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Impact Of Climate Variability On Groundwater Resources In Kolondieba Catchment Basin, Sudanese Climate Zone In Mali

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Abstract:

Climate variability impact on water resources are very perceptible in sahelian and soudanian zone of Mali where high evaporation demand and short recharge period had lead to groundwater level variability in this area. Steady state groundwater flow model in Kolondieba catchment basin showed that groundwater is flowing into the river network while transient flow model showed a decline of water level during the time by an average groundwater drop varying from 2 to 15 cm per year in the period of 1940-2008. The results indicate that the model can be used to predict the groundwater level using downscaling values of the Climate Global Model data.

Keywords: climate variability; groundwater model; groundwater recharge; Modflow; Mali.

1. Introduction

Climate variability is affecting groundwater recharge and level due to changes in precipitation and evaporation loss. Domestic and agricultural water demand, is sensitive to this variability in areas that rely to groundwater such as Kolondieba catchment basin, sub-catchment of Bani basin in Mali where interaction between groundwater and surface water have been widely discussed (Maillet et *al.* 2000 Lutz et al.2008, Mariko et al.2009, Kamagate et al 2009 , Kamagate et al.2010).

The catchment basin of Kolondieba is a sub-catchment of the Bani River in Sudanese climate zone of Mali with rainfall reaching 1400 mm.y^{-1}. It covers an area of about 3100 km^2 with an estimated population (2009) of 33000 inhabitants .The area is known to grow cotton and recently demand of the cotton in world markets has led to the growing of cultivated and populated areas and thus to the increase of a rural drinking and domestic water supply demand. Groundwater recharge assured by atmospheric percolation is only available in rainy season from June to October. Therefore all shallow traditional wells assuring more than 80% the water supply of the populations were drying few months after this recharge period. The main surface water is the Banifin, affluent of Bani flowing few months after rainy season. The area is located in the soudanian climatic zone characterized by average precipitations higher than 1100 mm. The monthly average temperatures in dry season are slightly lower than those of rainy season. The annual evapotranspiration computed by Penmann method (Penman 1948), is around 1530 mm. The highest precipitations, recorded in the area are distributed over approximately 90 days. The rains are concentrated between June and October with nearly 90% of the total rainfall with a maximum in August. The months of December January and February are dry.

The problem is then, to attempt to explain the interaction between the groundwater and the surface water and to determine the fraction of rainfall that consist the groundwater recharge and the spatio-temporal evolution of groundwater level.

Numerous studies have been done throughout the world on impacts of climate change or variability on groundwater resources or recharges (Scibek et al.2008, Allen et al 2004a, Allen et al 2004b.), but few studies have been made in the aspect in West Africa specially in Mali where predictions of some of climate models were towards aridity by 2015. (Taylor et al. 2002). A decrease of the groundwater storage in the Bani River basin is also reported by the decreasing of rainfall and runoff since the 1980's (Bricquet et al. 1997).

The main objectives of this study include the simulation of groundwater table in Kolondieba catchment basin and the prediction of the impact of climate variability on groundwater level fluctuations. Other objective of the study is the estimation of groundwater recharge through a groundwater flow model. The detection of the interaction between groundwater and surface water using groundwater flow model is also an objective of this study.

