Appl Water Sci (2017) 7:2255–2265
DOI 10.1007/s13201-016-0399-y

ORIGINAL ARTICLE

Groundwater recharge estimation in semi-arid zone: a study case from the region of Djelfa (Algeria)

S. E. Ali Rahmani[1] · Brahim Chibane[1] · Abdelkader Boucefiène[2]

Received: 27 July 2015 / Accepted: 21 February 2016 / Published online: 8 March 2016

Abstract Deficiency of surface water resources in semi-arid area makes the groundwater the most preferred resource to assure population increased needs. In this research we are going to quantify the rate of groundwater recharge using new hybrid model tack in interest the annual rainfall and the average annual temperature and the geological characteristics of the area. This hybrid model was tested and calibrated using a chemical tracer method called Chloride mass balance method (CMB). This hybrid model is a combination between general hydrogeological model and a hydrological model. We have tested this model in an aquifer complex in the region of Djelfa (Algeria). Performance of this model was verified by five criteria [Nash, mean absolute error (MAE), Root mean square error (RMSE), the coefficient of determination and the arithmetic mean error (AME)]. These new approximations facilitate the groundwater management in semi-arid areas; this model is a perfection and amelioration of the model developed by Chibane et al. This model gives a very interesting result, with low uncertainty. A new recharge class diagram was established by our model to get rapidly and quickly the groundwater recharge value for any area in semi-arid region, using temperature and rainfall.

Keywords Groundwater recharge · Hybrid model · Semi-arid area · Chloride mass balance · Djelfa

✉ S. E. Ali Rahmani
alirahmani101990@gmail.com

1 Geo-environment Laboratory, FSGAT, USTHB, Bab Ezzouar, Algeria

2 Earth sciences department, University of Djilali Bounaama, Khemis Miliana, Algeria

Introduction

In semi-arid area, the groundwater resources are the most requested to meet the water to supply population, industrial and agricultural activities. In the world 50 % of drinking water, 40 % of water intended for industrial activities, and 20 % of water for agriculture are groundwater (Foster and Chilton 2003). The daily water needs of the population increases with population growth. Therefore the concepts of sustainable management of water resources become indispensable. For that one of the major problems encountered in the management of groundwater resources is the evaluation of groundwater recharge to quantify groundwater reserves. Groundwater recharge is a difficult parameter; its estimation contains several constraints linked to the topography, the soil, the density of vegetation cover, geological heterogeneity and reliability of hydro-climatic data (Sibanda et al. 2009). Several approaches are followed to quantify this parameter which represents the core of groundwater management.

Reviews of groundwater recharge estimation technique Lot of methods were used in the entire world to quantify the rate of the groundwater recharge, as reported by Kinzelbach et al. (2002) and Osterkamp et al. (1995).

The most used method is the Hydrological water budget (HWB), Chemical tracers [Chloride mass balance (CMB); and isotopic tritium profile method] (Scanlon et al. 2006), and the soil water budget; and the water fluctuation level (WFL) method, Aquifer recharge rate relate directly to the soil texture, rock properties and to the velocity of infiltration and to the intensity of precipitation (Bonta and Müller 1999). Hydrological modeling shows a very rapid progress in the last decade due to the evolution of informatics systems (hard and software).

Limit of estimation of groundwater recharge The previous methods have a limit applications (water level fluctuation methods, Darcyian methods, soil budgets methods,

