Artificial Groundwater Recharge of Azraq Basin at the Northeastern Part of Jordan: A Case Study for Evaluating Arid Area Conditions

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ABSTRACT

This study was investigated to show the effects of arid conditions on water quantity and quality and the possibility of utilizing surface water for groundwater artificial recharge. Azraq Basin is considered to be the most important basin at the northeastern part of Jordan. It comprises an area of about 12710 km^2 and located between the Palestine Grids 250 to 400 E and 055 to 230 N. The thunderstorm annual rainfall, which forms the major part of precipitation decreases from 300 mm at the north to less than 50 mm at the south. The calculated runoff ranges from less than 1 MCM to about 80 MCM spread over 12 subcatchment areas. The water flows from all directions toward Azraq depression before it evaporates into atmosphere.

There are three aquifers in the basin, namely upper, middle and lower. They are hydraulically connected with each other by the effect of major faults and show different flow directions. The upper aquifer, which is the only utilized aquifer, is composed of basalts, alluvial deposites and carbonates (Rijam and Shallala Formation). It is suffering from overpumping to cover the agricultural and industrial activities, then salt water intrusion may occur in the near future. To maintain the groundwater quantity and quality, it is recommended to utilize the floodwater for artificial groundwater recharge purposes. The natural materials in the field will help in constructing low cost recharge dams. The expected volumes of flood water in the dams of the different subcatchments range from 0.24 MCM for Wadi Unqiya to 12.82 MCM for Wadi Rajil.

The infiltration model shows that the infiltrated water will need between 200 and 585 days to reach groundwater and the soil needs between 0.98 and 2.8 MCM to be fully saturated. On the other hand, the geochemical model shows that the recharge water will be positively affect the groundwater and the high groundwater quality will be assured. The evaporation model shows that the flood water remains of high quality even after 40 percent evaporation.

1. INTRODUCTION

Problems concerning water are considered to be the most important and significant facing Jordan in the near future. They arise from an arid to semi-arid climate with low annual rainfall ranging from 600 mm in the northwest to less than 50 mm in the eastern and southern deserts which form more than 80 percent of the country, a high population growth as a result of refugees coming to Jordan and as a result of natural multiplication and rapidly increasing demand for water to cover the agricultural and industrial needs.

The rainfall in the arid and semi-arid areas is mainly due the thunderstorms. Rainfalls in the Azraq basin occur mainly between October and May, sometimes ending a little earlier depending entirely on weather conditions of the particular year (dry, wet or average conditions). Heaviest rain occurs during the winter season from January to February (Meteorological Department of Jordan, 1988).

Groundwater in Jordan is considered to be the main source of water for industrial and agricultural development. However, due to rapid increase in population and overpumping of the aquifers, the water quantity became not sufficient to cover increasing demands. Resources are expected to deplete and salt water intrusion will inadvertently occur. The problems are obstacles in the way of establishing new agricultural and industrial projects and may affect the whole socio-economical development of the country.

The Azraq basin covers an area of about 12710 km^2. It is located between the Palestine grids 250-400 East and 55-230 North (Fig. 1). The basin is a major source for drinking water for three major cities in Jordan (Amman, Zerqa and Irbid) and the Azraq area itself. The oases are located in the central part of the depression, they are locally known as Shishan and Drouz springs, which have dried up recently. The Azraq Oasis is an outstanding example of an oasis wetland in an arid region with few parallels in the world. The wetland supports rich and varied aquatic fauna and flora characteristics with freshwater habitats. The Azraq Oasis is also famous with its date palm trees and important for the migration of several birds from all over the world. The wetland supports rich and varied aquatic fauna and flora characteristics with freshwater habitats. The Azraq Oasis is also famous with its date palm trees and important for the migration of several birds from all over the world.

The climate of the Azraq basin is characterized by hot and dries summers, and fairly wet and mostly cold winter. The mean annual rainfall in the basin ranges from more than 300 mm in the north, 150 mm in the west and to less than 50 mm in the south and east. The weighted average annual precipitation is 88 mm (Fig. 2).

2. Water Budget

The water budget is the distribution of rainfall between runoff, evapotranspiration and infiltration. The cyclones, which cross the Mediterranean Sea bring cold air masses from Europe that is a major cause of precipitation in Jordan. These cyclones are responsible for thunderstorm rainfalls, which are characterized by irregularity in intensity and duration. The connective rainfall is oriented along the major axis of the eastern Mediterranean and extends eastward into Iraq. The storms are triggered by temperature contrasts between the relatively warm sea and the cold land surfaces to the north. This mechanism produces unstable columns of air that depend upon laps rates and moisture flux convinces in the lower layer (Brenner, 1990).

The thunderstorm rainfalls are responsible for most of the precipitation in the Azraq basin especially in October, November, April and May. In spite of the prevailing thunderstorms, cyclonic rainfall may reach the area particularly in December, January, February and March.

All the wadis in the Azraq basin are ungaged and no flow measurements are available. The heavy thunderstorm rainfall causes high peak discharges and consequently causes severe inundation in parts of the drainage area. Many ungaged wadis drain into the Qa'-Azraq area. Water from these wadis remains several months in Qa'-Azraq area as puddles, before evaporating. Water flows to Qa'-Azraq area where the well field is located. The ground slopes range between 5-10 percent in the northern part, 3-5 percent in the other directions and exceed 15% in Jebel El-Arab area (Ayed, 1986).

Surface runoff is calculated using the United States Soil Conservation Service Method (SCS, 1969, 1972 and 1975) as follows :

$R - (P-0.2S)^2/(P+0.8S)$ .... (1)

where R is the accumulated depth of runoff, P is the accumulated depth of storm rainfall and S is the maximum retention of the soil related to an assigned. The curve number (CN) have been tabulated by the SCS on the basis of soil type. This relation is given as (United States Department of the Interior, 1960):

$S = (1000/CN)-10$ ....(2)

Initial abstraction (Ia) is the amount of rainfall loss before saturation of the soil and before runoff, which can be taken as Ia=0.2S, with S in inches.

The potential evapotranspiration was calculated using the Penman equation, which is shown below:

$E = \Delta / (\Delta + \gamma) Rc(1 - r) - \Delta / (\Delta + \gamma) Rb + \gamma / (\Delta + \gamma) Ea$ ....(3)

where E is the potential evapotranspiration, Δ is the slope of the saturation vapour pressure curve at mean air temperature (mb.2), γ is the psychometric constant, Rc is the incoming solar radiation, r is the reflection coefficient for the surface (Albedo factor), Rb is the outgoing solar radiation and Ea is the aerodynamic evapotranspiration.

Since initial abstraction of a rainfall storm is mostly the evapotranspiration between two consequent storms, the total loss of both the initial abstraction and the evapotranspiration during the storm will form the actual evapotranspiration during rainy seasons with acceptable e. Infiltration was calculated using the formula:

$I = P-E-R-I_a$ ....(4)

where I is the infiltration, P is the precipitation is the actual evapotranspiration, R is the runoff and I is the initial abstraction. All have the same units.

The evapotranspiration, runoff and initial abstraction are subtracted from the evaporation every year to calculate the water budget.

There are eighteen rainfall stations in the basin of which, fifteen stations are located in the Jordan side of the basin, and three stations are in Syria. Twelve stations measure the daily rainfall, and the rest are totalizator gages, giving annual totals.

