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Estimation of Groundwater Recharge Using Water Table Fluctuation Method in Bamako and Surrounding Areas, Mali

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Abstract

Bamako's geographic and demographic expansion is sure to increase the need for water, and the slow development of the water supply network seems unable to meet this need. The knowledge of the approximate quantity of water reaching the groundwater is crucial, given the high dependence of this city and its surrounding area on groundwater. The aim of this study is to estimate the average groundwater recharge on a monthly scale, based on measurements taken over a 24-month period by using Water Table Fluctuation (WTF). The monthly recharge values obtained from the 15 piezometers in the study area by using WTF method vary from 1.04 to 38.81 mm with an average value of 9.74 mm. As part of the precipitations, these values represent respectively 1.29%, 48.52% and 12.17% of monthly average precipitation. It appears in this study that despite the piezometers belonging to the same climatic zone, the recharge rate can be different because of many factors such as the thickness of the aquifers, the soil and geology type, the local land cover and land use activities.

Keywords

Groundwater Recharge, Specific Yield, Hydrograph, Precipitation

1. Introduction

The proper management of both surface and groundwater resources through systematic inventory, conservation and proper planning is essential for economic and social development of any country (Jaiswal et al., 2003). In arid and semiarid areas where groundwater is main source of freshwater, accurate groundwater recharge estimation is crucial for assessing scarce water resources and their sustainable management.

Groundwater resources provide the main supply of water in arid and semi-arid regions because freshwater resources on the land surface are not available or heavily polluted. The city of Bamako is largely dependent on groundwater, especially in the peripheral areas, due to the slow development of the drinking water supply network, linked to the very high cost of laying pipes and connecting users to the main pipes.

Only a drinking water distribution network serves the city center and a few districts of Bamako. The slow development of the network is pushing the inhabitants to drill water wells in their homes or in public places to have access to drinking water (Banton et al., 1991).

Population growth and the increasing urbanization of the city (4.45% per year on average according to Nlend et al., 2018) are accompanied by an increase in the need for drinking water. The increase in groundwater extraction might lead to perturbations in hydrological cycle (Gatwaza et al., 2016) and to a considerable reduction of groundwater storage as well as pumping rates have greatly exceeded natural recharge (Cooper et al., 2015).

Data and information on groundwater recharge, evolution and quality are necessary for the optimal utilization and sustainable management of groundwater resources (Nlend et al., 2018).

Many studies have been led to understand recharge processes and determine effective ways in which recharge can be enhanced (Berehanu et al., 2017; Foster, 1988; Igboekwe & Ruth, 2011). Due to its belonging to the arid and semi-arid areas, the country is coping this issue of groundwater recharge studies (Diancoumba et al., 2020). Information from this study could be used to effectively estimate groundwater recharge rate in the city and its surrounding areas.

2. Study Area

Bamako is the capital and largest city of Mali, with a 2009 population of 1,810,366 (United Nations, 2009) and an estimated 2023 population of 2,929,000 (United Nations, 2022). It is located on the Niger River, near the rapids that divide the upper and middle Niger valleys in the southwestern part of the country. The Niger River is the main surface water body. The study area has a total surface area of 245 Km^2 and is located in Infrcambrian Tabular Layer and is a sub-catchment of the Taoudeni basin and lies between the latitude: 12˚42'42.81"N and 12˚30'33.17"N and the longitude: 7˚54'25.20"W and 8˚04'24.94"W (**Figure 1**).

2.1. Climate

The study area has many piezometers, which are used for groundwater level monitoring and one metrological station to record and describe the climate of Bamako and surrounding areas.

The climate type of the study area is Sudano-Sahelian. The overall annual mean precipitation for the last 30 years (1990-2020) varies from 462.5 mm (year 2017) to 1142.6 mm (year 2008) recorded by the Bamako metrological situation (Figure 2). In the same station and for the area of interest, the highest values of temperature are recorded in April and May while the lowest values in December and January. The mean annual temperature recorded is 35.14˚C.

