DRILLING AND AQUIFER TESTING PROJECT IN THE NORTHERN BATINAH

EXECUTIVE SUMMARY

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For

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A drilling and testing program was designed by MRMEWR to investigate the Northern Batinah area of the Sultanate of Oman.

The Project Area occupies part of 18 coastal catchments, which from north to south are called: Wadis Hawrim, Hatta, Bid'ah, Rajmi, Fizh, Bani Umar Al Gharbi, Suq, Jizi, Hilti, Ahin, Sakhin, Sarami, Shafan, Hawasinah, Mashin, Mayhah-Mabrah-Hajir, Bani Ghafir and Fara. Altogether, the Project Area occupies an area of approximately 2,512 km^2 (**Figure 1**). Nearly all the major population centres in the Project Area are located along the coast. The most significant towns include Shinas, Liwa, Sohar, Al Khaburah, As Suwaiq, Saham and Al Musanaah.

The stated aims of this Project were to conduct a drilling and testing program to investigate the dimensions of the coastal aquifer, the depth and geology of the bedrock and the aquifer hydraulic characteristics.

Altogether, 26 boreholes were drilled during this Project. These comprised 22 exploration/monitoring boreholes and 4 test production boreholes. Geo Resources Consultancy (GRC) were employed by MRMEWR to provide drilling, hydrogeological, operational management and reporting expertise for this Project. Oman Drilling & Soil Technology Co. LLC (ODST) were awarded the drilling and testing contract for this Project.

In the Terms of Reference (TOR) and Inception Report, it was considered likely that the main geological target of the Project boreholes would be the Tertiary and Quaternary-aged alluvium, and that boreholes would be terminated in Hadhramaut and Aruma Group sediments, and Hawasinah and Samail Nappes.

The Tertiary-aged 'alluvium' can now be more precisely defined as belonging to the Neogene-aged Fars Group. The Quaternary-aged alluvium and Upper Fars were found to be the most important aquifers encountered beneath the plain. The majority of boreholes were terminated in the Middle Fars. North of Sohar, a few boreholes were terminated in Permian to Cretaceous aged Aruma Group sediments and Hawasinah Nappes. One borehole (NB-16) cut Palaeogene-aged Hadhramaut Group Formations and was completed in the Umm er Radhuma Formation.

Summary details of the boreholes drilled under this Contract are shown in **Tables 4** and **5**. **Figure 8** shows the location of these boreholes. More comprehensive data for these boreholes is presented in **Appendices 1** and **2**.

A simplified geological map of the Project Area is shown on **Figure 16**. The lithostratigraphy of these geological units is shown on **Table 7**. ***The recognition of different geological formations, the correct identification of formation contacts, the detection of different aquifer units, and the measurement of the hydrogeological characteristics of these aquifers was the main priority of the field work undertaken during this Project.***

The Oman Mountains were created in the Eoalpine and Alpine orogenic cycles. These tectonic movements deformed Hadhramaut rocks, which lie beneath the Project Area, and produced a basin (**Figure 17**) that was subsequently filled with Tertiary and Quaternary sediments. Geological cross-sections show that this basin extends from Wadi Jizi to Wadi Al Fara; that lithology of the Upper Fars sediments are highly variable; and that these thicken and widen from the north-west to the south-east of the Project Area.

During the Project selected boreholes were logged by the Technical Survey Section of the Water Resources Assessment Department of MRMEWR. It was concluded that alluvium/ Upper Fars contact can usually be distinguished by changes in the resistivity and gamma responses across the contact, and washouts that occur above the contact of these formations. The boundary between the Upper and Middle Fars Formations was usually not distinguishable on the downhole geophysical logs. However, in two boreholes (NB-10 and NB-22) where EC and temperature were logged there was a dramatic increase in these parameters below this contact, indicating that the Middle Fars contained higher salinity groundwater than the Upper Fars. ***At these two sites the most likely explanation for this result is that the groundwater encountered in the Middle Fars is connate and is not being recharged by modern-day water from the mountain range behind.***

MRMEWR carried out the TDEM soundings for this Project at the end of 2005 and in 2006. The results of MRMEWR's work are reproduced on **Figures 26** to **33**. From the TDEM soundings undertaken on profile lines H, I, J the following was concluded:

