DRILLING AND AQUIFER TESTING PROJECT IN THE WESTERN AL WUSTA DESERT

EXECUTIVE SUMMARY

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For

The Ministry of Regional Municipalities, Environment and Water Resources

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The main aim of this Project was to define the hydrogeological environment and potential areas where potable and brackish groundwater could be developed along the international border with the Kingdom of Saudi Arabia and the Republic of Yemen. This was carried out by drilling 45 boreholes (18 exploratory, 9 test and 18 observation boreholes) and analysing the data collected. The location of these boreholes is shown on **Figure 14**.

The Project Area is located in Dhofar, Al Wusta and Ad Dahirah administrative regions and covers an area of about 75,000 km^2. The southern, eastern and north-eastern boundaries of the Project Area are located 100 km from the international border with the Kingdom of Saudia Arabia. In Dhofar, the Project Area also abuts the international border with the Republic of Yemen. The Project Area lies within four MRMEWR Water Assessment Areas. For the purpose of this Final Report these areas are referred to as Project Area Water Assessment Areas (PWAA). These areas are:

- Najd PWAA.
- Al Wusta PWAA.
- Umayri PWAA.
- Al Massarat PWAA.

The location of the Project Area and PWAA's are shown on **Figure 1**.

The majority of drilling was undertaken in the southern part of the Project Area (Najd PWAA), which comprises some of the most challenging drilling in Oman because of the high artesian pressures and flows found in the underlying aquifers. The main drilling targets were aquifers in the Tertiary-aged Hadraumaut Group. These rocks comprise chalky, crystalline and dolomitic limestones, cherts, shales, marls, clays and gypsum. In the northern part of the Project Area, near Ibri, the Fars Group was investigated up to a depth of 480 m by two exploration boreholes. At these two locations the Fars Group comprised calcrete and cemented gravels and conglomerates, clay, evaporates, mudstone and shale.

In the Najd, four aquifer units are recognised as follows:

- **Aquifer A**. This is a zone of water strikes found largely within the Dammam and Rus Formations, but can include water strikes in the Fars Formation and alluvial aquifers. Yields are highly variable and ranged from zero to 200 L/sec. Where evaporitic deposits are present the water in this formation has a high electrical conductivity (EC).

- **Aquifer B**. This is a zone of water strikes found in the U.UER. In the Project Area this ranged from a sub-artesian confined aquifer in the southern part of the Najd PWAA to a confined artesian aquifer nearer the border with the Kingdom of Saudi Arabia.

  The first water strikes in the U.UER occur within the central part of this formation in brown micritic limestones located above a bluish grey shale member. In the north-western part of the Najd PWAA water strikes also occur below these micritic limestones and shales, within a few metres of the U.UER/ L.UER contact. This meant that Aquifer 'B' had to be fully penetrated and cased off in order to target the L.UER.

  Despite a number of reports suggesting that Aquifer 'B' is a significant regional aquifer very little water was generally encountered in the U.UER in the Project Area. Commonly, less than 1 L/sec was cut and in many boreholes in the eastern part of the Najd PWAA this aquifer was absent. It was concluded that the lack of proper stratigraphic identification in the majority of old boreholes might explain why many of these may have been incorrectly labelled as being completed into

Aquifers ‘B’ or ‘C’. The results in this Project indicate that Aquifer ‘B’ has generally poor development prospects.

- **Aquifer C**. This is a zone of water strikes generally found in the L.UER. In the Najd PWAA this was largely a confined artesian aquifer, located in the upper to middle parts of the L.UER.

  In the western part of the Najd PWAA this aquifer occurs within a few metres of the top of the L.UER, in a strongly defined solution channel which is normally 20 to 40 m thick. There large flow (i.e. 106 L/sec) and high artesian pressures (49.93 m head at WWD-12) were encountered.

  Towards Qitabit and Al Wusta PWAA Aquifer ‘C’ occurs at progressively deeper depths in the L.UER and is more variable in thickness.

- **Aquifer D.** This is a confined aquifer, usually encountered 50 to 100 metres below Aquifer ‘C’, which may extend to the base of the L.UER. Two or more water strikes are common in this zone. The base of the Lower UER is denoted by the Shammar Shale. Few details are known about this aquifer but it appears to have similar pressures to Aquifer C, lower discharges and zero H_2S content.

