DRILLING AND AQUIFER TESTING PROJECT IN THE NORTHERN AL MASSARAT

EXECUTIVE SUMMARY

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For

The Ministry of Regional Municipalities, Environment and Water Resources

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A drilling and testing program was designed by MRMEWR to investigate the Northern Al Massarat area of the Sultanate of Oman, close to the border with the UAE. The aims of this Project were as follows:

- Explore, locate and access the potential of shallow and deep aquifers.
- Carry out investigations to provide detailed hydrogeological data at key sites to support assessment and/or development priorities.
- Establish monitoring facilities.

The Consultants for this Project were Geo Resources Consultancy (GRC). Lalbuksh Voltas Engineering Services and Trading LLC (Lalbuksh) were awarded the drilling and testing contract for this Project. The field work was scheduled to be completed over the period 1 October 2005 to 24 April 2006. In the event, it was all completed by 27 March 2006.

In September 2005 GRC issued a manual to Lalbuksh and MRMEWR (Procedures for Wellsite Geologists) detailing the objectives of the Project, the location of drilling sites, drilling and testing procedures, and the information that was to be recorded during the Project.

In October 2005 GRC submitted an Inception Report to MRMEWR. This provided an overview of existing reports and background information on the hydrology, geology and hydrogeology of the Project Area. This overview included maps showing the location of existing boreholes, and a preliminary analysis of the yield and salinity distribution of these boreholes, a review of borehole designs and drilling locations, and a refinement of Project objectives.

The Project Area comprised lower part of five catchments (Wadis Ajran, Saifah, Sharri, Al Fatah and Dank) which occupy an area of approximately 5,075 km^2 (**Figure 1**). This area is bounded on the west by the United Arab Emirates (UAE) and on the east by the Oman Mountains (Jabal Al Gharbi). The study area consists of a stony alluvial plain that extends from the piedmont to the UAE border. Near the international border the alluvium is partly covered by sand dunes. Average rainfall ranges from 175 mm/yr in the mountains to 50 mm/yr west of As Sunaymah. The three wettest months occur over the period February to April when 50% of the total rainfall is precipitated.

Eight exploration/observation boreholes and four test production boreholes were drilled in the Project Area. In addition, two replacement production boreholes were drilled to the south of this area in the Bu'Bukhara and Al Massarat Wellfields. Summary details of the boreholes drilled under the Al Massarat Contract are shown in **Table 5**. **Figure 7** shows the location of these boreholes. Comprehensive data for these boreholes is presented in **Appendices 1** and **2**.

The recognition of different geological formations, the correct identification of formation contacts, the detection of different aquifer units, and the measurement of hydrogeological characteristics were the main priorities of the field work undertaken during this Project. Formations of interest were the Upper and Middle Fars Group sediments. These Neogene aged sediments comprise the following:

- **The Upper Fars Formation**. The top of the Upper Fars comprises dolomite, dolomitically cemented conglomerate, chalky limestone, and thin interbedded siltstone. Sometimes this formation is referred to as the 'Upper Conglomeritic Fars' due to the prevalence of conglomerates. The base of the Upper Fars aquifer is usually marked by the presence of a reddish brown mudstone or siltstone, varying in thickness between 5 and 30 m.
- **The Middle Fars Formation**. The top of this formation is similar to the base of the Upper Fars. It comprises dark reddish brown siltstone and mudstone/ claystone. Thin, variably cemented gravels, are interbedded with these sediments. A change in the colour of the siltstones and

mudstones marks the formation contact and appears to denote a change to a more reducing environment. In the Project Area these formations were more argillaceous than the Upper Fars. At depth this formation grades into grey shale and evaporates. This formation is sometimes referred to as the 'Fars Group Evaporites'.

The main drilling targets of this Project were aquifers located in the Upper Fars Group.

The geological structure of the Project Area was examined and a map showing the base of the Upper Fars Formation was created (**Figure 15**). This shows the Upper Fars dips uniformly in a west-south-westerly direction towards the international border with the UAE, at a gradient similar to the surface contours.

