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(RESEARCH ARTICLE)

Using the empirical formulas for estimation of groundwater recharge in the Lobo catchment (Center-West of the Ivory Coast)

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Abstract

Recharge estimation is a significant concern in any development project utilizing groundwater resources. In this study, groundwater recharge and recharge coefficient were determined using empirical methods applicable to tropical areas. Climatological data from January 2000 to December 2020 were collected at the Daloa synoptic station and were used to estimate the recharge of the area over this period. Using these empirical formulae, the results showed that groundwater recharge was on average 46.19 mm per year, actual evapotranspiration was 958.5 mm per year, and the recharge coefficient was 4.94% for the study area. The results also showed that about 3.86% of precipitation infiltrates the aquifer, 80% is lost through evapotranspiration, and 16.14% as surface runoff. The correlation between climatic parameters and groundwater recharge showed the highest correlation with rainfall. Minimum temperature, relative humidity and evapotranspiration have correlations with recharge of 0.159, 0.225 and 0.028, respectively. The results of the linear regressions showed that precipitation has a significant effect (R2 = 0.9958) on recharge.

Keywords: Aquifer; Evapotranspiration; Groundwater Recharge; Recharge Coefficient; Tropical Zone

1. Introduction

Groundwater, as a dynamic system, moves under the control of many factors, which are influenced by forces that depend on hydrogeology, hydrology and climatology [1]. In the Lobo catchment, in recent years, the adverse effects of climate change and high population growth have put great pressure on the water resources available to the population [2]. Thus, groundwater has become a key alternative resource in this region. This rush of populations to groundwater requires sustainable management of this resource, which involves controlling the renewal of this resource [3]. Indeed, the renewal of groundwater is an essential factor in any sustainable development programme based on its exploitation. This renewal is called recharge. It is the flow of water that replenishes or replenishes an aquifer, mainly by percolation through the soil [4]. Recharge can be done vertically or laterally from another aquifer system. Recharge, as one of the factors controlling groundwater status and fluctuation, is an important parameter that needs to be further assessed [5]. Recharge, which occurs on both small and large scales, in space and time, is influenced by several factors, such as meteorology, soil characteristics, geology, soil surface cover, slope and depth of groundwater level [6,7,8]. It can be natural and come from precipitation and/or surface runoff, or artificial and come from an intentional supply of water to the soil [8]). The mechanisms governing the natural recharge of aquifers can be described as follows [9]: recharge by vertical percolation of rainfall through the unsaturated zone, known as direct recharge; recharge from water from other aquifers; and recharge by percolation of water through river beds, known as indirect recharge. This description, which may appear very simplistic, does not reflect all the complexity of the recharging mechanisms that can take place simultaneously. Indeed, the recharge of an aquifer by precipitation is controlled by the complex process of infiltration,

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flow in the unsaturated zone and the phenomenon of evapotranspiration [10]. Despite this complexity, an estimate of groundwater recharge is essential for optimal management of this resource. For the estimation of this parameter, several methods such as geological, hydrogeological, geophysical and remote sensing techniques have been applied. [11] as there are no universally accepted standard methods as each method has its own advantages and disadvantages [12]. Estimating groundwater recharge from precipitation is an integral part of hydrology and hydrogeology [13]. Although precipitation is the most important source of groundwater recharge [14], the accuracy of currently available techniques for measuring recharge is not fully acceptable. A comparative analysis of empirical formulas for estimating recharge was carried out [15]. Groundwater recharge was estimated from rainfall data using three empirical formulae [16, 5]. The result revealed that the three formulas used gave comparable results, hence their conclusion that any of these formulas can be used for groundwater recharge estimation. In addition, in order to validate the formulas, recharge was estimated using empirical formulas in several regions (arid, semi-arid and tropical) [17,5,18, 19] and gave rather satisfactory results. Thus, the general objective of this study is to estimate the groundwater recharge of the Lobo catchment using empirical equations.

