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Quantitative Groundwater Resources Evaluation in the Lower Part of Yalamlam Basin, Makkah Al Mukarramah, Western Saudi Arabia

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Abstract. The search for and the development of new water resources in Makkah Al Mukarramah area are considered among the top priorities for the Saudi government as the water consumption is rising with time. Wadi Yalamlam is located 70 km south of Makkah. It drains a large catchment area of 1,600 km^2, which is characterized by a high rate of annual rainfall of more than 200 mm. Perennial streams flow along the main channel of the wadi most of the year. This research is aimed to study the water resources in the lower part of Wadi Yalamlam as additional strategic future water supply to Makkah city. The research includes hydrological, hydrogeological and geophysical investigations for determining the potential areas for fresh water sources. It is also concerned with the determination of the geometrical size and the hydraulic properties of the groundwater aquifer in Wadi Yalamlam in order to determine the available water reserves. The study indicates the possibility of drilling 14 water wells for producing a renewable amount of 7500 m^3/day to supply Makkah area, in addition to $9x10^6$ m^3 reserves in this basin.

Keywords: Arid Region, Groundwater, Water supply, Water reserves, Makkah Area, Saudi Arabia.

Introduction

Saudi Arabia has very limited water resources most of which are in the form of groundwater reserves, being located in an arid zone, where no perennial streams exist. Living under these conditions makes it necessary to conserve and develop every single drop of water in these areas. In the western part of Saudi Arabia, the Hijaz Scarp Mountains receive comparatively the highest rainfall in the region, due to its high mountainous nature and location within the subtropical zone.

The Saudi Arabian government has given a great attention and effort to supply water to every city in the Kingdom with sufficient amount of suitable water quality. The search for developing new water resources in this area is considered among the top priorities of the government. In Makkah area, the consumption of water rises day by day, especially during pilgrimage and Omra seasons. Major wadis exist herein, such as wadi Fatimah, Nu'man, and Khulays, have been developed and used for groundwater supply. These wadis receive water from rainfall over Hijaz Escarpment. The groundwater reserves, however, decreases significantly with time due to the extensive pumping for agriculture, domestic and industry uses. In the mean time, most of water supply for Makkah area (more than 90%) is dependent on the desalination plants along the Red Sea coast (Sogreah, 1968; Şen, 1983; Ministry of Economic and Planning, 1985 & 1990).

Wadi Yalamlam is one of the major undeveloped wadis in the Makkah area. It is bounded by latitudes 20° 30′ and 21° 10′N and longitudes 39° 45′ and 40° 30′E. It is located about 125 km southeast of Jeddah, and 70 km south of Makkah city (Fig. 1). This wadi drains a large catchment area of about 1,600 km^2, which starts from the Hijaz Escarpment (Ashafa area) with mean annual rainfall of more than 200 mm. It has runoff for most of the year, and therefore, it has been selected as a potential and additional fresh water source for Makkah area (Subyani and Bayumi, 2001a).

The present study is aimed at evaluating the groundwater resources in this basin using hydrological, hydrogeological, hydrochemical and geophysical techniques. All these information are then used for the determination of possible groundwater reserve and location of most suitable wells for setting up a new boreholes network for future groundwater development.

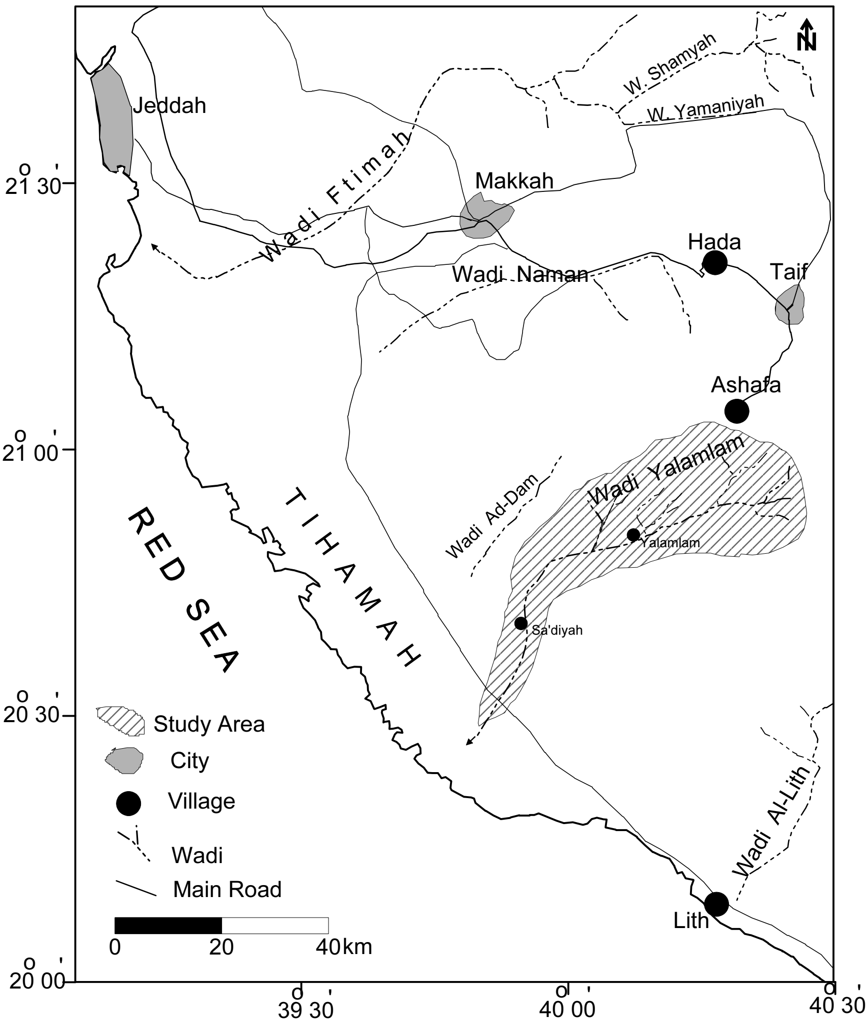

Fig. 1. Location map of study area.