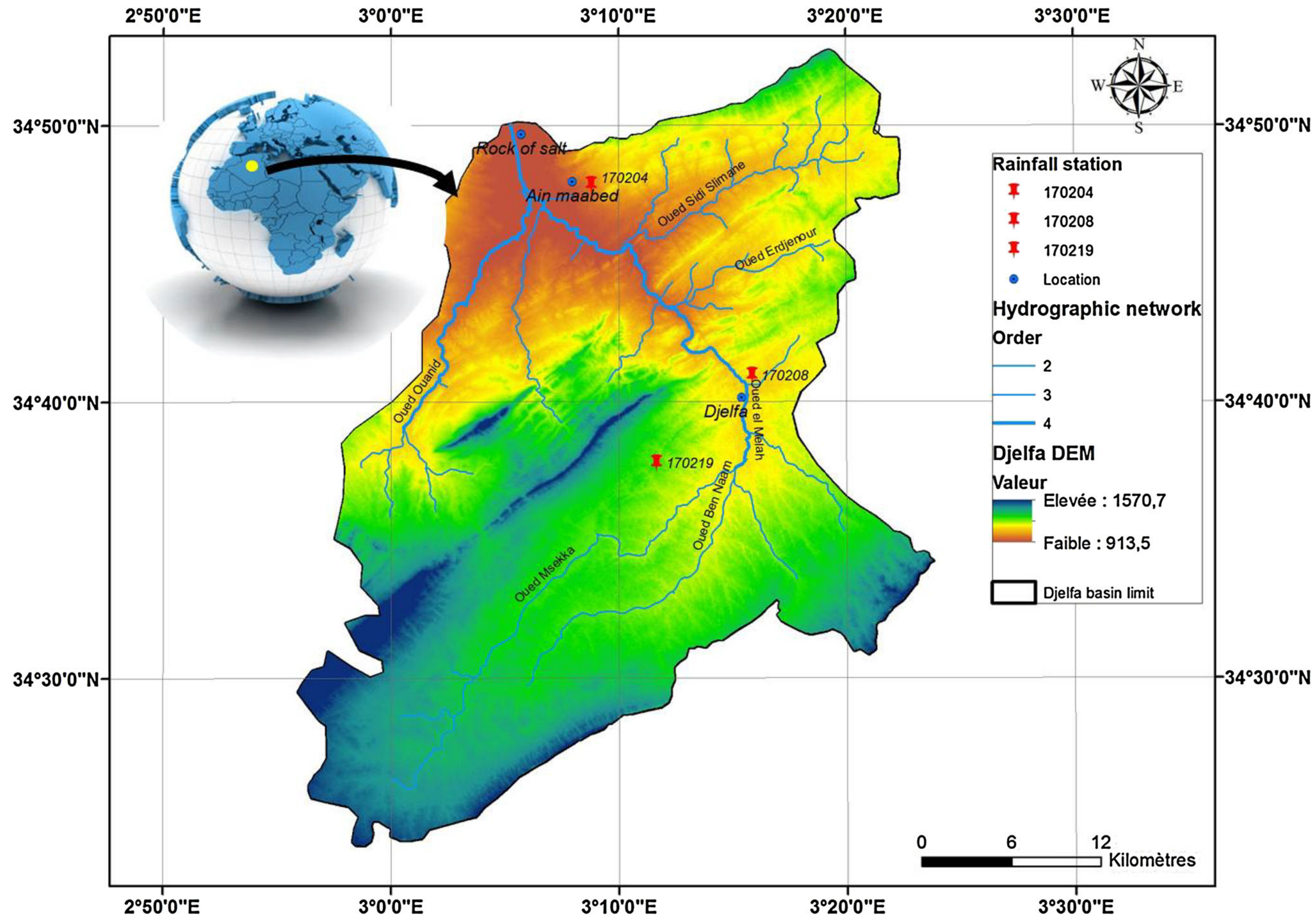

Fig. 1 Study area (Ali Rahmani et al. 2015)

and hydrological modeling) because of many problems in the fields of study: the geological heterogeneous of the study area; high depth of soil (up to 30 m), the fracturation density in some cretaceous deposits, and lack of data (water level control wells, spring source discharge, aquifers properties; and soils depth).

The hydrological balance has a high limit of groundwater estimation; this is principally due to the high uncertainty in the estimation of Real evapotranspiration (Turc, Penman, and Thornthwaite) methods. For this problem the model of Chibane et al. was derived to solve these problems. To minimize the high uncertainty in estimation of recharge using the Hydrological water budget (some hydrological balance in semi-arid give a negative balance) which makes estimation of recharge very complicated.

Materials and methods

In this paper we have combined three methods to evaluate the GWR: using the Chloride mass balance (CMB), a hydrogeological model based on soil and rock characteristic and a new Hybrid model. The combination between these methods lets us to adjust a general model to evaluate with high usefulness and with small error the rate of GWR.

Area of study

The area of study was located in the South of Algeria 300 km from Algiers (Capital of Algeria), situated between 34°40′30″North and 3°15′30″East (Fig. 1). It is placed between two groups of mountains; in the north we find the Tellian Atlas, in the south the Saharian Atlas (Chibane and Ali-Rahmani 2015).

Geological data

Our area is formed by different geological deposits, recently we found Mio-plioquaternary deposits, it is formed by Sandy loams and limestone crusts, also by clays and red marl and lenses chalky conglomerate-sandstone. Secondly we find the Santonian deposit is formed alternately by Limestone and marl and frequently by gypsum lenses. Thirdly the Turoniana deposit presents a high

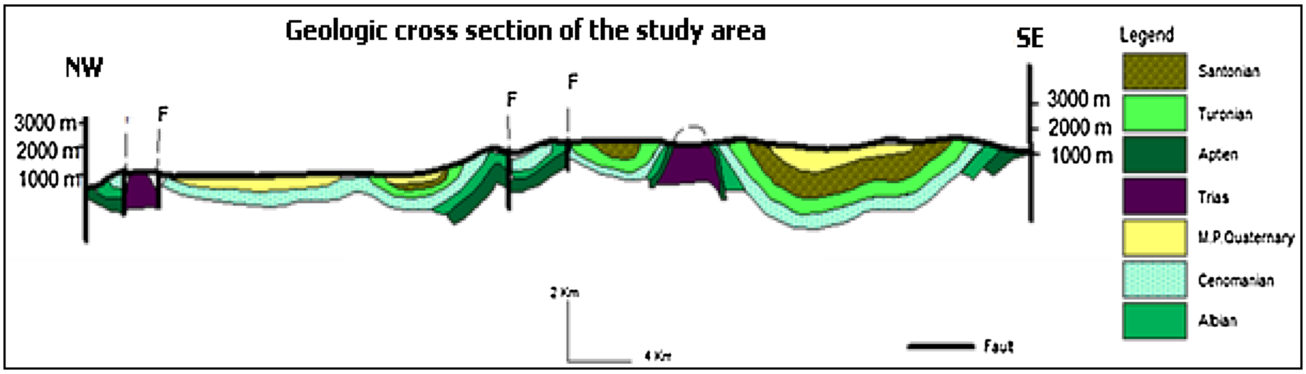

Fig. 2 Geologic cross section of study area (Cornet and Trayssac 1952, modified by Chibane and Ali-Rahmani 2015)

groundwater reservoir and it is formed by benches of Limestone to the top, marl and limestone in the middle part and gypsum at the base. Fourthly the Cenomanian deposits are composed of marl with few limestone and gypsum (Chibane and Ali-Rahmani 2015).

