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Report on Mission To the National Water Resources Authority Yemen

Groundwater Exploration Potential in the Ta'izz Region

10-21 September 2000

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00-0751

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MISSION IMPLEMENTATION

The mission was implemented upon the request of the National Water Resources Authority (NWRA) of the Republic of Yemen, and the approval of the Executive Secretary, during the period 10 -21 September, 2000.

The terms of reference of the mission was given as follows:

- Review the NWRA experience of well siting and drilling of the exploration wells in the Taizz area and evaluate the results.
- Make recommendations regarding the siting of two or three exploration wells in the Taizz area based on the above-mentioned review and on available hydrogeological a geophysical data.
- Make recommendations regarding well design and protection measures to prevent pollution of such wells.
- Make recommendations regarding protection zones for well fields.
- Make recommendations regarding the supervision of drilling of exploratory wells if possible a short course will be organized on the subject of supervision of deep well drilling and design and completion measures for deep production wells.

The following issues were implemented during this mission:

- Review of the current NWRA exploratory well drilling program in Taizz region.
- Review the available groundwater studies on Taizz region..
- Delineate potential areas for groundwater exploration and development.
- Identify and recommended potential drilling sites for groundwater exploration.

Upon return to ESCWA office in Beirut, the data obtained was analyzed and evaluated. Appropriate hydrogeological maps have been prepared, and a mission report has also been prepared.

During the mission, consultation meetings were made with the following persons:

1. Jamal Abdu / Director, National Water Resources Authority.
2. Nasir M. Nasir / Head, Monitoring and Implementation Sector.
3. Abdulla M. Al-Thary / Head, Water Policy and Programming Sector.
4. Mohammad Danich / Head, Water Studies Sector.
5. Abdallah Saleh Saif / NWRA Project Manager in Taizz.
6. Ahmed Ali Shami / Water Policy and Programming Sector.
7. Ahmed Abdul Rub Ali Qbadhi / Water Studies Sector.

PREVIOUS STUDIES AND FURTHER INFORMATION NEEDS

Although field survey was conducted for a large number of water wells during the previous studies, the data obtained, particularly on the sandstone aquifer, is considered insufficient and inadequate even for preliminary evaluation. Most of the inventoried water points were shallow wells, and the existing deep wells lack information on well design, pumping test data and lithologic logs. In addition, few of them penetrated the sandstone aquifer, and none of those were found in Wadi Warazan. Most of the wells tapping the sandstone aquifers were found in Wadi Al-Ghayl. As a result the data analysis conducted in the previous studies was just preliminary one,. and of the statistical type, rather than being hydrogeological. Very rough water level contour maps were prepared for the study areas without discrimination or separation between shallow and deep wells. This mixing would be misleading in delineating the groundwater flow pattern and the hydraulic connection between the shallow and deep aquifers. This is almost true for all the study areas. In addition, the lateral trend or pattern of change in the groundwater salinity was difficult to delineate.

The regional mapping effort was further complicated by the large lateral variations in the hydrogeological conditions and properties. Such large lateral variation in the hydrogeological and hydrochemical conditions may in fact have very pessimistic implications on the possibility of occurrence of well established, and dynamic large scale deep groundwater systems, with well defined recharge and discharge areas in Taizz Region. This pessimistic conception is also demonstrated by the following conditions:

a) Lack of physical continuity of the geological formations between the lower most reaches of the Wadies (discharge areas), and the upper most, high rainfall areas of the catchments (recharge areas). This could particularly be true for the Taweelah sandstone formation.
b) The latest volcanic eruptions through fault planes, and through a series of closely spaced volcanic necks have created a number of vertical barriers to the groundwater flow, whether through the sandstone or through the older volcanic flows. Such a case is well demonstrated in the southeastern part of Wadi Warazan. In addition, some existing fault planes, being filled with volcanics, are mostly acting as barriers rather than conduits in most of the cases (need verification).

The previous studies did not consider hydrogeological boundaries as basis for the exploration areas. Instead the surface water (hydrologic) boundaries were considered. Such consideration might be valid when talking about shallow aquifers, which is not the case in the present project areas.

There is a need to establish and prepare a map, which represents the lateral or areal distribution of the sandstone formation in the Taizz region. Such map should contain information on the external and internal boundary conditions, which demonstrates the degree of hydraulic connection between the various areas and sub-areas within the Taizz region.

On the other hand, there is a need to determine the vertical hydraulic connection between the shallow water-bearing zones (alluvial deposits and the upper volcanics), and the deep water bearing zones, the lower volcanics, and most importantly, the Taweelah sandstone aquifer.

Water level measurements and water quality sampling at different depths during drilling are the best means to understand such relationship. In addition, vertical leakage between the different zones can be qualitatively and quantitatively evaluated from the analysis of well-designed and executed pumping tests. Such tests should include at least one observation well near the test well.

Moreover, such well designed and controlled pumping tests, would provide better and more accurate estimation of the hydraulic properties of the aquifer(s), namely, the hydraulic conductivity and the aquifer storage coefficient. Such data well make it possible to assess the groundwater storage and well productivity.

GROUNDWATER OCCURRENCE AND FLOW

Groundwater, in the Taizz region occurs in three geological types of rocks, the quaternary alluvial deposits, which are mostly found along stream channels and in the plains, the tertiary volcanics, and the Taweelah sandstone formation.

The groundwater in the alluvial deposits is sometimes hydraulically connected with the groundwater found in the fractured upper parts of the volcanic rocks as in Wadi Warazan. The groundwater in this case is under water table conditions (not confined).

The occurrence of massive volcanic rocks at greater depths, and the anistropy in the different volcanic flows, may both lead to semi-confining conditions for the deep volcanics and for the Taweelah sandstone aquifers.

The groundwater recharge, to the shallow and the deep aquifers, seem to be mostly dependent on local vertical infiltration of rainwater and flood flows. The horizontal component or contribution to groundwater, from within and from outside the region is expected to be of lower importance.

Preliminary maps were prepared for the groundwater flow direction in the different study areas in the previous studies. These maps need to be validated by more appropriate data, which represent the shallow and deep aquifers separately.

Groundwater basins' boundaries in the study areas are not yet sufficiently clear and well defined. The lateral extent, boundary conditions, depth to aquifer and aquifer hydraulic characteristics are still poorly defined and evaluated. Such information is still spotty. In addition the large extent of variations of the hydrogeological properties, and the few number of site measurements, make it difficult to regionalize these properties.

It is not known yet whether the Taweelah sandstone formation has a continuous lateral extension underneath the volcanic rocks in the Taizz region. This formation has a number of scattered surface outcrops along faults and around and on top of the igneous intrusions. It has been penetrated by wells drilled south and west of Taizz only. It has not been encountered, so far, by any wells in Wadi Warazan or upper Wadi Rasyan.

On the other hand, the latest drilling program has shown that the depth to the sandstone aquifer, if existing, would be high, and greater than 750 meters in Wadi Warazan and Wadi Rassyan areas. It is expected to be too deep in Taizz area and in the southeastern area of Wadi Warazan. This is because of the occurrence of most of the volcanic flows in Taizz area, and because of the large number of closely spaced volcanic necks in the southeastern part of Wadi Warazan.

The hydraulic connection between the upper aquifer (alluvial and the fractured upper volcanic). is not also clear in all the areas of exploration. The design of the drilled exploratory wells did not provide for measurement of the vertical variations in the hydrogeologic conditions, namely, changes in water level and water quality.

GROUNDWATER POTENTIAL

The estimation of the groundwater annual recharge in the latest study may be considered as modest. It was based on the assumption of a percentage of the average of rainfall. Groundwater recharge for the shallow aquifer obviously takes place from direct infiltration or rainfall, as well as infiltration of flood flows along the mainstream channels. Recharge for the deep volcanic aquifer takes place from residual deep percolation, and seepage from the shallow aquifer in areas where the vertical hydraulic gradient is favorable.

Recharge to the sandstone aquifer takes place by direct infiltration of rainwater and runoff over the outcrop areas, as well as from vertical and lateral transfer of the groundwater from the volcanic aquifer.

A rough estimate of the total groundwater outflow (through flow) from the four areas has been calculated as follows in million cubic meters per year:

	Annual outflow (MCM/YR.)
W. Bani Khaulan	3
W. Al-Ghayl	9
W. Rasyan	15
W. Waran	24
Total	51

Adding about 20 MCM/YR, which leave the area as surface base flow, will yield a total recharge of 71 MCM/YR.

Backward calculation of recharge using an average area of rainfall of 500 mm, over a total area of 5000 km^2, and using of 71 MCM/YR. gives 4.2 mm of rainfall or 2.84% of the total average annual rainfall. This value may be considered as fair to high for an arid to semi region like Taizz area.

This means that the total annual recharge for all aquifers in Taizz regions should be equal or less than 71 MCM/YR. Subtracting the base flow (20 MCM/YR.), which may need to be sustained for down-stream users, leaves about 51 MCM/YR. available for well abstraction.

The annual pumping from all wells in Taizz region was estimated at 41 MCM/YR for all the four study areas. This means that there is a potential for exploitation additional 10 MCM/YR. through wells, in addition to the base flow of Wadi Warazan. (?)

It has been mentioned in the previous studies that the groundwater balance in Wadi Al-Ghayl and Wadi Bani Khawlan is almost even, with the total extraction equaling the total recharge. This means that any further well drilling and long-term extraction will upset this balanced condition, and will adversely affect the existing agricultural developments, particularly those based on shallow dug wells. The farmers in such case will be compelled to drill deeper wells to sustain their traditional way of living, thus investing a large sum of money. And even after all that, the state of imbalance will continue, resulting in additional lowering of the groundwater level, and consequently depletion of the groundwater storage, and the problem will be then more difficult to solve.

This depletion problem will be intensified in view of the small storage coefficient of the volcanic aquifer in particular.

On the other hand, the sustained base flow derived in Wadi Warazan, and the absence of any abstraction from the deep aquifer, in general, and from the sandstone aquifer in particular in this area, indicates a possible potential for additional groundwater abstraction, and justifies further exploration.

