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JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)

THE MINISTRY OF AGRICULTURE AND FISHERIES,
THE GOVERNMENT OF THE UNITED ARAB EMIRATES

THE MASTER PLAN STUDY ON THE GROUNDWATER RESOURCES DEVELOPMENT FOR AGRICULTURE IN THE VICINITY OF AL DHAID IN THE UNITED ARAB EMIRATES

VOLUME TWO: SECTOR REPORT

NOVEMBER, 1996

SANYU CONSULTANTS INC.

PACIFIC CONSULTANTS INTERNATIONAL

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FINAL REPORT

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CHAPTER ONE : HYDROGEOLOGY AND GROUNDWATER

1.1. Geography and Geomorphology of UAE

A general view of geography and geomorphology of UAE has been described in a number of works, such as UAE National Atlas, a special report on the ecology and environment in UAE (J.E. Statchell, 1978), and other of unpublished reports made by the government departments. The following paragraphs summarize these materials and their description.

1.1.1. Geography of UAE

The UAE comprises seven states with a total area of about 83,600 km^2 lying between approximately 22° 50' and 26° N and 51° and 56°E. One state, Fujairah, and enclaves of three others lie on the Gulf of Oman, the north western part of the Indian Ocean. The other six states, Abu Dhabi, Dubai, Sharjar, Ajman, Umm Al Qaiwain and Ras Al Khaimah, stretch along nearly 650 km^2 of the lower Gulf, an area of shallow sea with offshore islands, coral reefs and an intricate pattern of sand banks and creeks. Abu Dhabi, by far largest state, has an area of 67,000 km^2 and Dubai, by second largest, occupies 3,900 km^2. There are two distinct regions: (a) an eastern mountain region with a sub-mountain zone of outwash plains, and (b) a western desert region divided into a coastal belt and inland desert.

- ***Eastern Mountain Region***, roughly 80 km N-S and 30 km E-W, forms part of the Hajar range in the neighboring state of Oman, It has a Paleozoic core of metamorphic and basic igneous rocks flanked by latter limestone successions. The highest peak in UAE territories rise to 2,400 m and to 3,000 m in Oman. Two outcrops separated from the Hajar, Jabel Fayah and Jebel Sumaini, are Cretaceous and there is an Oligocene formation, Jebel Hafit, near the important oasis complex of Al Ain. The mountainous area are cut by wadis, which have formed terraces that may support Palms, Bananas Bamboo, Oleander and other semi tropical vegetation. Many of the wadis are periodically scoured by torrent floods and in some there is a small perennial flow.

-***Western Desert Region***, an alluvial belt separates the mountains from the Aeolian Sands of the western dune country. It is called the Jiri plain in the north and subsequent sub-divisions southwards are known as Dhaid, Gharif and Madam. The plains, and an area in the eastern state of Fujairah, are the most fertile and agriculturally productive area in the U.A.E. West of the main alluvial belt, a plain of the main alluvial belt, a plain of un-cultivable sandy desert and shingle flats merges into the northern sands, extending coast ward with a series of low Miocene ridges and intervening gravel and salt flats so called

Sabkha. Sabkha are former embayments of the sea cut off at the strand line to form great evaporating pans of gypsum, other evaporites and wind-born sand. The dunes are of two sorts: (i) those found along the coast are composed of white carbonate sands formed from fragments of marine shells; (ii) those found inland are red and composed of weathered quartz rocks. The northern dunes are relatively small and to some extent fixed by vegetation. To the south they increase in height and vegetation is almost absent. Very little surface water exist in the larger hollows between the dunes. There is an emergent coastal plain of sabkha and low-lying dunes cut by numerous inlets and sea creeks, the most important of which, at Dubai, extends 20 km inland. The coast is marked by tidal flats, sabkha, sands spits and lagoons. In the southern part of the country from Abu Dhabi to the Qatar peninsula, a zone of coastal sand lies between the salt flats of the beach and the dunes of the interior which from the threshold of the Rub Al Khali. The whole area is extremely barren and desolate. Liwa area, to the southwest of U.A.E. is a relatively isolated oasis center near one of the main inland areas of oil extraction. Modern roads link the capital, Abu Dhabi, with the northern states along a route roughly parallel with the coast, and eastward with the modern center developing around Al Ain area. Elsewhere, cross country communication can be hazardous.

1.2. Geology, Hydrogeology and Groundwater in UAE

1.2.1. General View of Geology in UAE

The territory of the UAE basically forms an inherent part of Arabian Plate which is bound by the Red sea rift system to the west and the Arabian Gulf to the east. The structural geology of the territory is complicated by the fact that the northern part of the UAE territory suffered from the complex tectonic events which affected the Oman mountains. The mountains form a part of the unstable mobile belt extending northwards to the Tauras and Zagros mountain.

The Oman mountain chain is through to originate from the plate subduction process which was responsible from the emplacement of the Semail Ophiolite. The Oman mountain thrust front forms a continuous structure which is occasionally interrupted by tectonic depressions, among which the Dibba fault zone is one of the most important. The mountain chain is through to have attained its structure during the Late Cretaceous.

On the Arabian peninsula, it consists of a plateau of crystalline basement and sedimentary cover which is gently inclined to the north east. The tectonic features which defined the area are largely post-Cretaceous. East of the peninsula, the basements have under-thrust the Zagraos Trough sediments. During the lower Tertiary, the Zagros Trough was being forced southeast towards its present position in the Arabian Gulf by tectonic events in Central Iran and Oman. Thus on the Arabian Peninsula itself, the Lower Tertiary was a period of relative quiescence with the exception of volcanism in Yemen. The only structural event to affect sedimentation were salt diapirism and the reactivation of certain basement features creating the Rub Al Khali and Ras Al Khaimah Basins. The two basins were separated by a series of isolated uplift structures which formed a barrier between the two basins. This ridge disappeared during subsiding (refer to Figure 1.2.1).

A simple subdivision system allow to identify two main geological province in UAE as below:

-The plain province

-The mountain province

These two provinces are physically separated by major fault systems. Moreover, they also have distinct histories and environmental geneses. Therefore, their litho-stratigraphy is also different. The analysis of the structural and sedimentological data show that the plain province was subject to the combined orogenic action of the Qatar arch and the Oman mountains to the east, and simultaneously to the influence of the sedimentation basins. These actions resulted in folding and faulting with consequent individualization of areas. Differences in sedimentation are shown by the important factor in litho-facies between the various areas in UAE.

(1) The Plain Province

Two main features had a profound influence on the geologic structure of plain province: the central Arabian Arch and the Rub Al Khali Basin. These two structures dip gently northeast towards the Arabian Gulf. General thickening of sedimentation is observed in this direction indicating an increasing rate of subsidence.

In western Abu Dhabi, gentle and simple folds are common features. Folds are aligned N–S, probably related to deep seated basement tectonics.

A Flash Syncline (Southeast of Abu Dhabi) has a fold trend NE–SW, subsequently the trend becomes NW–SE (Jam Yahour). This suggests a conformity with the Central Arabian Arch and may lead to the conclusion that the Abu Dhabi area is located on the southern flank of this arch. Diapiric salts are believed to underlie many of the structures of Abu Dhabi.

By intensity of folding, this geologic province is divided into 3 triangles as follows:

- The triangle lying to the west of the line Mender–Abu Dhabi is very folded. These folds contains the main oil fields
- The triangle lying between Mender–Abu Dhabi–Dubai is less folded and generally poor in geological events.
- The triangle Al Ain–Dubai–Ras Al Khaimah is folded and intensely faulted.

(2) The Mountain Province

This province constitutes a morphological and geological part of the Oman mountain chain. It is mainly covered with allochthonous and para-autochthonous metamorphic and ophiolite rock series and is divided by a major fault system, the Dibba line trends NNE–SSW.

The autochthonous rocks constitute an integral part of the Arabian platform to the east and north. They range in age from Cambrian to Cretaceous. These autochthonous formations were already folded and partly uplifted when they were overridden by the successive thrust sheets of the allochthonous rocks. The emplacement of the allochthonous rocks activated the pre-existing major faults and produced minor faults.

Overthrusting took place onto the irregular topography of the pre-existing autochthonous formation by a subduction process. The Oman mountains are separated from the Arab Basin by the Qatar–South Fars Arc. This structural high has influenced sedimentation from the early Mesozoic onwards.

This province can be subdivided into zones covered by sedimentary formation and zones covered by ophiolities and metamorphics.

In addition to the aquifer, it might include the mountain province that provides the catchment area for the aquifers of the plain province.

(3) Tectonics and the Evolution of Oman Mountains

As described above, the Oman Mountains originated from plate subduction. They had attained their structure in two both phase taking place during the Late Cretaceous.

The initial displacement phase is characterized by the subduction of an oceanic plate beneath the Mesozoic continental shelf of the Arabian Plate. The resulted in unstable sedimentary environment off the Arabian shelf with turbidites (Hawasina) and olistostromes.

The upper part of the oceanic plate was ripped off the substratum and then thrust onto the base of the overriding plate as an allochthonous element via a concave upward thrust plane development in symmetry with the downgoing slab. A later emplacement phase was dominated by an uplifting of the elements along various levels of a plane towards the west. This resulted in a pile of completely imprecated nappes, of which the westernmost represent autochthonous or para-autochthonous units, and the easternmost represent completely allochthonous units.

Folding, faulting and overthrusting produced two- or even more-fold tectonic repetitions of thrust sheets; such repetition can be observed at Al Fay, where lower peridotites with metamorphic melanges occur structurally two kilometers beneath the main ophiolites. The thrust sheets consist in the main of ophiolites. Thrust sheets in the center of the mountainous zone tend to have an almost sub-vertical to vertical dip, this reflects on the tectonic thickness of the green schists.

Folding of thrust sheets has resulted in a series of relatively simple large scale anticlines and synclines trending generally N-S to NE-SW and plunging southward. In the upper thrust sheet, Mesozoic sediments and volcanics developed along a transform controlled section of the northeast Arabian continental margin. After their displacement and as they started to reach the continental edge, Ophiolite thrust sheets were affected by the shape of margin. The Ophiolite sheet was fractured into two plates separated by NW-SE fault. The NE block collided with the Musandam block to the north resulting in an intensive imbrication of the thrust sheets in the Dibba zone.

The Mid-Late Tertiary folding and uplift of the Oman Mountains resulted in the formation of high angle normal faults with throws of less than 1500 ft. and trending mainly NE to SW. It is assumed that the Semail Ophiolite complex traveled a distance exceeding 120 km southeast over the Arabian continental margin.

The island-arc volcanism related to the Haybi volcanic rocks began in the Middle Cretaceous. The Semail ophiolite was completely emplaced by the end of the Maastrichian, as is attested by the fossiliferous shallow marine limestone deposited unconformably on top of the allochthonous units. The Ophiolite belt was uplifted with the latest emergence of the Oman Mountains during the Oligocene-Miocene.

Marked by deep fractures, which dislocated the mountainous territory of UAE into blocks and plates, the formation of the Oman Mountains generated a series of major tectonic events. The major line of tectonic dislocation is the Dibba line. The Dibba line of the fault system continues far away through the gravel plain and probably to the west of Dubai. Other major faults also dissect the gravel plain to the west of the mountains and parallel to the mountain in a generally N-S direction from Ras Al Khaimah to Al Ain area. Such system of faults in the gravel plain has been inferred from surface geology, but it is evident from the magnetic survey and subsurface data of drilled wells.

The faulting pattern in the gravel plain indicates that the sedimentary formations are in an echelon location vis-a-vis the fractured blocks to the east, which have been gradationally uplifted relative to the western blocks. This complicated structural situation would make water exploration very complicated. The complexity of structural geology explains the wide discrepancies encountered in some cases between neighboring wells.

(4) Regional Stratigraphy

After the Hercynian Orogeny (Upper Paleozoic) the prevailing sedimentary deposits changed drastically from mainly clastics to predominately shallow marine carbonates until the Eocene.

During the upper Cretaceous two major transgressive cycles of deposition occurred. The first cycle was constructed by the Laffan and Halul Formations, while the second cycle is represented by the Fiqa and Simsima. The end of Cretaceous shows a general regression over the whole of the Arabian peninsula resulting in the widespread disconformity at the base of the Umm Er Radhuma Formation. The ensuring transgression occurred in the early Palaeocene caused virtually the whole of the Arabian peninsula east of longitude 47° E to be covered by sea. These marine conditions prevailed until the lower or middle Eocene, during which time the neritic limestone and marls of the UER were deposited. The Rus Formation deposit is the final expression of the regression sequence seen in the UER before the transgression of the lower Dammam.

The Rus Formation is a shallow marine to supertidal deposit laid down in semi-barred restricted basins subsequent to the shallowing of a sea shelf on the eastern margin of the

Arabian Peninsula. At the end of the period of supertidal sedimentation that resulted in the Rus Formation, there was an influx of sea over the Arabian shelf causing widespread shallow water marine carbonate deposition. The Dammam formation outcrops over a wide area in the eastern coastal area of Saudi Arabia. In Abu Dhabi the Damniam is only exposed in Jabel Hahit.

The structural evolution of the Arabian platform has strongly inflated the sedimentation patterns in the UAE.

The formations mentioned above are described below and in Figure 1.2.2

a) Mesozoic: The Upper Cretaceous

Coincides with Aruma Group which consists of an alternation of limestone, marls, shales and dolomites. The top of the Upper Cretaceous is marked by a general discomformity which resulted from a major regression which started from the south as evidenced by the absence of the Aruma Group in the Mender area.

b) Cenozoic: The Lower Tertiary--Paleocene--Middle Eocene

During the period, two basins occupied the area:

- The Rub Al Khali basin to the south of Abu Dhabi, and
- The Pabdeh-Group basin with its center in the Northern Emirates.

The Hasa Group coincides with the Lower tertiary in the west and includes three formations:

-Umm Er Radhuma Formation

Coincides with an extensive transgression which started at the beginning of the Paleocene. Sedimentation started with the deposition of fine bedded shale at the base followed by shallow water carbonates consisting of shelly and bioclastic limestone and dolomites with occasional argillaceous horizons.

The top of UER is generally characterized by either Rus anhydrite or shale. The UER Formation displays great variations in lithology and thickness throughout the region; it is 1300 ft. thick in the northwest, 1600 ft. thick in the south and more than 2500 ft. thick in the east.

-Rus Formation

It is characterized by a dominant presence of anhydrite. The argillaceous limestone of the base of the Rus indicate lagoon conditions which are evidence of sub-area supertidal condition.

In the Bab area, the Rus starts with anhydrite and ends with argillaceous limestone. In Agrab, it consists of anhydrite with shale beds, in Mender it consists of anhydrite interbedded with limestone. Hydrogeologically, the Rus Formation is considered an aquiclude in Abu Dhabi

-Dammam Formation

Corresponds to a Middle Eocene transgressive phase with normal deposition of mainly nummulitic carbonates on shallow shelf conditions.

The base of Dammam is characterized by calcareous shales and argillaceous limestone overlain by foraminiferal packstone corresponding to very shallow shoal conditions. The upper part of Dammam consists of subtidal limestone dolomites and occasional shale beds.

c) Upper Tertiary: Upper Eocene–Oligocene–Miocene–Pliocene

The uplift and erosion which occur during the period extending from the Upper Eocene to the Lower Oligocene affected mainly the western part of Abu Dhabi. the opening of the Red Sea during the Miocene produced a northwestern rotation of the Arabian plate which resulted in the periodic closing of the Hormuz Straits. Massive deep marine salts precipitation from the Pabdeh Basin contemporaneously with the precipitation of Gachsaran evaporites (lower Fars) in Abu Dhabi.

- Asmari Formation

Consists of a fossiliferous, limestone, partly dolomitic, which was deposited during the Oligocene in shallow water corresponding to the shelf edge facies on the limit of the Pabdeh basin. Shales and marls are predominant towards the center of the basin.

- Low Fars (Gachsaran Formation)

Deposited in the Early Miocene in a closed evaporitic basin centered on on-shore Abu Dhabi. It is base unit consisting mainly of anhydrite with subordinate dolomite and clastics. The middle unit consists of dolomite and limestone. The upper unit includes anhydrite with interbedded shales, marls and carbonates.

d) Miocene–Pliocene

Uplift and erosion continued during the Upper Miocene and Pliocene over the entire area along with the further development of the Oman and Zagros mountain–alpine Orogeny. Active erosion took place during that period and led to the deposition of mixed sediments consisting of detritus sandstone and dolomitic limestones.

e) Quaternary

The whole territory of the UAE had already emerged and normal, continental erosion had taken place onshore and offshore which led to the deposition of the following types of sediments.

- Aeolian Dune / Sand

The dunes are of various shapes and sizes. The sand consists of Quartz, Zircon, Feldspars, Pyroxenes and Clay.

- Calcareous Sandstones

Occur as ridges and patches on masses mainly along the coast but also inland. They consist of Quartz grains or shell fragments around which a carbonate coat has precipitated.

- Sabkha:

Usually low lying, consisting of silty sandy clays rich in gypsum, carbonate of salt. Near with coast, they are richer in halite and sulfates and they are occasionally flooded.

- Fluviatile Deposits

They deposited as channel filling, scree piedmont outwash, and terraces. They are located within the mountain zones.

-Beach Type Deposits:

Consist of sand bodies close to the shore line.

- Gravel Plains:

These are intermediate zones located between mountain range at the desert plain. They consists of a mixture of gravel, sand, silt and clay. The deposits of the gravel plains extend from Ras Al Khaimah to Al Ain, which led to the formation of the new weathering minerals. Dissolution, migration, precipitation and cementation are common phenomena which have been boosted by active aquifers.

(f) Oman Mountains

The stratigraphy of the Oman Mountains has been mainly established through the work of Glennie (1974). The following stratigraphic units are differentiated:

- Pre-Campbrian Crystalline Basement

- Infra-Cambrian to Pre-Middle Permian essentially continental rocks.

- Middle Permian to Upper Cretaceous Shelf edge deposits forming Sumeini group

- Permian to Upper Cretaceous deposit of the Hawasina series

- Hayabi volcanics occurring in separate areas

- Permo-Trassic exotic limestones

- Melange Formation

- Metamorphic rocks

- Semail Ophiolites of the Upper Cretaceous age

- Maastritian and Tertiary marine sediments

- *Quaternary deposits.*

The first lower three units are considered autochthonous and correlate to the rest Arabian platform.

