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GROUNDWATER RECHARGE ESTIMATION FOR SHAQLAW-HARRIR BASIN IN KURDISTAN REGION, IRAQ

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Increasing water demand in Kurdistan region has prompted the need to quantify the available groundwater resources. In semi-arid region, the groundwater recharge estimation is difficult due to the large variability of hydrological events in space and time. Shaqlawa-Harrir basin covered an area about 1150 km^2, and rainfall is the main source for replenishment of moisture and recharge of ground water in the area. Groundwater recharge estimated by employing water balance method based on climatic data, water table fluctuation method (WTF), where measured water table rises are correlated to recharge events (rainfall) and estimating the specific yield of the zone of fluctuation of the groundwater level is required, and environmental tracer (CMB) method depending on chloride concentration in rainfall and groundwater. Four temperature-based equations methods were used to estimate the potential evapotranspiration, actual evapotranspiration, water surplus and deficit. Horton's infiltration capacity was determined by taking twenty points in different locations, and statistics were used to evaluate the relationship between time and infiltration rate. The result of infiltration capacity shows that the type of infiltration rate ranges between moderate-rapid to slow-moderate. Coefficient of permeability determined for these infiltration points by using the Bindeman method ranges between $1.8*10^{-6}$ to $1.4*10^{-4}$ m/s. The mean monthly potential evapotranspiration is 120, 174, 194, and 219 mm/year determined by Thornthwaite, Blaney-Criddle, Kharrufa, and Romanenko method respectively. Surface runoff is about 209.6 mm/year and groundwater recharge is 50.9 mm/year by water balance method, 144.5 mm/year by WTF method, and 87.4 mm/year by using chloride as environmental tracer. The water budget is about $10.8*10^7$ m^3/year based on the average groundwater recharge and area of the basin.

INTRODUCTION

Efficient and sustainable groundwater-resource management in arid and semi-arid regions requires the quantification of groundwater recharge. However, such recharge is difficult to estimate in semi-arid areas when potential evapotranspiration is equal to or even surpasses average rainfall; increasing aridity of climate leads to a decrease in groundwater recharge and potentially also greater recharge variation in both space and time (De Vries & Simmers, 2002; Sekhar et al., 2004; Sibanda et al., 2009).

Recharge estimation methods are requiring the analysis of a large number of hydrological data accumulated over a considerable time span which involving rainfall, runoff, evapotranspiration, water surplus and deficit parameter, changes in groundwater storage, and groundwater level fluctuations(Wang et al., 2008). Although some variables in the water-balance equation, such as precipitation and runoff, are relatively easy to measure, the recharge process is still difficult to quantify because it needs information on other metrological conditions like soil type, soil order, soil moisture, vegetation cover, slope, agriculture, and irrigation (Lee et al., 2006).

Groundwater recharge is controlled by many factors, such as the nature and geometry of aquifers in the catchment, soil and aquifer hydraulic properties, climate (amount and intensity of rainfall and evaporation), type and amount of vegetation cover and types of land use, topography, and soil moisture.

An important tool employed to determine the magnitude of both short- and long-term changes in groundwater recharge, WTF analysis has been widely used under different climatic conditions and is based on a rise in the water table due to recharge water reaching the groundwater (Gerhart, 1986; Hall & Risser, 1993; Healy & Cook, 2002).

Such techniques which depend on information regarding groundwater level are among the most widely applied in estimating recharge rates due to the availability of data and the simplicity of estimating recharge rates from temporal fluctuations in groundwater level.

Uncertainty in estimates generated via this method is related to the limited accuracy with which specific yield can be determined, and thus the method is applicable only to unconfined aquifers (Healy & Cook, 2002). The major disadvantage of this method is that it is only applicable when recharge occurs in a certain season.

STUDY AREA DESCRIPTIONS

The Shaqlawa-Harrir basin is divided into two major sub-basins (Shaqlawa and Harrir) and three small sub-basins (Tawska, Hiran and Harash) which have an area of about 1150 km^2 with GPS reading of 44^{O} 2′ - 44^{O} 34′ E and longitude 36^{O} 11′ - 36^{O} 39′ N, northeast of Erbil city. Characterized by a semi-arid climate, the area lies within the high folded zone (Stevanovic & Markovic, 2003; Jassim & Goff, 2006), and is bounded by the Greater Zab River to the northwest, the Harrir anticline to the northeast, and the Safin anticline to the southwest (Figure 1).

GEOLOGY AND HYDROGEOLOGY

Lithostratigraphic units consist of Cretaceous, Paleocene, Eocene, Miocene, Pliocene, and Quaternary deposits. Cretaceous formations represented by; Qamchuqa formation which forms the core of most anticlines in the region and is predominantly carbonate rock-based, including bituminous dolomitic limestone and massive organic limestone; Aqra-Bekhme formation comprises thick-bedded

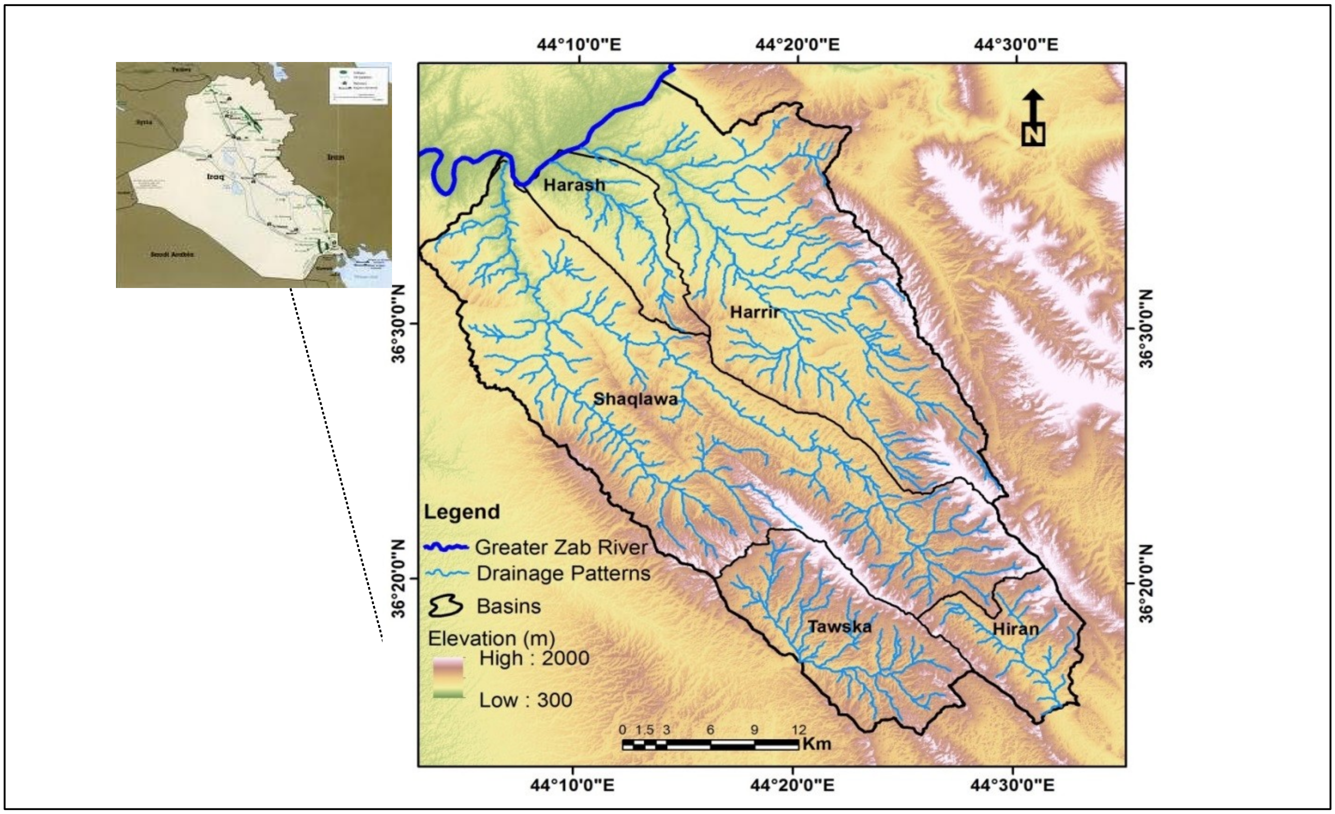

Figure 1. Digital terrain model of Shaqlawa-Harrir basins with drainage pattern

or massive limestones including dolomitic, fractured, fossiliferous reef, and bituminous; Shiranish and Tanjero formations comprise blue marl overlaying limestone and marly limestone.