However, we should keep in mind that this will be very costly, in view of the extensive depth required to tap the sandstone aquifer (>750m.) particularly in lower Wadi Warazan and upper Wadi Rasyan. We should also keep in mind the limitation on the aerial extent of the exploration area in Wadi Warazan due to the occurrence of the numerous volcanic necks. These volcanic necks appear as isolated hills on the ground surface. However, they are expected to join at depth, forming a continuous vertical barrier for groundwater flow, and eliminating the chance of encountering the sandstone formation at or adjacent to these areas. Such a barrier is expected to be responsible for the emergence of the base flow in the lower southwestern reaches of Wadi Warazan. In this case the base flow from the middle reaches of the Wadi are expected to be discharging the shallow aquifer, while the base flow emerging along the lower reaches would be discharging the deep aquifer through faults bordering the line of volcanic necks from the north. This explanation is supported by the fact that the electrical conductivity of the base flow in the lower reaches is much higher than that in the middle and upper reaches, which possibly indicates to the possible groundwater sources contributing to the base flow.

The situation in Wadi Rasyan catchment seems better, particularly north and north west of Taizz area. There would be more possible sites, and the depth to the sandstone aquifer would be less. The depth to the sandstone aquifer decreases towards the north and north-west. This fact should be kept in mind when locating a well site. Moreover, the Wadi channels provide good access to the potential well sites in addition to extra savings in well depths. It was found during the field visits to Wadi Rasyan area, and from desk studies, that most of the stream channels are located along tectonic lineaments (some times faults). Such conditions would result in creating zones of weakness and fracturing along these stream channels, and consequently higher rock permeabilities and concentration of groundwater flow.

ASSESSMENT OF THE CURRENT AND FUTURE WATER SUPPLY AND DEMAND

Current Water Supply For Taizz:

The city of Taizz witnessed significant urban development over the last ten years. This development was seen as accelerated increase in population due to migration from rural areas, and large housing development. According to the census of 1994, the population of the city of Taizz was 400,000 people.

The municipal water supply for the city was partly dependent on a limited water supply network and partly on water tankers. The supply sources for the network were as follows in 1996:

Well field	No. of wells	Supply rate	
		L/S	MCM/YR/
Taizz City	11	45	1.419
Haujelah/Hauban	7	56	1.766
Haima	7	35	1.104
Hbair	3	40	1.261
TOTAL	28	176	5.55

The supply was increased to about 8 MCM/YR. in the year 2000.

Most of these wells tap the alluvial aquifer, and range in depth from 20-60m., except Taizz and Hbair wells which reach down to 400 m.

Assuming a population growth rate of 4%, the population in 1996 would be about (432640) people, and the daily consumption per person (pcd) would be 35 liters/person/day (l/c/d). This rate is considered very low. With strict conservation measures, (80) liters per person per day would be required to provide a good standard of living. People in the rural areas depend on local dug or drilled wells.

Assuming, a daily water consumption per person of 60 and 80 l/c/d to provide a reasonable standard of living, the deficit in 1996 would be (4) and (7) millions cubic meters respectively, which is 42% and 56% of the demand respectively.

Future Municipal Water Demand:

A strong justification for a groundwater exploration program would be the failure of the existing water resources to meet the future demand. Therefore, it is important to prediction of such future water demands becomes necessary.

The future municipal water demand has been estimated based on annual population growth rate of 4% till the year 2005, then a decreasing rate to 3.5% till the year 2010.

In addition three scenarios have been applied for the per-capita daily demand:

1. A low estimate by increasing the daily consumption per person (pcd) to a maximum of 50 l/c/d by the year 2010.
2. A moderate estimate by gradually increasing the pcd to a maximum of 65 l/c/d by the 2010.
3. A high estimate by gradually increasing the pcd to 80 l/c/d by the year 2010.

A summary of the three estimates is given in **table (1)** and is shown graphically in **figure (1).** The detailed calculations are given in **Annex (1).**

It is obvious that the deficit in 2010 may range from a minimum of 7.6 to 15.5 MCM/YR above the 2000 supply rate (8MCM).

New groundwater supply sources should be expected to be in operation as soon as possible and before (2003), and should be increased gradually afterwards to meet the increasing future water demand.

Options For Future Water Supplies

Most of the wells in the Taizz region suffers from relatively high salinity and are polluted by municipal solid and liquid wastes, as well as from industrial wasters. Moreover, these wells are being pumped at their maximum capacity. Therefore, the supply rate of the current sources is not guaranteed and may not be sustainable for the future. In addition, the shallow aquifer is almost fully exploited for irrigation by the private sector, in addition to being highly vulnerable to pollution.

The transfer of desalinated sea water from Aden would be very costly with the prevailing high altitude and pumping lift. In addition, desalination of Wadi Warazan base flow may provide a potential water supply sources on the long-term.

On the other hand we should keep in mind the potential water saving which can be attained by improving the water supply network, in order to reduce the un accounted-for-water, which currently amounts to about 50% of the total water supply.

Flood water resources are not sufficient to meet the current supply deficit and the future water demand, in addition to the costly treatment requirement. The most important of the surface water resources in the region is the base flow of Wadi Warazan, which amounts to about 300 l/sec. Great part of this base flow can be intercepted by wells. However, downstream water rights need to be taken care of. In addition the salinity of this water is above 1000 ppm, and can be desalted by a reverse osmosis plant.

Finally, desalination of Wadi Warazan base flow may provide a potential water supply sources on the long-term.

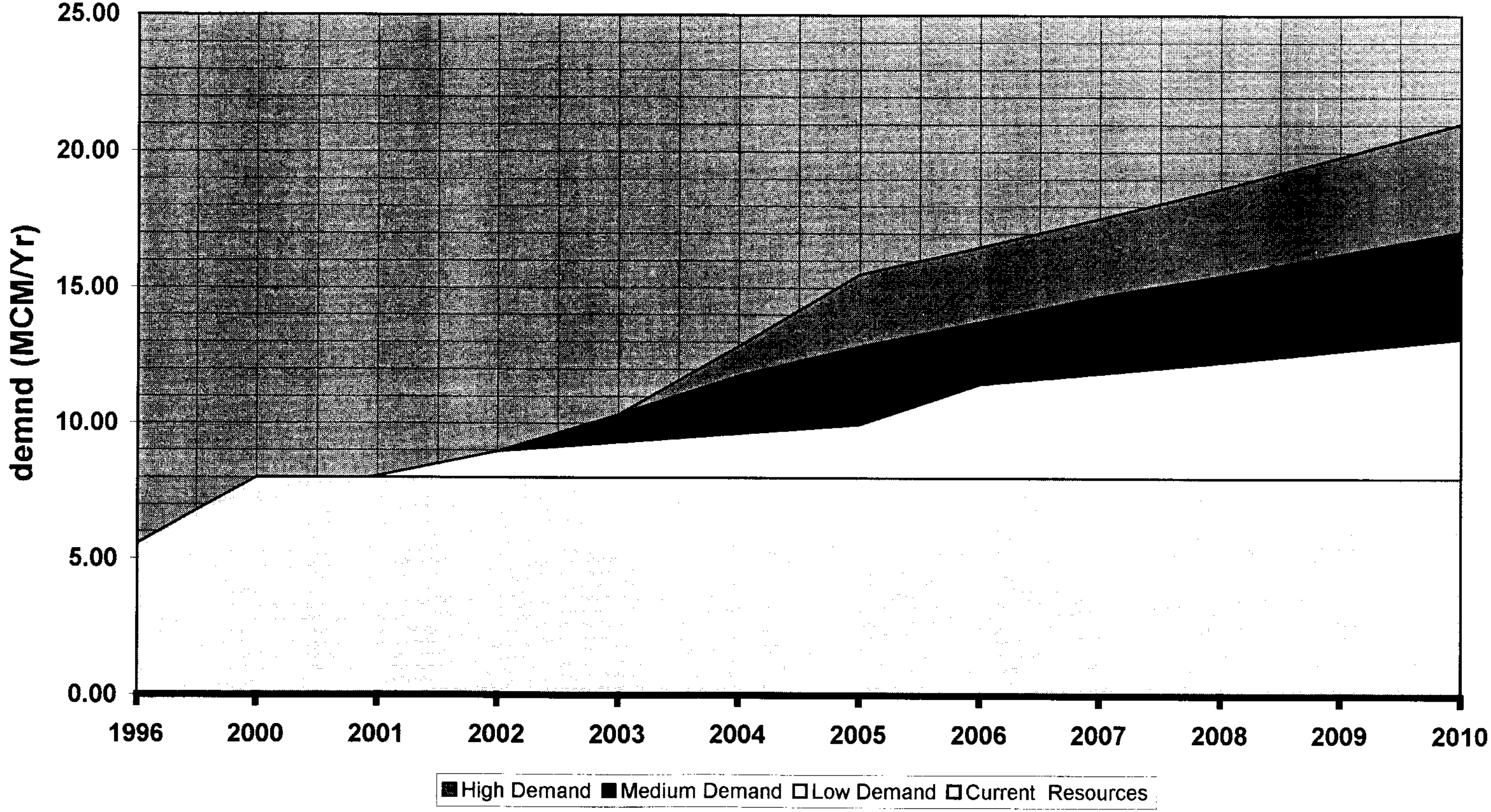
However, none of these resources seems economically feasible on the short and medium terms, and we remain with the option of the deep groundwater in the Taizz region as the first and most possible option, and this is the reason of starting the current exploratory well drilling program.