The Semail Group is considered para-autochthonous. The Semail Ophiolite and underlying Hawasina series are allochthonnous and have been thrust west-southward during the Late Cretaceous into the position they presently occupy.

Maastrichtian and Tertiary limestone unconformably overlie all other units.

1.2.2. Hydrogeology and Groundwater

The source water is rain falling on the Oman Mountains. Part of this rainfall percolates through the mountains and flows as groundwater under the plains, and part of it runs off as erratic flash floods in the numerous wadis that discharge onto the plains. Groundwater, recharged from the alluvial gravels, occurs throughout the area of the alluvial gravel in the Central Plains. The water table is usually 5–10 m below ground level. Where the groundwater occurs in sediments it is often too saline for permanent irrigation and salinity increase with depth by about 10,000 micro-S/cm. The salinity of the irrigation water originally used at Digdaga Experiment Farm caused a decline in agricultural yields to the point where certain wells had to be abandoned. Because of the salinity, gradient pumping rates have to be limited to restrict the drawdown. Groundwater recharge is derived from water percolating through the mountains and from flood waters percolating through the gravel of plains. The latter usually produce less saline water and in some area pumping rates of 30–40 m^3/hr for four hours a day can be maintained to yield water with salinity of less 400 ppm NaCl. Deep groundwater is believed to occur in aquifers at depths exceeding 250 m but it is expected to be highly mineralized. The source of the salinity is throughout to be old sea water or salts precipitated in former coastal deposits and, in some of the present-day sabkhas, direct contamination at depth with water of Gulf. Irrigation may be increasing the salinity of aquifers by carrying down salts from upper horizons.

1.3. Hydrogeologic Study in Study Area

(1) Location

The Study Area is located in the Al Dhaid area of UAE and is approximately 850 km^2 in extent. Generally the area is flat and forms the flood plains of wadis flowing off the Oman mountain range. Most of the Area is made up of constitutes gravel plains that are transacted in places by the channels of major active wadis. In certain area, the ground is covered by low sand dunes. Irrigation from wells and falaj has permitted the cultivation of large areas around the main population centers of Dhaid, Wishah, Mileiha, Falaj Al Mualla and other small villages in the area.

(2) Geology and Geomorphology

The northern Oman mountain are the topographical expression of a narrow elongate complex fold belt. The Mesozoic Hajar Group consists of a thick sequence of shallow marine limestones and dolomites with minor quartz sandstones, slate and granite. These basal metamorphics form the core of the Oman mountains. The typical continental shelf deposits of the Hajar group are overthrust by the Mesozoic Hawasina Nappe; a thick pile of thrust sheets of intensely sheared and folded cherts, turbiditites and deep water sedimentation. Recent sediments are predominantly wadi gravel in the form of coalescing alluvial fans deposited on both sides of the mountains. Although much of the comparatively high annual rainfall that falls on the mountain chain is lost by evaporation, occasional storms are of a sufficient intensity to result in infiltration into, and surface runoff from the head rock areas. The groundwater flow is essentially away from the mountain axis, and becomes increasingly saline towards the desert foreland. The study area is located within these alluvial fans which seem to have originated as detritus deposits. Recharge by flood waters may explain the presence of trees and shrubs that are characteristic of the wadi plains and other low areas. The natural vegetation supports a sizable population of camels and goats that are found around the several small villages in the area.

1.3.1. Geophysical Sounding

A geophysical survey of the Al Dhaid Plain, covering about 800 square kilometers, was begun in late April and concluded in early June of 1995. The primary objectives of this survey were to determine the thickness of alluvium in the survey area and to map the impervious basement beneath the study area. Secondary objectives of the study were to delineate aquifers, detect fault and fracture zones and to clarify the hydrology of the Al

Dhaid Plain. The measurements of Geophysical Survey covered the whole Study Area and were taken at locations where the results obtained from existing works (IWACO, 1986) could be applied for analysis of this survey. Transient Electromagnetic Sounding (TEM) was completed at 131 stations. The Natural Gamma Ray Survey was completed at 805 stations in which the vertical structure is drawn-out in resistivity map from TEM Result.

(1) Transient Electromagnetic Sounding

The transient, or time-domain, electromagnetic method, often referred to as TEM, is a method in which the ground is energized by a man-made magnetic field and its response is measured as a function of time to determine the resistivity of the earth beneath the observation point as a function of depth.

a) The Transient Electromagnetic Method

In this method, a steady current is passed through a loop of wire situated on the surface of the earth, which is inductively linked to the earth. The fact that loop sources, which have no direct contact with the earth, can be used, makes this method suitable in areas where high surface resistivities prohibit the use of conventional direct current methods. This would include regions covered by desert, sand dunes or extrusive volcanics.

In practice, the direct loop current is abruptly interrupted and the secondary field, which arises due to eddy currents induced in the earth, can be measured in the absence of the primary field. The eddy currents migrate from the transmitter loop into the earth and the pattern resembles the propagation of a 'smoke ring'. The rate of change of the magnetic field depends upon the underground resistivity structure. Given a poorly conductive medium, the receiver coil output voltage, which is proportional to the time rate of change of the secondary magnetic field, is initially large but decays rapidly. The response of a good conductor is initially lower but the voltage decays slowly. The time derivative of the transient magnetic field which results from these currents can be measured by a coil sensor.

The decay of the secondary field measured at surface can be analyzed to determine the resistivity of the earth at depth. The resistivities of geological materials are highly dependent upon porosity, water saturation, and pore fluid resistivity. Resistivity sounding, therefore, yields information about water content and quality, and TEM resistivity measurements are a valuable structural mapping tool for groundwater studies.

The TEM method was selected for this survey for the following reasons: (1) Stability of the transmitter signal; (2) Lack of static shift; (3) No near field phenomena; (4) uniqueness of the results; (5) High production rate; and (6) Suitability to the ungrounded source in rock desert.

b) TEM Equipment

The TEM system which was used in this survey was manufactured by Geonics Ltd., of Canada. The primary components of the system are a transmitter, a sensor coil and a receiver.

Two transmitters, an EM-47 and an EM-57, were used in this survey. The EM-47 is a battery powered transmitter which is capable of operating at high frequencies. It can be used to resolve shallow resistive units such as surface dune sands and dry alluvium. It is a low power transmitter, however, and has a limited depth of penetration. The EM-57 operates at lower frequencies and is powered by a gasoline motor generator providing a higher output current, leading to a greater depth of penetration. By combining measurements made from both sources, both the shallow and deep sections can be adequately resolved.

A responsive high frequency receiver coil with an effective area of 31.4 m^2 and an internal signal preamplifier was used for EM-47 measurements and a more sensitive low frequency coil with an area of 100 m^2 was used in the EM-57 measurements.

The receiver, a PROTEM 57 (C) unit, samples the coil response at a series of time intervals that are delayed by a prescribed amount from each turn-off of the loop current. There are 20 geometrically spaced gates or channel positions in each time range. Decay voltages were recorded at two EM-47 transmitter base frequencies (uh-237.5 and h-25Hz) and at three EM-57 base frequencies (H-25, M-6.25 and L-2.5 Hz) during the course of this survey.

A reference cable is used to establish precise timing between the transmitter and receiver.

c) Measurement configuration

Survey parameter tests were conducted at the beginning of the survey to aid in determination of the optimum measurement configuration for this survey. These tests were performed at a station near the center of the survey area where the thickest alluvial section was expected, so that the penetration of the measurements could be assessed. The test site was also chosen to be near a power line so that the effect of electromagnetic noise upon the measurements could be considered.

During these tests, measurements were made at the center of two square loops, fifty and one hundred meters in width, and with the receiver coil offset from the edge of a twenty meter loop by a distance of ten meters. While large loops yield higher signal and have a greater depth of penetration, they can be difficult and time consuming to deploy and retrieve. Small loops are more easily handled but they have limited depth of penetration and *offset* soundings are more sensitive to lateral resistivity variations.

In this survey a square transmitter loop 50 m a side was used to allow a high production rate while maintaining a high signal level and data quality. At each site, the receiver coil was located at the center of the loop and the loop was typically energized with a current of two to three amperes for high frequency EM-47 measurements and a current of about nine amperes for lower frequency EM-57 soundings. The 'central loop' sounding configuration was used rather than 'offset' loop sounding to minimize the effect of lateral resistivity variations and to maximize the depth of penetration.

d) Station Positioning

TEM measurement stations were positioned by first plotting the survey lines on topographic maps marked with U.A.E. national grid coordinates. The coordinates of the end points of each survey line were then converted to Universal Transmercator (UTM) coordinates and survey line azimuths were computed. UTM station locations were then generated at the desired azimuths and ranges from the starting points of the lines. The coordinate conversions and calculations were performed by computer program ". The UTM station locations were then entered into a Global Positioning System (GPS) and the GPS was used in the field to navigate to the approximate station location.

After selecting a suitable loop location in the vicinity of a station, a second GPS was placed at the receiver coil site and an accurate position "fix" was obtained by averaging hundreds of GPS measurements. These data were entered into the header of each sounding record as the measurements were recorded. UTM coordinates were used during all field operations and the datum which was used throughout this survey is Narhwan-U.A.E. (Clarke-1880 ellipsoid).

e) Station Locations

TEM measurements were made at a total of 131 stations spaced nominally one kilometer apart along five profile lines spanning the study area, Figure 1.3.1. The coordinates on this map are UTM grid coordinates and the datum is Narhwan-U.A.E.. Four of these profiles (A-D lines) are approximately parallel and run from west-northwest to east-southeast across Al Dhaid plain. The fifth line (E) is a longer north-south profile line through the center of the plain. The geometry of these survey lines is summarized in the following Table.

TEM Survey Line Geometry

Line	Start point, coordinates (UAE grid)	End point, coordinates (UAE grid)	Azimuth (dms)	Length (m)
A	A01, 659009N/230776E	A22, 648452N/249155E	119 22 55	21108
B	B01, 650580N/230393E	B23, 638994N/249071E	121 15 11	21969
C	C01, 634743N/232507E	C20, 626016N/248712E	117 37 49	18528
D	D01, 625376N/230507E	D19, 615162N/246131E	122 25 16	18836
E	E01, 615484N/238872E	E44, 658144N/244255E	006 34 40	43029

f) Noise

Electromagnetic noise is induced in the receiver coil by power lines, and from wind-driven movement of the receiver coil in the earth's magnetic field. Repetitive voltage measurements were made and averaged or 'stacked' to minimize these effects. The electromagnetic noise level was very low in the majority of the survey area but noise from power lines was appreciable in the vicinity of Al Dhaid.

Data can also be distorted by man made conductive objects such as pipelines or metal fences. Initial measurements produced transient data with polarity reversals at three stations near water-pipelines. These stations were moved a few hundred meters and usable data were obtained.

g) Data processing

The data analysis procedure used in this study is presented schematically in the flow diagram of Figure 1.3.2. The data which has been recorded in the field is first transferred from the PROTEM receiver to a personal computer, using the Geonics program. This data is stored in ASCII data files which are then read by a data inversion program.

In the first phase of data processing, the decay voltages for each gate are transformed into late-time apparent resistivity values, by normalization with respect to field data measurement parameters such as loop dimensions, receiver gain, current and sounding geometry.

The voltages, V_o (in units of mV), which are measured by the PROTEM receiver are converted to magnetic field decay rate, dB/dt (nV/m^2), by the following formula (Geonics, 1992).

$$\frac{dB}{dt} = \frac{V_0 \cdot 19200}{E \cdot 2^n}$$

where E is the receiver coil moment (m^2), and n is the amplifier gain setting21

. Apparent resistivities r_a (ohm-m) are then given as a function of time (t) by,

$$\rho_a(t) \cong \frac{\mu}{4 p t_c}\left(\frac{2\mu M}{5 t_c\, dB/dt}\right)^{2/3}$$

in which, m is magnetic permeability (*4p*10^{-7} H/m), t_c is measurement time or the gate center time in seconds, and M is transmitter moment which is the product of loop area (m^2) and current (A).

An automatic one dimensional inversion technique was used to generate resistivity models composed of up to 19 layers. In this process, the resistivities of the layers of a candidate model, which is chosen by the inversion program, are gradually changed and response curves are computed to determine the model whose response best fits the observed data. The model is not restricted by the condition that the resistivities of the layers change smoothly with depth, as they are with the Occam or 'smooth' inversion method. Models derived by this technique, without artificial parameterization, can be used to produce images which aid in visualization of underground structures. The imaging results were also used to estimate initial model parameters for the interactive one-dimensional inversions which followed.

Interactive inverse processing is used to obtain one-dimensional resistivity structures in areas where the geological section can be assumed to be composed of a more limited number of discretely layered geoelectric units. In this process we can estimate resistivity and thickness parameters for models composed of up to 8 layers. The inversions are done by the automatic ridge regression approach to nonlinear minimum square curve making. An inversion program was used in this study.

(2) TEM Sounding Results

Automatic one-dimensional data inversion was performed to generate 19-layer resistivity models for each of the survey data sets. The thickness of the layers increases with depth and these models extend to a depth of 600m from the surface. These results were used to produce resistivity sections and resistivity contour maps as shown in Figure 1.3.2. to 1.3.6. and to estimate initial model parameters for interactive one-dimensional inversions.

a) Geoelectrical Interpretation of the Resistivity Sections

The resistivity sections are images of the earth's resistivity beneath each of the survey lines, Figure 1.3.2. They can be used to aid in visualization of the underground structure and in estimation of groundwater distribution and quality. While the models from which these images were produced have a thickness of 600 m, sections below 600m are shown as blank.

The survey line coordinate in kilometers is given on the bottom axis of these plots. These line coordinates are calculated from point to point along the survey lines rather than along a best fit line through the survey points. The elevation above sea level is shown on the left vertical axis of the plots. The units of this axis are meters and the vertical exaggeration of the plot is twenty to one. There is a resistivity color scale at the right margin of the plots and information pertinent to data collection, processing and inversion is noted within a comment box near the lower right hand corner of the plots. The same color scale has been used for all plots in this section of this report.

-TEM Survey Line A

TEM Survey Line A strikes from WNW to ENE at 119° in the northern part of the survey area and is about 21 km long. There are 22 TEM stations on this survey line, Figure 1.3.1. Station A01 is 65 m above sea level (ASL) and the topography rises nearly monotonically to 197 m ASL at station A22 with a local topographic high at station A06, Figure 1.3.2. This section is, in general, highly resistive near the surface, conductive at intermediate depths and resistive at great depth. In the following text this and the following sections will be discussed as being composed of three layers, although in fact the resistivity of the sections vary continuously with depth. Resistive surface layers will be referred to as overburden and the bottom layer will be refereed to as the "electrical basement", or the deepest geoelectrical unit which can be detected from a given electrical sounding.

Stations A01 through A04 are located in a large dry wadi, A05 is in an agricultural area on the bank of the wadi and A06 is in high sand dunes. A07 is in a dry agricultural area and A08 is located in the village of Al Zarqah. A09 through A12 are in high to moderate sand dunes and A13 is on the edge of the dune field. A14 through A19 are on sand and rock desert with unconsolidated to weakly cemented sand and gravel at the surface. Stations A20 through A22 are within the reservoir of a large dry man-made earthen dam. The overburden in this section ranges in resistivity from 30 ohm-m to hundreds of ohm-m. The dry gravels in the wadi at the west end of the section are seen to be resistive and a more conductive area is seen at A05. The overburden is very resistive at A06 and a less resistive area is seen near Al Zarqah. Surface resistivities are high for the remainder of the survey line except at station 19 which is at the toe of the earthen dam. The base of the overburden rises gently in the west half of the section with the overburden thickening to the east. There are lows in the overburden base centered beneath stations A14 and A20. These may be caused by deformation or erosion of the underlying rocks.

The electrical basement of this section is conductive (20-45 ohm-m) in the west and more resistive (30-120 ohm-m) in the east. This could be due to a change in lithology, a facies change within a rock unit or a change in pore fluids in the basement rocks. Structurally, the basement is high from A11 to A22, lying at about sea level. There are vertical conductive zones beneath A13 and A19 which could reflect basement topography or could be caused by the presence of fluid bearing fractures or faults. The electrical basement drops to around -300m ASL from station A04 to A08 and there is an apparent basement ridge beneath A03. This basement ridge lies approximately along strike of the north-south striking ridge line known as Jabal Al A'zab or "Saddle Mountain", near Sha Biyyat Mileiha in the south-western survey area.

The middle of this section is seen to be very conductive with resistivities ranging from 1 to 10 ohm-m in the west and from 10 to 20 ohm-m in the east. There is a more resistive zone from A14 to A15 (25-30 ohm-m). The resistivities of this unit are quite probably controlled by the resistivities of pore fluids or by variations in the degree or type of cementation. The more conductive zones may represent areas where more saline pore fluids are present or areas of more resistive or dense cementation.

-TEM Survey Line B

Line B is approximately parallel to Line A and is about 22 km long. There are 23 stations along this line which runs through the center of Al Dhaid, Figure 1.3.3. Station B01 is 91 m ASL and the topography rises gradually to 190 m ASL at station B23 with local topographic highs at stations B03 and B05.

Stations B01 through B06 are located in moderately high sand dunes, B07 is near a village and B08 is in an agricultural area on the bank of Al Dhaid wadi, which lies between B07 and B08. B09 is in downtown Al Dhaid and B10 is located near the school. B11 through B13 are in low sand dunes near agricultural areas. The remainder of the stations on this survey line are on sand and rock desert with unconsolidated sand and gravel at the surface, except Station B21, which is located in an agricultural compound. This section is, in general, similar to the preceding section. It is highly resistive near the surface, conductive at intermediate depths and resistive at great depth.

The overburden resistivity again ranges from 30 ohm-m to hundreds of ohm-m over most of the profile, and the dune field at the west end of the section is seen to be resistive. From B07, which is at the edge of the sand dunes, to B20 the overburden is more conductive. At the east end of the profile (B21 through B23), where boulder beds are seen at the surface, the surface resistivities are only 10 to 15 ohm-m. The base of the overburden rises gently from B01 to B14 and the thickness of the unit is about 40m in this interval. At B15 the resistive surface unit thickens to around 130 m and at B18 it is about 90 m thick. This unit pinches out from B19 to B21.