Paleocene formations include the Kolosh formation, consisting mainly of alternating beds of mudstones, shale, sandstones, marlstones, and marly limestones, as well as a few thin beds and lenses of conglomerates. The Eocene formations represented by; Gercus formation which shales, siltstone, mudstone, sandy marls, pebbly sandstone, and little conglomerate; Pilaspi formation composed of dolomitic and chalky limestones and some shales. Miocene formations include; Fatha formation composed of alternating beds of sandstone, claystone, limestone, and rare evaporite (gypsum); Injana formation consists of alternating beds of massive and fractured sandstones and mudstones. The Pliocene is represented by the Bai Hassan and Muqdadeya formations, which include thick sandstone, siltstone, and conglomerate (Stevanovic & Markovic, 2003).

Quaternary deposits in the area are represented by river terraces which are present on the sides of river valleys; flood plain deposits include different-sized clastics, and a mixture of clay, sand and pebbles; slope and alluvial fans which occur either as angular rock falls on mountain slopes, or rounded gravels (Figure 2).

Hydrogeologically various types of aquifers exist in the study area, including porous, karstic, and fissured-karstic (Figure 3). The deposits in the Shaqlawa-Harrir basin comprise of Pliocene deposits, Middle and Upper Miocene deposits, Paleocene and Eocene deposits, and Cretaceous deposits (Stevanovic & Markovic, 2004).

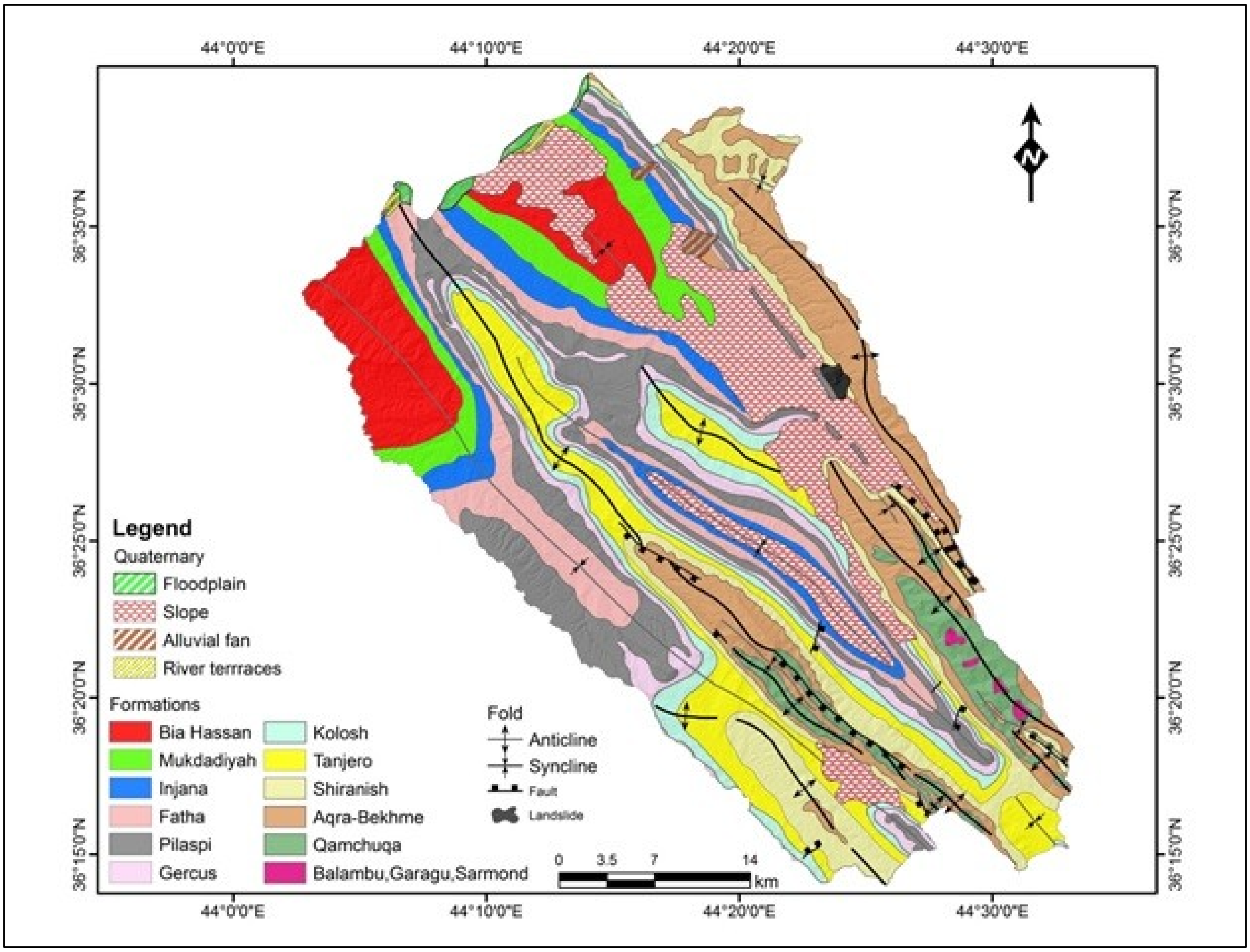

Figure 2. Geological Map of Shaqlawa-Harrir basin (after Sisakian, 1998)

MATERIALS AND METHOD

Climatic data

Water availability elements

Rainfall and relative humidity are the most important parameters influencing water availability. Meteorological data obtained from the Pirmam ground meteorological station for the period between 1992-2012 indicates to the mean of rainfall in the study area around 589 mm per year, while maximum and minimum mean monthly relative humidity were 73.8% and 33.9% in January and July respectively (Table 1).

Table 1. Mean monthly rainfall and relative humidity of Shaqlawa-Harrir basin for the period 1992-2012

Month	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Rainfall (mm)	113.3	111.1	90.6	64.2	24.8	1.5	0.8	0.02	3.7	35.7	55.1	88.6
R.H %	71.7	70.9	59.5	57.7	43.9	34.3	34.9	33.7	38.6	49.1	59.1	64.4

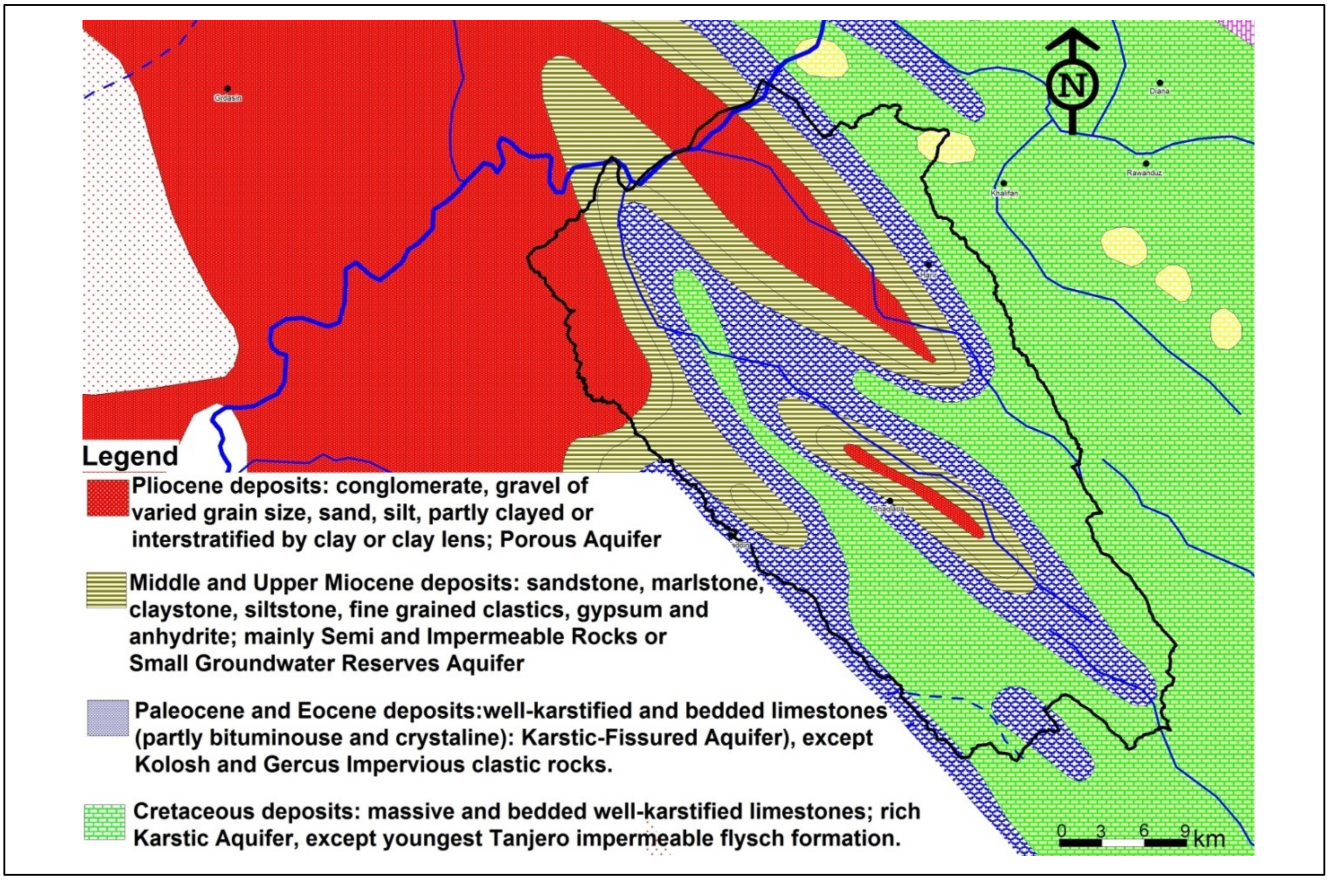

Figure 3. Hydrogeological map of Shaqlawa-Harrir basin (after Stevanovic and Markovic, 2004)