Fifthly we find the Albian deposits divided into two groups: the Upper Albian who has formed alternately by Limestone and marl and the Lower Albian formed by massive fine sandstone intercalated with gray clays. The two groups formed a high capacity reservoir. The next deposit is the Aptian composed alternately from Limestone and Marl. The Barremien was composed of Alternating sandstone and sandstone clay red with a cross-bedded common in sandstone and lot of joints and cracks. The Neo-comian deposits were specified by the presence of Clay sandstone rocksat in the base and dolomite limestone and calcareous sandstone. The Triassic is the last formation it was formed by Clay 'swine-colored sandstone and shale and marl colored with some inclusion conglomerates (Chibane 2010).

Figures 2 and 3 show a geologic cross section of the aquifer of study, and the geological map of the study area.

Hydro-climatic study

The region of Djelfa is characterized by a semi-aride climate with a cold winter and a warm summer.

The precipitation is moderate in the time and space scale, it varies at average between 300 and 360 mm/year; the intensity is different from the West to the East and from the North to the south (Chibane 2010) the variation of average monthly temperature and rainfall are given in Fig. 4.

Chloride mass balance

In many research papers the chloride mass balance method was applicated to evaluate the groundwater recharge in semi-arid area this methods assume that chloride does not have any chemical interaction with soils (Nimmo et al. 2005). This technique has been used in this work to give a reference value of GWR to calibrate the new hybrid model. The chloride is a conservative tracer used in hydrogeological studies; this technique is based on the ratio between the chloride concentration in rainfall and the chloride concentration in groundwater samples.

No previous work in the field of study has used the CMB method. 60 samples of rainfall and Groundwater were collected, prepared and analyzed in the laboratory for the hydrological year (2013/2014).

The GWR is estimated using the equation (Eq. 1):

$$\mathrm{GWR} = P \times \frac{[\mathrm{Cl}]_{\mathrm{p}}}{[\mathrm{Cl}]_{\mathrm{gw}}} \quad (1)$$

with: *GWR* recharge in mm, *P* average annual rainfall in mm, $[\mathrm{Cl}]_{\mathrm{p}}$ concentration of chloride in precipitation in mg/l, $[\mathrm{Cl}]_{\mathrm{gw}}$ concentration of chloride in groundwater in mg/l.

The hydrogeological approach

The groundwater recharge value was estimated using a hydrogeological model which depends on soil and rock infiltration coefficient. In Table 1 we give the methodology of calcul of GWR using infiltration coefficient ϕ the result of variation of recharge using the hydrogeological model shown in Fig. 5.

The equation of this model was given by Eq. (2) as follows:

$$\mathrm{GWR} = \frac{\phi \times P}{100} \quad (2)$$

We have uniformized the geological coefficient ϕ to derive a linear relationship (Eq. 3):