Table (1)

ESTIMATED WATER DEMAND FOR THE CITY OF TAI'ZZ

	HIGH ESTIMATE		*MODERATE ESTIMATE*		*LOW ESTIMATE*	
Year	**Demand** MCM/Yr	**Deficit / Shortage (Ref. 1996)** MCM/Yr	**Demand** MCM/Yr	**Deficit / Shortage (Ref. 1996)** MCM/Yr	**Demand** MCM/Yr	**Deficit / Shortage (Ref. 1996)** MCM/Yr
1994						
1996	5.55		5.55		5.55	
2000	7.39	-1.84	7.39	-1.84	7.39	-1.84
2001	8.06	-2.51	8.06	-2.51	8.06	-2.51
2002	8.97	-3.42	8.97	-3.42	8.97	-3.42
2003	10.33	-4.78	10.33	-4.78	9.30	-3.75
2004	12.84	-7.29	11.77	-6.22	9.63	-4.08
2005	15.51	-9.96	12.85	-7.30	9.97	-4.42
2006	16.51	-10.96	13.76	-8.21	11.46	-5.91
2007	17.56	-12.01	14.71	-9.16	11.87	-6.32
2008	18.67	-13.12	15.47	-9.92	12.28	-6.73
2009	19.83	-14.28	16.27	-10.72	12.71	-7.16
2010	21.05	-15.50	17.10	-11.55	13.16	-7.61

Figure (1) :Water Demand For Taizz



EVALUATION OF THE CURRENT EXPLORATORY WELL DRILLING PROGRAM

The current exploratory well drilling program was started in February 1998 for the purpose of exploring the potential for additional fresh water resources for the municipal Water supply of the city of Taizz. The program included the drilling of 5500 meters at several locations.

Until the time of this mission, September 2000, about 80% of the total drilling was completed at ten sites (4393m). The drilling was completed in two stages, where five wells were drilled in each stage. The two stages were separated by a private consultant mission, M.T. Johns in June 1999. The consultant evaluated the results of the first stage and recommended additional sites for drilling, where additional five wells were completed by the beginning of the year 2000.

The locations and well depths of these wells are given in **table (2)** and **Figure (2)**. The results of drilling for the two stages are compared in **tables (3,4)**.

It can be concluded from these tables that the first stage was more successful, where two wells had high and very high productivity and two wells had low productivity. While in the second stage two wells had moderate yield and the rest of wells had low productivity. The total yield of wells was 42.0 and 30.0 liters per second for the first and second stages respectively.

The high productivities were for wells tapping the sandstone aquifer. On the other hand, most of the wells tapping the alluvial or the volcanic aquifer had low yields.

Two of the most successful wells were in Wadi al-Ghayl (close to each other). The moderate yielding wells were in Wadi Warazan (well No. 9) and in Khzaija, west of Taizz , (well No. 7), **table (5).**

The overall yield from all wells was 72 l./sec., with an average of 7.2 l./sec. per well, or 1.69 l./sec. per 100 m. of drilling.

Table (6) compares the wells' productivity by aquifer type. It indicates that the sandstone aquifer wells were high to very high yielding, while wells tapping the alluvial and volcanic aquifers were moderate to low.

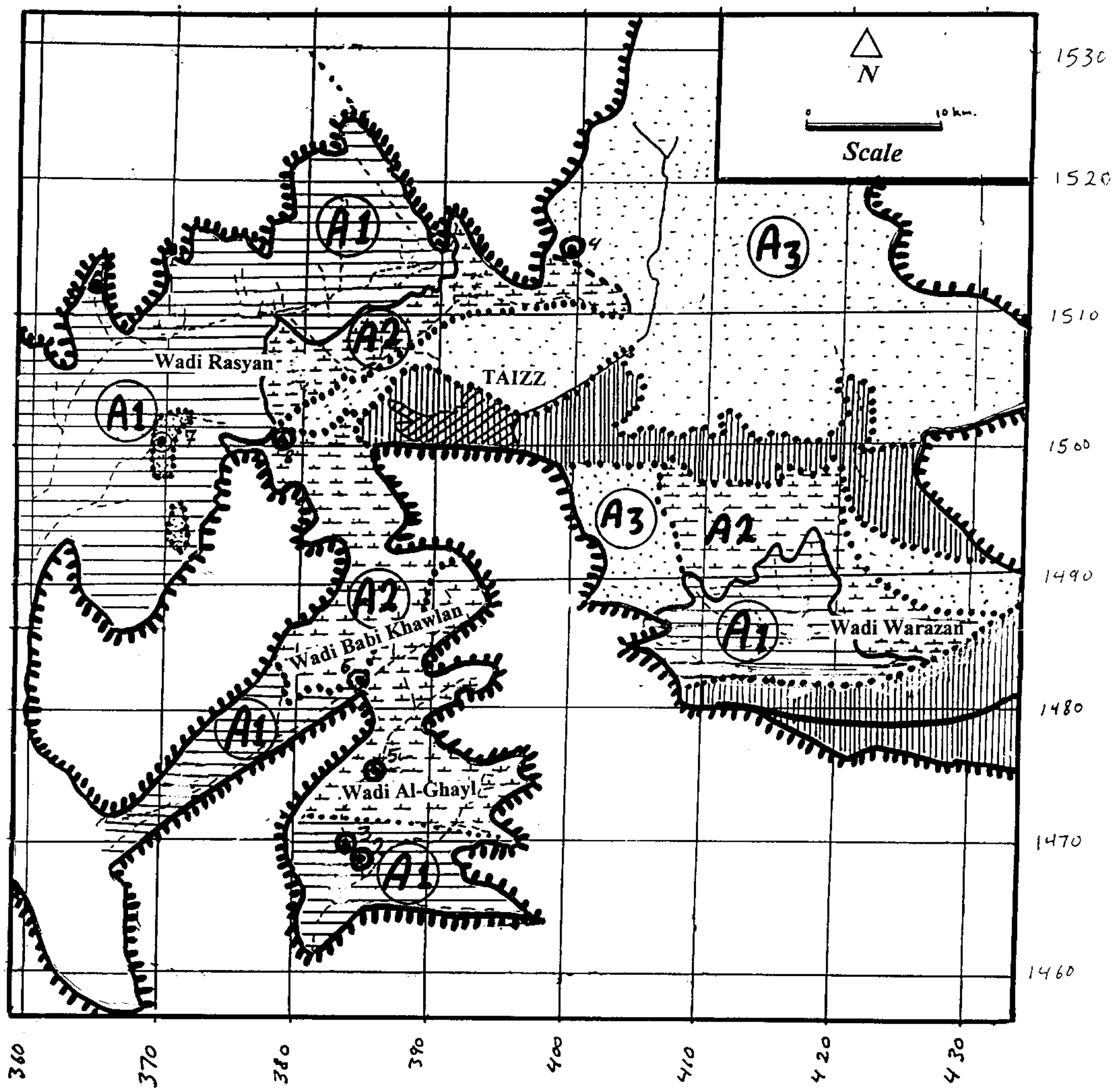
Water samples were taken for chemical analysis upon completion and testing of the wells. The electrical conductivity of the groundwater in all wells ranged from 1015 to 3800 u-mhos. The highest salinity was found in Wadi Warazan well (9). On the other hand, the lowest salinity was found in two wells in Wadi Al-Ghayl (2,3), and well number (7) in Kzeijah west of Taizz, followed by well number (10) at Qarqar in lower Wadi Rasyan, **table (7).**

- Groundwater salinity is less for the sandstone aquifer and in Wadi Al-Ghayl in particular, where the salinity ranged from 1015 to 1136 u-mhos.
- The highest salinity was found in Wadi Warazan, and was mainly from the volcanics aquifer at a depth of 535 m {well (9)}.
- The variation of salinity with depth can be summarized as follows:

Well depth m.	Well No.	Temperature C°	Electrical Conductivity
210	6	31.5	2150
298	2	31	1015
347	3	32.2	1136
353	7	35.5	1316
354	10	32.0	1450
535	9	40.0	3800
750	4,1	34,35	1900, 2150 respectively.

The figures in this table show a general increase of water salinity and temperature with depth for most wells. However well No. (9) in Wadi Warazan is rather anomalous with higher temperature and salinity.

Figure (3), demonstrates the variation of salinity with depth. The location and aquifer type are also indicated on the figure. Interpretation of this curve indicates the following:



GROUNDWATER EXPLORATION POTENTIAL AREAS - TAI'Z AREA

(Numbers indicate Priorities)

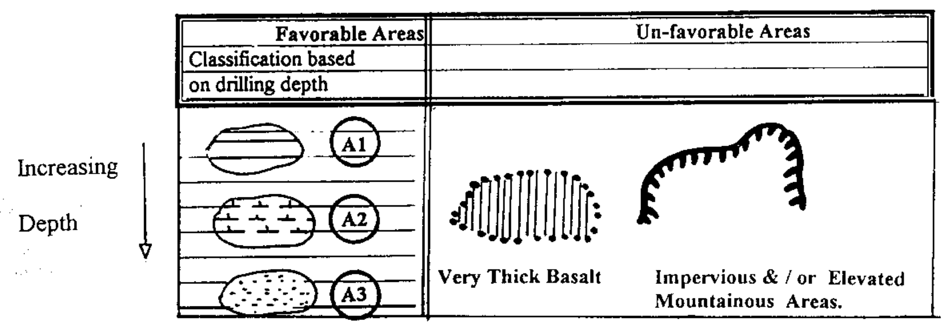


Figure (2) :DRILLED EXPLORATORY WELLS

Drilled Exploratory Well .... ⊙2

Table (2)

Location And Depth Of The Drilled Exploratory Wells

Well Number	Location		Coordinates		Well Depth
	Area	Wadi	East	North	M.
1	Al-Dhabab	Bani Khawlan	383848	1499693	750
2	Al-Hasb	Al-Ghayl	384848	1467427	298
3	Al-Qist	Al-Ghayl	382918	1486118	347
4	Al-Miqbabah	Rassyan	398050	1514123	750
5	Al-Siwa'a	Al-Ghayl	387262	14748822	234
6	Al-Minthafah	Al-Ghayl	375143	1476074	210
8	Al-Husaineh	West of Tai'zz	376989	1500574	562
9	Warazan	Warazan	416373	1480760	535
10	Qarqar	Rassyan	371353	1505350	354

Table (3)