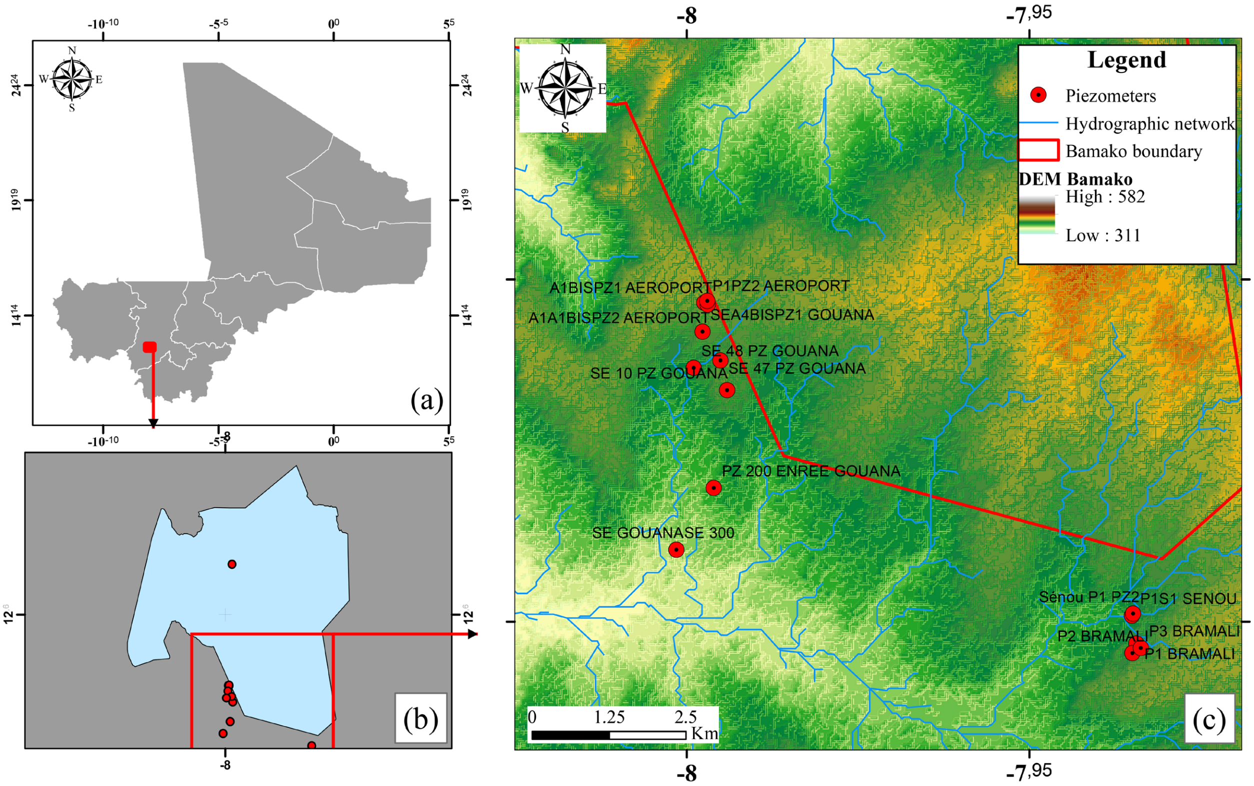

Figure 1. Location of study area: (a) Location of the study area in Mali, (b) Location of piezometers in Bamako and surroundings, (c) Zoom on piezometers used in the study area.

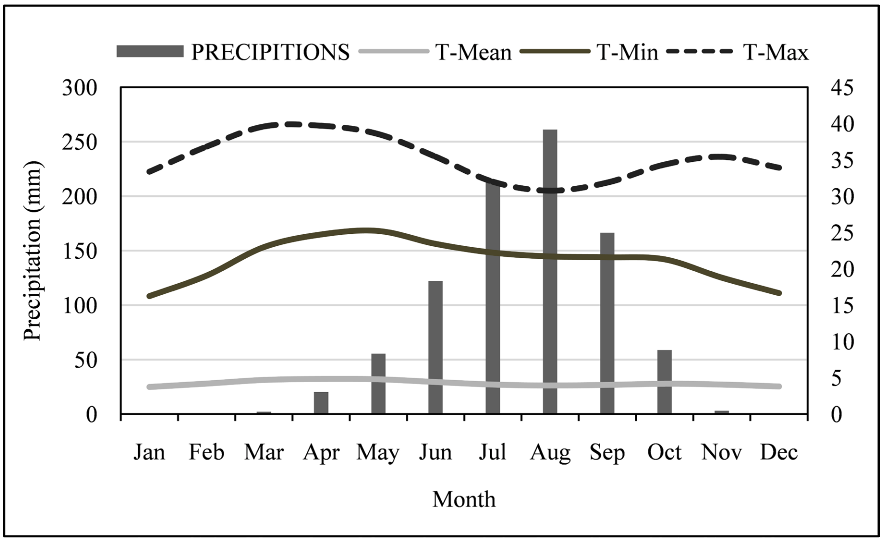

Figure 2. Monthly average (from 1990-2020) precipitation (mm) and temperature (˚C) in study area recorded at Bamako station.

2.2. Geological and Hydrogeological Setting

The Bamako region is located on the southern edge of the large Taoudeni sedimentary basin which extends over most of Mali. It straddles a geological boundary between sedimentary lands and crystalline and/or crystallophyllian terrains. The regions have a granito-gneissic and schistose base (to the south of the agglomeration) covered by a sedimentary cover of sandstone with pelitic intercalations (to the north of the agglomeration).

Geologically, the study area is located in the sandstone plateau unit as defined in (DNH, 1990). The area is mainly constituted by tabular sandstone dated of infra-Cambrian. Milestones and fine to coarse sandstones are the main geological formation and occupy the most area where the study is undertaken. Some geological formations, such as dolerites intrusions, conglomerate, glauconite, and quartzite are associated with the sandstone in Bamako area (Figure 3).

