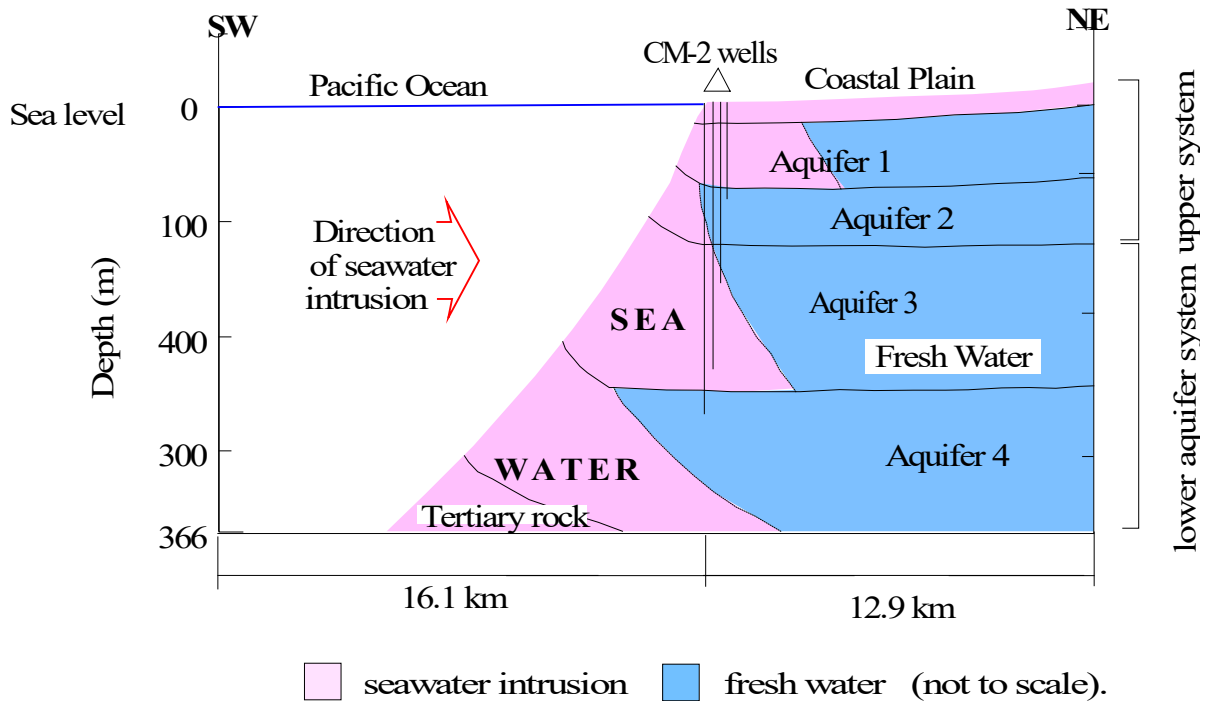


Figure 1b. Section showing saline intrusion in the RGS wells.

Figs. Modified from Bhatnagar and Ravenscroft (1986)

Fig. 4.1 Shape of the Saline Intrusion in the Al Khawd Fan (values as EC mS/cm)



Conceptual model with folded layers (from Nishikawa 1997).
Fig. 4.2 Multiple Saline Interfaces in coastal aquifers

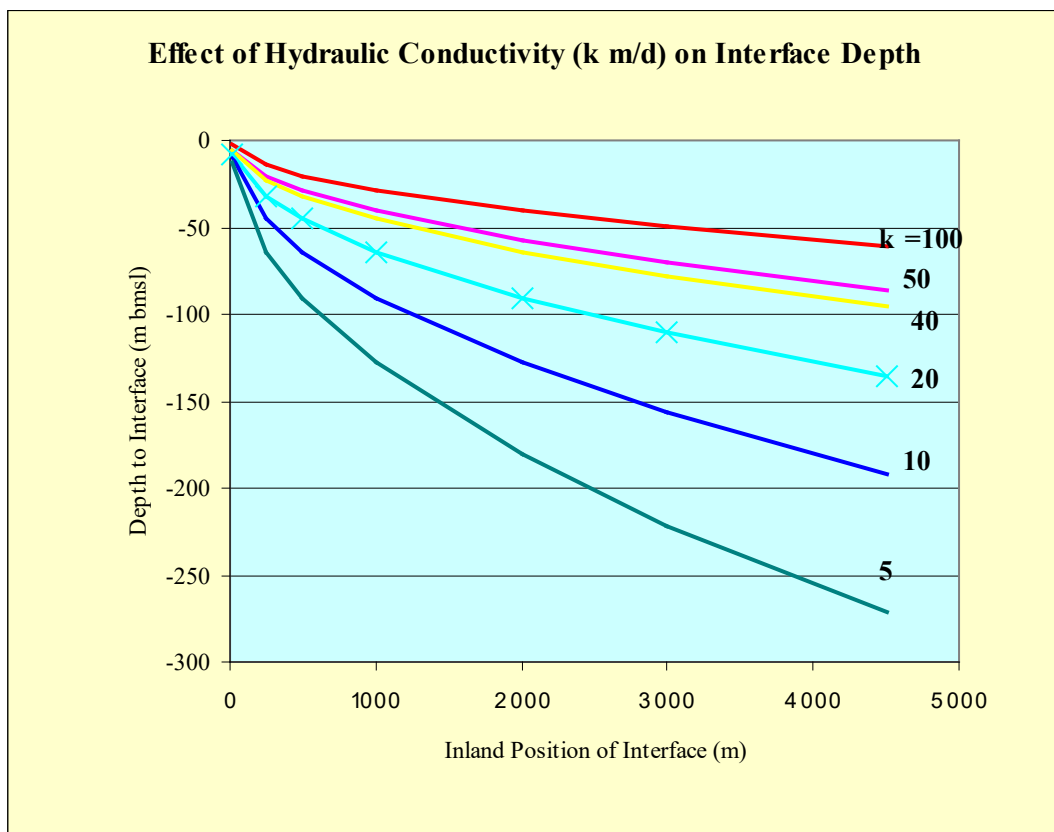


Fig. 4.3 Relationship Between Interface and Hydraulic Conductivity

Figure 4.3, based on the Glover relationship for the interface using data from the KWD-4 bore (interface at 104 m with $K = 34$ m/d), shows that high conductivity values lead to shallow interfaces, while low hydraulic conductivities give deep interfaces. The relationship is not linear, and once values fall below 20 m/d, the depth to the interface falls away rapidly.

A second and perhaps equally important factor in the development of a deep freshwater zone, beneath the saline wedge is the very strong vertically upward gradients within the aquifer. Here heads at depths of 300 m range from 5 to 10 m above sea level, whereas the water table is commonly less than 1 m above sea level. The inland extent of the saltwater intrusion, and hence its shape, will be effected by increasing potential with depth in the aquifer. The classic Ghyben-Herzberg shape is based on a hypothetical vertical equipotential passing from the water table to the base of the aquifer, giving horizontal flow. However, as the groundwater potential increases substantially with depth, the inland position of the interface is in turn forced to retreat, the equilibrium position and ultimate shape being determined by the nature of the vertical pressure gradient within the aquifer. The result would be similar to that resulting from the presence of a lower permeability horizon(s) at depth in the aquifer.

4.2.1 Water Table Trends in the Lower Al Khawd Fan.

A common guide to the position of the freshwater-saltwater interface is the level of the water table with respect to sea level (e.g. Fig. 4.4), and this is often used in conjunction with the Ghyben-Herzberg equation to determine interface depth and likely movement. However while water tables can provide indications of the movement of an underlying saltwater wedge, the relationship is far more complex than that offered by Ghyben-Herzberg approximations, and results can be grossly misleading, as in the case of the Al Khawd Fan.

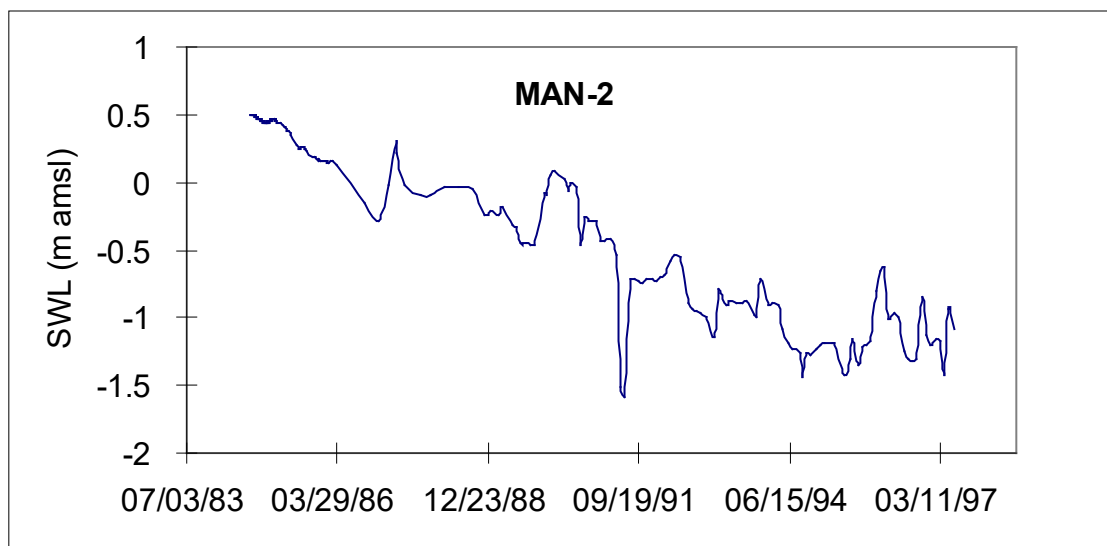


Fig. 4.4 Hydrograph of the MAN-2 Bore in the Western Al Khawd Fan (1983-1997)

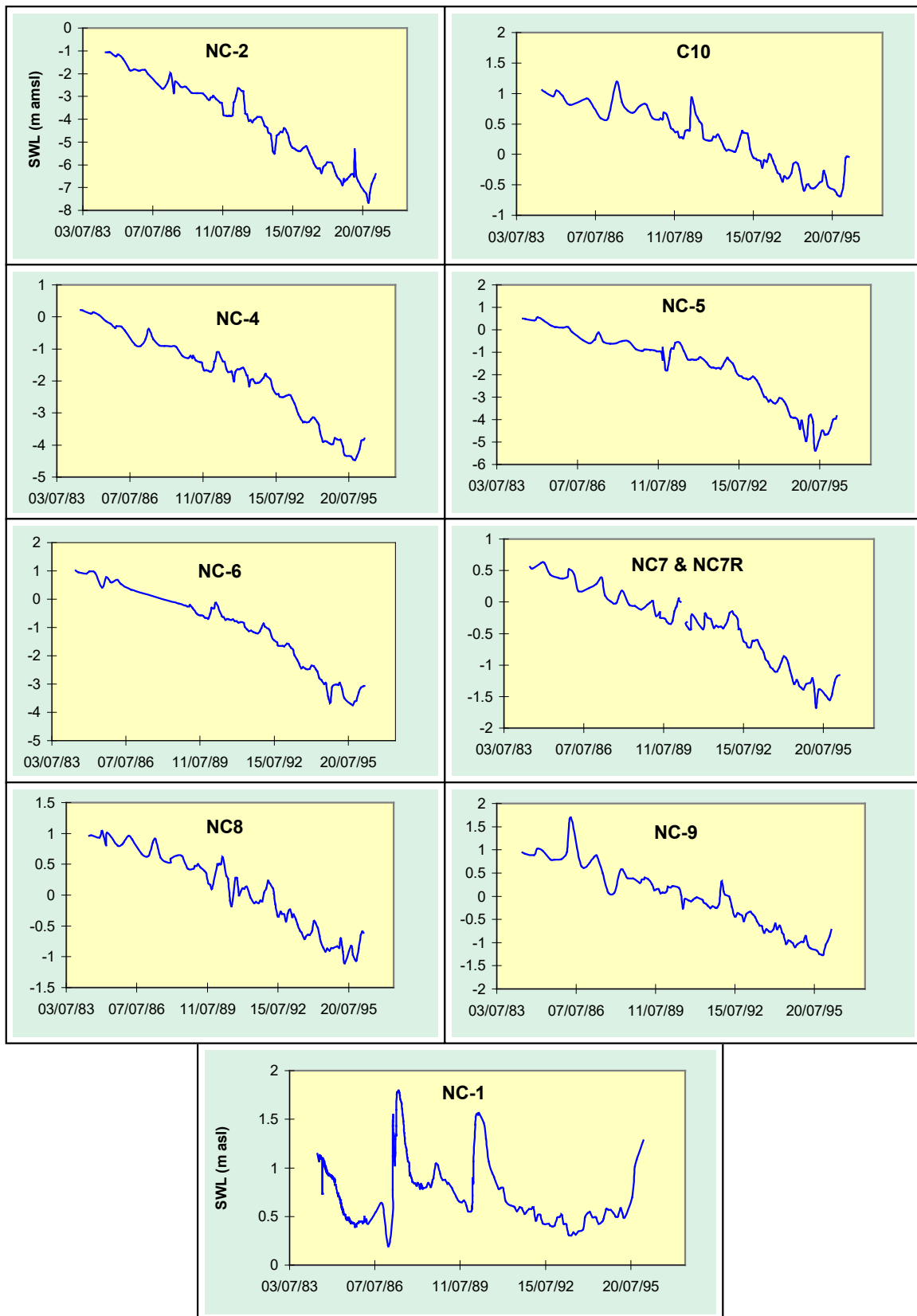


Fig. 4.5 NC-Series Salinity Monitoring Bores, Showing General Water table Declines. All Bores are from the Eastern Batinah other than the NC-1 Bore from the Al Khawd Fan.

The present trend in the coastal water table levels shows a slow fall, which suggests that there is a continued inland movement of the saltwater wedge into the western parts of the fan. This is visible in piezometers such as ADG-15 and MAN-2 (Fig. 4.4), which indicate that water levels have steadily fallen and are now below sea level. Similar trends occur in the Eastern Batinah (Fig. 4.5) and, although less pronounced, are visible in bores such as JT-29, JT-30 and DW-1 situated in the lower central parts of the Al Khawd Fan, all of which have a falling trend saw tooth pattern (Figs. 4.6 - 4.8). As shown in Section 3, the saw tooth pattern is generated by processes operating within the intermediate and regional flow systems.