Water loss elements

Temperature, wind speed, sunshine and evaporation represent water loss elements. Temperature is an important factor influencing both evaporation and evapotranspiration. In the study region the maximum mean monthly temperature is 35.6°C in August, and the minimum mean monthly temperature is 8.1°C in January. The average annual temperature is 21.5°C. Wind speed is restricted in the study area at between 1.9-2.9 m/sec; the annual mean wind speed is 2.3 m/sec. The maximum mean monthly sunshine is 11.7 hours/day in July, with the minimum of 4. 6 hours/day recorded in January; the mean annual is 7.8 hours/day. According to estimates calculated at the Pirmam station, the mean for maximum monthly evaporation is 266.7 mm in July, with the minimum 32.5 mm in January; average monthly evaporation is 137.4 mm

Table 2. Mean monthly water losses element for the period 1992-2012

Month	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Temperature (^oC)	8.1	9.1	13.5	18.9	25.4	31.1	35.5	35.6	30. 8	24.7	15.3	10.3
Sunshine (h/d)	4.6	4.9	6.2	6.6	8.9	11.5	11.7	10.7	9.9	7.6	6.2	5.1
Wind Speed (m/s)	2.0	2.4	2.8	2.9	2.6	2.7	2.4	2.3	2.1	2.2	1.9	1.9
Evaporation (mm)	32.5	38.4	94.2	116.1	188.9	253.9	266.7	258.8	180.7	122.7	53.4	43.0

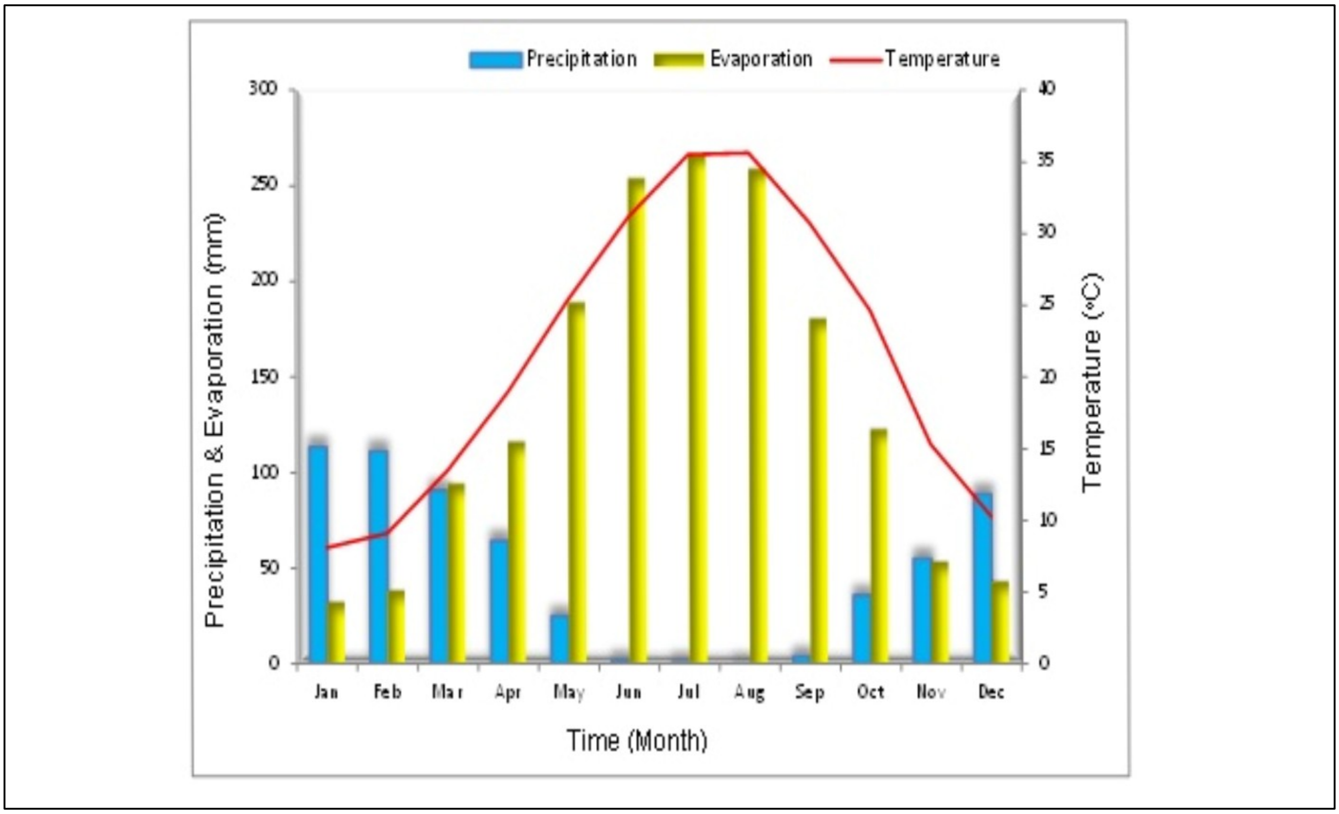

Figure 4. Relationship between mean monthly rainfall, evaporation and temperature for the period 1992-2012

Water balance method

A numerous methods can be employed to determine water balance depending on the availability of meteorological data. Hydrometeorological data recorded at Pirmam metrological station were used to calculate water balance parameters including potential and actual evapotranspiration, water surplus, water deficit, and surface runoff. When runoff values are obtained from rainfall data, the water balance technique can be employed to estimate the potential groundwater recharge, but not the aquifer yield (Aqrawi, 2003). According to the water balance parameters and data availability for the Shaqlawa-Harrir basin, recharge can be estimated via the following equation:

$$Re = WS - RS \quad (1)$$

where WS is water surplus, and RS is surface runoff.

Evapotranspiration

Evaporation is the conversion of solid or liquid precipitation that reaches the Earth's surface into water vapor, and thereby its return to the atmosphere. Transpiration is the process of water loss from plants. Due to the fact that these two processes are difficult to separate, the term evapotranspiration is generally used to describe the two combined processes. PET can be calculated using temperature-based methods for the estimation of evapotranspiration, depending on the available climatic data for the studied area:

Thornthwaite Method

Thornthwaite and Wilm assumed that the amount of water lost through evapotranspiration from a soil surface covered with vegetation is governed by climatic factors (Thornthwaite & Wilm, 1944) . According to this method, the potential evapotranspiration for a given month is based on the mean monthly air temperature of that month and on the annual air temperature (Serrano 1997) as follows:

$$PET = La\ 1.6\ (10t/j)^a \text{ (mm/month)} \qquad (2)$$

$$a = (675*10^{-9})J^3-(771*10^{-7})J^2+(179*10^{-4})J+0.492$$

where PET is potential evapotranspiration in mm, La is a monthly correction constant function of latitude, j is the monthly temperature parameter, J is the annual heat index (°C), and t is the mean monthly temperature (°C).

Blaney-Criddle Method

The Blaney-Criddle method is one of the most widely-used equations for the determination of evapotranspiration in semi-arid areas:

$$PET = KP(0.46t + 8.13) \qquad (3)$$

where K is a correction factor equal to $(0.0311t + 0.24)$, P is the percentage of sunshine hours in each month to sunshine hours in one year, and t is the mean monthly temperature (°C).

Kharrufa Method

Kharrufa derived a simple equation with which to calculate PET values depending on the relation between temperature and sunshine duration (Kharrufa, 1985) :

$$PET = 0.34\ \rho Ta^{1.3} \qquad (4)$$

where Ta is the mean monthly temperature in °C, and ρ is the percentage of total sunshine hours in each month to total sunshine hours in the year.

Romanenko method

Romanenko derived the following evaporation equation based on the relationship between mean temperature and relative humidity (Romanenko, 1961) :

$$ET = 0.0018(25 + Ta)^2(100 - Rh) \qquad (5)$$

where Ta is the daily mean air temperature (°C), and Rh is relative humidity (%).