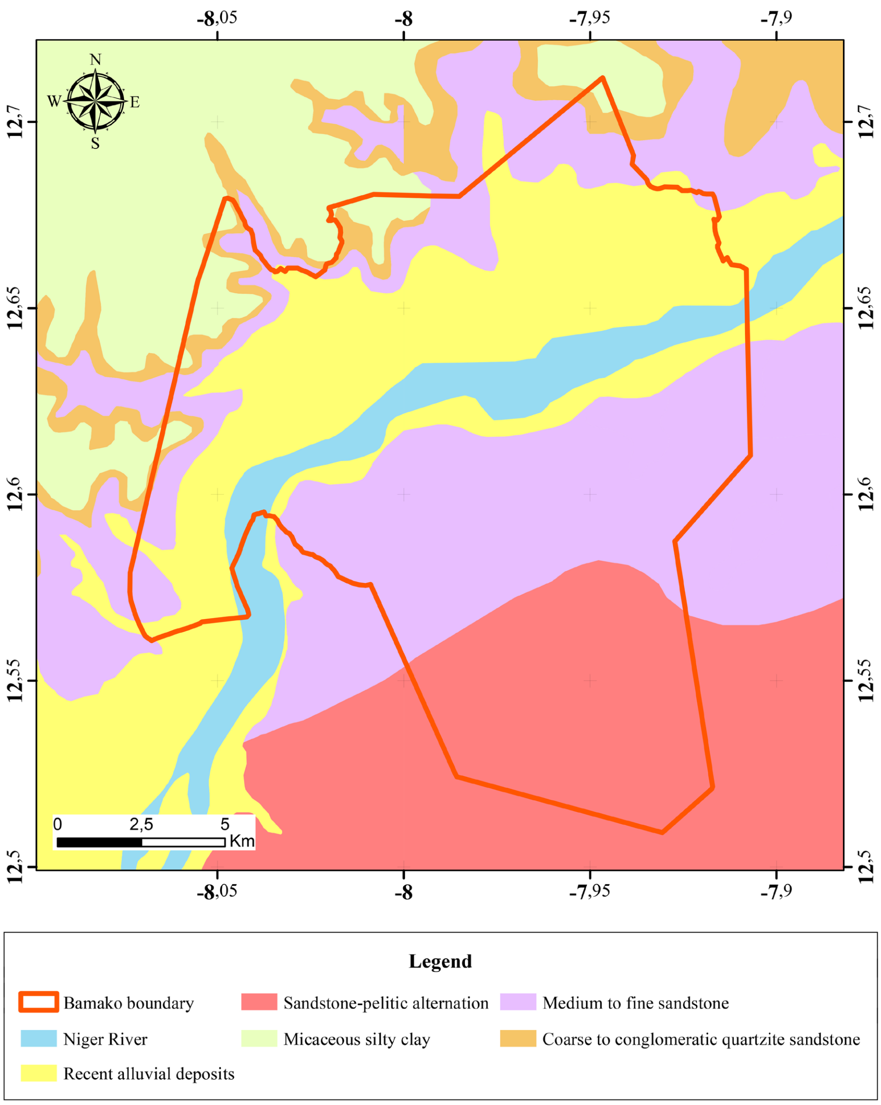

Figure 3. Geological map of the study area (modified from SYSMIN project).

The study area belongs to the 74b hydrogeological unit as specified in (DNH, 1990) and is characterized by two aquifers system: a shallow aquifers system in superficial deposits and a deep fractured aquifer system in fractured or fissured sandstone (Banton et al., 1991) (**Figure 4**).

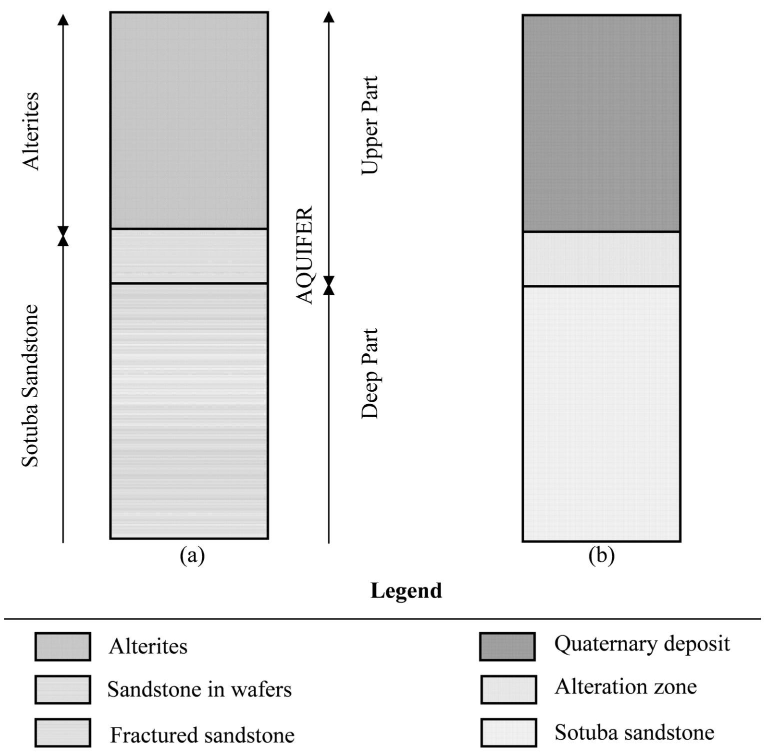

Figure 4. Lithological logs: (a) Schematic geological structure of the aquifer of Bamako, (b) Geological characteristics of the aquifer of Bamako (from Banton et al., 1991).

3. Materials and Methods

3.1. Data

To apply the Water Table Fluctuation (WTF) method, fifteen (15) piezometers have been selected in the study area as shown on the map in **Figure 1**. These piezometers have been chosen given to the availability of continuous data during the study period.

The monthly average groundwater recharge was estimated using monthly precipitation and groundwater levels data (**Table 1** and **Table 2**) over 24 months i.e. two (02) years (2018 and 2019).

Table 1. Monthly and annual precipitation, in millimeters, from Bamako's station.

Water Year	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Annual
2018	0.00	3.52	2.90	13.10	69.03	117.18	221.72	320.59	209.68	83.63	0.00	0.00	1041.36
2019	0.00	0.00	1.80	8.85	41.18	85.30	233.89	303.32	109.76	44.57	0.91	0.00	829.58

Table 2. Depth to water, in meters, in Bamako observation piezometers.