A west to east geological cross-section was drawn through Wadi Dank (**Figure 16**). This section indicates that the Upper Fars has a fairly uniform thickness of ~230 m in this wadi. The base of this formation parallels the ground surface and is underlain by a thick sequence of Middle and Lower Fars sediments. Hadhramaut carbonates dip towards the south-west, beneath the Fars Group. A north to south cross-section through the Project Area suggests that the Upper Fars also has a fairly uniform thickness across the majority of Project catchments. Although the thickness of the Upper Fars is fairly uniform, the lithology across the Project Area is highly variable.

The geologic structure of the Project Area was examined with the aid of geological maps and ETM Landsat imagery. It was concluded that faults occur in all pre-Neogene rocks (> 24 Ma), located to the east and below the Fars Group, but not in the Fars Group itself. In the north eastern part of the Project Area, faults occur in the Hadhraumaut jabals and these can be expected to extend right across the upper part of the Project Area. The significance of these faults is that they provide potential pathways for groundwater to recharge the Fars Group sediments.

During the Project seven boreholes were logged by the Technical Survey Section of the Water Resources Assessment Department of MRMEWR. From an examination of these geophysical logs it was concluded that the Upper/ Middle Fars contact was difficult to recognise but that careful examination could elicit a few distinguishable features including: an increase in gamma values; an increase in 64" resistivity values; and, divergence of the 16" and 64" resistivity. The alluvium/ Upper Fars contact could sometimes be identified by an increase in resistivity and decrease in gamma values.

The Technical Survey Section also undertook a detailed survey of the boreholes drilled during this Project.

In the Project Area three formations were cut: Quaternary alluvium and Neogene-aged Fars Group sediments. In the area investigated by Project boreholes the alluvium ranged in thickness between 0 and 12 metres and in each borehole this sequence was dry.

The Upper Fars ranged in thickness between 217 m and 246 m and averaged 230 m. However, the thickness of the aquifers within this formation was only a fraction (26 m) of the total thickness. The yield of boreholes completed in the Upper Fars ranged from 1.0 to 42.1 L/sec and averaged 17.9 L/sec. The final EC of the water obtained during development and pumping tests of boreholes completed in the Upper Fars ranged from 1,158 to 18,410 µS/cm and averaged 6,532 µS/cm

The top of the Middle Fars was investigated by Project boreholes. During drilling only two boreholes produced slight increases (< 2.3 L/sec) in yield from Middle Fars sediments suggesting that this formation has poorly developed aquifers. The yield of one borehole completed in these sediments was 0.1 L/sec. During drilling, the EC of the Middle Fars aquifers ranged from 3,332 µS/cm to 20,100 µS/cm.

An examination of the yield of Project and Pre-Project boreholes (**Figure 21**) suggests that relatively high and low yielding boreholes are fairly randomly distributed, i.e. there is no particular area where preference might be given to the location of a wellfield based on yield. Rather, it was the borehole diameter and length of screen that was of greater significance in determining final yield.

An examination of depth-yield data revealed that the Upper Fars yields water in discrete intervals. In the majority of boreholes it was found that at least four distinct aquifer zones, separated by aquitards, could be distinguished. The total thickness of these four aquifers ranged from 14 m to 67 m and averaged 26 m.

Pumping and aquifer tests were carried out to determine the yield and performance characteristics of the test boreholes and aquifer characteristics (transmissivity and storativity) of the Upper Fars aquifers. These tests comprised an initial calibration test, a step drawdown test, a constant rate discharge test and a recovery test. In general, the step-test data suggests that low yielding but efficient boreholes can be expected to result from the development of aquifers in the Upper Fars. The aquifer tests were carried out at six test sites. These data showed that the Transmissivity (T) and Storage Coefficient (S) varies significantly from site to site. The mean of these two aquifer characteristics are approximately 120 m^2/day and 0.001, respectively.

The aquifer response observed during the analysis of these tests indicates that the majority of aquifers are leaky-confined. In places barrier boundaries were encountered. A conceptual model that explains these results is that the water bearing formations comprise multilayered aquifers separated by aquitards that leak. Barrier conditions can be expected to occur if some of these aquifers thin out or form lenses.