$$\mathrm{GWR} = 0.034 \times P \quad (3)$$

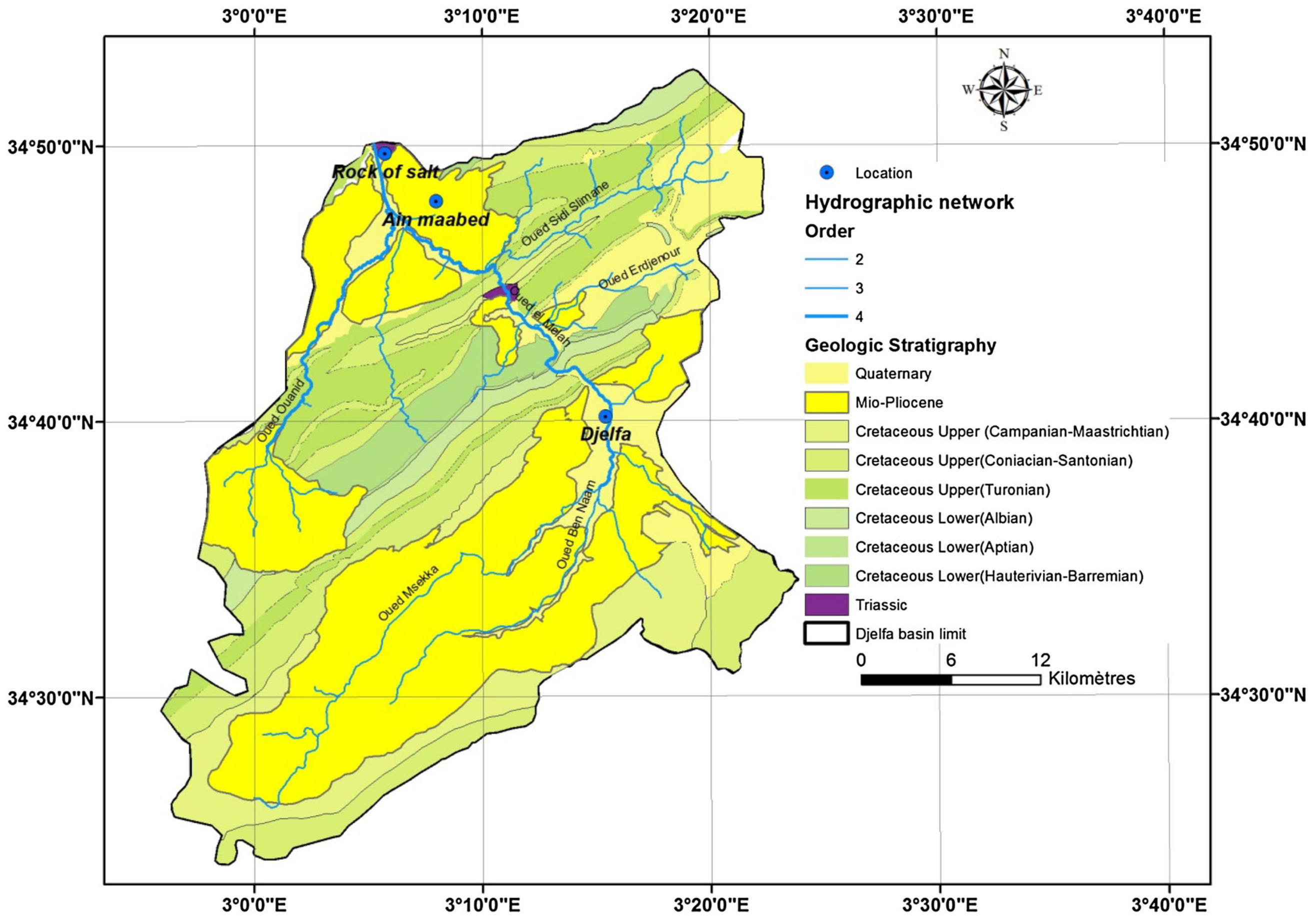

Fig. 3 Geologic Map of study area

Fig. 4 Monthly variation of average temperature and precipitation in the region of Djelfa

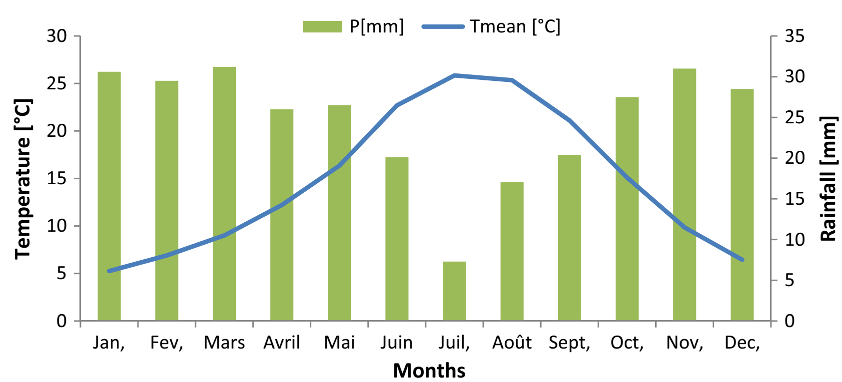

Table 1 Calcul methodology for a given type of Rock

iD	Rock	Infiltration coefficient (ϕ)	Rainfall P (mm)	GWR (mm)	Mean GWR (mm)
1	GRAVELS	6	320	$GWR = \frac{6.320}{100} = 19.2$	$GWR = \frac{19.2+6.4}{2} = 12.8$
2	Limestone	2	320	$GWR = \frac{2.320}{100} = 6.4$	

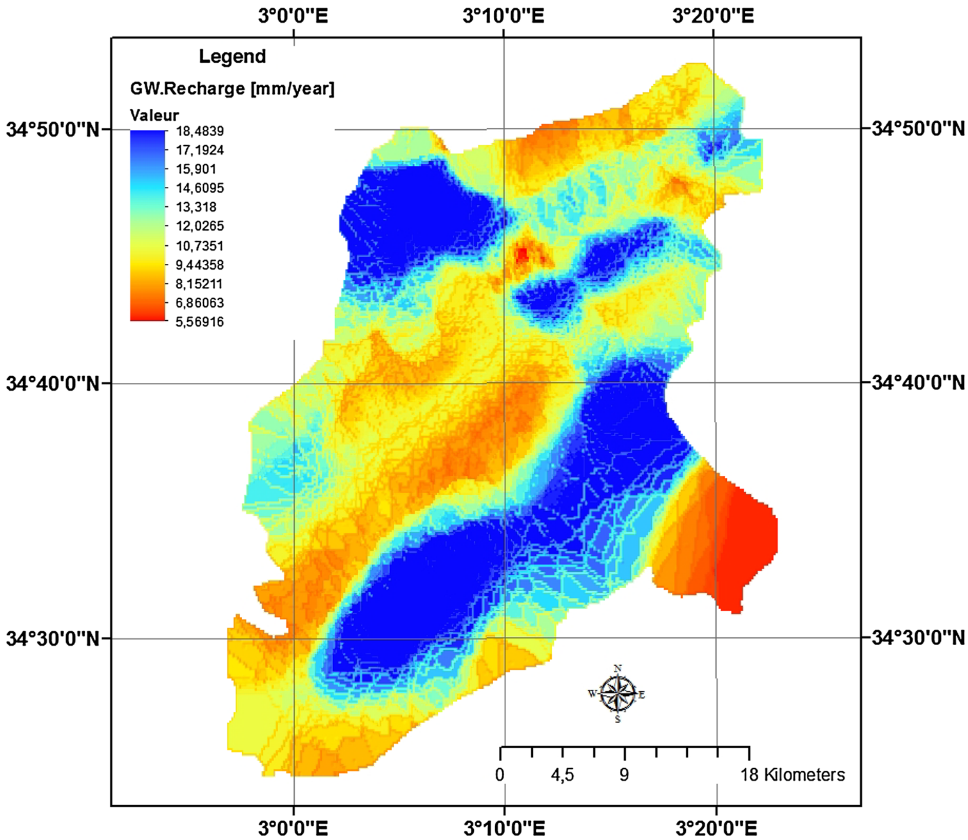

Fig. 5 Spatial ground water recharges variation in study region using hydrogeological model

where ϕ geological factor characterising the rock, and P annual rainfall given in mm.