Methodology

This study is part of a previous research project which included various aspects concerning geology, hydrology, hydrogeology, and hydrochemistry of the Yalamlam basin. The fieldwork included conduction of geological traverses to support previous studies. The hydrogeological investigations comprised well point inventory, pumping tests, water sample collection, cross- section measurements and surface water discharge measurements at various locations. Geophysical electrical sounding survey was also conducted during the project field work in selected sites to obtain the saturated thickness of the aquifer (Subyani and Bayumi, 2001a).

The water table map for the study area was plotted with reference to the sea level using "Surfer" program. Pumping test data were evaluated to determine the hydraulic properties of the aquifer using "Infinite Extent" program. Groundwater samples were chemically analyzed for major ion concentrations and plotted using "AquaChem" program.

All above information was utilized for determining possible groundwater reserves and locating the most suitable sites for drilling 14 new boreholes. Empirical equations were used to calculate the maximum allowable discharges and the radii of influence of those boreholes.

Topography and Geology

Yalamlam basin can be divided into three main topographic features. The Red Sea coastal plain (Tihamah), the hills, and the Scarp Hijaz Mountains. Tihamah area is a flat strip of land located in the southwest of Yalamlam basin, and bounded at inland by the hills and seaward by a shelf with about 30 km width. The elevation of Tihamah varies from sea level to 500 m above sea level (a.s.l.). The hills area is a vast peneplain sloping slightly at west of the Scarp Mountains. The elevation of these hills varies from 200 m to 1,000 m (a.s.l.). The Hijaz Mountains belt is characterized by knife-edged ridges and deep canyons. These high mountains are mainly located in Ash-Shafa area, the upstream of Wadi Yalamlam starts, where the elevation increases from 1500 m to 2,500 m (a.s.l.). These features are reflected in the form of the topographic and morphometric variations and also in the human settlements and their activities (Alsayari and Zőtel, 1978; Subyani and Bayumi, 2001b).

Geologically, this wadi is part of the Arabian Shield, which extends from north to south parallel to the Red Sea coast. This escarpment is one of the outstanding landscape features of Saudi Arabia. The Arabian Shield is composed of Precambrian crystalline, metamorphic and meta-volcanic sedimentary rocks, with local Tertiary and Quaternary basalt flows. These rocks form the mountain ranges east of the Red Sea coastal plain (Tihamah). Loose Quaternary sediments fill the wadi basin with a thickness ranging from 5 to 10 m in the upstream areas to more than 50 m in the downstream areas. These sediments consist of alternating layers of sand, gravel and clayey sand driven from the host rocks as shown on Fig. 2, (Brown *et al.*, 1963; Wier and Hadley, 1975; Pallister, 1983; Alshanti, 1993).

From structural point of view, these units are intensively faulted and folded as a result of various tectonic events. There are distinctive northwest and northeast trending faults, some of them are occupied by ablitic and andesitic dikes. These geologic features reflect the topographic and morphometric characteristics and also the human population and activity in the area.

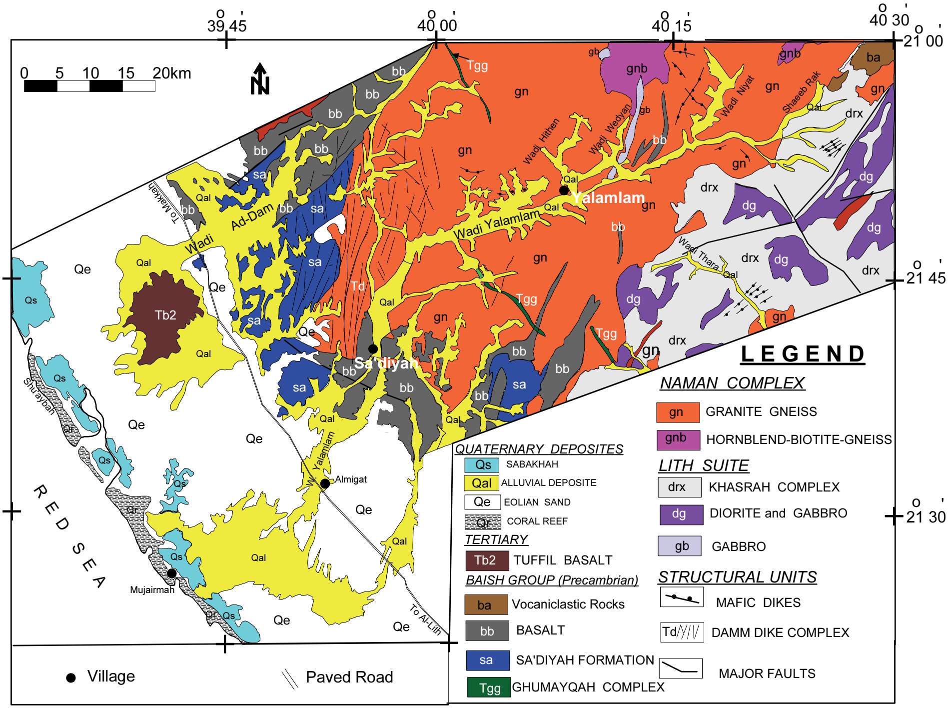

Fig. 2. Geologic map of Wadi Yalamlam (Adapted from Pallister, 1986).

Climate of the Study Area

Climate in Yalamlam basin is affected by the high pressure of the subtropical zone in addition to local topography. Both regional and local circulations have a dominant influence on the climate of the region. Yalamlam basin can be divided into three main climate types:

1) The hot desert climate that prevails in the Red Sea coast (Tihamah).

2) The worm, low latitude and semi-arid climate that prevails in the hill area.
3) The cold temperate, rainy climate with dry winters prevails in the scarp mountains.

Over the study area, rainfall occurs most of the year in the mountains area, but varies from year to year. It often occurs as thunderstorms of high intensity during a local storm followed by dry periods. The average annual rainfall exceeds 200 mm in the mountains and decreases to 80mm at the Red Sea coast.

