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Research Article

Characterization of Groundwater Recharge Using the Water Table Fluctuation Method in the Koda Catchment, Mali

Oumou Diancoumba[1, 2], Hamadoun Bokar [3], Adama Toure [3], Nelly Carine Kelome [4], Kwasi Preko [5]

[1]Graduate Research Program on Climate and Water Resources, West African Science Service Center on Climate Change and Adapted Land Use (WASCAL), Department of Applied Hydrology, University of Abomey-Calavi, Cotonou, Abomey-Calavi BP 2008, Benin
[2]Ecole Normale Supérieure de Bamako, Département Science de la Vie et de la Terre (SVT), B.P. 241, Bamako, Mali
[3]Ecole Nationale d'Ingénieurs Abderrahmane Baba TOURE, ENI-ABT, Bamako, Mali
[4]Université d'Abomey-Calavi, Faculté des Sciences et Techniques, Cotonou, Benin
[5]University of Kwame Nkrumah of Sciences and Technology, KNUST, Ghana

Correspondence should be addressed to Oumou Diancoumba, *oumoudianc@gmail.com*

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Abstract Groundwater is significantly requested in all the activities of the inhabitants of the Koda catchment. The knowledge on the approximate quantity of annual precipitation of water achieving groundwater table is then the key word on water resources management system, in particular for the decision makers of the Koda Catchment. Due to the lack of the measurement of historical observation data, the groundwater resources dynamics are poorly understood in this catchment. The main objective of this paper is to estimate the annual groundwater recharge from the annual precipitation of the Koda catchment using Water Table Fluctuation method WTF. The annual rainfall data and monthly piezometric level data have been used to estimate the annual groundwater recharge from 3 piezometers and 4 shallow wells. The values of recharge obtained from the three monitoring piezometers are ranged from 61 mm to 173 mm, i.e. to 7% and 29 % of annual rainfall while for the four wells the mean recharge is varying from 26 mm to 186 mm corresponding to 3% and 26 % of the annual precipitation. The results of the current study can be used for well managing the groundwater resources in the Koda where the surface water resources are limited.
Keywords *Annual Rainfall; Infiltration rate; Physical Method; Southern part of Mali.*

1. Introduction

In arid and semi-arid regions, groundwater resources are mainly used as the main source of water due to the limited availability of surface water resources. Over the last decades, the increase in groundwater extraction has led to a considerable reduction of groundwater storage as well as pumping rates have greatly exceeded natural recharge. Many researchers working in those regions aim to understand recharge processes and determining effective ways in which recharge can be enhanced naturally [[1]-[9]]. Mali, the country belongs to the arid and semi-arid areas, is coping this issue of groundwater recharge studies. It is useful to notice that the important aquifers in Mali in terms of quantity and quality are located in the sandstones plateaus dated of the infra-Cambrian [[10]].

According to PNMRE [[11]], the quality of water of the Infracambrian tabular layer is so far acceptable to be used for irrigation; that can increase the groundwater availability stress. The Koda catchment that is the study area belongs to that infra-Cambrian layer. Groundwater is the main water resources in the Koda catchment like many places in the arid and semi-arid zones. All the domestic water supplies as well as water used for agriculture, drinking and livestock are entirely depended upon groundwater through deep boreholes and hand dug wells during the dry season. During the rainy season (from May to October) rainfall added to groundwater are used for water needs in the Koda catchment. The groundwater resources dynamic is poorly understood in the study catchment may be due to the lack of measurement of historical observation data. According to Lutz et al. [[12]], a better understanding of groundwater levels and recharge patterns in a country is critical for development. This study area is an ideal region to characterize the recharge process because there is no appropriate groundwater management system to face the problems related to the use of groundwater.

Only a few studies have been done in infra-Cambrian sandstones in Mali to evaluate the groundwater recharge; most of the studies are undertaking in Bani catchment [[10], [13]–[16]]. For example, the ARP Development project [[14]] estimated the recharge value to 15% of the annual rainfall in the Sikasso region in the southern part of Mali using the WTF. Furthermore, Dakoure [[17]] used a various method different from the WTF method to characterize the recharge in the southern part of Taoudeni basin where the study area is located and found as recharge values of 75 - 120 mm from thornthwaite method and 127 mm (14% of annual rainfall) from a lumped model. Which differ from the value obtained by Bokar et al. [[15]] using thornthwaite method in the Kolondieba catchment (Sudanese Climate Zone in Mali) and found 147 mm.y-1or 13% of total rainfall as the annual total recharge. In addition, Toure et al. [[16]] used the lumped Earth model and acquired 156.8 mm as overall mean annual recharge for 2013-2014 representing 12% of the overall mean annual rainfall in the Precambrian sandstone aquifer in the semi-arid Klela basin.

These latter estimates have been, however, generated for the southern part of Mali but, no specific study has been undertaken in the Koda catchment regarding the estimation of the groundwater recharge at the catchment scale. There is then a need to study the spatiotemporal variation of groundwater in the Koda catchment using an appropriated method. A clear picture of the variation of annual groundwater resources in the Koda catchment was missing. As the infiltration is an important input parameter for most of all water budget models, it is essential to know what is the amount of the precipitation that goes into the aquifer as recharge? How the recharge rate is influencing by the precipitation regime? In order to fill this gap, the well-known Water Table Fluctuation (WTF) method was applied to four wells and three piezometers to characterize the recharge rate of the interest catchment.