The value of some infiltration coefficient ϕ is given in Table 2 as given by Banton and Et Bangoy (1997) and Castany (1982, modified).

The hybrid model

Combination between geological properties of the aquifers (rocks types) and the hydroclimatic data characterizes the semi-aride area and we derive a new mathematical formulae to evaluate the Groundwater recharge in these area.

Many empirical formulas used to explicit the hydrological water budget components underestimate the Recharge (GWR), especially in semi-arid areas.

This makes it difficult to look for other estimation methods, to give an approach value of recharge to sustainably manage the groundwater resources.

Combinations between the empirical formulas make us to formulate a new general model to estimate Groundwater recharge in semi-arid area.

Table 2 Coefficient of infiltration given in % for different type of Rocks (Banton and Et Bangoy 1997; Castany 1982; modified)

Type of rock	Coefficient of infiltration %	Infiltration
Gravels	6	High
Alluvium	6	
Sandstone	4	Medium
Sand	4	
Sandy loam	4	
Silt	4	
Clay loam	4	
Clayey sand	4	
Marl	4	
Sandy clays	4	
Limestone	2	Low
Crusting	2	
Dolomite	2	
Gypsum	1	Very low
Clays	1	
Silt	1	
Soil of Sebkhas	1	

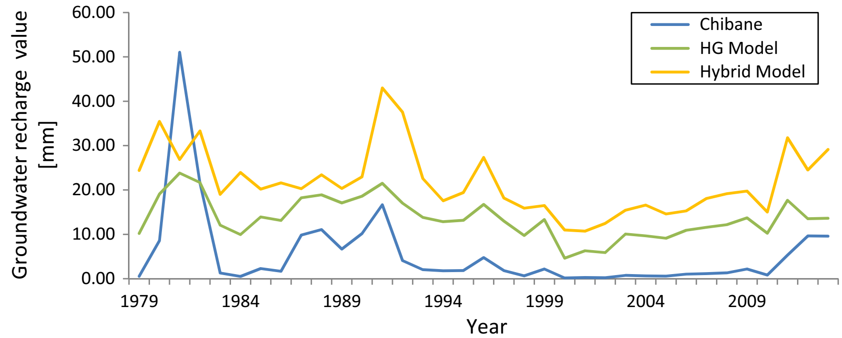

Fig. 6 Annual variation of ground water recharge estimated by the three models

Table 3 Results of chloride mass balance method for the hydrological year of 2013/2014

Well ID	Cl-well (mg/l)	*T* (°C)	pH	CE (µS/cm)	Cl-rain (mg/l)	Rainfall (mm)	Recharge (mm)
T	197.12	20.60	7.77	*622.00*	3.23	300.00	4.92
DF1	90.76	28.30	7.84	518.00	3.65	300.00	12.06
DF4 bis	76.58	24.60	7.96	529.00	3.55	300.00	13.91
DF4	73.03	24.70	8.15	565.00	3.58	300.00	14.71
DF5bis	69.49	26.60	7.94	713.00	3.43	300.00	14.81
OSF1	44.67	*16.60*	*8.14*	822.00	3.40	300.00	22.83
OSF2	41.13	19.90	8.07	769.00	3.45	300.00	25.17
OSF3	48.22	27.00	8.13	853.00	3.47	300.00	21.59
OSF4	44.67	37.50	8.22	744.00	3.55	300.00	23.84
OSF5	48.22	37.40	7.95	1860.00	3.36	300.00	20.91
OSF6	48.22	17.90	7.96	1906.00	3.37	300.00	20.97
OSF7	87.21	17.30	7.94	2030.00	3.44	300.00	11.83
OSF8	51.76	16.30	7.96	1365.00	3.41	300.00	19.76
OSF10	58.85	22.70	7.84	1165.00	3.36	300.00	17.13
OSF11	151.03	25.80	8.53	1214.00	3.48	300.00	6.91
OSF12	239.66	23.60	7.82	1057.00	3.39	300.00	4.24

Cl-well [mg/l]: chloride concentration in well in sample, Cl-rain [mg/l]: chloride concentration in rainfall sample

Table 4 Statistic summary of chloride mass balance methods

Statistics	Cl-well (mg/l)	*T* (°C)	pH	CE (µS/cm)	Cl-rain (mg/l)	Rainfall (mm)	Recharge (mm)
Mean	85.66	24.18	8.01	1045.75	3.45	300.00	15.97
Max	239.66	37.50	8.53	2030.00	3.65	300.00	25.17
Min	41.13	16.30	7.77	518.00	3.23	300.00	4.24
Stdv	57.21	6.26	0.18	489.78	0.10	0.00	6.48

Equation of model

The new equation developed to evaluate the groundwater recharge (R) is given by the following equation (Eq. 4):

$$R = \frac{T^2 - 1}{T^2 - 12T} \times \left[P - (P - 1) \times \left(\frac{\sqrt{T^2 - 1}}{T} \right) \right] \times T^{0.21} \quad (4)$$

with R annual average recharge given in (mm), T average annual temperature given in (°C), P average annual rainfall given in mm.

Model of Chibane et al.

The model of Chibane et al. is a hydrological based model developed and designated to estimate GWR in semi-arid areas.