Figure 3 shows the spatial variation of rainfall. It also reflects the topographic variation, which indicates that annual rainfall generally increases with elevation. In addition to the orographic effect, seasonality is a very important factor, which affects the rainfall amount and distribution in the study area. Wadi Yalamlam has perennial surface running water in the upstream area most of the year (Alehaideb, 1985; Subyani, 1997).

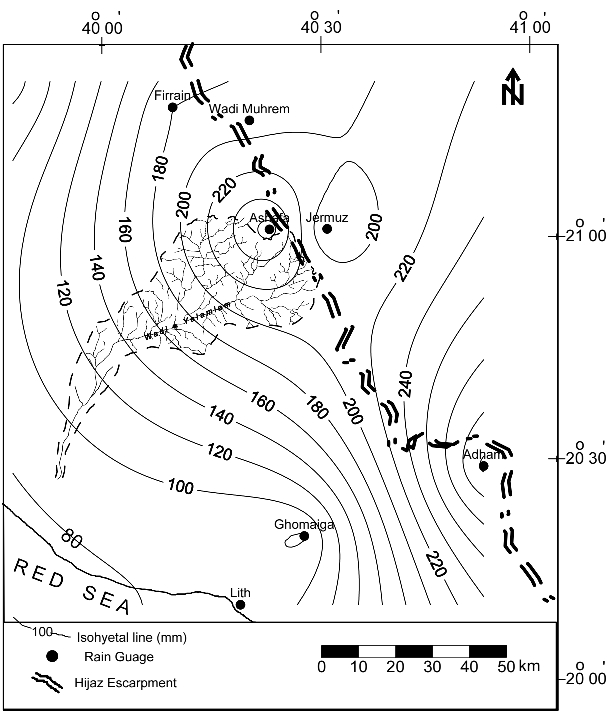

Fig. 3. Isohyetal map of mean annual rainfall over Yalamlam basin.

Hydrogeology

Information on the hydrogeology of the area was obtained first from existing wells, pumping tests, geophysical survey and geological observations. The significant water-bearing formation in the Wadi is the Quaternary alluvial deposits in addition to the underlying fractured and weathered part of the Precambrian basement rocks. In the upper reaches of the basin, the valley deposits tend to be coarse, consisting of cobbles and pebbles alternating with coarse sand. These grade laterally into sand and fine gravel in the middle stream areas near Sa'diyah village. In the coastal plain they grade into fine sand and silt. The thickness of the alluvial deposits varies from about 1 m upstream of Yalamlam village to more than 50 m at the coastal plain. Thinning out of the alluvial deposits is accompanied by the presence of several faults-filling dykes and shallow bedrock surface. Such barriers obstruct groundwater flow, which as a result appears at the surface as small springs forming semi-permanent streams that disappear some tens of meters downstream, where they soak back into the ground.

The thickness of the saturated zone within the aquifer varies from less than 1 m upstream of Yalamlam to about 30 m in the Almigat area. The aquifer is generally unconfined, especially in the upper parts of the wadi. Semi-confining conditions may exist in the lower parts where layers of clay exist.

There are about 31 wells in the basin of Wadi Yalamlam, out of which, 23 are hand dug wells and the others are drilled boreholes (Fig. 4). Detailed description of each well is given in Table 1.

Static water levels measured in the boreholes were used to construct the groundwater table map for the wadi (Fig. 4). Regional groundwater flow drains toward the south and southwest following the general trend of the main wadi channel. The gradient of the water table varies from one area to another according to the variations in the pumping rates and hydraulic properties of the aquifer. It has an average value of about 0.011.

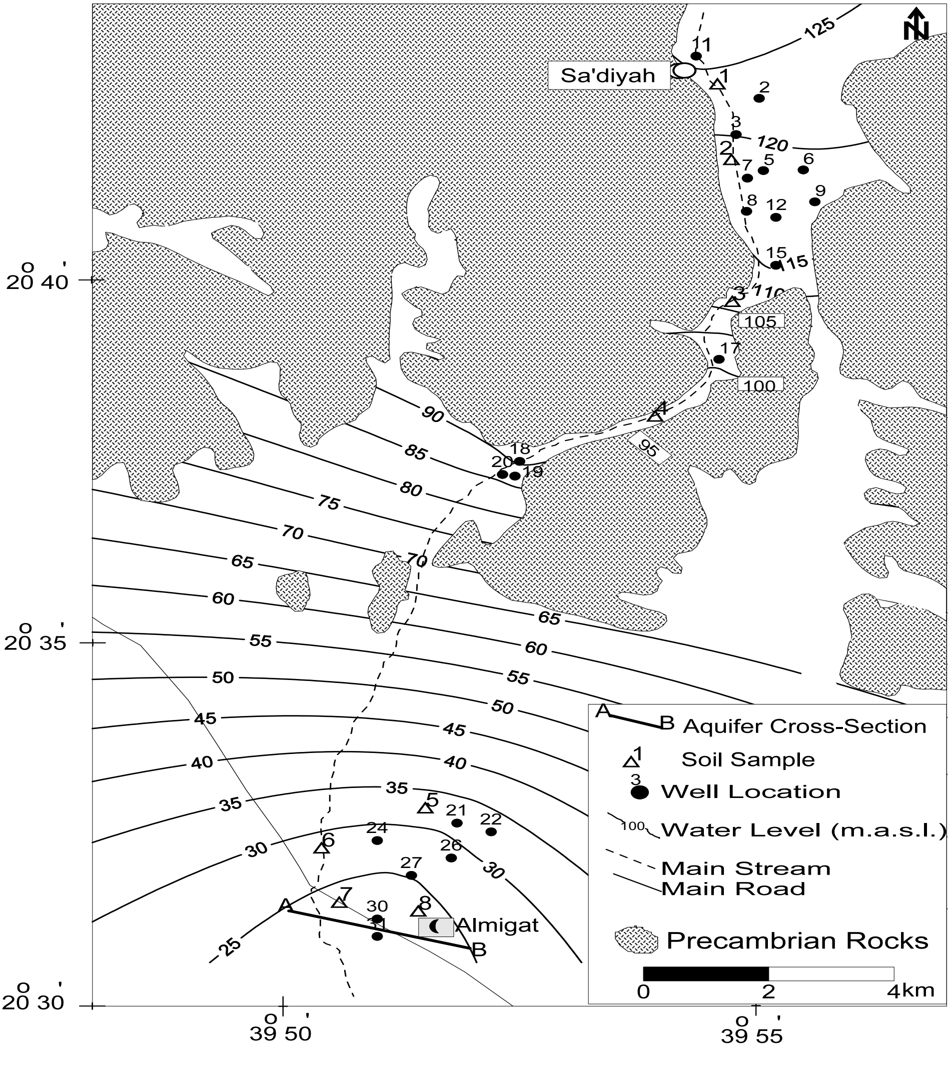

Fig. 4. Well locations, soil samples and water level map in Yalamlam basin.