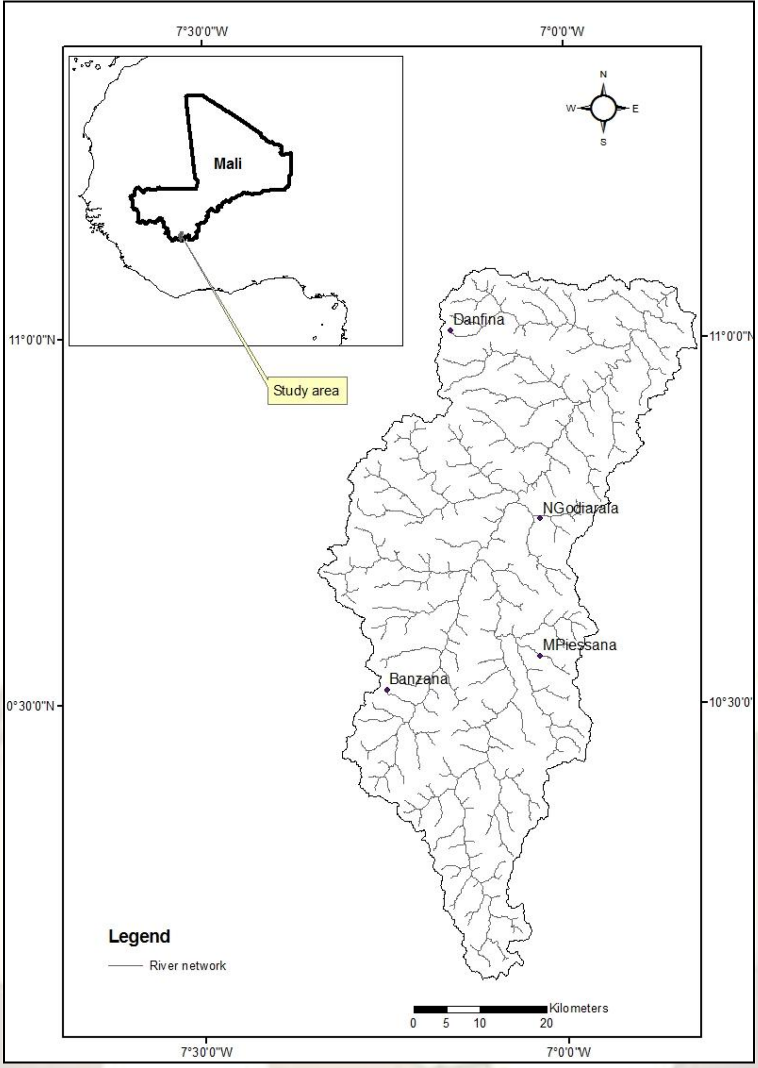


Figure 1. Kolondieba catchment basin

2. Geological and hydrogeological settings

The zone of the project extends exclusively on the formations from the Precambrian basement which covers nearly 40.000 km ^{2} in the south of Bamako and prolongs more in the south in Ivory Coast and Guinea. They are overlaid in the north and the east by the sandstone dated in the late Precambrian which constitutes numerous mountains at the central part of Mali in particular in the areas of Sikasso, Bandiagara and Bamako. The regional geological investigations showed that the formations of Birrimian are appeared as bands lengthened of a few tens of kilometers of width and being able to extend on several hundreds of kilometers, which are separated by granitized or migmatized zones (Bassot et al.1986, Feybesse et al. 2000). These crystalline rocks correspond, either to an antebirrimian basement, or a late granitisation related to the orogenesis, tectonic and metamorphic Birrimian formations. The early Birrimian is constituted with dominant detrital and volcano-detrital formations, while the late birrimian with volcanic sediments. The crystalline rocks are represented by granites and granitoids.

Three units were defined in the Birrimian of Mali:

- Unit of Bagoe: It extends to the east, between left bank of Banifing to the right bank of Bagoé ;
- Unit of Bougouni-Keikoro: It is inserted into a serial of granitic mountain of 100 km of width which borders in the west the unit of Bagoé;
- Unit of Yanfolila extends from the south of Bamako to the Ivory Coast. This unit is bordered in the west by the unit of Siguiri in Guinea showing the same geological characteristics mainly developed in Guinea.

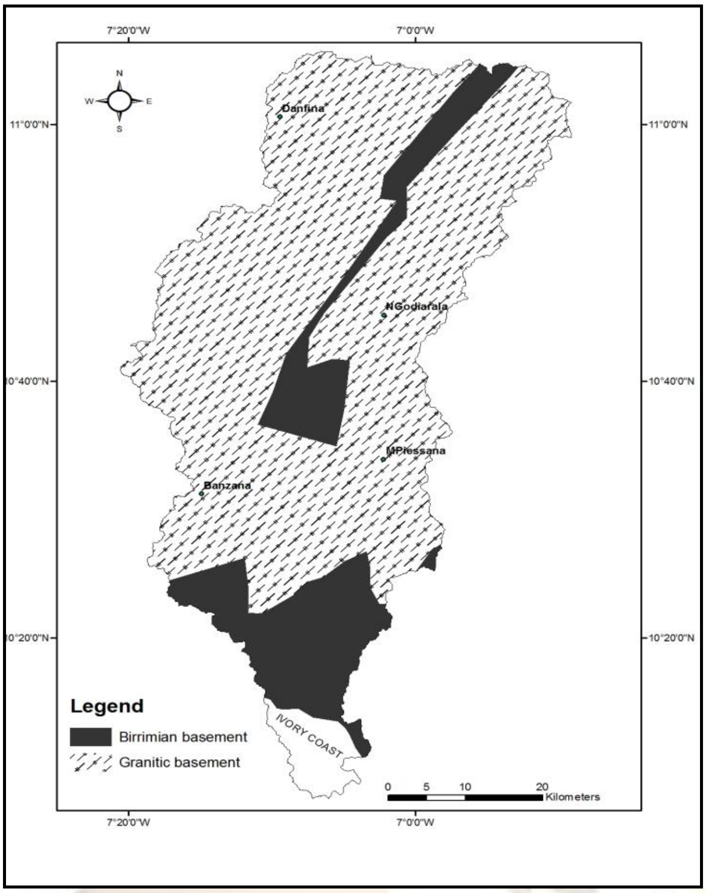


Figure 2 Geology of the study area

The lateritic and alluvium formations are omnipresent in the area and hide the crystalline basement. Some boreholes drilled by the Helvetas project showed that the thicknesses are generally exceeding 20 m above the granitic substratum and often higher than 50 m on the Birrimian formations.

The Hydrogeological conditions are directly related to the geological and tectonic structure of the area. Therefore two aquifers compose the hydrogeology of the area: Fractured aquifer in the fractured and fissured basement.