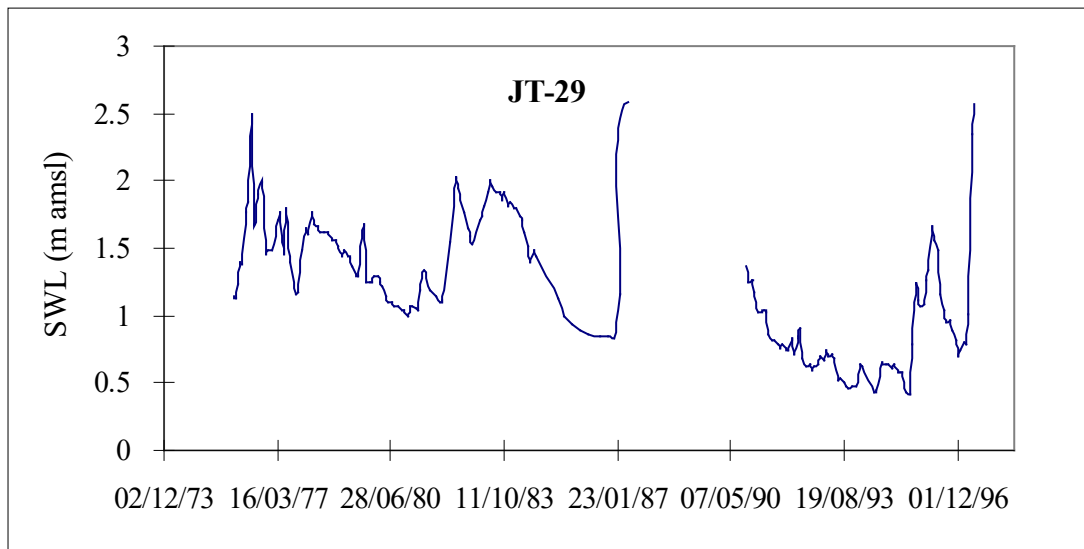


Fig. 4.6 Hydrograph of the JT-29 Piezometer, Central-Lower Al Khawd Fan

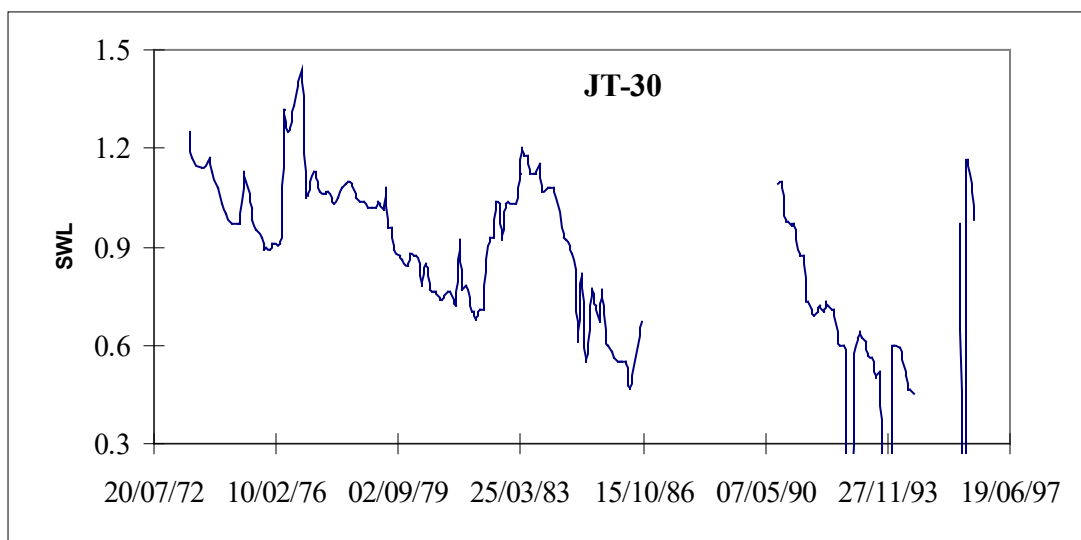


Fig. 4.7 Hydrograph of JT-30 Piezometer, Western Al Khawd Fan

Piezometers on the eastern parts of the fan, however, do not show such clearly marked falling trends as occur in the central and western fan. These piezometers include the WRD-Series (Fig.

3.3) and the NC-1 (Figs. 4.5 and 4.9) bore which have static water levels close to sea level. As has been shown in Section 3, very subdued trends are probably present, but are best understood in terms of influences of the intermediate and perhaps regional flow systems. However such trends are often on a scale which makes them almost imperceptible and in these instances are largely irrelevant to long term interface movements. The hydrographs in Fig. 4.9 show the NC-1 bore together with two other bores - WRD-11A and WRD-13A. While there is no obvious trend in the NC-1F piezometer, small changes are more readily identified in the WRD bores.

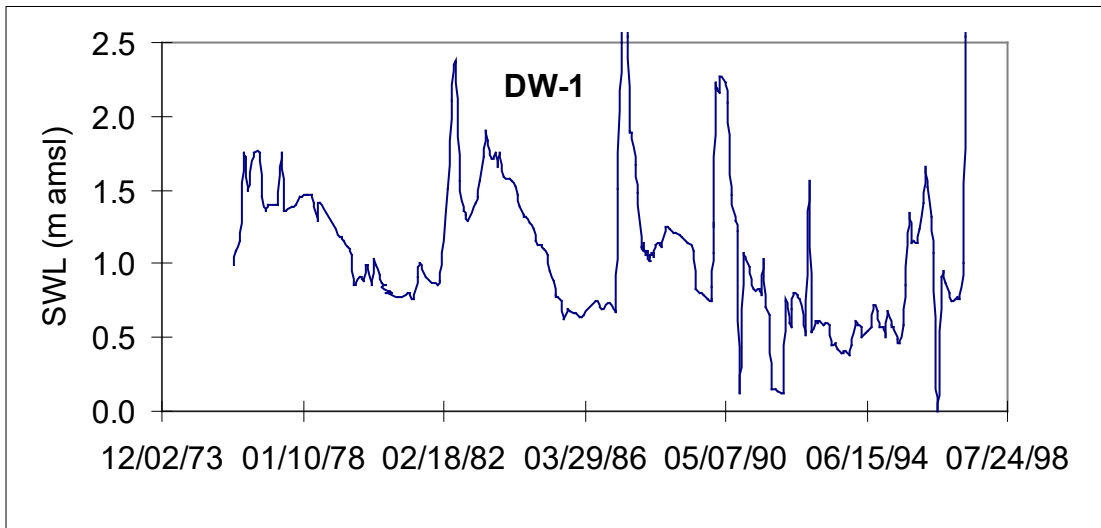


Fig. 4.8 Hydrograph of the DW-1 Piezometer, Central Al Khawd Fan (1974 to 1997)

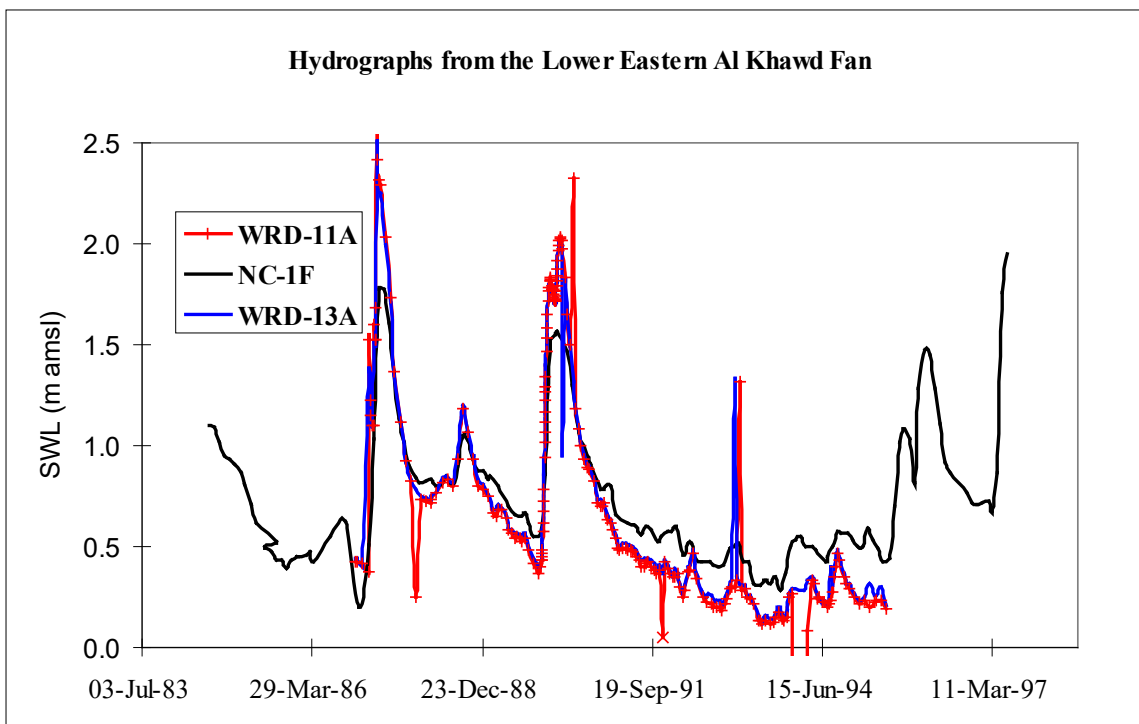


Fig. 4.9 Hydrographs of NC-1, WRD-11A and WRD-13A Piezometers

4.2.2 Water Table Movement in Response to Major Recharge Events

Hydrographs covering the period 1973 to 1995 show a slow decrease in water table levels across the western parts of the Al Khawd Fan, or a situation whereby the water table has reached an equilibrium and fluctuates often from 0 m to 1 m above mean sea level. The period from 1995 to 1997, was anomalously wet and hydrographs across the fan showed an upward swing, which marks the commencement of another longer term saw-tooth movement in the groundwater system as a whole. This upwards swing is well marked in the KWD-3L, KWD-1 and OW-1 bores.

During this period monitoring of the groundwater tables across the Al Khawd Fan, provided a further understanding of the recharge process on the Fan. The behaviour of the water table over the period from Jan 1995, that is prior to the July 1995 wet period, through until mid July 1997 (Figs. 4.10 and 4.11) shows the effects of sustained and repeated flood flows from the upper Samail Basin on groundwater levels in the Al Khawd Fan.

The period prior to July 1995 was very dry, and water tables in January 1995 were lower than previously reached. The zero contour came into the area of the Seeb and Al Khawd Dam Wellfields from the east and the west (Fig. 4.10). The heavy rains in July and subsequent flood flows in Wadi Samail impacted on water tables only in the vicinity of the wellfields in July. By August, however, a recharge mound had extended towards Seeb, roughly coinciding with the area of highest permeability of the central lower flood plain (see Geomorphology Map Fig. 1.3). It is also the region downstream from the Al Khawd Recharge Dam. Impacts in the western parts of the fan were minimal with little change to the position of the zero contour.

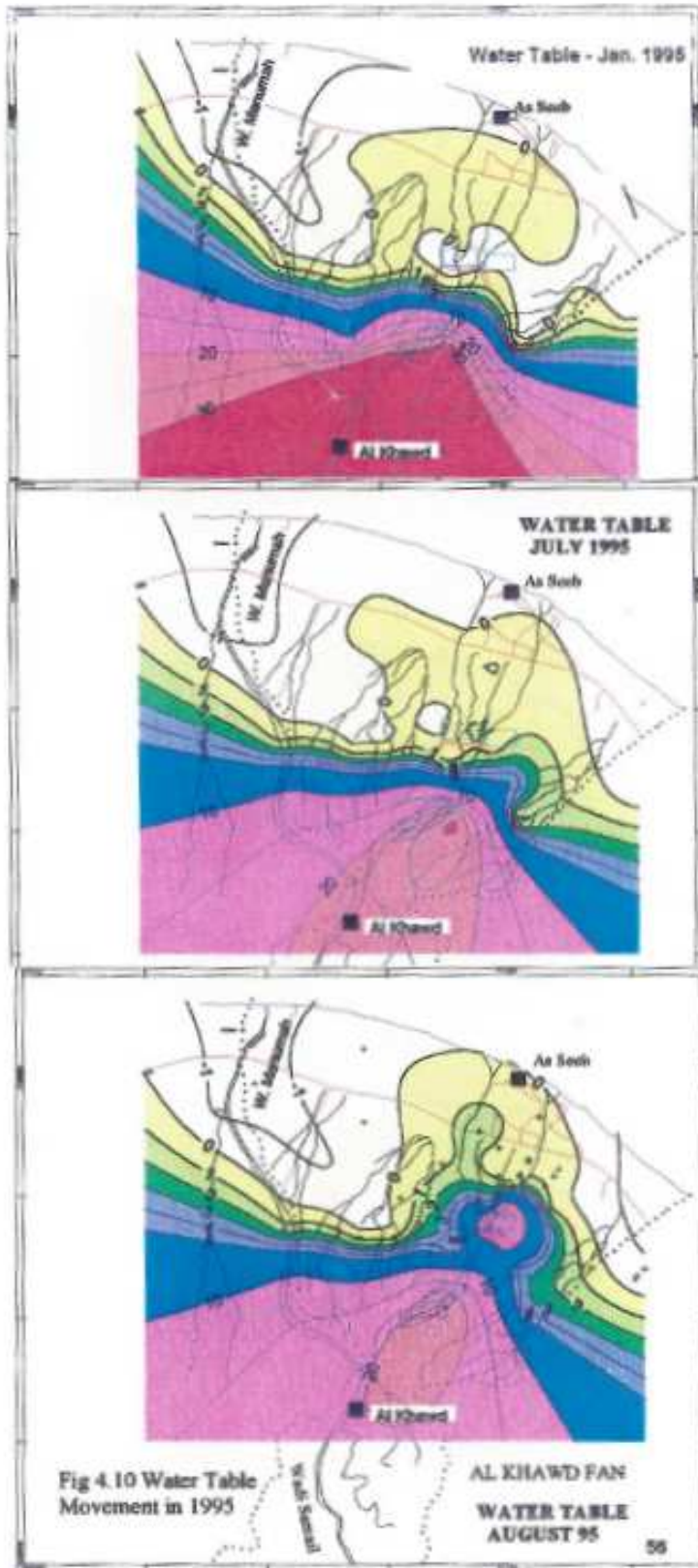
By January 1996, the water table aided by heavy rains in January remained mounded along an axis conforming roughly to a line following Wadi Samail between the Old Government Wellfield and the Highway (4.11). Some lateral spreading has occurred in the western area of the fan, shown by the position of the zero and -1 contours. During 1996, the mound gradually receded and by January 1997, for the western areas of the fan, the 1 m contour was in a similar position to that of January 1995, although the zero contour remained seawards of its earlier position.