Water Surplus and Water Deficit

An area with a water surplus means that the rainfall volume is greater than that of potential evapotranspiration during a given period, and vice versa in the case of a water deficit, which were determined as follow:

$$WS = P - PE\ if\ P > PE \qquad (6)$$

$$WD = PE - P\ if\ P < PE \qquad (7)$$

where WS is water surplus, WD is water deficit, P is rainfall, and PE is potential evapotranspiration.

Whereas during a period of water surplus actual evapotranspiration (AET) approaches its potential value, during a period of water deficit AET is equal to rainfall (Hassan, 1998) .

Water surplus represents the summation of surface runoff (*Rs*), groundwater recharge (*Re*), and soil moisture (*Ri*). The water table in the Shaqlawa-Harrir basin is sufficiently deep that no evaporation from groundwater takes place. Thus, soil moisture is consumed either by evaporation from the soil or by plants. The general equation for water balance can be expressed as:

$$P = Rs + I + AET \tag{8}$$

$$Rs + I = WS$$

$$WS = P - AET$$

where *AET* is actual evapotranspiration, *Rs* is surface runoff, and *I* is infiltration

Runoff

Khosla (1949) analyzed rainfall, surface runoff, and temperature for different basins in the USA and India which have similar climatic conditions with the Shaqlawa-Harrir basin. In Kurdistan region the runoff was estimated by many researchers like Shwani which is estimate runoff of Southern Erbil Basin -Bashtapa sub-basin, Kurdistan region, Iraq (Shwani, 2008) and Hamed used it in Shaqlawa basin in Kurdistan Region (Hamed, 2013) . Relationship between rainfall and surface runoff was calculated, with the relationship derived for monthly surface runoff as follows:

$$Rm = Pm - Lm \tag{9}$$

$$Lm = 0.48\, Tm \; with \; Tm > 4.5\,^{0}C$$

$$If \; Lm > Pm \; then \; Rm = 0$$

where *Rm* is monthly surface runoff (cm) with $Rm \geq 0$, Pm is monthly rainfall (mm), *Lm* is monthly losses (mm), and *Tm* is monthly temperature (°C).

The Khosla formula is indirectly based on the water-balance concept and the mean monthly temperature is used to reflect the losses due to evapotranspiration.

Water table fluctuation method (WTF)

Water table fluctuation is affected by many factors, including rainfall intensity, rainfall quantity, soil and rock infiltration capability, groundwater depth above sea level, topography, evapotranspiration, and water well discharge (Wilson, 1987) . The WTF method requires both water table fluctuation and specific yield data. In the present study the groundwater level was measured weekly during the period from July, 2011 to July, 2012 at six observation wells across the Shaqlawa-Harrir basin (Figure 5).

These observation wells penetrate karst and fissure-karst aquifers. Recharge estimation was carried out according to the following equation :

$$R(t_j) = Sy * \Delta h(t_j) \tag{10}$$

where $R(t_j)$ is recharge occurring between times t_o and t_j (cm), *Sy* is specific yield (dimensionless), and $\Delta h(t_j)$ is the peak water level rise attributed to the recharge period (cm).

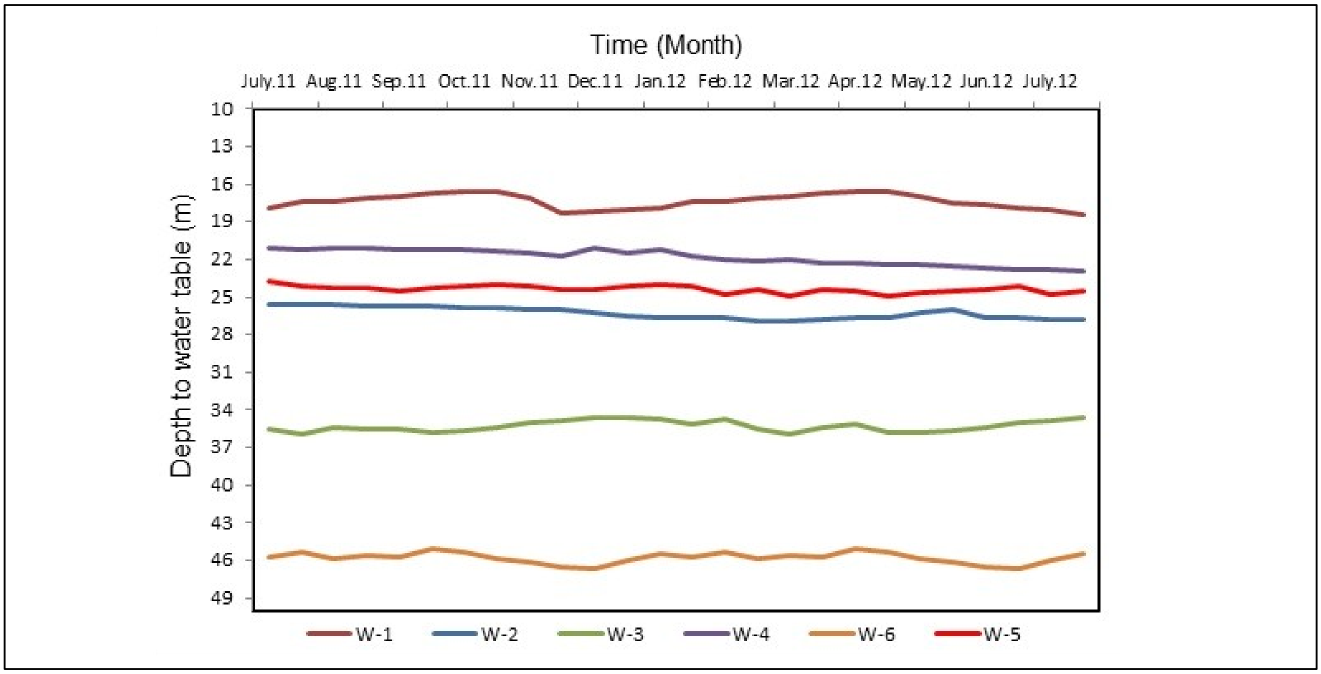

Figure 5. Water table fluctuation for different observation wells during on year July, 2011 – July, 2012

Δh was determined using the graphical extrapolation approach, with specific yield for the wells calculated according to Johnson (Johnson, 1955) via the Equation 11:

$$Sy = Saturated\ thickness / 100 \tag{11}$$

where saturated thickness is determined by the geological profile of the well, as represented by the latter's productive layer (saturated portion of the aquifer) (Table 3).

Table 3. Specific yield % in the study area according to Johnson (1955), and changing in water table.

Well No.	Δh (m)	Saturated thickness (m)	Sy %
W-1	1.86	89	0.089
W-2	1.32	98	0.098
W-3	1.31	100	0.1
W-4	1.81	93	0.093
W-5	1.1	95	0.095
W-6	1.58	105	0.11

Environmental tracer (CMB) method

Chloride concentrations in the unsaturated and saturated zones are typically employed for recharge estimation using a simple chloride mass balance (CMB) approach. The main sources of chloride are sea salt, rain and dry fallout, geological sources (halite and gypsum), and human activities (domestic and industrial sewage, fertilizers for agriculture, mining, etc). The CMB method is commonly used to estimate groundwater recharge in semi-arid areas where the recharge rate is generally low. Assuming an atmospheric source of chloride for groundwater in the Shaqlawa-Harrir basin and no surface runoff to be occurring, the following equation can be employed:

$$Re = P(Cl_P / Cl_{gw}) \quad (12)$$

where Re is recharge (mm/year), P is rainfall (mm/year), Cl_P is the weighted average chloride concentration in rainfall (mg/l), and Cl_{gw} is the average chloride concentration in groundwater (mg/l) (Marei et al., 2010; Ghanem, 2002).

A total of 40 groundwater samples were collected from different aquifers in the study area during wet season (Table 4), with rainfall samples taken at different times during rainfall periods. Chloride concentrations in these groundwater and rainfall samples were then measured via Ion Chromatography (Metrohm-Compact IC Pro) at TU-Bergakademie Freiberg (Figure 6).

Infiltration test

Horton's infiltration model (Horton, 1940) was used at 20 locations in the study area to calculate the infiltration rate and capacity via the double ring method. The Horton equation relates infiltration capacity to both initial infiltration rate (f_o) and the constant infiltration rate during long periods (f_c) (Figure 7). The statistical software package SPSS was employed to evaluate the relationship between time and infiltration rates, and to determine the Horton equation as follows:

$$f_t = f_c + (f_o - f_c) e^{-kt} \quad (13)$$

where K is a soil parameter describing the rate of infiltration decrease (standard).

The instrument used consists of two metal cylinders with an inner cylinder of 30 cm and an outer cylinder of 60 cm in diameter. Both cylinders were 50 cm in height.