Periods	SE A4 Bis PZ1	P1 PZ2 aéroport	A1 A1 Bis PZ1 aéroport	A1 A1 Bis PZ2 aéroport	SE 10 PZ	SE 47 Gouana	SE 48 PZ Gouana	P1 S1	P2 S1	P1 Bramali	P2 Bramali	P3 Bramali	SE Gouana PZ	PZ 200	PZ 300
01-2018	20.48	17.3	38.00	36.35	41.79	25.02	29.1	7.16	6.25	12.94	11.8	15.16	6.76	10.18	9.32
02-2018	21.05	17.83	38.82	37.17	41.74	25.68	29.24	7.69	6.25	13.00	11.92	16.98	7.19	10.57	9.76
03-2018	18.63	18.15	37.97	36.35	42.12	26.07	29.24	7.94	6.5	13.06	11.86	15.76	7.54	11.85	10.06
04-2018	22.95	18.63	35.16	33.49	42.37	26.68	29.82	8.33	6.77	13.59	12.43	16.89	7.78	11.06	10.32
05-2018	20.68	19.07	38.52	36.82	42.2	24.45	29.63	7.92	7.21	13.12	11.03	15.54	7.73	11.2	10.34
06-2018	22.6	18.91	38.02	36.55	42.05	26.41	29.26	8.5	6.76	13.4	11.8	15.18	7.28	10.96	9.85
07-2018	21.31	18.16	35.84	34.00	43.04	13.12	20.33	6.85	6.51	13.27	11.13	16.62	6.06	9.97	8.67
08-2018	20.5	18.51	34.07	31.25	41.73	12.2	22.59	5.23	4.06	12.2	10.45	15.06	4.32	8.68	6.97
09-2018	18.26	15.76	36.54	34.77	40.37	11.17	25.2	5.44	4.05	11.8	10.25	14.2	3.7	7.56	6.32
10-2018	18.34	16.47	31.07	30.12	41.00	11.18	22.2	5.46	4.21	11.42	9.2	14.2	4.05	7.76	6.62
11-2018	20.21	17.2	39.18	38.07	41.19	11.35	22.71	5.76	4.94	11.76	10.08	14.23	4.86	8.3	7.42
12-2018	20.72	17.73	36.97	35.22	40.8	25.1	19.82	6.61	5.54	12.06	10.54	13.89	5.65	8.94	8.19
01-2019	21.93	18.09	30.17	29.08	40.86	25.35	22.66	6.93	6.09	11.83	9.88	12.8	6.25	9.6	8.8
02-2019	21.85	18.67	33.3	33.89	42.1	13.25	24.36	8.98	6.72	12.43	10.62	13.51	6.79	10.14	9.34
03-2019	19.15	19.05	32.12	37.63	40.79	25.68	25.07	9.14	7.04	13.32	11.5	14.7	7.18	10.33	9.37
04-2019	18.8	19.29	37.00	35.76	39.64	25.12	24.44	8.23	6.28	13.08	12.29	16.8	7.58	10.82	10.2
05-2019	21.87	18.71	39.11	36.69	41.45	25.63	24.64	8.25	6.63	13.52	11.43	15.28	6.96	10.61	9.59
06-2019	21.98	19.13	31.73	36.22	22.25	27.31	15.49	9.35	7.03	13.02	12.28	16.82	6.92	10.3	9.5
07-2019	21.92	18.92	35.42	36.45	31.85	26.47	24.2	6.83	5.59	11.47	11.19	15.7	6.15	10.33	8.8
08-2019	20.37	16.56	38.91	36.33	40.87	25.93	20.19	4.74	3.28	11.2	8.93	12.63	4.27	8.75	6.91
09-2019	19.2	15.58	37.16	34.89	39.26	24.74	20.84	4.84	3.56	11.00	9.35	14.17	3.47	7.58	6.08
10-2019	18.16	15.34	26.33	35.61	38.44	24.54	20.26	5.13	3.9	10.86	9.21	13.44	3.82	7.7	6.4
11-2019	17.6	16.27	38.36	35.25	39.04	25.05	13.88	5.7	4.82	11.28	9.79	14.36	4.7	8.25	7.23
12-2019	20.54	17.5	40.00	35.43	39.72	25.1	24.29	5.4	5.48	14.31	10.2	13.97	5.48	8.33	8.2

The piezometers used for this study are part of the network of the National Direction of Hydraulic of Mali (DNH-Mali) established for groundwater monitoring. The climate data have been collected from National Meteorological Agency of Bamako.

3.2. Method

Among the multiple methods (physical and chemical (Diouf, 2012)) that can be used to estimate groundwater recharge, the WTF method is considered to be an attractive method due to its accuracy (Addisie, 2022; Diouf, 2012) and because of the ease of use and low cost of the application in the semiarid areas (Diancoumba et al., 2020).

The Water Table Fluctuation method provides an estimate of groundwater recharge by analysis of water level fluctuations in observation wells or piezometers. The method is based on the assumption that a rise in water table elevation measured is due to the addition of recharge across the water table as shown in **Figure 5** for the piezometer PZ 300.

This approach is assuming that in dry period, the recharge to the water table is negligible and the groundwater levels decline while, in the rainy season, the recharge rate to the water table is considerable (Allison, 1988). These increases and decreases cause the water table fluctuations (**Figure 6**). The WTF method is appropriate in fractured aquifer (György, 1981) and requires determining for its application two important parameters: the groundwater level rise Δh and the Specific yield Sy.