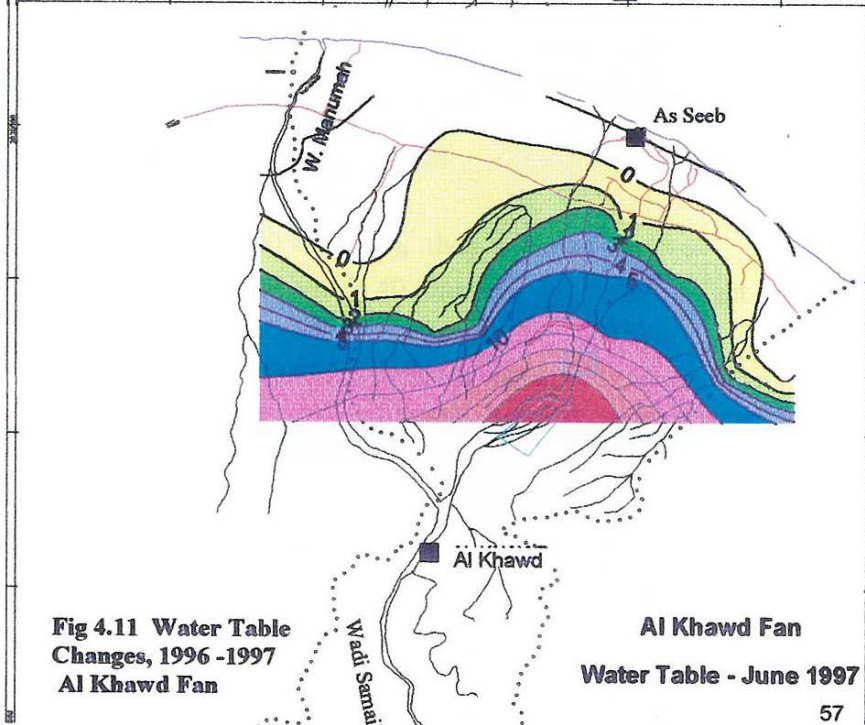
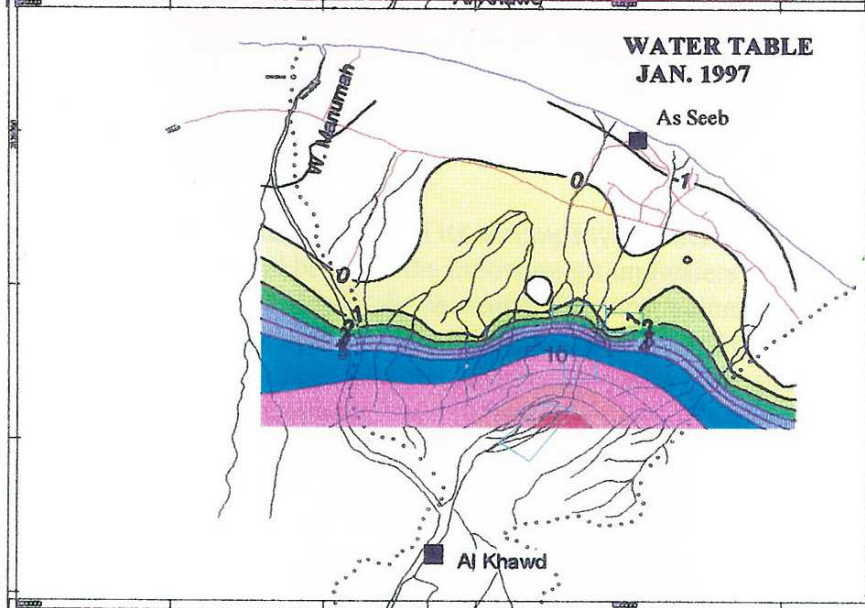
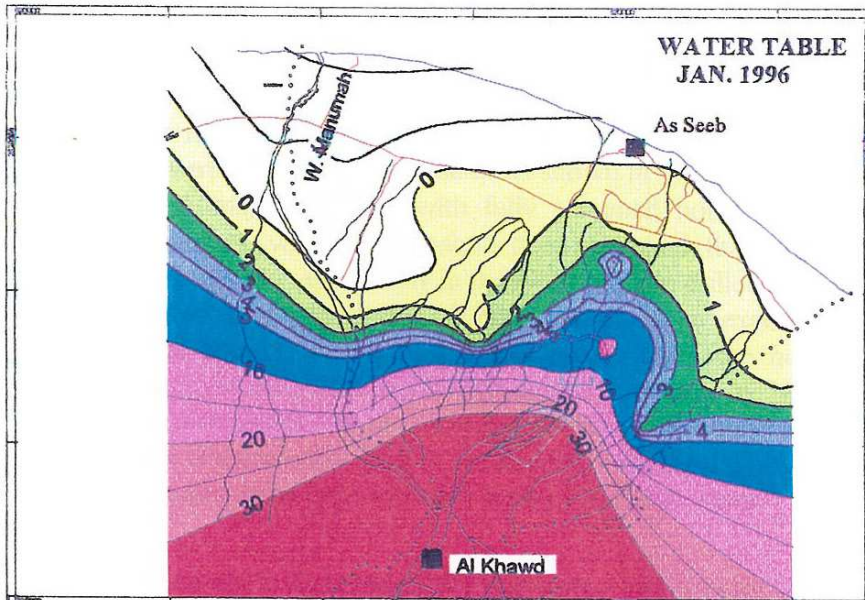
4.3 Measurement of the Freshwater-Saltwater Interface

4.3.1 Previous Work

During the mid 1980's the PAWR (precursor of MWR) established a monitoring network across the Al Khawd Fan largely based on deep bores penetrating the saltwater intrusion, and screened across large intervals spanning the interface. The assumption was that the salinity profiles in the bores would echo those in the surrounding aquifer. At the same time several piezometer nests (RGS-5 and NC-1 bores) were established, each nest having piezometers screened across short intervals in both the freshwater and saline water parts of the aquifer.

The position of the saltwater wedge was determined by downhole geophysical logging, principally with a conductivity probe to gain a salinity (electrical conductivity) profile. Profiles were compared at various times to determine the extent (if any) of interface movement.





**Fig 4.11 Water Table
Changes, 1996 -1997
Al Khawd Fan**

**Al Khawd Fan
Water Table - June 1997**

However, the Al Khawd Fan is a zone of regional groundwater discharge. Across the Fan there are strong vertically upward gradients as shown in the RGS-2L, KWD-1, KWD-3L and 21 Series bores. A major problem with fully screened holes in such situations is that the distribution of salinities within the borehole does not match that in the aquifer due to vertical flow. This was observed very clearly in the C-2 borehole drilled by cable-tool in the Eastern Batinah where close sampling during drilling permitted an excellent record of the salinity profile within the aquifer. However the EC profile from the borehole showed that the freshwater-saltwater interface was displaced vertically upwards by 30 m in the bore. A further example is that of the RGS-3 bore where Bhatnagar and Ravenscroft note that “the (salinity) profile in the hole is more saline than in the aquifer, and that the observed profile is caused by the upward flow from a relatively restricted zone of brackish water.”

4.4 Analytical Methods to Determine the Saltwater-Freshwater Interface

It is important to understand the methods and assumptions adopted for freshwater-saltwater interface calculations. This is especially the case where these methods are themselves used as a basis for more sophisticated approaches to determine the position or character of the interface

4.4.1 Ghyben-Herzberg Approach

The existence of a saltwater wedge and its accompanying interface in a coastal situation arises from the density differential between the inflowing groundwaters and the salt water occupying the aquifer on the seaward side of the shoreline. The most common approach adopted to gain a rough estimate of the depth to the saltwater/freshwater interface is that of the Ghyben-Herzberg approximation. The Ghyben-Herzberg equation for the depth to the interface between the salt and fresh waters is:

$$Z = (r_f * H_f) / (r_s - r_f) \quad (1)$$

$$\text{or } Z = r_f H_f / d \quad \text{where } d = (r_s - r_f) \quad (2)$$

where Z is the depth to the freshwater/saltwater interface below sea level

H_f is the height of the water table above the lake datum

r_f is the freshwater density - the regional groundwater - = 1.00

r_s is the salt water density = 1.025

Since $(r_s - r_f) = (1.025 - 1.00 = 0.025)$, then $Z = 40 * H_f$

and therefore interface depth equals 40 times the water table height for Ghyben-Herzberg.

The use of the Ghyben-Herzberg concept results in an approximation for the depth of the interface below the surface, the equation being in terms of water densities and 'fresh' water head (water table height in this case) above mean sea level.

However in the case of the Al Khawd Fan, the Ghyben-Herzberg approximation gives a totally wrong picture. Were it to be applied across the central and lower Fan, where water tables are less than 1 m above sea level, then calculated interface depths would all lie between forty and

zero metres above sea level. In the case of the Seeb and Al Khawd Dam Wellfields the zero water table contour intrudes from the west and the east, yet the interface is known to be at depths of about 160 m in the 21/6 piezometer. One reason for the error is that the Ghyben-Herzberg approximation is based on hydrostatics, it does not take into account vertical flow or the existence of a varying wide transition zone. The basic assumption is that while water tables rise, there is no pressure movement in the underlying saline zone. From the hydrographs, this is clearly not the case, and instead the pressure rises in the saline zone accompany rises in the freshwater zone. The Ghyben-Herzberg approximation is therefore a very much simplified version of other equations such as Hubbert (1940) and Lusczynski (1962) which accommodate these additional factors.

Perhaps the most reliable means of assessing the depth to the freshwater-saltwater interface, and the subsequent fluctuations of the interface is by the use of piezometer nests screened across small intervals, one in the saltwater and the other in the freshwater. This permits the measurement of static water levels and fluctuations in both the freshwater and saltwater zones, In the Hubbert and Lusczynski approaches, the depth to the interface is directly related to the pressure head differential between the shallow (fresh) and deep (saline) piezometers and to the groundwater densities.

4.4.2 Hubbert's Equation for the Saltwater-Freshwater Interface

The Ghyben-Herzberg concept gives an indication of the depth to the interface and the manner in the interface moves however the concept is based on hydrostatics and assumes no saline water movement. In coastal fresh water/sea water systems there is normally not only a significant fresh water movement towards the coast, but also considerable motion in the underlying salt water. In order to deal with the dynamic equilibrium of the mobile fresh water - saltwater interface, Hubbert (1940), showed that the depth to the interface could be more accurately defined by the equation:

$$Z_i = (\rho_s H_s) / (\rho_s - \rho_f) - (\rho_f H_f) / (\rho_s - \rho_f) \quad (3)$$

where Z_i is the elevation of the interface.

H_f is the static level of fresh water in a bore screened in fresh water,

H_s is the static level of saline water in a bore screened in salt water,

ρ_f is the fresh water density, ρ_s is the saline water density.

The Hubbert equation is commonly expressed as:

$$\rho_f H_f = \rho_s H_s - Z_i (\rho_s - \rho_f) \quad (4)$$

or more generally where it is applied to two immiscible liquids of density ρ_1 and ρ_2 where $\rho_2 > \rho_1$, each having hydrostatic heads H_{1p} and H_{2p} respectively, it becomes:

$$\rho_1 H_{1p} = \rho_2 H_{2p} - Z_i (\rho_2 - \rho_1) \quad (5)$$

Where the static level of the saline water in equation 12 is at sea level, i.e. $H_s = 0$, indicating no flow in the intruded water, then the equation reduces to the Ghyben-Herzberg equation. Hubbert's equation implies a sharp interface, however there is commonly a varyingly wide transition zone of intermediate density water between the intruded salt water and the overlying fresh water. A further limitation is that it implies that, as in the Ghyben-Herzberg equation, there is no vertical groundwater flow component.

4.4.3 Lusczynski's Equation for the Saltwater-Freshwater Interface

As previously noted, the Ghyben-Herzberg approximation for the freshwater-saltwater interface assumes static conditions within the salt water, which may introduce considerable error. Hubbert's equation uses data from two points, one fresh and one salt, from some distance apart in a vertical column. However, it ignores any vertical flow component and assumes that the interface is sharp. Lusczynski's equation for the theoretical position of the interface is derived from a more general equation, which expresses the relationship between the point-water head in fresh water (therefore a fresh-water head), and the elevation of the contact between fresh water and diffuse water in a vertical sequence within an aquifer. Proof of the validity of the general equation is given in Lusczynski (1961, p. 4255). The interface equation is:

$$H_1 \rho_1 = \rho_1 h + \rho_2 H_{2p} - Z_2 (\rho_2 - \rho_a) - Z_d (\rho_a - \rho_1) \quad (6)$$

where h is the environmental-water head loss, $(H_{1n} - H_{2n})$, between any two points - one in fresh water (1) and the other in salt water (2), in a vertical sequence in the aquifer containing fresh-water, diffuse water (water in the transition zone) and salt water.

Z_d is the level of the contact between fresh-water and diffuse water (transitional water). It is also the reference point from which ρ_a is measured.

Z_2 is the elevation of point 2 (m, amsl).

H_{2p} is the point-water head at point 2 (m, amsl).

H_1 is the point water head at point 1 (equals the freshwater head - m, amsl).

ρ_1 is fresh-water density (g/cm^3),

ρ_2 is saltwater density (g/cm^3).

ρ_a is the average density between Z_d and point 2 (g/cm^3)

The equation expresses a relationship between $H_{\square p}$ a pointwater head (or freshwater head in fresh water), and Z_d - the elevation between the contact between freshwater and the top of the transition zone. The first term on the right hand side of the equation accounts for vertical flow in the section (as determined by environmental-water heads), the second term expresses the pointwater head in the salt water, and the third and fourth terms account for variable density in the transition zone.

It follows that in situations where there is no vertical flow, that is $h = 0$, and where the interface is sharp with no transition zone, that is $\rho_a = \rho_2$, the third term vanishes, leaving:

$$\rho_1 H_{1p} = \rho_2 H_{2p} - Z_d (\rho_2 - \rho_1)$$

This equation is the same as equation (5), Hubbert's equation for the interface. In a similar manner Lusczynski shows that the Ghyben-Herzberg approximation is a further simplification of the general equation in which the point-water head in salt water is at sea level. Thus if $H_{2p} = 0$, then the Ghyben-Herzberg equation is obtained.

In order to accommodate the strong vertical flow component present in coastal groundwater discharge areas, such as the Al Khawd Fan, it is necessary to include the term $\rho_1 h$ in Hubbert's equation, thus giving:

$$\rho_1 H_{1p} = \rho_1 h + \rho_2 H_{2p} - Z_d (\rho_2 - \rho_1) \quad (7)$$

where Z_d is the elevation of the theoretical contact between salt water and fresh water.

H_{1p} is the pointwater head in fresh water and therefore equals the freshwater head H_f of equation (4). As noted above, h is the environmental-water head loss, $(H_{1n} - H_{2n})$, between any two points - one in fresh water (1) and the other in salt water (2), in a vertical sequence in the aquifer containing freshwater, diffuse water (water in the transition zone) and salt water.

One difficulty with the use of the Lusczynski equation (6) or the modified Hubbert equation (7) for a fluctuating saltwater/freshwater interface is the requirement to provide values for the average density between the two measuring points in salt and fresh water. However, any value obtained will automatically change as the interface rises or falls. A technique adopted here is to obtain the interface position using the Hubbert equation and use these values to calculate approximate average densities at different times. These average density values are in turn plugged in to the Lusczynski equation to get a further interface. This technique has been adopted in Figure 4.12, which shows saltwater/freshwater interfaces calculated using Hubbert's and the modified Hubbert equations. While they give different depths to the interface, either of the equations can be used to determine long term trends in its movement.

In both instances, the interface curve is essentially the same, except that the modified Hubbert curve is displaced downwards, relative to the Hubbert curve. The degree of displacement is determined essentially by the $\rho_f h$ component in the modified Hubbert equation (7) which reflects the vertical hydraulic gradient, (based on environmental water heads, not static water levels). The displacement is zero where there is no vertical flow, upwards when there are downwards gradients, and downwards under upwards gradients.

Downhole logging by Hydrotechnica in July 1992 of the nearby RGS-4 piezometer showed an interface within the borehole at a depth of 60 m which is about 47 m below sea level. This compares with a depth of about 40 m determined by the modified Hubbert calculation which

takes into account the vertical upwards gradient in the aquifer. The July 1992 value for interface depth measured within the borehole was essentially the same depth as previously measured in 1984, (47 m below mean sea level). That is, there is no indication of interface movement in the borehole over this period. By contrast the equations based on the static level data show a gradual rise in the interface.