The WTF method is widely used in groundwater recharge study, mainly in the areas where the data availability is an issue. The large application of the WTF method in the semi and arid areas is related to its accuracy, the ease of use and the low cost of application [[18]]. The WTF method requires water level data, the specific yield to estimate the groundwater recharge. Details of the method will be discussed throughout this paper. The overall objective of that study is to evaluate the seasonal and annual variations in water level rise and to estimate the groundwater recharge in the stud catchment. Furthermore, the infiltrated water will be determined in terms of the percentage of annual rainfall in the Koda catchment.

2. Study area

The study area of the Koda catchment is located in the semi-arid zone of West Africa, precisely in the southern part of Mali at 120 kilometers in the North of Bamako, the capital of Mali. The Koda catchment is located in Infrcambrian Tabular Layer (112 000 km^2) and is a sub-catchment of the Taoudeni basin [[19]]. The area lies between the latitude: 13° 56’00" N and 12° 57' 80 " N and the longitude: 7° 30' 8" W and 8° 28′5 " W with 333,233 inhabitants. The main surface water body occurring in the study area is Koda stream, one of the tributaries of the Niger River. The study catchment has a total surface area of about 4921 km^2 (see Figure 1).

The study area is surrounded by two metrological stations: Bamako and Katibougou stations and record data from these two stations have been used to describe the climate of the Koda catchment. The climate type of Koda catchment is Sudano-Sahelian. The overall mean annual rainfall for the last 30 years (1987-2016) fluctuates from 500.4 to 1,164.3 mm, recorded at Katibougou station while at Bamako station, the annual average of rainfall over the last 30 years varies from 644.3 mm (the year 2007) to 1,205 mm (the year 2008). The overall annual mean rainfall ranges from 1987-2016 is 862.62 mm. In the Koda catchment, the rainfall seasons are pretty known but the onset is unpredictable, mid-May to end of June [[20]]. See Figure 2.

In the interested catchment, the highest values of temperature are recorded in April and May while the lowest values in December and January. The mean annual temperature recorded at Katibougou and Bamako stations were about 28.3°C and 28°C respectively. The overall mean annual value of the Evapotranspiration for the period 1987-2016 recorded at Katibougou station is about 2082 mm while the PET value recorded at Bamako station is 2068 mm. See Figure 2.

The Koda catchment is located in the sandstone plateau geological unit as defined in [10]. 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 of the Koda catchment. The dolerite intrusion is dated to Permian or Trias [[21]].

The Koda catchment is part of the 74 b hydrogeological unit as defined in [10]. Two types of aquifer have characterized the aquifer of the study area:

- The shallow aquifer in the unconsolidated superficial-altered formations (laterites, clay, sand,) is reached in the first 15 meters below ground surface with the thickness values ranged from 4-34 m. The transmissivity of the superficial aquifer is ranged from 1 to 176 m^2/ day [[11], 22].
- The deep aquifer in the epicontinental sandstones with obliques stratifications, schist, and dolerites formations is located around 20-60 m underground surface in most of the several boreholes. The aquifer transmissivity is varying from 1 to 541 m^2/ day [[11], 22]. There is an interconnection between the two aquifers depending on the pluviometry and the degree of fracture of the sandstone. Figure 1 describes the localization of the study catchment.