3. Subcatchments

According to drainage and topographic characteristic of the main wadis in the Azraq Basin, the present study divided the basin into twelve subcatchments. These are: Wadi Rajil, Wadi Hassan. Wadi Aseikhim, Qa' Khanna, Wadi Rattam, Wadi Unqiya, Wadi Butum, Wadi Harth, Wadi Uweinid, Wadi Mudeisisat, Wadi Ghadaf, and Wadi Jesha (Fig. 3).

Wadi Rajil subcatchment is the largest one in the Azraq Basin. This wadi is entering the basin form the north and is not gaged like other wadis in the basin. The only available hydrological data are rainfall data. The total drainage area is about 3910 km^2. The general shape of the subcatchment is trapezoidal, with the longer axis oriented NW-SE. The average annual rainfall precipitated over the area is about 108 mm.

Wadi Hassan subcatchment covers and area of about 490 km^2, and also enters the basin from the north. The average annual rainfall over this area is 152 mm. The general shape of this catchment is fern leaf, with the longer axis oriented N-S direction.

The total drainage of Wadi Aseikhim subcatchment is 1180 km^2. The average annual rainfall in this catchment is about 90 mm. The general shape of this subcatchment is trapezoidal, with the longer axis oriented NW-SE direction. The general slope of the stream channels varies between 1 and 3 percent. Considerable part of the drainage is nearly flat.

Qa' Khanna subcatchment covers an area of about 650 km^2. The general shape of this catchment area is fern leaf, with the longer axis oriented NE-SW direction. The average annual rainfall precipitated over this subcatchment is 140 mm. The general slope of the stream channels is from north to south.

The total drainage of Wadi Rattam subcatchment is 476 km^2, and enters the basin from the north. The average annual rainfall over this area is 90 mm. The general shape of this catchment is fern leaf with the longer axis oriented N-S direction.

Wadi Unqiya subcatchment covers an area of about 214 km^2. The general shape of this catchment is fern leaf with the longer axis oriented N-S direction. The average annual rainfall over this area is about 86 mm. The general slope of this area is from north to south.

The subcatchment area of Wadi Butum is further subdivided into three subcatchments, Shi'ban El-Butum, Wadi Harth and Wadi Uweinid, the areas covered by each of the subcatchments are 310, 280 and 185 km^2, respectively. These subcatchments are entering the basin from the west. The average annual rainfall over these areas range from 100 to 110 mm.

The total drainage area of Wadi Mudideisat subcatchment at Qa' Azraq is about 1350 km^2 and entering the basin from the west. The general shape of this catchment is fern leaf with the longer axis oriented W-E direction. The average annual rainfall in this subcatchment is 123 mm.

Wadi Ghadaf subcatchment covers an area of about 2430 km^2, and enters the basin from south. Considerable part of this area is flat, and the general slope from SW to NE. The average annual rainfall precipitated over this subcatchment is about 58 mm.

The total drainage of Wadi Jesha subcatchment at the outlet in Qa' Azraq is about 1350 km^2. The general shape of the subcatchment is fern leaf with the longer axis oriented SW-NE direction. Great part of this area is flat and the annual mean rainfall over this area is 47 mm.

Daily rainfall data from 11 rainfall stations with adequate records from (1967/1968-1999/2000) had been analysed in terms of storms and frequency distributions. Curve Numbers were chosen in the range 65 to 75 for the individual wadi catchments, which gave long-term runoff equivalent to 2.4% of rainfall over the 33 years period of analysis. Table 1, represents the distribution of selected curve numbers for the main subcatchments in the basin. Calculations were performed for each storm of each wadi catchment from the water year 1967/1968 to 1999/2000. According to these calculations the heaviest floods occur between November and March and no significant floods occur in October and May. The estimated mean annual runoff volume is 27.4 million cubic meter (MCM) over the 33 years period of record (Table 2). The water budget calculation of the basin is presented in Table 3.

4. Aquifer Characteristics of the Azraq Basin

Three major aquifers were identified in the Azraq basin, the upper aquifer complex, the middle aquifer complex and the lower aquifer complex.

4.1. Upper Aquifer Complex

The upper aquifer complex consists of alluvial deposits (JA)-(Quaternary), Basalts (BS)-(Miocene-Quaternary), the Shallala Formation (B_5)-(Eocene) and the Rijam Formation (B_4)-(Paleocene).

Near the Qa'-Azraq area, the upper aquifer is very shallow and the water table can be found only a few meters below the ground surface and hand dug wells are commonly found. All of the hand dug wells are located in farm areas northeast of Azraq Drouz and east of the well field area. They excavated within the first ten meters of the alluvial deposits to obtain water for irrigation. The alluvial deposits are subdivided into three parts in the Qa'-Azraq area: (a) the upper part includes permeable sediments layers with thickness ranging between 10 and 30 m, (b) the middle part includes a low permeable clay and marl layer with thickness between 20 and 40 m, (C) the lower part includes permeable and semipermeable Quaternary age sediments or lithologies of the Shallala formation.

Geoelectrical surveys which were made by Worzyk & Hüster, 1987 have shown local salt water bodies at depths of 50 to 80 m. Changes from salt to fresh water in greater depths can be explained by an existing aquitard layer between the two aquifers. Quaternary sediments are composed of sandy clay with plates of gypsum and occasional laminations of halite crusts at the surface.

The Basalt aquifer is intercalated with thin layers of red clay, which may give rise to perched groundwater bodies. It extends through the northern part of the Azraq basin into Jebel El-Arab. The basalt flows lie uncomfortably above the sedimentary rocks of the Shallala and Rijam Formations. Water percolates from the basalt into the Rijam aquifer. In the west, the basalt flows are above the saturated zone for two reasons (Al-Momani, 1991): (a) gradual thinning of the basalt from east to west (b) sharp increase in the hydraulic gradient of the complex in the same direction. The transmissivity of the basalt ranges between $3.1*10^{-3}$ and 0.76 m^2/s with an average of 0.12 m^2/s (Humphreys, 1982).

Table 1. Distribution of Curve Numbers on the Main Catchment Areas of Azraq Basin.

Catchment Area	Area (km^2)	Curve Number (CN)	Potential Abstraction S (mm)	Initial Abstraction Ia (mm)
Wadi Rajil	3910	70	108.9	21.8
Wadi Hassan	490	75	84.7	16.9
Wadi Aseikhim	1180	65	136.8	27.4
Wadi Unqiya	214	65	136.8	27.4
Wadi Rattam	476	68	119.5	23.9
Qa' Khanna	750	65	136.8	27.4
Wadi Butum	310	70	108.9	21.8
Wadi Harth	280	68	119.5	23.9
Wadi Uweinid	185	70	108.9	21.8
Wadi Mudeisisat	1135	70	108	21.8
Wadi Ghadaf	2430	70	108	21.8
Wadi Jesha	1135	70	108	21.8
Total	12710	69.3	112.5	22.5

Table 2. Average Monthly and Annual Runoff of the Subcatchments of Azraq Basin in (MCM) for Period (1967-2000).