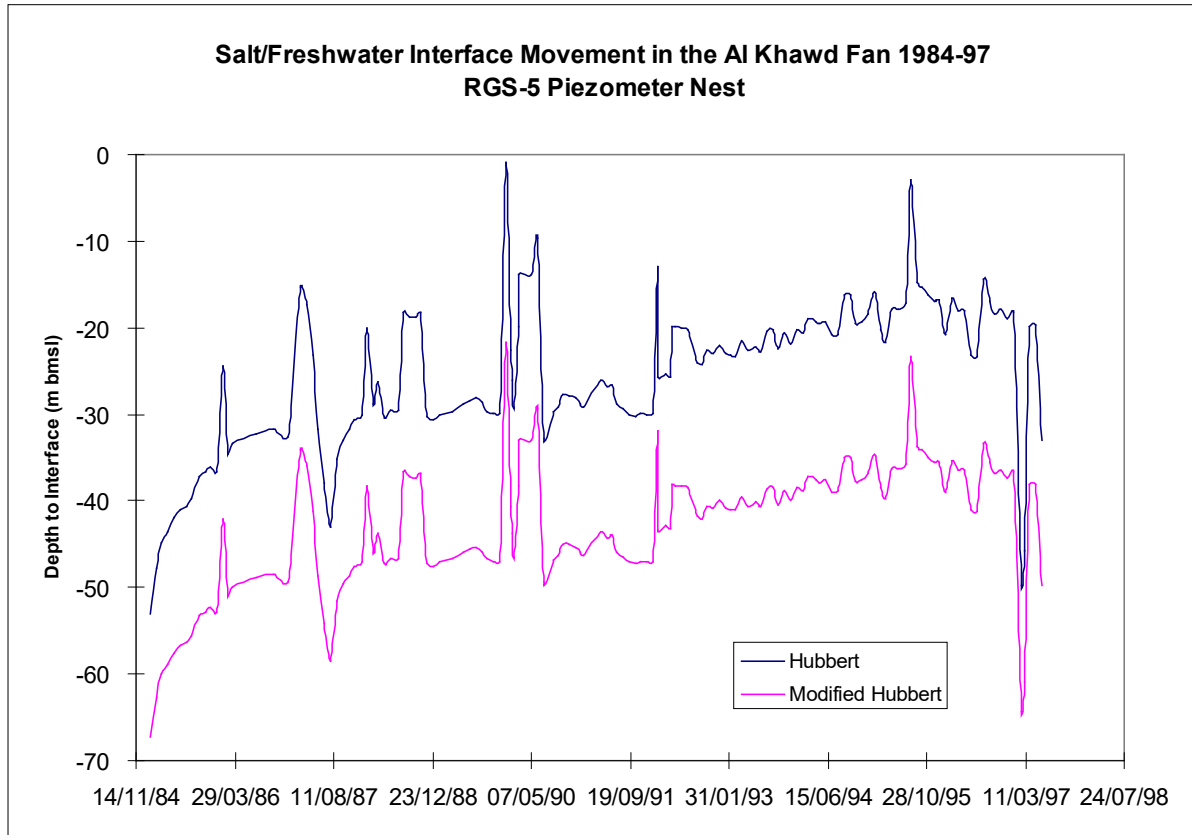


Fig. 4.13 Freshwater-saltwater interface for the RGS-5 Piezometer Nest - 1984 to 1995

A similar trend pattern (up to the limits of data in 1995) was obtained from the WRD-11 piezometer nest situated on the KWD-line in the vicinity of the NC-1 piezometer nest (Fig. 4.14). In this case the Hubbert equation (6) has been used, as details of the salinity profile between the two screened intervals were not known.

4.4.4 Comparison between Hubbert's and Ghyben-Herzberg Analyses

A comparison of respective interface positions using the Ghyben-Herzberg and Hubbert's unmodified equation is given in Figure 4.15. Marked differences occur showing the dissimilarities between the results from the different methods. Of especial note is the deep falls in the Ghyben-Herzberg interface, which commonly coincide with rises in the Hubbert interface.

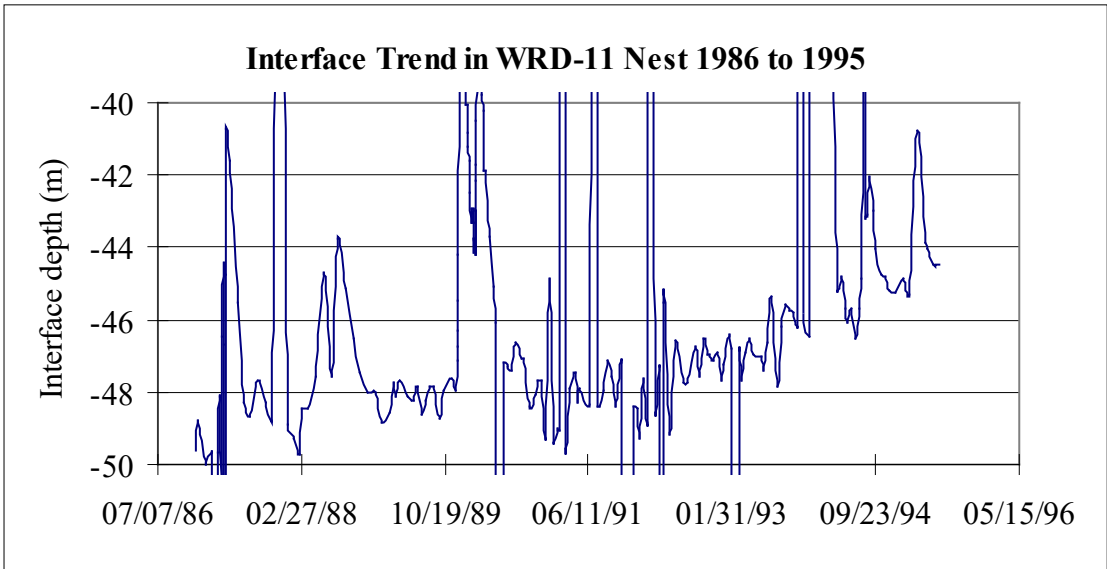


Fig. 4.14 Interface Movement in WRD-11 Piezometer Nest. 1985 to 1995

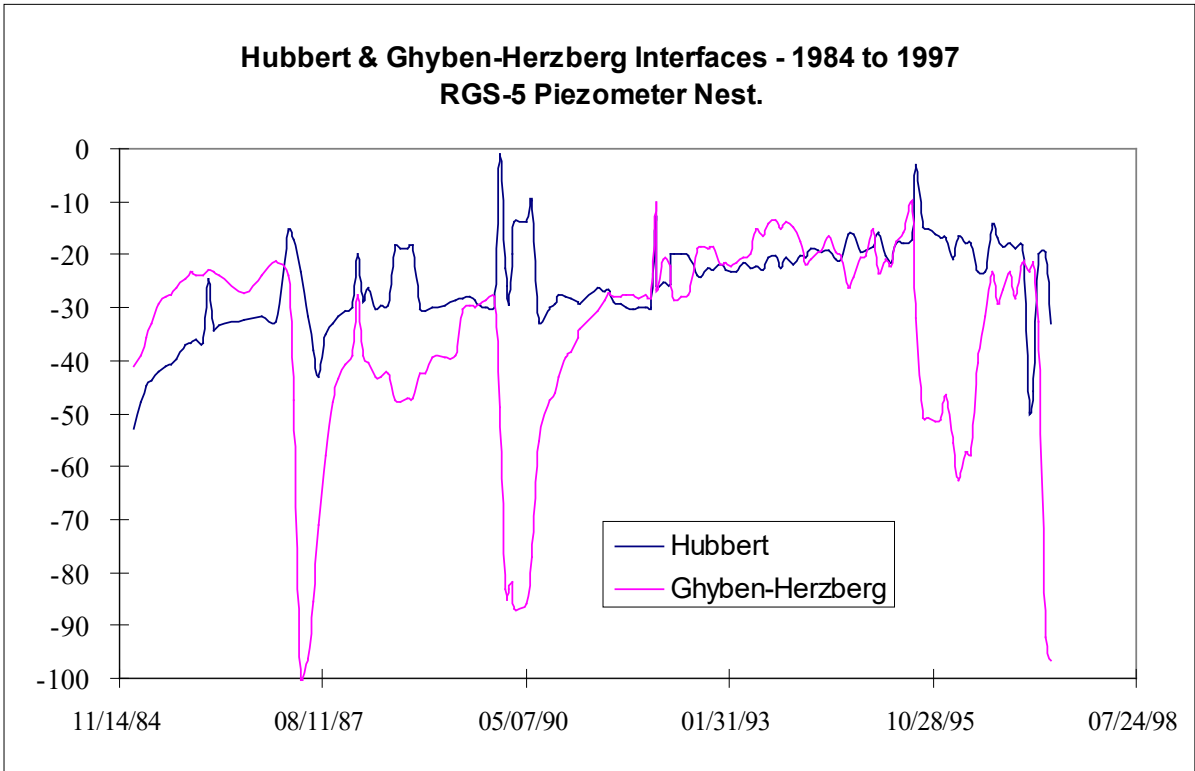


Fig. 4.15 Interface calculated using Hubbert (1940) and Ghyben-Herzberg approaches.

4.4.5 Trends in Interface Movements

Apart from the greater depth shown by the Lusczynski plot to that of the Hubbert plot, a number of important points can be made from the graphs which represent the trend in interface movement over the central parts of the Al Khawd Fan

1. The interface shows a gradual rise of about 25 m over the period 1984 to 1995, but following the exceptionally wet years 1995 to 1997, it begins to decline.
2. The period from 1987 to about 1991 shows a very slow rise, punctuated by short lived sharp rises and falls, as occurred in 1987, 1988 and 1990. This period is followed by one having a more uniform, but steeper, rise from 1991 to 1995, prior to its subsequent decline in response to the 1995 to 1997 wet years.
3. The events causing the sharp rises (and later falls) in the interface calculations correspond with significant recharge events, such as occurred in 1990. That an interface rise (or increased potential for one) should accompany a recharge event, appears to contradict the conventional understanding which relates recharge events to water table rises and hence interface falls. This latter assumption is, however, based on the premise that the depth to the interface is solely determined by the height of the water table above sea level. That is, the Ghyben-Herzberg approximation which does not take into account the strongly fluctuating hydraulic heads within the saline groundwater, which accompany the recharge events.

Instead, it can be shown by the Hubbert and Lusczynski equations, that the depth to the interface is proportional to the head difference between the saltwater and freshwater zones, as measured in two piezometers, one in the freshwater and one in the saltwater zones. Examples are piezometers NC-1F and NC-1S in Fig. 4.17 and RGS-5F and RGS-5HS, in Figs. 4.18).

4.4.6 Recharge Events, Hydrograph Response and Interface Movement

During the period from late 1989 to August 1990, Wadi Samail at the Al Khawd gauging station flowed strongly in December 1989 and flows also occurred in January and February 1990, with base flow continuing until April 1990. Static water levels in the saline and fresh water zones from the NC-1 piezometer nest both show major recharge spikes in 1987 and 1989/90, and a smaller one in 1988. Each recharge event causes pressure response in the shallow (15-21 m) freshwater NC-1F and in the saline (116-121 m) NC-1S bores. At these times, the pressure differential between the piezometers shows a clear reduction of about 0.4 m (Fig. 4.17). While this does not appear significant, it would result in a theoretical 16 m upwards displacement of the interface were there sufficient time to reach a new equilibrium .

This relationship is further detailed in Figures 4.18 and 4.19 which shows the static water levels in the RGS-5 piezometer nest during the recharge event of early 1990, and the head differential between two bores, RGS-5F (17 m - 23 m, fresh) and the other RGS-5HS (180 - 186 m, saline). Prior to recharge, the head differential is about 1 m. It is important to stress that this head differential is **not** a true measure of the vertical hydraulic gradient, since the head measurement in the deeper bore would have to be corrected to obtain an *environmental water head* required for vertical gradient calculations (Lusczynski, 1961)

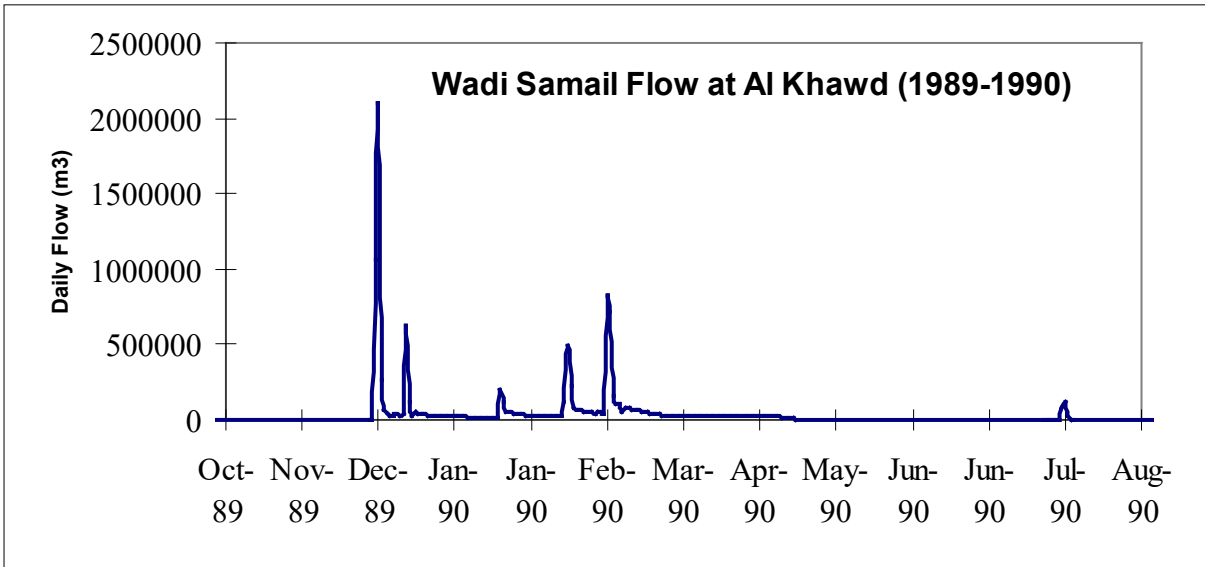


Fig. 4.16 Wadi Flow at Al Khawd - Oct. 1989 to Aug. 1990

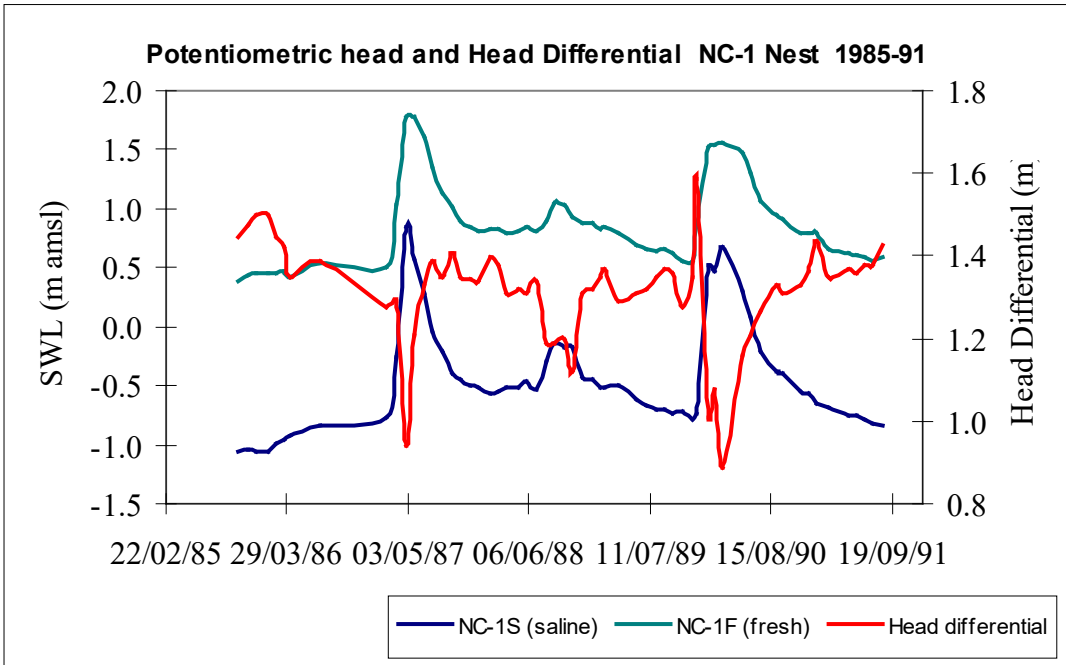


Fig. 4.17 Static water Levels and Head Differential in the NC-1 Nest 1985 to 1991

During the 1989/90 recharge event, the hydrographs clearly show that the first pressure pulse to reach the piezometer nest is that occurring in the deeper part of the aquifer (180-186 m), that is, in the saline zone (Fig. 4.4). The shallow water table bore (17-23 m) rises a little later. The impact of the recharge event on static water levels is seen in the deeper bore commencing to rise in December 1989, but this rise is delayed in the shallow bore until December. Heads

rise quickly in the deeper bore to be level with those in the shallow bore about 1st January 1990, but then taper off. Although rising later and more slowly, the water level in the shallow bore continues to rise through this period, before levelling out at the end of January. After dipping a little in early January, the head in the deeper bore again rises before levelling off in early March. Levels in the shallow freshwater bore commence to fall in May, prior to the deep saline bore in June, and they level off to elevations similar to what existed prior to the event.