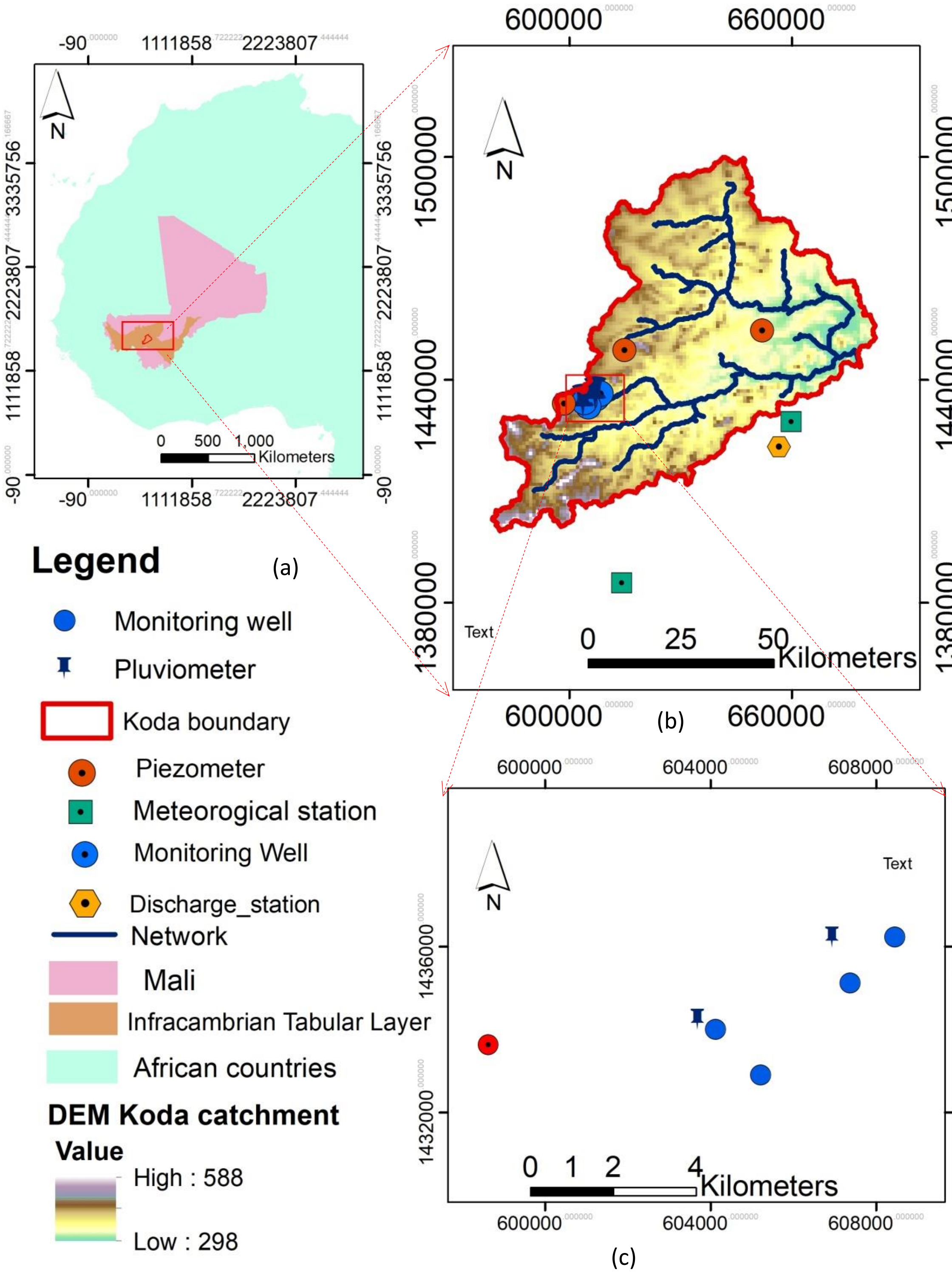


***Figure 1:** Location of the Koda catchment: (**a**) Localization of the study area over West Africa; (**b**) Zoom on the study catchment and (**c**) Zoom on the monitoring wells*

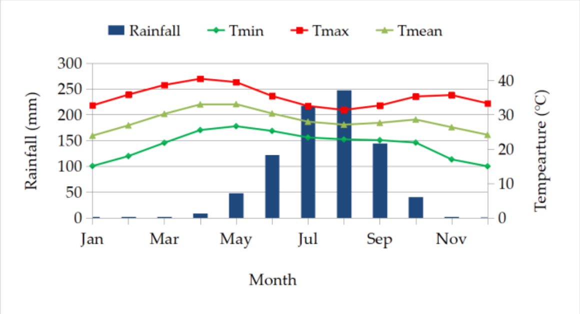


Fig.2a: Monthly Temperature (max, mean, min) and Rainfall from 1987 to 2016 at Katibougou station (data source from DNM of Mali).

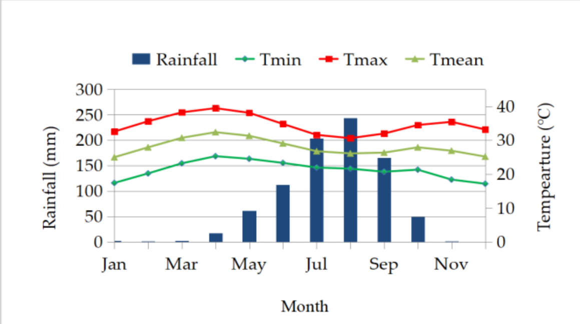


Fig.2b: Monthly Temperature (max, mean, min) and Rainfall from 1987 to 2016 at Bamako station (data source from DNM of Mali).

Figure 2: *Monthly average rainfall (mm) (blue bars) and temperature (green and red lines) in the Koda catchment from 1987–2016 (data Source from DNM), (a) data recorded at Katibougou station and (b) data recorded at Bamako station*

3. Materials and Methods

3.1. Data

The Koda catchment as most of the catchment in Africa have limited on data availability caused by the data gaps in most of the recorded piezometers, Three (3) piezometers, and four (4) wells have been selected in the study area to apply the Water Table Fluctuation method. The monthly rainfall and weekly piezometric data have been used to estimate the annual groundwater recharge. From this recharge result, it has have been deduced the percentage of annual rainfall that has been infiltrated into the water table in the Koda catchment.

The piezometers were from a network established since 1984's by the PNUD in sedimentary formations in the study area. The monitoring wells were established by the “Association Malienne Pour l'Education du Public et la Protection de l'Environnement (AMEPPE)” and WaterAid Mali since 2012 to monitoring groundwater level. To achieve the objective of the study, monitoring piezometers and wells with short record duration time (i.e. less than one year) and also those with excessive gaps and incorrect values have not been taking into account in the current study. The seven monitoring sites e selected (three piezometers and four wells) are located in the same hydrogeological environments. The wells were used for the water supply of the inhabitants.

The groundwater level in the piezometers Fansiracoura F1 and Kossaba K1 was recorded manually once a week using a probe, while that of Nossombougou N1 was recorded automatically every minute. The static groundwater level data in all the wells have been measured twice a month using a probe. The complementary hydrogeological data (drilling boreholes, water level, pumping test, etc.) and rainfall data have been collected from the National Direction of Hydraulic of Mali (DNH-Mali), NGOs (WaterAid, AMEPPE) and field. The climate data have been collected from National Meteorological agency of Bamako and the regional meteorological Agency of Koulikoro (Katibougou). Some meteorological data have been collected from the farmers and NGOs within the basin. The length of the available data is varying from one to nine years.