- **Alluvium and top of Upper Fars.** The alluvium and top of the Upper Fars can usually be correlated with the higher resistivity values (>40 ohm-m).
- **Upper Fars.** Middle ranging resistivities (10/20 to 40/50 ohm-m) correlate to the bulk of the Upper Fars Formation.
- **Base of Upper Fars.** The geometry of this boundary, as it dips north-east off the piedmont, correlates fairly well with 10 ohm-m resistivity contour lines. On the seaward side of these profiles TDEM cannot be used to determine the base of this formation.
- **Saline water.** It is speculated that the geometry of brackish/saline water (saline intrusion) in the Upper Fars can be identified from low resistivity (<15 ohm-m) values seen on the seaward side of the TDEM profiles.

In the area investigated by Project boreholes the alluvium ranged in thickness between 8 m and 123 m. In the north-western part of the Project Area in Wadis Bid'ah and Fizh the alluvium was dry. In Wadi Rajma groundwater was encountered in the alluvium 4 m to 7 m above the bedrock. In these three wadis Project boreholes were screened either in the bedrock or into alluvium/bedrock formations. All these boreholes produced yields of less than 0.1 L/sec.

A sedimentary basin is formed south-east of Wadi Suq. Thick Quaternary alluvial sediments form near the axis of this basin in Wadi Ahin. The yield of test borehole NB-6T, which was completed in these sediments, had the highest final air-lift discharge (85.9 L/sec) of any borehole tested during the Project. During development, this borehole had an EC of 495 µS/cm. The alluvium in the sedimentary basin thins outwards from Wadi Ahin.

The Upper Fars ranged in thickness between 114 m and 582 m and averaged 357.8 m. These sediments thicken between Wadi Suq and Wadi Bani Ghafir, and between the foothills and the coast. However, the thickness of the aquifers within this formation was only a fraction of the total thickness. The total aquifer thickness of the Upper Fars ranged between 31 m and 103 m and averaged 61.8 m. The yield of boreholes completed in the Upper Fars ranged from 3.7 to 38.9 L/sec and averaged 13.3 L/sec. The final EC of the water obtained during the development of boreholes completed in the Upper Fars ranged from 555 to 21,800 µS/cm and averaged 2,077 µS/cm.

From yield-depth and TDEM data it's concluded that the Middle Fars is generally impermeable and forms the base of the coastal aquifers located between Wadi Jizi and Al Fara.

One borehole (NB-16) cut Lower Fars and pre-Neogene formations (Dammam, Upper UER and Lower UER), in the foothills of Wadi Mashin. Measurable quantities (0.46 L/sec) of groundwater were only encountered in the Lower UER at 426 m.bgl. During the development of this aquifer this produced water with an EC of 11,100 µS/cm. This result, the geometry of the Neogene Basin and the TDEM results suggests that groundwater from the upper catchments recharges the Project Area through shallow Pliocene and Quaternary-aged sediments, i.e. through alluvial gaps in the foothills.

Pumping and aquifer tests were carried out at four sites to determine the yield and performance characteristics of the test boreholes and aquifer characteristics of the alluvium and Upper Fars aquifers. A summary of the step drawdown results is presented on **Tables 16** to **19.** ***The most prominent information presented on these tables is the high efficiency (65 to 96 %) of the boreholes that were tested.***

A summary of the aquifer tests results is presented on **Table 24**. The mean Transmissivity (T), Hydraulic Conductivity (K), and Storage Coefficient (S) of these tests are approximately 370 m^2/day, 7.7 m/day and 0.00026, respectively. An unconfined aquifer response was observed at Site 1 in the alluvial aquifer. Leaky confined responses were observed in all the Upper Fars aquifers. ***A conceptual model that might explain these results is that alluvium receives modern-day recharge and this percolates downwards into multilayered Upper Fars aquifers through leaky aquitards.***

Table 25 details the results of aquifer test results carried out on other boreholes in the Project Area. The mean T, K, S and Sy (Specific Yield) values of these data and the Project data are approximately 1330 m^2/day, 36 m/day, 0.0007 and 3.5%, respectively.