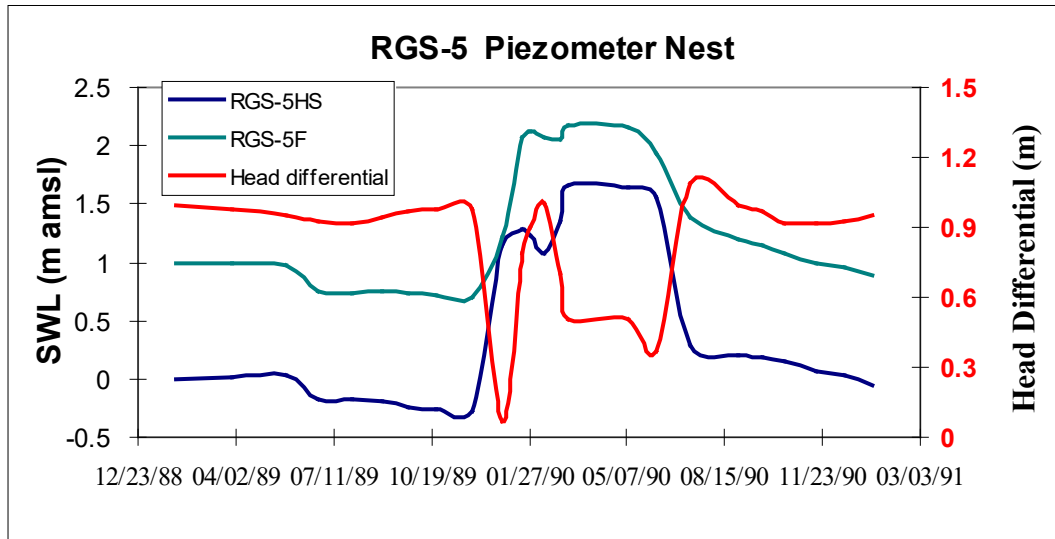


Fig. 4.18 Potentiometric Head and Head Differential in the RGS-5 Piezometer Nest

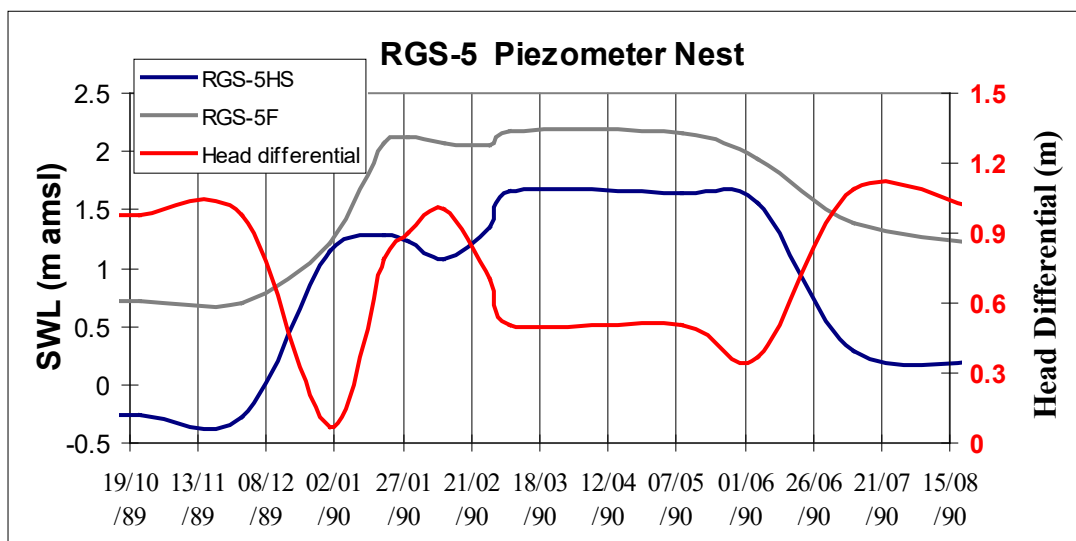


Fig. 4.19 Static Water Level Fluctuation and Head Differential in 1990 (Detail)

The differential between the static water levels, is about 1 m initially but has fallen to almost zero in January 1990. Between February 1990 and June 1990 it is at about 0.5 m, but then returns to a level closer to that of October 1989 by September 1990. The period of reduced head differentials between the deep and shallow aquifer is therefore almost 9 months.

While the calculations give precise values for interface rises, the extent to which the interface actually rises will be determined by a number of factors such as the time over which the pressure differential remains. With the rapid return to the earlier base levels, it is likely that in most instances there is insufficient time for a new higher interface equilibrium to develop. Whatever the case, it is clear that at such times, the potential for upconing in pumping bores increases, and caution should be exercised in those instances where any threat of upconing might be present under normal conditions.

A further indication of the trends in the freshwater-saltwater interface is given using data from the NC-1 piezometer nest (Fig. 4.20). There are differences between the long term records from the NC-1 nest situated on the KWD-line and the records from the nearby WRD-11 nest and RGS-5 nest on the RGS-line, further west. Here, again using the unmodified Hubbert (6), the data suggests that the interface in the NC-1 nest is more stable and fluctuates around the -55 m mark. A rise covering the period from about 1992 to 1996 is evident, culminating in a sharp rise from about 1995 coinciding with the wetter period from 1995 to 1996. Later, but much later than in the case of the RGS-5 nest, the impact of the 1997 wet period appears to have caused a fall in the interface. The reason for the differences are probably due to difference in the groundwater flow regimes in different parts of the Fan, perhaps stemming from permeability variations. But this is essentially conjecture, and the answers must await the development and analysis of further piezometer nests on the Fan.

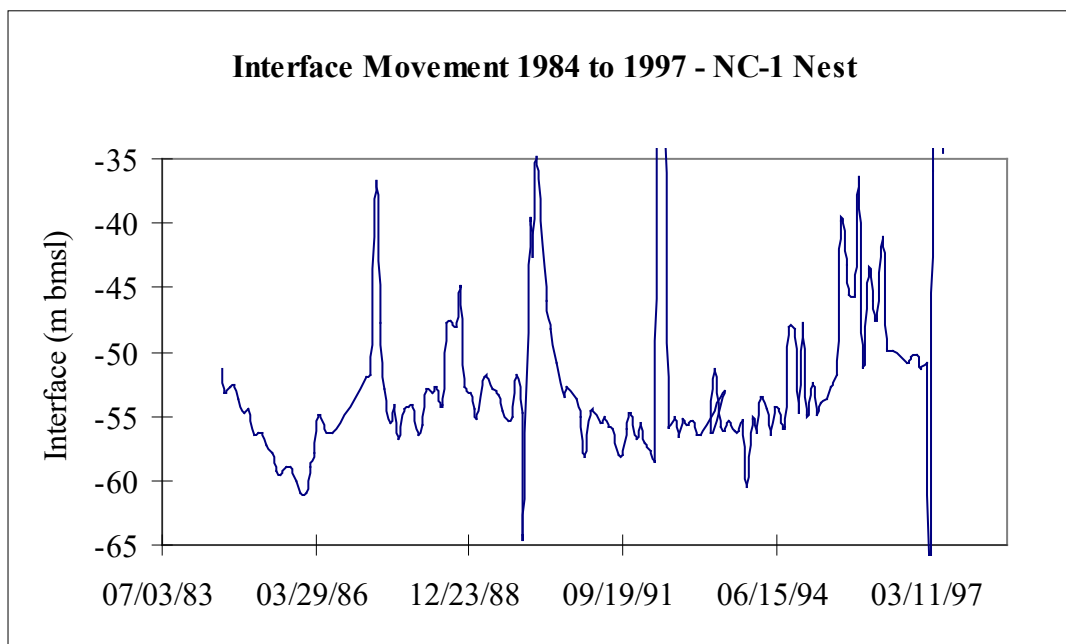


Fig. 4.20 Interface Movement in NC-1 Nest 1983 to 1997.

4.4.7 The Lower Saltwater-Freshwater Interface

The 21/6 piezometer nest is established northwards of the western end of the Al Khawd Dam, a little to the north of the western end of the Al Khawd Dam wellfield. It is essentially 1 km west of the RGS-3 bore which encountered brackish water between 190 m and 220 m, before passing back into freshwater. The 21/6 bore was drilled through gravels, calcreted gravels and calcrete to 350 m (Fig. 2.9).

Freshwater occurs in the upper part of the bore until about 170 m, then in a transition zone, salinity increases to an average of 19500 $\mu\text{S}/\text{cm}$, and reaches a high of 24500 $\mu\text{S}/\text{cm}$. The salinities in 21/6 are less than the 50000 $\mu\text{S}/\text{cm}$ levels of the main body of the saltwater intrusion. Below 247 m, the lower boundary of the saltwater wedge is crossed and freshwater (1200 $\mu\text{S}/\text{cm}$) again occurs in the calcrete formations in the bore. The saline water has a salinity close to that occurring at the interface (ca. 26000 $\mu\text{S}/\text{cm}$) and it represents the centre of the transition zone occurring at the inland limit of the wedge, in advance of the fully saline zone of the intrusion. The same is the case for the RGS-3 bore, which is not as saline and therefore lies within the transition zone further from the interface. The RGS-3 bore also passed into the underlying freshwater zone.

4.4.8 Response of the Lower Interface to Recharge Events

Two zones were screened in the 21/6 bore, one from 208 to 218 m in the saline formation, and a second in the underlying deep freshwater zone, from 289 to 297 m. The hydrographs of the two piezometers show static water levels well above sea level. Prior to 1995, the more saline piezometer had a 2 m lower static water level than that in the deeper freshwater zone. Water levels rose in 1995, and again in 1997 to reach 7-9 m amsl (Fig. 4.21).

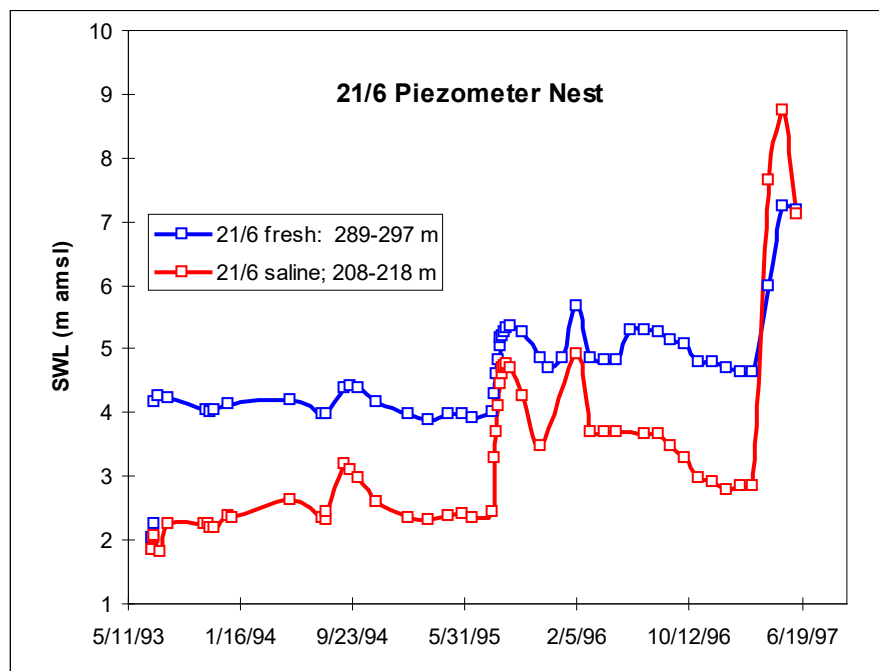


Fig. 4.21 Hydrographs of 21/6 Piezometer Nest

The response to the 1995, 1996 and 1997 recharge events are very pronounced throughout the aquifer. In 1995/96 levels rose 2.5 m in the saline zone and 1.5 m in the deeper freshwater zone. In 1997 however levels rose 6.5 m in the saline bore and about 4 m in the freshwater bore. During this event, the static water levels of the saline bore briefly surpassed those in the freshwater bore. The overall record shows while the recharge events are strongly felt across the aquifer, the saline zone is more sensitive to these events than the underlying freshwater zone. At these times there is a rapid decrease in the head differential commensurate with a downward expansion of the interface. The diminished head differential remained for almost a year. A second pressure pulse occurred in March 1997, when static water levels in the saline bore briefly exceeded those in the deeper bore.

This response at the lower interface between the saltwater wedge and the underlying fresh water is similar to that previously noted for the upper interface (Section 4.4.6), where the interfaces rises as pressures increase more rapidly in the saltwater zone than in the overlying freshwater zone. The inference from all the piezometer observations is that whenever recharge events occur, the manner in which the saline wedge reacts is to undergo a temporary bulge both upwards and downwards, with perhaps some retreat of the toe. That is, there is no simple coastward retreat of the wedge. Retreat of the wedge occurs only under extreme, and perhaps repeated, wet conditions, as observed over the period 1995 to 1997. This latter situation is shown by the RGS-5 nest (Fig. 4.13) from 1995-97, and the NC-1 nest (Fig. 4.20) in 1996-97.

Finally, it is important to again stress that the water levels are static water levels (*point water heads* of Luszczynski, 1961) and are not a true indicator of vertical hydraulic gradient. For this purpose *environmental water heads* must be calculated by taking into account the density of the saline water. The actual vertical head differences for hydraulic gradient purposes will be less than the differences measured in the bores.

4.5 Factors Influencing Seawater Intrusion.

While a more detailed assessment of the contributing factors is made in Section 5 - Water Balances - a summary is included here. Of all factors likely to effect the saltwater wedge, the following two are most readily understood.

4.5.1 Increased extraction on the Al Khawd Fan

With the increased recharge of about 4 Mm³ expected from the construction of the Al Khawd Dam, the Seeb and Al Khawd Dam Wellfields were refurbished with new wells constructed. Abstractions doubled over the period from 1984 to 1997, and are now more than 8 Mm³/yr.