Results of aquifer tests carried out on older boreholes was also examined. The average T of these boreholes was 145 m^2/day, the mean S value was 0.0016 and the Specific Yield (Sy) was 2.6%. For water resource calculation purposes the following mean aquifer characteristics were adopted:

- *T value = 145 m^2/day.*
- *S value = 0.0015.*
- *Sy value = 2.5 %*

A composite piezometric map of the Project Area, for the period January 1982 to March 2006, is presented (**Figure 22**). This shows the piezometric gradient and direction of groundwater flow is towards the west-southwest, generally mirroring the ground level contours. The gradients are steepest in the northern part (Wadis Ajran, Saifah, Sharri and Al Fatah) of the Project Area and shallowest in the south (Wadi Dank). A groundwater sink appears to have developed in Wadi Saifah near the international border, which is presumably caused by large abstractions in the UAE. These abstractions appear to be drawing in groundwater from Wadis Ajran, Saifah, Sharri and Al Fatah.

Figure 23 shows a cross-section of potential groundwater pathways, running east to west, between the catchment boundaries of Wadis Dank and Sawmahan. This section indicates that groundwater moves between the jabals and the international border along four main aquifers in the Upper Fars. Recharge originates from wadis that debouch from the jabals, from groundwater that flows through the Hadhramaut Group carbonates, and from occasional rain storms that occur on the alluvial plain.

The salinity of the groundwater is discussed. *In summary, it appears that the groundwater quality deteriorates as the groundwater moves down-gradient. Near the jabals, uniformly low salinity water occurs with depth. Down-gradient the groundwater initially gets more saline with depth, but later this trend is reversed with slightly less saline water occurring at depth in the lower plain.* It is suggested that the pattern of salinity shown on this cross-section is caused by the following effects:

- **Natural salinisation**. As groundwater moves down-gradient from the jabals and the Hadhramaut Group it picks up salts and gradually gets more saline.
- **Upper-plain recharge**. Flash floods running down from the jabals allow fresh water to recharge the surface aquifer in the upper plain, between the jabals and NMP-1, and so the top aquifer tends

to be less saline for a greater distance than the deeper aquifers. Flood waters are prevented from travelling between the mid-plain and the international border by the presence of sand dunes or the size of the flood.

- **Increased hydraulic head with depth and evaporation**. It's speculated that increasing hydraulic heads with depth enable less saline water to be driven beneath more saline aquifers in the lower plain west of NMP-7 and NMP-5. It's also possible that the top aquifer in the lower plain has been evaporated at some period in the past.

Attempts were made to obtain groundwater level records for the Project Area but few exist and it became clear that inadequate groundwater monitoring occurs in the Project Area. *In order to make useful deductions about long-term trends it is essential that long-term data be collected. At least three boreholes need to be monitored in each catchment if calculations and conclusions are to be made about recharge, outflows, changes in storage and groundwater resources in these wadis. In each catchment, these monitoring points should be located at the top, middle and bottom of the alluvial plain.*

One of the first indicators of water's likely usefulness, for drinking or agricultural purposes, is its EC. **Figure 25** shows the EC of all known boreholes in the Project Area, including boreholes inventoried by the NWI. The majority of these boreholes were completed into Upper Fars aquifers. This figure highlights where fresh to saline groundwater is know to occur. This map has been classified using the following intervals:

- **<2,300 µS/cm**. Suitable for potable use
- **2,300** to **4,000 µS/cm**. Suitable for most agriculture and livestock purposes.
- **4,000** to **6,000 µS/cm**. Suitable for selected crops, livestock and oilfield use.
- **6000** to **10,000 µS/cm**. Suitable for more resistant crops, certain livestock and industrial use.
- **>10,000 µS/cm**. Suitable for industrial purposes only (e.g. oilfield).

Figure 25 shows the groundwater deteriorating westwards towards the international border. East of the main road that runs between Al Qabil and As Sunynah the groundwater generally has and EC of < 2,300 µS/cm. Three low salinity fingers extend westwards in Wadis Saifah, Al Fatah and Dank, perhaps indicating where significant amounts of recharge occur.

