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HYDROLOGICAL BASED MODEL TO ESTIMATE GROUNDWATER RECHARGE, REAL-EVAPOTRANSPIRATION AND RUNOFF IN SEMI-ARID AREA

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ABSTRACT

In semi-arid area, the groundwater recharge (GWR) is a very complicated process, because of several factors: lack of data and complexity of land. Proper management of the groundwater resources needs an organized approach to develop a new model for estimating the GWR, runoff and real-evapotranspiration. To do so, we have based our approach on two hydro-climatic parameters (temperature and precipitation). The results obtained by our formula are compared to the results provided by the analysis of the hydrological water budget (HWB). The objective of this research article is to test the reliability of the model by five criteria: Nash-Sutcliffe efficiency, Mean absolute error (MAE), Root mean square error (RMSE), Coefficient of determination (R^2) and the Arithmetic mean error (AME). In this study, we demonstrate for a semi-arid region that a method, to the moderate data requirements, can be used and can represent a system of understanding useful for the management of groundwater without application of complicated models.

Keywords: Groundwater Recharge, groundwater management, new model, semi-arid area, hydrological water budget.

RESUME

En zone semi-aride l'estimation de la recharge est une opération très compliquée à cause de plusieurs facteurs : absence de données et complexité de terrain. Pour mieux gérer les ressources en eau souterraine dans la région d'étude, on a procédé à une méthodologie pour développer une formule mathématique afin d'estimer la recharge, le ruissèlement et l'évapotranspiration (ETR). Ce modèle tient compte de deux paramètres hydroclimatiques (Température et précipitation). Les résultats obtenus par ce modèle sont comparés aux résultats obtenus par l'analyse des composants du bilan hydrologique. La fiabilité du modèle est testée par cinq critères (Nash, Erreur moyenne, absolue et RMSE). Une limitation des marges d'erreurs sur la surestimation ou la sous-estimation du bilan hydrologique est observée.

Mots clés : Zone semi-aride, Recharge, Modèle mathématique, Bilan hydrologique.

INTRODUCTION

The scarcity of water becomes increasingly a crucial issue. The number of population increases and climate change continues to affect rainfall patterns. The water management, in most countries of the world, has only recently gained traction as a public policy priority. While the populations of the arid and semi-arid areas have coped with water shortages thus far, the water scarcity in the future is likely to become a pervasive source of economic and food insecurity for these populations, especially in rural areas.

The difficulties in the assessment of the annual recharge in semi-arid areas are due to many reasons. We will quote among them the geological characteristics of heterogeneous soils, the morphology of the watershed and the scarcity of precipitation (Sibanda et al., 2009). Several methods were used, in different regions of the world, to estimate the rate of the recharge of aquifers. The most used method is the hydrological water budget (HWB), (Scanlon et al., 2006). In this paper, we give an approach to evaluate the components of the hydrological budget (Rain-off, actual evapotranspiration and groundwater recharge). Two parameters were introduced (temperature and precipitation). In arid and semi-arid area, aquifer recharge rate is directly related to the permeability of the soil, the infiltration speed and to the intensity of precipitation (Bonta et Müller, 1999).

METHODOLOGY TO QUANTIFY THE RATE OF GROUNDWATER RECHARGE

The idea of this article is to simulate the HWB, identify the parameters of the general model, and quantify the rate of groundwater recharge, runoff, and the real-evapotranspiration. At this level, we take into account, only, two parameters (Temperature and Rainfall) to estimate the different components of the HWB. We compare the results obtained with this model to the results obtained by the HWB and we try to apply it in one of the semi-arid areas of Algeria (Djelfa region).

General characteristics of the study area

The area of Djelfa is located at the South of Algiers (Algeria capital); between 2° and 5° East longitude and between 33° and 35° North latitude (Figure 1). The head of this district is located 300 km from the capital. According to the last national recencements of the National Office of statistics (ONS, 2010); the Djelfa district which extends over an area of 32362 km^2 is occupied by a population that would be some 1.224.966 inhabitants. The region is characterized by a semi-arid climate, with a moderate rainfall of 398 mm /y and an annual average temperature of 15.6 °C (Chibane, 2010). All categories (excluding irrigation) total water demand is estimated in 2010 to 304.547 m^3/day, and the demand for irrigation water has totaled 128.3 hm^3.This demand for irrigation water is expressed in hm^3/year because consumption is not daily, but rather seasonal, it evolves based on irrigated surfaces that they cannot be increased indefinitely.