3.2. Method

According to Allison [[23]] and Foster [[24]], the recharge method is outlined by physical and chemical method, the WTF method is among the physical method which is considering as an attractive method due to its accuracy, the ease of use and low cost of the application in the semiarid areas The WTF method is widely applied throughout the world by scientists since the 1920s to estimate groundwater recharge [[25]]. Many studies under different climatic conditions since the 1920s until now have been carried out [[13], [16], [26]–[31]]. The large application of this method is due to its simplicity but also the availability of groundwater level data. The method is also appropriate to the fractured media [[32]]. The application of the Water Table Fluctuation Method is based on assuming that any fluctuation of the water table is due to the recharge water reaching the groundwater. To apply the method, the estimation of parameters such as the groundwater level rise Δh and the Specific yield S_y are required. The Specific yield is linked to the change in water table height by Equation 1:

Equation 1

$$R_t = S_y \frac{\Delta h}{\Delta t}, \qquad 1)$$

Where R [LT $^{-1}$] is recharge, Sy is specific yield (dimensionless), Δh is a change in water table height and (L) through time Δt (T).

3.2.1. Determination of the water level Δh

According to Healy and Cook [[32]], Δh is the difference between the top of the rise of water level and the lowest point at the time of the top of the extrapolated antecedent recession curve (see Figure 3). The recession curve is defined as the trend that the well hydrograph will follow when there is no presence of any rising of rainfall [[32], [34]].

In this current study, the graphical exploration was used to determine the water level rise in the monitoring wells and piezometers. It is a simple method and used a visual examination method, which makes it very subjective because from one to another user the provided MRC can be different, therefore the value of annual recharge can be affected (see
Figure **3** below):

For the year 2008 in Fansiracoura piezometer while Sy=0.011; Δh = 4.2 m. The annual recharge was estimated as follow R=0.011*4,200 = 46.2 mm. The groundwater level is measured in meters below ground level (mbgl).

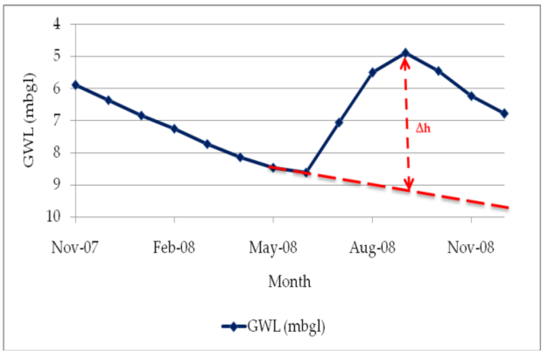


Figure 3: *Recharge estimated using the graphical approach to the WTF method.*

3.2.2. Determination of the specific yield S_y

Once the groundwater level rise is determined, there is a need to determine the specific yield. S_y of a rock or soil is considering as the portion of the volume of water that will drain by gravity from a saturated rock to total volume of the rock [[26], [35]]. The specific yield S_y is linked to the porosity and specific retention by the following

Equation 2:

Equation 2

$$S_y = \phi - S_r \quad (2)$$

Where ϕ is porosity and S_r is specific retention [[32]]

The Sy is playing a crucial role in the calculation of groundwater recharge [[36]]. To get an accurate value of the Sy, many methods have been developed to estimate the Sy parameter. Some of them are field methods such as aquifer tests, water budget methods, volume balance methods, geophysical methods, and Laboratory methods. Lerner et al. [[37]] considered the Laboratory methods as more reliable than all the other methods. Theoretically, the Sy parameter of a rock or soil is defined as a constant while in practice it is dependent of the lithology of the rock. It is varying as a function of depth to water table [[35], [38]]. According to many authors like Lerner et al. [[37]] and Obuobie [[39]], the use of the value of Sy from literature is highly recommended when the laboratory measurement values of specific yield are not available. When the geological conditions and climatic conditions are the same, the use of the specific yield value can be used for each other.

In the current study, the value of specific is taking from literature. Lerner et al. [[37]] and Sinha & Sharma [[40]] used the value of Sy of the sandstones ranged from 0.01 to 0.08 in the recharge calculation in India. According to Healy and Cook [[32]], the values of Sy of the sandstones are ranging from 0.005 to 0.19. Toure [[16]] determined the specific yield of Klela basin in Mali from pumping test data of ten boreholes using Ramsahoye and Lang [[41]] method. Klela basin and Koda basin are all located in the plateaus infra-Cambrian sandstones and both of them are located in the southern part of Mali with same climatic conditions. Toure [[16]] found the values of Sy ranged from 0.011-0.081, with a mean value of 0.042. Therefore, the values of 0.011 and 0.042 are used as the values of Sy.

3.3.3. Estimation of Recharge

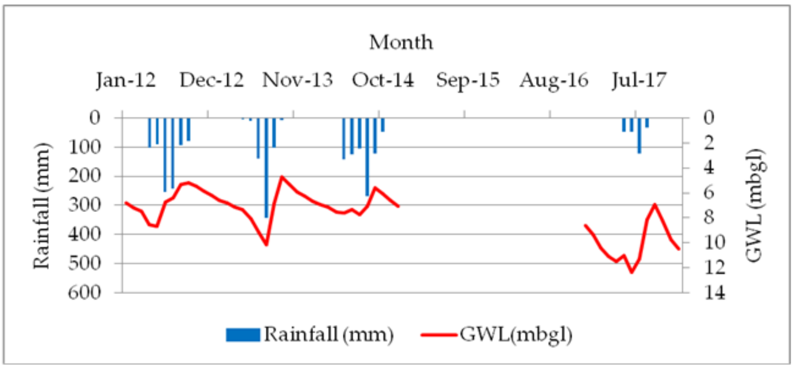
Recharge was calculated at an annual scale based on the observed groundwater level fluctuation [[16], [31], [32], [39], [42]– [44]].