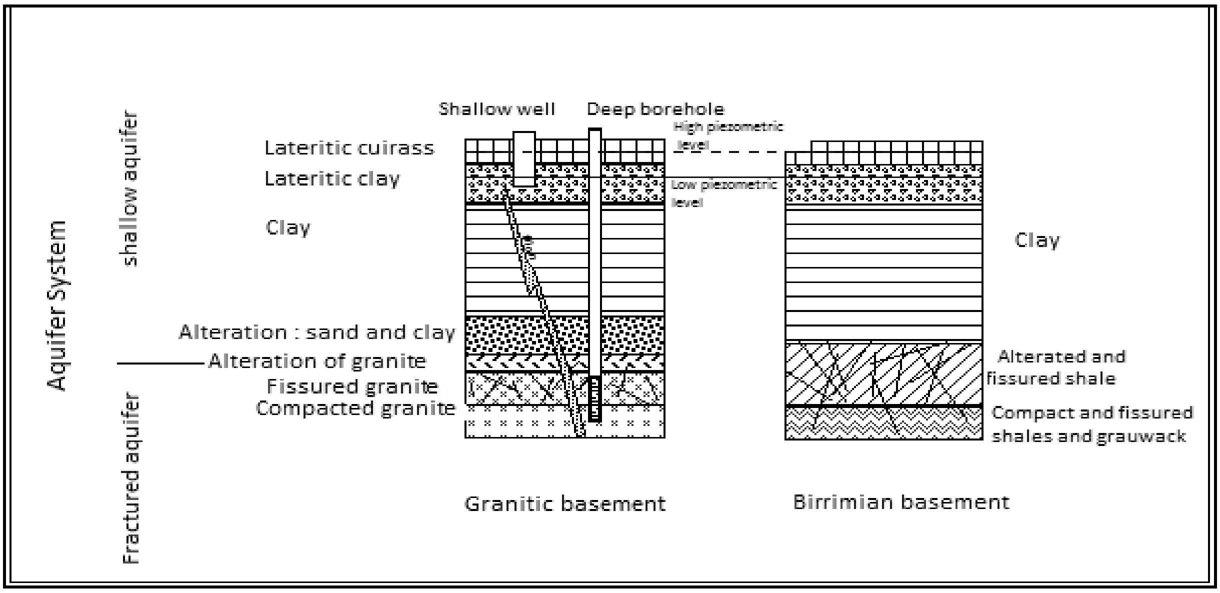


Figure 3 Aquifer system compartment in granite and Birrimian basements (From : Rapport Programme d'appui institutionnel au secteur eau Mali sud 2003, modified)

The hydrogeology of the later is very complex however it provides a great amount of drinking water through the deep boreholes. Shallow aquifer with a thickness varying up to 50m is constituted by laterits, alluvium and clay resulting of the desegregation of the crystalline rocks. Shallow groundwater is mostly used for water supply through poorly dug wells. The two aquifers were affected by same seasonal fluctuations.