Composite piezometric maps of the Project Area are presented on **Figures 35** and **36**. In the coastal areas of Wadis Suq, Jizzi, Ahin, Sakin, Shafan, Hawasinah and Mashin there are large areas where groundwater levels are below sea-level. Small areas of Wadis Rajma and Liwa also have groundwater levels below sea-level. In Wadi Bani Ghafir there are insufficient monitoring points to check the groundwater levels near the coast but it's likely that these are also below sea level.

Figure 37 shows a hydrogeological cross-section through Mashin. This section indicates that groundwater moves between from the jabals into the coastal plain via wadis that debouch onto the plain. Little or no groundwater is thought to move between the Cretaceous bedrock and the Alluvium/ Upper Fars aquifer. Occasional storms on the coastal plain will also contribute to recharge of the coastal plain. Fresh groundwater occurs between the foothills and the coast. This water drains towards the coast, where it flows into the sea and is consumed or evaporated by coastal settlements and farms. The fresh groundwater sits on saline water, which extends to the base of the Upper Fars into the central part of the coastal plain. The other catchments in the Project Area can be expected to have similar hydrogeological profiles.

Available groundwater level data was examined to indicate the water balance status of Project Area catchments. These data show that end-1986, end-1995 and end-2004 were dry periods when groundwater levels reached minimum levels. A comparison of these base-levels provides a means of determining whether groundwater is being depleted over the long-term in these catchments**.** ***It was concluded that groundwater levels are dropping in most of the Project Area catchments and that these are likely to be in water balance deficit. The largest falls in groundwater levels were recorded in Wadis Fizh, Suq, Shafan, Hawasinah and Mashin.***

One of the first indicators of water's likely usefulness, for drinking or agricultural purposes, is its electrolytic conductivity (EC). **Figures 41** and **42** show the EC of all known boreholes in the Project Area, including boreholes inventoried by the NWI. As expected, these figures show high salinity groundwater occurs near the coast where saline intrusion occurs. Saline intrusion is particularly noticeable in Wadis Bid'ah, Fizh, Hawasinah, Mashin, Bani Ghafir and Fara. There is relatively limited saline intrusion in Wadis Hawrim, Ahin and Sarami.

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. An examination of all these analyses shows that there were two major water types (Na-HCO_3 and Mg-HCO_3) and four minor (Mg-Cl, Na-Cl, Na-SO_4, Mg-SO_4) water types. ***The dominance of groundwater with Na or Mg-HCO_3 signatures suggests the majority of the groundwater encountered was young, recently recharged, water.***

MRMEWR's laboratory was unable to carry out comprehensive water analysis in accordance with Omani Drinking Water Standard No. 8 (1998). Despite this difficulty, the analyses were sufficiently detailed to be able to conclude that water from 11 boreholes (NB-1, 2, 3, 4, 6, 15, 16, 19, 20, 21T and 22) were not potable for human consumption. The water from the other boreholes is probably potable but all Omani Drinking Water Standard parameters would have to be tested to confirm this. In order to get a regional overview of groundwater potability, chemistry data (major ions) from the NWI were collated and classified. The results of this classification are shown on **Figure 43.** ***This map shows that nearly all the groundwater in the Project Area fails to meet one or more of the Omani Drinking Water Standard's Maximum Allowable Limits (MAL).***

Groundwater requiring minimal treatment (e.g. lowering the Mg levels and pH) can be expected to coincide with areas that have an EC of less than 2,700 µS/cm (shown on **Table 27** and **Figures 41** and **42**). These areas are generally located south-west of the main road, although it was observed that parts of this may be polluted by man-made activities. For instance, whilst drilling borehole NB-12 in Wadi Shafan a large sewage lagoon was found to be located 150 m from this site. Also, the downstream parts of Wadi Suq have the potential of being contaminated by the Chromite mine and settling ponds located in this catchment.

Livestock needs fresh drinking water for normal health and high production. The TDS content of water is the most important characteristic in determining the suitability of water for stock. **Table 27** can be used as an indicator of the area of groundwater that all farm animals can utilise.