Catchment Area	October	November	December	January	February	March	April	May	Annual Mean
Wadi Rajil	0.04	1.1	2.3	2.1	3.61	3.5	0.1	0.07	12.82
Wadi Hassan	0.02	0.45	0.6	0.57	0.82	1.1	0.04	0.06	3.66
Wadi Aseikhim	0.02	0.19	0.17	0.23	0.3	0.48	0.01	0.03	1.43
Qa' Khanna	0.01	0.14	0.18	0.24	0.33	0.42	0.01	0.02	1.35
Wadi Rattam	0.01	0.04	0.03	0.07	0.09	0.0	0.01	0.01	0.32
Wadi Unqiya	0.01	0.02	0.04	0.05	0.06	0.04	0.01	0.01	0.24
Wadi Butum	0	0.1	0.24	0.11	0.09	0.16	0.11	0	0.81
Wadi Harth	0	0.11	0.16	0.12	0.08	0.14	0.15	0	0.75
Wadi Uweinid	0	0.05	0.05	0.06	0.07	0.05	0.01	0.01	0.3
Wadi Mudeisisat	0	0.94	0.95	0.45	0.63	0.76	0.98	0	4.71
Wadi Ghadaf	0	0.05	0.06	0.06	0.25	0.13	0.03	0	0.58
Wadi Jesha	0	0.18	0.02	0.06	0.12	0.02	0.01	0	0.41
Monthly Total	0.11	3.36	4.8	4.12	6.45	6.86	1.47	0.221	27.38

Table 3. Calculated Water Balance for the Azraq Basin.

Water Year	Rainfall (MCM)	Runoff (MCM)	Loss (MCM) (Ed)	Loss (MCM) (Ia)	Loss (MCM) Total	Infilt. (MCM)	Runoff Rate (%)	Infilt. Rate (%)	Loss Rate (%) (Ed)	Loss Rate (%) (Ia)	Loss Rate (%) Total
1967/1968	1119.8	5.7	251.8	857.5	1109.3	4.8	0.5	0.4	22.5	76.6	99.1
1968/1969	1273.5	48.8	560.5	618.6	1179.1	45.6	3.8	3.6	44.0	52.6	92.6
1969/1970	784.2	12.5	341.1	414.2	755.3	16.4	1.6	2.1	43.5	52.8	96.3
1970/1971	1471.8	69.3	646.3	703.3	1349.6	52.9	4.7	3.6	43.9	47.8	91.7
1971/1972	1657.4	13.2	307.8	1317.5	1625.3	18.9	0.8	1.1	18.6	79.5	98.1
1972/1973	730.8	21.0	204.2	483.2	687.4	22.4	2.9	3.1	27.9	66.1	94.0
1973/1974	2043.8	80.0	421.7	1452.5	1874.2	88.8	4.0	4.3	20.6	71.1	91.7
1974/1975	1244.3	13.3	211.9	964.7	1176.6	54.4	1.1	4.4	18.0	76.5	94.5
1975/1976	1240.5	21.6	354.7	841.0	1195.7	23.2	1.7	1.9	28.6	76.8	96.4
1976/1977	719.4	13.0	419.8	266.7	686.5	19.5	1.8	1.8	2.8	58.3	37.1
1977/1978	738.5	3.3	117.0	613.8	730.8	4.4	0.4	0.6	15.8	83.2	99.0
1978/1979	542.7	3.1	110.5	421.6	532.1	7.5	0.6	1.4	20.4	77.6	98.0
1979/1980	1736.2	65.8	433.4	1165.3	1598.7	71.7	3.8	4.1	25.0	67.1	62.1
1980/1981	1165.5	54.8	361.2	702.8	1064.0	46.7	4.7	4.0	31.0	60.3	91.3
1981/1982	1137.5	6.9	164.4	953.4	1117.8	12.8	0.6	1.1	14.5	83.8	98.3
1982/1983	995.2	53.1	322.2	549.0	871.2	70.9	5.3	7.1	32.4	55.2	87.6
1983/1984	610.1	15.5	332.7	240.9	573.6	21.0	2.5	3.4	54.6	39.5	94.1
1984/1985	1075.3	18.9	429.0	583.4	1012.4	44.0	1.8	4.1	39.9	54.2	94.1
1985/1986	1042.2	19.1	351.4	649.8	1001.2	21.9	1.8	2.1	33.7	62.4	96.1
1986/1987	1009.2	48.2	364.6	544.7	909.3	51.7	4.8	5.1	36.1	54.0	90.1
1987/1988	1629.4	17.5	438.7	1136.3	1575.0	36.9	1.1	2.3	26.9	69.7	96.6
1988/1989	1422.2	26.3	301.0	1054.6	1355.7	40.2	1.8	2.8	21.2	74.2	95.4
1989/1990	1182.0	10.8	227.3	928.7	1156.0	15.2	0.9	1.3	19.2	78.6	97.8
1990/1991	1238.0	47.2	309.8	822.3	1132.1	58.7	3.8	4.7	25.0	66.5	91.5
1991/1992	1074.0	38.9	312.9	670.4	983.3	51.8	3.6	4.8	29.0	62.5	91.0
1992/1993	795.7	22.1	406.5	349.4	755.9	17.7	2.8	2.2	15.2	43.9	95.0
1993/1994	866.8	2.2	31.9	827.4	859.3	5.3	0.3	0.6	3.7	95.4	99.1
1994/1995	1150.3	13.4	255.9	855.4	1111.3	25.6	1.2	2.2	22.2	74.4	96.6
1995/1996	610	5.2	354.4	238.0	592.4	12.4	0.85	2.03	58.1	39.0	97.1
1996/1997	1037	18.7	352.0	642.5	994.5	23.9	1.80	2.30	33.9	62.0	95.9
1997/1998	1033	13.4	399.5	593.2	992.7	26.9	1.30	2.60	38.7	57.4	96.1
1998/1999	254	0.5	56.5	193.5	250.0	3.3	0.20	1.30	22.2	76.3	98.5
1999/2000	256	1.1	75.9	176.4	252.3	4.1	0.43	1.60	29.4	68.6	98.0
Average	1132.0	27.4	321.1	749.5	1070.6	34.0	2.4	2.9	26.4	66.2	94.6