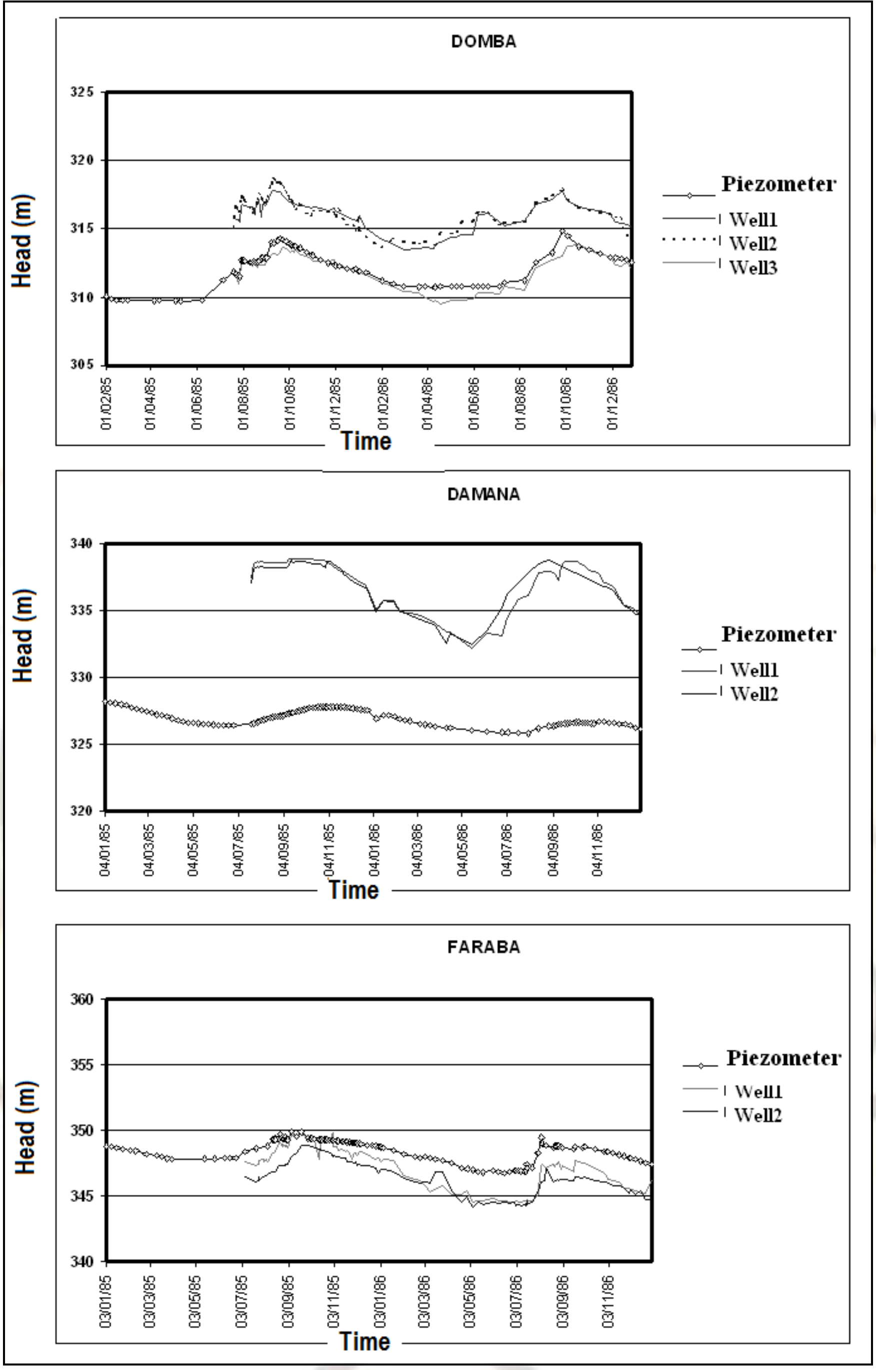


Figure 4 Comparison between piezometric responses in shallow aquifer (well) and fractured aquifer (piezometer) at the sites of Domba , Damana and Faraba (by Helvetas Project Mali reports 2003)

The comparison of the piezometric fluctuations (Figure 4) at the shallow aquifer and the fractured aquifer confirm their hydraulic exchanges and their combination in a single aquifer system but with important variations at the local scales.

3. Data and methods

. Data and methods included:

- Historical climate data at the station of Bougouni from 1940 to 2008.
- Inventory of 199 shallow wells and 95 boreholes data .The elevations values were recorded with GPS.
- Depth of water in wells were been recorded with a probe.
- Boreholes data are provided by the SIGMA database of de National office of Hydrology of Bamako (DNH).
- Aquifer hydrodynamic data are provided by pumping test data.
- Other data were found in the reports carried out during past projects
- Water balance techniques method was used to compute recharge.
- The recharge was calculated in terms of percentage of annual rainfall
- Visual Modflow for groundwater flow model.

3.1 Historical climate data

The historical rainfall data of the station of Bougouni has been used as reference. Bougouni is located about 60 km of the center of the catchment basin .The mean annual rainfall is slightly lower than that of the study area but the series is complete and data are more reliable than the other stations of the area. The historical rainfall data of the station of Bougouni is available from 1940 to 2010. It can be broken up into several periods with definitely differentiated rainfall: Between 1940 and 1969 a wet period, between 1970 and 1989 a dry period and an increase of rainfall from 1990.

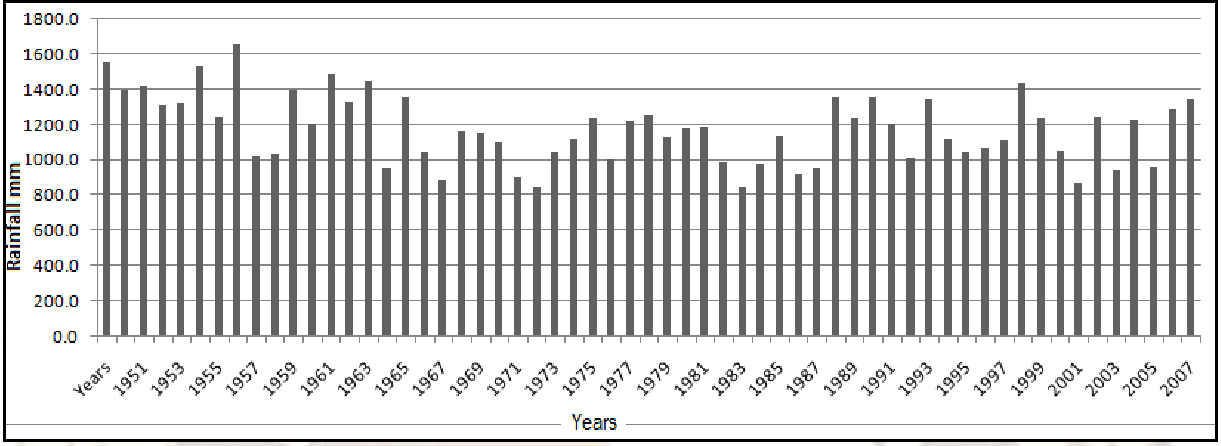


Figure 4 Histogram showing history of rainfall data at Bougouni station 1950-2010

3-2 Downscaling Global Climate Model data

In Africa, number of available downscaled data remains limited compared to Europe and North America and one of few African institutions that generate empirically downscaled climate data based on the Intergovernmental Panel on Climate Change (IPCC) assessment report is Climate Systems Analysis Group (CSAG) at the University of Cape Town. The results from CSAG's downscaling are freely available online since late-2007. Downscaled data (African downscaling) are based on 6 different Global Climate Models (GCMs) for a numerous stations across the African continent including the synoptic station of Bougouni in Mali. The Figure 5 showed observed rainfall and downscaled Canadian Global Coupled Model (CGCM) data (Flato et al.2000) at Bougouni station.