Productivity Comprison Between the Two Exploratory Drilling Stages

WELL NUMBER	Location	Well Yield liters/sec	Draw-down m.	Specific Capacity l/sec/m	Productivity	Aquifer Type (Material) ***
First Stage						
1	الضباب/ بني خولان	4.0	84.87	0.047	Low	All+B
2	العصب/ الغيل [illegible]	20.0	12.50	1.600	High	SS
3	القبة/ الغيل	15.0	0.29	51.724	Very High	SS
4	[illegible]/ رسيان	3.0	190.00	0.016	Low	All+B
5	الشواء/ الغيل	0.0			Dry	SS
Total Well Yield (l/sec) :		42.0				
Second Stage						
6	المتلقفة / الغيل	0.5	_	_	Low	All+B
7	خريجة / غرب تعز	10.0	82.11	0.122	Moderate	SS
8	الحسينة / غرب تعز	3.0	103.43	0.029	Low	ALL+B+SS
9	ورزان	13.0	21.16	0.614	Moderate	B
10	قرقر / رسيان	3.5	12.00	0.292	Low	ALL+B+SS
Total Well Yield (l / sec) :		30.0				

*** All : Alluvium , SS : Sandstone , B : Basalt

Table (4)

Results of the Two Exploratory Well Drilling Stages

Comprison Parameater	First Stage	Second Stage	The whole Project
Number of wells	5	5	10
Total Drilling Depth	2379	2014	4393
Successful Wells			
Number :	2	2	4
% Success :	40%	40%	40%
Location :	(2) W. Al-Ghayl	(1) Warazan , (1) Rassyan	
Total Well Yield (l / sec.)	42	30	72
Ave. Yield Per Well (l /sec)	8.40	6.00	7.20
Ave. Yield Per 100 m. of drilling l / sec)	1.77	1.49	1.64

Table (5)

Well Productivity By Area

Area	Number of Drilled Wells	Well Productivity				
		V. High	High	Moderate	Low	Dry
Wadi Al- Ghayl /	4	1	1		1	1
*** Aquifer :		SS	SS		B	SS
Wadi Bani Khawlan	1				1	
*** Aquifer :					B	
Wadi Warazan	1			1		
*** Aquifer :				B		
Wadi Rassyan	2				2	
*** Aquifer :					B	
West of Ta'izz	2			1	1	
*** Aquifer :				SS	SS+B	
Total	10	1	1	2	5	1

Summary :

Out of 10 drilled wells there are:

1 Well	Of very High Productivity
1 Well	Of High Productivity
2 Wells	Of Moderate Productivity
5 Wells	Of Low Productivity
1 Well	Dry

*** SS : Sandstone , B : Basalt

Table (6)

Well Productivity By Aquifer Type

Well Productivity	Number Of Wells In each aquifer			Total
	Alluvium	Sandstone	Basalt	
Very High		1		1
High		1		1
Moderate		1	1	2
Low	5	2	5	5
Dry Well		1		1
Total	5	6	5	10

Note : Total Number of Wells = (10)

Well Yield (l / s)	Aquifer			Total
	Alluvium	Sandstone	Basalt	
Total Well's Yield (l / s)		51.5	20.5	72
Average Well Yield (l / s)		12	4.5	

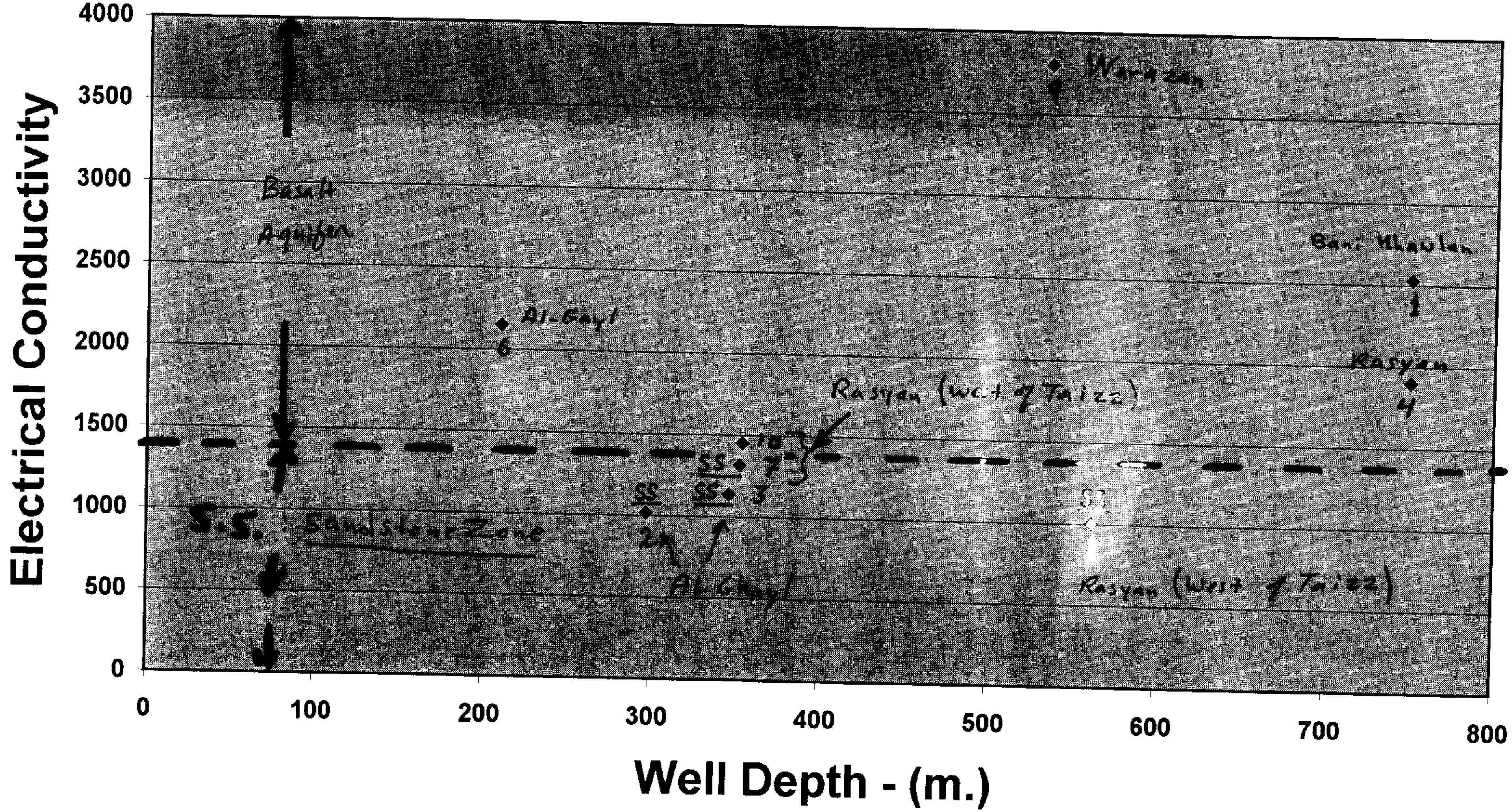
Table (7)

Grounwater Quality In The Drilled Exploratory Wells

Well Number	Location		Electrical Conductivity	Tempreture deg. Cent.	Well Depth M.
	Area	Wadi			
B					
9	Warazan	Warazan	3800	40	535
All + B					
1	Al-Dhabab	Bani Khawlan	2530	35	750
4	Al-Miqbabah	Rassyan	1900	34	750
10	Qarqar	Rassyan	1450	32	354
6	Al-Minthafah	Al-Ghayl	2150	31.5	210
Range :	1450 - 2530				
Average :	2008				
All + B + SS					
8	Al-Husaineh	West of Tai'zz	1002	50.45	562
SS					
2	Al-Hasb	Al-Ghayl	1015	31	298
3	Al-Qist	Al-Ghayl	1136	32.2	347
5	Al-Siwa'a	Al-Ghayl	dry		234
7	Khzeijah	West of Tai'zz	1316	35.5	353
Range :	1015-1316				
Average :	1156				

lluvium , SS : Sandstone , B : Basalt

Figure ( ) : Variation ofElectrical Conductivity with Depth



JUSTIFICATIONS AND STEPS FOR ADDITIONAL EXPLORATORY WELL DRILLING

Exploratory drilling is expensive, however, it is necessary before deciding on any groundwater exploitation scheme. Exploratory drilling could provide information on the following:

- The availability of groundwater based on hydrogeological and economic criteria. This includes information on location and depth of productive aquifers, the potential storage and well yield, and the water quality.

- The parameters required to design the production wells, and the selection of the required pumps.

- Finally the most promising sites for production wells.

However, there should be reasonable justifications for any groundwater exploratory drilling program, among these are the following:

1. There is an urgent need for municipal water supplies for the city of Taizz, at the present and in the future. Such need is expressed in terms of water deficit or shortage between the available water supply sources, and the current or future water demands as will be seen later.

2. There are no alternative water supplies to meet such water shortages, with regard to the water quantity and quality, and cost.

3. there are potential aquifers which may provide such additional water demands.

For Taizz city, the first two justifications apply very well. As for the third justifications, the currently exploited aquifers are suffering from quality deterioration due to pollution from infiltration of municipal and industrial effluents. The specifications of the current supplies are below the WHO standards for drinking water supplies.

On the demand side, the accelerated urban growth in Taizz city, due to increasing population growth and health and sanitation needs, are pressing the current water supply sources. It is also a fact that only a relatively small percentage of Taizz population is currently serviced by municipal water supply.

Therefore additional water sources are need to:

- Extend services to the rest of Taizz population.
- Improve the services for the currently served sector.
- Meet the water demand at least until the year 2000.

We conclude that the currently used groundwater aquifers are not only short of providing the present demand, but are not seen potentially sustainable for the future. Therefore there will be a double need for locating new groundwater supplies.

In addition, the results obtained from the current exploratory well drilling program so far, are not yet confirmative in Wadi Rasyan and Wadi Warazan areas, which may be considered promising, but at the same time are more complexed hydrogeologically

The large vertical and horizontal variations in the hydrogeological conditions of these areas are also justifications for additional drilling. Only one well was drilled, and without successful completion, in Wadi Warazan area. The same applies to Wadi Rasyan. I believe 2-3 wells need to be drilled in each of these two areas.