The electrical basement of this section is generally somewhat conductive (15-45 ohm-m) and deep (about 200m), except between stations B07 and B11, where it is very resistive and quite shallow and beneath station B02, where a basement ridge, similar to that seen in profile A, is implied. While the basement ridge at the west end of the profile is probably real, the resistive anomaly beneath B09 may result from masking of geology by hydrology rather than the presence of basement rocks.

The middle layer of this section is generally thick and resistivities range from 1 to 15 ohm-m. There is a very conductive zone beneath B04, which may represent a more saline area. From station B21 to B23 the entire section is conductive.

-TEM Survey Line C

Survey line C is roughly parallel to lines A and B and it is about 18.5 km long. There are 20 stations on this line which passes near Sha Biyyat Mileiha and spans the Al Dhaid Plain in the southern half of the survey area, Figure 1.3.1. Station C01 is 155m ASL, C04 is 138m ASL and C20 is 231m ASL, Figure 1.3.4. The Saddle Mountain ridge line lies between C01 and C02.

Stations C01 through C04 are located in sand dunes, C05 through C07 are near agricultural areas and the remainder of the survey stations are on sand and rock desert covered by broad wadis. This section is somewhat different from the sections in the northern half of the survey area.

There is a thin resistive overburden at the margins of the profile, but this pinches out between C08 and C10. The conductive middle layer is much thinner (100-200m) and the basement is much more complex. The conductive zone from -20m to 80m ASL between C01 and C02 is false. It is a result of interpolation by the data girding program.

The electrical basement of this section varies in resistivity from 10 to more than 180 ohm-m. The basement is resistive from C01 to C05 and there are peaks in the basement topography beneath C03 and C05 which correlate well with similar peaks beneath B02 and B06. From C06 to C12 the basement resistivity is 8 to 10 ohm-m, which may imply a high clay content. The basement resistivity is 25 to 90 ohm-m from C12 to C15a and from C18 to C20 there is a very resistive unit near the surface. This unit is probably an ultrabasic formation which outcrops just east of this profile. The contact region between these resistive units (C15a-C17a) is very conductive and, while it may be a zone of fluid bearing faults or fractures, it is more likely a more conductive facies of the basement rocks, which can be seen in the following section.

-TEM Survey Line D

Survey line D is approximately parallel to lines A through C and is nearly 19 km long.

There are 19 stations on this line which passes near Fili at the southern edge of the survey area, Figure 1.3.1. Station D05 is 158m ASL and D19 is 265m ASL, Figure 1.3.5. There is a high limestone ridge line between D01 and D05.

Stations D01 through D04 are located in sand dunes on the flanks of the ridge line, D05 through D17 are on sand and rock desert covered by broad wadis, D18 is at the edge of outcropping ultrabasic rocks and D19 is on ultramafic outcrop. This section is similar to that of survey line C.

There is a resistive overburden at the center of the profile, but this pinches out at D07 and D17. The sands on the flanks of the ridge line are thin and less resistive than those in the northern survey area. The conductive middle layer is again thin (100-200m) and there are very conductive zones from D03 to D06 and from D15 to D17. The basement is somewhat more complex than that of Section C. The near surface conductive zone between D02 and D03 is probably a false result of interpolation during girding.

The electrical basement of this section varies in resistivity from about 1 to 45 ohm-m. Beneath D02, the basement is resistive above sea level and conductive at depth. From D04 to D07 and D14 to D17 the basement resistivity is 1 to 10 ohm-m, which again may imply a high clay content. These conductive zones correlate with similar zones of Profile C. The fact that the eastern-most of these has broadened may imply the presence of a conductive facies of the basement rocks rather than the presence of fluid bearing faults or fractures. The basement resistivity is 15 to 45 ohm-m from D07 to D13 and this zone corresponds to a similar resistive zone centered beneath C14. Ultrabasic rocks outcrop at the east end of this profile where very high resistivities are seen.

-TEM Survey Line E (south)

TEM Survey Line E strikes nearly north-south from near Fili in the south and is about 43 km long. There are 44 TEM stations on this survey line, which passes through Al Dhaid, roughly in the center of Al Dhaid Plain, Figure 1.3.1. Due to the length of this survey line, the resistivity section will be addressed in two overlapping parts. The southern half of the line will be addressed first. Station E01 is 200m ASL and the topography falls monotonically to 148m ASL at station E24, Figure 1.3.6. This section is resistive near the surface, conductive at intermediate depths and moderately resistive at depth.

Stations E01 through E20 are on sand and rock desert with unconsolidated to weakly cemented sand and gravel at the surface. This part of the survey line is covered with broad dry wadis, which run roughly normal to the survey lines. Station E21 is on a low rocky hill and E22 through E24 are in an agricultural area.

The overburden in this section ranges in resistivity from 20 ohm-m to 120 ohm-m and in thickness from zero to 50m. The upper surface of the underlying unit appears to be terraced or eroded with steps at E09 and between E18 and E19. The center of these channels (E06 to E07 and at E18) are beneath present day wadis and a broad wadi lies between E10 and E13. This unit ranges in thickness from 170 to about 300m and in resistivity from about 5 to 15 ohm-m.

The resistivity of the electrical basement is 15-45 ohm-m. Structurally, the basement deepens from E01 to E17 and there is a basement high beneath E18. This basement high is approximately on strike of a limestone ridge which outcrops 4 km east of the survey line and plunges toward it. Initial measurements made midway between E19 and E20 displayed polarity reversals, which theoretically cannot occur above a horizontally layered earth. Data of this sort usually imply subsurface faulting or fracturing, extreme lateral resistivity variations or current channeling by man made objects such as pipelines or grounded power lines. Station E19 was moved closer to E20 and normal data were obtained but the basement resistivity was found to be quite low. The zone between E19 and E23 is very conductive (8-15 ohm-m) and may be faulted or fractured.

-TEM Survey Line E (north)

The northern half of this line is topographically nearly flat. Stations E21, E28, E34, E37 and E44 are 160, 141, 146, 142 and 146m ASL respectively, Figure 1.3.7. E21 through E27 are located in or near agricultural areas and E28 through E30 are on sand and rock desert. Stations E31 to E35 are in agricultural areas within the town of Al Dhaid and E36 to E41 are on sand and rock desert. There are sand dunes which increase in size from E42 to E44 at the north end of the survey line.

This is a remarkable section with a broad zone of anomalously high resistivity extending from the surface to depth in the vicinity of Al Dhaid, which is an historic oasis. To the north and south of Al Dhaid there is a normal resistivity section quite similar to that seen in the southern part of this line. There is a thin resistive overburden, a thick conductive second layer and a moderately resistive electrical basement. Rather than discuss the northern and southern parts of the section, attention will be focused upon the resistive central zone in the vicinity of Al Dhaid.

In this region it is quite probable that hydrology is masking the geology of the area. The upper resistive cone which is seen beneath the more resistive overburden has a resistivity of about 30 to 90 ohm-m. A cone of this sort could represent a cone of depression in the local water table created by pumping. The elevation of the water table in Al Dhaid was around 100m in 1985 and it has been dropping since then. A second possibility is that this cone represents a lens of relatively fresh water floating on the much more conductive fluids of the middle layer. The shape of the conductive layer beneath this zone would be correct for a zone of brine incursion.

The resistivity of the lower cone is the same as that of the upper cone. This cone could, of course, represent a resistive basement high, but its occurrence directly beneath the upper cone is interesting. It could be that the lower cone is the water source that is currently supplying Al Dhaid and that the upper and lower cones are separated by a discontinuous impermeable layer. The vertical resistive zone beneath E38 and E39 may be caused by seepage of fresh water through another discontinuity of this layer.

A resistivity section all along survey line E is presented in Figure 1.3.8 with a vertical exaggeration of thirty to one.

b) Geoelectrical Interpretation of the Resistivity Contour Maps

Contour maps of the earth's resistivity at the surface and at five discrete depths were also produced. These can be used to aid in determination of the resistivity distribution in the survey area and to analyze correlation between the TEM survey lines. Information was collected only along the five survey lines and areas between the survey lines has been blanked in these sections. The software which was used to grid and contour this data, given the lack of data normal to the survey lines, assumes that trends along a survey line are normal to the line. Geologic trends in this area appear to be roughly normal to the east-west lines but they are nearly parallel to the north-south line and this gives a distorted picture. The reader should bare in mind that the data is only valid within about one kilometer of the survey lines and that this is especially important near line E.

(3) Natural Gamma Ray Result

The data of Natural Gamma Ray Survey was analyzed graphically and largely qualitatively. The four gamma-ray count values and the two count ratios which are recorded are plotted along survey lines. Mean values (M) and standard deviations (S) for each count and count ratio are also calculated for each survey line. With these mean values and standard deviations, the two threshold values, M + 2S and M + S are calculated and used to determine anomalous zones along the lines.

The result of Natural Gamma Ray Survey, 50 anomalies were also detected in Study Area, and several stations out of these were coincided with the vertical structure indicated by the resistivity pattern obtained by the TEM survey (refer to Figure 1.3.9. to 1.3.13).

1.3.2. Core-Boring and Test-Well Drilling

(1) Core Boring

Core Boring and Geophysical Logging were made to ascertain the underlying condition of Hydrogeology and Stratigraphy. Lithological data obtained from drilling were utilized to identify strata units and their stratigraphical positions. Lugeon values measured after drilling were referred as a hydraulic conductivity as well as used as an indexes for clarifying the permeable zones in the drilling section. Geophysical Loggings were completed for both purposes of revealing an aquifer characteristics and geophysical correlation to TEM survey.

Based on the result of Natural Gamma, Gamma-Gamma, Neutron and other analyses, the porosity of strata, so called Bulk Volume Water, i.e., BVW, which is the retrievable rate from aquifers, were estimated. The physical values themselves, such as resistivity logs measured in vertical section gave good evidences for a correlation to lithological changes. Through such correlative comparisons between the Geophysical Log and the result of TEM, Gamma Ray and further Fieldwork Surveys, the spatial view of hydrogeological structure in this area can be inferred. Therefore, all drilling sites comprising B1 and B2 were selected on the TEM lines. On TEM Line C, the two Core Boring sites were positioned apart five km from each other as shown in Figure 1.3.1. Line C was set on "Potential Area for Deep Aquifer in the south of Study Area" suggested by the IWACO Report (1986). The most productive well, namely GP6 drilled by IWACO Study, is also involved in this C line. Upon this regional situation recommended by existing study, the Coreborings of which are drilled to clarify the geological constituent, water bearing property on the extent of aquifer were planned to be completed on this C line. Besides, these locations are also confirm the positioning between the existing observation wells. The actual drilling works of B1 and B2 were completed from June to end of July 1995.

a) Scope Of Work

The objective of this Core Boring and Geophysical Survey is to obtain information of the lithological features and hydraulic feature and hydraulic characteristics of the aquifer and aquiclude down to a maximum depth of 300 m below the existing ground level. The technical means to achieve the results presented in this report can be summarized in three groups, which are described below:

-Core Boring

The scope of the work specified, included two no. borehole to be core drilled to depth of B1 = 200 m and B2 = 300 m, with a minimum core diameter of HQ or NQ size.

-Lugeon Test

To identify the test strata and depth for each down the hole packer test, the core recovery from the drilling operation was studied and as a result a total of 20 tests were performed. Each test section was limited to a length of five meters making a double packer configuration necessary.

-Geophysical Logging Details

A series of geological test in the boreholes were specified to determined the hydrological feature of the geological formations encountered. The various type of tests conducted can be described as follows:

**Natural Gamma* The Natural Gamma log which measured with caliper is used to relate the detectors response to the API standard.

**Caliper* A single arm is activated for the upward logging run and provides an accurate measurement of borehole diameter as well as side-walling by the sonde.

**Resistivity* The resultant potential between the 16"/64" electrode and remote bridle electrode is and used via Ohm's law and a geometric factor to provide resistivity.

**SP.* The spontaneous Potential (SP) log is a record of the electrical potential developed between the borehole fluid and the surrounding formation

**Sonic.* The fully compensated sonic sonde provides the average formation velocity / transit time for which porosity, rock strength (combination with density data) and lithology determinations can be made.

**Formation density* Measurement of back scattered gamma radiation is made using for formation density and porosity.

**Neutron* The response is a function of the presence of the lighter elements (mainly hydrogen) and after correction for borehole effects may be used to derive hydrogen index of Formation porosity.

**Temperature* Identifies zones of inflow / outflow and data for correction other logs (mainly resistivity).

**Conductivity* The conductivity of the fluid is measured with a tree ring contract cell which is driven by a constant voltage source using an alternating square wave to reduce electrode polarization. The log provides data to localize zones of different water quality.

**Hydrochemistry (pH, Eh, Do).*This log is a record of Eh potential and Dissolved Oxygen of groundwater.

b) Result of Core Boring

-Core Boring

The full lithological description along with the core details such as Total Core Recovery (TCR), Solid Core Recovery (SCR) and Rock Quality Designation (RQD) are given in Appendix 2.2. According to observation of the core, the lithology of the two borehole can be described as follows:

**CEMENTED GRAVEL*

Cemented gravel found at the surface and near surface are usually competent, brown to dark brown, elongated, such rounded to sub angular in shape, with fragments of limestone, often cemented by white carbonate/silty sand.

**CALCAREOUS MUDSTONE*

Calcareous mudstone is generally white in color, fine grained grading from very weak to moderately weak in terms of strength. There is a gradation color change with depth to bluish gray at some places.

**LIMESTONE*

In the Study Area the two important constituents of limestone are calcite and dolomite. Calcareous limestone is found in both types of borehole for a considerable thickness, and is usually white in color. Dolomite is a limestone which is usually brownish in color and was found in boreholes especially in Borehole No. (B2) at deeper depths. These limestones are usually massive and competent with very closely spaced joints. In these limestones some gravel inclusions are also found at some places. Due to the presence of other detritus material, sandy and marly limestone are also found.

The limestone is often interbedded with brown to dark brown weakly cemented CONGLOMERATE at some places.

A number of fissured or loose horizons found from 228-234 m and from 261-271 m. These fissured horizons are identified by GRAVEL fragments.

- Lugeon Test

Summary of the results is shown in the Appendix 2.2. As seen in table of result, maximum lugeon value is observed at the top sand and gravel layer of B2 hole. The other layer excluding sand and gravel layer is shown a less value than 1 Lu.

c) Result of Geophysical Logging

The summary of Geophysical Logging is given in Supplementary Drawings. The geophysical logs run in the open hole can be divided into those responding to properties of the formations (Formation Log), and those of the borehole fluid (Fluid Log) and are discussed in below on that basis.

-Geophysical Interpretation of B1

**Formation Log.*

Throughout the logged section, the caliper log is in gauge suggesting that a competent formation has been intersected, however the drilling method would have also aided the smooth nature of the borehole. A porosity log calculated from the sonic transit time log (calibrated in % Lst) has been presented. Due to the nature of the sonic transmission in the borehole, the sonic porosity log can be useful in distinguishing between primary and secondary porosity (Secondary porosity in the form of joints and fissures). Sonic porosity has a tendency to measure primary porosity whereas both the density and neutron porosity logs measure total porosity, subsequently the difference between the two sets of log data infers secondary porosity.

Gravel alluvium identified in the core from ground level to 16.5 m corresponds to lower formation porosity where an average value of 35% Lst is recorded. Gamma activity increases within the gravel alluvium above 10 m and thin clay horizons are suggested by gamma peaks, however the overall clay content of the gravel alluvium is interpreted as being low.

Limestone with thin interbedded dolomite/dolomitic clay is interpreted from the formation logs between 16.5–84.5 m. Gamma activity remains low throughout the interval and whilst the formation resistivity ranges from 3.9 ohm-m to 9 ohm-m, the lower density porosity compared to the neutron porosity is through to represent dolomite rather than clay. The average formation porosity recorded is 40% Lst. A primary porosity origin is indicated in the limestone where sonic porosity records similar value to that of density and neutron porosity.

Dolomite is interpreted between 84.5–133 m where the density porosity is typically some 5% Lst lower than the neutron porosity. The average formation porosity decreases to 36% Lst with corresponding increase in formation density (up to an average of 2.3 g/cc). A thin, hard, low porosity limestone is identified at 110.5 m. Increased gamma activity between 84.5–109.5 m correlates within increased formation resistivity (up to 23 ohm-m). The high gamma activity is unlikely to be associated with clays. A thin fissure is identified by the caliper log at 124 m. Throughout the dolomite, sonic porosity is lower than both the density and neutron porosity values, which indicates the presence of secondary porosity. Joints and fractures are noted in the core over this interval. Low formation resistivity between 122–133 m correlates with a large amount of secondary porosity and a highly fracture nature noted in the core.

Limestone is interpreted from 133–200 m where gamma activity decreases to an average of 4 API. The limestone is identified as being dolomitic in places and has variable porosity; between 20% Lst and 47% Lst. A number of thin clays are identified by thin gamma peaks and lower formation resistivity. A slight development of secondary porosity is indicated between 169–190 m.

-Geophysical Interpretation of B2

**Formation Log*

Gravel alluvium is interpreted from ground level to 29 m where a slight increase in overall gamma activity is noted. A limestone dominated matrix and/or clasts is indicated by the overlaying density and neutron porosity logs. Gamma activity reaches a maximum of 13 API above 10 m. Formation porosity records a range of 32% Lst to 58% Lst.

Limestone with thin interbedded dolomite is interpreted between 29-101 m where gamma activity averages 4 API and for the majority of the logged section the density and neutron porosity logs record the same values. The thin interbedded dolomites are identified by lower density porosity and formation porosity. Thin fissures are identified by the caliper log at 33-39 m. The sonic porosity logs indicates a dominance of primary in the carbonate formation, with the exception of a limited development of secondary porosity between 60-74 m.