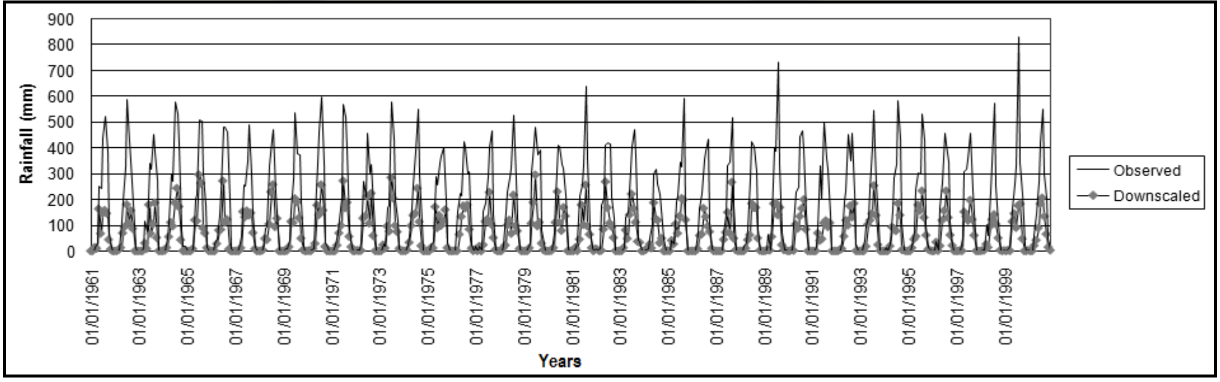


Figure 5 observed and downscaled CGM data at Bougouni station

3.3 Groundwater Recharge estimation

The analysis of the piezometric histories on the study area showed that there is no simple linear relation between the aquifer recharge during the rainy season characterized by an increase of the piezometric level and the corresponding rainfall. The increase of water level depends on multiple factors (temperature, evapo-transpiration, etc.) related to the local conditions which are not quantifiable. A regional approach based the integration of various physical conditions of observation sites, were been adopted.

Integrated recharge in the groundwater model was computed using following water balance equation:

R= P-ET-Runoff
P: Rainfall
R: recharge
ET: evapotranspiration.

Basing on the previous studies done in the area total runoff coefficient is assumed to be 15% of total rainfall with the Rational Method Calculation. In addition a value of PAW (Plant-available water) is deducted from the inflow values. In area the PAW value is assumed to be 100 mm.

3.4 Groundwater Flow model

Rather than to generate, arbitrary and without quantitative references, of the values of hydraulic conductivity for the 2 layers, it was considered more representative for this regional model to compare the aquifer system to a single aquifer by simulating it like a quasi-homogeneous medium having equivalent hydraulic characteristics. This simplification is imposed by the availability of the data remains coherent with the regional hydrogeologic context. For long periods of simulations the response of the actual aquifer system is close to that of a single aquifer. The comparison expressed above of the piezometric fluctuations between the two aquifers maintains the proposed simplification .Visual mudflow a commercial program was used for the groundwater flow.

Visual MODFLOW is a computer GIS- based program based on USGS MODLOW code with pre and post processor. It simulates three-dimensional ground-water flow through a porous medium by using a Finite-difference method. The partial-differential equation of ground-water flow used in MODFLOW is (McDonald and Harbaugh, 1988)

Where:

$$\frac{\partial}{\partial x}(-K_{xx}\frac{\partial h}{\partial x})+\frac{\partial}{\partial y}(-K_{yy}\frac{\partial h}{\partial y})+\frac{\partial}{\partial z}(-K_{zz}\frac{\partial h}{\partial z})-w=S_s\frac{\partial h}{\partial t}$$

Kxx , K yy , and K zz are values of hydraulic conductivity along the x, y, and z coordinate axes, which are assumed to be parallel to the major axes of hydraulic conductivity (L/T); h is the potentiometric head (L); w: volumetric flux per unit volume represents source and /or sink of water. Groundwater flow within the aquifer is simulated using a block-centered finite-difference approach. The finite-difference equations can be solved using different solvers.

The modeled zone was divided into 30X50 grids. Each grid occupies 4km^2. The aquifer top elevation is recorded as ground surface elevations while for the aquifer bottom elevation data where extracted from boreholes data. River boundary condition was assigned to the Banifin affluent inside the basin. Constant and no flow boundaries were assigned at some limits of the domain corresponding either to a Bani affluent or groundwater divide zones.

4. Results and discussions

4.1 Recharge Estimation

The table 1 below shows the Tornthwaite computing method to determine the recharge.