To investigate the characteristics of these aquifers each aquifer was isolated from its neighbour. This was done by selectively casing and cementing off the formations above the target aquifer. At selected locations aquifer tests were undertaken to determine the hydrogeological characteristics of Aquifer ‘C’, the response of adjacent aquifers, and the chemical properties of groundwater cut by these boreholes. Potential sites for wellfields were identified in the Najd Project Water Assessment Area (PWAA) with the aid of water chemistry, piezometric and yield data. Aquifer test results, geophysical logs, aquifer thickness, depth and piezometric information were used to estimate the groundwater reserves and sustainable yield of the aquifers in the Project Area.

Geo Resources Consultancy (GRC) was the Consultant for this Project and Oman Drilling and Soil Technology Company (ODST) was the drilling and testing Contractor. ODST commenced work on the field investigations on 10 November 2003 and completed these on 18 May 2005.

To investigate the hydrogeology of the Project Area, six basic borehole designs were used. These designs catered for the construction of Aquifer ‘A’, ‘B’. ‘C’ and ‘D’ exploration, monitoring and test boreholes. Although a large number of different designs appear to have been used, there was a commonality about these. With the exception of the Aquifer ‘A’ monitoring boreholes, all boreholes were drilled with three or four different drilling bits. 17 ½” and 12 ¼” drilling bits were used on every borehole and were generally completed open-hole using either a 6 $^5/_8$” (observation borehole) or an 8 $^5/_8$” (test boreholes) drilling bit. Only Aquifer ‘A’ monitoring boreholes had screens installed. This design helped maintain the integrity of boreholes in loose and caving formations.

In observation and exploration boreholes the final string of casing employed was generally 8 $^5/_8$”. In test wells the last string of casing was generally 9 $^5/_8$” in diameter. Unfortunately, thick-walled casings were not generally available for the Project and were only used on WWD-42. Using the corrosion criteria developed for MWR in 1994, it is estimated that the integrity of most Project boreholes might be less than 9 years.

When boreholes are drilled into the top of the L.UER Formation particular care was taken to ensure isolation of this from adjacent aquifers. Firstly, to isolate Aquifer ‘A’ from Aquifer ‘B’ a casing string and cement shoe was set within the top 20 metres of the Upper UER and the annulus was then grouted up. Next, to successful isolate Aquifer ‘B’ the U.UER had to be fully penetrated, but not so far as to cut Aquifer ‘C’. Casing was then set in the borehole and the annulus was grouted through a cement shoe before drilling into the underlying aquifer. In the western Najd, this was particularly difficult because artesian water strikes occur just above and below the U.UER/ L.UER contact. There, no more than two metres of the L.UER could be cut or Aquifers ‘B’ and ‘C’ would join together. To prevent premature penetration of Aquifer 'C' it was necessary to drill slowly and to often halt the drilling in the U.UER so that index foraminifera and the formation could be properly identified. As a safety measure, all boreholes had a flange welded onto the casing before Aquifer 'B' was cut, so that the borehole could be shut-in in the event that an artesian aquifer was prematurely cut.

These difficulties diminished as the Project moved eastwards towards Qitabit and Al Wusta PWAA because Aquifer 'B' was often absent (practically dry) and Aquifer 'C' occurred at progressively deeper depths. In these areas the design of the borehole was modified by doing away with the intermediate 13 $^{3}/_{8}$" casing string. This had the added benefits of increasing the rate of progress, reducing costs and avoiding use of a casing that was in short supply.

The construction of Aquifer 'D' boreholes also presented particular engineering problems that needed to be overcome. The main concern about the construction of Aquifer 'D' boreholes was the need to contain the high yields and artesian pressures (i.e. up to 100 L/sec at 4 bar at surface) in Aquifer 'C', before these boreholes could be completed. Data from old drilling reports indicated it would be impossible to grout off Aquifer 'C', and that attempts to do so would result in 1000's of cubic metres of cement being lost to this aquifer with no visible results. The problem was resolved by containing Aquifer 'C' between two casing strings.

During this Project the use of bentonite and weighted drilling fluids was generally avoided because information on the water quality and yield were required. In the western part of the Najd PWAA the rocks were generally hard and indurated and these boreholes were drilled with air, foam and then flushed with water. In the central and eastern parts of the Najd PWAA, the younger and more friable Fars Group collapsed very easily when saturated. In other places the Rus Formation and U.UER contained large cavities and volumes of water which had to be controlled. At many locations bed-rock at surface obviated the ready construction of mud pits and so where these problems occurred procedures employing reaming, backfilling, cement grouting, concreting and temporary casing had to be employed.