Table 1. Well Inventory of Yalamlam Basin.

Well No.	Latitude	Longitude	Elevation (m.a.s.l.)	Total Depth (m)	Depth to Water (m)	Water Level (m.a.s.l.)	Well Diameter (m)	Pumping rate m^3/day	TDS (mg/l)
1	20 42 25	39 54 40	130	11	4.2	125.8	2.50	75	1540
2	20 42 50.7	39 54 56.2	126.5	8.4	4.45	122.05	3	20	1600
3	20 41 53.7	39 54 59.5	125	8.7	5.3	119.7	3	25	1880
4	20 41 38.6	39 54 59.3	121.8	14.2	2.2	119.6	3	20	2350
5	20 41 40	39 54 59	122	27.7	4.8	117.2	0.45	18	2410
6	40 41 26.3	39 55 0.9	121.6	8.7	4.5	117.1	3	25	2560
7	20 41 14.1	39 54 55.5	121.4	8.3	4.4	117	3	30	2565
8	20 41 11.4	39 54 54.7	121	6.3 8	3.55	117.45	3	10	2450
9	20 40 50.5	39 55 56.4	119.5	7.7	4.8	114.7	3	20	2510
10	20 40 55.1	39 54 57.9	120	7.4	3.1	116.9	3	15	2360
11	20 40 39.5	39 54 54.4	119.6	15	3.6	116	0.45	18	2480
12	20 40 44.8	39 55 06.1	119.9	6.6	3.6	116.3	0.45	15	2400
13	20 40 55.1	39 54 50.7	121.6	10	7.2	114.4	3	20	1650
14	20 40 53.4	39 55 00	120	15	3.6	116.4	0.45	15	1720
15	20 40 37.7	39 54 59.4	120.7	12.35	3	117.7	0.45	20	1900
16	20 40 31.9	39 54 54	119	8	3.5	115.5	3	18	1910
17	20 38 31	39 53 49	104	15	8	96	0.45	20	1750
18	20 37 30	39 52 30	100	21	9.35	90.65	0.45	10	1980
19	20 37 29.8	39 52 22.8	98	14.3	12.8	85.2	3	30	2100
20	20 37 21.2	39 52 19.2	95	11.5	9.3	85.7	3	20	2230
21	20 32 31.8	39 51 48.6	62.43	35	31.76	30.67	3	15	1790
22*	20 32 25.4	39 52 13.2	65	60	ND	ND	0.45	200	1550
23	20 32 35.3	39 51 48.3	63.3	34	31.8	31.5	3	25	2100
24	20 32 18.5	39 51 32	60.97	33.5	32.38	28.59	3	25	1950
25	20 32 07	39 51 45.5	59.13	33	31.08	28.05	3	15	1835
26	20 32 03	39 51 48.4	59.48	32.5	30.44	29.04	3	12	1950
27	20 31 52.4	39 51 37.4	57.69	36	33.08	24.61	3	15	2060
28	20 31 48.7	39 51 42.3	57.88	34	31.72	26.16	3	20	1986
29	20 31 38.4	39 51 32.7	58.06	36	31.95	26.11	3	30	2120
30	20 31 26	39 51 26.3	55.55	36	33.55	22	3	50	1834
31	20 31 18.9	39 51 22.3	54.97	34	32.7	22.27	3	45	1930

*Almigat well
ND= Not determined

Pumping Tests Methods and Analysis

Four pumping tests were carried out on well nos. 15, 16, 21 and 26 (Fig. 4). The conditions under which the pumping tests were performed can be summarized in the following points:

1- The aquifer is unconfined.
2- The thickness of the aquifer is variable.
3- The tested wells were either completely or partially lined with concrete or steel pipes (see the well inventory).

4- Most of the wells tested are partially penetrating.
5- The well's owner determined the time allowed for each test.
6- Except for the test on well no 21, all measurements of water level were taken in the pumped wells only.
7- Test durations were short.

Several methods are available for analyzing the pumping test data. The choice of a certain method for a certain test is based mainly on how far the field conditions and aquifer types are close to such a method, though almost all field conditions are far from being ideal in the sense used. The following analytical methods were found most suitable: Slope-matching method (Şen, 1986), Papadopulos-Cooper's method for large-diameter well (Papadopulos-Cooper, 1963), Boulton's method for unconfined aquifers (Boulton, 1963) and Theis's recovery method (Theis, 1935). The basis of each method, analysis of data and its ability to predict aquifer behavior can be obtained from the original papers as mentioned in the list of references.

Results obtained from all the above-mentioned techniques are listed in Table 2. Examples of the application of the analytical techniques on number of the tested wells are shown on Fig. 5. The average transmissivity values calculated for the wells in the Sa'diyah area range from 91 to 147m^2/day. Using the criteria of the aquifer potential, it follows that the aquifer in this area is of moderate potential (Şen, 1995). In the Almigat area (downstream) the transmissivity values increase sharply possibly as a result of the increase in the aquifer thickness. They range between 267 and 731 m^2/day (average 500 m^2/day), which indicates that the aquifer is of high potential therein. On the contrary of the grain size analysis technique, the hydraulic conductivity values calculated for this area attain a high average of about 16 m/day. This could be attributed to the possibility that the alluvial sediments at depth are coarser and more permeable than the surficial deposits.