4.5.2 Decreased Wadi Flow from the Samail Basin

Surface water flowing from the Samail catchment passes on to the coastal plain at Al Khawd where it recharges the aquifer between Al Khawd and the coast. An indication of the changes in usage within the upper catchment can be had by comparing the measured flows at the Al Khawd gauging station over the periods 1966 to 1980 which averaged 17.5 to 20.5 Mm³ (depending up on author). However, the average flow at Al Khawd from 1983 up to 1990 averaged just under 7 Mm³, and up to 1995 was about 5 Mm³. Only the highest flows (recorded in 1983 and in 1997) are close to that previously reported as being the average annual flow. The average annual surface flow passing the Al Khawd gauging station since 1984 - 4 to 5 Mm³ - is less than that

extracted from the Seeb/Al Khawd wellfield alone, let alone private extractions, PDO extractions and necessary losses to the sea to limit the seawater intrusion.

Explanations for the lower flows from 1983 are:

- * Data errors in the respective data sets - pre 1983 and post 1983
- * The pre-1983 data set is not truly representative of the pre-1983 wadi discharge
- * Decreased rainfall over the catchment after 1983.
- * Increased water usage within the Samail Basin over the past 15 years.

4.5.3 Interface Response to Climatic Cycles

The steady falls in the western piezometers (and water tables) of the Al Khawd Fan (Figs 4.4, 4.6-4.8), which echo similar trends occurring throughout the Eastern Batinah (Fig 4.5), are clearly due to abstractions, and perhaps decreased wadi flow over the last 15 years.. But no comparable falling trend is seen in the piezometers established in the eastern areas of the fan, nor has there been a comparable interface rise to that occurring at the RGS-5 site (Fig. 4.20) a little further west. It appears that additional factors buffer the eastern region against the processes seen elsewhere on the Batinah. The same factors have countered the incursion of the seawater intrusion, and up to now have protected the wellfields. The simplest explanation is that this occurs because of the development of strong intermediate and regional flow systems generated by a large catchment to fan ratio, together with the close proximity of the significantly elevated hinterland and its associated steeply sloping water table. In addition, covering much of the coastal plain there is the development of a regional groundwater discharge zone induced by the presence of the seawater intrusion. The high hydraulic heads present at the head of the fan are transmitted coastward and in turn create the strong vertical upwards gradients required for groundwater outflow at or near the coast.

The periodic waxing and waning of this deeper pressure system (with an amplitude measured at 6 m in the KWD-1 bore from 1983 to 1994) will clearly have a marked impact upon seawater intrusion. The periods of lower pressure will see the landward advance of the saltwater wedge, but this will be countered during the phases of higher pressure when the wedge retreats coastward.

An indication of the similarity between the pressure fluctuations observed in the OW-1 bore in the upper Al Khawd Fan and the freshwater/saltwater interface calculated from the RGS-5 nest in the lower Al Khawd Fan is given in Figures 4.22a and 4.22b Here the period between 1987 and 1992 is one where the interface rises slowly and almost levels out, only to rise more sharply from 1992 until 1995. In the OW-1 piezometer, water levels fall from 1987 to 1990, when they peak again prior to falling more steeply from 1991 to 1995, being steepest from 1992. The sharp rise in pressures seen in the OW-1 bore in 1995 and again in 1997 is reflected in a falling interface over this period.

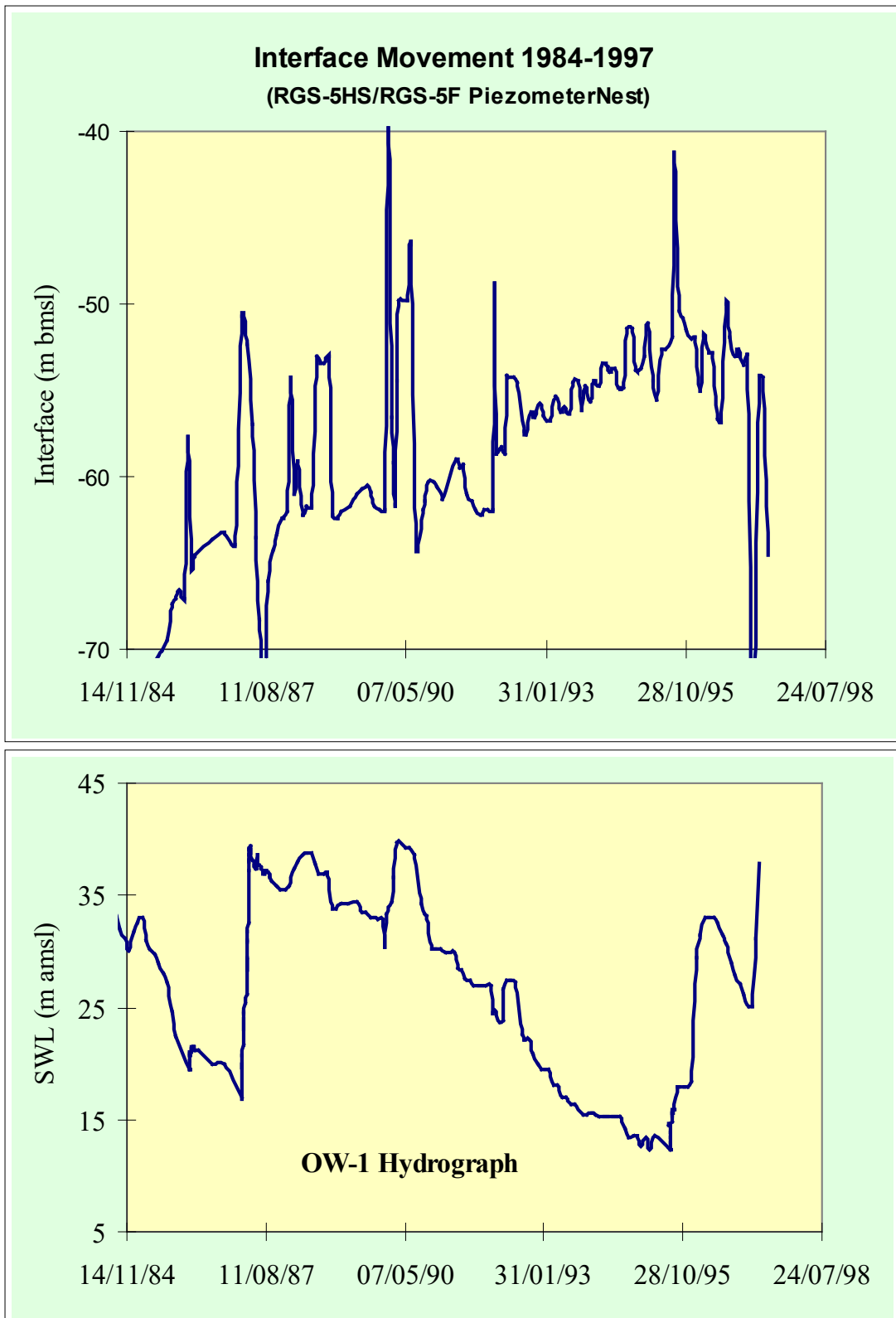


Fig. 4.22a and 4.22b. Hydrograph of OW-1 Bore and Saltwater Interface Fluctuation

4.5.4 Other Contributing Processes - Impact of the Sloping Water Table

A number of other important linked processes will also be varyingly active effecting the flow system and in turn, the interface movement. For instance, in the case of the Old Government

Wellfield, groundwater pumping is on a steeply sloping water table, which must induce a groundwater divide on the downbasin side of the wellfield (Fig. 4.23). Once established, all groundwater flow to the wellfield will come from upbasin. Groundwater pumping will not greatly effect other coastward bound groundwater flow coming from upbasin which passes outside and around the zone of capture created by the divide.

The extent to which this is the case with the other wellfields is not known, but in combination with the high groundwater pressures at depth, would help explain the stability seen in the flow system and in the interface downstream of the Al Khawd Dam. Major recharge events will change the situation, but only in an advantageous way, as the groundwater depression around the wellfields becomes a transient groundwater mound.

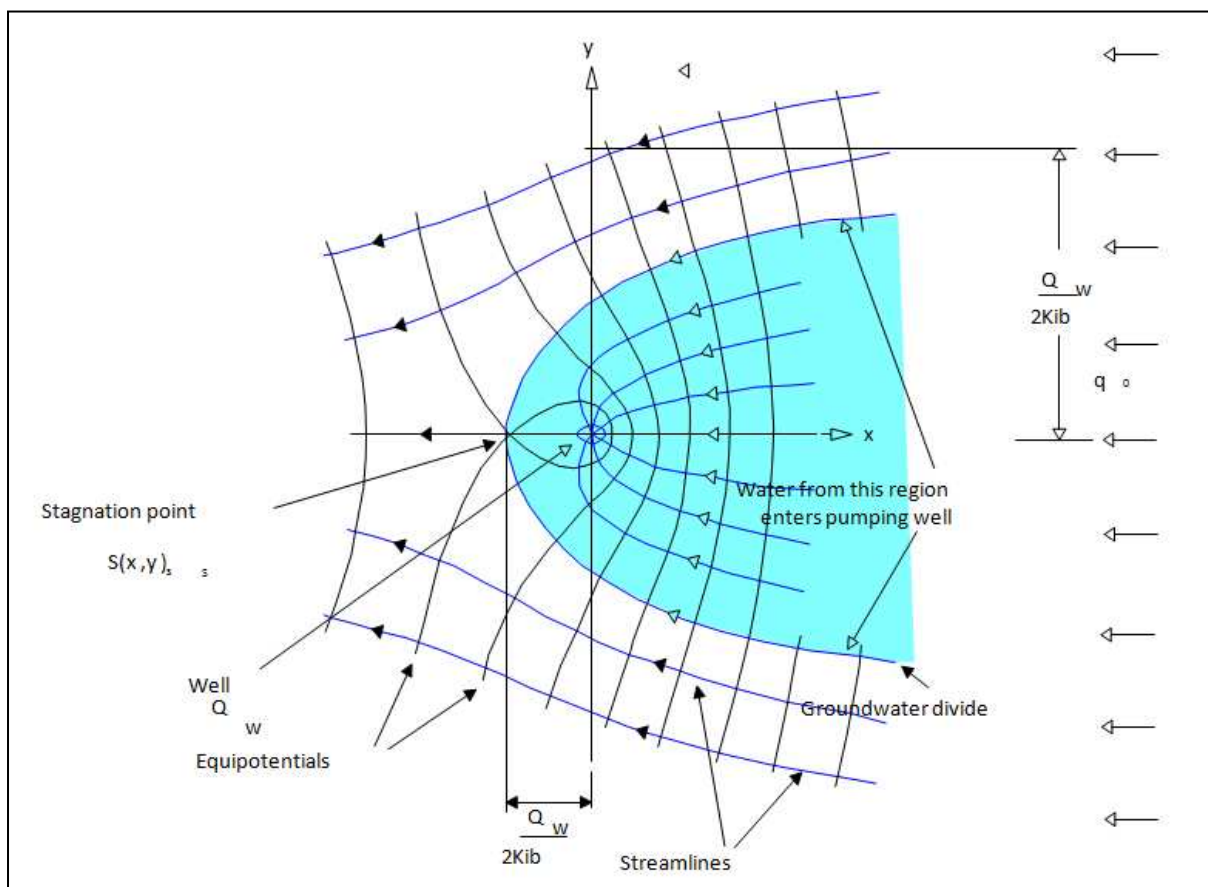


Fig. 4.23 Flow Net around a Single Bore Pumping on a Sloping Water Table in Uniform Flow (from Macumber, 1991, after Bear, 1979)

An example of the process is given for a large 26 km long salt lake (Lake Tyrrell, from Macumber, 1991) lying across the flow path in a semi-arid region of very gently sloping water table (Fig. 4.24). The lake is a discharge zone, dry and undergoing evaporative pumping for most of the year, and wet in winter. When dry, it behaves like a pump or wellfield straddling the sloping water table. Despite the low regional hydraulic gradient, a

groundwater divide has still formed, and **all** water entering the lake from both sides, comes from upbasin. A similar response would be expected from a wellfield as from the lake. At Lake Tyrrell, the position and elevation of the downbasin groundwater divide were established by drilling and piezometry.

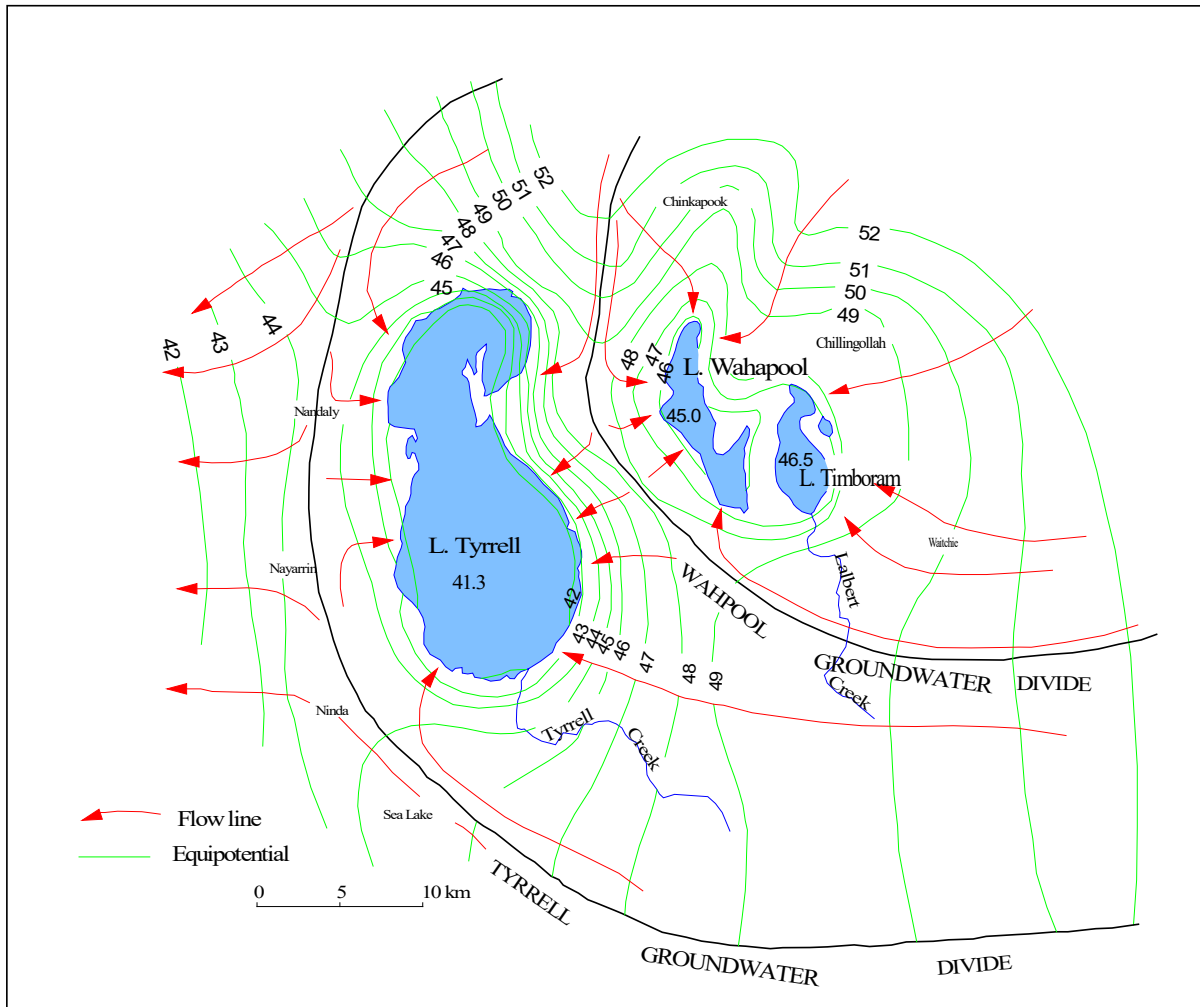


Fig. 4.24 Development of Groundwater Divides around Dry Lakes undergoing Evaporative Pumping (from Macumber, 1991)

Note that all groundwater entering the lakes on the downbasin side comes from upbasin..