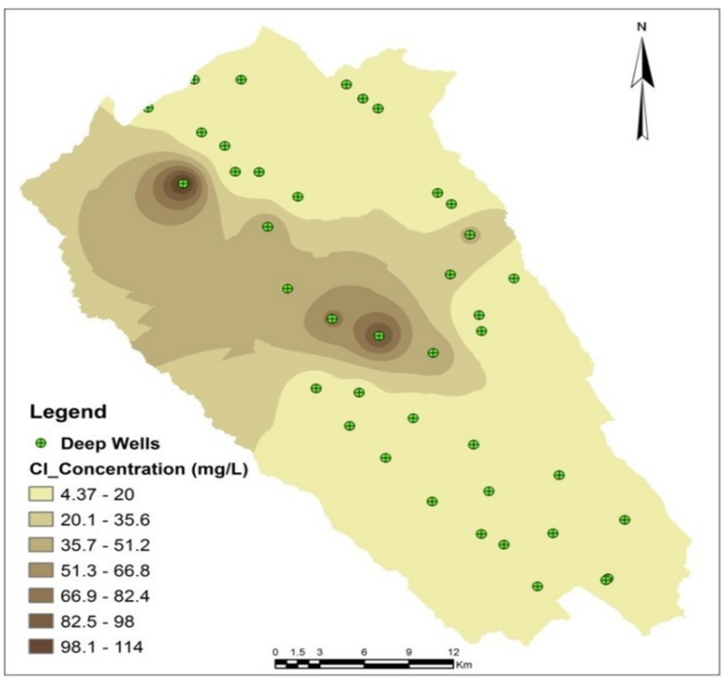

Figure 6. Distribution of chloride concentration (mg/L) in groundwater samples, Kriging method used for interpolation chloride concentration by using GIS program.

Table 4. Chloride concentration, coordination (UTM), and type of aquifer for the groundwater samples

SN	Name of well	Coordination (UTM)			Aquifer type	Chloride (mg/l)
		X	Y	Z		
1	Hujran Girdachal	434565	4029794	855	Fissured-Karstic	10.1
2	Tawska	436826	4026925	982	Fissured-Karstic	5.0
3	Qalasinji Saru	439260	4024480	1190	Fissured-Karstic	5.5
4	Khoran	442401	4021134	1190	Fissured-Karstic	5.1
5	Zyarat	445706	4018649	1139	Fissured-Karstic	4.9
6	Birokan	449501	4014632	1041	Fissured-Karstic	4. 9
7	Swlawki Saru	447231	4017831	1088	Fissured-Karstic	4.8
8	Garota	450540	4018701	1011	Fissured-Karstic	4.7
9	Hiran Well	454249	4015254	962	Fissured-Karstic	4.7
10	Punjina	454109	4015105	978	Fissured-Karstic	4.3
11	Aqubani Saru	446219	4021918	1044	Fissured-Karstic	6.0
12	Jneran	445194	4025489	959	Karst	13.9
13	Sarmaydan	437470	4029479	1015	Fissured-Karstic	13.6
14	Shaqlawa - 24	441109	4027518	987	Fissured-Karstic	4.8
15	Mirawa	442463	4032525	871	Porous	50.2
16	Mama Jalka	445724	4034192	805	Karst	6.4
17	Shakrok	445563	4035420	777	Fissured-Karstic	5.9
18	Sisawa	447906	4038217	861	Fissured-Karstic	5.1
19	Bawyan	444936	4041578	762	Karst	40.3
20	Khiwatan	443686	4043931	774	Fissured-Karstic	5.2
21	Harrir - 10	442771	4044773	781	Fissured-Karstic	5.6
22	Gulak	438756	4051244	616	Fissured-Karstic	5.8
23	Amokan	436619	4053091	633	Fissured-Karstic	6.2
24	Barbian	429517	4053458	483	Porous	5. 7
25	Qandil	426356	4053458	382	Karst	9.1
26	Qura Bag	423239	4051304	379	Fissured-Karstic	17.0
27	Harash	426842	4049420	379	Porous	5.1
28	Basirmay Kon	443621	4038528	741	Karst	20.5
29	Afryan	437716	4052001	606	Fissured-Karstic	5.6
30	Babachisk	425603	4045496	648	Porous	114.1
31	Kuba	429116	4046402	510	Karst	5.9
32	Kani Khazal Well	428404	4048388	446	Porous	6.4
33	Kebur	430723	4046385	522	Porous	5.6
34	Chamasur	433337	4044484	522	Karst	5.7
35	Azaran	431312	4042191	653	Karst	45.2
36	Sarkand Khaylani	432638	4037451	727	Karst	35.1
37	Mawaran - 1	435647	4035139	754	Karst	69.7
38	Mawaran New	438818	4033822	876	Karst	98.4
39	Friz	455383	4019726	1005	Fissured-Karstic	4.7
40	Aspendara well	450956	4023153	973	Fissured-Karstic	13.1

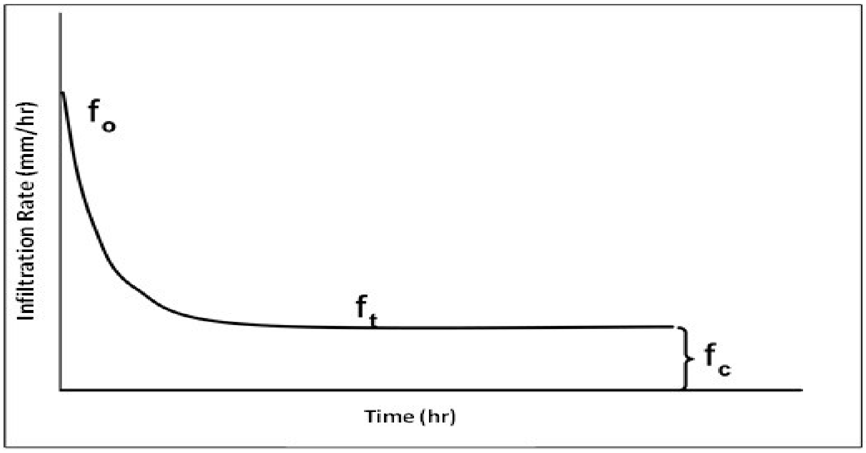

Figure 7. Infiltration rate and time relationship

Permeability

The Bindeman method (Bindeman, 1951) was used to determine permeability based on the recorded infiltration test data obtained as above. This procedure is appropriate for steady–state flow conditions and does not require full water level stabilization during percolation (non-constant head).

The infiltration test data obtained via the double ring method was used to estimate coefficient of permeability values according to the following formula:

$$C = \frac{\beta * V}{F * t} \tag{14}$$

where C is the coefficient of permeability (m/s), β is a coefficient determined from a diagram (β= f(t/t_1)), t/t_1 is the ratio of total test time to the time corresponding to half the water used in the test (Figure 8), V is the total water volume used for the test (cum), F is the area of the internal cylinder ($\pi * r^2/4$), and t is the total time required to complete the test (hr).

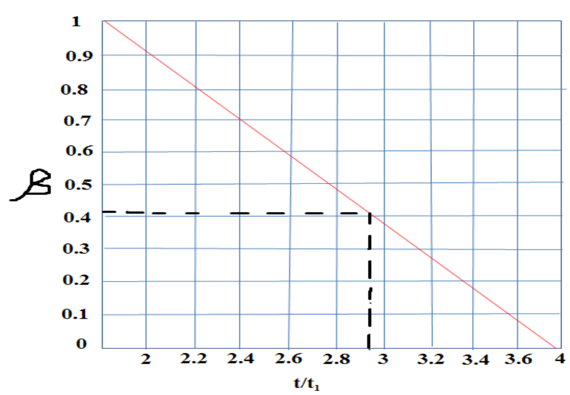

Figure 8. Coefficient determination (β) by Bindeman

Soil moisture

The monthly gridded soil moisture data set (available since 1948) were obtained from the National Oceanic and Atmospheric Administration (NOAA) (Noaa, 2009) and the Climate Prediction Center (CPC) (Table 5 & Figure 9).