4. Results and Discussion

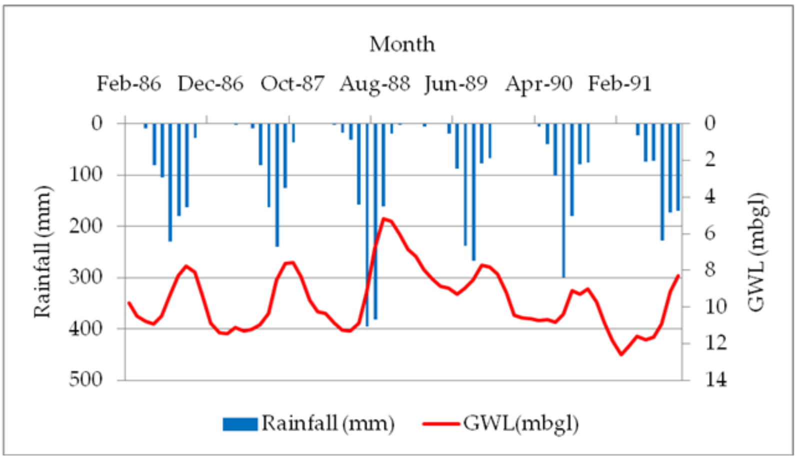
4.1. Relationship Rainfall-Infiltration

From the visual inspection of hydrographs, the water level starts rising during the rainy season, it means that precipitation is the main source of groundwater recharge in the study catchment. In the three piezometers, we noticed that the groundwater level is rising in July two months after the onset (May) and it is decreasing in October corresponding to the end of the rainy season. For more details See
Figure ***4*** (4a, 4b, and 4c).

Figure *4*, Figure 4.a – 4.c are shown the groundwater level against rainfall in the three monitoring piezometers and figure 4e -4d for the four monitoring wells.



(a)



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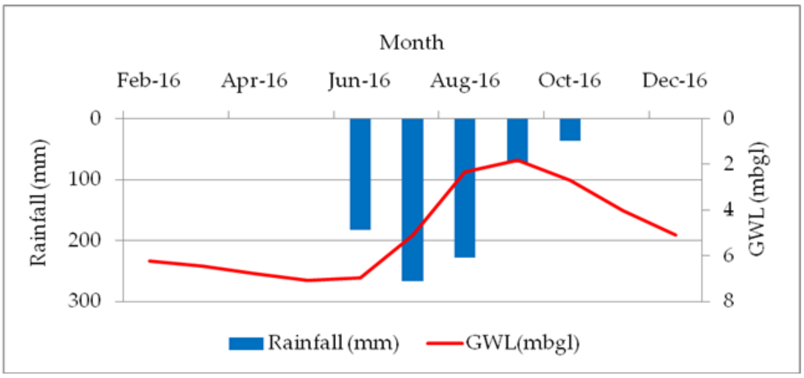
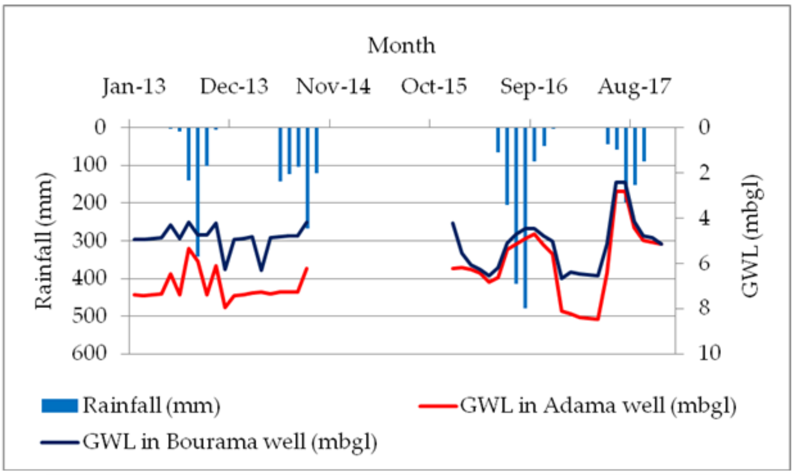
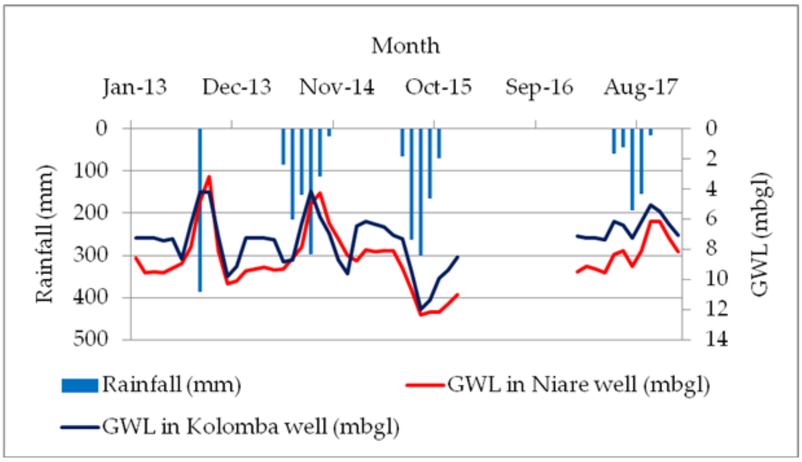