5. WATER BALANCES ON THE AL KHAWD FAN - AN OVERVIEW

5.1 Wadi Flow at Al Khawd

Section 5.1 on Samail Wadi flow contribution to water budgets on the Al Khawd Fan is taken verbatim from the contribution by Macumber to the Samail Basin report of Bhatnagar and Macumber, 1997. It has also been included in this report as it summarizes the work of previous workers on inflows from upbasin on to the Al Khawd Fan.

5.1.1 Previous Work

Surface water passing from the Samail Basin via the Wadi Samail arrives eventually at the Al Khawd at the mouth of the Samail gorge. It arrives as -

- (a) baseflow passing into the lower Wadi Samail emanating from excess recharge over consumptive use within the basin. During the earlier years there was a strong seasonal pattern of lower base flow in summer but rising in winter in response to less usage and higher recharge within the basin.
- (b) flood flows - overland flow in response to high rainfall and runoff within the basin. The downstream impacts as floods, closely follow the rainfall event.

There have been a number of water balance studies on the lower Samail catchment to determine the surface input of water to the Al Khawd Fan. However, much of this data is derived from the reworking of earlier data, often without clear reference to this fact. One of the earliest work was that of Horn (1979) - Table 5.1.

Table 5.1 Total Surface Flow from Samail Basin arriving Al Khawd (Horn, 1979)

Year	Flood Flow (Mm ³)	Base Flow (Mm ³)
1974	0.3	2.9
1975	4.7	0.9
1976	32.4	14.7
1977	(20.5)	10.6
1978	6.7	4.2
Average	12.9	6.7

Additional data on the total surface flow (base flow and flood flow) exiting the Samail Basin as measured at Al Khawd is given in Table 5.2

5.1.2 Base Flows at Al Khawd

In an early work, Gibb (1974), put the average annual base flow at Al Khawd as being 14 Mm³. Horn, (1979) suggested that this should be reduced by 25% to cater for velocity factors associated with the form of flow measurement. This would reduce the base flow to about 10.5 Mm³. Horn's study, based on the five years 1974-78, puts the base flow (without underflow) at 6.7 Mm³ (Table 5.1).

Table 5.2 Total surface flow in Wadi Samail at Al Khawd (Mm³)

Year	Surface (a)	Flow (b)	Composite Flow	Flood Flow	Total_Flow Flood + Base
1966	7.4	9.65	10.4	*	
1967	3.5	4.23	6.5	*	*
1968	16.7	16.95	19.7	*	*
1969	9.8	9.47	12.8	*	*
1970	2.2	2.02	4.2	*	*
1971	0.8	0.39	2.3	*	*
1972	16.7	17.76	19.7	*	*
1973	13.3	15.66	16.3	*	*
1974	2.9	3.09	5.5	0.3	5.8
1975	1.4	2.88	3.4	4.7	8.1
1976	14.7	12.94	17.7	32.4	50.1
1977	10.6		13.6	20.9	34.1
1978	4.2		7.2	6.7	13.9
Mean	8.0	8.6	10.7		

(a) PC&R (1980)

(b) Hydroconsult (1978) * not available

The various attempts at providing base flow at Al Khawd are given in Table 5.3. The estimate of the base flow component of the Wadi Samail flow made by MMP/ Preece, Cardew & Rider (1980) - Table 5.3, without underflow is 8 Mm³. Hydroconsult (1978) disregard all flows above 1 m³/s as not contributing to base flow. The mean average annual base flow they put at 8.6 Mm³ (the median value is 8.5 Mm³).

Table 5.3 Base flow at Al Khawd exiting the Samail Basin (Mm³)

	Gibb	FAO	MPP	Hydro- consult*	Hydro- consult**	PCR
Base Flow + underflow	15.9	9.7	10.4	10.4	8.6	10.7
- ignoring underflow	-	6.7	-	-	-	8.0

Gibb- (1976); FAO - Horn (1979); MPP (1980); Hydroconsult (1986)*; (1978)**
PC&R (1980)

5.1.3 Flood Flows

Average flood flows including losses to the sea are documented in Table 5.4 taken from FAO field document 10.

Table 5.4 Flood Flows and Losses to the Sea 1974 - 1979

Year	Flood Flow (Mm ³)	Loss to Sea (Mm ³)	Recharge (Mm ³)
74-77	14.5	5.3	9.2
77-79	15.2	4.2	11.0

The flood flows involved in discrete flow events are provided in the study of flood flows from the Wadi Samail -1974 to 1978, by Horn & Nielson (1978) - Table 5.5.

Table 5.5 - Peak flood flows at Al Khawd - Mm³ (Horn & Nielson (1978))

1974	19 Feb.	0.01		1976	4 Aug.	0.91
	4 Oct.	0.27			14 Aug.	0.63
1975	10 Feb.	4.73			16 Sept.	0.78
1976	2 Jan	0.26			13 Oct.	0.82
	30 Jan	0.43		1977	24 Jan	6.00
	6 Feb.	4.07			26 Feb.	6.00
	10 Feb.	1.53			27 May	2.9
	13 Mar	0.55			19 Nov.	3.00
	22 Mar	1.03			21 Nov.	0.32
	27 Mar	5.91			28 Nov.	2.7
	10 Apr.	16.36		1978	13 Feb.	0.13
	14 Apr.	0.34			27 Feb.	0.15
	23 Apr.	0.73			11 Mar	6.60

These values are essentially the same as the flood flows given by PC&R (above); the latter are derived from Horn (1979 - Table 5.5, above), who gives an average annual flood flow over the period of 13 Mm³

Hydroconsult estimated that the average flow (flood and base flow) passing to the Batinah from the Samail Basin at 20.8 Mm³ containing a flood component of 10.4 Mm³ and baseflow component of 10.4 Mm³. Here again, an average flow is almost a misnomer given its variability and extreme values. (Ref. Prelim Studies for Recharge Schemes. Hydroconsult Feb. 1986. Vol. 8 p.1-9; Table 3). Individual floods ranged in size from about 1 to 20 Mm³, with the frequency of flood flows of the order of 20 Mm³ estimated at about 1 in 33 years. On the basis of the above data, the flood flows passing from the Samail Basin average about 10 Mm³ to 13 Mm³ per year over the measured periods.

5.1.4 Water Flows at Al Khawd upto 1980 - Summary

A review of the literature upto 1986, based on data upto about 1980 shows that individual water balances based on a wide variety of studies give an equally wide range for individual flow components. However, despite differences, there is some broad agreement, at least at discrete points along the system. The data is summarized in **Tables 5.6**. On the basis of the above studies, average flows to the Batinah were put at about 7 to 8 Mm³ base flow and 10.5 to 12.5

flood flow, giving a range from 17.5 upto 20.5 Mm³ for total surface flow. Clearly, the best estimates of the water passing between the upper catchment and the coastal plain comes from the direct measurements taken at the Al Khawd gauging station. This station has perhaps the longest record of any station on the Batinah. Even so, the relatively short time span for which earlier measurements were been made, and the very wide temporal and volumetric ranges concerned, when coupled with the impacts of antecedent conditions within the upper catchment all go to make analysis of flows, and the statistical inferences drawn about their size and frequency of annual flows, somewhat tentative.

Table 5.6 Water arriving at Al Khawd (average Mm³)

Base Flow	6.7 - 8
Flood Flow	10.0 - 12.5
Total	16.7 - 21.2

5.1.5 Flow at Al Khawd Gauging Station - 1983 to present

An analysis of more recent data from the gauging station at Al Khawd over the period 1983 to 1996 provides a significantly different picture to that previously observed. Here the average flow is only 5.1 Mm³. This is very much lower than the previous values of 16.7 to 21.2 Mm³. Only the highest value in 1983 is close to that previously reported as being the average annual flow. The average flow (base and flood) passing Al Khawd since the construction of the Al Khawd dam is therefore little more than the 4 Mm³, shown as lost to the coast in earlier analyses (**Table 5.7**).

Table 5.7 Surface Water Flow at Al Khawd - 1983 to 1996

Year	Total Flow (Mm ³)
1983	21.74
1984	0.99
1985	0.66
1986	0.60
1987	13.00
1988	5.78
1989	5.55
1990	7.11
1991	1.29
1992	1.57
1993	0.42
1994	1.78
1995	7.60
1996	3.57
Average 1983-1996	5.12

5.1.6 Possible explanations for the more recent low flows are:

- a. Data errors in the earlier data sets, or in their extrapolation to represent a longer term situation.
- b. Increased water usage within the Samail Basin over the last decade
- c. A significant decrease in rainfall over the catchment after 1983.

Of these possibilities, there is no evidence of a significant decrease in rainfall over the period in question, and it seems likely that the best explanation is a combination of increased water usage, and perhaps extrapolation from a limited data set. Indeed, the total average annual flow arriving at the Al Khawd gauge is little more than the increased extractions from the Seeb-Al Khawd wellfields alone since 1988 (total extractions have doubled and now exceed 8 Mm³), let alone private extractions, PDO extractions and the necessary losses to the sea to limit the seawater intrusion (Macumber - 1992) calculated as being in 1991 about 5 Mm³ across the full width of the Al Khawd coastal strip. The calculation for groundwater flow required to balance the seawater intrusion is given below.

5.2 Recharge from Precipitation on the Al Khawd Fan

The boundaries of the main surface water catchments of Al Khawd Fan were subdivided by Morgan et al. (1994) into Wadis Samail, Ma'abilah and Hayl, however as they note, "the topographic relief is low, and it is very difficult to distinguish between the three main catchment boundaries. The respective catchment areas and recharge estimates are given in Table 5.8

Table 5.8 Catchment Areas, Rainfall and Initial Estimates of Aquifer Recharge (Modified from Morgan et al., 1994)

Al Khawd Fan Sub-Catchments	Area (km ²)	Estimated Rainfall Volume (Mm ³ /y)	Estimated Aquifer Recharge (1) (Mm ³ /y)	Estimated Aquifer Recharge (2) (Mm ³ /y)
Wadi Samail	60	4.8	0.24	0.48
Wadi Hayl	34	2.7	0.14	0.27
Wadi Ma'abilah	87	7	0.35	0.7
TOTAL	187	14.5	0.73	1.45

- (1) Aquifer recharge = 15% on hard rock and 5% on soft rock
- (2) Aquifer recharge = 35% on hard rock and 10% on soft rock

5.3 Water Loss on the Al Khawd Fan

5.3.1 Irrigation Extractions

Significant groundwater extraction occurs from the alluvial aquifers of the Al Khawd Fan, both privately to irrigate the date palm plantations on the Batinah, nearer the coast, and to provide additional backup to the Muscat municipal water supply. Estimates by Gibb (1974) based on village surveys, were that about 13 Mm³. year of groundwater were being extracted from the Al Khawd Fan, from over 400 pumped wells alone, near Seeb. He further noted that

(1974 - Water Resources Survey of Northern Oman Interim Report 1, p 22) that in a 22 km coastal section centred on the Al Khawd Fan, there were 1100 hand dug wells, 600 fitted with pumps.

For the purpose of a water balance, the present net extraction from domestic wells on the Al Khawd Fan is put at 15 Mm³/annum, however this is purely a speculative figure, and assumed to be highly conservative, given Gibb's earlier estimate. It is adopted in this report not as a definitive number, but instead as a minimum value, mainly to emphasize the gross imbalance, even given a low estimate for irrigation usage.

5.3.2 Wellfield Extractions

In Gibb's 1974 survey extractions from discrete wellfields - Government and PDO, were put at 1.3 Mm³ at the time. This gradually rose to about 3.0 Mm³/year in 1983. Following the completion of the Al Khawd dam in 1985, a revamped Seeb/Al Khawd wellfield with additional wells began operation. The total extraction from all wellfields was 6.6 Mm³ in 1990, with a gradual increase to 6.4 Mm³ in 1991. It is now about 9 Mm³ of which over 8 Mm³ come from the three Government Wellfields

5.4 Coastal Outflow

In coastal aquifer systems, the inland movement of the seawater intrusion is balanced by a coastward flow of freshwater, which discharges in a zone of regional groundwater outflow, at or near the coast. The outflowing groundwater is normally lost to the sea often after it merges with the seawater in a transition zone of mixed freshwater and seawater. This is most clearly seen the case of Wadi Dayqah, where there is a measured annual freshwater loss of 16 Mm³/year from the wadi, into the aquifer, and then towards the sea, about 4 km away. Despite this flow, there are no freshwater springs along the coast, but instead there occur only brackish to saline springs of mixed freshwater and seawater composition.

The approach to calculating the coastal outflow is based on the existence of a relationship between the rate of fresh water discharge to the sea and the extent of the saline intrusion. Bear (1979) comments in his introduction to chapter *Fresh water - Salt water interface in Coastal Aquifers* "This (relationship) makes sea water encroachment a management problem as the fresh water discharge to the sea is the rate of natural and artificial discharge and that of pumping". The analytical approach adopted here to calculate fresh groundwater flow to the sea, is the use of Glover's Equation.

5.4.1 Use of Glover's Equation for Seawater Intrusion

Glover (1964) developed an approximation for the shape of the seawater-freshwater interface within an aquifer which expresses a relationship between groundwater flow at the coast (Q m³/m/d), hydraulic conductivity, distance inland to measurement point, interface depth and groundwater density.

$$z^2 = 2 Q \rho_f x / K (\rho_s - \rho_f) + \rho^2 Q^2 / K^2 (\rho_s - \rho_f)^2$$

where:

z = the depth to the interface

Q = flow in aquifer per unit length of coastline (m³/m/d)

K = hydraulic conductivity of the aquifer (m/d)

x = the distance inland at which the depth to Z is measured

ρ_s = the saltwater density (taken as 1.025 gm/cm^3)

ρ = freshwater density (taken as 1.00 gm/cm^3)

In cases where Glover's equation is normally used to determine the position of the interface, it is necessary to have values for Q and K to find Z and x . There is, however, already a vast amount of data on the position of the saltwater wedge - depth (Z), and inland extent (x) - in a number of bores, provided by previous workers, especially Bhatnagar and Ravenscroft (1986) in their comprehensive study of the hydrogeology of the Al Khawd Fan. A value for hydraulic conductivity (K) is also given by Bhatnagar and Ravenscroft of 34 m/d (obtained from MMP - 1985) as the average in the upper part of the aquifer (to 150 m depth).

With the position of the interface already obtained, then the only unknown parameter is outflow to the sea (Q). Values for this can be readily found by substitution of the known parameters for each established interface in the various bores where it has been determined. While there may be some doubt as to the veracity of interfaces in some bores, it nevertheless gives an important estimate of coastal outflow. It is worth noting that for interfaces, the respective bores are coastward of the various wellfields.