In Wadis Saifah and Sharri the groundwater between the border and main road generally has an EC of less than 10,000 µS/cm. This might explain why UAE groundwater abstractions are concentrated in this area. In the other three Project Wadis the international border swings westwards and so these wadis have poorer quality groundwater in their lower reaches. Wadi Ajran has high salinity groundwater that extends further eastwards into Oman than the other Project wadis. It is interesting to note that despite the high salinities along the border UAE farmers are able to crow crops using this water.

Water samples were collected during the drilling of each borehole, on completion of each borehole and during the aquifers tests. These samples were analysed by the MRMEWR laboratory in Muscat. Altogether 62 results were received from the laboratory. The interpretation of the results from each borehole, in relation to the water's potability, usefulness for agriculture and its tendency to corrode or scale metalwork, is discussed.

An examination of all the data shows that the majority of samples (54) have Na-Cl signatures. Five samples from NMP-13 have Na-HCO_3 signatures, with significant amounts of SO_4 and Cl. One shallow water sample, taken from NMP-3 at 28 m, had a Ca-HCO_3 signature. The dominance of groundwater with Na-Cl signatures suggests these are mostly older end-point waters.

Despite incomplete water quality analyses, they were sufficiently detailed to be able to conclude that only NMP-13 and NMP-14 are likely to be potable for human consumption. NMP-1 to NMP-12 failed to meet the maximum allowable limits (MAL) of the Oman Drinking Water Standard. All these boreholes had total dissolved solids (TDS) and Cl in excess of the MAL. Also, they commonly had excessive Mg, Na and SO_4. Two boreholes (NMP-4 and NMP-5) also had F in excess of the MAL.

In order to get a regional overview of groundwater potability, chemistry data (major ions) from the NWI were collated and classified as potable or non-potable according to Omani Drinking Water Standard No. 8. This information was combined with Project borehole information (**Table 31**). The results of this classification are shown on **Figure 27**. The greatest areas of potable groundwater occur in Wadis Saifah and Dank and the smallest areas occur in Wadis Ajran and Al Fatah.

Livestock needs fresh drinking water for normal health and high production. The TDS/EC content of water is the most important characteristic in determining the suitability of water for stock. It was concluded that most stock animals would probably be able to utilise all Project Area groundwater, but that delicate animals such as poultry would not be able to use water with an EC in excess of 4000 µS/cm.

Using data obtained from Project boreholes, the NWI, and GRC (2000) a map showing the location of areas that have 'good to suitable', 'suitable to doubtful', 'doubtful to unsuitable', and 'unsuitable' groundwater for irrigation was produced using Driscoll's (1986) classification (**Figure 29**). This map shows that the majority of groundwater located to the west of the Al Qabil-Mazim highway has 'doubtful' to 'unsuitable' water. Better quality water is found to the east of this road. Unsuitable quality water is found along the international border in Wadis Al Fatah and Dank.

Despite the conclusion that poor quality groundwater ('doubtful to unsuitable', and 'unsuitable' water) occurs west of the highway and occupies the largest part of the Project Area, it is clear that farmers in the UAE are successful using this groundwater on farms even though conventional wisdom suggests this is unwise. It is likely that the UAE farmers are using coarse-textured soils with excellent drainage, are applying considerable excess irrigation (drip to avoid leaf damage) water to flush out accumulating salts, have selected salt tolerant crops, and are applying mineral additions to make these waters usable. This being the case, irrigated farms should also be possible in Oman in the zone of where 'doubtful to unsuitable' water occurs (2,781 km^2) as long as suitable precautions and appropriate farming practices are carried out[1]. Areas with 'unsuitable' water should be avoided since these can contain very brackish water (e.g. 17,000 µS/cm at NMP-5).

The Langelier (LI) and Ryzner (RI) Indices of the groundwater taken from the screened section Project boreholes were examined. These two indices show whether water might cause corrosion or scaling in pipe-work. The majority of LI results suggest that scaling is likely but the RI results suggest that the majority of samples are corrosive. It is probable that the RI and LI results are ambiguous and unreliable because they were calculated using samples that had been stored for many days or weeks.