These parameters are linked to each other and to the recharge by the expression indicated below in Equation (1):

$$\text{Rt} = \text{Sy}\,\Delta h/\Delta t \quad (1)$$

where Rt is the recharge, Sy is specific yield, Δh is the change in water table level (water level rise) and Δt is the time period.

3.3. Determination of Water Level (Δh)

According to Deg-Allier (Deg-Allier, 1963), the rise in water level due to recharge can be determined by calculating the total level oscillation amplitude if the overall recession regime i.e., the behavior of the aquifer without external recharge is known (**Figure 6**).

Deg-Allier (Deg-Allier, 1963) also found that the component forming a groundwater hydrograph, including those from a groundwater system, frequently each had a recession (**Figure 6**) that could be approximated by simple exponential relationships of the from as following in Equation (2):

$$h = h_0 \mathrm{e}^{-at} \quad (2)$$

where h_0 and h are the water level above discharge level at the beginning of the measurement period; and after a certain time (t) respectively and (a) is known as coefficient of recession or discharge coefficient.

After plotting the water levels above discharge level in semilogarithmic paper (when water level is plotted to the log scale and time to the arithmetic scale), the recession curves plot as nearly as straight lines (**Figure 6**). In the log system with base 10, the formula is a follow (Korkmaz, 1988) (Equation (3)).

$$\log h = \log h_0 - 0.4343at \quad (3)$$

According to (Johansson, 1987), the shape of the recession curves is function of parameters such as water yielding properties of the aquifer material, the transmissivity and the geometry.

For this study, the water levels have been measured monthly during 24 months through 15 piezometers. The oscillations amplitude due to infiltration have been calculated using recession curve displacement as indicated in Figure 7.

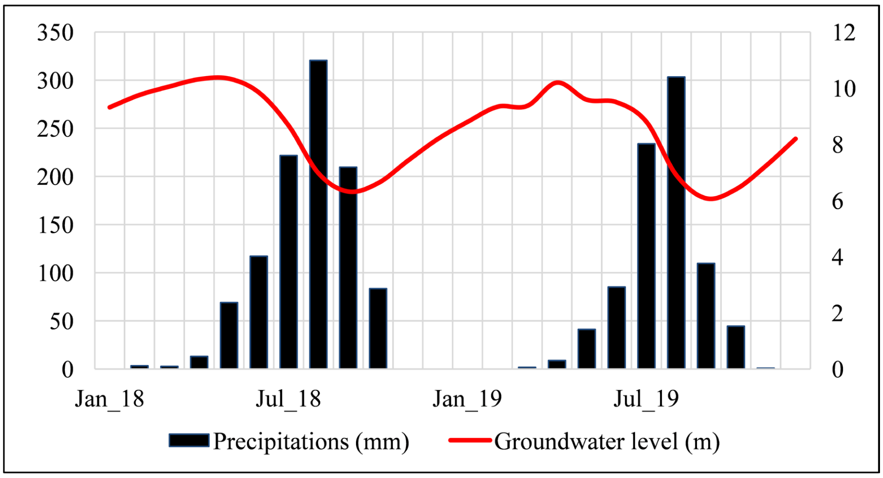

Figure 5. Fluctuations in water levels in piezometer PZ 300 due to precipitation.

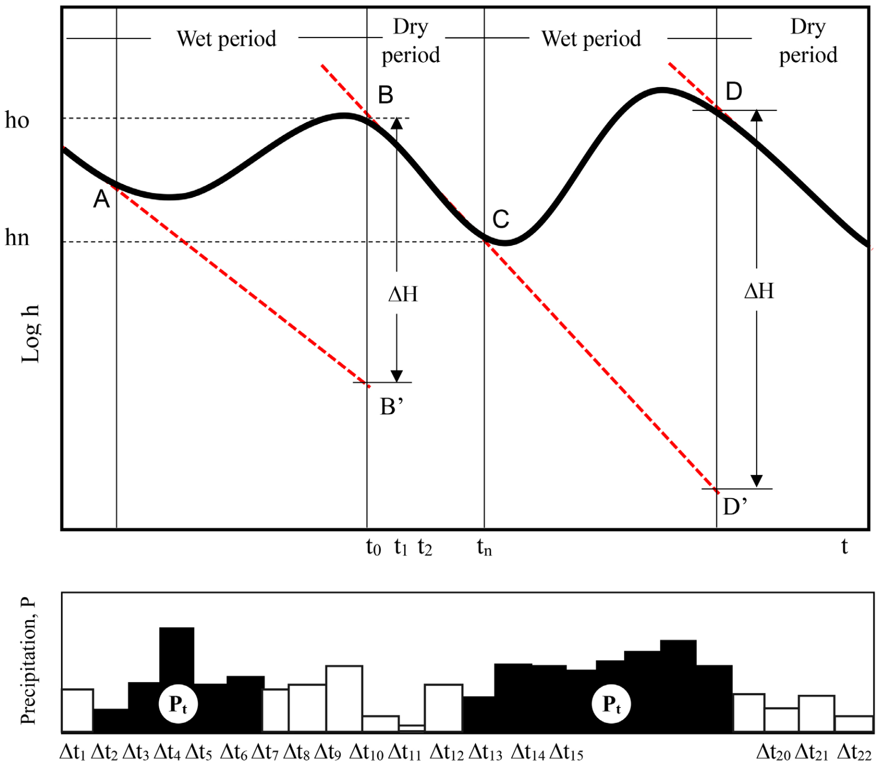

Figure 6. Fluctuations in water levels caused by recharge from precipitation from (Korkmaz, 1988).