Table 1. Tornthwaite recharge calculation method

	J	F	M	A	M	J	J	O	S	O	N	D
P(mm)	0	1	8	43	106	145	243	307	214	63	7	0
ETP(mm)	123	129	156	153	153	130	120	112	115	121	111	111
PAW (mm)	0	0	0	0	0	15	100	100	100	42	0	0
AE (mm)	0	1	8	43	106	130	120	112	115	63	49	0
R+% Run (mm)							23	195	99	0	0	0

P: 10 years average rainfall (1998 to 2008)
ETP: 10 years average evapotranspiration (1998 to 2008)
AE: Actual Evaporation
R: Recharge
% Run: percentage of runoff coefficient

The annual total recharge is estimated at 147 mm.y^{-1}or 13% total rainfall

The value of this method is close than that one found with Alain Guerre (2003) in the study in Helvetas Project of south Mali estimated at 15% of total rainfall.

4.2 Groundwater Flow model Output

4.2.1 Steady State Flow:

14 shallow wells monitored in December 2008 have been used to calibrate the model in steady state flow. The steady state groundwater flow model showed that the shallow groundwater is discharged in to the river catchment area (Figure 6).

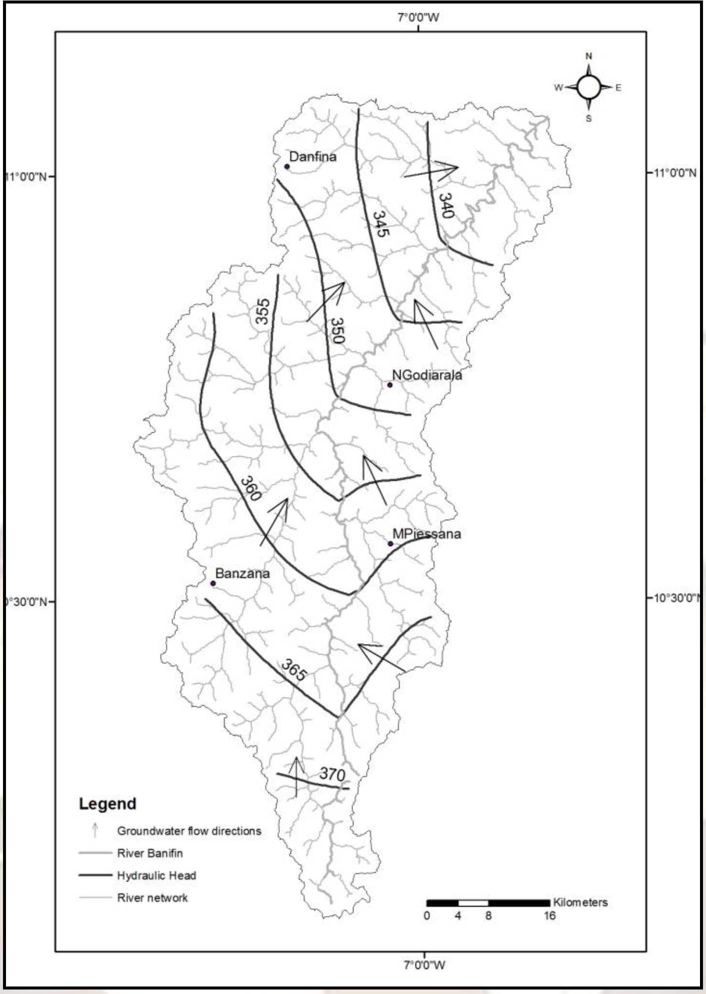
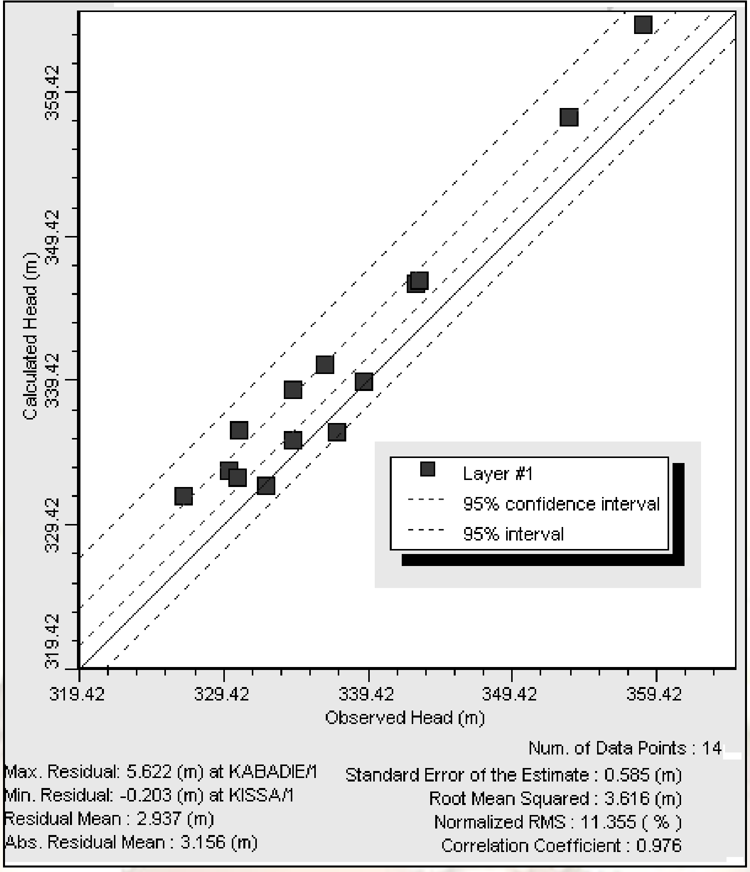