Table 5 Result of recharge [R (mm)] calcul using three models (hybrid model, hydrogeological model, and Chibane et al. models)

Year	P (mm)	T (°C)	R_Chibane et al. model	R_hybrid_model	R_HG_model
1979	654.79	15.16	26.55	20.66	22.26
1980	560.93	14.64	8.58	22.61	19.07
1981	379.51	15.68	1.68	13.49	12.90
1982	637.53	15.06	21.59	21.01	21.68
1983	355.25	15.61	1.28	13.37	12.08
1984	292.35	14.55	0.50	16.99	9.94
1985	409.21	15.70	2.29	13.89	13.91
1986	385.65	15.34	1.66	14.89	13.11
1987	536.42	16.37	9.85	13.52	18.24
1988	555.87	15.90	11.08	15.37	18.90
1989	502.37	16.18	6.67	13.65	17.08
1990	547.18	15.93	10.19	15.11	18.60
1991	632.36	14.39	16.70	26.77	21.50
1992	500.49	14.31	4.08	24.20	17.02
1993	406.18	15.30	2.03	15.41	13.81
1994	377.62	16.05	1.77	12.34	12.84
1995	386.63	15.71	1.82	13.49	13.15
1996	492.24	15.10	4.77	17.98	16.74
1997	382.46	15.94	1.82	12.71	13.00
1998	285.96	15.82	0.65	11.66	9.72
1999	392.01	16.41	2.19	11.60	13.33
2000	136.20	16.01	0.14	9.07	4.63
2001	184.62	16.69	0.26	8.58	6.28
2002	172.56	15.85	0.20	9.91	5.87
2003	296.02	16.01	0.75	11.30	10.06
2004	284.25	15.64	0.61	12.13	9.66
2005	268.00	16.03	0.56	10.87	9.11
2006	321.11	16.24	1.01	11.09	10.92
2007	340.84	15.70	1.12	12.83	11.59
2008	358.10	15.60	1.32	13.44	12.18
2009	403.66	15.75	2.19	13.62	13.72
2010	301.08	16.17	0.81	11.00	10.24
2011	519.54	14.78	4.58	20.58	17.66
2012	396.87	15.00	6.38	16.68	13.49
2013	300.18	14.54	5.01	17.21	10.21

Table 6 Statistic summary of recharge (R) calcul

	P (mm)	T (°C)	R_Chibane et al. model	R_hybrid_model	R_HG_model
Mean	398.74	15.58	4.65	14.83	13.56
Max	654.79	16.69	26.55	26.77	22.26
Min	136.20	14.31	0.14	8.58	4.63
Stdv	128.520731	0.6077063	6.10548797	4.24072007	4.36970484

it published in 2015. it uses the precipitation and average annual temperature as input. This model underestimates the recharge value for the medium rainfall values ($p < 400$ mm).

The equation of this model is given by (Eq. 5):

$$\mathrm{GWR_c} = 0.135 \times \left(\frac{\varphi}{\alpha}\right) \times \mathrm{e}^{0.01047 \times P} \quad (5)$$

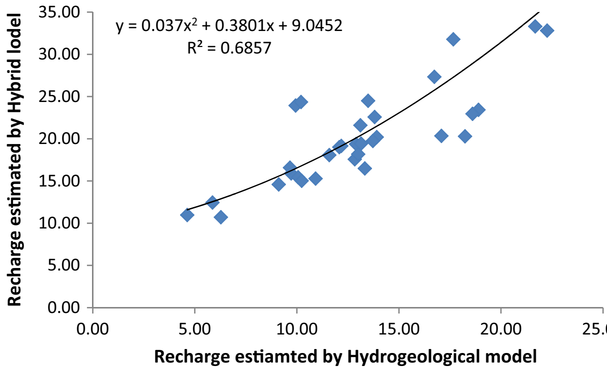

Fig. 7 Correlation between GWR_HG and GWR_HWB

with φ and α coefficients depending on temperature, GWR_c is annual groundwater recharge given in mm, and P average annual precipitation given in mm.

Results and discussion

The summary of calcul is given in Tables 5 and 6, the annual variation of groundwater recharge estimated by the three models is illustrated in Fig. 6. As we see the annual mean rainfall approached 390 mm/year, which characterised the climate of the region; a high precipitation value was observed in the north of the region and it varies from the West to the East. The temperature with an average of 15.6 °C varies between 14 and 17 °C. The results of chloride mass balance method are shown in Tables 3 and 4.

According to the results given in Tables 5 and 6 and the graphic results showed in Fig. 6, we see that the variation of groundwater recharge given by the hybrid model is between 14 and 26.77 mm/year, with a standard deviation 4.24 mm, the value of recharge calculated by the model of Chibane et al. varies between 4 and 26.55 mm/year with a standard deviation 6.10 mm; in addition the variation of recharge given by the hydrogeological model is between 13.56 and 22.66 mm/year with a standard deviation 4.36 mm; the two models (Hybrid and hydrogeological) have the same variation with present a best estimation of recharge in the opposite side the model of Chibane present a deficit in the estimation of recharge when the annual rainfall is less than 450 mm (Vivoni et al. 2009).

The correlation between the values of GWR estimated by the two methods gives a best.

Estimation with a determination coefficient of ($R^2 \approx 0.7$) (Fig. 7).