2. Materials and methods

Lobo catchment area is located in central-western Côte d'Ivoire, between 6°05' and 6°55' west longitude and between 6°02' and 7°55' north latitude (Fig. 1). This area is limited to the regions of Haut Sassandra, whose capital is Daloa, and part of Worodougou region (Seguela). Daloa is economic hub of this area. In Nibéhibé, this watershed has a surface area of 7,000 Km^2. This basin is drained by Lobo River and its main right bank tributary the Dé. Average rainfall over period 1971-2020 is about 1200 mm and average temperature is 25°C.

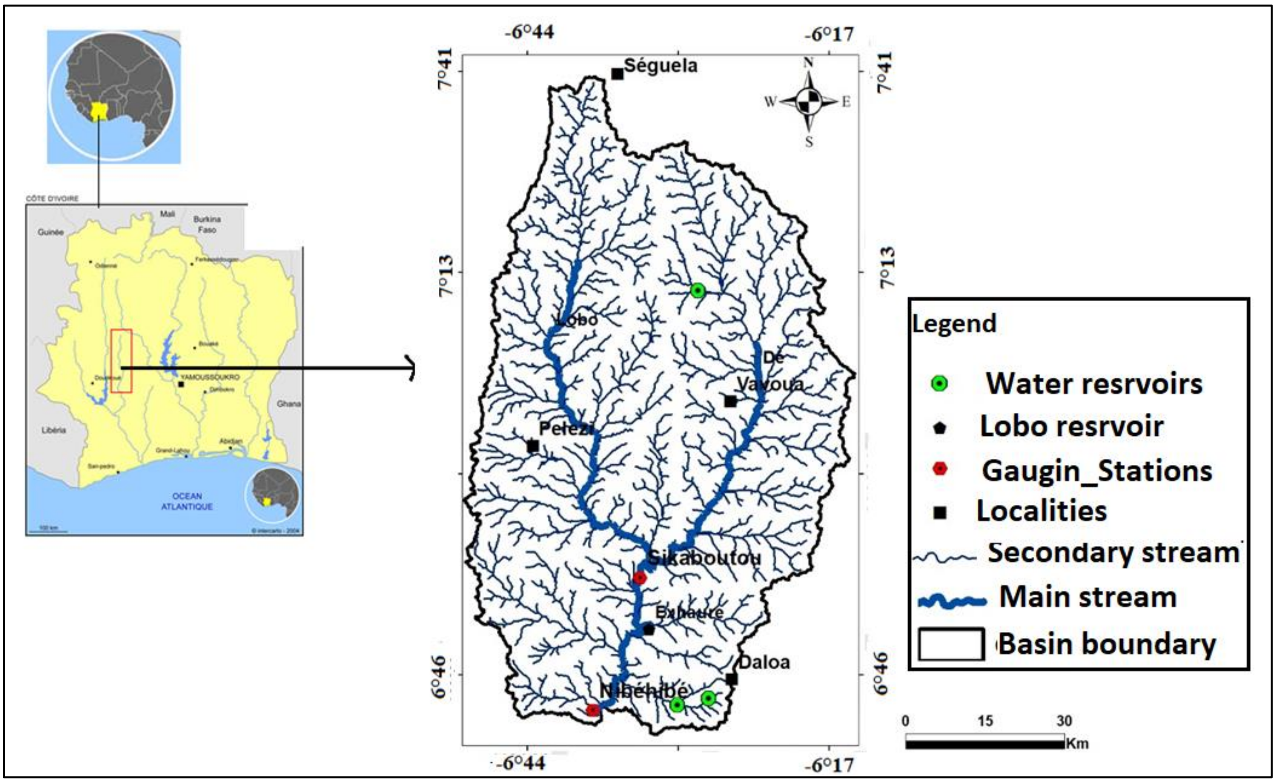

Figure 1 Lobo watershed in Nibéhibé

3. Materials and methods

3.1. Data

For this study, meteorological data including minimum and maximum temperature, sunshine hours, relative humidity, wind speed and rainfall were collected at the Daloa synoptic station over the period 2000-2020, i.e. 20 years of meteorological data collected at this station. These data were used to calculate evapotranspiration, recharge coefficient, runoff and recharge using empirical formulae. Potential evapotranspiration was determined using CROPWAT version 8.0 based on the Penman-Moteithe FAO formula.