Figure 6. Modeling groundwater contour map of Kolondieba catchment basin

A score of simulations were necessary with successive adjustments of the hydraulic conductivity in several sectors and the recharge estimated to represent the main features of regional groundwater contour map. The estimate recharge by the model is 7% of the total rainfall corresponding to 90 to 105 mm .y^{-1}, it's almost the half value estimated by the water balance method. Adjusted hydraulic conductivities were ranged from 3.3 10^{-4}m/s in birrimian basement to 4.10^{-4} m/s in granitic basement. The steady state flow model is highly sensitive to recharge and evaporation extinction depth and less sensitive to the variation in hydraulic conductivity.



Num. of Data Points : 14
Max. Residual: 5.622 (m) at KABADIE/1
Min. Residual: -0.203 (m) at KISSA/1
Residual Mean : 2.937 (m)
Abs. Residual Mean : 3.156 (m)
Standard Error of the Estimate : 0.585 (m)
Root Mean Squared : 3.616 (m)
Normalized RMS : 11.355 (%)
Correlation Coefficient : 0.976

Figure 7 Calibration of the model in steady state flow.

4.2.2 Transient Flow:

The estimate monthly recharge rates (7% of the total rainfall during the recharge period) were inputted in the model to show spatio-temporal evolution in hydraulic head. Transient flow was calibrated with data of 14 shallow wells monitored during 30 months starting in December 2008. Recorded groundwater level data were incomplete in most of wells due to unavailability of water in most of wells from Mars to June. Figure 8 showed transient observed and modeled plot at Mafele observation well. Adjusted specific storage were ranged from to 2.10^{-3} to 5.10^{-3} /m in the area.

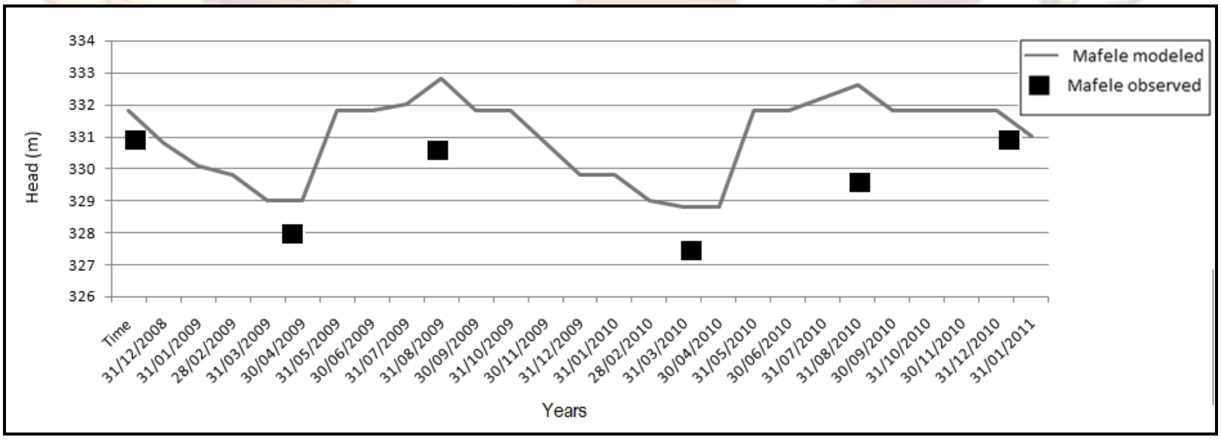


Figure 8 Time serie plot showing modeled and observed head from 2008 to 2011.

4.2.3 Spatio-temporal evolution of hydraulic head

Figure 9 showed the map of hydraulic heads difference in the study area from 1940 to 2008.The map showed a decline of water level from 1940 to 2008 for nearly of the study area with average downward slope varying from 2cm to 15cm per year.