3.4. Determination of Specific Yield (Sy)

Specific yield (Sy) is defined as the volume of water released from storage by an unconfined aquifer per unit surface area of aquifer per unit decline of the water table (Freeze & Cherry, 1979; Johansson, 1987). This parameter depends on the nature of the aquifer material and is related to the porosity through the Equation (4) according to Jacob Bear (Bear, 2012).

$$\eta = \text{Sy} + \text{Sr} \tag{4}$$

where:

η: porosity;

Sr: specific retention.

According to Sophocleous (Sophocleous, 1985), the specific yield is a crucial parameter for groundwater recharge calculation and its value varies according to the type of the aquifer material (Johnson, 1967; Sophocleous, 1985). To get an accurate value of the specific yield authors have developed many methods such as aquifer tests (Banton et al., 1991; Lv et al., 2021; Machiwal et al., 2017), water budget methods (Alex Thomas & Pankaj Kumar, 2021), volume balance methods (Walker et al., 2019), geophysical methods (Frohlich & Kelly, 1988), and laboratory methods (Islam et al., 2016; Lerner et al., 1990). The use of multiple methods aims to find out which of them gives the best value of Sy. According to many authors, the laboratory methods are considered as more reliable than all the other methods. They highly recommended to use the Sy value from literature when laboratory measurement values of specific yield are not available (Sinha & Sharma, 1988). They also recommended the use of same value of Sy for regions with the same geological and climatic conditions.

Many studies have been conducted in many parts of the world and near the study area to determine the value of specific yield in consolidated sandstone aquifers. Authors like Sinha and Sharma (Nygren et al., 2020) found that the value of Sy varies from 0.01 to 0.08 in sandstones in India. Values of specific yield have been determined by Touré (Toure et al., 2016) in Kléla basin and Koda basin which are all located in the same climatic and geological conditions as the study area. He found that the Sy ranged from 0.011 - 0.081, with a mean value of 0.042.

3.5. Estimation of Recharge

Seasonal cycles have influences on groundwater levels in such factors as recharge from precipitation, evapotranspiration, and discharge from wells and show a seasonal pattern of fluctuations (Nygren et al., 2020). The degree of correlation between fluctuations of groundwater level and fluctuation of total precipitation (Pt) in wet period furnishes a clue as to the freeness of the connection between recharge (water levels) and total precipitation (**Figure 5**) (Pt) in wet period (Korkmaz, 1988).

In this study and as applied by (Korkmaz, 1988) and (Blarasin et al., 2016), the estimated recharge was obtained by a direct estimation using recovery of the groundwater level (Δh) and total precipitation (Pt) during wet period (**Figure 4**). The line regression (Korkmaz, 1988) is Equation (5):

$$\Delta h = a + b\text{Pt} \tag{5}$$

where Δh is recovery of groundwater level, and Pt is total precipitation during the wet period, a and b are the regression coefficients.

To estimate the recharge, water level fluctuations curves have been established (Figure 8) for each piezometer form which the amplitudes of oscillation were calculated. The global recharge was calculated as the average of the values obtained from the piezometers in month time step.

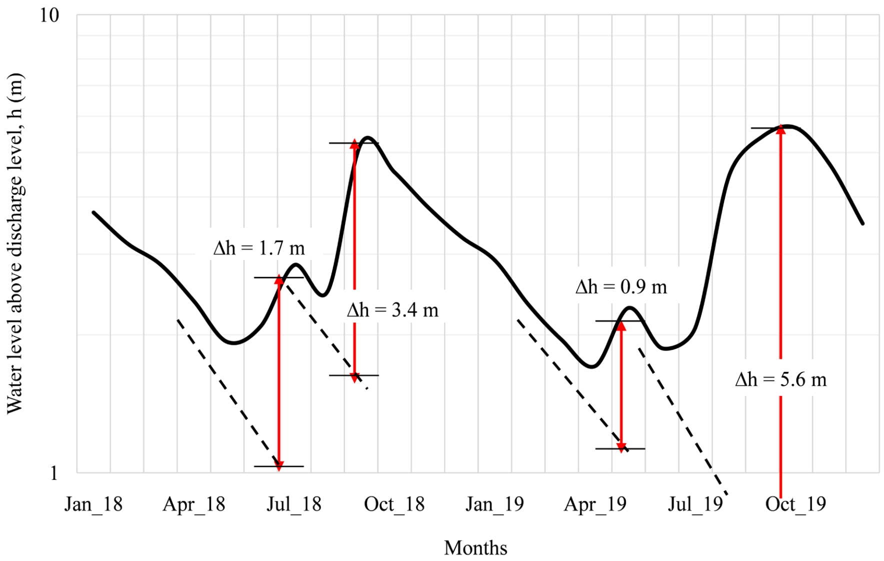

Figure 7. Determination of water level (Δh) in the piezometer "P1 PZ2 aéroport".

4. Results and Discussion

A visual inspection of hydrographs (Figure 8) reveals that the rise of the water level starts mainly during the rainy season (generally from Jun to October) and decreases during the dry season. These observations mean that groundwater is mainly due to precipitation in the study area.