(c)

In the four wells, the rising of the groundwater level is sometimes observed at the beginning of the onset, which could assume that they are located on the unsaturated (vadose) zone (depths are varying from 9 to 17m).See figure 4 (4d-4e) below:



(d)



(e)

***Figure 4**: Monthly Groundwater –Level – Fluctuations (m) and Rainfall (mm) records: (**a**) Piezometer Fansiracoura F1 (2008-2017); (**b**) Piezometer Kossaba K1 (1986-1991); (**c**) Piezometer Nossombougou N1 (2016-2017); (**d**) Wells Adama and Bourama (2013-2017); (**e**) Wells Niare and Kolomba (2013-2017).*

As already expected by many authors cited in Kotchoni et al. [[31]] we observe that the fluctuation of the water table is influencing by many phenomenon apart from the rainfall. The increase of the gas pressure in the vadose zone, the earth tides, the pumping, and the lateral flow are some of the causes of the rising of the water.

The results show that recharge occurs annually in response to the seasonal rainfall. The values of recharges are varying from shallow to deep aquifers through wells and piezometers respectively. From place to place, from year to year the value of recharge is also varying. These differences could be primarily due to local climate conditions (precipitation and temperature regimes. Others additional causes can be the exploitation of the wells by the inhabitants of the Koda catchment (the measured values of the groundwater level could be the dynamic level instead of the static level), the thickness of the aquifer, the soil and geology types, the local land cover and land use activities.

4.2. Estimation of the recharge

For the piezometer Fansiracoura F1, the greatest annual recharge occurred in 2013 with 298 mm (45% of annual precipitation) for the Sy=0.042, although the greatest annual of recharge with Sy=0.011 is 78 mm, i.e. 12% of annual rainfall. The minimum recharge occurred in 2014 for Sy = 0.011 and Sy =0.042 respectively 97 mm (12% of precipitation) and 25 mm corresponding to 3% of the annual rainfall, which is also the minimum of the period. The mean recharge values for piezometer Fansiracoro F1 was varying from 61 mm to 133 mm representing respectively 8 % to 29 % of annual rainfall. The mean maximum value obtained in the year 2013 is 133 mm about 29 % of the 538 mm recorded as annual rainfall. For the second piezometer Kossaba K1, the greatest annual recharge occurred in 1988 with 265 mm, which was 33% of the annual rainfall, although the highest percentage recharge period was in 1991, with 30% of rainfall (244 mm of 812 mm of Precipitation). The minimum recharge occurred in 1989 with 69 mm, i.e. 6% of 1164 mm of precipitation, for Sy =0.042 and 22 mm (3% of P) for Sy =0.011 which is also the minimum of the period. The mean values of groundwater recharge range from 7% to 19 % for the period 1986 to 1991. The highest value of recharge recorded in Nossombougou N1 in the year 2016 is 223 mm (25 % of annual P) and minimum recharge is estimated to 58 mm of 902 mm as annual precipitation representing 6 % of the annual rainfall. The mean recharge value was estimated at 15% of annual rainfall in the year 2016.

The mean annual recharge estimated in Adama well from 2013 to 2017 was varying from 26 mm to 152 mm representing respectively 3 % to 28 % of the annual rainfall, while for Bourama well, the mean annual recharge is ranged from 40 mm to 109 mm (5 % to 20% of annual rainfall). The highest value of water infiltrated in Niare well and Kolomba well is getting in the year 2013 respectively 159 mm and 186 mm about 22% and 26 % of the annual rainfall. The lowest value is estimated in the year 2017 for Niare well with 80 mm (14%) while for Kolomba well, the lowest amount of recharged water is 53 mm (6% of annual rainfall) in the year 2015.

These values were closed to the results obtained from previous studies undertaken in similar zones using the WTF method. The UNDP project in 1990 applied the WTF in the fissured aquifer in Sudanian and Sudano-Sahelian zones of Mali where the Koda catchment is located and found that the water that is infiltrated is varying from 140-220 mm/year (10-20 % of annual rainfall). The project ARP Development [[14]] evaluated the recharge value as 15% of the annual rainfall in the southern part of Mali using the WTF method. Dakoure [[17]] used various method to characterize the recharge in the southern part of Taoudeni basin where the study area is located and found as recharge values 75 - 120 mm from thornthwaite method and 127 mm (14% of annual rainfall) from a lumped model. CIEH-USAID 1987 cited in Dakoure [[17]] estimated the mean annual recharge for sandstones aquifers varying from 0 to 200 mm. Varni et al. [[46]] applied the WTF method to characterize groundwater recharge in Argentina and found as minimum recharge about 23 mm (4% of annual P) and the greatest value of recharge equal to 539 mm, i.e. 33% of annual rainfall. Jassas and Merkel [[44]] used the WTF to estimate the mean groundwater recharge by year about 111.6 mm (17 % of annual Precipitation) in North Iraq under the semi-arid climatic zone. Naylor et al. [[47]] used a one dimensional 1D Hydrus model to estimate the recharge rate of 16 to 58 % of the annual rainfall in the various glacial settings of the mid-continental USA. Atta-Darkwa et al. [[48]] used the WTF method for 14 piezometers in Ghana, to quantify the values of recharge at 9%-31% in 2009 and 4%-34% in 2010 of the annual rainfall. Toure et al. [[16]] acquired 156.8 mm as overall mean annual recharge for 2013-2014 representing 12% of the overall mean annual rainfall in the Precambrian sandstone aquifer in the semi-arid Klela basin. Most of the values obtained applying the WTF method to characterize the groundwater recharge in the Koda catchment are ranged in that interval. The results of the current study seem to be reliable because the values of the recharge are closed to previous recharge values found in others previous studies undertook in the infra-Cambrian sandstones aquifers in the arid and semi-arid regions. The values of annual rainfall, recharge and