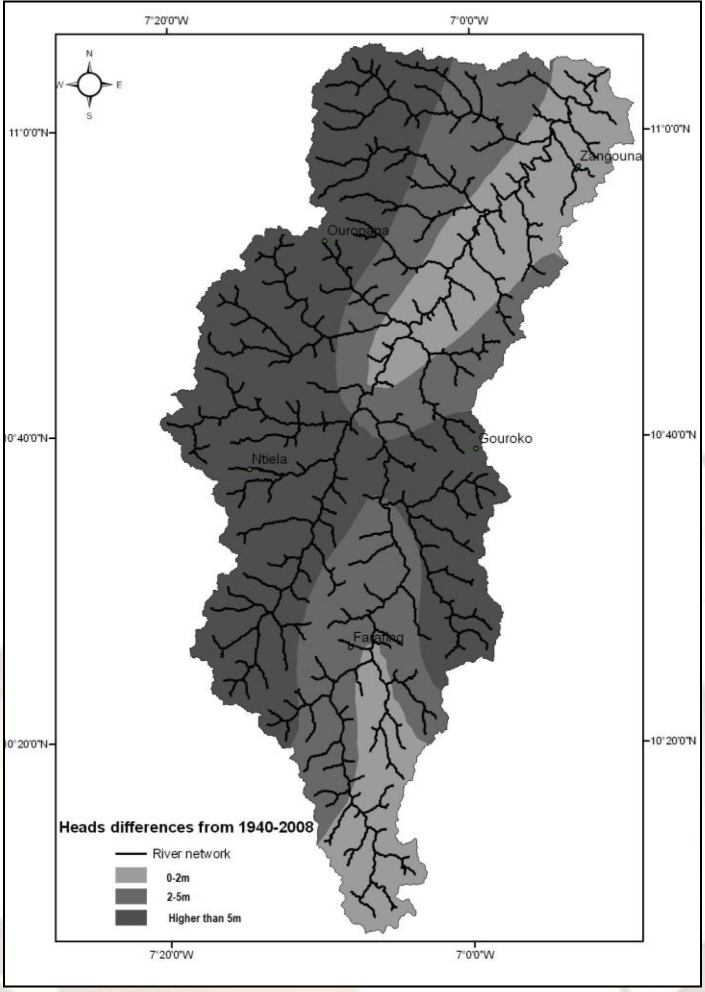


Figure 9 Groundwater level fluctuations showing by head differences from 1940-2000.

4.3 Impact of Climate variability

The previsions of aquifer recharge deduced by the monthly output downscaled rainfall data provided by African downscaling version 2 data were used to predict change in groundwater level at the period of 1940 to 2065 at the reference at Bougouni station. The graphs showed in Figure 10 a downward trend from 1940 to 2065 indicating a decrease of groundwater level over time. The average downward slope value at periode of 2010 - 2065 is estimated to 4cm per year.

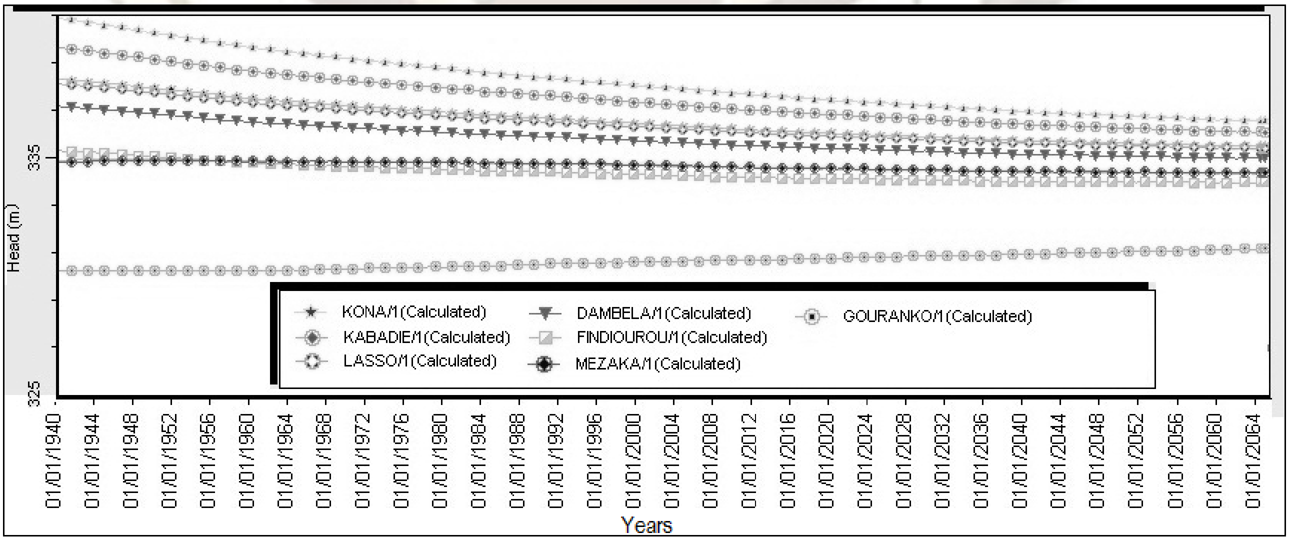


Figure10 Previsions of modeled hydraulic heads in observation wells from 1940 to 2064

5. Conclusion and recommendations

The groundwater flow model showed that groundwater is discharge into network catchment basin and groundwater levels were depending upon rainfall. Aquifer recharge is estimate by the model to be 7% of total annual rainfall.

The spatio temporal study showed decrease of water level over the time from 1940 to 2008. For the predicted values from 1940 to 2065, decrease tendency is much lower in hydraulic head from the period of 2010- 2065.

The head values predicted by the groundwater flow model might be over estimated because did not consider the seepage along deep faults or fractures. Piezometers set and data records will be necessary to better prediction of the impact of climate variability on groundwater resources at Kolondieba catchment basin.

This study may help environmentalists and decision makers.

Acknowledgment

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