Table 2. Transmissivity (T m^2/day) and storativity (S) values obtained from the analytical techniques.

Well No.	Slope matching Method (Şen)		Boulton method		Papadopulos & Cooper method		Recovery method (Theis)	Average	
	T	S	T	S	T	S	S	T	S
15	114.6	0.052	46.8	0.11	-	-	112.7	91.4	0.08
16	247.7	0.11	-	-	166	0.09	109	147.2	0.1
21	923.3	0.007	408.2	0.007	-	-	862.3	731.3	0.007
26	297.3	0.015	-	-	260	0.09	244.2	267.2	0.053

The average storativity values obtained for Sa'diyah area range between 0.08 and 0.1, which fall within the practically acceptable region of such values for unconfined aquifers. On the other hand, lower values are estimated for Almigat area ranging between 0.007 and 0.05, which possibly indicate prevalence of leaky aquifer conditions (Kruseman and D. Ridder, 1989).

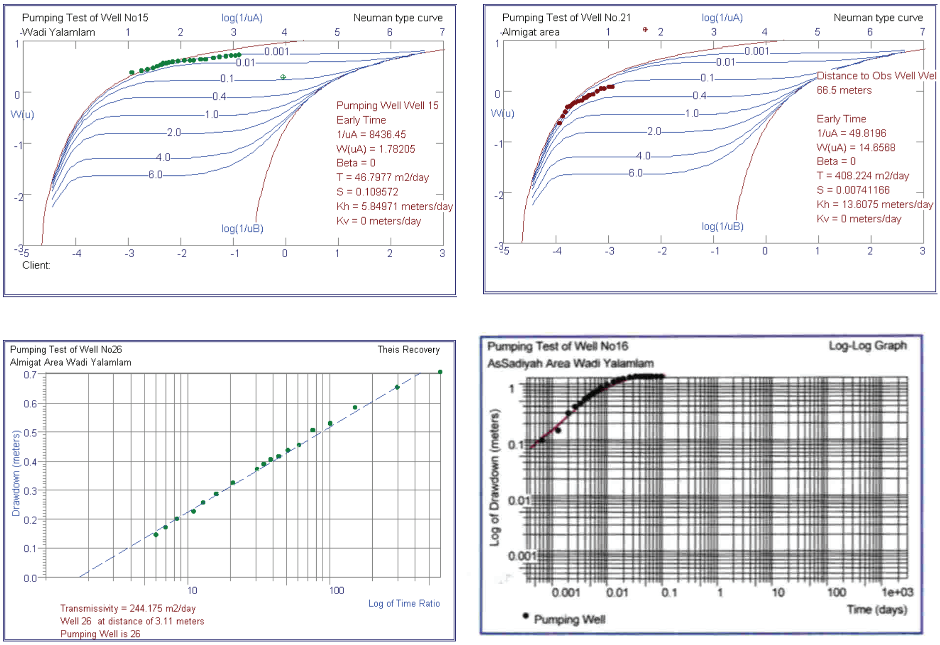

Fig. 5. Examples of analyzing pumping test data using various analytical techniques.

Recharge Rate

There are generally two principal types of recharge in arid zone areas: direct and indirect (FAO, 1981 and Lloyd, 1986). Direct recharge can be defined as water added to the aquifer through the unsaturated zone by direct percolation of rainfall at the spot where it falls. Indirect recharge occurs where water fulfills the soil moisture deficits and evapotranspiration process before reaching to groundwater reservoir.

Indirect recharge occurs from percolation to the aquifer following surface water runoff (surface water category) and localization (localized category) in joints, pondings, and lakes or through the wadi beds. Indirect recharge produced as a result of infiltration during flood pulses is considered as the most important contribution to the groundwater table in wadi channels. The amount of water that is added to the aquifers by such processes is much larger than the direct recharge. In Yalamlam basin, floods occur frequently, because the uppermost part of the basin receives considerable amount of rainfall (Fig. 3). The duration of flooding is extremely variable, ranging from few hours to several days. Direct infiltration from local rainfall is less significant, but it probably occurs when heavy rainfall takes place.

Due to the lack of information for estimating recharge rate by different methods, such as empirical approaches and water-balance techniques, the recharge rate in this basin was calculated using the chloride mass-balance method (Bazuhair and Wood, 1996; Wood and Sanford, 1995; Harrington, *et al.*, 2002, Edmunds *et al.*, 2002). This method suggested that the recharge rate is about 10% of the annual rainfall.

It is possible to deduce from chloride-mass balance method that the recharge rate in Yalamlam basin is about 20 mm/year in the upstream areas. This implies further that a considerable amount of rainwater does not contribute to groundwater recharge but causes to precipitation of salt on the surface. In addition, high slope of the wadi surface increases the runoff velocity, which reduces the rate of infiltration into the alluvium.

Groundwater Quality

The aquifer of Wadi Yalamlam is unconfined and the water table is not deep enough to be protected from the pollution effects. The salinity of groundwater increases due to the long distance flow, rock types, and aridity of the environment. In order to determine the chemical properties of the groundwater, samples were collected from existing wells. Major elements dissolved in these samples were analyzed.

Thirteen groundwater samples were collected from the water wells that are present in the middle and lower parts of Wadi Yalamlam. These samples were analyzed for the major cations and anions. In addition, electrical conductivity (EC), pH and temperature were measured *in situ*.

Table 3 summarizes the groundwater samples analysis. These results show that the total dissolved solids (TDS) of groundwater varies from 1450 –2564 mg/l, while the mean and standard deviation are equal to

1930 and 312 mg/l, respectively. Electrical conductivity (EC) of groundwater varies from 2700-3570 µS/cm, the mean and standard deviation are 3250 and 290 µS/cm, respectively. To explain the water type, the chemical analyses data of the groundwater samples were processed by AquaChem program (Aquachem, 1997). According to Durov diagram (Fig. 6) the groundwater in the study area is divided into two groups; upstream (recharge area) and downstream (discharge area). In the upstream area, calcium (Ca^{+2}) and sulfate (SO_4^{-2}) are the dominant ions, indicating that the groundwater character is calcium sulfate water. In the lower parts sodium (Na^{+}) and chloride (Cl^{-}) are the dominant ions, indicating that the groundwater character is sodium chloride water. This simple dissolution or water type changing from calcium sulfate to sodium chloride water distinctly matches the general flow of groundwater (Fig. 4) (Lloyd and Heathcote, 1985).