INITIAL STEP FOR PLANNING THE DEVELOPMENT OF GROUNDWATER RESOURCES

The initial steps to be taken, before deciding on a new, costly groundwater exploration program are to:

1. Appraise the specific water requirements in quantity and quality.
2. Investigate the possibility of rehabilitating the current groundwater supply wells and well fields to increase their productivity.
3. Investigate the possible savings from rehabilitation works to improve the efficiency of the overall water supply system (unaccounted for water).
4. Investigate the feasibility of other water resources such as surface water and desalination water.
5. Investigate the possibility of water supply augmentation by a reallocation process of the available water sources, as well as the possible exchange of water resources between different uses based on their quality requirements.

Prior to planning an exploratory well drilling program, we should assess which of the following categories apply to our area:

1. Current groundwater use is intensive, the additional supply can be obtained, however, with either:

    a)- no adverse effects on current public and private schemes, or
    b)- with a calculated non- or slightly detrimental effects.

2. Groundwater resources are intensively developed, and the reserves are appreciably depleted. In this case additional extraction will accelerate depletion and quality deterioration, and consequently will shorten the life of existing wells and reduces any further development opportunities.
3. Existing groundwater resources are not adequate in quantity and quality.
4. Groundwater development in the area is minor relative to its potential. In this case the most promising areas should be identified bearing in mind the water quality and the economic well depths and pumping heads.

The situation in the Taizz region is between the first and the second cases, were there is an intensive development, but mostly in the shallow aquifer. However, there is a strong hydraulic connection of the shallow aquifers with the deep aquifers, and intensive development of one aquifer especially the deep one, will adversely affect the development in the other.

In this case there will be hydraulic interference with existing wells, particularly in Wadi Al-Ghayl and Wadi Bani-Khawlan. However, proper well design of the exploratory and production wells will minimize this interference and make it a delayed one.

The proper well design should secure complete isolation of the shallow from the deep aquifers through appropriately performed cementing job within the shallow aquifer.

A close look would show that case one above, specifically applies to Wadi Al-Ghayl and Wadi Bani Khawlan. While case two applies to Taizz area. Case four applies to a certain extent to Wadi Rasyan and Wadi Warazan

Consequently deep aquifer exploration should be planned according to these relationships.

IDENTIFICATION OF EXPLORATION AREAS AND SITES

Revision of the previous studies, and the results of the latest drilled exploratory wells, have shed some light, although not as needed on the hydrogeological features of the study areas. Additionally the following three criteria have been used to identify and assess new potential areas and sites:

1. The hydraulic characteristics, namely the permeability and porosity of the geological formations occurring within the study areas. According to these criteria, areas where the Precambrian rocks and the tertiary granites are exposed are eliminated from any exploratory drilling efforts. These areas are indicated as "PC" or "GR" on the map in **figure (4).**
2. The expected depth to the sandstone aquifer is the second criteria. This criteria is the most uncertain. However, based on the available data and information, and through interpretation and interpolation, it is possible to come up with acceptable conclusions. Accordingly the following areas can be eliminated from additional exploratory drilling, on the bases of extensive depth to the sandstone aquifer , and are indicated as "DP" on **figure (4):**

   a. The south eastern zone of Wadi Warazan catchment.
   b. Taizz and east-Taizz area.

3. The topographic and terrain conditions: these conditions would affect the following aspects in any exploration program:
   a. The total and final well depth will be greater at higher altitudes.
   b. The depth to the groundwater level, which influences the pumping lift will also be greater at higher altitudes.
   c. Rough mountainous terrain would provide poor accessibility to the drilling site during well construction and any possible future well operation. An expensive access road may be required. Based on this criteria, areas indicated as "TOP" **in figure (4)** are eliminated.

4. Taizz area is also eliminated because of the groundwater pollution problem.

Sometimes, the two zones 3-b and 3-c described above, may overlap. After this elimination process, we remain with the promising groundwater potential areas, **figure (5).**

However, within each of these areas, there are some variations in their potential for various hydrogeological factors. These areas have been classified into "A, B & C , with "A" having the highest potential, and "C" having the lowest potential. In addition these zones may be sub-divided sub-zones, such as A1,A2 , with the lower number indicating higher rank and priority.

The deep Taweelah sandstone aquifer is exposed in scattered localities in Taizz region. It is already encountered and tapped by few wells in Wadi Al-Ghayl area, and has also been encountered in two wells in Wadi Rasyan west and north west of Taizz. It is also expected to be found at moderate depth (500-700m) in western and the central area of Wadi Rasyan, and at a greater depth, 700-800m in Wadi Warazan and upper Wadi Rasyan.

So far, the current exploration program proved that high to very high productive wells (10-20 l/s) may be available in Wadi Al-Ghayl area in the sandstone aquifer. However, since the current irrigation abstraction in this area almost balances the total annual recharge, few wells can be drilled with a maximum annual yield of 1-2 MCM to augment the current and near future water supply of Taizz.

The same applies to the area west of Taizz. Production wells can be drilled in these areas, and conveyance systems are to be installed as soon as possible. The drinking groundwater supply from these areas can be increased by enforcing proper regulations to control drilling and abstraction by the private sector, particularly for irrigation.

However, there are some constraints or limitations on the deep aquifer exploitation, most important of these are the following:

1. High drilling cost of deep wells,
2. Limited groundwater storage and recharge,
3. Relatively low to moderate well yields (maximum of 20-25 l/sec.),
4. Marginal water quality with regard to salinity (above 1000ppm),
5. Social and legal constraints on development, particularly in Wadi Bani Khawlan.

The relative depth to the sandstone aquifer in the different study areas is estimated as follows:

AREA	Relative depth	Expected depth (m)
Wadi Al-Ghayl	x	200-300
W. Bani Kawlan	x	250-350
West of Taizz	xx	300-400
W. Rasyan (west)	xxx	350-550
W. Rasyan (central)	xxxx	500-700
Upper Wadi Rasyan	xxxxx	700-900
Middle and Upper Wadi Warazan	xxxxx	700-900
Lower Wadi Warazan (southeast)	xxxxxx	>>1000

On the other hand the relative thickness of the volcanic rocks on top of the sandstone aquifer or other igneous rocks would be in the reverse order of the upper classification for the depth to the sandstone aquifer.

- ✓ Eight sites have been located, for additional groundwater exploration drilling, in the four study areas **figure (5) and Annex (2)**. Their coordinates of these sites are given in **table (8).**
- ✓ A tentative drilling depth at these proposed sites can be estimated according the above table.
- ✓ The priority for drilling is according to the number assigned to the well.
- ✓ Recommendations on well design, drilling method, and well development are given under special recommendations at the end of this report.

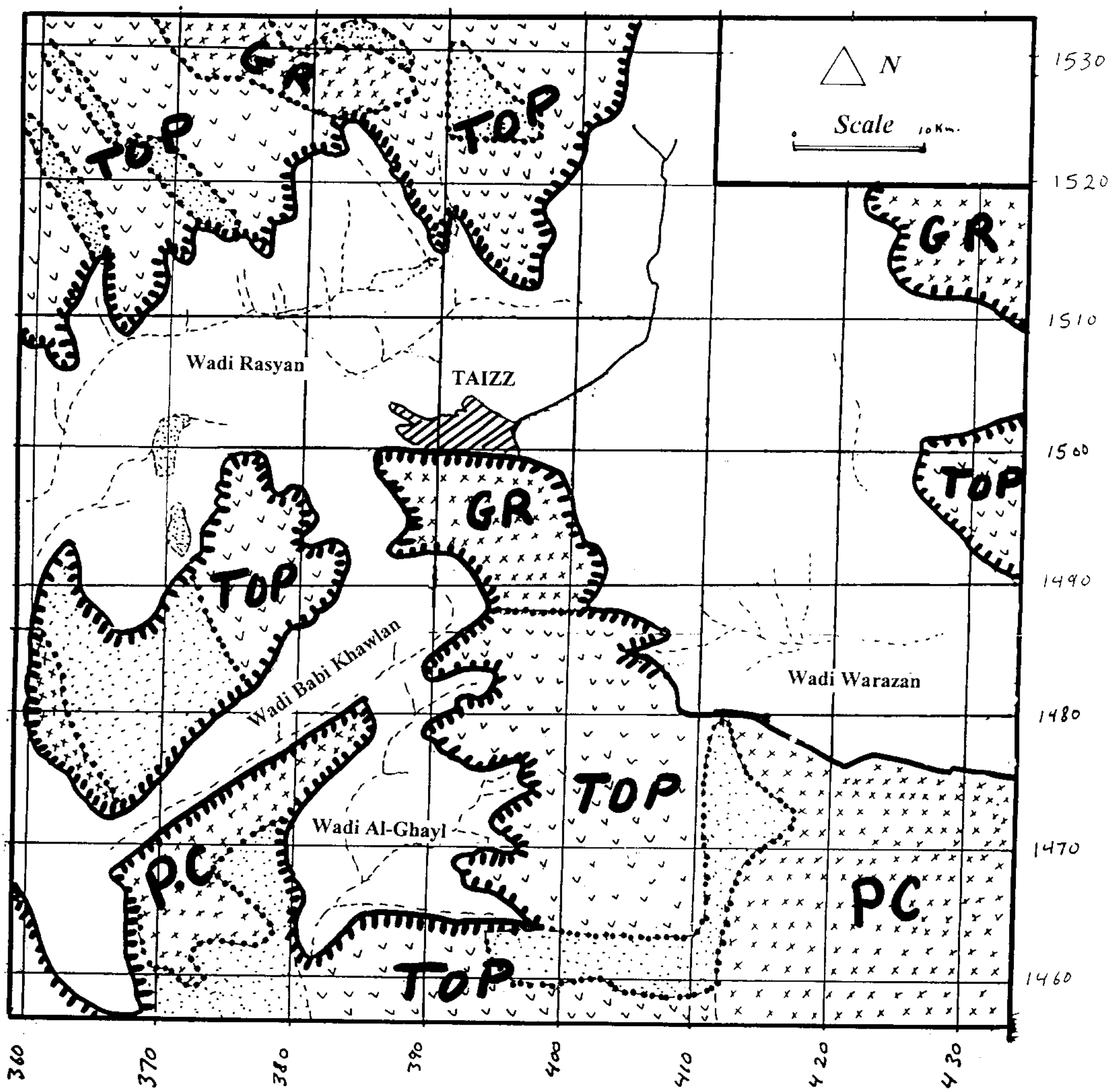
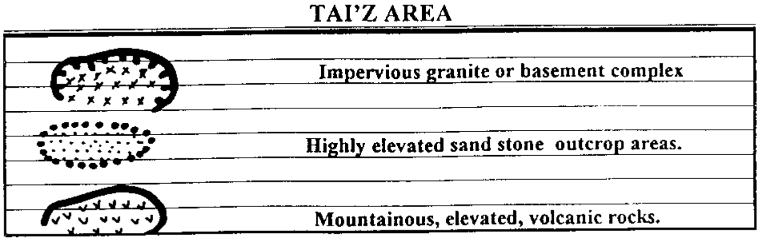


Figure (4) : UNFAVOURABLE LOW GROUNDWATER POTENTIAL AREAS.