Water reserve calculation was made. A summary of these calculations are shown on **Table 40**. This table indicates the following:

- **Total Reserves**. The total groundwater reserves in the Project Area are estimated to be 4,456 Mm^3 (million cubic metres) of water. This equates to approximately 0.88 Mm^3 of water per km^2. 1,157 Mm^3 of this water is held in confined storage and 3,299 Mm^3 is held in unconfined storage. Only some of these reserves can be utilised by humans and agriculture.
- **Potable Reserves**. It is estimated that there are 1,206 Mm^3 of potable quality groundwater reserves in the Project Area. 354 Mm^3 of this water is held in confined storage and 852 Mm^3 is held in unconfined storage.
- **Water that can be used by Conventional Agriculture**. It is estimated that there are 1,894 Mm^3 of groundwater reserves in the Project Area that are suitable for conventional agriculture. 541 Mm^3 of this water is held in confined storage and 1,352 Mm^3 is held in unconfined storage.

[1] Obviously, using this water is a high risk strategy and crop damage and low yields may occur in some places.

- **Water that can be used by Specialised Agriculture**. It is estimated that there are 2,397 Mm^3 of groundwater reserves in the Project Area that might be suitable for specialised agriculture. 589 Mm^3 of this water is held in confined storage and 1,808 Mm^3 is held in unconfined storage.

It should be noted that the reserve estimates of potable water and water that can be used for conventional agriculture are overlapping. That is to say if these resources are used for agriculture they will no longer be available for human consumption.

These estimates are very dependent on the S and Sy-values that are used: doubling these values doubles the reserves.

In reality only part of these reserves can ever be fully exploited because pockets of air and isolated patches of water will remain in the aquifer, which will not be easily extractable, and because the efficiency of the wells and pumps will deteriorate as the water reserves are depleted and maintenance and pumping costs become prohibitive. The amount of recoverable reserves is difficult to estimate. Professional judgement suggests that all of the confined storage should be recoverable and perhaps 50% of the unconfined storage. *This would indicate that there are ~2,800 Mm^3 of recoverable reserves of water in the Project Area. ~780 Mm^3 of these reserves are of potable water quality.*

Estimates of recharge were made. Wadi flow data provided one estimate of the recharge to the Project Area. Another estimate of recharge was made from the amount of groundwater flow moving though the Project Area. The average of these two estimates suggest mean annual recharge to the Upper Fars is: 3.3 Mm^3/yr in Wadi Ajran; 2.8 Mm^3/yr in Wadi Saifah; 1.5 Mm^3/yr in Wadi Sharri; 3.2 Mm^3/yr in Wadi Al Fatah; and, 5.3 Mm^3/yr in Wadi Dank. *Total mean annual recharge is in the order of 16.1 Mm^3/yr. This is the sustainable yield of the Project Area.*

The water balance and sustainable yield of the Project Area was determined by estimating wadi flows, groundwater throughflow, domestic and household demand, livestock demand and crop water demand. The sustainable yield or net available water of the Project Area is given by the difference between the inflows (recharge) and ouflows (water use in Oman). The results of these calculations are shown in **Table 43**. *This indicates that the net available water in the Upper Fars is: 2.1 Mm^3/yr in Wadi Ajran; 2.4 Mm^3/yr in Wadi Saifah; 1.5 Mm^3/yr in Wadi Sharri; 1.9 Mm^3/yr in Wadi Al Fatah; and, 3.3 Mm^3/yr in Wadi Dank. In total, this suggests that ~11 Mm^3/yr is surplus to current requirements. At present, this water flows across the Oman international border and is being used by farmers in the UAE.*

Figure 30 highlights the areas where groundwater suitable for potable, conventional agriculture and specialised agriculture are likely. The available data suggests potable quality groundwater is most prevalent in Wadi Saifah and Dank, where tongues of water feed down into the lower alluvial plain. Only a small area of potable groundwater has been identified in Wadi Ajran, which is possible due to the influence of extensive groundwater abstractions across the border in the UAE.

Two areas have been identified as priority development areas. It is recommended that these areas be developed first before proceeding to other locations.