Total loss =1150.3 ED (Evaporation of the storm) and Ia is Initial Abstraction

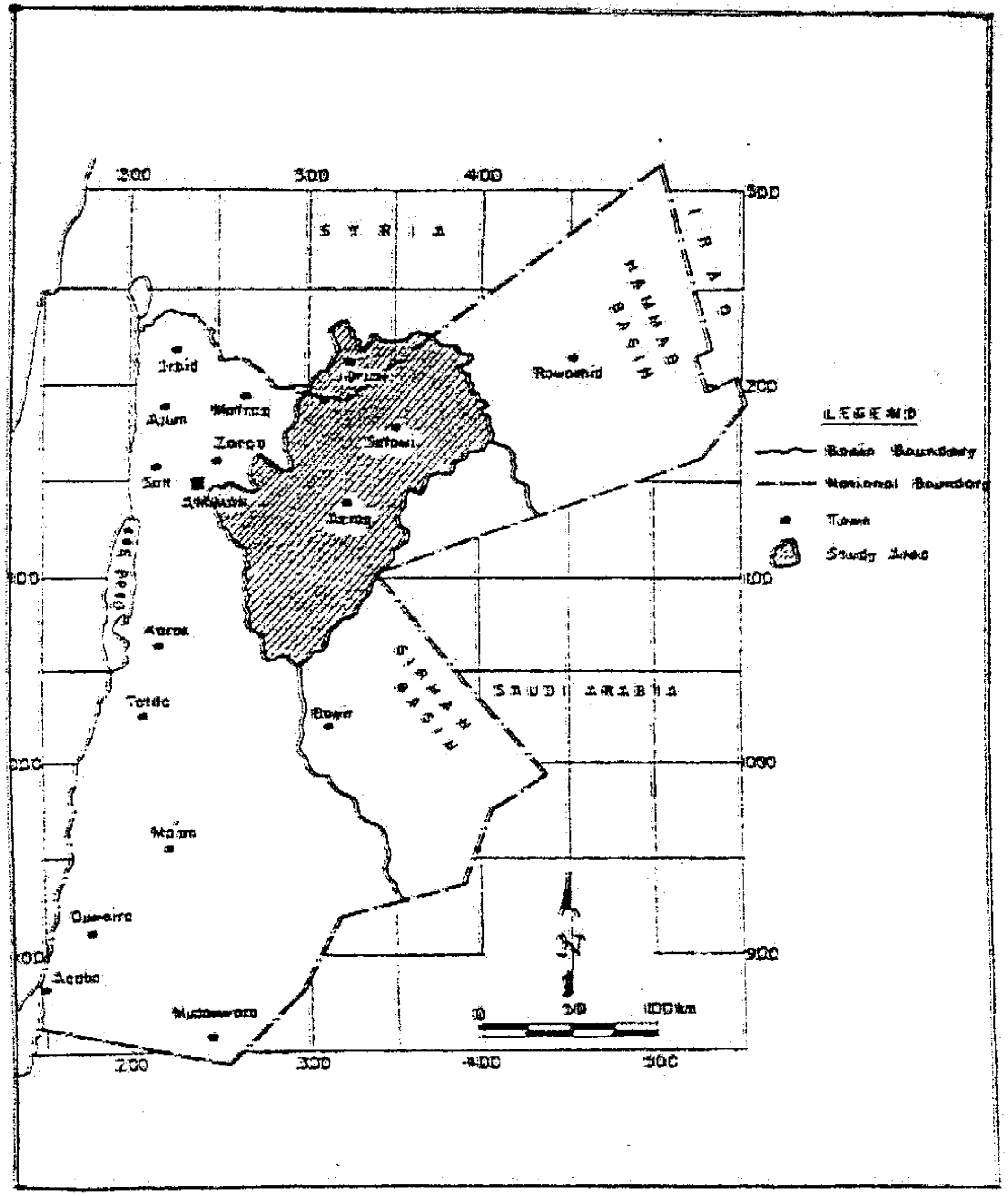

Fig. 1. Location Map of the Azraq Basin.

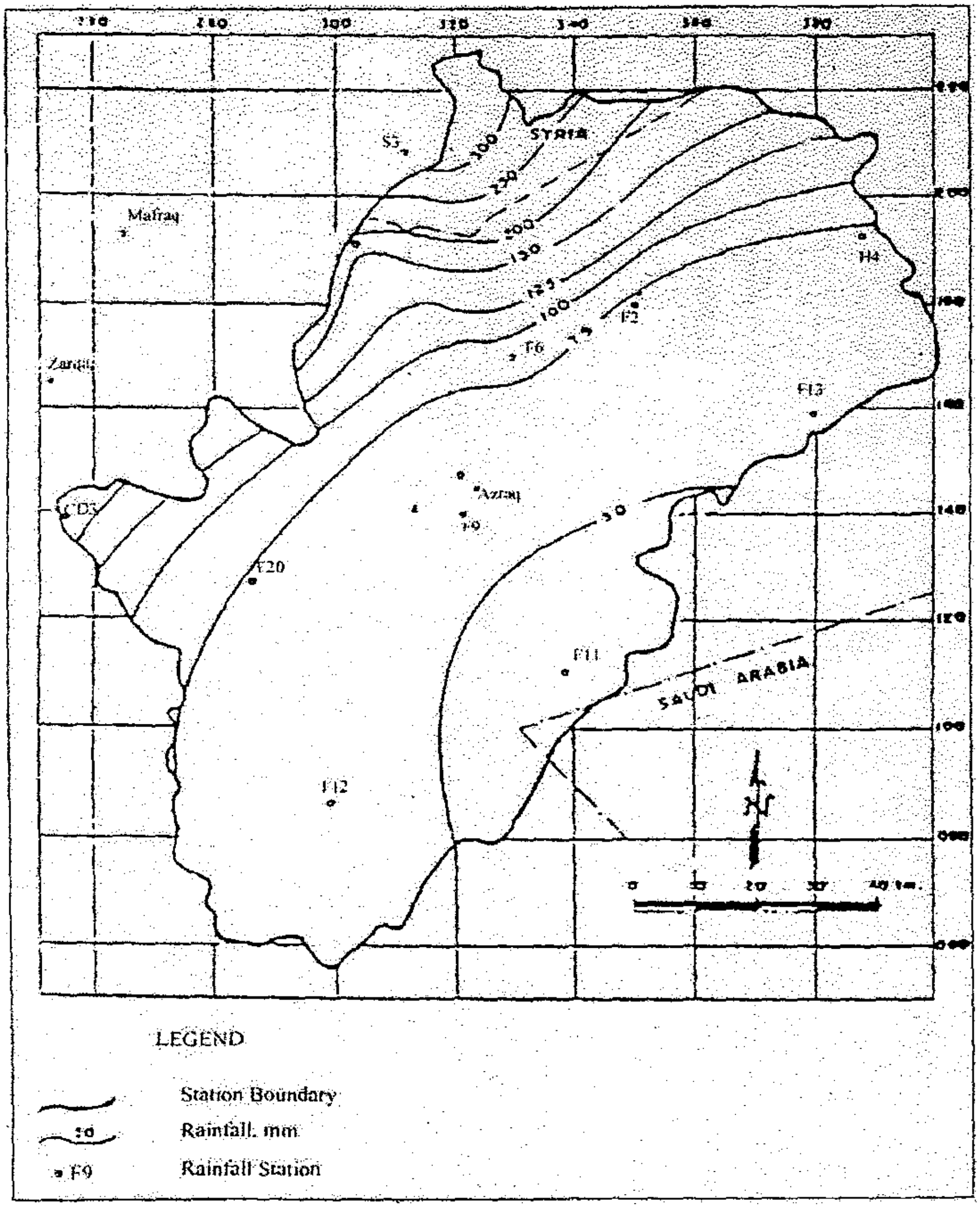

Fig. 2. Isohythat Map of Azraq Basin-Average Water Year.