TAI'Z AREA



PC : Impervious Pre-Cambrian Rocks.
Top : Topograghic / Terrain Problems.
GR : Impervious Granite.

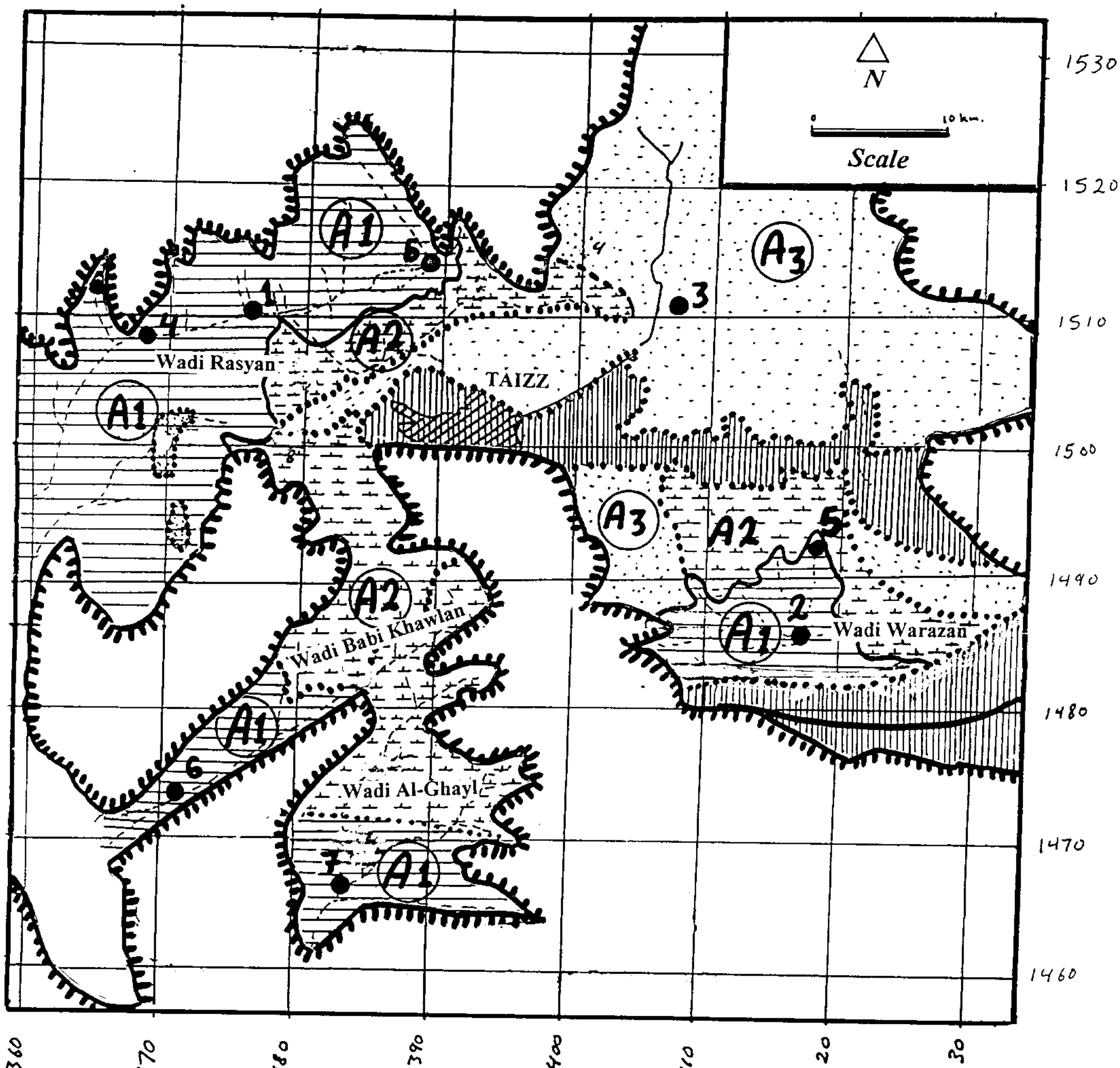
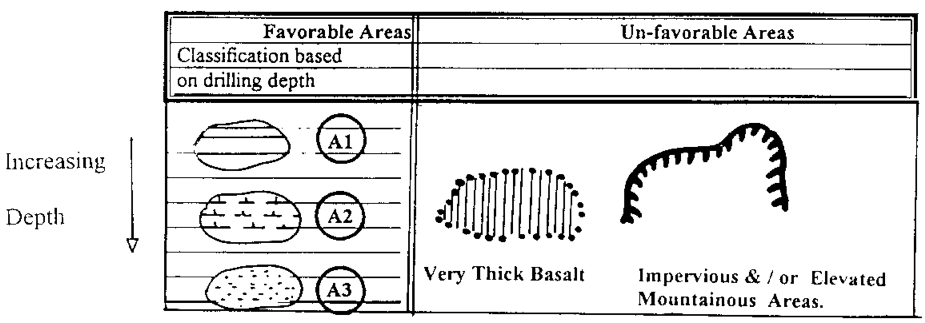


Figure (5) : POTENTIAL EXPLORATION AREAS AND RILLING SITES.

TAI'Z AREA
(Numbers indicate Priorities)



RECOMMENDED EXPLORATORY DRILLING SITES & PRIORITIES

●	First Stage : (1) (2) (3). Second Stage : (4) (5) (6) (7).

Table (8)

Location Of The Proposed Exploratory Wells

Well No.	Location	Coordinates	
		East	North
1	W. Rasyan	376.5	1510.3
2	W.Warazan	418	1483.5
3	Upper W. Rasyan	409.5	1511.3
4	W. Rasyan	368	1508
5	W.Warazan	418	1492
6	W. Rasyan	390	1514.7
7	W. Al-Ghayl	385.5	1467.7
8	W. Bani Khawlan	371	1474.5

CONCLUSION AND RECOMMENDATIONS

A. General:

1. Good planning and use of appropriate drilling, development, cementing, logging, monitoring and testing techniques are the keys for satisfactory completion of a deep exploratory well.

2. Knowledgeable understanding of field conditions, particularly for wells sitting, and reasonable anticipation of the possible problems, and preparations for adequate solutions, will also help achieve a successful deep well drilling program.

3. Proper technical specification and contract conditions, and assurance that the contractor(s) understands these very well are essential.

4. Most importantly select a capable qualified drilling contractor for implementation.

5. Knowledgeable and strict supervision are essential.

6. Some problems will remain to be solved throughout the fieldwork. Close cooperation with the drilling engineer or with the chief driller, and fair settlements should be always sought according to the contract conditions.

7. An improper approach and implementation of work may lead to faulty conclusions and assessment of the groundwater potential at a site or in an area.

B. Specific Recommendations:

Well design:

1- Because of the high cost of deep well drilling, and for economic reasons, it is advised to design the exploratory wells to also serve as a test holes and later on as a production wells. A test well requires isolation of the shallow aquifer from the deep aquifer by appropriate cementing procedure.
A production well requirement is similar to that of a test well, in addition that an upper pump chamber should be of appropriate depth and diameter to accommodate the pump required for production.

2- In this respect, a single diameter hole to the final depth is not adequate.

3- Instead, a telescopic borehole would allow for alleviating the losses problems of the drilling fluid, by allowing for installing and cementing a casing line.

4- The final hole diameter through the aquifer could be as small as (6) inches without significantly reducing the well production capacity. This is because the water level in the wells will be much higher than the top of the aquifer. In hard rock aquifers, the bore hole may be left without casing or screen, unless the sandstone aquifer is friable. In this case the well may be completed with (8) inches in the sand aquifer with appropriate well screen. Gravel pack will be difficult to place in deep wells.

5- The hole may be started as follows:

	Diameter (inchesl)	
Depth	**Hole**	**Casing/screen**
0-≤ 30	17 1/2	13 3/8
30-(200-500)	12 1/4	9 5/8
Aquifer	8 3/4	6 5/8 casing or 4 screen

Well Drilling:

1. In hard rock, it is preferable and more efficient to use the air and foam hammering method. It is fast, effective, and maintains a clean hole free from mud.

2. If an adequate air compressor, with sufficient air volume and air pressure delivery, is used, problems in losses zones can be minimized. If the air circulation loss persists, we may temporarily switch to mud rotary. Complete plugging of the circulation losses areas or zones should not be allowed at all, as these zones are expected to be the most productive.

Well Development:

An efficient mud cleaning procedure should be used including but not limited to:

a) Hole reaming
b) Washing with polyphosphates, while using jetting or surging as feasible. The use of appropriate tools is important.
c) Surging by the airlift technique.
d) High and variable rate pumping and surging.

Wadi Warazan Well No. 9:

The well is probably located too close to the linear series of volcanic necks seen in the area. Therefore, it is expected that the volcanics would be too thick (much greater than 800m).

The procedure followed for plugging the loss of circulation zone by dumping about 9 tons of diesel oil in a fractured zone of a saturated aquifer is considered dangerous and will pollute the groundwater. The well should be rehabilitated by pumping it for long period until the pumped water is clean from diesel oil. An attempt to deepen the well should be tried again using a large compressor.