the mean annual ration recharge /rainfall for the three piezometers and four wells are outlined in the tables (
Table ***1***-
Table *2***Error! Reference source not found.**) below.

Table 1: *Annual rainfall and calculated recharge in the three piezometers.*

Date	Name of piezometers	Annual rainfall (mm)			Annual recharge (mm) Sy=0.011-0.042			Mean annual ratio Recharge/rainfall (%) Sy=0.011-0.042		
		Max	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**
2008-2017	Fansiracoura F1	901.8	732.2	538	173	109	61	29	15	8
1986-1991	Kossaba K1	1,164	846	658	167	95	53	12	10	7
2016	Nossombougou N1		902			141			16	

Table 2: *Annual rainfall and calculated recharge in the four wells.*

Date	Name of wells	Annual rainfall (mm)			Annual recharge (mm) Sy=0.011-0.042			Mean annual ratio Recharge/rainfall (%) Sy=0.011-0.042		
		Max	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**
2013-2017	Adama well WA1	1,127	767	539	152	82	27	28	13	3
2013-2017	Bourama well WB1	1,127	767	539	109	67.25	40	20	10	5
2013-2017	Niare well WN1	885	760	567	159	139	80	22	18	14
2013-2017	Kolomba well WK1	885	760	567	186	122	53	26	17	6

The main differences between piezometers and wells may due to the fact that monitoring wells are located in the vadose zone where the phenomenon of evapotranspiration occurs.

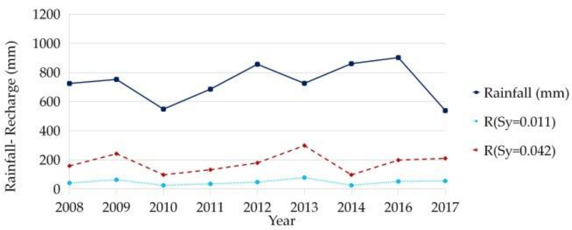
4.3. Magnitude of recharge

The magnitude of the recharge is based on its minimum and maximum values obtained over the study area. These values of recharge obtained from WTF method applied to Koda catchment are ranged from 61 mm to 173 mm, i.e. 7% and 29 % of annual rainfall for the three monitoring piezometers while for the four wells the mean recharge is varying from 26 mm to 186 mm corresponding to 3% and 26 % of the annual precipitation.

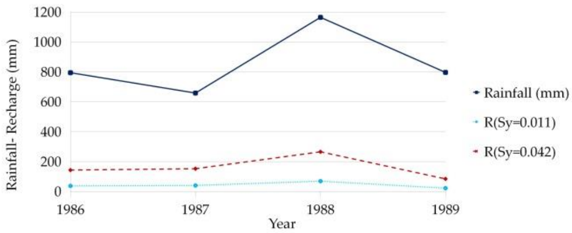
4.4. Uncertainty

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 fund, we, therefore, used two values of the Specify yield (Sy=0.011 and Sy= 0.042) in order to get the range for the recharge values in the Koda catchment. The change of Sy values shows the uncertainty related to that parameter. The groundwater recharge is directly proportional to the Sy value. For the piezometer Fansiracoura F1, the greatest annual recharge occurred in 2013 with 298 mm (45% of annual precipitation) for the Sy=0.042, although the greatest annual of recharge with Sy=0.011 is 78 mm, i.e. 12% of annual rainfall. The minimum recharge occurred in 2014 for Sy = 0.011 and Sy =0.042 respectively 97 mm (12% of precipitation) and 25 mm corresponding to 3% of the annual rainfall, which is also the minimum of the period. The mean recharge values for piezometer Fansiracoro F1 was varying from 61 mm to 133 mm representing respectively 8 % to 29 % of annual rainfall. The mean maximum value obtained in the year 2013 is 133 mm about 29 % of the 538 mm recorded as annual rainfall. For the second piezometer Kossaba K1, the greatest annual recharge occurred in 1988 with 265 mm, which was 33% of the annual rainfall, although the highest percentage recharge period was in 1991, with 30% of rainfall (244 mm of 812 mm of Precipitation). The minimum recharge occurred in 1989 with 69 mm, i.e. 6% of 1164 mm of precipitation, for Sy =0.042 and 22 mm (3% of P) for Sy =0.011 which is also the minimum of the period. The mean values of groundwater recharge range from 7% to 19 % for the period 1986 to 1991. The following Figure 5 (a-g) shows the annual variations in precipitation and groundwater recharge (depending on the value of Sy) of the monitoring sites.