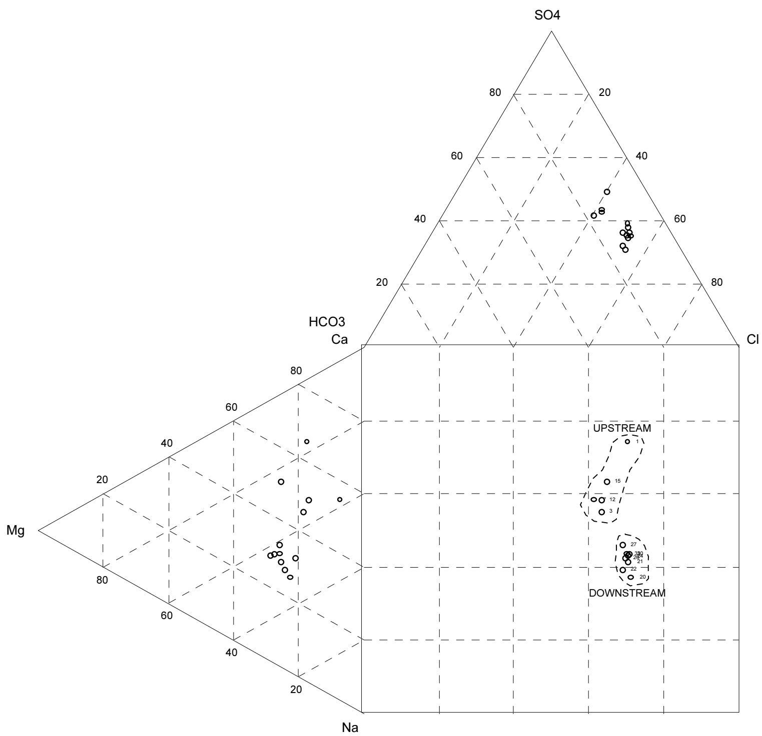

Fig. 6. Water Samples grouped using Durov diagram.

Table 3. Chemical analysis of groundwater samples in Yalamlam Basin (ppm).

Well No.	SO_4^{--}	Cl^-	HCO_3^{--}	CO_3^{--}	Na^+	K^+	Ca^{++}	Mg^{++}	TDS (mg/l)	EC (µS/cm)	pH
1	456.1	448.8	151.5	ND	98.5	18.4	317.3	50	1540.5	2750	7.3
3	696.5	503.6	305.1	ND	283	6.06	308.5	74	1880	2980	7.0
7	782.2	580.4	427.5	ND	330	7.3	405.6	31	2564	3300	6.8
12	740.3	552.2	335.3	ND	300	8	382.8	76.6	2394.7	3420	6.8
15	680.8	419.5	187	29.8	170	17.4	303.4	91.4	1899.4	3390	6.9
20	438.8	506.9	176.9	49.7	335	12	143.1	75.4	1737.8	3100	7.0
21	468.4	543.7	206.6	ND	302	15.8	160	84.5	1781	3370	7.1
22	370.4	466.1	220.3	ND	275	15.4	130	69.6	1546.8	2700	7.2
24	624	643.9	220.3	ND	340	25.9	194	117	2164.8	3200	7.2
26	450.6	598.9	274.2	ND	328	32.2	190.6	74.3	1948.8	3380	7.3
27	469.2	500.6	213.4	ND	258	15.4	176.8	82.2	1715.6	3550	6.9
30	504.6	557.5	199.7	ND	290	15.8	171.7	95.4	1834.8	3570	7.0
31	475.8	535.1	213.4	ND	285	15.4	171.7	86.9	1783.4	3540	6.9
Mean	550.6	527.5	240.6	ND	276.5	15.7	235.0	77.5	1929.8	3250	7.04
Standard Deviation	134.8	62.3	75.9	ND	69.4	7.2	94.8	20.9	312.2	290	0.18

ND = Not determined.

Area Selected for Future Groundwater Development

The essential guidelines considered for selecting a certain area for further ground-water development comprise the results of hydrology, hydrogeology, geophysics and groundwater quality. These studies indicate that the area located immediately upstream of Almigat Mosque (Fig. 7) is the most favorable because of the following points:

1- It is easily accessible.

2- Average aquifer thickness is about 30 m, according to the well inventory and geophysical studies.

3- Pumping test results show that the aquifer has high potential.

4- Largest depth to groundwater table is about 30 m, which provides reasonable protection from surface contamination, and,

5- the groundwater pumping from the area is low compared to the potential of the aquifer (Table 1).