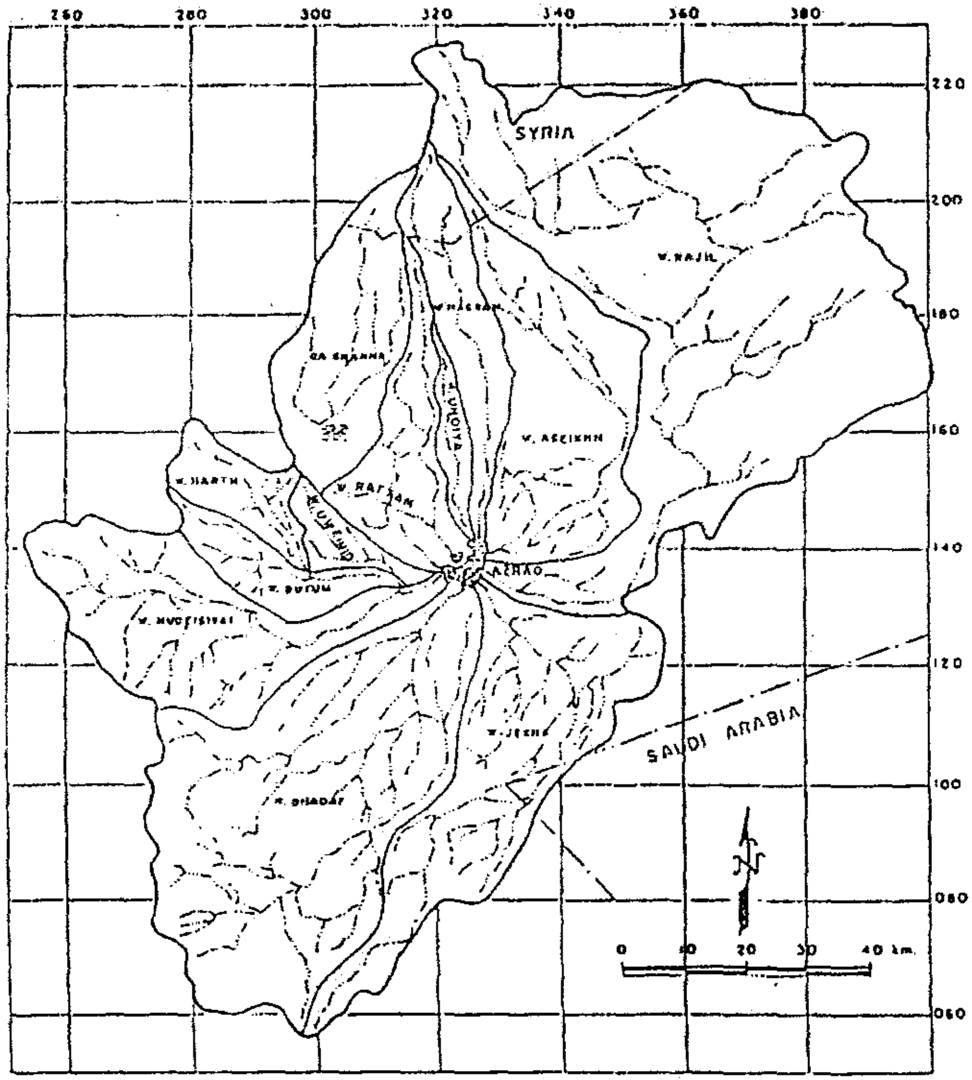

Fig. 3. Azraq Subcatchment Areas

The Shallala Formation is composed of marly clayey layers and acts as aquitard to the groundwater between the Basalts and Rijam aquifers in the northern part of the basin. In south Azraq, the Shallala Formation consists of sandy layers and can be locally classified as an aquifer (Water Authority, 1989).

The Rijam aquifer covers most of the central and southwestern parts of the basin. It is classified as a good aquifer and is composed of white colored chalky limestone and brown chert, underlain by the green marls of the Muwaqqar Formation, containing occasional gypsum (NRA. 1987). The Rijam aquifer is unconfined in the western and southern parts of the basin. It is overlain in some places by alluvial clays which give rise to localized artesian conditions. This aquifer dips in the south-east below the chalks and marls of the Shallala Formation, acting as confining beds to the Rijam aquifer. Permeability of the Rijam Formation varies with the degree of karstification. It ranges from 1.2 10^{-4} to 3.310^{-4} m/s and transmissivity ranges from 4.63*10^{-4} to 1.23*10^{-3} m^2/s (Water Authority, 1989). The gross hydraulic connection between the Basalts and the Rijam Formation classifies them as one aquifer (ACSAD. 1982).

The upper aquifer complex is an unconfined aquifer and forms the major aquifer to the Azraq basin. This aquifer consists of four different members which makes large differences in the chemical and physical characteristics of the groundwater. The water of this aquifer differs in depth, quantity and quality from one place to another. Depth to water ranges between few meters to more than 200 m. Regional drawdown in the groundwater ranges between 8 and 12 m (German Water Engineering GMBH, 1991).

The average transitivity is approximately 11000 m^2/d with values ranging between 16 and 26352 m^2/d. The permeability shows values of less than 0.5 m/d to more than 115 m/d and decreases towards the north and east from the well field area. Saturated thickness varies between 130 and 190 m in the north and decreases to 50 m in the south.

The groundwater contour map of the upper aquifer complex shows that the major recharge from the north, northeast, and northwest, with minor recharge from the west. Groundwater flows from Jebel El-Arab to reach the graben structure, where the well field is located. This relates to the high permeability of the rocks. The Fuluk fault acts as a barrier to the groundwater, because of different hydraulic characteristics of the groundwater flows north and south of the barrier. The hydraulic velocity of water from Jebel El- Arab to the well field area is very slow (Al-Kharabsheh, 1995). The age of the groundwater was determined to be about 500 to 20000 years. Measurements (Fröhlich et al., 1987) showed that, because of withdrawal from the well field area, the groundwater is becoming younger in age as a result of the increase of the hydraulic gradient towards the cone of depression.

4.2. Middle Aquifer Complex

The middle aquifer complex is separated from the upper aquifer complex by low permeability marls of the Muwaqqar Formation (B_3) and is composed of the Amman Formation (B_2)-(Campanian), the Ruseifa Formation (B_1)-(Santonian) and the Wadi Es-Sir Formation (A_7)-(Turonian). This aquifer outcrops in the west and southwest of the basin and underlies most of the area.

The Amman Formation is classified as a good aquifer and is composed of chert, chalk and limestone. Depth to the aquifer ranges between 420 and 590 m. The hydraulic conductivity ranges between $3.06*10^{-6}$ and $4.73*10^{-3}$ m/s with an average value of $7.16*10^{-4}$ m/s (Water Authority, 1989).

The Ruseifa Formation is a thin layer of marl and shale ranging in thickness between 0 and 20 m. Hydrogeologically, this formation is considered to be an aquitard.

The Wadi Es-Sir Formation forms a good aquifer with a thickness of more than 300 m. It is composed of marl, marly limestone and occasionally of sandstone. Bands of marl and marly limestone form local aquiclude layers within the middle aquifer complex in the Azraq basin. Permeability of the Wadi Es-Sir Formation ranges from $1*10^{-7}$ to $1*10^{-4}$ m/s.

4.3. Lower Aquifer Complex

The lower aquifer complex is separated from the middle aquifer by low permeability marls and limestone of Ajlun group (A_1-A_6). The vertical permeability of these aquicludes has a large influence on the leakage characteristics between the aquifers (Lioyd, 1992). This aquifer complex consists of poorly consolidated multicolored sandstones of Lower Cretaceous age intercalated with thin beds of shales and clays. It underlies most of the Azraq area and classifies Hydrogeologically as a good aquifer with highly saline waters. Thickness exceeds 200 m.

The lower aquifer complex is a confined aquifer of varying depths which underlies most of Azraq basin. The depth to the aquifer is more than 1000 m. Recharge to the aquifer comes partly though the B_2/A_7 aquifer complex. The lower aquifer complex has many lateral and vertical variations in permeability, due to the presence of clay strata in different horizons. Permeability coefficients range from $6*10^{-}$ to $5*10^{-4}$ m/s with an average $4.4*10^{-5}$ m/s. The average porosity is 4.6 to 13.1 percent. Well AZ-1, the only flowing well in the area, produces carbon dioxide, hydrogen sulfide and radon gases indicating the confined nature of the aquifer. Upward and downward leakage within the B_2/A_7, Basalt-Rijam and the deep aquifers may occur because of tectonic situation of the basin.

5. Infiltration and Geochemical Modeling

5.1. Infiltration Model

The infiltration model was made using the MODRET computer program (ANDREYEV, 1992). The program estimates the infiltration capacity of storm water during and following the storm event using the formula:

$$t = (f/k)\,(L-(H-h)\ln\{(H+L-h)/(H-h)\}) \qquad (10)$$

where t is the time since infiltration start, k is unsaturated hydraulic conductivity, H is the depth of ponded water, h is the capillary suction potential at the wetting front, L is the depth of penetration of the wetting front and f is the effective storage coefficient.