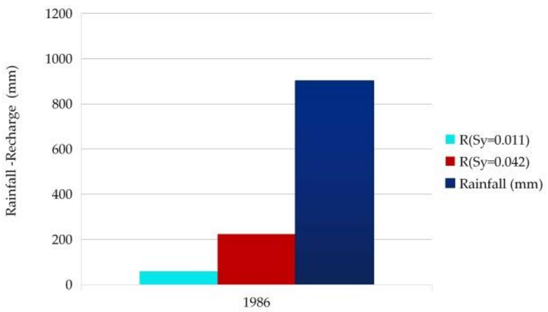
The annual recharge follows rainfall variations but in some figures, we observed an augmentation of the annual rainfall and the decreasing of the annual recharge (i.e. fig 5 g in the year 2015) that might be due to the intensity of the rainfall, heavy rainfall tend to increase surface runoff. Additional causes of that the wells are located in the unsaturated zones and also the degree of facture of the rocks. In conclusion, the relationship between the recharged water and the amount of rainfall is not linear, it seems to be logarithmic. The same remark has been done by ARP Developpement [[14]] using the WTF method in the southern part of Mali.



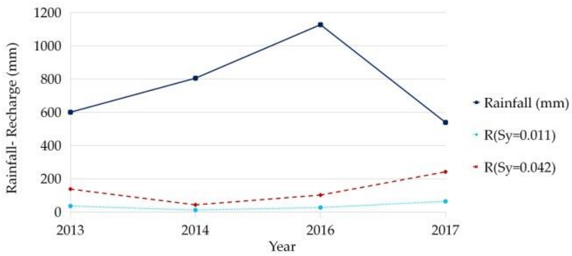
(a)



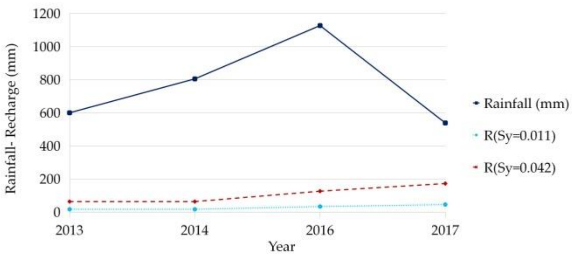
(b)



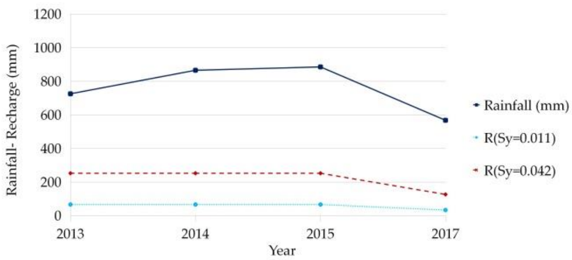
(**c**)



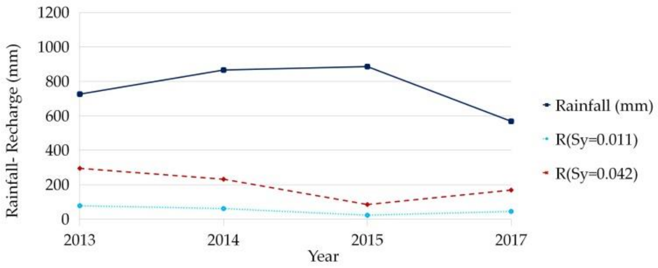
(**d**)



(**e**)



(f)



(g)

***Figure 5**: Annual variations in precipitation and groundwater recharge while Sy=0.011 and Sy= 0.042: (**a**) Piezometer Fansiracoura F1 (2008-2017); (**b**) Piezometer Kossaba K1 (1986-1991); (**c**) Piezometer Nossombougou N1 (2006) ; (**d**) Well Adama (2013-2017); (**e**) Well Bourama (2013-2017); (**f**) Well Well Niare (2013-2017); (**g**) Well Kolomba (2013-2017).*

5. Conclusion

The WTF method is considering as an attractive method due to its accuracy, the ease of use and low cost of the application in the semiarid areas. The results obtained as mean annual recharge are very similar to those found in the previous studies undertaking in similar aquifers systems and under same climatic conditions. The values of recharge obtained from WTF method applied to Koda catchment were ranged 7% and 29 % of annual rainfall for the three monitoring piezometers while the mean recharge is varying from 3% and 26 % of the annual precipitation. The relationship between recharge and rainfall is not linear. Groundwater recharge estimation is very complex using an empirical method such as WTF method because of the determination of the value of Sy, which is very crucial and also the use of water level fluctuations, which is subjective. The accurate knowledge of the groundwater recharge is essential for the sustainable groundwater management system in the irrigated zone like Koda catchment; therefore, the results of the current study can be used for well managing the groundwater resources in the Koda where the surface water resources are scared.

Recommendations

This study results will help policy makers:

- To take an informative decision about allocation and protection of groundwater.
- To plan future irrigation based on the annual recharge value.
- To implement more piezometers with automatic data loggers which are easy to use, the measurements are accurate and they are low of a price.

Also, the complementary techniques (i.e. tracers, numerical modeling) is required for the best understanding of the recharge processes of the Koda catchment.

Author Contributions

O. D. was responsible for this current research paper in the framework of her Ph.D. program. O.D. collected data, performed the analysis and initially wrote the manuscript. O.D, H.B., and A.T. designed the study, developed the methodology. H.B. and A.T. supervised the data analysis and contributed to paper write up while N.C.K. and K.P. improved the quality of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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