The only time bentonite had to be employed was whilst drilling boreholes WWD-43 and WWD-44 in the Fars Group in Al Massarat PWAA. In this area substantial thicknesses of swelling clay had be countered by using this drilling fluid.

The Drilling Specifications provided for three different wellheads. These designs catered for artesian and non-artesian monitoring wells, and artesian and non-artesian test wells. The pressure (water level) in artesian boreholes was measured using a digital and analogue WIKA gauges. After completing the wellheads camel troughs and water tanker points were constructed at selected locations.

Records of all activities were recorded by hand on a series of A4-sized forms by the Contractor's Wellsite Geologists. The information on these data sheets was abstracted to enable the Composite Borehole Logs to be produced and were used for pumping test and aquifer test analyses. The typed data sheets form the basis of the Borehole Completion Reports, shown in **Appendix 4**. The Borehole Completion Reports provide a description of the drilling objectives of each borehole, the borehole's construction, the downhole geophysics, the lithology, the wellhead discharge, water level and borehole's physio-chemistry, an analysis of the water chemistry and the groundwater's potability, its suitability for irrigated agriculture, and the water's corrosiveness.

The main geological units of interest to the Project were the Tertiary-aged chalky, crystalline and dolomitic limestones, cherts, shales, marls, clays and gypsum of the Fars and Hadraumaut Groups detailed. 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 and Tertiary-aged formations, was the main priority of the field work undertaken during this Project. In the Inception Report the main characteristics of the Hadhramaut Group were tabulated so that these formations and aquifers could be readily identified in the field. In this Final Report these descriptions have been updated, expanded upon and modified with reference to the boreholes drilled during the Project and the type descriptions of these formations. Using these data a new table (**Table 11**) showing the characteristics of the Tertiary formations is presented.

The identification of microfossils was critical to the successful identification of the contact between the U.UER and L.UER, and the successful completion of Aquifer 'B' and 'C' boreholes. No other geological tool can readily differentiate this contact. On a number of occasions a discrepancy was noticed between the lithologic logs of the Project and existing boreholes, which is attributed to the lack of proper palaeontological investigation. The lack of proper stratigraphic identification in old Najd boreholes might explain why its previously been reported that there is little difference between the average EC and yield of the different UER aquifers across the Najd and Dhofar.

The geological structure of the Project Area was examined with the aid of geological maps, Landsat and DTEM data, a database of existing boreholes and two hydrogeological cross-sections, which were drawn through the Project Area. The North-South section (**Figure 21**) shows that the formations above the base of the Rus gradually thicken from Jabal Qara northwards. The West to East section (**Figure 22**) shows the formations above the base of the Rus thinning eastwards between Site 17 and Site 10, thickening between Sites 16 and 27, and thinning again between Sites 15 and 13. Noticeable features of the West to East section include the absence of groundwater in the U.UER and the upward displacement of this formation at Site 13. A displacement of formations also occurs between Sites 25 and 23 suggesting a significant regional north-north west to south-south east trending fault is located here. This fault/ lineament can be traced for approximately 100 km and extends under and adjacent to Wadi Qitabit.

During the Project 30 boreholes were logged by the Technical Survey Section of the Water Resources Assessment Department of MRMEWR. At the commencement of the Project it was intended that each borehole would be logged just before each casing string was run into the hole. In practice this proved impractical for MRMEWR to implement. More usually one borehole was logged on each site; sometimes several days or weeks after the borehole had been completed. This meant that the identification of formation contacts was almost entirely largely dependent on foraminifera and lithological identification. Despite this, useful geophysical features of the Rus, U.UER and L.UER were identified.

The use of the terms Aquifer 'A', 'B', 'C' and 'D' appears to have been introduced by Hydrotechnica in the mid-1980's and was subsequently adopted by Mott MacDonald International, MAF, the PAWR and MWR. The author of this document has reservations about using this nomenclature and lumping together diverse formations into monolithic units such as Aquifer 'A', and separating the UER into Aquifers 'B' and 'C', especially if these are incorrectly identified. However, a significant number of references and databases now refer to these aquifer units in the Najd and so their use has been maintained in this document.