The effective storage coefficient is the difference between the initial moisture content and the moisture content in the transmissive zone) can be approximated as follows:

$f = 0.9n-(Wyd/Yw)$ .... (11)

where f is the effective storage coefficient, n is the porosity, W is the moisture content (fraction on a dry weight basis), Yd is the dry unit weight of soil and Yw is the unit weight of water.

Table 4 shows results of the unsaturated infiltration analyses. The relation between the storage coefficient, volume of water to saturate the soil below the dam and the time needed to reach the groundwater are shown in Fig.'s 4 and 5.

5.2. Geochemical Modeling

The chemical analyses of the floods and groundwater were used as inputs for the PHREEQE Computer Program (Koelling, 1991). The goal of the geochemical models of this study is to explain the chemical characteristics of groundwater when mixed with flood water. The program based on themodynamically approached chemical species distribution by equilibrium constants and GIBBS free energies. The program calculates p, and pE values, speciations and the concentration of the cations and anions in the groundwater that must dissolve or precipitate during the mass balance and saturation indices of the different, minerals during the simulation.

Two types of models were used: The first one depends on the different rations of mixing of flood and the groundwater to show the effects of flood quality on the groundwater quality. The second shows the effect of evaporation rate on water quality stored in the reservoir and lastly its influence on the groundwater quality by its mixing with it.

5.2.1. Mixing Model

The Basalt-Rijam aquifer complex forms the major aquifer in the Azraq Basin. Recharge occurs from Jebel El-Arab through the Basalt flows covering and the Rijam Formation. Mixing between average chemical compositions of floods and groundwater of this aquifer was set at 10%, 30% and 50%. Results of the runs show that the concentration of cations and anions sharply decrease with increasing the mixing ratio (Table 5). The groundwater under all mixing ratios is alkaline with high chloride content.

5.2.2. Evaporation Model

An evaporation model with 10%, 20%, 30% and 40% evaporation rate was simulated to show the effects of evaporation on water quality through the recharge dams. Results of these runs show that all evaporation rates do not affect found water quality (Table 6). The flood waters were alkaline with prevailing bicarbonate under all evaporation rates. Generally, mixing of such water will have no negative effect on the original groundwater quality, but it will improve it.

Table 4. Unsaturated Infiltration Analyses of the Wadi Butum Catchment Area.

Parameters	Average Effective Storage Coefficient		
	0.1	0.2	0.3
Average Dam Reservoir Length (m)	152	152	152
Average Dam Reservoir Width (m)	105	105	105
Average Dam Elevation (m) above mean sea level	650	650	650
Permeability (m/d)	0.06	0.06	0.06
Safety Factor	2.00	2.00	2.00
Dam Height (m)	30	30	30
Dam Side Slope (Horizontal/Vertical)	4.00	4.00	4.00
Catchment Area (km^2)	140.00	140.00	140.00
Curve Number	78.00	78.00	78.00
Time of Concentration (Hour)	3.9	3.9	3.9
Maximum Daily Rainfall for 100 Years Return Period (mm)	62.5	62.5	62.5
Average Separation between Dam Bottom and Groundwater Level (m)	65	65	65
Unsaturated Infiltration Volume (MCM)	0.98	1.9	2.8
Effective Time to reach the Groundwater (Days)	200	393.00	585

Table 5. Average Chemical Composition of Groundwater in the Basalt-Rijam Aquifer Complex before Mixing with the Floods and after 10 %, 30 % and 50 % Mixing Ratios.

Element (mg/l)	Groundwater (GW) before Mixing	10 % Mixing 90 % native GW	30 % Mixing 90 % native GW	50 % Mixing 50 % native GW	Flood Water
Ca	30.91	30.02	28.28	26.54	22.2
Mg	12.98	12.07	10.25	8.44	3.9
Na	109.41	102.31	88.22	74.12	38.9
K	4.97	4.97	4.98	4.98	5
Cl	137.61	124.77	99.22	73.67	9.8
HCO_3	114.31	119.34	133.73	148.11	172
SO_4	68.709	62.74	50.86	38.99	9.3
NO_3	8.51	8.1	7.3	6.50	4.5
Fe	0.134	0.15	0.2	0.24	0.35
Mn	0.0167	0.015	0.012	0.008	-
Zn	0.0267	0.024	0.019	0.013	-
Cd	0.001	0.001	0.001	0	-
Cr	0.0269	0.024	0.019	0.013	-

Table 6. Average Chemical Composition of the Floods Before Evaporation and After 10 %, 20 %, 30 % and 40 % Evaporation Ratios.

Element (mg/l)	flood water units	10 % Evaporation	20 % Evaporation	30 % Evaporation	40 % Evaporation
Ca	22.2	24.66	27.74	31.7	36.99
Mg	3.9	4.33	4.87	5.57	6.50
Na	38.9	43.21	48.61	55.55	64.82
K	5	5.55	6.25	7.14	8.33
Cl	9.8	10.88	12.25	14.00	16.32
HCO_3	172	204.52	230.1	262.96	306.78
Fe	0.35	0.39	0.44	0.50	0.58
Al	0.27	0.3	0.34	0.38	0.45
SO_4	9.3	10.33	11.62	13.28	15.50
NO_3	4.5	5	5.62	6.43	7.50
F	0.07	0.078	0.087	0.10	0.12
Li	0.1	0.11	0.12	0.14	0.17
Br	0.24	0.27	0.30	0.34	0.40
NH_4	0.34	0.38	0.42	0.49	0.57