Table 5. Monthly Soil Moisture for the period 1992-2012 for Shaqlawa-Harrir Basin (in mm)

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
1992	124.5	144.1	153.0	181.2	205.4	195.3	144.6	108.1	84.9	69.7	87.2	116.9
1993	128.3	144.1	176.7	224.9	264.9	244.0	187.9	141.9	109.6	111.5	161.4	209.6
1994	228.7	245.3	249.1	249.6	242.0	213.8	163.9	122.9	101.9	103.3	139.9	170.8
1995	184.8	201.9	205.7	228.2	230.6	194.3	161.7	122.8	96.4	85.8	90.7	92.5
1996	104.7	126.9	144.3	169.3	175.6	140.7	106.0	78.6	64.8	55.8	52.9	69.0
1997	88.0	100.4	127.0	145.1	136.2	114.5	107.6	89.6	69.5	64.3	74.2	85.4
1998	107.0	123.2	128.4	150.8	161.3	135.5	103.5	76.5	58.1	46.9	44.3	62.2
1999	78.6	86.3	87.4	85.8	73.2	55.4	40.9	30.2	23.1	19.5	20.4	22.1
2000	35.1	46.0	57.7	72.4	66.9	52.4	40.1	30.0	23.5	29.5	53.3	80.8
2001	94.7	100.5	107.7	106.1	104.0	88.5	68.4	51.3	39.3	37.1	48.9	73.5
2002	116.1	142.5	163.7	200.6	211.7	171.9	128.8	94.7	70.8	58.8	58.4	68.5
2003	78.4	89.4	117.7	150.9	148.9	125.6	93.4	68.0	51.2	50.3	69.3	98.8
2004	134.7	156.7	157.7	173.0	188.7	158.0	126.5	102.8	81.7	69.7	93.8	121.6
2005	137.5	160.4	185.2	196.0	180.8	140.1	102.7	76.6	60.5	56.5	62.5	74.8
2006	93.3	132.3	162.7	178.7	182.7	144.6	105.6	77.8	59.0	89.2	138.5	156.1
2007	159.1	176.4	200.5	245.0	252.8	200.7	155.2	119.2	92.7	82.0	84.2	93.3
2008	107.7	135.8	159.4	154.3	133.6	105.7	79.2	59.2	53.7	88.1	119.6	113.5
2009	111.1	116.0	144.5	181.2	173.7	145.3	112.2	83.5	67.0	62.2	80.4	106.1
2010	113.1	118.6	140.7	164.3	174.9	155.8	117.5	87.2	66.1	55.0	48.0	59.9
2011	95.1	126.6	140.7	171.2	177.4	138.8	102.9	76.5	58.9	57.1	62.9	72.9
2012	94.8	114.2	133.8	139.3	119.7	96.2	72.3	53.2	40.7	40.2	75.5	124.2

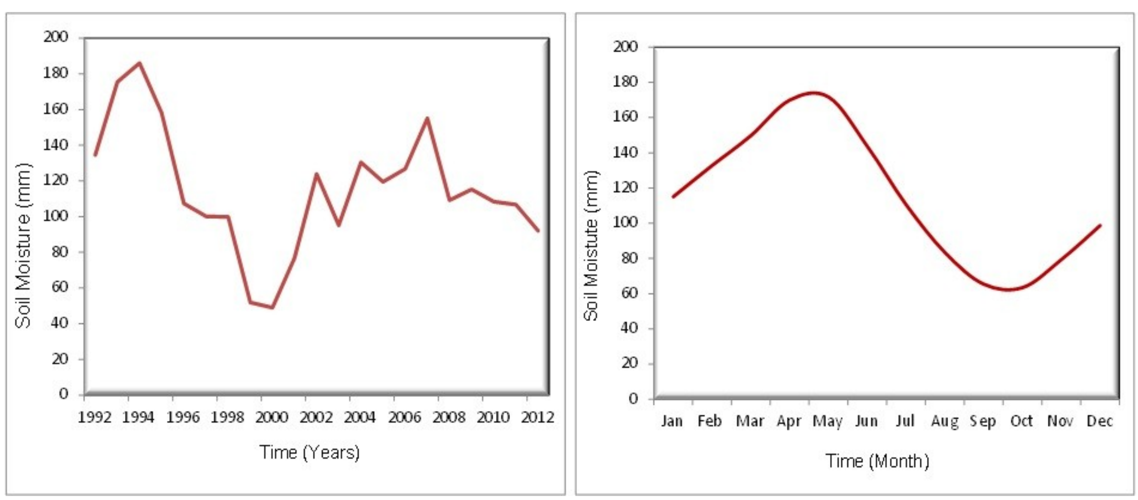

Figure 9. Mean annual and mean monthly soil moisture during period 1992-2012 for Shaqlawa-Harrir basin

Soil Moisture (mm)

RESULTS AND DISCUSSIONS

Evapotranspiration, water surplus and water deficit, and surface runoff

PET data were obtained as long-term monthly means, with values of 120.1, 173.8, 193.8, and 218.6 mm produced by the Thornthwaite, Blany-Criddle, Kharrufa, and Romanenko methods, respectively (Table 6).

Table 6. Mean monthly of PET (mm) value calculated by different methods

Month	Thornthwaite	Blaney-Criddle	Kharrufa	Romanenko
January	17.0	28.3	25.8	51.6
February	20.6	33.7	34.0	60.5
March	47.4	62.2	72.7	104.1
April	89.3	98.7	113.6	150.4
May	158.1	194.8	224	260.8
June	221.1	331.9	377.4	373.3
July	273.5	409.0	444.6	435.8
August	253.9	377.8	411.1	436.6
September	173.4	281.0	312.8	337.2
October	119.1	158.3	181.4	228.8
November	45.2	71.5	84.7	111.4
December	23.1	39.1	43.4	72.9
Average	**120.1**	**173.9**	**193.8**	**218.6**

PET was greater than pan evaporation (137.4 mm) according to all methods with the exception of the Thornthwaite method (Figure 10). The difference between the methods is depending on the parameters used like the latitude correction in Thornthwaite method. The best method for Shaqlawa-Harrir basin is Kharrufa and Blaney-Criddle method, because many researchers used these methods in Kurdistan Region.

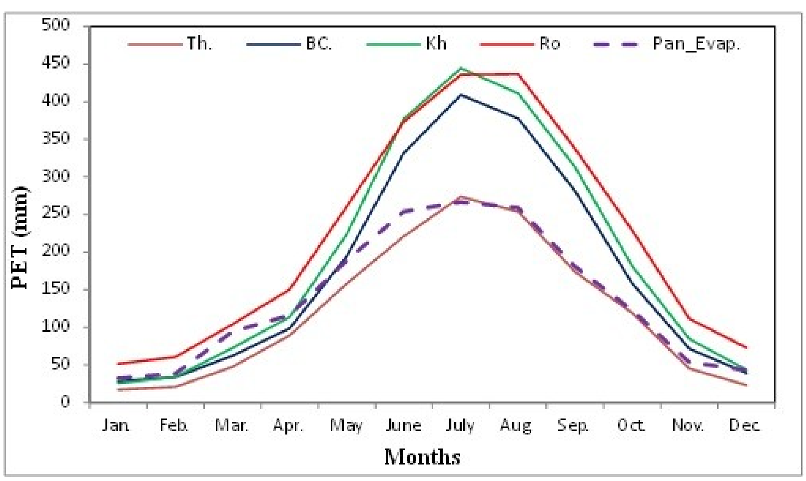

Figure 10. Mean monthly PET by different method and pan evaporation during the period 1992-2012

Water surplus values of 305.4, 240.3, 227.7, and 128 mm/year, and water deficit values of 1158, 1737, 1964, and 2162 mm/year were recorded according to the same four methods (Table 7).

Surface runoff in the study region is an average of 206.9 mm/year during December, January, February, and March according to the Khosella method (Table 8).

Table 7. Monthly precipitation, actual evapotranspiration, water surplus, and water deficit calculated for different methods (P-Precipitation, Th-Thornthwait, BC-Blany Criddle, Kh-Kharrufa, Ro-Romanenko, WS-water surplus, and WD-water deficit)

Month	P (mm)	AET (mm)				WS (mm)				WD (mm)			
		Th	BC	Kh	Ro	Th	BC	Kh	Ro	Th	BC	Kh	Ro
Jan.	1133	17	283	25.8	516	96.3	85	87.5	61.7				
Feb.	111.1	20.6	33.7	34	60.5	90.5	77.4	77.1	50.6				
Mar.	90.6	47.4	62.2	72.7	90.6	43.2	28.4	17.9					13.5
Apr.	64.2	64.2	64.2	64.2	64.2					25.1	34.5	49.4	86.2
May	24.8	28.4	24.8	24.8	24.8					133.3	170	199.2	236
Jun.	1.5	1.5	1.5	1.5	1.5					219.6	330.4	375.9	371.8
Jul.	0.8	0.8	0.8	0.8	0.8					272.7	408.2	443.8	435
Aug.	0.02	0.02	0.02	0.02	0.02					253.9	377.8	411.1	436.6
Sep.	3.7	3.7	3.7	3.7	3.7					169.7	277.3	309.1	333.5
Oct.	35.7	35.7	35.7	35.7	35.7					83.4	122.6	145.7	193.1
Nov.	55.1	45.2	55.1	55.1	55.1	9.9					16.4	29.6	56.3
Dec.	88.6	23.1	39.1	43.4	72.9	65.5	49.5	45.2	15.7				
Av.	49.1	24.0	29.1	30.1	38.5	61.1	60.1	56.9	42.7	165.4	217.1	245.5	240.2
Sum.	58942	287.6	349.1	361.7	461.4	305.4	240.3	227.7	128	1158	1737	1964	2162