An examination of the yield data from the 45 borehole drilled during this Project indicates that the average yields were 13.6, 9.3, 60 and 28.8 L/sec, from Aquifers 'A' 'B' 'C' and 'D' respectively. *The results show that the yields of boreholes completed into Aquifer 'C' were consistently higher and much more reliable than those from Aquifers 'A' and 'B'.* Insufficient data are available from Aquifer 'D' to draw conclusions about this aquifer but the three results indicate this is also a productive aquifer. *The conclusion that Aquifer 'B' is unreliable and usually produces little or no water in the Project Area is one of the more alarming findings to come out of this study. This conclusion directly contradicts previous studies that assumed this aquifer was often comparable to Aquifer 'C' and has significant negative implications for water resource estimates for the Najd.*

An examination of aquifer thicknesses shows that the aquifer thickness of the boreholes that cut Aquifer 'C' is fairly uniform and normally ranges from 20 to 40 m thick. The median thickness of Aquifer 'C' is 31 m across the Project Area. The thickness of Aquifers 'A' (1 to 112 m) and 'B' (1 to 43 m) is more variable. Insufficient data are available from Aquifer 'D' to draw conclusions about this aquifer but the three results indicate this aquifer may be thicker than Aquifer 'C'.

Pumping and aquifer tests were carried out to determine the yield and performance characteristics of the test boreholes and aquifer characteristics of the Tertiary formations. These tests comprised an initial calibration test, a step drawdown test, a constant rate discharge test and a recovery test. The most prominent feature of the step test results was the generally low efficiency (1 to 62 %) of the boreholes that were tested. The other noticeable attribute of the step-test results is that the Specific Capacity (Q/s) of each borehole declines significantly with discharge, as the efficiency decreases. *The importance of the step-test results is that they show that significant drawdown will occur in production boreholes, well in excess of what would normally be predicted.*

Constant rate discharge and recovery tests were carried out at nine sites to determine the aquifer characteristics, including Transmissivity (T), Coefficient of Storage (S) and presence and distance to aquifer boundaries. The results of these tests indicated the following:

- **Aquifer A** had a T-value of 485 m^2/d and an S of 3.2 x 10^{-6}.
- **Aquifer B** had a T of 47 m^2/d and an S of 1.0 x 10^{-6}.
- **Aquifer C** had a mean T of 448 m^2/d and a mean S of 2.0 x 10^{-4}.

At seven sites (Sites 12, 15, 16, 17, 18, 21 and 23) barrier boundaries were encountered. The preponderance of these barriers suggests that the L.UER is extensively faulted across the Project Area or that the fissures making up Aquifer 'C', in a particular location, have limited horizontal extent.

It is possible to imagine a scenario whereby the L.UER is split into a series of cells or compartments bounded by barriers, each perhaps several square kilometres in aerial extent, and each leaking some water into adjacent downstream cells. This might explain several unusual hydrogeological features of the Najd such as: the occurrence of large drawdowns in places such as Thumrait Military Camp, Al Hashman and Maitan, even though the T values are fairly high; why groundwater several 10,000's of years old still exists even though rapid groundwater velocities occur; and, why significant pizometric gradients are maintained in the face of limited recharge.

Whatever the reality, *the presence of a large number of hydraulic barriers in the L.UER indicates that production wells should not be concentrated in one area if excessive drawdown and over-exploitation is to be avoided.*

A piezometric map of the Najd PWAA is presented (**Figure 30**). This was constructed using data collected from boreholes drilled during the Project and data from older boreholes drilled to the south of the Project Area. There was insufficient data to draw similar maps for the other PWAA's. The piezometric gradient, and thus direction of groundwater flow, is towards the northeast in a similar direction as the ground level contours.

A hydrogeological cross section (**Figure 31**) shows that the piezometry and potential groundwater pathways run between Jabal Qara and the Kingdom of Saudi Arabia. This section shows that the force driving groundwater northeast through the Tertiary Formations in Dhofar is groundwater located in the L.UER, in Jabal Qara. It also shows that the large head differential between the jabals, in the south, and Rub al Khali, in the north, is sufficient to drive groundwater from the L.UER to ground surface. Where faults, fractures and solution features occur pathways will be created for groundwater to flow from the L.UER (Aquifers 'C' and 'D') into the U.UER (Aquifer 'B'), and pre-Palaeocene Formations (Aquifer 'A').