Dolomite with thin, interbedded limestones is interpreted between 101-219 m where gamma activity increases slightly to an average of 6 API, the baseline of the formation resistivity logs decreases to around 3 ohm-m and lower density porosity is recorded compared to neutron porosity. The thin limestone are highlighted by increased formation resistivity (up to 17 ohm-m), lower formation porosity and lower sonic transit times. Formation porosity records an average of 40% Lst. Primary porosity is present in the formation as indicated by the sonic porosity values being similar to that of the density and neutron porosity values. A number of sandstone horizons are recorded in the core over this intervals. The typical geophysical signature for a sandstone is not recorded which may be attributed to a fine grained nature.

Below 219 m, the formation becomes increasingly clay rich where gamma activity reaches a maximum of 14 API. Interbedded limestone and some thin dolomite horizons are identified by increased formation resistivity reaching 23 ohm-m, low sonic transit time and increased formation density. Formation porosity average 32% Lst but decreases to less than 20% Lst in places. A number of fissured or loose horizons are identified by the caliper log. A number of shales, however this feature is not recorded by the geophysical logs.

(2) Well Drilling

a) Location of Survey

The well locations were selected based on previous survey, inclusive of TEM survey, Natural Gamma Ray and reconnaissance survey of area. In the same period, a series of permanent benchmarks were installed allowing topographical surveying of each well to obtain their elevation. A summary of wells drilled is given below:

Well No.	Northing	Easting	Bit Size	Drilling Fluid	Total Depth (m)	Elevation (m)
PW1	2793594	397342	17 1/2	Bentonite mud	600	182.60
PW2	2785600	394300	8 3/8	-ditto-	150	177.86
OW2	2785600	394300	17 1/2	Airform	70	177.96
PW3	2782369	391000	8 3/8	Bentonite mud	300	162.52
OW3	2782369	391000	17 1/2	Airform	250	162.32
OW4	2805856	386558	8 3/8	Bentonite mud	300	100.00
PW4	2802981	391257	17 1/2	-ditto-	350	131.55
PW5	2771060	387299	17 1/2	-ditto-	300	178.10

(b) Water Well Drilling Program

- Introduction

Two drilling rigs were employed to complete the water well drilling for the Survey. Drilling tools diameter were specified as 8 3/8" bit for the observation wells and a 17 1/2" bit for the pumping wells.

All observation wells (OW-2, OW-3 and OW-4) and those pumping wells where no observation wells are present (PW-1, PW-4 and PW-5) were drilled by the rotary method using a bentonite mud flush. The wells were drilled with mud in preferable to the much faster air form method in the competent formations encountered in this area, in order to minimize the amount of cuttings dilution by cave in form higher horizons. The pumping wells at those sites with observation wells (PW-2 and PW-3) were drilled by rotary method employing direct circulation air foam.

A sample of the cuttings were collected at one meter intervals and stored in core boxes in order to facilitate viewing and retrieve of the samples.

-Well Design

Following the geophysical borehole logging of the observation wells and a description of the drill cuttings, a design was completed in the field followed by the immediate installation of the screen and casing. The production wells were designed based on correlation of the drill cutting with the observation well.

Once the screen and casing had been installed, the annular space between the borehole and the screen and casing was backfilled with well rounded ophiolite gravel. Care was exercised so that equal amount of gravel were introduced on all sides of wells. The gravel was filled up to six meters from the surface.

In two of wells (OW-3 and PW-3) a concrete plug was installed above the screened interval in order to isolate the aquifer from water bearing horizons at shallower depths. A tremie pipe was used to wash down a one meter thick layer of sand on top of the gravel pack. This served to prevent the grout from entering the gravel pack. The grout, a cement-bentonite mixture, was also installed using a trimmer pipe. After setting grouting, the rest of the borehole annulus was backfilled with gravel.

Once the wells had been developed, the gravel level was checked and topped up if subsidence, due to a break-up of the bridges in the gravel pack, had occurred. A 0.5 meter thick sand layer was installed on top of the gravel prior to pouring the cement grout. This serves as a filter to prevent grout from entering the gravel pack. The wells were grouted to surface. Once the grout had set, a 1 x 1 x 0.75 meter deep elevation was dug around the well head to accommodate a 1 m x 1 m x 1 m concrete plinth which was installed inside steel shutters.

A steel surface casing was set in the concrete plinth to protect the well against any interference from the surface. The observation wells are completed with a 6" and the pumping wells with a 14" surface casing.

- Observation Wells

The observation wells were completed in 4" casing and screen. the observation wells were designed to open the entire aquifer interval penetrated by the borehole. The base of the well was sealed by a wooded casing plug. A removable wooded plug was also installed at the surface.

-Pumping Well (Production Well)

Pumping wells were completed in 12" casing and screen. Production wells PW-1 and PW-4 were completed in bridge slotted steel. The cased wells PW-1 and PW-4 were designed to be screened over the aquifer interval penetrated by the borehole. Due to the meterage of available bridge slotted casing, only highly productive intervals of PW-1 and PW-4 were screened. All wells were completed with a pump sump at their base. This was sealed at its base by a wooded casing plug for the cased wells and a steel plate for the steel cased wells. A removable wooded plug was also installed at the surface.

-Well Development

The observation and pumping wells were developed by airlift pumping until the water was clear of sand and bentonite. An element of raw hiding was accomplished by switching the compressor on and off a number of times. Any residual bentonite was generally removed during the calibration pumping test.

(c) Geophysical Borehole Logging Program

Geophysical borehole logging was carried out in the observation wells and in the pumping wells where no observation wells were present. The logging was conducted during two visits. The first visit was immediately after the completion of drilling in order to record the following formation logs:

- Caliper and natural gamma

- 16" and 64" normal resistivity and spontaneous potential
- Neutron
- Density (gamma-gamma)
- Sonic

The geophysical field logs supplied on site were used in conjunction with the cuttings logs in the design of the wells.

The second field logging visit was accomplished after the wells had been completed and developed. The following fluid logs were recorded:

- Temperature and Conductivity
- Hydrochemistry (pH, Eh, DO)

Temperature and conductivity were logged throughout the well. Due to a depth limitation of the sensors used in the hydrochemistry tool, pH, Eh and DO were recorded to a maximum submergence depth of 150 m. Below this depth, water samples were taken with a pressurized depth sampler and brought to the surface for measurement.

d) Pumping Test Program

The pumping test were carried out with a range of pumps 0.3 L/sec to 25 L/sec. the maximum pumping head was generally 100 m in order to accommodate the very high drawdowns anticipated in the Study Area. The pumps were installed at a depth exceeding 100 m so that the wells could be stressed to the maximum available capacity of the pumps. the pump discharge was controlled by a valve located after a pressure gauge which gave the operator a direct control over the working head of the pump. The drawdown in the pumping wells and the observation wells (if present) was measured by electrical contact dippers and recorded at regular intervals.

The pumps discharged directly into V-notch weir tank which was calibrated in order to give an accurate reading of well discharge. The water was then collected in a tank and pumped to a distance of 30 m. This water was then collected in a tank and pumped to a distance of 300 m. this distance was considered adequate to ensure no re-circulation of the pumped water over the test intervals.

- Airlift Test

During the well development by airlift pumping, the approximate yields obtained from the wells was ascertained by the driller on site. This information was used to choose the most appropriate pump capacity required fro the subsequent pumping test.

-Calibration test

A calibration test was the first test run after pump installation. The pump, generator, lights and other equipment necessary for the pumping test were run for a sufficient length of time to ensure that everything was in good working order; this was usually a period of 30-60 minutes.

The drawdown in the well was recorded at regular interval to establish the maximum likely discharge test could be obtained from the well without dewatering it. Once this discharge rate was found, three further discharge rates were selected from the pump discharge specifications to give an even distribution of well discharges for the subsequent variable rate discharge test.

-Variable Rate Discharge Test (Step Pumping Test)

A variable rate discharge (step pumping test) was completed in every pumping wells after the calibration test. The step pumping test considered of four increasing and three decreasing pump discharge steps. The discharge rates employed for the step test were chosen during the calibration test. Each step was of one hour duration, after which time the pumping water levels had usually reached to quasi-equilibrium. The transition from one step to the next was an immediate, smooth change in discharge.

The temperature and electrical conductivity of the water was recorded at regular interval throughout the step pumping in some of the wells. The well yield was measured by the 90° V-notch weir and checked with the time required to fill a 210 L drum.

The recovery of the water level was recorded for a short period of time (usually one hour) after the end of the step test.

-Constant Rate Discharge Test

A 24-hour constant rate test was completed once the water levels in the aquifer had achieved a full recovery. The pumping rate used for the constant rate was chosen after consideration of the step test result. A maximum pumping rate was chosen that did not risk the complete dewatering of the pumping well over the 24-hour period.

The well yield was monitored by V-notch and drum readings. The temperature and conductivity of the water was also measured at a regular interval in some of the wells.

-Recovery Test

A recovery test followed immediately on from the constant rate discharge test until the water levels had approached their previous static water levels.

c) Result of Well Drilling

PW-1 and PW5 are single wells without observation wells. PW-2 and PW3 have observation wells at 10 m and 20 m distance respectively (OW-2 and OW-3). OW-4 was a dry well, so PW-4a was drilled at a location approximately five kilometers away. Due to drilling problems in PW-4a, the required depth could not be achieved, and its present depth is 170 m. A second well was drilled 20 m away, PW-4b, This was completed to 350

m. A summary of the well design for all wells is given in below:

Items	PW-1	OW-2	PW-2	OW-3	PW-3	OW-4	PW-4b	PW-5
Casing diameter (inches)	12	4	12	4	12	4	12	12
Screen (m)	0-46 160-300 380-430	0-13	0-15	0-196	0-195	0-17	0-42 85-131	0-98
Plain casing (m)	460-597	144-150	66-70	294-300	248-250	-	234-350	297-300
Total depth (m)	600	150	70	300	250	300	350	300
Surface grout interval (m)	0-6	0-6	0-6	0-6	0-6	0-6	0-6	0-6
Sand interval (m)				189-190	189-190			
Bentonite plug (m)	-	-	-	188-189	188-189	-	-	-
Grout/bentonite plug (m)	-	-	-	160-188	160-188			
Driller's yield (gallons/h)	3,500	3,500	1,500	3,500	1,500	0	little	3,500

d) Lithology

The cutting logs of the wells that were drilled indicate a very variable and complicated geology over the Study Area. This can be visualized in terms of a multi-layer of gravel, sand, silt, calcareous mudstones, silt and chalky dolomitized limestone that show a distinct cyclicity. Each cycle is represented by a coarse clastic base, usually in the form of gravel, which frequently shows reworking of the underlying carbonates of the previous cycle. This grades upwards in all parts of the sequence, and the base is sometimes represented by sands or silts. The carbonates at the top of the cycle are a pure chalky white in the classical cycle, but if this is not fully developed, they may end in a carbonaceous mudstone or silty limestone, before the next cycle starts.

Data from geophysical borehole logging indicates that some of the carbonate horizons may be dolomite. The gravel are generally composed of rocks of ophiolite origin, ranging from mafic to ultramafic rocks in various states of weathering. Below 200 m in OW3, the gravel are a distinctive green color, well sorted and graded (3–5 mm). This is viewed as the 'fossil aquifer'. This cyclicity can be explained by a series of marine transgressions and regressions, whereby the gravel and sands represent detritus from the Oman mountains that gradually get replaced by marine carbonates as the transgression progresses. At the top of this sequence aeolian sand from a thin superficial cover e.g. PW/OW-2 site. The influence of aeolian sands may be lower down in the sequence in the form of reworked sand dunes that are incorporated in the fluvial deposits.

The lithological sequence is shown in Appendix 2.3.

e) Geophysical Logging

This paragraph described and interprets the borehole geophysical logging which was part of the Study. The aim of the geophysical logging was to produce data on the rock formations that were penetrated by the borehole. The work contains a description of the method used to make measurement in the well, followed by an interpretation of the results. In the Study, the different logs were run in the boreholes, the various physical parameter which measured by these logs are described as follows:

- Three Arm Caliper

This log measures the internal diameter of the well. It is used to identify fissures and fractures in the rock formation, which may show up as sharp increases in diameter on the log. The caliper may also identify softer or less consolidated rock formations which trend to "wash out" during the drilling process. Finally, for safety, the caliper is a standard means for determining the stability of the well prior to running the radioactive logs (density and neutron).

-Natural Gamma Log

This log is measure of the naturally occurring radioactive isotopes which may be present in rock, namely potassium, thorium and uranium. These are most commonly found in clay minerals, and hence the neutral gamma log (GR) is used primary as a clay indicator.

-Formation Density Log

This log measures the bulk density (RHOB) of the formation. This can be used to identify changes in formation type, to detect fractures, and after processing to measure total porosity (the porosity being inversely proportional to density). This is displayed as the DPHI log.

-Neutron Porosity Log

The neutron log is essentially a measure of the hydrogen in the rock formation, and since hydrogen is an element of water (H_2O), the neutron log is thus a measurement of water content of the formation. Assuming that below groundwater level the pores that are contained within the rock formation are fully saturated with water, the neutron log can effectively measure total porosity, NPHI. Some care has to be taken in interpreting neutron logs since clay usually contains water that is 'chemically bound' within the clay, and since this is not 'free water' the log will not be a measure of true porosity in this case. In addition, in the Study Area the wadi gravels contain serpentinite which contain chemical -OH group and so will affect the log.

- Sonic Log

The sonic log continually passes an acoustic (sound) wave through the rock to a receiver on the tool. The log makes use of the fact that sound travels faster through a hard material than through a relatively softer material, and so the log can differentiate between hard and soft formation of rock. Harder (more competent) formations give shorter sonic transit times (TT values) and show up as a kick to the right on the log. More porous rock formation may often show longer TT values. The porosity can be processed to give a 'sonic porosity log' (SPHI).

The sonic porosity log normally responds to primary porosity of rock. This is in contrast to the neutron and density (NPHI, DPHI) porosity logs which measure total porosity, namely the primary porosity, plus in addition any secondary porosity from joints and fissures. Thus any difference between the SPHI log and the NPHI, DPHI logs infers secondary porosity by default.

f) Geophysical Log Interpretation

-PW1

From the geophysical logs and drill cuttings the borehole can be divided into four broad lithological divisions at the following depth intervals:

0m–160 m

Lithology. Cemented gravels and silty cemented gravel with occasional bands of calcareous mudstone and limestone.

Geophysical log. The uppermost division from 0–160m comprises mainly cemented gravels and silty cemented gravels with less frequent interval of calcareous mudstone and a little limestone. Minor clay content in the gravels is indicated by the GR log from 21.5–25.5 m, and also to a lesser extent at several thin bands between 127–142 m. These bands also show up as relatively lower resistivity values under 20 ohm-m. The overall clay content of the cemented gravel however is low. The caliper log shows the borehole was slightly washed out from 25–30 m, and a significant diameter reduction to 200 mm (8") between 84–91 m within the cemented gravel. Formation porosity was mainly 15–20%, with sonic porosity in places lower than both the density and neutron porosity, indicating secondary porosity.

****160–271 m***

Lithology. Calcareous mudstone with some cemented gravel (160–216.5m), and alternating of limestone, calcareous mudstone, and silty cemented gravels (217–271m).

Geophysical log. The second division from 160–271 m can be divided into two units. The upper unit from 160–217 m is a thick unit of calcareous mudstone with only a small amount of cemented gravel. The calcareous mudstone is overall more washed-out than the overlying gravels, to 600 mm (23.5") in places. Porosity are in the range 5-20% Lst, with slight secondary porosity developed over some interval, e.g. 195–206 m. The lower unit from 216–271m comprises limestone, calcareous mudstone, and silty cemented gravels. Porosity, interpreted as mainly primary porosity, are mainly in the range 10–20% Lst.

271–450 m

Lithology. Predominately limestone and brown silty limestone with some calcareous mudstone and cemented gravels. Fissure / fracture at ophiolite boundary 419–423 m.

Geophysical log. The third main division from 271–450 m comprises predominantly limestone and brown silty limestone, with smaller intervals of calcareous mudstone and cemented gravels. The top of this division from 271 m to around 303 m is a slightly harder formation, with shorter sonic transit times, higher resistivity values (505 ohm-m), and lower porosity of around 2–21% Lst. Possible localized dolomitisation is indicated in a few places where the density porosity is lower than the neutron porosity, e.g. 317–320 m.

Between 325–360 m the porosity values of the limestone were higher, around 15–20% Lst, with a little secondary porosity in places e.g. 339–346 m.

The rest of the division from 360–450 m showed porosity of around 10–15% Lst, these porosity are interpreted as being mainly primary. A significant fissure / fracture is identified by the caliper from 419–423 m at the first ophiolite / calcareous mudstone boundary.

450–600 m

Lithology. Weathered zone 509–549 m. A number of small fissures, particularly 467–502 m.

Geophysical log; The forth division from 450–597 m comprises the ophiolite basement. Some of the ophiolite is highly weathered, in particular a broad band identified on the cuttings from 509–549 m. A few limestone cuttings were found down to around 500 m. The caliper log show a mainly regular bore, with a number of small fissures particularly from 497–502 m. Most of the ophiolite shows resistivity values of around 15–70 ohm-m, however low resistivity 3–15 ohm-m is seen between 593–549 m, possibly associated with weathering. Secondary porosity is developed below this depth with SPHI values lower than the NPHI and DPHI values.

- OW-2

From the geophysical logs combined with the logs of the drill cuttings, two broad geological divisions have been identified at the following depths. The Upper division from 0–86.5 m is predominantly comprised of cemented gravels with less frequent horizon of calcareous mudstone. Five units have been identified within this division coming at 0–4 m, 4–39 m, 39–63 m, 63–72 m and 72–87 m.

**0–87 m*

Lithology Cemented gravels, with occasional bands of calcareous mudstone. Some of the cemented gravel beds are very hard.

Geophysical Log. The top unit, from 0–4 m comprises unconsolidated sand that has been washed out. The lithological log shows 0–2 m as fine dune sand, 2–4 as coarse sand. The second unit is from 4–39 m, and comprises mainly cemented gravel (silty in places) interbedded with calcareous mudstone below 28 m. The top nine meters of cemented gravels from 4–12 m are poorly consolidated and have been washed out during drilling. From 13–17 m is a hard cemented gravel with a fast sonic TT value of under 320 micro-sec/m, and with low neutron porosity (NPHI) values of between 2 and 5% Lst.