Table 8. Surface runoff calculated according to Khosla method

Month	P (mm)	Monthly T_m (°C)	L_m (mm)	Rs (mm)
Jan.	113.3	8.1	38.9	74.4
Feb.	111.1	9.1	43.7	67.4
Mar.	90.6	13.5	64.7	25.9
Apr.	64.2	19.0	91.0	
May	24.8	25.4	121.8	
Jun.	1.5	31.1	149.4	
Jul.	0.8	35.5	170.4	
Aug.	0.02	35.6	171.1	
Sep.	3.7	30.8	147.7	
Oct.	35.7	24.7	118.4	
Nov.	55.1	15.3	73.3	
Dec.	88.6	10.3	49.3	39.23
Sum	589.4	258.4	1239.7	206.9

Infiltration capacity and permeability

The results of statistical analysis revealed a significant relationship between time and infiltration capacity at the 98-99% confidence level for all the studied infiltration points. Infiltration capacity (F_c) ranges from 14.3 to 146 mm/hr, initial infiltration capacity (F_o) between 151.8-1930 mm/hr, and K values from 4.1 to 39.6 (Table 9). The infiltration rate in the Shaqlawa-Harrir basin was found to range between slow-moderate to moderate-rapid according to the Nikolov classification (Nikolov, 1983) , which classified the infiltration capacity into six types according to constant infiltration capacity (f_c) (Table 10).

Table 9. Infiltration capacity, infiltration types, coefficient of permeability, and geological units for twenty locations for infiltration test, coordination (UTM).

Locations	Coordination (UTM)			F_c (mm/hr)	F_o (mm/hr)	K	Infiltration type	Permeability
	X	Y	Z					
1	419371	4046768	382	19.4	198	4.3	slow-moderate	$1.2*10^{-5}$
2	423743	4043442	510	18.8	203	4.2	slow-moderate	$2.8*10^{-5}$
3	426842	4049420	379	19.6	267	5.1	slow-moderate	$9.8*10^{-6}$
4	430285	4036013	770	16.2	215.7	4.1	slow-moderate	$3.3*10^{-6}$
5	437713	4040781	663	14.3	151.8	3.5	slow-moderate	$8.7*10^{-6}$
6	438756	4051244	616	39.2	281.4	8.6	moderate	$3.3*10^{-5}$
7	438274	4032794	756	42.8	376.9	8.8	moderate	$6.0*10^{-5}$
8	443320	4032893	1016	146	1930	32.5	moderate-rapid	$1.4*10^{-4}$
9	443686	4043931	774	44.1	725.1	13.0	moderate	$1.6*10^{-5}$
10	433125	4032422	888	37.3	393.8	8.4	moderate	$1.8*10^{-5}$
11	442456	4026297	1052	61.9	683.1	14.6	moderate-rapid	$2.9*10^{-5}$
12	449163	4024480	950	51.7	480.5	10.9	moderate	$2.7*10^{-5}$
13	448801	4027229	962	47.7	456	10.3	moderate	$2.4*10^{-5}$
14	451691	4023307	1027	43.2	464.8	10	moderate	$1.9*10^{-5}$
15	453963	4021014	1009	80	1126.6	21.2	moderate-rapid	$3.2*10^{-5}$
16	449642	4017742	1302	128.5	1395	39.6	moderate-rapid	$5.0*10^{-5}$
17	450836	4020690	976	19.2	203.7	4.4	slow-moderate	$2.0*10^{-5}$
18	438998	4030296	1002	55.7	1197.5	14.9	moderate	$9.4*10^{-6}$
19	453451	4016086	1111	76.6	1152	22.1	moderate-rapid	$3.6*10^{-5}$
20	430723	4046385	522	18.9	146.3	4.3	slow-moderate	$1.8*10^{-6}$

Table 10. Infiltration rate classification according to Nikolov, 1983

Infiltration rate (F_c) mm/hr	**Type**
> 160	Rapid
60-160	Moderate - rapid
20-60	Moderate
5-20	Slow - Moderate
1.2-5	Slow
< 1.2	Very Slow

The relation between the time and infiltration rates was plotted by Statistical Packages for Social Sciences (SPSS) to infiltration parameters (Figures 11A, 11B).

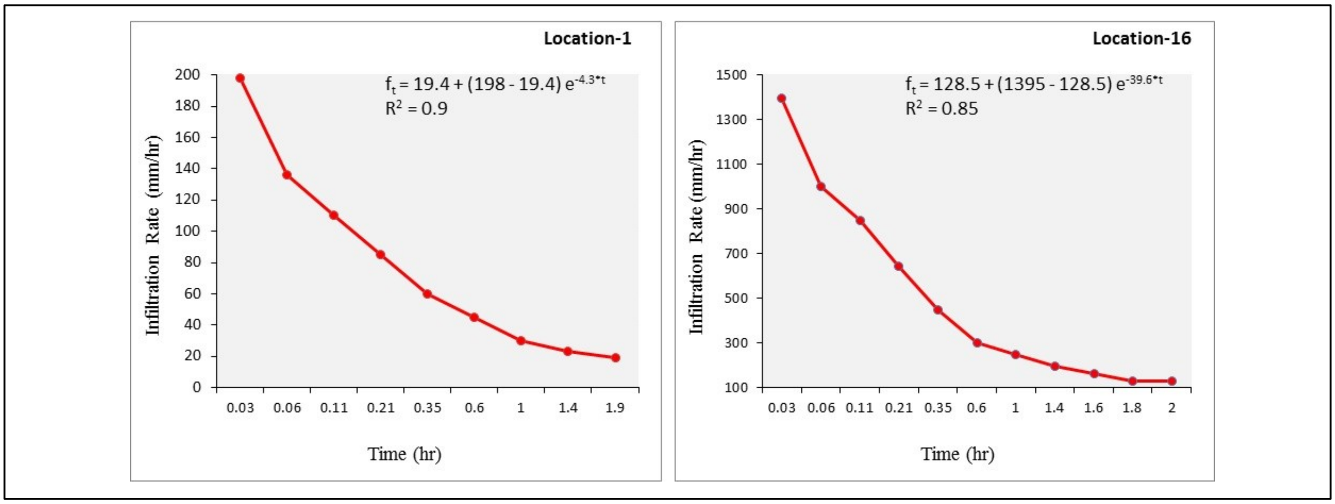

Figure 11A. Infiltration Rates as a Function of Time for two locations, Fitted to Horton's Equation

Areas characterized by slow-moderate infiltration rates are located predominantly in the north and northwest, with a small region also found in the southeast of the basin; areas with moderate infiltration rates are found in the lower part of the basin; and finally those with moderate-rapid rates appear as two small areas in the middle and south of the basin (Figure 12A). The variation in the infiltration capacity comes from the type of soil, degree of soil compaction, vegetation dense, texture, and joints existence (Potter & Colman, 2003) .

Calculated coefficient of permeability values range between $1.8*10^{-6}$ and $1.4*10^{-4}$ m/s. Permeability is lower in the northern part of the basin and near the Greater Zab River, as well as a small area in the southeast (Figure 12B).

Groundwater recharge

Different groundwater recharge results were obtained depending on the calculation method employed. The average groundwater recharge based on the water balance is 50.9 mm/year by taking average water surplus according to Thornthwait, Blany-Criddle, and Kharrufa (305.4, 240.3, 227.7 mm/year), with surface runoff which is equal to 206.9 mm/year and using the equation (1); Re = 257.8 – 206.9 = 50.9 mm/year, which represents about 8.6% of annual rainfall. No difference between recharge values for the same PET method and different AET can be observed because surplus happens during the wet season when potential and actual evapotranspiration are equal.

According to the WTF method, the average specific yield (Sy) is equal to 0.097, and Δh was estimated as 1.49 m, which is the average change in WT elevation during one year (July 2011 – July 2012) for six observation wells in the area, by using the equation (10); $R(t_j)$ = 0.097 * 149 cm = 144.5 mm/year (about 24.5% of annual rainfall).

Chloride concentrations in groundwater samples range between 3.02 and 256.4 mg/l, with an average of 18.2 mg/l, and the average concentration in rainfall is 2.7 mg/l; accordingly, groundwater recharge by CMB method with using the equation (12); Re = 589.4 (2.7 / 18.2) = 87.4 mm/year (about 14.8% of annual rainfall). Recharge determined via the chloride method might be affected by human activities such as fertilizer application for agricultural and irrigation, as well as chloride from rock sources (gypsum, halite, and anhydrite).