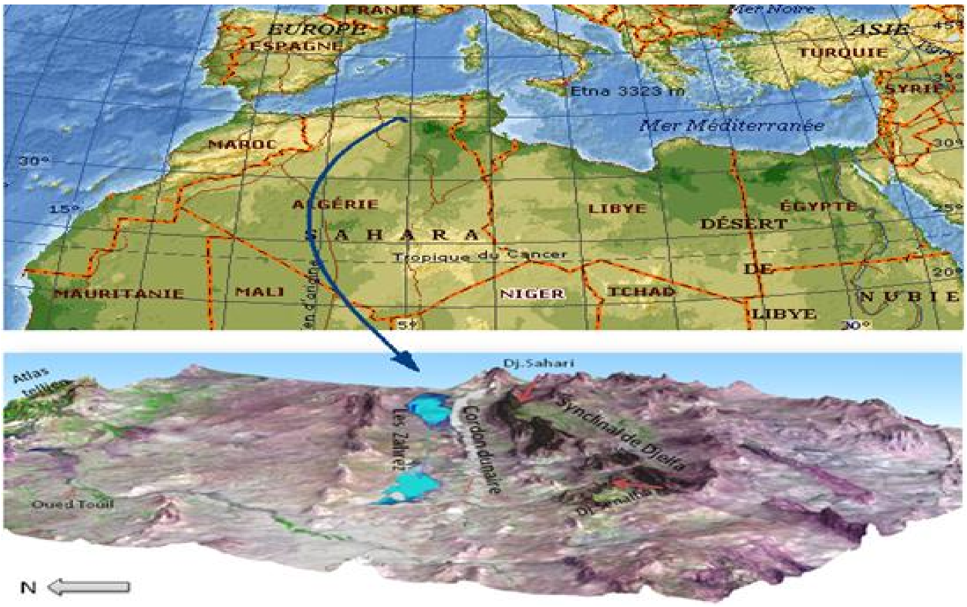

Figure 1: Location of the study area

The majority of precipitation is distributed during the period "September – June", July and august are the driest. From thermal viewpoint, the accentuation of contrasts is noticed (0.67 ° C in winter and 36.6 °C in summer), what gives a strong enough annual thermal amplitude of the order of 32.9°C. Prevailing winds are in their majority, North, Southwest and South. The average relative humidity is more or less dry in the order of 59%. All aridity indices used for the characterization of the climate of the region suggest a fresh semi-arid climatic regime where we can meet seasonally, bioclimatic stages ranging from temperate steppes, semi-arid, to the hyper-arid (Chibane, 2010).

Different geological deposits (Figure 2) form our area; we find The Barremian consisting essentially of alternating sandstones and Sandy clays intensely cracked form a major aquifer, very productive, 1500 to 2000 meters in thickness. The lower Albian consisting primarily of continental sandstones with a dense cracking there is the place of the emergence of multiple sources. Its thickness is about 400 meters, it is one of the aquifers most important. The Turonian is limestone majority with marls alternations in its uppermost part. The density of these limestones fractures indicates that the aquifer is Karst type. Its thickness is 450 meters. The Mio-plio-Quaternary mainly sandy, silty and conglomeratic is surmounted by a calcareous crust. Due to it is low permeability, the Mio-plio-Quaternary is operated by small wells, its thickness is variable (250-300 m).

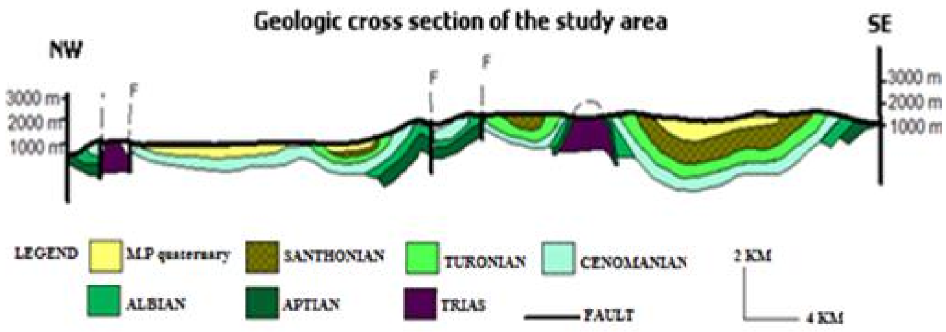

Figure 2: Geologic cross section of the study area (Cornet and Trayssac, 1952)