Water level monitoring data is sparse in the Najd. However, comparisons of two measurements were possible from 31 boreholes. Making deductions about water level trends from only two different measurements is hardly scientific. Even so, it is interesting to note that the majority of data show a decline in water levels between measurements. Many of the apparent falling water levels occur in areas of groundwater development, e.g. Shisr, West Hanfeet and near the JICA Farm. At these three locations water levels (piezometric surface) has fallen by between 20 and 30 metres over 10 to 15 years. It's likely that most of the drop in water levels seen at these three locations is due to localised pumping effects rather than a regional depletion of groundwater resources. However, there is another source of groundwater 'abstractions' that might be causing more widespread groundwater depletions: leaking boreholes. Boreholes constructed without casing, or with leaking casing and under high artesian pressure can be considered pumping wells with water being naturally pumped into pre-Palaeocene Formations. *The apparent drop in water levels, rate of decline of levels, and potentially large number of leaking boreholes is of concern and warrants more detailed examination by MRMEWR to ascertain the scale of losses.*

Care should be taken to ensure that all future boreholes are designed and constructed properly, using properly trained personnel and suitable equipment, to ensure that these losses are not exacerbated. Construction of illegal boreholes should also be prevented as these allow leakage between aquifers.

Wellhead chemistry was collected from every borehole. Its main purpose was to provide a tool to help identify different aquifers. The parameters measured included temperature, pH, Eh, dissolved Oxygen (DO), dissolved CO_2 and alkalinity. The most useful parameter to be measured at the wellhead was electrolytic conductivity (EC), since this is one of the first indicators of a water's likely usefulness for drinking or agricultural purposes. The EC of all known boreholes in the Project Area, including PDO water wells and boreholes inventoried by the National Well Inventory is presented on **Figure 32**. This figure highlights where fresh to hyper-saline groundwater is know to occur. This shows that Al Wusta and Umayri PWAA only contain brackish and saline groundwater that has an EC in excess of 6,000 µS/cm. The majority of Al Massarat PWAA also contains saline water except in the immediate vicinity of Al Massarat Wellfield. The available data suggests that little or no fresh groundwater flows from Oman into the Kingdom of Saudi Arabia from these three areas. *The only significant part of the Project Area that contains groundwater with an EC of less than 6,000 µS/cm is the Najd PWAA*. These data along with the information shown on the piezometric map shows that relatively fresh groundwater flows from the Najd towards the Umm As Samim: some water flows into Saudi Arabia

Water samples were collected from the different aquifers cut by each borehole. These samples were analysed by the MRMEWR laboratory in Muscat. Altogether 197 results were received from the laboratory. The results of from each borehole are interpreted in relation to the water's potability, usefulness for agriculture and its tendency to corrode or scale metalwork.

These data shows that the majority of water samples have either Mg-SO_4 or Na-Cl signatures. In general the water type is not dependent on the aquifer type. This supports the concept that all the aquifers have a similar recharge source.

The laboratory analyses show that none of the waters tested during the Project are potable for human consumption. Most commonly, the total dissolved solids (TDS), total hardness, Mg, SO4 and fluoride exceeded the Omani Drinking Water Standard's. Levels of Sr was also very high is these samples and although there is no standard for this, this constituent may also preclude these waters from human consumption. Significant levels of H_2S gas were common in many boreholes including most Aquifer 'C' boreholes. Noticeably, Aquifer 'D' did not contain this gas. *However, the data suggest that most farm animals can drink the groundwater in the Najd PWAA, sourced from Aquifers 'B', 'C' and 'D'.*

Irrigation quality class ratings were calculated for each sample. A summary of these interpretations is presented. This indicates that all of the groundwater tested in Al Massarat and Al Wusta PWAA is unsuitable for irrigation. *The majority of the groundwater tested in the Najd PWAA is suitable for irrigation*, however, there are notable exception to this:

- The water from Aquifer 'A' all is of doubtful or unsuitable quality.
- The water from Aquifer 'B' is of doubtful or unsuitable quality.
- Sites 10, 12 and 13 have unsuitable quality water in Aquifer 'C' for irrigation.
- Sites 16, 23, 20 and 15 have doubtful quality water in Aquifer 'C' for irrigation.

Langelier (LI) and Ryzner (RI) indices show whether water might cause corrosion or scaling in metal pipe-work. The results of each sample are discussed in the Borehole Completion Reports (**Appendix 4**) and a summary of these data from the uncased section of each borehole are presented in the Main Report. The LI indices suggest that the majority of samples are scale forming whilst the RI index suggests that the majority of samples are either corrosive or have ambiguous results. It is likely that the RI and LI results are unreliable because they were calculated using laboratory pH and alkalinity measurements made on samples that had been stored for many days or weeks.