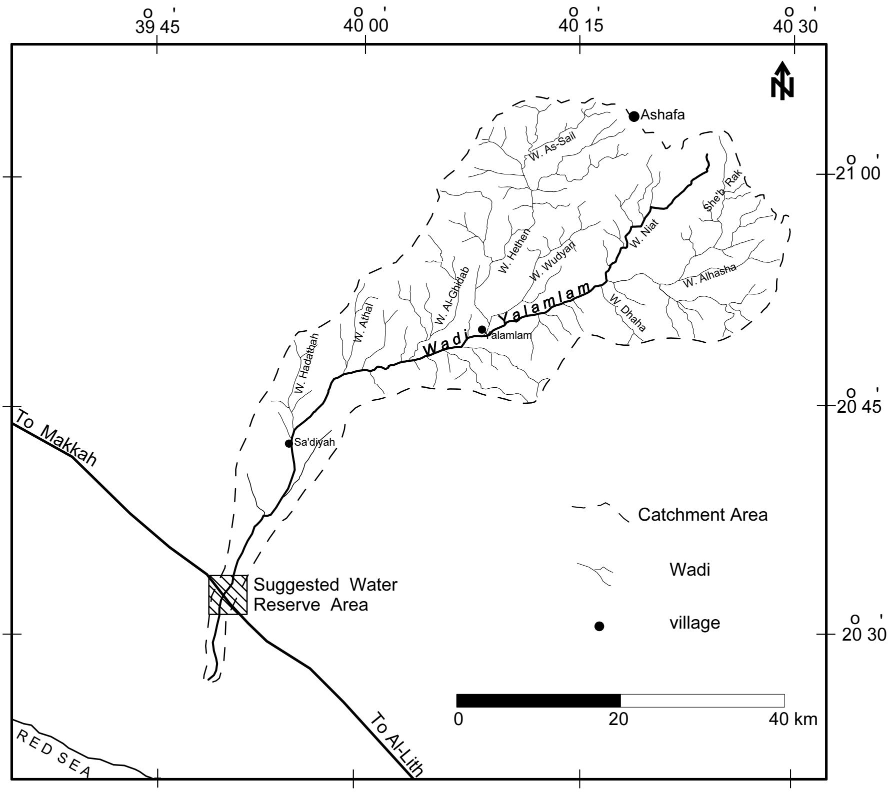

Fig.7. Selected water reserve area in Yalamlam basin.

Aquifer Geometry and Groundwater Reserve Estimation of the Selected Area

Selection of the location and geometry of the developed area is based upon the availability of control points, such as the Vertical Electrical Sounding (VES) stations and drilled boreholes that can provide essential information about the subsurface of the area (Subyani and Bayumi, 2001a).

The boundary of the chosen area is delineated on Fig. 8, which covers an area of about 10 km^2. The average saturated thickness is about 30 m and hence, the volume of the saturated thickness is about 300×10^6 m^3. The average value of storativity in this area is about 0.03 (Table 2) and the reserve estimation is approximately 9×10^6 m^3.

Since the selected area is not bounded by any outcrops it can be argued that the groundwater recharge, therein, takes place in two ways; namely, surface recharge from rain and floodwaters and subsurface inflow from upper parts of the wadi. On the other hand, discharge occurs in the form of subsurface outflow toward the lower parts.

Subsurface inflow to this area is calculated using Darcy's law by considering 3km length of the upper side, 0.005 as an average hydraulic gradient and as an average transmissivity of about 500 m^2/day. This yields an estimated subsurface recharge of 7500 m^3/day. Although part of this groundwater inflow departs toward the sea. However, the volume of groundwater outflow can be greatly minimized by constituting a cone of depression therein. The potential volume of abstractable groundwater is 7500m^3 daily.

Suggested Well network

Based upon the above estimation, it was suggested that a number of boreholes can be drilled in the reserved area to pump groundwater and transport it to cities and towns in need of water supply. Although the volume of pumped water is not very high, it may be increased by pumping more quantities from surrounding catchment areas.

The maximum allowable discharge (MAD) for each well can be calculated from the following empirical equation (Şen and Alsomayien, 1991).

$$Q_m = 2\pi r_w m \sqrt{K} / 60 \qquad \textbf{(1)}$$

where Q_m is the maximum allowable discharge (m^3/day), r_w is the radius of well (m), m is the saturated thickness (m), and K is the hydraulic conductivity (m/sec).

The well radius is normally 0.15 m. On the other hand, considering 30m as an average saturated thickness and 1.8×10^{-4} m/sec as average hydraulic conductivity yields MAD value of 546 m^3/day. It is possible to conclude that the safe yield of each well is 550 m^3 /day, which means that 14 wells must be drilled to pump the required volume of groundwater.

In order to avoid the interference between adjacent well depression cones the radii of influence (R) of the wells can be calculated from the following empirical equation (Şen and Alsomayien, 1991):

$$R = 3000 s_w \sqrt{K} \quad \textbf{(2)}$$

where
R= radius of influence (m), and,
s_w= maximum drawdown in the well (m).

By considering a maximum drawdown of 10 m, which is obtained under a higher pumping rate of 3700m^3/day, it can be found that R is equal to 408 m. This indicates that wells should be drilled 816 m apart. Obviously under lower pumping rate, such as that suggested above, a smaller radius of influence is expected. Based on the geophysical survey, the minimum total depth of the wells should be 60 m (Fig. 8 and Table1).