Form of the Model equation

The general form of the hydrologic balance equation is as follows:

$$P = R + GWR_E + ETR + SM + \Delta S \quad (1)$$

The problem formulation for the new model is given by Eq (2)" as shown below:

$$GWR_m = A\left(\frac{\cdot\cdot}{\sim}\right)e^{B\times P} \quad (2)$$

When the variation of ground reserve (ΔS) and the soil moisture (SM) were goes to the zero for a long period of time. Comparing Eq. (1) and Eq (2) results in:

$$\left\{\begin{array}{l} \text{we suppose } GWR_E = GWR_m \\ P - [R + ETR] = A\left(\frac{\cdot\cdot}{\sim}\right)e^{B\times P} \\ [R + ETR] = P - A\left(\frac{\cdot\cdot}{\sim}\right)e^{B\times P} \end{array}\right\} \quad (3)$$

Where:

P: annual average rainfall; *R*: Runoff; ETR: Real water evapotranspiration.

GWR_E and GWR_m: Annual estimated and modeled groundwater recharge.

α, *φ*, *A*, *B*: parameters of model.

RESULTS AND DISCUSSION

Estimation of the different terms of hydrologic balance given by the new model was discussed in this section. We begin by estimate the Runoff and real-evapotranspiration and compare the results given by the model to the results given by the Hydrological balance. We use the equation of Tixeront-Berkaloff modified by Romantchouk (1974) to estimate runoff and the formula of Turc to estimate the real-evapotranspiration.

Estimation of model parameters:

The numerical analysis of the data gives an approximate equation for α, φ: (eq.4, eq.5), the graphical result is illustrated in the figure 3.

$$\alpha = \frac{T^2+1}{T(T-12)} \tag{4}$$

T: annual average temperature in °C;
For *φ* we find:

$$\varphi = \frac{\sqrt{T^2-1}}{T} \tag{5}$$

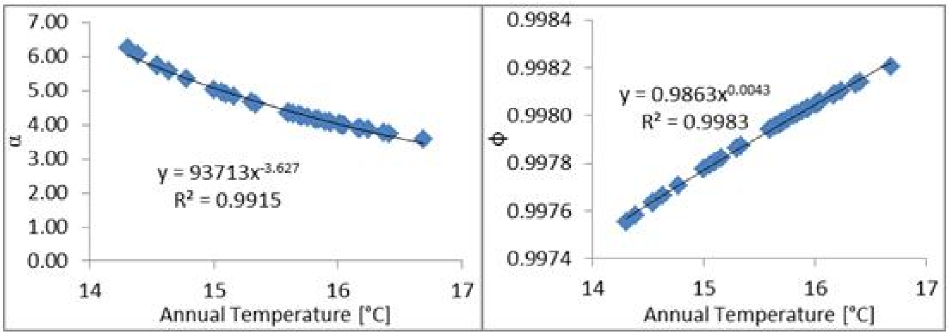

Figure 3: Variation of the two coefficients (α, φ) of the model in term of average annual temperature

After we have adjusted the two constants of the model A and B, the equation (eq.2) who give the amount of annual natural groundwater recharge becomes:

$$GWR_m = 0.135\left(\frac{\varphi}{\alpha}\right)e^{0.01047p} \tag{6}$$

Figure 4 below shows the annual variation of GWR modeled and estimated from the HWB.