It is clear from the results of this Project that fresh groundwater in Aquifer 'A' is only found in isolated localities. The extent of these near surface aquifers is difficult to determine without a significant amount of surface geophysics. Often, Aquifer 'A' is too saline to be of use. Aquifer 'B' occurs only in the north eastern part of the Najd PWAA, and usually produces only small yields of groundwater. Little is know about Aquifer 'D' because it was only cut in 3 places. However, it appears to produce reasonable yields and water quality.

During this Project, Aquifer 'C' was found to be ubiquitous throughout the Najd PWAA. This aquifer is uniformly thick and provides consistently high yields. Estimates of groundwater reserves have therefore been restricted to this aquifer. This provides a conservative estimate of groundwater resources.

The area where usable fresh and brackish groundwater occurs, for stock animals, is assumed to coincident with the Najd PWAA although west of Mugshin this groundwater is probably only suitable for camels. This covers an area of 32,780 km^2. The area where suitable quality irrigation water occurs covers an area of 17,759 km^2 (**Figure 36**). These two areas represent approximately 26% and 14% of the total area of fresh and brackish water in the Najd. The median thickness of Aquifer 'C' is 31 m. This is much thinner than the 400 to 500 m assumed by the MWR (1993f) when they calculated the fresh groundwater reserves in the Najd. Using an average Coefficient of Storage (S) of 2.0 x 10^{-4} and a specific yield of 1% the total useable groundwater reserves in the Najd PWAA are estimated to be 12,581 Mm^3 (million cubic metres) of water. In the area suitable for irrigation, groundwater reserves are estimated to be 6,481 Mm^3 of water. This equates to 0.38 Mm^3 of water per km^2. This compares with 2.0 Mm^3/km^2 of water estimated by JICA (1989) and 1.85 Mm^3/km^2 of water estimated by MWR (1993f).

It should be noted that all these estimates are very dependent on the S and Sy-values that are used: doubling these values doubles the reserves. Given this caveat, the available evidence suggests that the resources are significantly smaller than previous thought.

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. Professional judgement suggests that all of the confined storage should be recoverable and perhaps 50% of the unconfined storage. *This would indicate recoverable reserves of 7,501 Mm^3 of water from the Najd PWAA and 4,088 Mm^3 of water from the area that has suitable water for irrigation. These two estimates of recoverable reserves equate to 0.23 Mm^3/km^2 of groundwater.*

The recharge potential of each PWAA is difficult to quantify. It is clear that very little fresh groundwater enters Al Massarat, Umayri and Al Wusta PWAA. In the Najd PWAA potential sources of recharge include direct rainfall, recharge from wadis and groundwater throughflow sourced from rock outcrops in Jabal Qara and southern Yemen. It is argued that direct recharge from storms and runoff is likely to be relatively small and that the main source of recharge will be into the L.UER Formations in the jabals of southern Yemen and Jabal Qara. The amount of recharge, or groundwater throughflow, entering the Project Area is calculated to be approximately 20,600 m^3/day (7.5 Mm^3/yr).

In order to avoid depleting the groundwater reserves groundwater extractions should not exceed 7.5 Mm^3/yr in the Najd PWAA. For planning purposes, this is the estimated sustainable yield of fresh and usable brackish water in the Project Area, which is equivalent to the development of approximately 375 Ha of irrigated land using 20,000 m^3/Ha/yr of water to grow fodder crops (e.g. Rhodes grass). Additional groundwater can only be extracted by mining the aquifer.

Estimates of reserves, sustainable yields and the impact on the groundwater system is an on-going process of improved understanding as more and better information is collected. To better understand these processes these estimates should be verified using a groundwater model before proceeding with any developments in this area.

The most important factor effecting the selection of suitable land for agricultural is likely to be the thickness of soils. These have to be sufficiently thick to allow adequate drainage to prevent the build up of salts in the soil profile. The thickest soils are likely to occur in the wadis. Other important factors will be to try and minimise pumping costs. This can be achieved by developing groundwater in areas where there are artesian heads and limiting the yield of each wellfield to prevent excessive drawdown. If wellfield and cropped areas are located close to the main road this will also reduce the haulage costs between the farms and the market. The area that best meets all there requirements is shown on **Figure 37**. It is recommended that this area be developed first before proceeding to other locations.