The average annual ground water recharge given by the two models is between 13 and 15 mm. In the opposite side the mean value of recharge given by the model of Chibane et al. is 4 mm/year. These results confirm the relationship

Table 7 Error of calcul for each model by tacking the hydrogeological model as a reference

Error	Chibane et al. model	Hybrid model
Nash	0.52	0.54
MAE	9.16	8.14
RMSE	9.60	9.37
AME	67.57	60.04

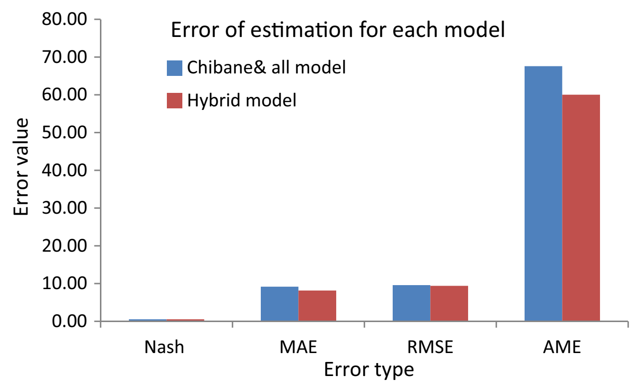

Fig. 8 Graphic show the variation of error of each model

between the new hybrid model designated to the semi-arid area and the hydro-geological model applicated to estimate the groundwater recharge.

Performance of this model was proved using a statistical error mostly used in hydrological modelling as given by Chai and Draxler (2014).

The four error criteria used in this work give a very good estimation of the GWR, which confirm the efficiency of the model. The summary of error calculus are shown in Table 7.

Comparing error of the two model vs the hydrogeological model lets us to take a conclusion that this new hybrid model is better than the model proposed by Chibane and Ali-Rahmani (2015) where RMSE is 9.37, the error of calcul given by the model of Chibane (RMSE = 9.60). The graph in Fig. 8 gives the variation of each error for each model.

The methods of chloride balance give an average annual recharge about 16 mm/year which is compared to the hydrogeological model and the hybrid model (10 and 17 mm). In the opposite side the model of Chibane et al. give 0.54 mm/year. The CMB method confirms the results obtained by the two new models (Hybrid model and the Hydrogeological model).

The 2d contour plot given in Figs. 9, 10, and 11 give the variation of recharge by the three used model, analysis of this graphic let us to appreciate that the Hybrid model work correctly with the precipitation and the temperature

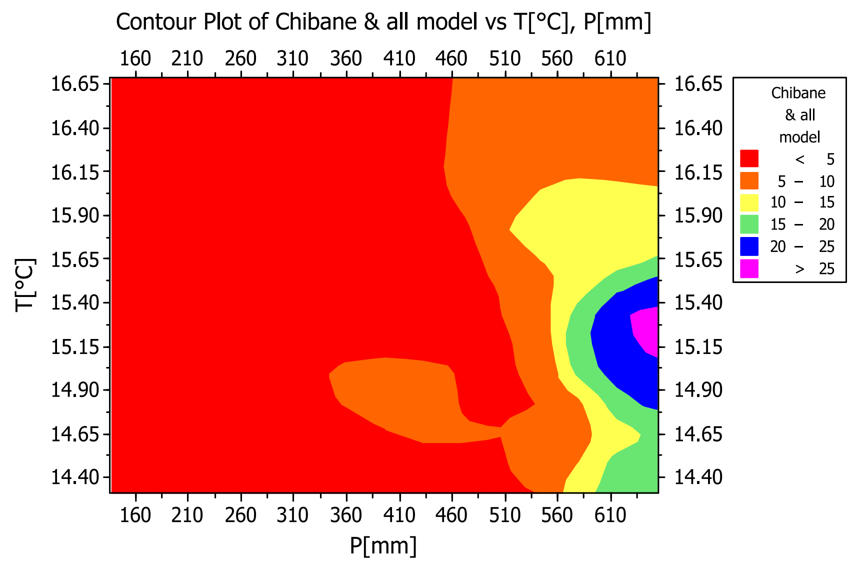

Fig. 9 2D contour plot of recharge [R (mm)] estimated by the Chibane et al. model vs annual rainfall and average annual temperature

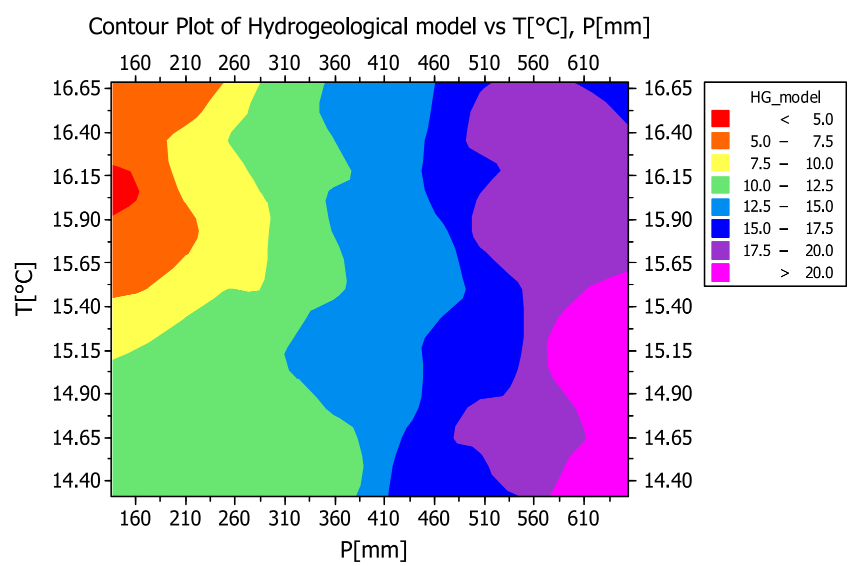

Fig. 10 2D contour plot of recharge [R (mm)] estimated by the hydrogeological model vs annual rainfall and average annual temperature

(Fig. 11), in the opposite side the model of Chibane et al. gives a high uncertainty when the amount of precipitation is less than 450 mm (Fig. 9), the hydrogeological model does not take in the interest the factor of temperature which can deviate in the high temperature values (Fig. 10).