Potential Areas for Exploration:

1- Based on well productivity, water quality, depth to the sandstone aquifer and social constraints, the areas may be ranked as follows, with the first being the best:
   1) Wadi Al-Ghayl.
   2) West of Taizz.
   3) Lower and middle Wadi Rasyan.
   4) Wadi Warazan.

2- However, as the aquifer potential for further exploitation is concerned, Wadi Warazan, and lower Wadi Rasyan seem the most promising.

Potential Drilling Sites:

Eight exploratory well sites have been located in the different areas. Table ( )gives a list of the location and the tentative depths of these wells.

The priority for drilling may be stated as follows:

Well No.	Location
1	Middle W. Rasyan
2	W. Rarazan
3	Upper W. Rasyan
4	Lower W. Rasyan
5	W. Warazan
6	Upper W. Rasyan
7	W. Al-Ghayl
8	W. Bani Khawlan

ANNEX (1)

ESTIMATION OF THE FUTURE WATER DEMAND

Table (1-1)

ESTIMTION OF THE FUTURE MUNICIPAL WATER DEMAND FOR THE CITY OF TAI'ZZ

(High Estimate)

Year	Population Grawth Rate	Population	Consumption/Demand Per Person	Total Annual Demand		Additional Water Supply Needed		
						Per Year	Cummulative	
	%		L/s/day	MCM/Yr	L/s	MCM/Yr	MCM/Yr	L/s
1994	4	400000						
1996	4	432640	35	5.55	176	0		
2000	4	506128	40	7.39	234	0.00	0.00	0
2001	3.9	525867	42	8.06	256	0.67	0.67	21
2002	3.8	545850	45	8.97	284	0.90	1.58	50
2003	3.7	566046	50	10.33	328	1.36	2.94	93
2004	3.6	586424	60	12.84	407	2.51	5.45	173
2005	3.5	606948	70	15.51	492	2.66	8.12	257
2006	3.5	628192	72	16.51	523	1.00	9.12	289
2007	3.5	650178	74	17.56	557	1.05	10.17	323
2008	3.5	672935	76	18.67	592	1.11	11.28	358
2009	3.5	696487	78	19.83	629	1.16	12.44	394
2010	3.5	720864	80	21.05	667	1.22	13.66	433

Table (1-2)

ESTIMTION OF THE FUTURE MUNICIPAL WATER DEMAND FOR THE CITY OF TAI'ZZ

(Low Estimate)

Year	Population Grawth Rate %	Population	Consumption/Demand Per Person L/s/day	Total Annual Demand		Additional Water Supply Needed		
						Per Year	Cummulative	
				MCM/Yr	L/s	MCM/Yr	MCM/Yr	L/s
1994	4	400000						
1996	4	432640	35	5.55	176	0		
2000	4	506128	40	7.39	234	0.00	0.00	0
2001	3.9	525867	42	8.06	256	0.67	0.67	21
2002	3.8	545850	45	8.97	284	0.90	1.58	50
2003	3.7	566046	45	9.30	295	0.33	1.91	60
2004	3.6	586424	45	9.63	305	0.33	2.24	71
2005	3.5	606948	45	9.97	316	0.34	2.58	82
2006	3.5	628192	50	11.46	364	1.50	4.08	129
2007	3.5	650178	50	11.87	376	0.40	4.48	142
2008	3.5	672935	50	12.28	389	0.42	4.89	155
2009	3.5	696487	50	12.71	403	0.43	5.32	169
2010	3.5	720864	50	13.16	417	0.44	5.77	183

Table (1-3)

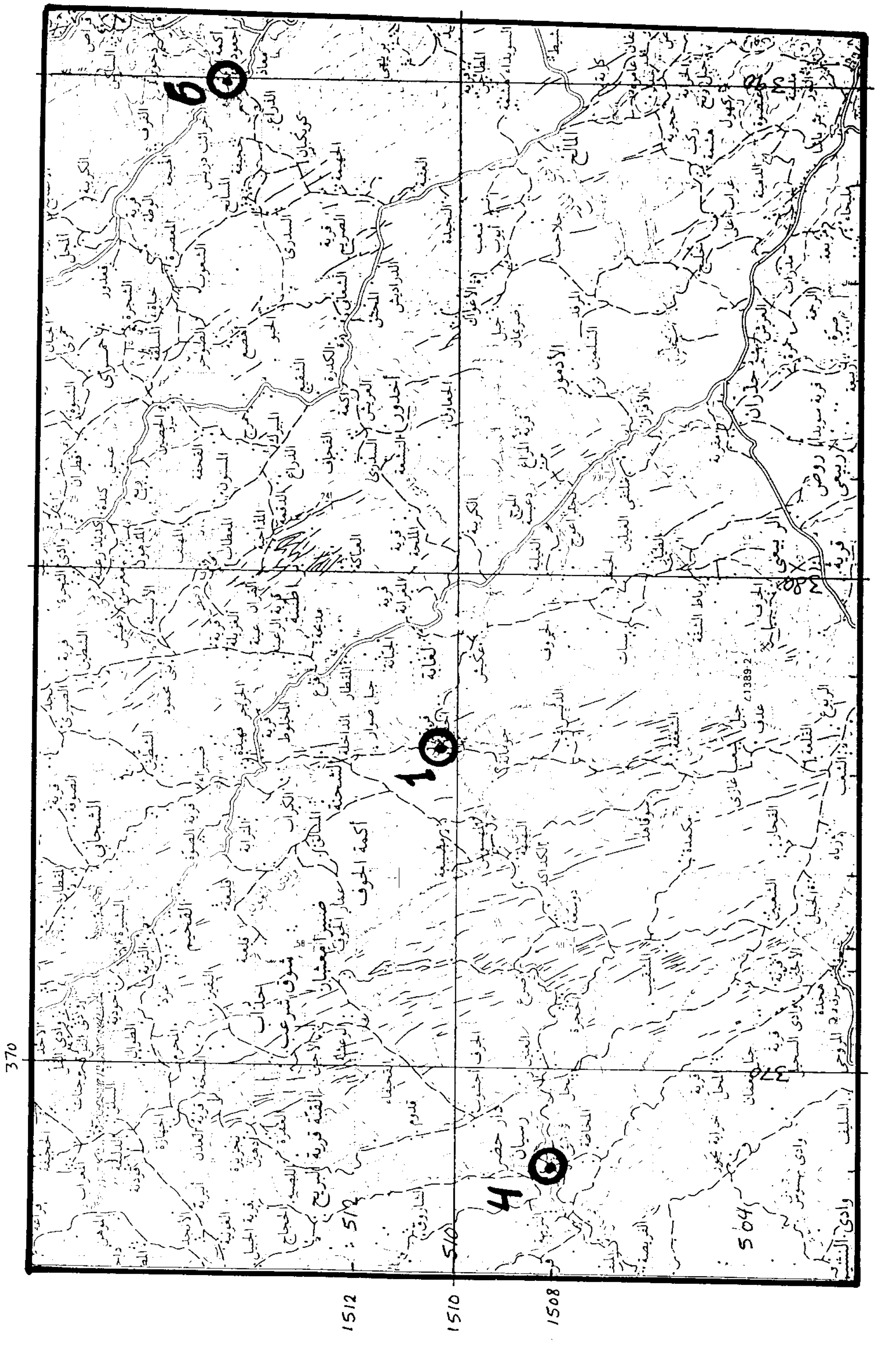
ESTIMTION OF THE FUTURE MUNICIPAL WATER DEMAND FOR THE CITY OF TAI'ZZ

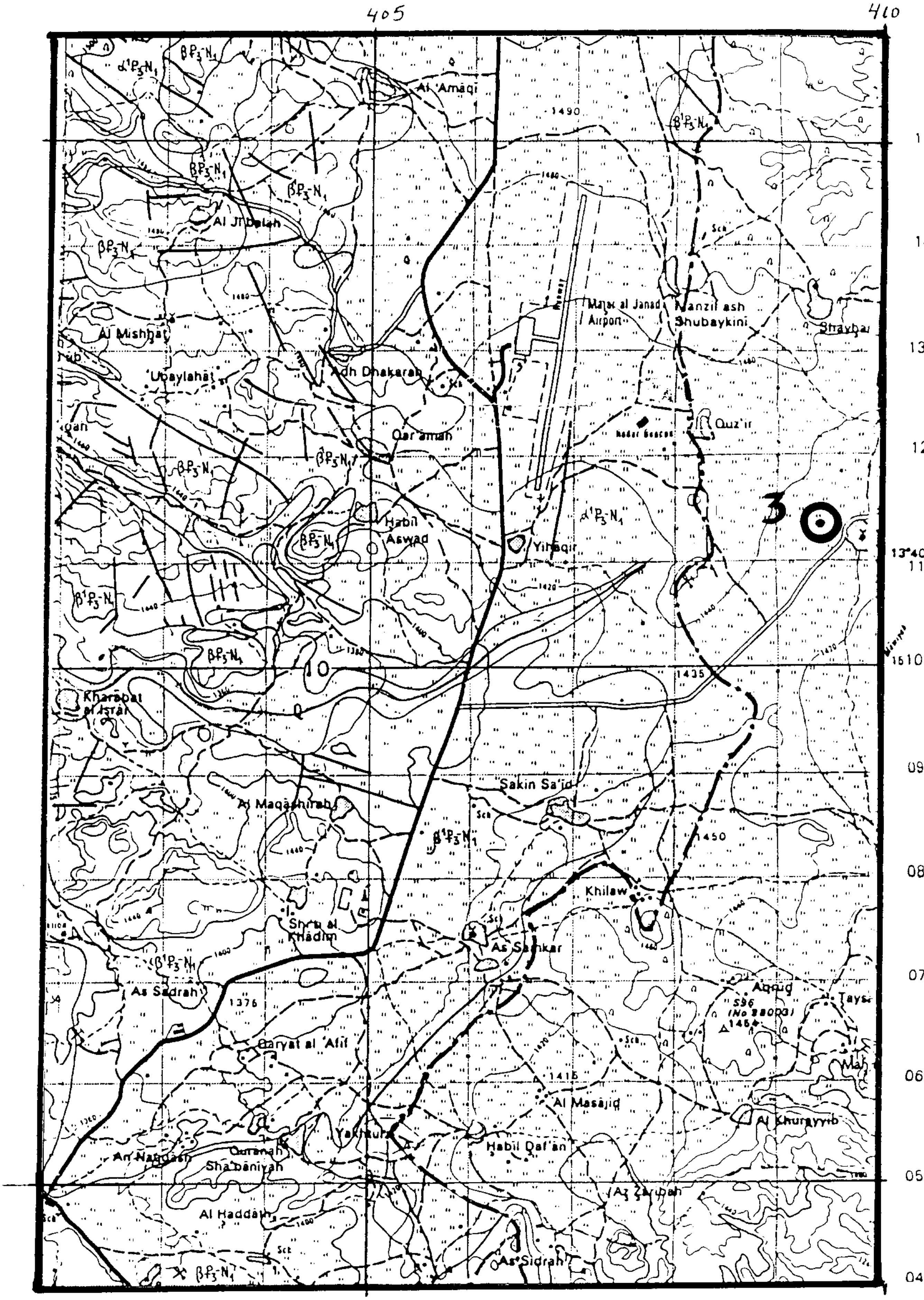
(Medium Estimate)