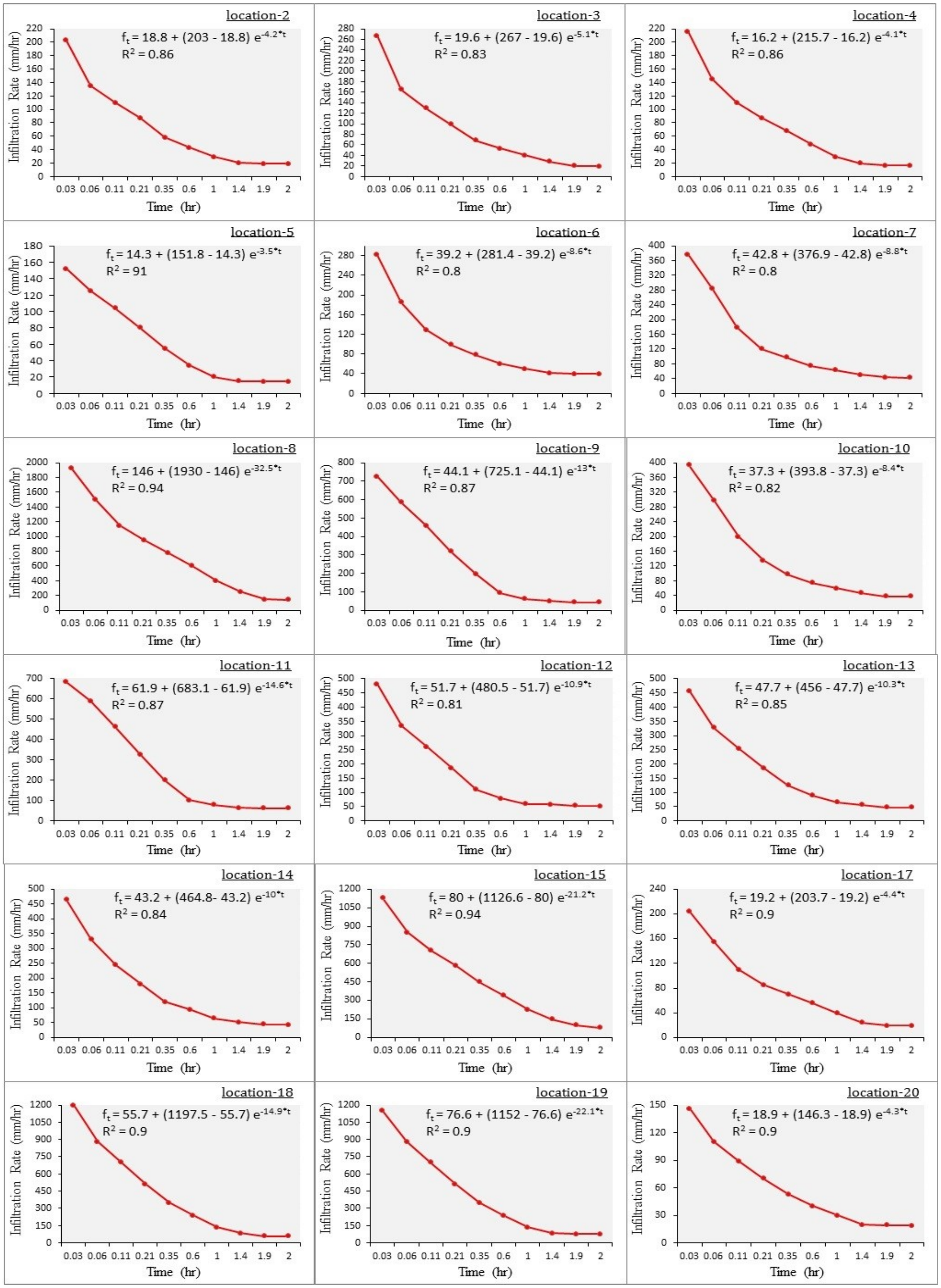

Figure 11B. Infiltration Rates as a function of time for eighteen locations, Fitted to Horton's Equation

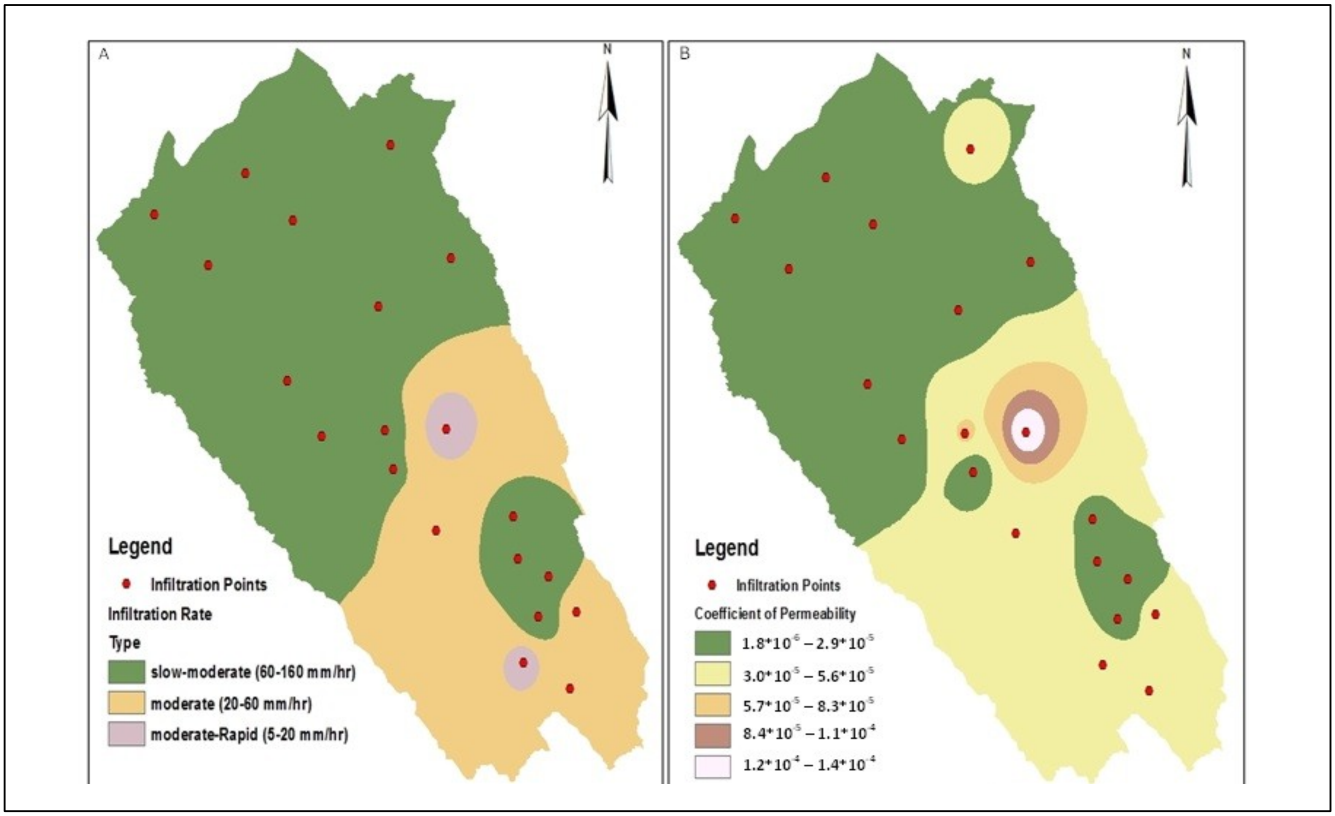

Figure 12. (**A**) Distribution of Infiltration rate of Shaqlawa-Harrir basin according to Nikolov, 1983, (**B**) Distribution coefficient of permeability according to Bindeman, 1951. Kriging method used for interpolation chloride concentration by using GIS program.

Groundwater budget

Based on an average groundwater recharge value of 94.3 mm/year and the area of the Shaqlawa-Harrir basin (1150 km^2), the basin water recharge is $10.8*10^7$ m^3/year according to the annual water budget formula which is equal to: Water budget = Groundwater recharge * Area.

CONCLUSIONS

The current study has shown that the estimation of recharge using the water balance method is significantly harder to apply than simply WTF and chloride mass balance methods, because of its numerous data requirements. The WTF method depends on groundwater table fluctuations, which can vary between different wells and aquifers, and is also limited in terms of the accuracy with which specific yield can be determined. The chloride method relies on concentrations in groundwater and rainfall. In this study the period of rainwater sampling was very short and thus may be biased; furthermore, some chloride may be as well stem from human activities and rock leaching.

Infiltration rates were slow-moderate in the low elevation area located towards the Greater Zab River with a low coefficient of permeability, and moderate to moderate-rapid in the mountainous area with a higher coefficient of permeability. A water surplus and surface runoff occur only during the wet season.

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