The interval from 17–39 m comprises mainly cemented gravels and cemented gravels, with some bands of calcareous mudstone below 29 m. The neutron porosity values are mainly 10–20% Lst with some peak values at 25% Lst. Gamma activity remains low, with GR value of mainly 5–10 API. There is possibly a small fissure at 27 m seen on the caliper. There are relatively soft bands of cemented gravel in the intervals 17–19 m, and 32–34 m.

The third unit from 38–63 m is characterized by notably harder bands of cemented gravel. Overall the unit comprises mainly cemented (mostly silty) gravel, interbedded with calcareous mudstones. The harder. more competent bands of gravel with sonic TT values faster than 200 micro-sec/m are at the depths 38–43 m, 49–55 m and 58–63 m. these harder bands have low porosity (NPHI 2–15% Lst), and the upper two bands also show high resistivities of 60–70 ohm-m. with their upper and lower boundaries marked by kick on the SP Log.

The unit from 63–72 m comprises calcareous mudstone with neutron porosity values around 15% Lst. From the drill cuttings, the possibility that there were thin beds of gravel within this unit of calcareous mudstone was indicated, and this is borne out by the resistivity logs, which show a typical oscillating 'thin bed effect'.

The unit from 72–87 m comprises cemented gravels, mainly silty or sandy, with formation porosity values of around 10–20% Lst.

**87–155 m*

Lithology Calcareous sandstone with some thinner horizons of cemented gravel. Several bends of calcareous mudstone.

Geophysical Log The second division from 87–155 m comprises mainly calcareous mudstone. Neutron porosity are mainly in the range 10–20% Lst with a mean value of around 15% Lst, these being interpreted as primary. Natural gamma value are low, around 15% Lst, these 88 API, and the caliper log detected few or no fissures in the rock. Compared with the lithology above 87 m, this lower division has more frequent bands of very low resistivity of less than 2 ohm-m, these being in the interval of 87–90 m, 107–108 m, 121–124 m, 128–129 m, 135–193 m, 140–143 m and 148–153 m. The bands of low resistivity are more frequent towards the bottom of the well, and may coincide with slightly higher sonic and neutron porosity values.

-OW-3

From the geophysical logs and the drill cuttings, four main geological divisions have been identified at the following depths. 0–21 m, 21–197 m, 197–229 m and 229–300 m.

0–21 m

Lithology Alluvial sediments, comprising sand, well-sorted gravel, and silt with calcareous mudstone at base.

Geophysical Log Gamma activity in this division decrease gradually with depth from around 30 API to under 10 API at 24 m. This division can be sub-divided into an upper unconsolidated unit, and a lower slightly more consolidated unit of calcareous mudstone.

From 0–14.5 m the formation is relatively unconsolidated with washouts on the caliper, particularly above 6.5 m and in the silt horizon 13.5–14.5 m. The sand, gravel and silt show low density and high neutron porosity up to 30% Lst. The long sonic transit times (TT) 450–500 micro-sec/m indicate unconsolidated formation. The interval 15–21 m comprises calcareous mudstone that is less washed out, with slightly shorter TT values of 350–500 micro-sec/m indicating a more consolidated unit. Porosity value are around 15% Lst.

21–197 m

Lithology Silty limestone and limestone, with occasional bands of sand or well-sorted gravel up to 5 m thick. The borehole through this division shows a uniform bore with very few wash-outs or fissures. Four sub-units were identified as follows:

a. 27–49 m Uniformly very dense limestone of formation porosity about 7% Lst;

b. 49–84 m Formation porosity 7–20% Lst;

c. 84–118 m Hard bands of limestone shown by short sonic transit times and low formation porosity down to 0% Lst.

d. 118–197 m Formation porosity 7–20% Lst

Geophysical Log Unit 27–49 m. The top 4 m of this unit are a transition zone from the calcareous mudstone above, below which the log shows a uniform, very dense, low porosity limestone with porosity values around 7% Lst. The limestone is of fairly uniform competence with a TT value of 300-400 micro-sec/m with resistivity values fairly constant around 40-60 ohm-m. Below 41 m the resistivity values goes down to around 10 ohm-m. GR values are very low, around 7 API.

The unit from 49-84 m shows less dense limestone than the overlying unit, with higher neutron porosity in the range 7-20% Lst, interpreted as primary, and slightly higher GR value up to 18 API: much of this limestone unit is silty or sandy, and is not as hard as the overlying limestone unit, with a TT value in the range 300-550 micro-sec/m. A relatively harder silty gravel horizon lies between 67-69 m, shown by quicker TT values and higher resistivity. A clean sand horizon lies between 80-84 m, shown by kicks on the SP and GR values less than 5 API.

The unit from 84-118 m contains several hard bands of limestone of low porosity. These bands are several meters thick and are identifiable from the short transit times of less than 320 micro-sec/m, high densities, higher resistivities and low neutron porosity down to 0% Lst. The boundaries of these low porosity limestone bands are mostly defined by kicks on the SP log. Two bands of gravel are identified on the lithology log in the intervals 101-103 m and 116-118 m.

The unit from 118-197 m is mainly limestone of fairly uniform physical properties, with occasional bands of gravel. Neutron porosity are mainly between 7 and 20% Lst. In the interval 141-170 m the density and neutron porosity curves diverge slightly, indicating a less pure limestone. The GR log has value mainly from 10-18 API, with some thinner peaks up to 30 API indicating clay.

**197-229 m*

Lithology Gravel, well-sorted, with bands of silty sand, calcareous mudstone and silt.

Geophysical Log GR values are low, mostly under 10 API. With the exception of the gravel horizon from 225-229 m % Lst. and this is coincident with slightly longer sonic TT values of over 400 micro-sec/m in places.

**229-300 m*

Lithology Calcareous mudstone with occasional bands of well sorted gravel in intervals 227-269 m and 283-287 m.

Geophysical Log. GR values are low. Formation porosity value are mainly from 10% to 15% Lst, and are interpreted as primary.

- PW-4

Three broad geological divisions have been delivered from the logs and the drill cuttings at the 0-85 m, 85-225 m and 225-350 m.

**0–85 m*

Lithology Sand overlying cemented gravels and limestone occasionally mixed with silty layers. Very washed-out at 0–8 m due to weak and poorly cemented formation

Geophysical Log From the surface to 8 m the caliper log shows the borehole to be washed out indicating a weak or poorly cemented formation. The slightly higher natural gamma activity in the gravel down to 20 m indicates a minor clay content in these gravels. The very high sonic transit times above 18 m show this horizon to be the non-saturated zone. The porosity are between 15–25% Lst above 39 m. At depths below 39 m the porosity, at 15% Lst, is lower. The porosity is mainly primary except for 2 zones from 56–59 m and from 68–70 m. The porosity is interpreted as being secondary here as the sonic porosity (SPHI) is lower than the other porosity.

****85–225 m***

Lithology Limestone. From 148–174 m and from 180–223 m, cherty layers are intercalated.

Geophysical Log The resistivity over this interval is higher, rising to nearly 500 ohm-m from 109–115 m, from 140–151 m and from 200–260 m. The limestone has porosity of between 10–20% Lst. Much of this porosity is secondary in nature especially from 104–128 m, 137–140 m, 144m–160 m, 168–170 m, 184–193 m and from 207–213 m. The caliper is in gauge over most of the interval, except at the base from 211–224m where the borehole is slightly enlarged.

****225–350 m***

Lithology Mudstone with some dolomite, cherty in places. Three dolomite layers at 226–231 m, 246–257 and 318–319 m. The middle dolomite layer is cherty.

Geophysical Log The resistivity over this intervals are low, generally being less than 10 ohm-m. The self potential log (SP) shows considerable differences between the dolomite and mudstone beds. The log has much higher values over the mudstone units. The gamma activity is generally higher in the mudstone beds indicating higher clay content. The is borne out by the low resistivity and the fact that the neutron porosity (NPHI) is higher than the density porosity (DPHI). The low sonic porosity in the dolomite between 247–249 m is interpreted as secondary porosity. The caliper log shows the hole diameter to be generally larger due to the softer nature of the mudstone. This is especially so from 233–238 m to 244 and from 262–265m.

- PW-5

Four broad geological divisions were in evidence from the logs at 0–22 m, 22–81 m, 81–158 m and 158–300 m.

**0–22 m*

Lithology Sand, and fine sandy silt overlying silty gravel and calcareous mudstone. Weak / Poorly cemented formation very washed-out 11.5–22 m

Geophysical Log The top division is very washed-out, and also indicated by long sonic transit times.

****22–81 m***

Lithology Mainly limestone or silty limestone with calcareous mudstone and occasional cemented gravel. Secondary dolomite in places.

Geophysical Log The second division from 22–81 m comprises limestone or silty limestone, with calcareous mudstone and occasional horizon of cemented gravel. Dolomite is present in places, e.g. 66–69 m and this is interpreted by as incomplete by the density porosity being about 10% lower than the neutron porosity. Porosity are mainly between 10–20% Lst, interpreted as primary, The borehole has irregular bore, being partially washed-out throughout, and a soft band of limestone is washed-out from 74–76 m

****81–158 m***

Lithology Alternating limestone, calcareous mudstone, and silty cemented gravels. Secondary dolomite in places. Small fissures are indicated at 183 m, 185 m, 126 m.

Geophysical Log Some secondary dolomitisation is indicated by the neutron and density porosity, e.g. 110–113 m, 147–149 m, also coincident with low resistivity value of around 7 ohm-m. Porosity are mainly between 10–20% Lst, interpreted as primary, The borehole is less washed-out than the overlying division, with small fissures.

****158–300 m***

Lithology Limestone and secondary dolomite with occasional thin beds of cemented gravel.

Geophysical Log Dolomite is indicated by the density porosity being 5–10% Lst. lower than the neutron porosity. Porosity, throughout to be primary, are mainly in the range 10–20% Lst. Small amount of ophiolite present in most of the cuttings indicate occasional thin beds of cemented gravel. Small fissures were indicated in places e.g. 228–240 m. Resistivity value gradually reduced with depth. Between 195–250 m, resistivities were variable from 4 to 30 ohm-m and below this depth the receptivity were more constant at 4–7 ohm-m.

g) **Pumping Test**

- Step Pumping Test

The details of step pumping test is summarized in the table below.

Well No.	PW1	PW2	PW3 (i)	PW3 (ii)	PW3 (iii)	PW4	PW5 (i)	PW5 (ii)
[Step 1] Discharge (L/sec)	1.13	0.27	2.48	0.10	0.47	14.7	1.20	1.63
Drawdown (PW, m)	2.77	1.54	60.06	1.93	14.16	0.65	7.30	8.68
Drawdown (OW, m)	-	0.2	2.01	0.24	0.97	-	-	-
[Step-2] Discharge (L/sec)	2.84	0.66		0.28	0.65	16.7	2.48	2.96
Drawdown (PW, m)	7.25	4.6		6.41	27.67	1.04	17.68	19.31
Drawdown (OW, m)	-	0.57		0.68	2.58	-	-	-
[Step-3] Discharge (L/sec)	4.47	1.04		0.90	0.88	19.3	4.02	4.67
Drawdown (PW, m)	13.04	8.84		28.19	43.75	1.37	34.70	35.58
Drawdown (OW, m)	-	1.05		2.31	4.57	-	-	-
[Step-4] Discharge (L/sec)	5.0	1.45		1.20	1.09	23.9	4.45	5.38
Drawdown (PW, m)	14.54	13.3		46.39	58.85	1.68	44.83	46.10
Drawdown (OW, m)	-	1.59		4.55	6.80	-		-
[Step-5] Discharge (L/sec)	4.38	1.02		-	0.65	16.7		3.75
Drawdown (PW, m)	13.61	8.77		-	50.96	1.65		31.60
Drawdown (OW, m)	-	1.27		-	8.14	-		-
[Step-6] Discharge (L/sec)	2.26	0.57		-	0.55	14.8		2.10
Drawdown (PW, m)	6.95	4.25		-	45.86	1.74		15.75
Drawdown (OW, m)	-	0.81		-	8.69-	-		-
[Step-7] Discharge (L/sec)	0.95	0.21		-	0.25	14.7		1.62
Drawdown (PW, m)	3.46	1.82		-	33.75	1.7		7.58
Drawdown (OW, m)	-	0.47		-	8.54	-		-

Note:

-*Well Site PW-3/OW-3.* Three pumping tests were conducted in PW-3. Finally, the pump with the lowest capacity, 0.33 to 1.33 L/sec, among the three was put in action to test the very low yield of the well. Two further step pumping tests concluded that the yield of well was very low. Hence the nearby municipality well was used as for the 24 hour pumping test.

- *Well Site PW-4.* Well PW-4a was used for Well site PW-4 to perform all the pumping test.
- *Well Site PW-5/OW-5.* The first step pumping test at well site PW-5 was interrupted by the generator had failed during the forth step, hence the second testing was followed next day.

-Well Efficiency

The drawdown of water level in pumping wells was assumed to be due to head losses from two sources. The first are head losses due to laminar flow within the aquifer. The second are head losses due to turbulent flow within the aquifer adjacent to the well and within the gravel pack and screen of the well itself. A well performance or well efficiency analysis, the determination of head losses due to laminar and turbulent flow, was completed for the five pumping wells PW-1 to 5 pumping the data obtained the step discharge tests as mentioned above.

All the wells show a fairly clear straight line relationship between drawdown and discharge. With the exception of PW-2, all the wells show a higher drawdown during the three declining rate steps 3-7 than when using the increasing rate steps 1 to 4. This is particularly pronounced in PW-3. PW-3 and PW-5 show higher drawdowns during the highest pumping rates that are predicted by the straight line relationship. This is probably due to increasing turbulence losses at these pumping tests as mentioned below.

Well	Discharge Range (L/sec)	B	C	n
PW-1	0.95-5.00	2.20	0.1471	2
PW-2	0.21-1.45	6.60	1.7001	2
PW-3 (i)	0.10-1.20	17.7	16.699	2
PW-3 (ii)	0.25-1.09	30.0	25.000	2
PW-4a	14.7-23.9	0.13	-0.0026	2
PW-5 (i)	1.20-4.45	4.48	1.1594	2
PW-5 (ii)	1.60-5.38	4.37	0.8169	2

The calculated drawdowns and well efficiencies of wells PW-1 to 5 at a range of discharges is given below.

Q	PW1		PW2		PW3		PW4A		PW5 (i)		PW5 (ii)	
L/sec	s (m)	L (%)	s (m)	L (%)	s (m)	L (%)	s (m)	L (%)	s (m)	L (%)	s (m)	L (%)
0.25	0.56	98	1.79	94	5.47	81	9.06	83	0.03	100	1.14	96
0.50	1.14	97	3.72	89	13.02	68	21.25	71	0.06	100	2.39	91
0.75	1.73	95	5.91	84	22.66	59	36.56	62	0.1	100	3.74	88
1.25	2.35	94	8.3	80	34.39	51	55	55	0.13	100	5.19	84
1.50	2.98	92	10.9	76	48.2	46			0.16	100	6.74	81
2.00	3.63	91	13.72	72					0.19	100	8.39	78
3.00	4.99	88							0.26	100	12.01	73
4.00	7.92	83							0.38	100	20.46	64
5.00	11.15	79							0.5	100	30.55	57
6.00	14.68	75							0.63	100	42.27	52
									0.76	100	55.62	47

Wells PW-1,2 and 5 show high well efficiencies at low discharges with 80% or greater efficiency at less than 1.0 L/sec. This decreases to 70% or greater efficiency at less than 1.5 L/sec.

PW-3. PW4a well was the most efficient well of all the wells, with negligible turbulence losses inside the well, even at high discharges.

- Constant Rate Discharge Test

The pumping wells PW-1,2,4 and 5 were pumped continuously for a period of 24 hours. PW-3 was not subjected to a constant rate test as the very high well losses in the well resulted in very low yield. The municipality well in vicinity of PW-3 was used instead and PW-3 was used as an observation well. Complete details of the constant rate pumping test result are given below

Well Site	PW-1	PW-2	PW-3	PW-4	PW-5
Discharge (L/sec)	4.95	1.42	7	22	5.25
Distance to observation well	-	10		98	
Aquifer Thickness (m)	394.8	>150	>300	>350	>300
Drawdown (Pumping Well)	15.4	13.67	*32.88	3.3	51.91
% of aquifer thickness	3.75	-	-	-	-
" (Observation Well)	-	2.18	**0.35	-	-
% of aquifer thickness	3.75	-	-	-	-
Water temperature at start of test	-	33.3	-	-	33.7
" at end of test	-	33.3	-	-	34
Water conductivity at start of test	-	2,550	-	-	2,520
" at end of test	-	2,410	-	-	2,990

Note: * Municipality well
** PW-3

Well responses to pumping showed that the Dhaid area is not uniform. The result of PW-5 show the classical three segments characteristic of an unconfined aquifer exhibiting delayed gravity yield. During the first segment, drawdown due to production well discharge is governed by the Theis equation (1935), and the aquifer behaves as a confined aquifer. During the second segment, the drawdown goes through a transition period where the rate of drawdown decline due to 'recharge' of the water table from above by water which is released from the dewatered aquifer by gravity drainage. During the third and final segment the water levels decline at an increasing rate, as the falling water levels and gravity drainage of the pores reaches equilibrium. The nuemen method (1975) was used to analyze the data.

The pumping test in all of the other wells on the other hand indicate leaky confined conditions, where the drawdown initially follows the Theis curve (1935), but then begin to flatten out as the drawdown is reduced by the input of recharge from leaky horizons. The Hantush and Jacob (1995) method was used to analyze the data.

-Aquifer Parameter

The aquifer parameters calculated from the pumping test is summarized below. The aquifer transmissivity varies from approximately 5-20 m^2/day, with the exception of a value of 290 m^2/day in PW4a and a value of 232 m^2/day obtained from the pumping test in the municipality well. The aquifer is leaky and confined over most of the area, but may be unconfined in the PW-5 area, although this cannot be definitely proven in the absence of an observation well.