Year	Population Grawth Rate %	Population	Consumption/Demand Per Person L/s/day	Total Annual Demand MCM/Yr	Total Annual Demand L/s	Additional Water Supply Needed: Per Year MCM/Yr	Additional Water Supply Needed: Cummulative MCM/Yr	Additional Water Supply Needed: Cummulative L/s
1994	4	400000						
1996	4	432640	35	5.55	176	0		
2000	4	506128	40	7.39	234	0.00	0.00	0
2001	3.9	525867	42	8.06	256	0.67	0.67	21
2002	3.8	545850	45	8.97	284	0.90	1.58	50
2003	3.7	566046	50	10.33	328	1.36	2.94	93
2004	3.6	586424	55	11.77	373	1.44	4.38	139
2005	3.5	606948	58	12.85	407	1.08	5.46	173
2006	3.5	628192	60	13.76	436	0.91	6.37	202
2007	3.5	650178	62	14.71	467	0.96	7.32	232
2008	3.5	672935	63	15.47	491	0.76	8.08	256
2009	3.5	696487	64	16.27	516	0.80	8.88	282
2010	3.5	720864	65	17.10	542	0.83	9.71	308

ANNEX (2)

LOCATION MAPS FOR THE PROPOSED EXPLORATORY WELLS

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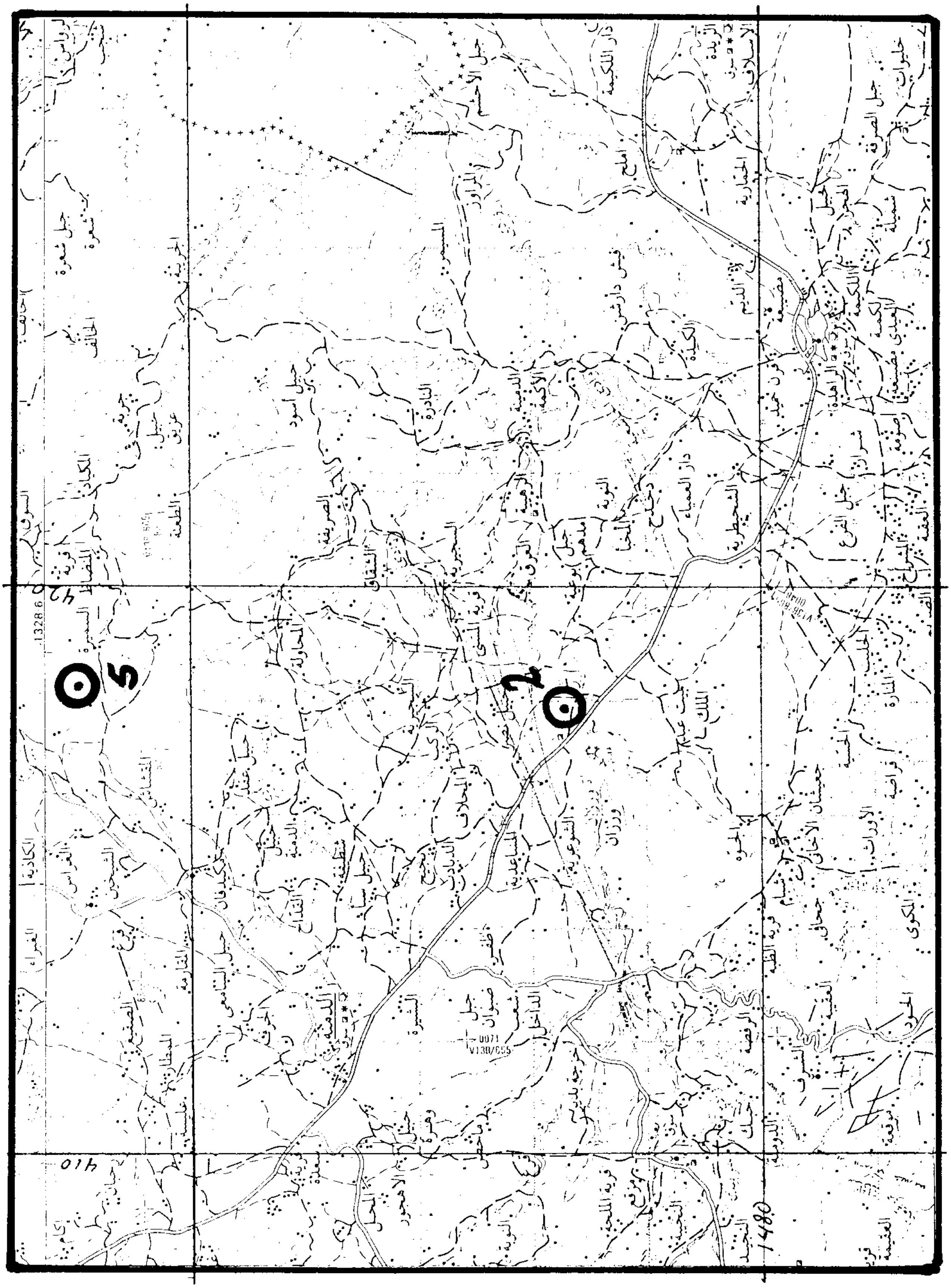
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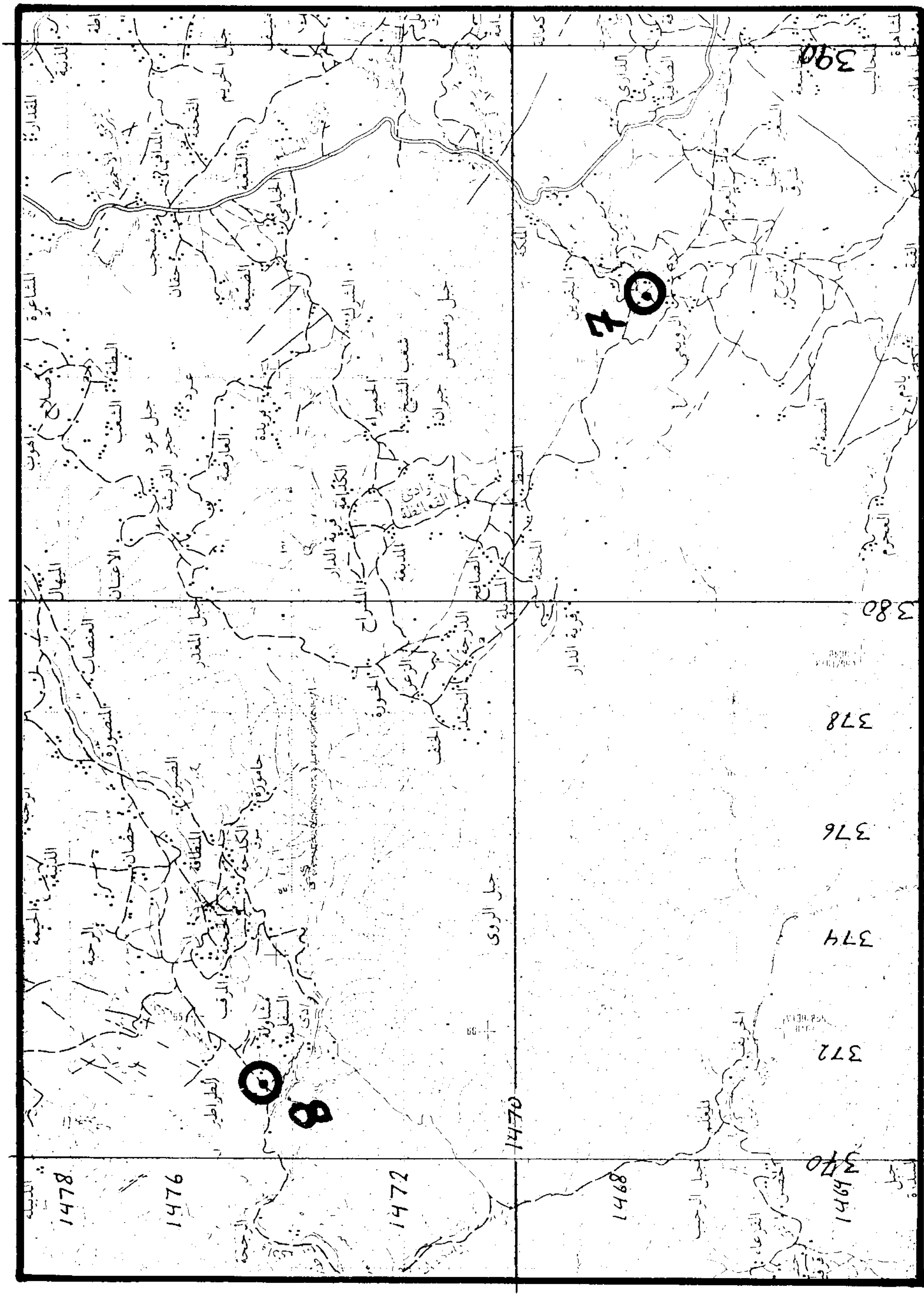
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