5.4.2 Examples from RGS-2U and KWD-4 Bores

In the cases of sharp interfaces such as occur in the Khawd 4 and RGS-2U piezometers, and substituting values for Z , x and K , it leaves only Q as the unknown, and this can be readily calculated. For example, the RGS-2U piezometer has an interface at 105 m and is 4.5 km from the coast. The KWD-4 piezometer has an interface at 85 m and is situated 3.0 km from the coast.

Using the data from the RGS-2U bore, and substituting values of $K = 34$; $z = 104$ and $x = 4,500 \text{ m}$ gives a value of about $1.0 \text{ m}^3/\text{d}$ for Q . That is, about 1 m^3 of water passes to the sea via the groundwater systems.

If outflow is uniform, then the value of $1.0 \text{ m}^3/\text{d/m}$ for Q should be similar in those cases where similar values for aquifer characteristics, such as hydraulic conductivity, exist. In this situation, by substituting the value for outflow derived from the RGS-2U interface back into Glover's equation, the depth to the interface can be back-calculated for a bore situated, say, 3 km from the coast. This may be the case for the KWD-4 bore where the depth to the interface calculated by using outflow data from the RGS-2U bore is 85m , which is the same as that observed in the KWD-4 bore (Bhatnagar and Ravenscroft, 1986). The results suggest a degree of uniformity in the aquifer, at least to depths of 105 m in that region of the fan covered by the RGS-2U and KWD 4 bores.

5.4.3 Application to other Measured Interfaces on the Al Khawd Fan

While this value of coastal outflow is based only on an initial examination of the data, the methodology is simple, and provides perhaps the best estimate of the coastal outflow yet attained. A similar approach was adopted to cover the range of interfaces previously observed in order to obtain a range of outflow values. Differences in outflow to those occurring for KWD-4 and RGS-2 will reflect the variability of hydraulic conductivity across the Fan, and probably the validity of the interface depth observed within the borehole. The latter, as previously observed, is not always a true guide to the actual interface position in the aquifer, so individual results must be treated with some reserve and accepted only as a guide.

An indication of the variability of outflow in each instance is given in the plot (Fig. 5.1) of *flow versus hydraulic conductivity (K)* for bores with measured interfaces.

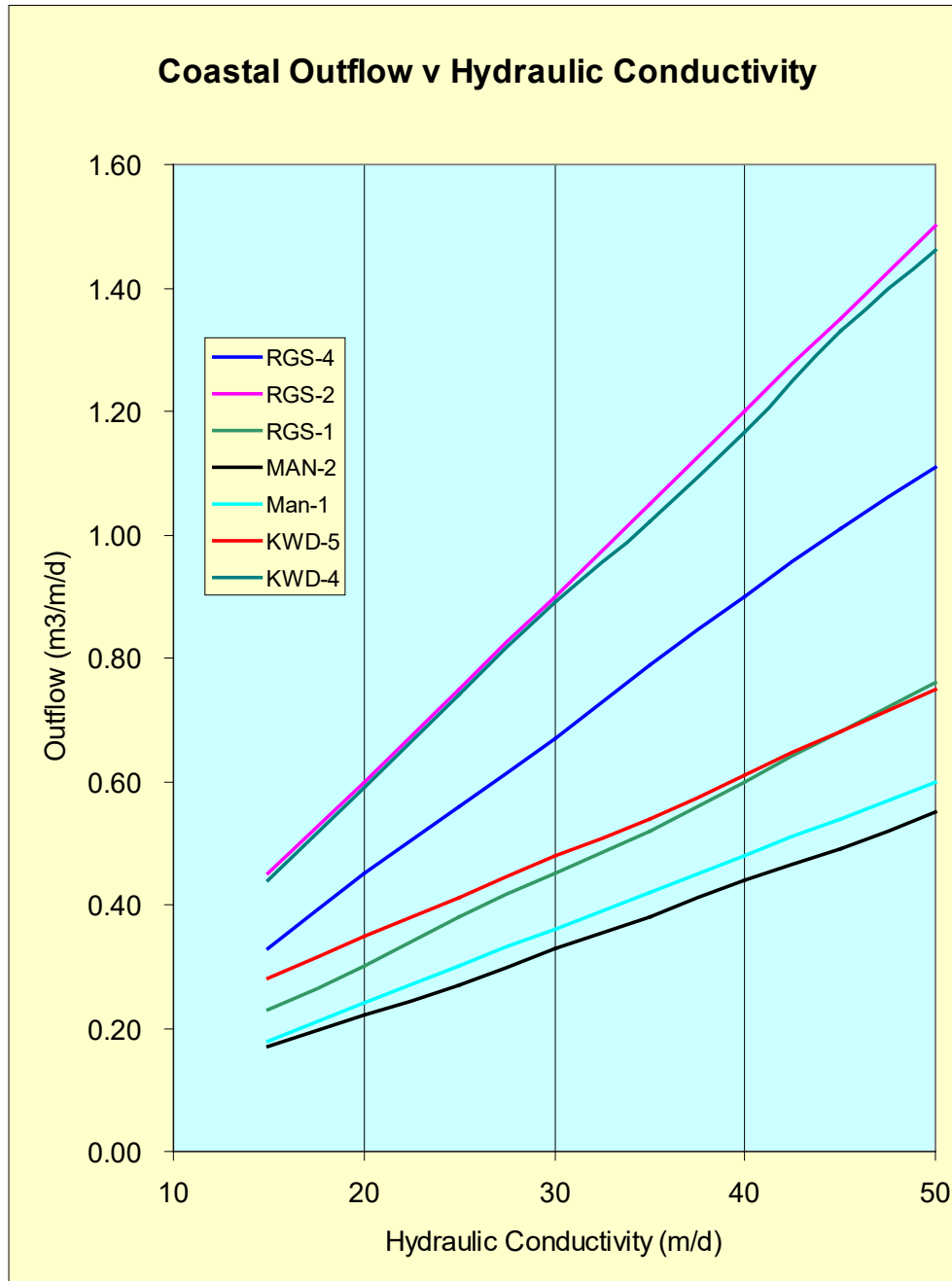


Fig. 5. 1 Coastal Flow Versus Hydraulic Conductivity, for Various Interfaces.

With an average value for hydraulic conductivity taken as 34 m/d, then a range of outflows occurs from about 0.3 to 1.02 m³/d/m, with an average outflow of about 0.65 m³/d/m.

Where a broader range of hydraulic conductivities is chosen, say from 40 m³/d/m to 20 m³/d/m, then the total range for **all** measured interfaces is from about 1.2 m³/d/m down to 0.2 m³/d/m, and averaging about 0.7 m³/d/m.

The figure suggests that for any given value of K, coastal outflows indicated by saltwater-freshwater interfaces are lower in the western areas of the fan (Man-1 and Man-2), than those occurring further east. Similarly the more southerly RGS-2U and KWD-4 piezometers indicate a higher coastal flow for any given value of hydraulic conductivity, than their more coastal equivalents, RGS-4 and KWD-5. The data from Fig. 5.1 suggests that the average outflow along the Batinah coastline ranges between 1.1 and 0.3 m³/d/m (say averaging 0.65 to 0.7 m³/d/m), giving an overall outflow over the 20 km of coastline of about 4.7 to 5 Mm³/yr. This is approximately the same amount as the annual wadi flow from the Samail catchment, at least since 1984.

5.5 Summary

A summary of the above water balance components is given in Table 5.9

Table 5.9 Estimated Water Balance on Al Khawd Fan

<u>Input</u>	Mm ³ /year
Flow at Al Khawd (measured)	5
Precipitation on the Fan (measured)	1
Groundwater	?
Seawater	1
Total Input	7 - not including groundwater
<u>Output</u>	
Wellfields (measured)	9
Groundwater flow to sea (calculated)	5
Net domestic usage (estimated)	15
Total Output	29 including groundwater
<u>Deficit</u> (attributed to groundwater)	22

Of note is that surface flow is less than that extracted annually by the Seeb/Al Khawd/PDO/ Old Government Wellfields, taken as 9 Mm³. On this basis it appears that the principle wellfields and coastal outflow, together consume more than twice the average annual wadi inflow from upbasin.

In addition there is an annual domestic usage for irrigation of date palms etc which must lie in the vicinity of 15 to 20+ Mm³, alone. In the above balance, a minimal value is taken for the irrigation usage. Whatever the domestic irrigation usage, it is clear that surface flows, even with added coastal precipitation, provides only a minor part of the total inputs into the alluvial aquifers of the coastal plain.

While there is some inland interface movement, especially in the west, it is not such as would occur if the imbalance between surface water inputs and extractions/outflow were real. That is, there must be a major recharge to the Batinah from an alternative groundwater source(s), which

by default, is almost certainly the fractured rock aquifer system developed in the ophiolites at southern limits of the Al Khawd Fan.

This fact was recognized during the earlier 1992 study of the Al Khawd Fan (Macumber, 1992), in which there was a PDO groundwater modelling input (not included in the text, but incorporated in to the conclusions). Using the data of Bhatnagar and Ravenscroft and the surface inflow data from pre and post 1983 Al Khawd wadi flow, the result was: “the model shows that a very much larger coastal area should be below zero water table in 1985, and therefore predicts a significantly more severe salinization problem than was in fact occurring”. Only by boosting the surface inflow and by decreasing the coastal extractions could a satisfactory result be obtained commensurate with the Bhatnagar and Ravenscroft water table data.

Conclusion 2 of the 1992 Report stated “ Although no water balance was carried out, it is clear that the present recharge from the wadi Samail Catchment cannot provide the extractions now occurring on the fan. An additional significant resource is indicated, possibly from the ophiolite fractured rock system bordering the Batinah to the south.”

5.6 Water Balance - Conclusion

The water balance components are summarized in **Table 5.9**, however, it is stressed that this is at best an estimate and its gross accuracy largely dependent on the value (minimum guesstimate in the Table) for domestic irrigation extractions. This was put at about 13 Mm³ by Gibb (1976), however there must be strong doubt about present day (1997) extractions.

Largely because of the uncertainties, especially the total domestic irrigation abstractions, a fully acceptable water balance for the Al Khawd Coastal Plain is yet to be carried out. However it is clear that whatever the domestic extractions, the contribution from the groundwater system emanating from the upbasin basement catchment must be the dominant component of the water balance.

Groundwater inflow to the Al Khawd Fan from the basement rock aquifer would not be constrained by the present surface catchment boundaries, but probably includes intercatchment flow from the upper bedrock areas of the neighbouring Russayl and Taww catchments.

6. CONCLUSIONS

1. On the Al Khawd Fan, local, intermediate and regional flow systems are present. The local flow systems are short term and create a 'spikey' hydrograph response to large and small wadi flow events. Intermediate and regional flow systems are always present and wax and wane in response to climatic variability and aquifer saturation; they provide the basis for 'saw-tooth' pressure cycles occurring within the aquifer.
2. The water balances on the Al Khawd Fan point to the major input to the alluvial aquifer system as coming from the basement (ophiolite) aquifer to the south.
3. The surface water component that recharges the alluvial aquifer, mainly as flood flow, provides less than one third of the total recharge to the Al Khawd Fan aquifer.
4. The average total annual flow of Wadi Samail of about 5.1 Mm^3 (average 1983 to 1996) at Al Khawd, is significantly less than the 17 to 21 Mm^3 calculated as occurring prior to 1984.
5. The original assumption of an annual loss to the sea of 4 Mm^3 used as a basis for the construction of the Al Khawd Dam, if previously valid is no longer so, and increased groundwater usage cannot be based on recovering this earlier supposed loss.
6. The increased extraction from the Seeb and Al Khawd Dam Wellfields, which has doubled since 1983 from 3 Mm^3 to 8 Mm^3 , is catered for by increased use of the regional groundwater, not from a savings of flood losses to the sea. The groundwater availability is greatly enhanced by the steep hydraulic gradient at the head of the fan.
7. Seawater intrusion into the Al Khawd Fan is greatest in the western parts of the fan where the saltwater interface has gradually risen (Fig. 4.7 and Fig. 4.13). This was temporarily reversed following the 1995-97 wet period. In the northeastern areas of the lower Wadi Samail, a low groundwater mound is permanently present (Figs. 4.10 and 4.11) and advances of the saltwater wedge over the last decade have been only slight (Fig. 4.5 and Fig. 4.20).
8. Seawater intrusion into the Al Khawd Fan is significantly less than might be expected, given the wellfield and private irrigation extractions. The inflow of seawater into the coastal aquifers is countered by strong vertical flow gradients generated upbasin by the presence of strongly developed regional and intermediate flow systems.
9. While affected by groundwater extractions, the overall movement of the saltwater wedge into the Al Khawd Fan is more in sympathy with longer-term cycles (5 to 10 yr.) of high and low pressure generated within the regional and intermediate flow systems. Pressure heads at 300 m depth in the coastal plain can range vertically over 5 m, and may reach as high as 10 m above sea level, yet overlying water tables remains close to sea level. Under low pressure regimes the seawater intrusion advances, but is paused or retreats once the high pressure regime reappears.
10. The periodicity of the cycles in the aquifer pressures is not due solely to climatic cyclicity, but depends also upon the intervals between discrete rainfall events. Where large events appear close together as in 1987 and 1990, they maintain the high stage of the cycle. During the following prolonged dry period the aquifer pressures slowly fall until a further wet period ushers in a new cycle. In this case, the initial cycle consists of two wet events and a long dry period. This accounts for the prolonged cycle in Al Khawd from 1987 to 1996. An important factor affecting this relationship, is the extent of aquifer saturation, whereby once the aquifer is full, additional rain, even smaller amounts, only reinforces the long high level or plateau period prior to the drying phase of the cycle. This factor is largely determined by the geomorphology of the landscape, more specifically the level of the wadi channels responsible for recharge.

11. The tripartite division of Gibb (1976) is at best a gross generalization, and does not hold for most of the Al Khawd Fan, where the permeability of the aquifer is reduced by the largely random groundwater diagenetic alteration of ophiolitic gravel to give dolomite. Dolomitic development is best seen in the vicinity of the Old Government Wellfield, but is found throughout the alluvial sequences of the Al Khawd Fan. While commonly found at depth in the aquifer, dolomitization is found throughout the alluvial sequence, randomly alternating with non-dolomitized or partially dolomitized sections. Aquifer permeability will show a similar vertical variability.
12. While dolomitization leads to plugging of the aquifers and a greatly decreased primary porosity, this is at times compensated for by the development of secondary porosity, caused by joints, fissures, cavities etc which then become an alternative pathway for groundwater movement, as seen in SAG-13.
13. While dolomitization is best recorded in the vicinity of the Old Government Wellfield developed on the oldest Terrace 1, the terrace as a whole is not all similarly dolomitized, and no generalizations can be made as to its overall transmissivity. The PDO Wellfield attests to high yields, while the DP-2 bore in the middle of the old Terrace 1, and UG-1 bore on Terrace 2 shows little evidence of dolomitization and have relatively high transmissivities.

7 RECOMMENDATION

The above study is an initial attempt to disentangle the various components making up the groundwater flow system on the Al Khawd Fan. While, hydrograph analysis, together with limited hydrochemistry, provide some understanding, this is largely concerned with the local and intermediate flow systems. It is suggested therefore that a more detailed study based largely on hydrochemistry and isotopes, be carried out to better determine the character of the regional flow system, which must provide the bulk of the groundwater in the coastal plain alluvial aquifer.

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