Three out of the five pumping test sites do not have observation wells. The storativity can therefore not be determined for these sites, and the transmissivity values obtained are less accurate as they have to be corrected for well loss effects. The fact that the pumping wells are less deep than the observation wells leads to partial penetration effects. Although these have been corrected for the result from PW-2 and 3 demonstrates that the aquifer cannot be viewed as a simple homogeneous which may lead to large errors in the calculated values of transmissivities.

Well	Method	Trans-missivity (m^2/day)	Storativity	r/B	Aquifer type
PW-1	Hantush-Jacob	8.22	-	-	leaky confined
	Recovery	8.92	-	-	
PW-2	Hantush-Jacob	2.75	-	-	"
PW-2/OW-2	"	16.35	1.60E-03	0.20	"
	Recovery	18.59	-	-	
PW-3	"	1.15	-	-	"
	Hantush-Jacob	0.35	-	-	
Minu. Well	"	12.21	-	-	"
PW-3/Minu. Well	"	231.60	3.27E-03	0.56	"
PW-4a	"	290.00	-	-	Dual porosity, possible confined
	Recovery	244.00	-	-	"
PW-5	Neuman	4.59	-	-	unconfined
	Recovery	2.74	-	-	"

- Aquifer characteristics

The hydrogeology of the Study Area is complicated, and no clear correlation exits between drill sites or even between wells at one site. The multiple layers shown by the cutting logs can be viewed as an equally complex multi-aquifer system with a much higher horizontal than vertical permeability. The silty, and possibly the carbonate horizons may represent local confining or semi-confining layers in the system, that isolate the various gravel layers from each other. Equally there may be important fissure flow in some of the competent dolomitized limestone formation.

The following table summarize the pertinent aquifer characteristics obtained from the geophysical logs and pumping test data. It should be noted that the transmissivity and storativity values obtained from the pumping test result are somewhat speculative, due to penetration effects and the lack of sufficient observation wells.

Hydraulic Property of Aquifer	
Porosity	20-30 %
Transmissivity (T)	5-300 m^2/day
Storativity (S)	2~3 10-3

1.3.3. Groundwater Quality Testing and Hydrochemistry

Hydrochemistry is necessary at several points in the Study. Basic measurement, both temperature and conductivity were measured at 190 existing well sites, and among these, 100 samples were tested for 12 items, including of Ca, Mg, Na, K, SO_4, Cl, HCO_3, Mn, Fe, EC and pH. In the test wells, basic water quality testing, inclusive of 8 items of quality testing for basic items were conducted for existing wells. For the test wells the temperature, Ec, Eh (redox potential) pH and dissolved oxygen and major ion and bacterial (35 items) were analyzed to determine the health risk of consuming water.

(1) Existing Well Survey

From May 1995, 200 water samples were taken from private farms. These farms were selected by GPS coordinates with a separation distance of two kilometers of each other. Samples were taken from existing surface facilities, i.e. connected well pipeline outlet to storage tank while water was flowing from well to tank. Temperature and EC measurements were taken as well as visual check of flow facilities, inclusive of pipe-size, pump-size, diesel or electricity, depth of well or wells as in some cases more than one well was located. Further information was collected from on-site workers as to flow pumping discharge per hours on daily basis as well as general information as to owners name and so forth. Out of the 200 samples taken, 100 were selected based upon location of farm shown on maps being used within the Study Area and forwarded to MAF for distribution to Al Ain and Ras Al Khaimah central laboratories for analysis.

(2) Supplementary Existing Well Survey

To further supplement the data from the existing wells, a survey was conducted in May 1995, and to gain further understanding on the present groundwater conditions, particularly concerning the existing wells currently being utilized by local farmers to irrigate their lands, an additional well survey was conducted in January 1996 on 50 farms out of the original 200 farms selected from the previous survey as mentioned above. These farms were selected randomly but within the extension areas of Falaj Al Mualla, Dhaid I, Dhaid II, Mileiha and Khadrah. All of the selected farms were physically measured to determine groundwater depth, conductivity and temperature. The study team hastens to acknowledge that this survey was conducted after heavy rainfall was recorded in the Study Area, and that some wells showed higher groundwater depth than previous survey. Results of Existing Well Survey are shown in Appendix 2.5.

a) Analytical Constituents

For the 100 samples, the groundwater quality test, concerned with for determining water type was carried out. For this purpose, 12 items were made as blow.

1)	Calcium (Ca),	2)	Magnesium (Mg),
3)	Sodium (Na),	4)	Potassium (K),
5)	Sulfate (SO_4),	6)	Chloride (Cl),
7)	Carbonate (CO_3),	8)	Hydro-Carbonate (HCO_3),
9)	Manganese (Mn),	10)	Iron (Fe),
11)	EC (Electric Conductivity),	12)	pH

b) Major Constituents

To delineate the groundwater flow system and the course of groundwater flow, chemical analyses of waters collected around the Study Area and in the Oman Mountain Range were carried out. Major constituents of groundwater were analyzed by MAF Laboratory. The distribution of major constituents of groundwater is shown in Figure 1.3.14 as the Piper diagram. The distribution of electric conductivity of groundwater are shown in Figure 1.3.15.

Water samples from surface runoff and shallow wells were taken in the Oman Mountain Range and those can be distinguished into the circled area by dashed line in Figure 1.3.14 from the groundwater samples around the Study Area. It does not mean, however, that the source of groundwater around the Study Area is not the water in the Oman Mountain Range. Mountain water is characterized by the chemical type of Mg^{2+}- HCO_3^-, whereas the groundwater in Study Area by the type of Na^+-HCO_3^-. This trend in hydrochemical distribution can be deduced to be an evolution of natural water toward sea water.

As shown in Figure 1.3.15, the means of electric conductivity which represents the total concentration of dissolved ions and the chemical type of water is shown in Figure 1.3.16.

(3) Hydrochemistry Logging

The temperature (T), conductivity (EC), redox potential (Eh), pH and dissolved oxygen content (DO) of the groundwater were recorded during the hydrochemistry logging of observation wells and boring holes. During some of 24 hours constant discharge and step pumping at test wells, Both T and EC of groundwater were monitored.

a) B-1

Temperature and conductivity logs were recorded in the polymer mud filled borehole and inside casing after well development.

In the polymer mud filled borehole, a positive fluid temperature gradient is record below 24 m and reaches a bottom hole temperature (BHT) of 37.3°C. No vertical fluid movement is indicated by this feature. A number of slight changes in the fluid temperature gradient are noted at 74 m, between 101–108 m and from 130–139 m which suggests an inflow of groundwater into the polymer mud filled open hole. The fluid conductivity range measured in the open hole is form 1200 μS/cm to 2150 μS/cm and the slight decreases in fluid conductivity close to 74–130 m would tend to confirm the inflow of fresher groundwater into the borehole.

A number of interesting features are noted on the formation logs. No large clay horizons have been interpreted from the formation logs, therefore it is difficult to establish a SP baseline. However there is a trend towards a negative shift in the SP log above 109 m which would suggest the groundwater is more resistive than the fluid within the bore. This would support the dilution of the polymer mud by groundwater.

The groundwater table is identified by higher sonic transit time above 17 m. Also increased formation resistivity (ILD) above 35 m, where no significant change in either clay content or formation porosity is noted, would suggest partially saturated formation.

For the majority of the logged section increased formation resistivity correlated to lower porosity, limestone/dolomite horizons, hence the increased resistivity is associated with the lower porosity and hence less fluid in the pores. There is a significant increase in the formation resistivity (ILD) below 133 m which does not appear to correlate with any significant change in either formation porosity and/or clay content. It is therefore most likely to be related to a more resistive and hence higher water quality in the formation.

However between 122m and 133 m, low formation receptivity is recorded within an interval of interpreted secondary porosity and joints/fractures recorded in the core. The low formation resistivity is most likely related to the water filled nature of the joints/fractures. This interval also correlates with interpreted groundwater flow from the fluid temperature, conductivity and hydrochemistry logs.

In the cased well, three distinct water bodies can be identified from the fluid logs:

An upper lens (water level to 31 m) of relatively fresh, low-temperature groundwater which is slightly oxygenated. The Ec range from 2500–3000 μS/cm^2.

The water quality is slightly poorer from 31–122 m where the fluid conductivity is constant at 3000 μS/cm. Both the dissolved oxygen and Eh potential log readings are very low. The pH is constant at a value of 8. The hydrochemistry signature suggests of an oxygenated recharge signature. Despite the low positive value of the Eh potential logged, a slightly oxidizing nature is indicated.

A relatively high temperature, fresh water body is identified below 122 m with inflow of groundwater restricted between 122–129 m and below 196 m. The fluid conductivity is constant at 2275 μS/cm. Fluid temperature increases in this relatively fresh water. Inflexion also correlates with an interpreted zone of secondary porosity in the form of joints/fractures as identified by the low formation resistivity (ILD). The development of the joints/fractures has aided the flow of the groundwater. The development oxygen continues at a zero value, the Eh potential decreases to negative values indicating reducing conditions. Both signatures indicate that the groundwater has had a long residency time. The pH decreases between 104–174 m to a minimum value of 5.8.

b) B-2

In the mud filled borehole, a positive fluid temperature gradient is recorded below 60 m and reaches a bottom hole temperature (BHT) of 39.1°C. No vertical fluid movement is indicated by this feature. From the mud level to 60 m, the fluid temperature decreases slightly with depth which suggests some inflow of groundwater from the formation was occurring at the time of logging. The measured fluid conductivity was 2550 μS/cm; the fluid conductivity value is lower than the mud pit value throughout. The lower fluid conductivity can be explained by either a dilution by groundwater flowing into the borehole or by the dilution from water pumped in from the surface during logging to allow formation logs to be recorded at the surface.

A number of interesting features are noted on the formation logs. The SP logs shows slight negative deflections between 105–200 m. These horizons correlate with the interpreted interbedded thin limestone/dolomite horizons and indicate that these horizons are permeable to some degree. For the majority of the logged section, increased formation receptivity correlates to lower porosity. limestone horizons, hence the increased resistivity is associated with the lower porosity an hence less fluid in the pores. However, between 34–70 m, the higher formation resistivity peaks are not associated with lower formation porosity and/or increased gamma activity with more resistive and hence higher water quality in the formation.

In the cased well, the fluid logs indicate three distinct water bodies;

A slightly poor quality water from the water level at 230 m where the fluid conductivity fluctuates between 1700 μS/cm and 2000 μS/cm. Inflexions on both the fluid temperature and fluid conductivity logs between 69–71 m and from 113–122 m infer an inflow of groundwater. Both the dissolved oxygen and Eh potential logs are high, which is to be expected because the logs were recorded immediately after well development using compressed air. Interestingly, the dissolved oxygen begins to decrease below 78 m where inflow of groundwater is interpreted from the fluid temperature and fluid conductivity logs. Within this water body, the pH fluctuates between 6.5 and 9.2.

A fresh water body was identified below 230 m where the fluid conductivity decreased to 1129 μS/cm. Fluid temperature increases in this fresh water and a number of inflexions are recorded at 230 m, at 250 m, from 264–266 m and from 280–282 m. The inflexions are interpreted as inflows of groundwater from the formation. The inflexions also correlate with 'fissured and/or loose ground interpreted from the caliper log which would be aiding the flow of groundwater in the formation. The dissolved oxygen decreases significantly at the water boundary at 230 m indicating that the regional groundwater has been long resident in the formation, and that no recent recharge of the groundwater has occurred. The Eh potential decreases slightly at 230 m but decreases further below 260 m. Little change in pH 8 was recorded between the water bodies.

a) PW-1

In well PW-1 during testing five distinct types of groundwater were identified from the hydrochemistry logs, below are some of the significant inflows over the screened intervals:

46–52 m The groundwater is fresh with an EC of 600 micro-S/cm. A deflection in differential temperature log at 52 m indicates groundwater inflow which is mirrored by an increase in the conductivity to 1000 micro-S/cm and a rise in the temperature;

116–164 m Another inflow is indicated at this interval, resulting in EC of 2700 micro-S/cm below 116 m, the temperature gradient also increases more steeply over this interval reaching 40°C at 164 m.

300–380 m The next major inflows are over the screened interval between 300–380 m, especially between 346–378 m, these result in a slight increase in temperature, but do not affect the conductivity;

488–510 m The groundwater temperature increases to 46°C, and EC to 3400 micro-S/cm over an interval of major inflows, between 548 and 534 a fresher groundwater with and EC of 2400 micro-S/cm enters the well.

The pH is unusually low in the top section of this well with value down to 5. The pH increases to a value of approximately 9 at a depth of 160 mm where it remains with some minor fluctuations between 9 and 9.5 below 31 m.

The dissolved oxygen drops from 3 mg/L at 50 m to 0 at 130 m, below which it fluctuates at negligible levels. The Eh follows from 3 mg/L at 50 m to 0 at 130 m, below which it fluctuates at negligible levels. The Eh follows a similar pattern with oxidizing conditions of +500 mV recorded to a depth of 120 m below which it drops rapidly to negative, reducing below 130 m.

b) OW-2

The temperature and conductivity log of OW-2 shows a fresh groundwater with a conductivity of 1700 micro-S/cm to a depth of 136 m. Two zones of inflow were recorded at 91–128 m. The conductivity increases to 3900 micro-S/cm below 136 m.

During the 24-hour pumping test in PW-2 the conductivity dropped from 2550 to 2410 micro-S/cm, followed by stabilization. Lower conductivity were also recorded during the higher pumping rates of the step tests, indicating that the fresh water originates from more permeable horizons.

To a depth of 120 m the DO, Eh and pH remained constant at just under 3 mg/L, 300 micro-S/cm and 8 respectively. below 120 m there is a very slight drop in the pH. the Eh remains constant, and the DO drops to below 1 mg/L. These water quality changes are not reflected by the conductivity of water, although there is an increase in the temperature shown on both the temperature and differential temperature log.

c) OW-3

The water quality logging in OW-3 was completed up to 180 m. Breaks in water quality can be as seen by temperature and conductivity changes in the well. There are important at 54 m (conductivity increases from 2200 to 3000 micro-S/cm), 120 m (2800 to 2900 micro-S/cm) and at 152–170 m.

The step test in PW-3 (screened from 195–248 m) showed a constant EC of 2500 micro-S/cm. This suggest that there are at least three different water qualities in the different layers of the aquifer in Study Area.

d) PW-4a

The temperature log shows a gradually increase with depth due to the geothermal gradient indicating that here are no major vertical flows within the well which is supported by the fact that no significant groundwater inflows can be seen on the differential temperature log. The conductivity is virtually consistent throughout the well at approximately 1200 micro-S/cm.

The pH range from 8–8.05 from the water level to 45 m and below 125 m. Between 45–125 m it fluctuates around an average of 8.1. The Eh decrease from 315 mV at the water table to 290 mV at 40 m from where increase up to 325 mV at 80 m. Below 125 m it drops down to 290 mV at the base of the well. This pattern is mirrored by the dissolved oxygen contents which fluctuate from 2.7 to 0 mg/L.

e) PW-5

The constant increase in the groundwater temperature with depth from ca. 33–39°C over 300 m due to the geothermal gradient indicates that there are no significant vertical flows of water within the well. With the exception of a peak at 297 m, the differential temperature log is fairly smooth, indicating that there are no significant groundwater inflows into the well. The conductivity drops gradually from 2200 micro-S/cm to 2100 micro-S/cm at 60 m and then increases gently to 2700 micro-S/cm at 200 m where it remain stable until an inflow of fresher water at 297 m causes it to drop to 1700 micro-S/cm. The oxygen remains more or less constant throughout the well at 1 mg/L, the Eh at 800 mV and the pH just below 8.

f) Chemical Analysis of Sampling water from Test Well

All Samples were taken by using following sample bottles:

Bottle A; No treatment	Bottle B; 2 ml conc. H_2SO_4
Bottle C; 2 ml conc. HNO_3	Bottle D; Sterilized

Within 6 hours for the time of sampling sample bottles were delivered to laboratory to test the water quality and check the bacteria Especially sample bottles D, there were kept in cool box and care was taken not to expense the samples to high temperature.

Test Items	PW-1 (mg/L)	PW-2 (mg/L)	PW-3 (mg/L)	PW-4 (mg/L)	PW-5 (mg/L)
Calcium	20	24	56	18	52
Magnesium	26	6	46	21	39
Sodium	88	390	210	90	395
Potassium	4	5	5	6	5
Sulfate (as SO_4)	34	132	59	26	137
Chloride	119	447	400	140	604
Carbonate (as CO_3)	0	0	12	0	0
Bicarbonate (as HCO_3)	153	183	183	140	183
pH	8	8.2	8.7	8.3	7.7
Turbidity (Formazine Turbidity Unit)	1	4	6	1	7
Total hardness (as $CaCO_3$)	155	85	330	130	290
Calcium hardness (as $CaCO_3$)	50	60	140	45	130
Magnesium hardness (as $CaCO_3$)	105	25	190	85	160
Total Dissolved Solid (TDS)	440	1190	970	450	1420
Chemical Oxygen Demand (COD)	< 5	< 5	< 5	13	16
Ammoniac Nitrogen	< 1	< 1	< 1	< 1	< 1
Nitrite	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Nitrate	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Fluoride	< 0.1	14	5	< 0.1	5
Phenols	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Organo Phosphate	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Mercury	< 0.0002	< 0.0002	< 0.0002	< 0.0002	< 0.0002
Arsenic	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Cyanide	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
Odor	none	none	none	none	none
Color (Hazen units)	< 10	< 10	< 10	< 10	< 10
Cadmium	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Copper	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Chromium	< 0.02	0.2	< 0.02	< 0.02	< 0.02
Lead	< 0.01	< 0.01	< 0.01	< 0.01	0.2
Manganese	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Iron	0.1	0.1	< 0.01	0.1	0.3
Zinc	0.1	0.2	0.1	0.1	0.2
Total Bacteria 48 h at 30°C (colonies/100 ml)	180	10	many	many	70
Fecal Coliforms 24 h at 42°C	0	0	0	0	0

The groundwater can be classified as a Na–Cl type with high SO_4 and HCO_3 levels. the TDS are within the MAC level recommend by the WHO. Nitrate level are below the detection limit in all wells, indicating that either denitrification reactions are occurring in the aquifer (s) or that the water recharged from the Oman mountains is essentially nitrate free. The second possibility is less likely, as nitrate is usually detected in the wadi gravel aquifers in the Oman mountains.