A new recharge class diagram was established to evaluate GWR in semi-arid zones. Three class of groundwater recharge rate are distinguished in function of the annual rainfall in the order of low, medium and high recharge (Fig. 12).

The first class was started from less than 200 mm/year; where the GWR recharge is less than 15 mm/year, the second medium class is situated between 450 and 200 mm, the corresponding GWR is located between 15 and 32 mm/year; the high class started more than 400 mm/year, the GWR was up and more than 32 mm/year.

This new classification corresponds to the climate regime and the geological structure of the semi-arid area as explained by Goes (1999).

Isotopic study of the aquifer of region established by Chibane (2010) confirms that the recharge is medium and localised; the age of the groundwater is old, which proves that the recharge velocity is slow.

Limit of model This work is an attempt to find an equation which takes into account the properties of a semi-aride area (geological, hydro-climatic characteristics); however, the limit of application of this model is depending on the two parameters (rainfall, and temperature) (Table 8).

In the previous work of Chibane et al. the hydrological model was derived from the hydrological water budget,

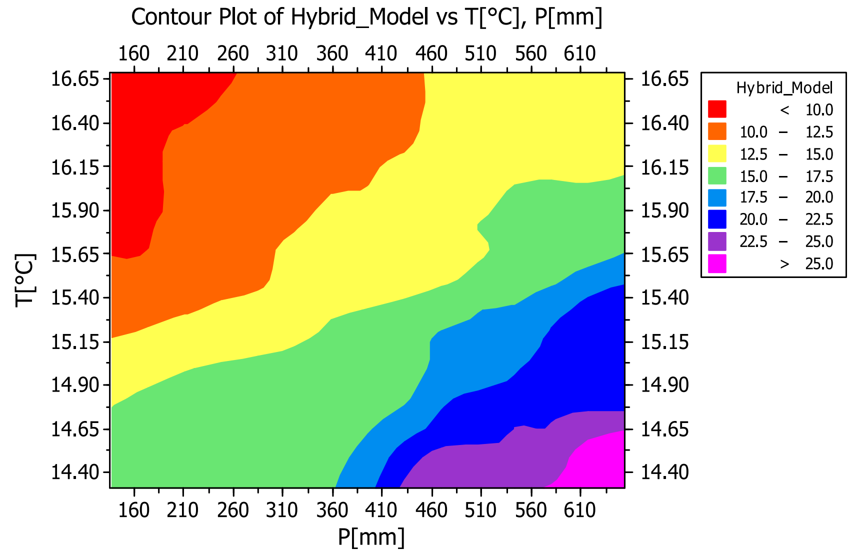

Fig. 11 2D contour plot of recharge [R (mm)] estimated by the new hybrid model vs annual rainfall and average annual temperature

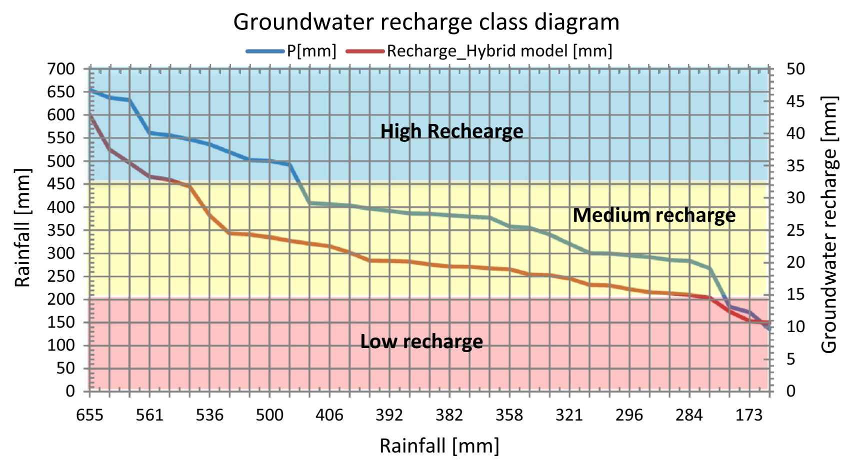

Fig. 12 Diagram shows the class of GWR in function of annual average rainfall

Table 8 Limit of application of model used to evaluate recharge in semi-aride media

Model	Rainfall (mm)	Temperature (°C)
Chibane et al.	$400 < P < 700$	$13 < T < 20$
Hydrogeological model	$P < 600$	–
Hybrid model	$100 < P < 600$	$13 < T < 30$

however, this model presents a high deviation in estimation of recharge for low precipitation value ($P < 400$ mm).

The hybrid model and the hydrogeological model work correctly when the average annual precipitation is lower than 600 mm, it work also correctly in arid and semi-arid zones.

The hybrid model was calibrated using chemical tracer methods (Chloride mass balance) to compare the rate of recharge in the study area vs the three models.

Conclusions

In light of the result a good approximation was approached, and a best estimation of GWR with this new hydrological hybrid model was achieved.

The error types used to test the efficiency of the model confirm that this model gives a best estimation for the GWR in semi-arid area, in our case study of Djelfa (Algeria) where we have tested the model, it gives a very acceptable result. From Fig. 10 our region was located in the medium recharge interval with an average annual recharge between 15 and 32 mm. This new model can be used in all semi-arid areas which have an annual rainfall less than 700 mm/year.

The application of the chloride mass balance gives us a very interesting result ($R = 16$ mm/year) which is similar to the results obtained by the hybrid model for the same year. The combinations between these results let us to use the new hybrid model with low uncertainty in groundwater recharge assessment.

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