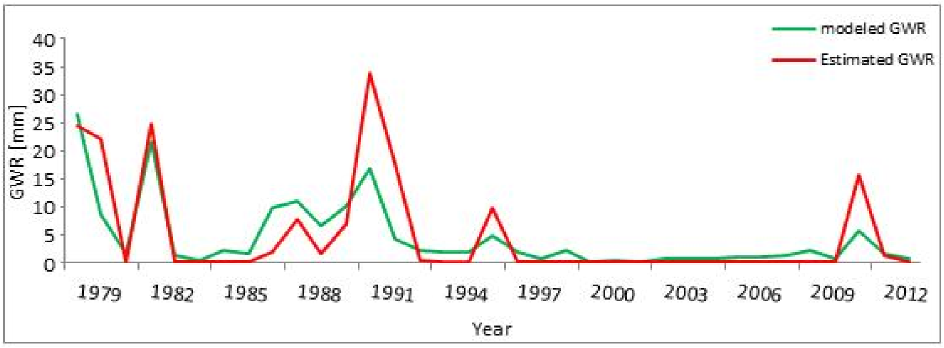

Figure 4: Variation of Groundwater recharge calculated by the two models (New developed formulae and the Hydrologic water budget HWB).

The results in the graphic (Figure 4) show clearly the best correlation between the estimated and modeled GWR the difference here is due to the divergence of the hydrological water budget at the annual scale.

EVALUATION OF RUNOFF AND REAL-EVAPOTRANSPIRATION

Runoff and the Real-evapotranspiration were the most important variables in the hydrologic water balance. Our model gives the sum of these two components by using the (eq.7).

$$ETR_m + RainOff_m = P - \left[0.135\left(\frac{\ddot{\ }}{\sim}\right)e^{0.01047\,p}\right] \tag{7}$$

We have derived a formula to calculate the runoff from the equation of Tiexeront berkaloff and Romantchok, and we have found the following results:

$$RainOff_m = (0.01P)^2 \tag{8}$$

We can now extract the real-evapotranspiration and the equation (7) becomes:

$$ETR_m = P - \left[0.135\left(\frac{\ddot{\ }}{\sim}\right)e^{0.01047\,p}\right] - 4(0.01P)^2 \tag{9}$$

Where:
$Runoff_m$: modeled runoff [mm]
ETR_m: modeled real-evapotranspiration [mm].

The graphic in figure 5 shows the annual variation of the runoff calculated empirically and the runoff calculated by the (Eq.8).

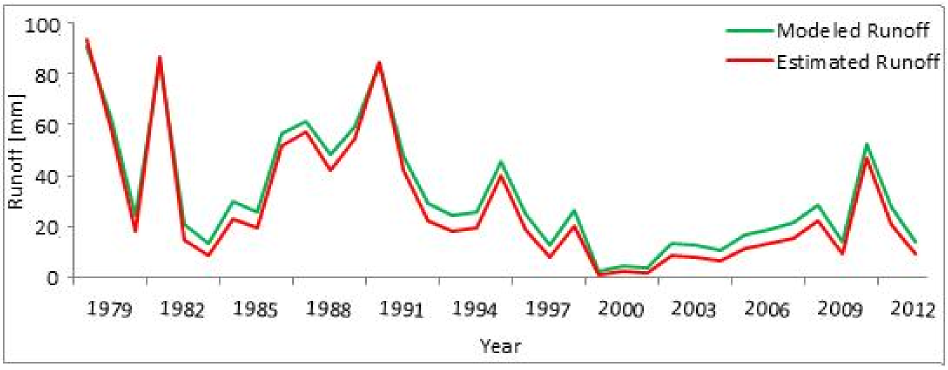

Figure 5: Annual Variation of estimated and modeled runoff

The variation of the Modeled and Estimated Runoff was the same, the graphical test shows a very good correlation between the two values of modeled and estimated runoff; the same things for the estimated and modeled real-evapotranspiration.

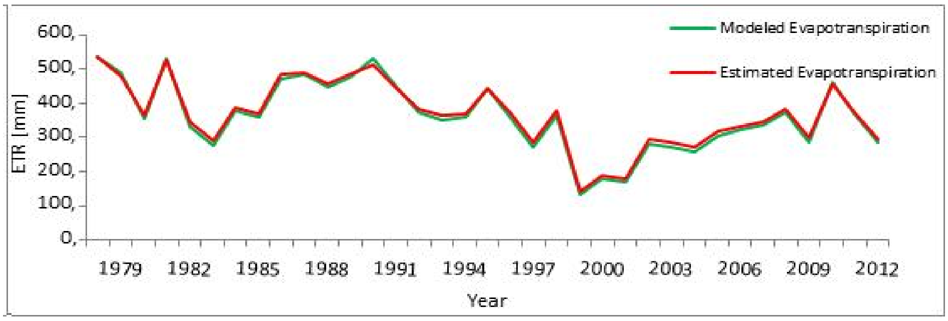

Figure 6: Annual Variation of estimated and modeled real-evapotranspiration (the estimated real-evapotranspiration calculated by Turc Formulae)

The percentage of modeled and estimated GWR (Figure 8) to the total of annual rainfall was varies between 1% and 5%. This variation is the characteristic of the semi-arid area where the GWR present a small part of precipitation that vary between 1 to 6% in general. Table 1 and table 2 show the statistics summary and the modeling input and output results.