3.2. Methodology

3.2.1. Determination of evapotranspiration

Evapotranspiration is regarded as the sum of evaporation and transpiration. It is a climatic index integrating the effect of air temperature, humidity, wind speed, and solar radiation. CROPWAT software version 8.0 was used to estimate evapotranspiration. The software is based on the FAO Penman-Monteith formula [20].

3.2.2. Estimation of Groundwater

Estimation of groundwater recharge of the study area was conducted using a modified version of for tropical regions based on water level fluctuation and rainfall depth [21, 5]. The equation is given as:

$$R = 1.35(P - 14)^{0.5} \qquad (1)$$

where R is the net recharge due to precipitation in mm, and P is the precipitation in mm.

3.2.3. Recharge Coefficients

The value of the recharge coefficient is defined as the ratio of recharge to effective rainfall; it is expressed in percentage [21] as:

$$\boldsymbol{R_{coefficient} = \frac{R}{P_e}} \qquad (2)$$

where R is the recharge and Pe is the effective rainfall.

3.2.4. Estimation Direct

Runoff Estimated runoff for water budget was developed by [22], and is given as

$$\boldsymbol{R_{off} = 0.85 \times P - 30.5} \qquad (3)$$

where Roff is the direct runoff and P is the precipitation.

3.2.5. Co-Integration Analysis

The climatic data was analyzed using co-integration analysis. The analysis involves a unit root test performed on levels, the first difference and the second difference were used to determine whether the individual input series are stationary and exhibit similar statistical properties. It must be noted that regressing a non-stationary time series data over another non-stationary time series data gives a spurious or unreliable regression. To correct for this, a unit root test is performed [23].

A time series is stationary when X(t1), X (t2) …, X(tn) is the same as the joint distribution of any set of X's(t1+k), X(t2+k) …, X(tn+k), for all n and k.

$$\boldsymbol{Y_t = \rho^{Y_{t-1}} + U_t} \qquad (4)$$

where p ≤ 1 and U is the white noise error.

If the estimated ρ is statistically equal to 1 when Yt is regressed on Yt−1, then Yt is non-stationary; that is, has no unit root (I (0)).

The Augmented Dickey–Fuller (ADF) test was used to test for the stationarity of the data. The test consists of the following regression

$$\boldsymbol{\Delta Y_\tau = \beta_1 + \beta_{2\tau} + \delta Y_{\tau-1} \alpha \sum_{\tau=1}^{n} \Delta Y_\tau + \varepsilon_\tau} \qquad (5)$$

were

$$\boldsymbol{\varepsilon_\tau = \Delta Y_{t-1} = (Y_{t-1} - Y_{t-2}), \Delta Y_{t-2} = (Y_{t-2} - Y_{t-3})} \quad (6)$$

The Johansen procedure was used to test for the number of co-integration vectors in the model. The Johansen technique was used not only because it is vector auto-regressive-based but because it performs better in multivariate models [24]. If Xt and Yt are then co-integrated, their short-run dynamics can be described by an error correction model (ECM). The theory states that if two variables, Y and X, are co-integrated, then the relationship between them can be expressed as an ECM [24]. The co-integration model is given as:

$$\boldsymbol{P_t = \beta_0 + \beta_1 R_t + \beta_2 SR_t + \beta_3 MT_t + \beta_4 XT_t + \beta_5 ET_t + U_t} \quad (7)$$

3.2.6. Correlation and Regression

Analyses Pearson correlation coefficient was used to evaluate the strength of the relationship between meteorological factors. The impact of independent variables (that is, humidity, temperature, rainfall, wind speed, and duration of daily solar radiation) on estimated recharge was evaluated using linear regression

4. Results and Discussion

All parameters presented in Table 1 were calculated over the period 2000-2020, i.e. a period of 20 years. These parameters are: groundwater recharge, evapotranspiration, recharge coefficient, and surface runoff. The ratio of recharge to total rainfall is 3.86%, which according to [21] is classified as a low recharge rate. The average precipitation and evapotranspiration over the study period are estimated at 1197.72 mm and 1357.8 with lower and upper quartiles of 1379; 1081.8 for precipitation and 1495.12; 1234.17 for evapotranspiration. There is evidence that apart from precipitation (with a high rate), other parameters (such as land use) could also have a key role [25] in groundwater recharge.