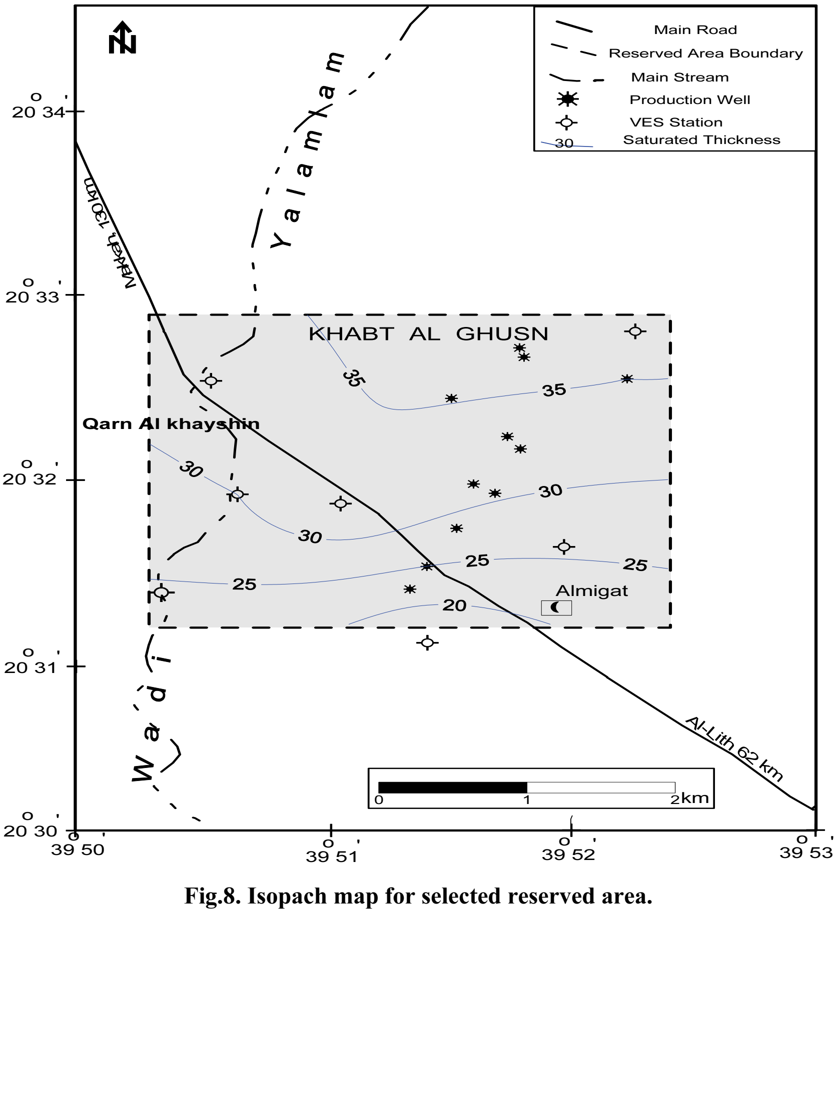

Fig.8. Isopach map for selected reserved area.

Water Supply and Consumption in Makkah City

In addition to the actual inhabitants of Makkah, the holy city hosts annually millions of pilgrims during the Hajj and Omrah seasons. This adds more pressure on the water authorities in the Kingdom to provide the city with its water needs. Makkah receives its water supply mainly from the desalination plant in Sho'aibah (>90%) and partly from the Wadis Fatima and Nu'man. Table 4 lists the present and expected yearly water demand, supply and shortage in the holy city. It indicates that during the next few years the water shortage will reach more than 50% of the distributed quantities.

During the Hajj season water demand increases at least by 20 times, whereas the distributed quantities rise by 25 times. This increase is met by storing water obtained from the Sho'aibah and Jeddah desalination plants during the months preceding Hajj.

Table 4. Present and expected yearly water demand, supply and shortage (Al Kheder, 1998).

Year	1418 H 1997G	1421 H 2000G	1430 H 2009 G	1440 H 2019 G
Water Demands (m^3)	330,000	375,000	520,000	720,000
Distributed Quantities (m^3)	154,000	270,000	270,000	270,000
Water Shortage (m^3)	176,000	105,000	250,000	450,000
Shortage %	53%	28%	48%	63%

Conclusions

Wadi Yalamlam is one of the most important and undeveloped wadis in the western Saudi Arabia. It drains a large catchment area of about 1,600 km^2 and flows to the Red Sea. Over the study area, rainfall occurs as thunderstorms of high intensity during local storms followed by dry periods. It receives more than 200 mm of annual rainfall.

Subsurface investigations in wadi Yalamlam indicate that water bearing zone within the aquifer varies from less than 1 m upstream to about 30 m in the Almigat area. The aquifer is generally unconfined especially in the upper parts of the wadi. Semi-confining conditions may exist in the lower parts where layers of clay exist. There are about 31 wells in the basin of Wadi Yalamlam. The total daily abstraction from these wells is 1,000 m^3.

The average value of hydraulic conductivity estimated from soil samples is about 20 m/day, whereas the average transmissivity and storativity values in the lower parts near Almigat mosque are 500 m^2/day and 0.03, respectively, which indicates that the aquifer has a relatively high potential.

Hydrogeological and geophysical studies indicate that the area located around Almigat Mosque is most potential. The reserve estimation in this area is about $9x10^6$ m^3, whereas the daily recharge to this suggested area is about 7500 m^3. A network of 14 boreholes, 800 m apart, is suggested to be drilled in the developed area. The maximum allowable discharge of each well is 550 m^3/day.

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تقييم كمي لمصادر المياه في الجزء السفلي من حوض وادي يلملم، منطقة مكة المكرمة – غرب المملكة العربية السعودية

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المستخلص. تحتاج منطقة مكة المكرمة بكثافتها السكانية وما يفد إليها من حجاج ومعتمرين إلى مصادر للمياه بصفة مستمرة ومتزايدة، وإن تأمين المياه للاستعمالات المتعددة من أهم الأولويات التي توليها حكومة المملكة العربية السعودية جل اهتمامها. وهناك عدة مصادر حاليًا تؤمن المياه بشكل جيد لهذه المنطقة من خلال محطات التحلية ومصادر المياه الجوفية من الوديان المجاورة. ويعتبر وادي يلملم والذي يقع على بعد ٧٠ كلم جنوب غرب مكة المكرمة من الأودية الواعدة، والتي لم تدرس مصادر المياه بها وكذلك فإن الكثافة السكانية قليلة والنشاط الزراعي قليل أيضًا.

يتميز هذا الحوض بمساحة تبلغ حوالي ١٦٠٠ كلم^{٢}، ويحده شرقًا خط توزيع المياه على قمم جبال السروات (منطقة الشفا)، حيث تتواجد في أعالي الوادي مياه جارية طوال العام كما إن معدل الأمطار السنوي حوالي ٢٠٠ ملم.

يرتكز البحث على دراسات هيدرولوجية وهيدروجيولوجية وجيوفيزيائية لحساب التغذية الحقيقية، وتعيين الخصائص الهيدروليكية للخزان المائي، ومن ثم تحديد أفضل موقع لاستغلال المياه وتعيين المخزون المائي المتوفر. وبناءً على هذه الدراسات تم

اقتراح مواقع لإنشاء شبكة من الآبار (١٤بئرًا) في منطقة الميقــات لضخ حوالي ٧٥٠٠ متر مكعب يوميًــا بــشكل آمــن ومتجــدد، بالإضافة إلى تسعة ملايين متر مكعــب متــوفرة فــي المنطقــة المقترحة، وذلك للاستفادة منها كمخزون استراتيجي ومساند لمنطقة مكة المكرمة.