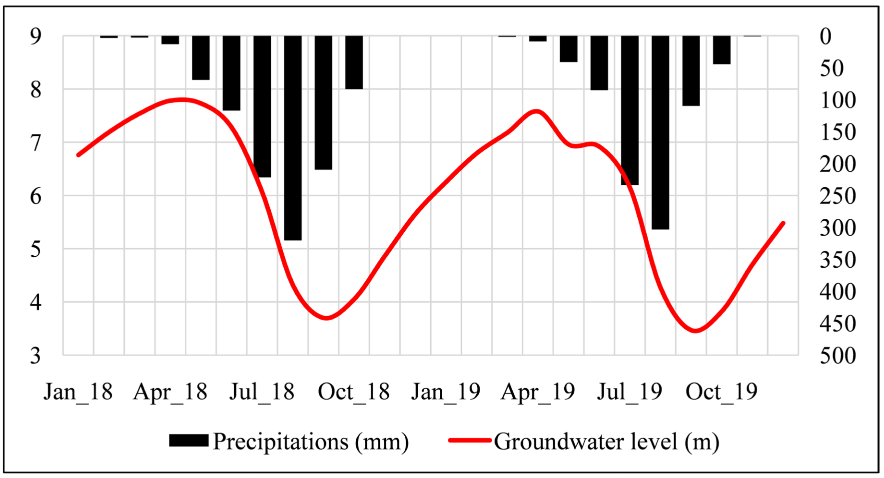

Figure 8. Monthly groundwater level fluctuations (m) and precipitations (mm) in piezometer SE Gouana PZ.

In addition to precipitation effects on groundwater levels, the fluctuations can be also caused by factors as the thickness of the aquifers, the soil and geology type, the local land cover and land use activities (Ajami, 2021; Diancoumba et al., 2020).

The monthly recharge values obtained from the 15 piezometers in the study area by using WTF method vary from 1.04 mm (for piezometer P1 Bramali with Sy = 0.011) to 38.81 mm (for SE 47 Gouana with Sy = 0.081) with an average value of 9.74 mm calculated with Sy equal to 0.042. As part of the precipitations, these values represent respectively 1.29%, 48.52% and 12.17% of monthly average precipitation during 24 months as detailed in **Table 3**.

Table 3. Monthly precipitation and calculated recharge in the piezometers.

Date	Piezometers	Monthly precipitation (mm)			Monthly recharge (mm) Sy = 0.01 - 0.08			Mean monthly ratio Recharge/Precipitation (%)		
		Max	Mean	Min	Max	Mean	Min	Max	Mean	Min
2018-2019	SE A4 Bis PZ1	320.59	80	0	25.18	13.06	3.42	31.47	16.32	4.27
2018-2019	P1 PZ2 aéroport	320.59	80	0	9.03	4.68	1.23	11.29	5.85	1.53
2018-2019	A1 A1 Bis PZ1 aéroport	320.59	80	0	22.23	11.53	3.02	27.78	14.41	3.77
2018-2019	A1 A1 Bis PZ2 aéroport	320.59	80	0	31.85	16.52	4.33	39.81	20.64	5.41
2018-2019	SE 10 PZ	320.59	80	0	27.17	14.09	3.69	33.96	17.61	4.61
2018-2019	SE 47 Gouana	320.59	80	0	38.81	20.13	5.27	48.52	25.16	6.59
2018-2019	SE 48 PZ Gouana	320.59	80	0	21.49	11.14	2.92	26.86	13.93	3.65
2018-2019	P1 S1	320.59	80	0	16.71	8.66	2.27	20.88	10.83	2.84
2018-2019	P2 S1	320.59	80	0	13.84	7.18	1.88	17.30	8.97	2.35
2018-2019	P1 Bramali	320.59	80	0	7.63	3.96	1.04	9.53	4.94	1.29
2018-2019	P2 Bramali	320.59	80	0	12.56	6.51	1.71	15.69	8.14	2.13
2018-2019	P3 Bramali	320.59	80	0	15.04	7.80	2.04	18.80	9.75	2.55
2018-2019	SE Gouana PZ	320.59	80	0	20.42	10.59	2.77	25.52	13.23	3.47
2018-2019	PZ 200	320.59	80	0	11.48	5.95	1.56	14.34	7.44	1.95
2018-2019	PZ 300	320.59	80	0	8.27	4.29	1.12	10.34	5.36	1.40

By analyzing the mean monthly ratio recharge over precipitation values, it appears difference between piezometers despite the fact that piezometers are mainly located in same climatic conditions. The difference in these values can be related to the thickness of the aquifers, the soil and geology type, the local land cover and land use activities as specified by (Ajami, 2021; Diancoumba et al., 2020). In the study area, the lowest recharge value (**Figure 9**) is observed in the piezometer P1 Bramali which is located in area mainly covered by industrial activities, whereas the highest value is observed in the piezometer SE 47 Gouana located in a mainly unoccupied zone.