Table 1: statistics summary of the results (Mean and standard deviation, and the coefficient of variation CV)

Data			B.CHIBANE & ALI-RAHMANI Model					Hydrologic water Balance		
Parameter	*P[mm]*	*T [°C]*	*α*	*φ*	*GWRm*	*Runoffm*	*ETRm*	*Runoffc*	*ETR_{turc}*	*GWRc*
Mean	398.74	15.58	4.49	0.998	4.42	32.48	361.84	27.84	369.42	4.79
Sdv	128.52	0.61	0.69	0.00017	6.16	23.43	101.07	24.60	96.56	8.93
CV	0.32	0.04	0.15	0.00017	1.39	0.72	0.28	0.88	0.26	1.86
Max	654.79	16.69	6.23	0.998	26.55	90.92	537.32	93.58	536.64	33.72
Min	136.20	14.31	3.57	0.998	0.14	2.10	133.96	0.84	141.80	0.00

Where:
P[mm]: annual rainfall in mm; T [°C]: annual average temperature in °C; *α, Φ: Model parameters*
GWR_m: Modeled Groundwater recharge calculated by (eq.6); Runoff: Modeled runoff calculated by (eq.8)
ETR_m: modeled real-evapotranspiration given by (eq.9).
$Runoff_c$: empirical runoff calculated with the Tixeront-Berkaloff modified by Romantchouk (1974) as:

$$Runoff_c = \frac{(0.01P)^3}{3}$$

ETRturc: real evapotranspiration estimated by the formulae of Turc (1961).
GWR_c: Groundwater recharge calculated by the hydrologic water budget (GWR_{HB}=P - (ETRturc + Runoff)).

Table 2: Results of Estimation of Groundwater recharge, Evapotranspiration, Runoff, with the two methods.