Of the metals, only Chromium, iron and zinc were detected. These are probably alteration by-products of the ophiolite rocks incorporated in the aquifer.

Although the fluoride levels were below detection limit in PW-1, five mg/L were measured in both PW-3 and PW-5 wells, furthermore, 14 mg/L in PW-2. These are above the MAC levels recommended by the WHO.

Although the wells were distinguished by chlorination prior to the bacteriological sampling, high levels of total bacteria were recorded. It is unlikely that this is due to actual bacteria in the aquifer, and is probably due to bacteria present in the pipe works associated with the pump.

1.3.4. Infiltration Experiment

(1) General

In order to measure the infiltration condition contributed to the groundwater recharge on to the Study Area., a field Infiltration Experiment is conduct in the pits dug in different depths at three selected sites in Bahada Plain. The works under this section include the furnishing, transporting to project site to required material and equipment for execution of Infiltration Experiment. The works consists of:

- Excavation of Test Pit
- Grain Analysis
- Infiltration Test

(2) Excavation of Test Pit

Test Pits were likely situated at the main wadi channels in which intersects active streams of Wadi Siji, Wadi Khadrah and Wadi Shoukah. In addition, Test Pits was set up in between Gravel Plain and Rocky Mountain Area which posses maximum capability to natural groundwater recharge.

The depth of each Test Pits will be three of 1.5 m, 3.0 m and 6.0m. In case of rocks area encountered, which could not be crushed or removed without heavy blasting, the hole was to be re-located to re-excavated beside previous location. Cross section of each Test Pit depend on the size necessary for the work executed had a minimum of 1.5 m x 1.5 m. In excavating sand and gravel, timbering was required for protecting the side walls of test pit and pumping was also be required for drainage. After completion of excavation, the soil logs were drawn for each test pit.

(3) Grain Analysis

The material excavated was placed around the test pit so as to classify the different material of each depth of test pit. The excavation of test pit was interrupted at the established level due to the sampling. For better sampling and material classification, the bottom of the test pit was to be horizontal. The sieve analysis of the samples taken from the infiltration pits was classified as poorly sorted alluvial sediments ranging in size from fine sands to cobbles. Most samples typically contain 20 to 30% sands, the rest being gravels with minor (Usually less than 10%) cobbles as shown in Appendix 2.4. An exception to this could be seen in pit DW2-3 between 4.5–6.0 m where 30% of the alluvium was in the cobble size range. This was probably indicative of a major flood event at that location. The analysis were typical of the grain size distributions of wadi alluvium in the gravel plains adjacent to the Oman mountain range, The lack of sorting was explained by the nature of deposition–rapid flash floods.

(3) Infiltration Tests

The infiltration experiment was carried out using two 11 m^3 water tanks and a 12m^3 water tanker to replenish the water supply when the tanks became empty. A pump was used to discharge the water into the screened PVC pipe located at the center of the infiltration pits. A second screened PVC pipe was used to monitor the head of water inside the pit. This was done by two techniques. A pressure transducer with a one minute sampling rate was installed at the base of the monitoring pipe. A float with a graduated pipe gave a visual check on the water level inside the pit. The water level inside the pit was kept constant by regulating the flow from the pump. The infiltration tests showed a surprisingly high ground permeability, in particular in the zone below two meters. The test results is summarized as below.

Summary of Infiltration Experiments

Site	Pit depth (m)	Infiltration Rate (m^3/sec)	Head of water in pit (m)
DW1-1	1.5	0.0100	1.15
DW1-2	3.0	0.0175	1.67
DW1-3	6.0	0.0270	4.20
DW2-1	1.5	0.0017	1.09
DW2-2	3.0	0.0040	1.43
DW2-3	6.0	0.0029	2.22
DW3-1	1.5	0.0015	1.07
DW3-2a	3.0	0.0031	1.20
DW3-2b	3.0	0.0110	2.47
DW3-3	6.0	0.0165	3.49

1.3.5. Well Inventory Survey

(1) General

The well inventory survey aims to grasp the existing situation of wells within the Study Area by means following questionnaire. The survey was completed with the Farm Inventory Study which involve 200 farms classified by their major types of farms by size, cropping, soil type, water source and so forth through the review of available information (maps, aero-photographs, existing farm inventory in the Ministry and others) amongst some 4,000 farms in the survey area, Sampling of 1134 wells was made from theses selected farms and others such as the water supply well, test well and so forth.

(2) Design of Forms of Questionnaire

The design of form of questionnaire for well covers, at least, the following items and the items covered by the existing form of well and farm inventory in the Ministry:

Form For Well

(1) Inventory No. and the related farm inventory No.,

(2) Date of survey,

(3) Name of investigator,

(4) Respondent: name and position (owner/family/employee),

(5) Owner: name and ethnic or tribal group,

(6) Location: Emirate, Region, Village and Coordinates,

(7) Date of construction,

(8) Drilling firm (name, address and drilling method applied),

(9) Depth of well,

(10) Type, size and position of casing and screen,

(11) Type, size, position and motor/engine output of pump installed,

(12) Yield as of 1994/95 by m^3/hr, m^3/day, $m^3/year$,

(13) Depth to static water level in the survey Date and recent summer and winter seasons,

(14) Water quality on the survey Date (electric conductivity and temperature),

(15) Major use of well (domestic/animal watering/irrigation/others),

(16) Others

(3) Data Entry and Statistical Analysis

Upon the completion of the well inventory survey, the survey data were entered into floppy diskette (s) in a designated format of worksheet. The statistical analysis was made on the survey data and arranged into a value of the maximum, minimum, mean values and standard deviation and so forth. The number of wells surveyed in the Study is summarized as follows:

Area	Number of sampling farms (No.)	Number of sampling wells (No.)	Number of Wells in a Farm (Min–Max. No.)	Number of Wells in a Farm (Avg. Nos.)	Well Depth (Min–Max. No)	Well Depth (Avg. No.)
Dhaid	100	496	1-18	4	30-609	250
Mileiha	60	306	1-24	4	24-350	80
Khadrah	15	140	1-8	3	9-200	50
Falaj Al Mualla	25	192	1-17	6	30-365	130
Total	200	1134	-	-	-	-
Average	-	-	-	4	-	130

The well construction commenced from 1960's was at its peak in a decade from 1980 to 1990. The life of well estimated by the abundant wells was calculated as seven years. Most are constructed in the form of un-cased wells and not have a screen installed or even a casing. The pump position is ordinarily set up at the bottom of well down to a depth of 100 m on average. The majority of pumps were of the submersible type with a capacity of 0.5 to 5.0 L/sec (outlet diameter is 1–3"). The water quality measured in the inventory survey was indicated as a wide range from 500–10,000 micro-S/cm, especially in Mileiha and Falaj Al Mualla, salt-damage from groundwater irrigation had been reported. There was also some anxiety concerned to a depletion of water head and decreases in yield.

1.4. Hydrogeology and Groundwater of Study Area

1.4.1. General

The Study Area is a multi-layered of detritus from the Oman mountain and marine carbonates that have been subjected to secondary dolomitization. The sediments range from gravel to sand, silt, silty carbonates and pure dolomitized limestone. The sediments are probably laid down in a series of marine transgressions and regressions. However, the sequence is extremely heterogeneous and anisotropy with little lateral correlation over the project area.

The main water bearing horizons are the cleaner gravel and some of the dolomitized limestone with secondary porosity. These are multi-aquifer between semi-confining layers of more silty, finer grained sediments or low porosity limestones. These layers are leaky and transfer water to the permeable zones during pumping. Although overall aquifer is quite thick, the transmissibility and storativity are low in most places. This has resulted in large drawdowns in pumping wells in the Study Area and a fast depletion of the groundwater in storage.

1.4.2. Hydrogeologic Mapping in Study Area

(1) Photo-Interpretation Map

Through the interpretation of aerial photographs, the surface information related to geological and hydrogeological characteristics was obtained. The actual on-foot survey for verification of information obtained from aerial photographs, was an by On-foot survey. As the first step of the survey, an index map was prepared on which every photographic position overlays on to the 1:50,000 map and subsequent scanning of aerial photographs was made in the stereo-scope view. Information picked up from each photographs was linked to that from others and are compile in a map in a smaller scale, which is generally called a Photo-Interpretation Map. In this period of the field study, the basic elements concerned in the geographical or hydrogeological characteristics were identified as shown below.

Topographical Division and Geological Unit

Topographical Division	*Land Form Type*	*Geological Unit*
Oman Mountain Range	Erosional Slope,	[Os]Semail Ophilite Sequence, [Os]Hayabi Complex and/or Hawasina Assemblages
Foot-Hill Highland and Gravel Plain	[Tr]Trace (or Dissected), Limestone and carbonates,	[Cs] Allochthonous Unit (the Batinah Complex) [Cs]Neoautochthonous Unit (Maastrichtian-Tertiary Sediment)
	[Pd]Pediment Plain	
Inland Plain and Sand Dune	[Af]Alluvial Fan (old and dissected), [Af]Alluvial Fan (new and active), [Fp]Flood Plain, [Rd]River Bed (active wadi) [Sd]sand dune and trough	Superficial Deposit (Recent alluvial gravel, sands and screen)

In Figure 1.4.1, Photo-Interpretation Map covering the Study Area is shown in accordance with the above division of land form types and classifications. The major Geological Units in this area are comprised of Semail Ophiolite Sequence, Allochthonous Unit (The Batinah Complex) and Neoautochthonous sediments (Maastrichtian Sediments)

1.4.3. Regional Stratigraphy

Through the correlation of lithological descriptions of test wells and boreholes drilled so far and resistivity layers detected by the geophysical prospecting in the Study, the regional stratigraphy was interpreted as shown following Table and Figure 1.4.2. The typical geological sequence obtained from the borehole logs of B1 and B2 was classified and described in the following paragraph.

Geological age		Stratigraphy	Major stratum	Resistivity layer	Aquifer
Quaternary	Holocene	Superficial Alluvium Talus	Gravel layer, Sand and gravel layer and Sand and gravel mixed with sand and clay (Party consolidated sand and gravel layer)	1st resistivity layer (Avg. 100 ohm-m)	Upper Aquifer
	Pleistocene	Post-Fars Formation	consolidated clay layer, Limestone layer	2nd resistivity layer (Avg. 50 ohm-m)	
Tertiary	Neogene	Upper-Fars Formation Razzak Formation	Marl layer, Calcareous gravel layer and Calcareous sand layer		Aquiclude
	Palaeogene	Umm al Radhuma Formation Qahlah Far Formation Fars Formation Fars Formation (Eocene shale)	Shale, Limestone layer, Marl layer, Sandstone layer and Dolomitic layer	3rd resistivity layer (Avg. <10 ohm-m)	
Mesozoic	Upper Cretaceous	Aruma Group (Juweiza Formation, Fiqa Formation and Muti Formation)	Melange layer or Carbonate rocks with serpentinites, Gravely layer, Marly and Shalely layer and Dolomitic layer	4th resistivity layer (Avg. 20 ohm-m)	Lower Aquifer
	(Maastrichtian – Santonian)	Semail Ophiolite complex	Ophiolite, Basic rock and Ultrabasic rock		

1.4.4. Hydrologic Structure in Study Area

(1) Aquifer Classification

IWACO (1986) reported that the Quartenary and Juweiza Aquifers behave as a single aquifer system, but the regional aquiclude composed of wide distributed clay or shalely layers were observed from the Test Well survey. Four geological groups were identified on the regional scale by the Study. Their characteristics were described as follows.

- UPPER AQUIFER (HOLOCENE AQUIFER):

The Holocene deposit is generally made up of lose to semi-consolidated gravel layer and consists of a number of sedimentary cycles. An unit of cycle shows a well-grading of particles of silt to gravel which was provided from an ancient flood onto the gravel plain. The thickness of this layer does not exceed 50 m. High porosity and permeability are observed in the infiltration experiment.

-UPPER AQUIFER (PLEISTOCENE-NEOGENE AQUIFER)

This formation is correlated to Razzak or Fars Formation aged as Pleistocene to Neogene.

The typical facies of this formation is observed in the horizon of 18–74 m in B2. From the lithological record of B1, this formation is composed of several sets of alternation, involving gravel (consolidated), sand and calcareous layer, so that the multiple aquifer structure is inferred.

-AQUICLUDE (PALEOCENE AQUICLUDE)

The Paleocene Aquiclude can be correlated to Asmari/Pabdeh Formation. A peculiar property for this layer, thick shale layers are interbedded in the lower part of formation. These shale layers normally act as an aquiclude of a deeper aquifer, and occasionally contain saline water. The other upper and lower layer are mainly comprised of calcareous sandstone and gravely Limestone.

-LOWER AQUIFER (MAASTRICHTIAN-CENOMANIAN AQUIFER)

Maastrichtian to Cenomanian Formations in this Study Area are correlative to Semail Ophiolite or Juweiza Formation. Within the Study Area, Semail Ophiolite is only identified on the Oman Mountain Range and the foothill of Jabel Mileiha. Semail Ophiolite has poorly productive with the exception of the major line and intersection point of fault zone. Other layers originated simultaneously, Juweiza Formation, has appropriate property for a productive aquifer which include various facies of carbonate and even Non-carbonate facies. The significant layer in this aquifer is a coarse succession which is made of all the clean and uniform granule gravels. In OW3, this layer is found in several horizons below 195m depth and the thickness of respective layer as over 10m. The layer of saline water is not found in this aquifer.

(2) Distribution of Aquifer Classified

Aquifers in this Area were classified into two types, Upper and Lower Aquifers as described above. The Upper Aquifer is composed of Holocene and Pleistocene to Neogene sequences and is widely distribute beneath the Study Area. The structure and thickness of Upper Aquifer are shown in Figure 1.4.3 to 1.4.5 and Figure 1.4.6 to 1.4.8 The shallower ridge, presenting less than 50 m in thickness, run from the center of Study Area in North to South trend. Toward both sides of this zone, the Upper Aquifer increases in its thickness. The maximum thickness is observed in the north of Dhaid which is estimated over 150 m. The Aquiclude underlies the Upper Aquifer. As shown in Figure 1.4.9 and Figure 1.4.11., the layer has an average thickness of 50 m and frequently contains impervious Shale layers which shows become thicker and frequent toward lower horizon. The Lower Aquifer lies under the Aquiclude and is characterized to contain pervious gravels. From the borehole log and other existing well records, this Aquifer classified into several types of rock masses. As shown in Figure 1.4.9 to 1.4.12, the lower Aquifer is made of Marly Limestone, Gravely Limestone, Dolomite and Melange facies of Serpentinite. Out of these layers, the Gravely Limestone has high potential for productivity. These productive parts are recognized in three zones run in the center of the Study Area in the NE-SW trend.

1.4.5. Hydraulic Properties of Aquifer

(1) Aquifer Coefficients

Aquifer properties in the Study Area were evaluated by both the existing records of IWACO and Test Well Survey in the Study, and were arranged into three aquifer types, as shown below and in Table 1.4.1. and Figure 1.4.13.

Aquifer Coefficient in Study Area

AQUIFER TYPE	S/C (m^3/hr/m)	T (m^2/day)	S (%)	EC (mS/m)	SWL (GL-m)
Upper Aquifer	3	85	0.4	14	19
Lower Aquifer	2	51	0.3	19	23
Fissure Water	28	776	2.4	87	15

The Upper Aquifer composed of Alluvial and Pleistocene Deposits behaves an unconfined aquifer and Specific Capacity (S/C) of 3 m^3/h/m and 85 m^2/day of Transmissibility (T). The existing well where the pumping test was completed was located on the channel of Wadi Siji so that the value of S/C and T may indicate a higher limit of hydraulic coefficients of the Upper Aquifer. However, it is noted that the pumping tests were completed beneath the Upper Aquifer, and testing sections covered various layers such as the Upper Aquifer, Aquiclude and Lower Aquifer as well. Consequently, the testing results shows higher value than the proper Lower Aquifer, The S/C of 2 m^3/h/m and 51 of T were obtained from testing made in multiple aquifers. The Lower Aquifer possess a variety of lithological facies, inclusive of uniformly grained gravel to massive Dolomite and hard Ophiolite, resulting in these changes, the yield in Lower Aquifer drastically varies from dry to moderate yield up to about 5 m^3/hr/m. The coefficient observed from fissure water shows far high value compared with the average of the Upper and Lower Aquifer. The S/C of 28 m^3/h/m and 776 m^2/day of T were obtained from both results completed in both of Test Well and IWACO Study.

1.4.6. Groundwater Table and Changes

The data of Groundwater head observed in Study were arranged in daily basis. As shown in a change in Dhaid area, particularly in record from Lower Aquifer, the groundwater has dropped up to 60 m during last 10 years, the water production have decreased and some of them have resulted in completely dried up at the present.

The relation between rainfall and groundwater change is clearly identified in time-series groundwater hydrograph. The delay in groundwater change after falling rain however seen in all record. Their period range three months to 12 months from the beginning of rainfall.. The infiltration rate and hydraulic conductivity in unsaturated zone are esteemed from these timing and soil property, the common value of infiltration rate (vi) = 10^{-5} to 10^{-6} cm/sec can be obtained.

The distribution of groundwater head in Study Area is shown in Figure 1.4.14 and 1.4.15. The head in Upper Aquifer is characterized by a mono-inclined distribution that it is gently lowering to the north-east of Study Area with minor modifications of depressions at Dhaid and Mileiha. These positions are also correlative with the sub-surface valley. The Lower Aquifer has a different distribution of head which is pronounced large sink laid on Dhaid Area. With magnification of groundwater draft in Dhaid area, the drop of groundwater head has been developed. The maximum drawdown at present has reached to 100 m. The drop from 1985 to 1995 is drawn in Figure 1.4.16.

1.4.7. Groundwater Quality

As mentioned above paragraph, groundwater quality in Study Area was examined two occasions of Water Quality Testing of Existing Well and Test Well Survey. The analysis for the groundwater quality and water types are described as follows.