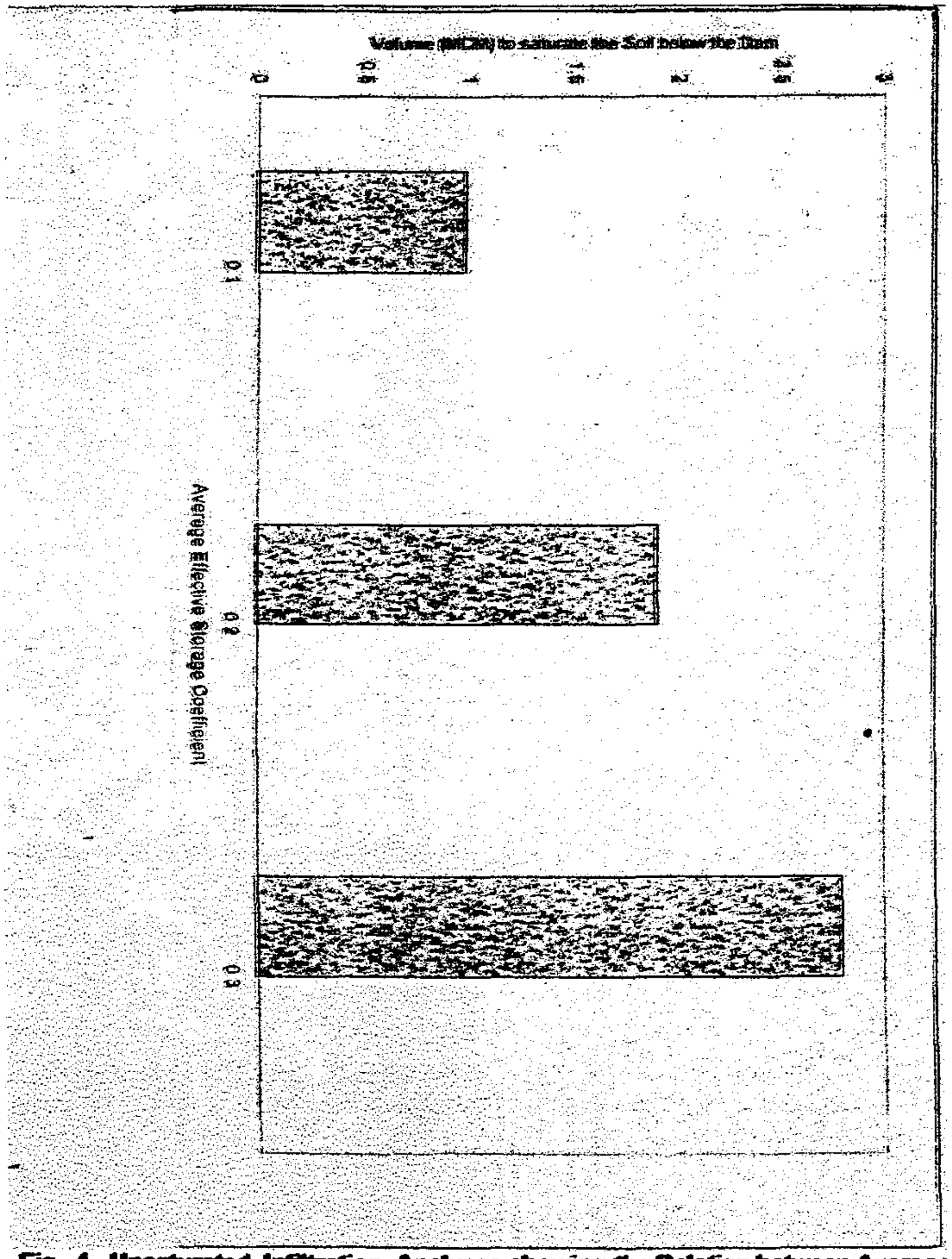

Fig. 4. Unsaturated Infiltration Analyses showing the Relation between Average Storage Coefficient and the Volume of Water Needed to Salurate the Soil below Wadi Butum Dam.

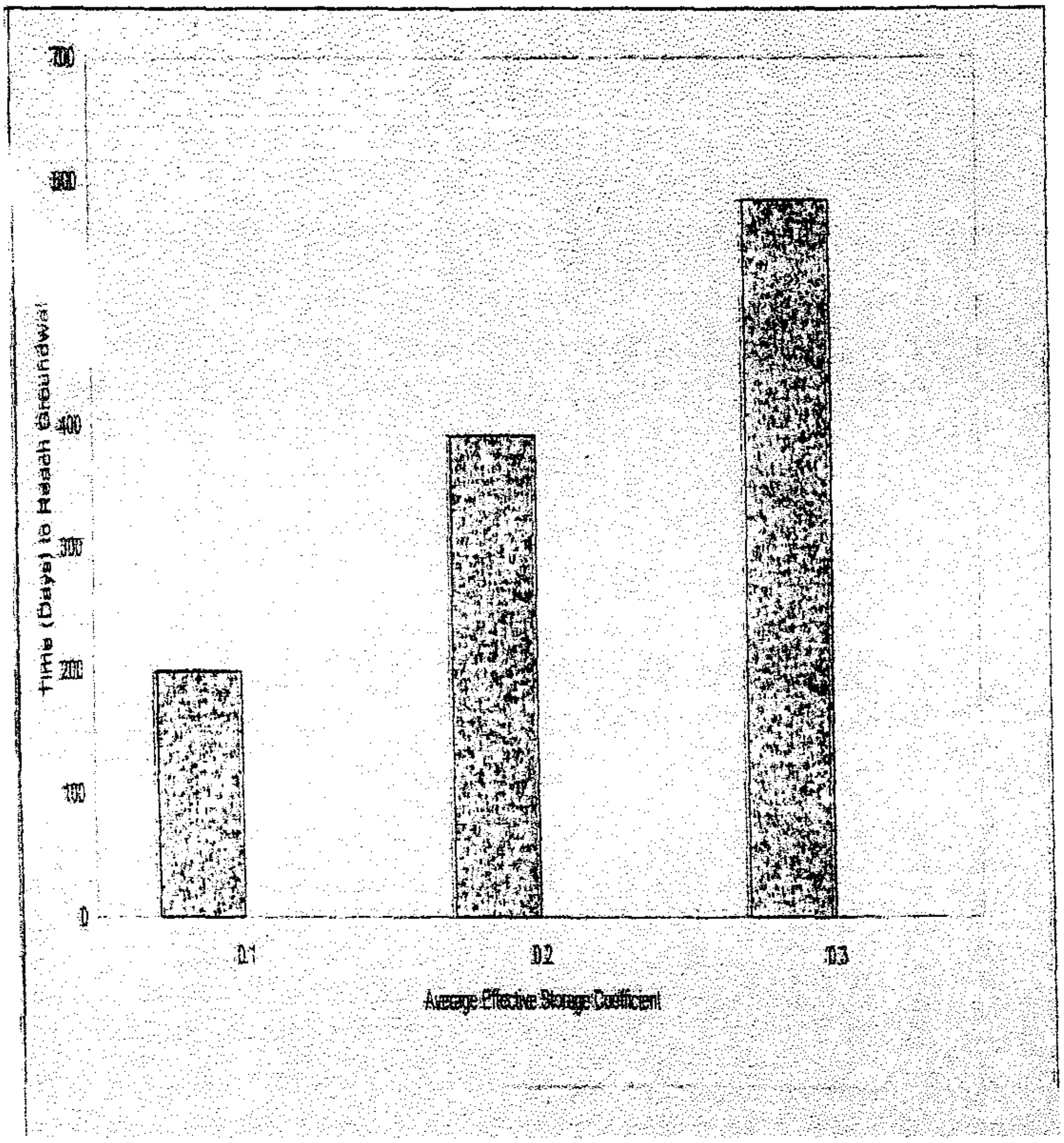

Fig. 5. Unsaturated Infiltration Analyses showing the Relation between Average Storage Coefficient and the Time Needed for Surface Water to Reach Groundwater for Wadi Butum.

6. RESULTS AND DISCUSSION

The water problems are considered the most important challenge facing Jordan, which shows an arid to semi-arid climate. The annual rainfall decreases from 600 mm at the northwest to less than 50 mm at the southeast. The problems are accelerating, due to high population growth and the increasing demand to cover the agricultural and industrial activities.

The scarcity of water in the Azraq Basin which is a major source for drinking water for three major cities in Jordan (Amman, Zerqa and Irbid) has led to suggest constructing recharge dams to provide the Upper Aquifer Complex with good water. The construction of a dam at the outlet of the catchments will help in utilization of the surface water, which evaporates completely in the Qa' area at the central part of the Azraq Basin. Furthermore, the dam will prevent the problems associated with the heavy floods and puddles as which result of the heavy thunderstorms.

The water quantity and quality have deteriorated in present times in the Azraq basin, because of overpumpage of the upper aquifer complex to cover increasing demand to water and limited renewable sources. The springs, which form the oasis, have totally dried. This means that, searching about new water resources is very necessary for development of the country and to protect groundwater from the probable salt water intrusion.

The Azraq basin forms the northeastern part of Jordan's territory. The basin shows a gentle relief from Jebel El-Arab area, the highest point is located at 1570 m above mean sea level in Syria, while the lowest is located at 500 m above mean sea level in the Azraq depression itself. It forms a very important source for drinking water for three major cities in Jordan (Amman, Zerqa and Irbid) and the Azraq area itself. Shallow depth and high quality of groundwater increase the ability for the development of water supplies and planning.