Table 1 Hydrological data of the study area for 20 years (2000 to 2020)

Years	P (mm/y)	R (mm/y)	Max T °C	Min T °C	ET (mm/y)	Roff	Roe(%)
2000	1329.1	48.96	37.04	16.89	1291.34	1099.24	4.62
2001	841.2	38.83	37.63	19.30	1343.94	684.52	5.78
2002	1214.4	46.77	36.80	20.51	1476.72	1001.74	4.83
2003	1379	49.88	36.48	20.48	1847.42	1141.65	4.53
2004	1242	47.31	35.48	20.66	1693.69	1025.20	4.77
2005	1152.5	45.55	34.09	20.25	982.26	949.13	4.95
2006	1129.1	45.08	32.70	19.56	1367.90	929.24	5.00
2007	1133.9	45.18	32.26	19.78	983.39	933.32	4.99
2008	1443.5	51.04	33.51	19.81	1620.80	1196.48	4.43
2009	1264.4	47.74	33.60	19.79	1529.83	1044.24	4.73
2010	1412	50.48	34.73	20.11	1284.45	1169.70	4.48
2011	981.6	41.99	34.84	16.45	1301.49	803.86	5.36
2012	1440	50.98	34.14	19.86	1315.87	1193.50	4.44
2013	1614	54.00	32.75	19.84	1495.12	1341.40	4.19
2014	1594.9	53.68	36.24	20.16	1789.69	1325.17	4.22
2015	1009.3	42.59	34.13	16.50	1345.67	827.41	5.29
2016	1188.2	46.26	33.65	20.01	982.32	979.47	4.88
2017	722.6	35.94	34.78	19.89	1325.85	583.71	6.23
2018	1081.8	44.11	34.89	20.21	1113.92	889.03	5.11

2019	1237	47.21	35.08	16.55	1188.08	1020.95	4.78
2020	741.6	36.41	37.41	20.06	1234.17	599.86	6.15
Average	1197.72	46.19	34.87	19.37	1357.8	987.56	4.94
Maxi	1614	54	37.63	20.66	1847.42	1341.4	6,23
Mini	722.6	35.94	32.26	16.45	982.26	583.71	4,19
Q (25%)	1081.8	44.11	33.65	19.56	1234.17	889.03	4.53
Q (75%)	1379	49.88	36.24	20.16	1495.12	1141.65	5.11

In Table 1, P is the annual precipitation, R is the annual groundwater recharge (mm), ET is the evapotranspiration (mm/year), MinT is the minimum temperature (°C), MaxT is the maximum temperature (°C), Roff et the surface runoff (mm/y) and Rcoeff. is the recharge coefficient (%). Q: Quartile

Fig. 2 shows the evolution of mean annual precipitation, runoff, evapotranspiration and recharge between 2000 and 2020 in the study area.These parameters (groundwater recharge and surface runoff) increase and decrease with precipitation over the entire study period. However, evapotranspiration shows another trend which is different from the other parameters. This is not unexpected since ET is a function of solar radiation, daily dew point wind speed and temperature [21,5]. Indeed, over the period, these parameters, mainly temperature, have increased. It should be noted that low rainfall in the study area leads to low groundwater recharge and vice versa. This decrease in rainfall over the period 2000-2020 could be due to the adverse effects of climate change which could lead to increased temperature and evapotranspiration in the area [2] .