Driscoll (1986) presents a classification of irrigation water based on Adjusted Sodium Adsorption Ratio (SAR) and Electrolytic Conductivity (EC). Project and NWI data was classified using this system and a map showing the location of areas that have "good to suitable" and "doubtful to unsuitable" groundwater for irrigation was produced (**Figure 45**). This map shows that the majority of groundwater located to the south-west of the main highway has "good to suitable" water. The majority of "doubtful to unsuitable" water occurs adjacent to the coast. However, large inland areas of Wadis Bid'ah, Fizh, Suq, Sakin, Shafan, Hawasinah, Mashin, Bani Ghafir and Fara also have "doubtful to unsuitable" quality water.

Table 28 also shows the Langelier (LI) and Ryzner (RI) Indices of the groundwater taken from the screened section of Project boreholes. These two indices show whether water might cause corrosion or scaling in pipe-work. This table shows that 15 water samples were corrosive. The other samples were ambiguous with the LI results generally suggesting that scaling is likely from these groundwaters but the RI results suggesting that the majority of samples are corrosive.

Table 32 shows the mean annual water balances calculated for each Project Area catchment. It is clear that the largest consumer of water (~387 Mm^3/yr) in the Project Area are crops that are using groundwater pumped from the ~ 4,800 wells and boreholes inventoried by the NWI. This water use accounts for ~87 % of the total outflows. The other outflows (aflaj crop demand, domestic, commercial, municipal use and natural outflows) only account for ~ 13 % of the total outflows**.**

Table 32 suggests that three catchments (Wadis Hawrim, Bid'ah and Ahin) have a surplus of water. The other 13 catchments have groundwater deficits. The largest water balance deficits occur in Wadis Shafan, Hajir, Bani Ghafir and Fara.

A summary of these water reserve calculations are shown on **Tables 33** and **34**. These tables indicate the following:

- **Groundwater Reserves in Areas with an EC < 2,700 µS/cm**. It is estimated that there are 4,307 Mm^3 of water that could be used by all livestock (untreated water). 99.6 % of these groundwater reserves are held in unconfined storage and 0.4% are held in confined storage. These reserves can also be used for human use ('nearly-potable water'), but to comply with Omani Drinking Water

Standards it is highly likely that this water would have to be treated. Very few reserves are located north of Wadi Jizi.

- **Water that can be used by Conventional Agriculture**. It is estimated that there are 3,224 Mm^3 of groundwater reserves in the Project Area that are suitable for conventional agriculture. The majority of this groundwater is held in unconfined storage**.**

It should be noted that the reserve estimates of 'nearly-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.

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 ~2,112 Mm^3 of 'nearly-potable' recoverable reserves of water in the Project Area.***

The available data suggests that the majority of Project Area catchments have long-term water balance deficits. In these catchments the water situation and salinity along the coast can be expected to deteriorate year by year. The exception may be Wadi Ahin where excess water (7.3 Mm^3/yr) occurs. However further development of this catchment is likely to be at the expense of Wadis Hilti and Sakhin, which benefit from groundwater sourced in Wadi Ahin. Wadis Hawrim and Bid'ah appear to have balanced water budgets but groundwater reserves in these wadis are negligible (~ 9 Mm^3). Development in these catchments is unlikely to be sustainable**.**

It's concluded that there is little scope for further development in the Project Area without mining the groundwater reserves. Sustainable increases in domestic, municipal and commercial supplies can best be achieved by reducing the amount of water abstracted for irrigated agriculture along the coast. A 50 % reduction in irrigated agriculture is required to bring the Project Area back to its historic situation of a balanced water budget.

Small improvements (1 to 1.5 Mm^3/yr) to the water situation of Wadis Bani Ghafir and Fara might be possible by construction or extending recharge dams in these wadis. Elsewhere recharge dams are likely to make only marginal differences to the water situation (<0.4 Mm^3/yr per catchment)**. *To put this in perspective, the impact of stopping and recharging all surface flood flows to sea (5.35 Mm^3/yr) could be similarly achieved by reducing agricultural consumption by 2 %.***

Despite these conclusions it was considered useful to identify the best locations to construct wellfields for emergency water supplies. The largest reserves of groundwater occur in the southern Part of the Project Area where the coastal plain is widest. Unfortunately these catchments also have the largest groundwater deficits. By dividing the groundwater reserves by the current deficit an index of the most sustainable catchments can be found. Using this index the best five catchments to develop emergency supplies are (in order of preference): Wadis Ahin; Hawasinah; Mashin; Hilti; and Bani Ghafir.