The exposed rock units in the Azraq basin are Upper Cretaceous, Tertiary and Quaternary recent deposits. They are composed of sanstones, carbonates, shales, volcanics and alluvial deposits. The lithostratigraphy shows unconformities between some formations. Tectonically, the Azraq basin is a northwest-southeast trending graben, formed as a result of three tectonic phases during the Paleozoic to recent.A gradual thinning of the sediment can be observed in the southeastern part of the basin.

The amount of precipitation ranges between 300 mm in the north at Jebel El-Arab to less than 50 mm in Umary to the south. The thunderstorm rainfalls, characterized by their irregularity in intensity and duration, form the major precipitation of the Azraq basin. Flood water flows toward the depression area where puddles accumulate, remaining for few months until evaporation.

The calculated runoff volumes range from less than 1 MCM during droughts to about 80 MCM during wet years divided over 12 subcatchments. The water flows from the edges of the basin to the central part of the depression. The annual infiltration volume in the basin is 34 MCM. Around 1 MCM flows from the basin towards Sirhan. Another 14 MCM can be divided into direct evapotranspiration of the shallowest water table near Qa'-Azraq area, and long-term average discharge of the springs. The total recharge to the upper aquifer complex is considered to be 20 MCM per year.

There are three different aquifers in the Azraq basin. The upper aquifer complex is divided into two subunits, the first is composed of Basalts, alluvial deposits, Shallala and Rijam Formations in the northern part of the Azraq basin. It is the most important one in the area, because of good groundwater quality and low drilling costs. The second is composed of Shallala and Rijam Formations in the south. The hydraulic connection between these two subunits classifies them as one aquifer. The Shallala Formation is composed of clayey layers and acts as an aquitard, but in south Azraq it is more sandy and acts as an aquifer in some places. Depth to aquifer ranges between few meters to more than 200 m. Average transmissivity of the upper aquifer complex is 11000 m^2/d. Permeability of the upper aquifer ranges between less than 0.5 to 115 m/d. Saturated thickness ranges from 50 to 190 m.

The middle aquifer complex is composed of the Amman, Ruseifa and Wadi Es-Sir Formations. Depth to aquifer is more than 600 m. Average permeability is $9.75*10^{-4}$ m/s. Depth to piezometric heads ranges from 1 to 278 m. Transmissivity ranges between 3800 and 4800 m^2/d.

The lower aquifer complex consists of kurnub sandstone with depth more than 1000 m and average permeability is $4.4*10^{-5}$ m/s. Porosity ranges from 4.6 to 13.1 percent.

The aquifers are hydraulically interconnected by the effect of the major faults and show different flow directions: water of the upper aquifer complex flows from north at Jebel El-Arab area toward south to reach the Qa'-Azraq, water of the middle aquifer complex flows from west and southwest (Zerqa and Mujib basins) and from the east (Hammad Basin) to reach the Azraq depression, water of the lower aquifer complex flows from east to west to discharge in its lowest point at the Dead Sea Basin.

To keep the surface water from evaporating and pollution, puddling of the water within populated Azraq areas must be prohibited and soil erosion must be minimized. Twelve major subcatchment areas must increase groundwater resources in the Azraq basins were chosen to construct earth dams on them. The goal in constructing these dams is to overcome water problems by making an equilibration between the aquifers and to avoid probable salt water intrusion. The catchment areas dip in the direction of the well field area and are receiving the major rainfall and floods in the basin.

The watershed land cover and hydrologic soil groups define the Curve Numbers used to calculate the runoff quantities. Curve Numbers depend on catchment characteristics, antecedent moisture conditions, type of the soils, initial abstraction of the rainfall, slope and length of the channel system, watershed boundary, urbanization and cover categories. The amounts of surface water that could be collect in the catchments range from 0.24 MCM for Wadi Unqiya to 12.82 MCM for Wadi Rajil.

To decrease the effect of the silt accumulation in the recharge dams, it is recommended to construct the dams in several parts to avoid the erosion problems in the dam body. The first parts act as sedimentation dams and the others as recharge sources for groundwater.

The natural materials in the field will help in constructing a low cost recharge dam. An infiltration model for Wadi Butum as case study explains the infiltration capacity during and following the storms was developed. The results of this model indicate that the infiltrated water needs from 200 to 585 days to infiltrate reach the groundwater depending on the storage coefficient of the unsaturated zone. The volumes of the surface water needed to saturate the soil below the dams range between 0.98 and 2.8 MCM, which means that the recharge will begin in the second or third year.

Mixing geochemical model between the flood water of Wadi Butum and the native groundwater in the Basalt-Rijam aquifer complex shows that the groundwater quality will improve with increasing the mixing ratio. The evaporation ratios of the flood water show a high quality water after 40 % flood ratio. The recharge processes with flood water will positively affect the groundwater.

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الملخص العربي

التغذية الاصطناعية للمياه الجوفية في حوض الأزرق في الجزء الشمالي الشرقي من الأردن: حالة خاصة لتقييم المناطق الجافة

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تمت هذه الدراسة لبيان تأثير أوضاع الجفاف على نوعية وكمية المياه و إمكانية استغلال المياه السطحية في التغذية الاصطناعية للمياه الجوفية في حوض الأزرق. يعتبر هذا الحوض الأهم في الجزء الشمالي الشرقي من الأردن وتقدر مساحته بحوالي ١٢٧١٠ كم٢ ويقع بين الإحداثيات الفلسطينية ٢٥٠-٤٠٠ شرقاً و٥٥-٢٣٠

شمالاً. تشكل أمطار العواصف الجزء الأهم من أمطار الحوض حيث تتناقص من ٣٠٠ ملم في الشمال إلى ٥٠ ملم في الجنوب ويتراوح معدل الفيضانات ما بين ١ الى٨٠ مليون متر مكعب موزعة على ١٢ وادي رئيسي وتفيض المياه من كل الجهات باتجاه منطقة قاع الأزرق قبل ان تتبخر في الهواء. هناك ثلاثة خزانـــات مائيــة جوفية في الحوض تسمى العلوي والأوسط والسفلي وهي متصلة مع بعضها بواسطة الفوالق الموجودة وبمختلف الاتجاهات. يعتبر الخزان العلوي المكون من البازلت والرسوبيات الحديثة والكربونات (تكاوين الرجام والشلالة) هو الأهم حيث يعاني من الضخ الجائر لتغطية النشاطات الزراعية والصناعية المتزايدة بسبب قلة تكاليف الحفر ونوعية المياه الجيدة حيث أن تملح الحوض ممكن أن يحصل في القريب جدا. ولتحسين نوعية وكميـــة الميــاه الجوفية فانه يوصى باستغلال المياه السطحية للتغذية الاصطناعية للمياه الجوفية. المواد الطبيعية الموجودة فــي الموقع ستساعد في بناء سدود رخيصة الثمن. تبلغ الأحجام المتوقع تجميعها بواسطة هذه السدود ما بين ٠,٢٤ - ١٢,٨٢ مليون متر مكعب. نموذج الرشح الذي تم عمله أشار أن المياه بحاجة إلى ٢٠٠-٥٨٥ يوم حتى تصــل للمياه الجوفية وان الحجم المتوقع لجعل التربة مشبعة بالماء يتراوح ما بين ٠,٩٨ و ٢.٨ مليون متر مكعب. من جانب آخر فان النموذج الجيوكيميائي الذي تم عمله أشار أن نوعية المياه الجوفية ستتحسن بالتـــأكيد. نمــوذج التبخر يشير أن نوعية المياه الجوفية ستبقى ذات نوعية عالية حتى بعد ان يتبخر ٤٠% منها.