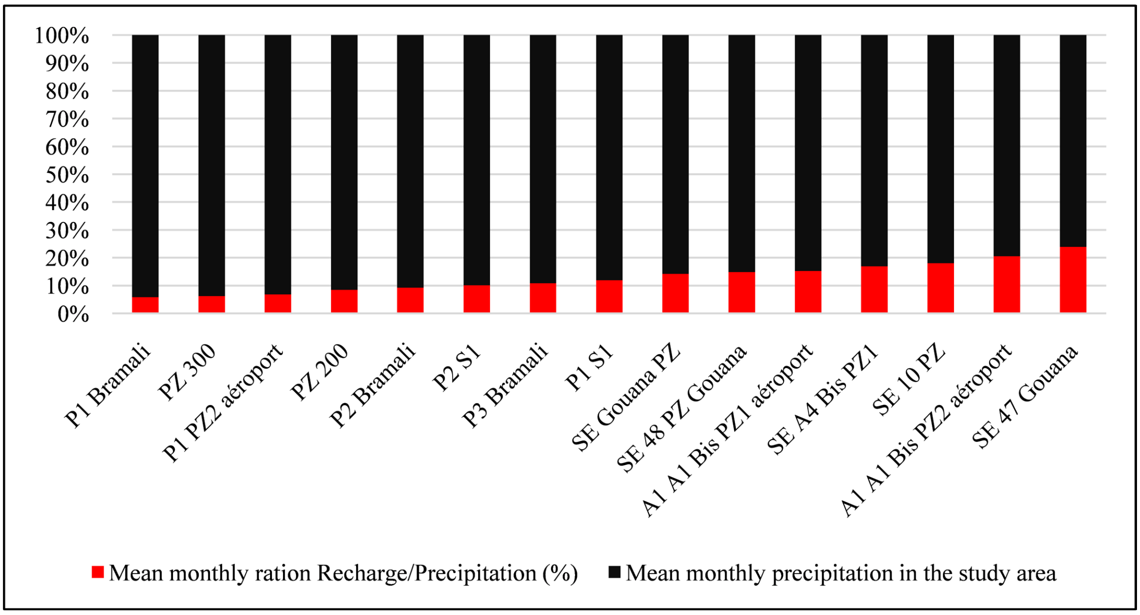

Figure 9. Relationship between mean monthly ratio of recharge over precipitation and mean monthly precipitation in the study area.

To see the main causes of the difference in recharge value between piezometers, lithological data obtained the piezometers drilled by (DIWI Consult International, 2000) have been analyzed. The analysis of these data has led to two lithological logs (**Figure 10**): the P1 Bramali piezometer zone log-type (**Figure 10(a)**) and the SE 47Gouana piezometer zone log-type (**Figure 10(b)**). These log-types show difference in the alteration thickness which can considerably affect the recharge rate.

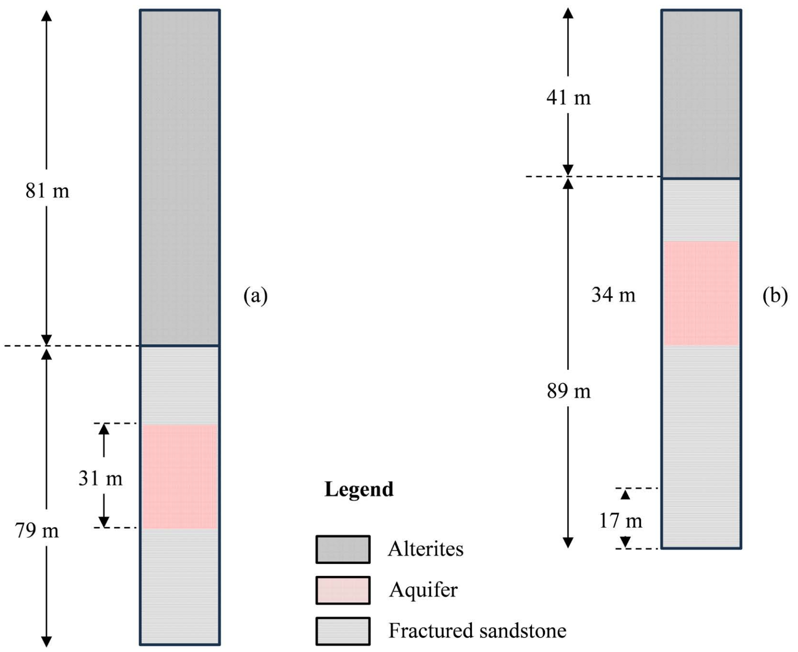

Figure 10. Lithological log-types in the study area: (a) P1 Bramali piezometer zone log-type and (b) SE 47Gouana piezometer zone log-type.

The most of the uncertainty using the WTF method is related to the Sy values. As the reliable value for a specific aquifer is difficult to find, values of Sy used in this study are experimentally obtained from regions with the same characteristics as the study area (Diancoumba et al., 2020).

The calibration of groundwater recharge has been done by comparing the results to those obtained in studies conducted in similar conditions like the study area through different methods. This external calibration of the recharge rate is due to the poor hydrogeological exploration of the study area. Thus, (Diancoumba et al., 2020) found that the recharge rate in the Koda catchment (in the North of the study area) varies from 3% to 26 % of annual precipitation by using the WTF method. The average recharge rate is 519 mm/year in the southern Mali according to (Henry et al., 2022) using a combination of modeling and stable isotopes. Through these comparisons, the results can be considered as reliable and the differences in the values might depend on factors specified above.

5. Conclusion

The estimation of groundwater recharge is important for its efficient management specially in semiarid areas like Bamako and surrounding areas. This study aimed to estimate the monthly groundwater recharge using the WTF method. The results obtained are exclusively based on the water level fluctuations analysis observed during two years (24 months). The monthly average recharge obtained during 24 months is 9.74 mm which is about 12% of the monthly average precipitation in the study area. It appears in this study that despite the piezometers belonging to the same climatic zone, the recharge rate can be different because of many factors such as the thickness of the aquifers, the soil and geology type, the local land cover and land use activities.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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