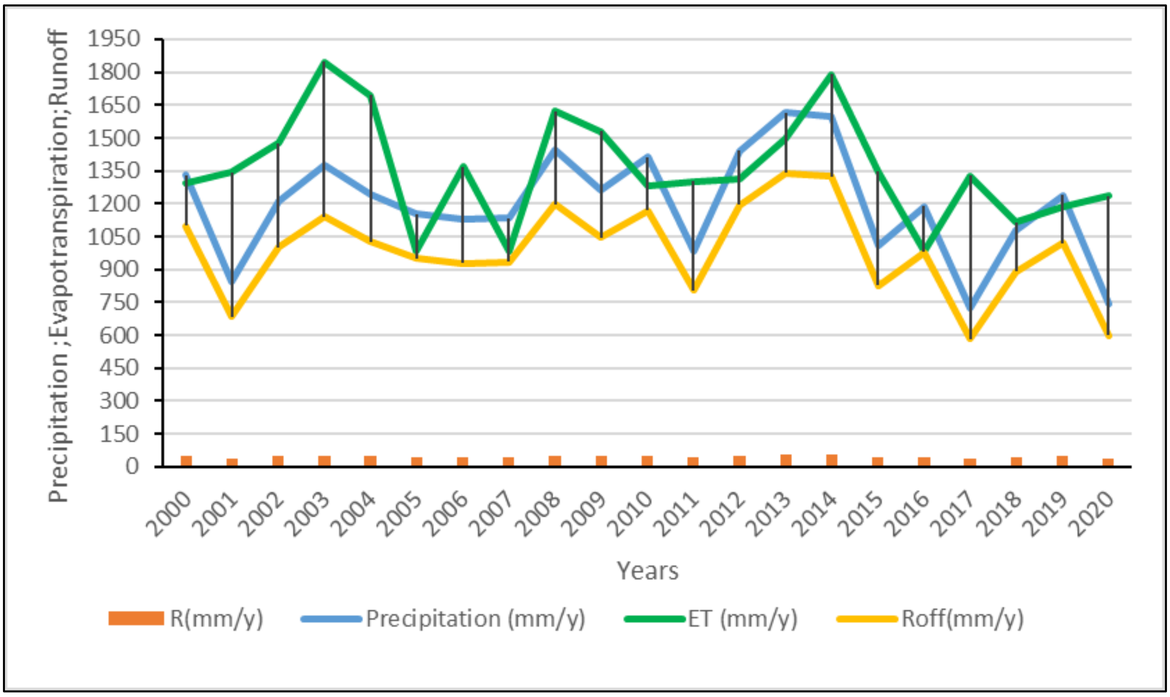

Figure 2 Total annual precipitation, recharge, runoff and evapotranspiration

4.1. Co-integration

Table 2 shows the results of the ADF test. These results show that recharge and precipitation are non-stationary, but are stationary after the second differentiation. The other climate parameters are non-stationary. It was verified that the variables have a unit root at their levels, but are stationary after differentiation, so there is a long term relationship between the climate parameters. These observations were also made by [5] in a similar environment.

Table 2 Result of stationary test from the Augmented Dickey-Fuller Test

Climate parameters	Level	1st Difference	2nd Difference	Decision
Precipitation	-3.454448	-6.542228	-5.315195	Stationary
Recharge	-3.524826	-6.658083	-5.442094	Stationary
Evapotranspiration	-4.013366	-6.164948	-6.960297	Non-Stationary
Max temperature	-2.000817	-4.726188	-5.739369	Non-Stationary
Min temperature	-1.237497	-6.630274	-4.156138	Non-Stationary
Relative Humidity	-2.232637	-4.287431	-3.959210	Non-Stationary

Critcal level (5%): -3.808546

Table 3 presents the results of Johansen's co-integration. The likelihood ratio shows that there is only one cointegration equation in the analysis. According to the equation, the precipitation variable precipitation was considered to have a significant effect on the estimated recharge in the study area during the study period.