					B.CHIBANE & ALI-RAHMANI Model				Hydrologic Water Balance			
Year	P mm	T°C	α	Φ	GWR	GWR/P	$Runoff_m$	ETR_m	GWR_c	GWR/P	$Runoff_c$	ETRturc
1979	654.79	15.16	4.82	0.9978	26.55	4.06	90.92	537.32	24.57	3.75	93.58	536.64
1980	560.93	14.64	5.58	0.9977	8.58	1.53	62.72	489.63	21.95	3.91	58.83	480.15
1981	379.51	15.68	4.28	0.9980	1.68	0.44	24.56	353.28	0.00	0.00	18.22	364.53
1982	637.53	15.06	4.94	0.9978	21.59	3.39	85.27	530.67	24.64	3.86	86.38	526.52
1983	355.25	15.61	4.34	0.9979	1.28	0.36	20.96	333.02	0.00	0.00	14.95	344.59
1984	292.35	14.55	5.73	0.9976	0.50	0.17	13.13	278.72	0.00	0.00	8.33	288.37
1985	409.21	15.70	4.26	0.9980	2.29	0.56	29.42	377.49	0.00	0.00	22.84	387.83
1986	385.65	15.34	4.61	0.9979	1.66	0.43	25.52	358.47	0.00	0.00	19.12	367.82
1987	536.42	16.37	3.76	0.9981	9.85	1.84	56.34	470.23	2.01	0.37	51.45	482.96
1988	555.87	15.90	4.10	0.9980	11.08	1.99	61.37	483.42	7.86	1.41	57.25	490.76
1989	502.37	16.18	3.89	0.9981	6.67	1.33	48.14	447.56	1.62	0.32	42.26	458.49
1990	547.18	15.93	4.07	0.9980	10.19	1.86	59.09	477.90	6.88	1.26	54.61	485.69
1991	632.36	14.39	6.05	0.9976	16.70	2.64	83.62	532.04	33.72	5.33	84.29	514.36
1992	500.49	14.31	6.23	0.9976	4.08	0.81	47.70	448.71	17.60	3.52	41.79	441.10
1993	406.18	15.30	4.66	0.9979	2.03	0.50	28.90	375.25	0.42	0.10	22.34	383.42
1994	377.62	16.05	3.98	0.9981	1.77	0.47	24.26	351.60	0.00	0.00	17.95	364.56
1995	386.63	15.71	4.25	0.9980	1.82	0.47	25.67	359.13	0.00	0.00	19.26	370.32
1996	492.24	15.10	4.89	0.9978	4.77	0.97	45.84	441.64	9.66	1.96	39.76	442.82
1997	382.46	15.94	4.06	0.9980	1.82	0.48	25.01	355.62	0.00	0.00	18.65	368.01
1998	285.96	15.82	4.16	0.9980	0.65	0.23	12.45	272.86	0.00	0.00	7.79	285.60
1999	392.01	16.41	3.73	0.9981	2.19	0.56	26.54	363.28	0.00	0.00	20.08	377.71
2000	136.20	16.01	4.01	0.9980	0.14	0.10	2.10	133.96	0.00	0.00	0.84	141.80
2001	184.62	16.69	3.57	0.9982	0.26	0.14	4.36	180.00	0.00	0.00	2.10	190.65
2002	172.56	15.85	4.13	0.9980	0.20	0.11	3.70	168.65	0.00	0.00	1.71	178.25
2003	296.02	16.01	4.00	0.9980	0.75	0.25	13.53	281.75	0.00	0.00	8.65	295.01
2004	284.25	15.64	4.31	0.9980	0.61	0.22	12.27	271.36	0.00	0.00	7.66	283.72
2005	268.00	16.03	3.99	0.9981	0.56	0.21	10.65	256.79	0.00	0.00	6.42	269.71
2006	321.11	16.24	3.84	0.9981	1.01	0.32	16.44	303.66	0.00	0.00	11.04	317.68
2007	340.84	15.70	4.26	0.9980	1.12	0.33	18.97	320.74	0.00	0.00	13.20	332.95
2008	358.10	15.60	4.35	0.9979	1.32	0.37	21.36	335.43	0.00	0.00	15.31	346.89
2009	403.66	15.75	4.21	0.9980	2.19	0.54	28.47	373.00	0.00	0.00	21.92	383.83
2010	301,08	16.17	3.89	0.9981	0.81	0.27	14.09	286.18	0.00	0.00	9.10	299.86

2011	519.54	14.78	5.34	0.9977	5.81	1.12	52.18	461.55	15.54	2.99	46.75	457.26
2012	396.87	15.00	5.02	0.9978	1.71	0.43	27.34	367.82	1.23	0.31	20.84	374.80
2013	300.18	14.54	5.74	0.9976	0.54	0.18	13.99	285.65	0.00	0.00	9.02	295.08

Performance of model

To evaluate the performance of this new model we use five statistics criteria: the Mean absolute error (MAE) , the Root mean square error (RMSE) detailed in (Chai and Draxler, 2014), the Nash coefficient and the coefficient of determination(R^2), and the arithmetic mean errors (AME).

Table 3: Performance of model criteria using RMSE, MAE, Nash, and the determination coefficient (R^2)

	RMSE	MAE	Nash	R^2	AME %
Runoff	5.182	4.899	0.979	0.99325577	17.601
ETR	10.700	10.089	0.999	0.99624377	2.731
GWR	5.160	3.146	0.717	0.6862478	69.673

In general, the five types of statistical errors show that this new model gives a good approximation for runoff, groundwater recharge, and evapotranspiration. According to the results, this new hydrological model seems to give a good approximation, better than the hydrological water budget. To perform more, it is necessary to optimize the calibration of some coefficient model in order to minimize the estimation error (Kashyap et al., 1976). This will be the main goal of our future research within this field.

CONCLUSION

The proposed model was described and tested in the semi-arid area of Djelfa, We have developed it to express a decision support tool, useful for managers that take into account the economic and environmental costs of water. This approach to establish a new model that will calculate the annual recharge of groundwater (water runoff and real evapotranspiration), lies in its simplicity and its advantage to take only two hydroclimatic parameters, and it gives directly the amount of GWR unlike HWB that gives the amount of GWR as a residue.

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