(1) Existing Well Survey

From May 1995 to January 1996, 200 water samples were taken from private farms located within the Study Area. Out of the 200 samples taken, 100 were selected based upon location of farm shown on maps being used within the Study Area and forwarded to MAF for distribution to Al Ain and Ras Al Khaimah central laboratories for analysis. For the 100 samples, the groundwater quality test, concerned with for determining water type was carried out on these 12 items, of which are (1) Calcium (Ca), (2) Magnesium (Mg), (3) Sodium (Na), (4) Potassium (K), (5) Sulfate (SO_4), (6) Chloride (Cl), (7) Carbonate (CO_3), (8) Hydro-Carbonate (HCO_3), (9) Manganese (Mn), (10) Iron (Fe), (11) EC (Electric Conductivity), (12) pH.

(2) Hydrochemical Properties of Groundwater

Major constituents of groundwater were analyzed by MAF Laboratory. The distribution of electric conductivity in Study Area are shown in Figure 1.3.15. The value of Ec was shown as a wide range from 1,000 to 10,000 μS/cm. However, the general trend that high concentration is in the western sand dune and the low is in the eastern mountain are commonly recognized. Along the wadi courses, the lower zones of Ec is extended. Particularly in the Upper Aquifer, these zones are traced out along Wadi Hamdah and Wadi Tiqubah. For Aquifer more than 100 m deep, the fresher water was observed along Wadi Khadrah to Wadi Dhaid.

The distribution of major constituents of groundwater was interpreted by Piper and Stiff Diagram as given in Figure 1.3.14 and 1.3.16. There were two types of water categorized into Non Carbonate Alkali (SO_4 + Cl, Na + K type) type and Carbonate Hardness (CO_3 + HCO_3, Ca + Mg type) type as follows:

- *A Group (Carbonate Hardness type)*: this type of water is distributed in mountain area to Bahada plain, and is stored in Ophiolite complex.
- *B Group (Non-Carbonate Alkali type)*: This type is originated from the direct recharge through Bahada plain, and has wide distribution in Study Area. Most of groundwater in Study Area is classified into this type.

In the Piper Diagrams, A evolution trends, from A and B group to a range of saline water, were recognized and their intermediate type was also identified on their courses.

1.4.8. Groundwater Utilization

Groundwater Utilization in Study Area was estimated based on the well numbers, actual pumping rate and the cultivated areas.

(1) Well Numbers in Study Area

Total number of well was evaluated from the well inventory survey completed in 1995. The ratio to well number in 1995 was analyzed for every year by means of their installation data as well as their expired Date. As a result from these analysis, the following ratio, assumable ratio of well numbers to that of 1995, were obtained.

Year	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995
Upper Aquifer (Depth 0-200m)	0.34	0.38	0.41	0.46	0.50	0.51	0.55	0.63	0.62	0.62
Lower Aquifer (Depth deeper 200 m)	0.12	0.15	0.18	0.21	0.26	0.28	0.34	0.36	0.39	0.38
Total	0.46	0.53	0.59	0.67	0.76	0.80	0.89	0.99	1.01	1.00

The number of wells has doubled during last decade and the maximum number was estimated at 1994. The depth of existing wells also increasing year by year, which is evidence of a serious shortage of irrigated water to supply farms. Most of the deep wells which exceed 300 m, were found the Dhaid Area.

(2) Pumping Rate

Actual pumping rate was estimated based on the groundwater draft survey carried out from 1995 to 1996. To estimate the total amount of groundwater consumption in the Study Area, a sample-survey on actual water used in 10 farms was selected during both periods of Field Survey (I) and (II). Although pumping rate at an irrigated area changes in some degree, the average groundwater drafting was estimated at about 65 m^3/day/ha. The results of this survey are summarized below.

Summary of Groundwater Draft Survey

Farm Location	Farming Area (ha)	Total Area (ha)	G.Draft (avg. 1995) (m^3/day)	Pumping Rate (m^3/day/ha)
Fili	2.15	3.36	498	148
Mileiha	2.08	4.67	298	64
Mileiha East	1.19	2.23	160	72
Jabal Mileiha	2.20	7.00	100	14
Ikhedir	3.68	6.20	825	133
Khadrah	4.18	6.20	250	40
Wishah	3.16	4.15	157	38
Dhaid East	1.23	2.06	15	7
Dhaid West	1.36	3.39	104	31
Falaj Al Mualla	0.91	2.65	289	109
Average	**2.21**	**4.19**	**269.6**	**65.6**

(3) Estimation of Cultivated Area

Total cultivated area is estimated by interpreting aerial photographs taken in 1995. The cultivated area defined in this survey study was included all parts of farm, including even the housing area and fallow fields. The cultivated area interpreted in this estimation was as follows.

Sub-basin (simulation model)	Cultivated Area (ha)	Estimated Pumping Rate (m^3/day/ha)	Groundwater Draft ($100m^3$/a)
8	65	148	2,895
9	217	64	4,169
10	80	40-148	3,012
11	477	14-64	4,392
12	312	40-72	3,840
13	147	14-40	1,680
14	466	40-72	7,006
15	445	38	5,071
16	629	7-40	4,440
17	564	7-40	2,706
18	737	20-31	4,936
19	1,008	7-31	4,945
20	62	31	579
21	304	31	2,830
Total/ (Average)	ca. 5,500	(49)	ca. 52,500

The total groundwater used for farming can be obtained by a product value, pumping rate multiplied by total cultivated area. About 52.5 MCM was given if pumping was done 300 days a year as shown in Table 1.4.2.

(4) Public Water Supply

In the Study Area, the production for public water supply was reckoned at 37,060 gallon/hr (i.e. 1.5 MCM/a) from the MEW information, 1992- 1995. The production, location and number of wells are shown below.

Town	No. of Wells	No. of Working Wells	Average Production Ability for 1992-1995	Remarks
	(No)	(No)	(gallon/hr)	
Suhelah	5	2	1,800	
			2,400	
Nasim	1	-	-	Not Working
Dhaid	10	-	-	Well dried up 1990,
Wishah	1	1	4,200	
West Khadrah	1	1	4,200	
East Khadrah	3	1	1,500	
Hamdah	1	-	-	Well supplied from Sharjah
Mileiha	5	2	1,500	
			1,500	
Ikhedir	1	1	3,600	
Bahayis	1	1	1,260	
Fili	4	4	1,200	
			3,000	
			8,400	
			2,500	
Total	33	13	37,060	1.48 MCM/a

The Ministry of Water and Electricity supplies tap water sourced from above the well fields to all parts of Study Area except Falaj Al Mualla. Falaj Al Mualla has own water supply system to provide 1.10 MCM/a (IWACO 19860) to their municipal area. Their well field is located out of Study Area.

(5) Groundwater Draft in Study Area

The total amount for Irrigation was estimated about 52.5 MCM/a and the water production for tap water was 1.5 MCM/a. Hence, the total abstraction of groundwater amounts to about 54 MCM in Study Area as follows:

52.5 MCM (Irrigation) + 1.5 MCM (Public Water Supply)

= 54.0 MCM (Total Groundwater Amount) in 1995

1.5. Evaluation and Development of Groundwater Resources

1.5.1. General

When the undergroundwater development in the Study Area is established, it is necessary to examine the following requirements:

1) Whether the undergroundwater use level at the current situation is appropriate, and whether this continued use is possible;
2) Whether the use undergroundwater is economical;
3) Whether the quality of undergroundwater suitable for the purposes that it is used for;

In addition to these basic items, the following issues need to be considered to form a broad, long-term perspective;

4) Whether a sharp drawdown in a groundwater head will occur in the future;
5) Whether the groundwater resource will be depleted in the future; and
6) Whether the water quality of groundwater maintained in the future.

Item (1) is pertinent to the "Amount of the of groundwater resource". As for establishing the development plan, an examination of "the Hydrologic properties of catchment area" and "Hydraulic properties of the aquifer," such as composition, distribution, scale, productivity, and the storage coefficient of the aquifer is needed

Item (2) relates to "Economy of the undergroundwater use" and its examination should be made through a comparison between the convenience of groundwater usage and the facility cost of which includes the construction, operation and maintenance cost of intake facilities. This item is closely related to above-mentioned "Hydraulic properties".

Items (3) is connected with the "Chemistry of undergroundwater". If the water quality does not match with the use to which it is put, and if it requires treatment, it will be less cost-effective.

Item (4) and (5), are also related to the "Amount of the undergroundwater resources". Groundwater is a recoverable resource within the limits of the hydrologic cycle. Sustainable development is possible as long as it remains within the recharge potential.

Consequently, this groundwater recharge has the same meaning as "Amount of the groundwater resource" and the understanding of "hydrologic behavior of undergroundwater" is essential for this evaluation. This understanding is also important for determining plans for "Groundwater Resource Management" and "Environmental influence evaluation".

Item (6) may occur if salt water intrudes into the development area. This relates to Items (4) and (5) mentioned above; however, this often occurs secondarily as a result of a sharp drawdown in the groundwater head or the expansion of groundwater resources.

In any case in Item (4) to (6) will affect "Influence on the environment", which includes elements of the natural environment such as the eco-system and soil contamination, as well as the socio-economic environment (i.e. existing water rights).

For the consideration of Items (1) and (2), the construction of a simulation model of the current situation and forecast analysis used by this model is required. Moreover, this model should be able to be used for "Preservation of the groundwater resource" in the future.

To examine all above items concisely, a "Synthetic Storage Model" by which the groundwater balance in the Study Area was able to be expressed overall was used to establish a groundwater development plan.

1.5.2. Introduction of Groundwater Simulation

(1) General

Along with the development of modern irrigation, especially groundwater irrigation, several kinds of water balance studies have been undertaken to evaluate groundwater potential and to discern the reasonable limit of groundwater utilization. For a global water balance, the natural conditions are summarized by the following equation. Based on natural condition, the equation consists of rainfall, surface runoff, evapotranspiration, drafting, inflow and outflow of groundwater and so forth is commonly applied, that is;

Surface Runoff + Subsurface Inflow + Precipitation +
Imported water + Decrease in surface storage +
Decrease in groundwater storage
=
Surface outflow + Subsurface Outflow + Consumptive Use +
Export Water + Increase in Surface Storage +
Increase in Groundwater Storage

The concept is very simple and a balance must exist between the quantity of water supplied into the basin and the amount leaving the basin. The equation can give the static water balance at a certain period rather easily. With the availability of hardware and software and innovations in computer technology, dynamic balance simulations to analyze the present condition, or for prediction have also been rapidly developed recently. Several kinds of methodology and related algorithm have been proposed for computer simulations, such as FEM, FDM, and so on. In this Study, a so-called synthetic storage model was applied to the water balance study.

(2) The Synthetic Storage Model

The synthetic storage model has been developed to make the said simulation possible in practical use basins. The model is mathematical and encompasses a basin-wide hydrological balance analysis for both surface and subsurface systems simultaneously, in an unsteady and quasi-three dimensional state. In addition to modeling both of the water balances and hydraulic analyses of a multi-aquifer system inclusive of aquicludes, the model can be applied to solve other phenomena such as multi-phase density flow, land-subsidence, substance balance and so forth. The concept of the model is illustrated in Figure 1.5.1, and described below.

The basin of interest is divided into sub-basin in arbitral rectangles in accordance with the characteristics of topography, drainage system, hydrology, water and land uses, etc. For the groundwater system, the aquifer and aquicludes are to be grouped in accordance with the conditions of hydrogeology and water drafts from aquifer in different depths. The aquifer groups in the same horizon in the neighboring sub-basin are provisionally defined as well as the up and down stream relation of the surface flow system in neighbored sub-basins.

The surface system is a serial depletion model of an exponential type. The model is known as "Serial Storage Model" or "Tank Model" the basic concept of which is that water flows into, is stored in and flows out of a container (tank) with orifices; the lowest orifice of the tank plays the role of groundwater recharge.

Groundwater storage is to take place in the uppermost unconfined aquifer and confined aquifers separated by leaky aquicludes. In usual hydraulic analyses which apply to the potential solutions, such as FEM and FDM, the water head is initially solved, followed by secondary water storage. On the contrary, this model initially solves the change of storage balance of an aquifer in a sub-basin, and the water head is steered through the relationship between the storage and head which was previously defined. This methodology is the most specific of the models, and is the origin of the model name. The balance of storage in an aquifer of a sub-basin is the sum of the recharge from the surface system, the leakage through the contacted aquiclude (s), the inflow (GI) and outflow (GF) from/to the aquifer in the same horizon in the neighboring sub-basin (s) and the draft (DF). The components except RE and DF are to be estimated, the seepage area and the hydraulic gradient. the product of permeability and seepage area in the model can be expressed by a concept of runoff coefficients α, a' and a". The model constructed is to be identified through the trial runs of model to meet with the actual hydrological behaviors observed by the time-series hydrograph of surface runoff for the surface system and groundwater heads at each aquifer for the groundwater system. Needless to say, that the artificial draft from each aquifer have to be known as precisely as possible to identify the model.

1.5.3. Model Construction

(1) Meteoro-hydrologic Record

The hydrologic balance model at the current situation which synthesizes the surface and sub-surface system was constructed and the forecast analysis was done to evaluate the groundwater resource in Study Area and to clarify the appropriate development potential. In this paragraph, the meteoro-hydrologic records which are used as the input parameters of the simulation are described.

a) Input Parameter

The meteoro-hydrologic parameters required to apply the model are rainfall data, evapotranspiration data and groundwater draft data. The rainfall data consisted of the daily records of the Massafi station during 19 years from 1977 to 1995. Furthermore, since the amount recorded at the mountain stations was different from Bahada Plain, a, Rainfall Coefficient (Rc) was introduced to each Sub-Basin (Rc: 0.83-1.11). To express this variation result in areas, the amount was modified by multiplying the Massafi records by Rc in the Models.

Detennining a basis for area rainfall calculations was done the Thiessen Polygon Method from the observatory (eight observatories) of the Study Area; the Rc was determined by giving the area a rainfall of 155 mm/year over the whole of the Study Area. For the evapotranspiration potential, the monthly mean value of pan-evaporation at the Mileiha station was applied. Hence, 3760 mm/year was applied as the evapotranspiration potential. Moreover, the amount of present groundwater draft was assumed by analyzing the well inventory data and the aerial photograph. The amount in the whole Study Area in 1995 was being 54 MCM, comprising from 12 MCM of Upper Aquifer and 33 MCM of Lower Aquifer.

b) Verification Parameter

The parameter which verifies the model is "groundwater hydrograph" of each aquifer for sub-surface system and "flood record" for surface system. The verification for sub-surface system was made by processing the daily data from original charts obtained from the six observatories in the Study Area. Six were selected out of 12 existing stations as parameters by eliminating unreliable data, such as an un-trustworthy readings, and closely locating and identifying inadequate changes in the groundwater head for the Simulation Model results from fissure water. Out of six records, four were obtained from Upper Aquifer and two of the remainder were from Lower Aquifer. the period of the verification years were about 10 years from 1986 to 1995 when all observation records were in order.

The four sets of records maintained from Wadi Siji, Wadi Sifuni, Wadi Ashuwani and Falaj Al Mualla stations were selected to verify the wadi flow data. However, the catchment areas of these stations were different from that of the sub-basin which was the object of the Model, consequently, the specific runoff was calculated by making observations, and the flood amounts for each sub-basin were corrected in their dominant areas. The records of Wadi Sifuni and the Wadi Ashuwani were combined together to generate the data for Wadi Khadrah. The three sub-basins of Wadi Khadrah, two mountain basins located on Wadi Siji and Wadi Khadrah, and one groundwater basin lying at Falaj Al Mualla, in the most downstream in the Study Area were then verified. The period of the verification was assumed to be 19 years of 1995 to 1977.

(2) Construction of Simulation Model

a) Sub-basin Division

As previous section, refers to the sub-basin classification for drainage systems. In the model simulation, the sub-basin division as a rule includes analysis of both surface and groundwater systems. However, the drainage sub-basins should be sub-divided into smaller divisions to get a more accurate analysis of each spot within the Study Area and the areas that make up these sub-divisions will be considered to be simple rectangular shapes. On the other hand, to make the model as simple as possible, the minor drainage system shall be ignored. Thus the surface sub-division for the model is made up as shown in Figure 1.5.2. The area is sub-divided into 21 basins, and dummy basins at the downreach of the model area have also been added.

b) Aquifer Modeling

The formation in the Study Area can be classified into two aquifers and one aquiclude as discussed in the previous paragraph. For constructing the storage model the same aquifer classifications are to be taken into account.

c) Sub-basin Structures

The aquifer and aquiclude constants to be given into the simulation program are assumed from the comprehensive study of the result of drilling, pumping test, groundwater hydrograph, water quality and so forth. Further, several components of sub-basin structure such as representative surface elevation, thickness and elevation of aquifer or aquicludes, H-Q curve (refer to Appendix 2.6), H-S Curve (area of aquifer, refer to Appendix 2.6), permeability, orifice structure, outlet structure and their height, etc., have to be decided for each sub-basin. The initial water heads for each aquifer also must be included in the program. The final sub-basin structure will be constructed through hydrological study, although they will be devised through the course of trial runs until the model is identified by verification data.

d) Input and Verification Data

The following are the five sets of input and one set of verification data are required for the model identification:

-Rainfall (daily basis, as long as possible)

-Pan Evaporation (mean monthly basis)

-Groundwater Hydrograph (daily basis, for each aquifer if available, as long as possible)

-River runoff (daily basis, for each drainage system if available)

-Groundwater draft (monthly basis, for each aquifer)

The groundwater draft can be estimated from farming areas and the actual groundwater draft survey. For river runoff, data for major wadis--Wadi Siji, Wadi Aswan, Wadi Sifuni and Wadi Khadrah--are available in daily basis. The groundwater level records can be collected from the 6 stations for 10 years from 1986 to 1995 as an available duration.

e) Program

The program for the synthetic storage model was written by FORTRAN-IV, originally it was prepared for main frame computer usage. However, the Study team have translated the program into MS-WINDOWS for operation on desktop computers: the source program, data forms shall be provided by the Study Team at the end of Study, together with the final parameters of the model.

(3) Model Parameters

a) Outline

The simulation model requires parameters to begin calculations, and the parameter are classified into two categories as follows;

- General Parameters: parameters to define the overall model configuration
- Basin Parameters: peculiar to each sub-basin

These two set of parameters are arranged into an adequate form for computing and are