Table 3 Johansen co-integration result

Hypothèsised No. of CE (s)	Eigen Value	Max-Eigen statistic	0.05 Critical Value	Prob**
None*	0.991926	91.56295	40.07757	0.0000
At most 1	0.706763	23.30872	27.58434	0.1607
At most 2	0.432674	10.76961	21.13162	0.6703
At most 3	0.353743	8.294612	14.26460	0.3495
At most 4	0.032378	0.625368	3.841465	0.4291

The adjusted R2 shows that about 91% of the variation in recharge is explained by rainfall effects (Table 4). This shows that an increase in precipitation value leads to an increase in recharge value and vice versa.

Table 4 Results from the Error Correction Model

Variable	Coefficient	Standard. Error	t-Statistics	Probability
Recharge	-7.678405	1.365982	-5.482105	0.0003
Evapotranspiration	-0.043558	0.055815	-0.780404	0.4448
Relative Humidity	-0.000730	0.003615	-0.202026	0.8410
MaxTemperature	-0.000151	0.008734	-0.017312	0.9864
Min Temperature	-0.004451	0.003615	-0.202026	0.8420

Depend vatiable : precipitation. R^2 = 0.9148; Durbin-watson stat: 2.133321

4.2. Correlation and Regression Analysis

Tables 5 and 6 show the Pearson correlation coefficient for the meteorological parameters and the regression analysis of these parameters on the estimated recharge in the study area. This analysis was done in order to study the correlation between the estimated recharge and the climatic parameters. The results show that evapotranspiration is correlated with estimated recharge at the significance level of 0.028, with R2 = 0.0178. The estimated recharge is correlated with precipitation at the 0.998 threshold (R2 = 0.998), but shows no significant correlation with other parameters. This would mean that rainfall is the only climatic parameter that has a significant impact on groundwater recharge in our study area. Thus, an increase in rainfall leads to an increase in groundwater recharge and vice versa [5].

Table 5 Matrice de correlation (Pearson)

Variables	Precipitaion	Recharge	Max T	Min T	ET	Relative Humidity
Precipitatio	**1**	**0.998**	-0.245	0.174	0.074	0.223
Recharge	**0.998**	**1**	-0.259	0.159	0.028	0.225
Max T	-0.245	-0.259	**1**	-0.043	0.245	0.130
Min T	0.174	0.159	-0.043	**1**	0.174	-0.106
ET	0.074	0.028	0.245	0.174	**1**	0.023
Relative Humidity	0.223	0.225	0.130	-0.106	0.223	**1**

Values in bold are different from 0 at significance level alpha=0.05

Table 6 Regression analysis of weather parameters on estimated recharge

Weathered Parameter / Recharge	Determination Coefficient (r^2)	Regression Equation
Precipitation	0.9958	Y=0.0202x+21.997
Max Temperature	0.0545	Y=0.3953x+39.544
Min Température	0.0245	Y=0.5639x+35.27
Relative Humidity	0.12572	Y=0.8749x+61.049
Evapotranspiration	0.0178	Y=25.038x+206.06

5. Conclusion

The application of empirical methods for the estimation of groundwater recharge in the study area has made it possible to estimate this parameter over the period 2000-2020. The average recharge over this period is 46.9 mm. The average recharge coefficient is 4.94%, the evapotranspiration rate is about 80%, and the groundwater recharge is about 3.86%. Therefore, 16.14% of the rainwater contributes to surface runoff. The study shows that there is variability in climate parameters and that climate has a significant effect on groundwater resources. This is clearly revealed in the precipitation variable; however, evapotranspiration and temperature have a relationship with each other. The study also shows that climate change has a significant effect on recharge, clearly revealed by the variability of rainfall. The correlation between the parameters showed that the highest positive correlation exists between recharge and rainfall. Furthermore, the correlations between min temperature, relative humidity, and ET and estimated recharge are 0.159; 0.225 and 0.028. The results of the linear regressions showed that precipitation has a significant effect (with R2 = 0.9958) on the recharge estimate.

Compliance with ethical standards

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Disclosure of conflict of interest

The authors declare that they have no conflict of interest.

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