

Assessing the Effects of Land Use/Land Cover Change on Groundwater Recharge in a Sudano-Sahelian Zone: Case of Koda Catchment, Mali, West Africa

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How to cite this paper: Diancoumba, O., Toure, A., Daou, I., Konare, S., Hermassi, T., Kotti, M., Bokar, H., Galoul, N., & Bargaoui, Z. (2022). Assessing the Effects of Land Use/Land Cover Change on Groundwater Recharge in a Sudano-Sahelian Zone: Case of Koda Catchment, Mali, West Africa. *Journal of Geoscience and Environment Protection*, 10, 39-54.

<https://doi.org/10.4236/gep.2022.108004>

Received: June 29, 2022

Accepted: August 15, 2022

Published: August 18, 2022

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Abstract

Groundwater is the main source of water in the studied area; therefore, it is significantly requested in all the activities of the inhabitants. These natural resources are affected by some drivers especially Land Use/Land Cover (LULC) and Climate Change. A Land Use/Land Cover (LULC) dynamics study is crucial for any global environmental change evaluation. For instance, for a given place, its change could affect considerably water cycle components. Therefore, the knowledge of the effects of LULC on groundwater recharge is then the key in water resources management system, in particular for the decision makers of the Koda Catchment where the scarcity of the water availability for agriculture is real. The spatiotemporal variation of the different units of LULC present in the catchment has been examined in this study. The Envi 4.5 Software coupled with ArcGIS using the Supervised Classification method, was applied to subset Landsat images from 1990 to 2016. Five (5) major LULC categories, cultivated land, bare land, herbaceous savannah, shrubby savannah and degraded savannah, were identified in the catchment. In a parallel direction, the groundwater recharge has been estimated through the conceptual Gardenia model for the same period 1990-2016. The results showed that the portion of cultivated land and bare land increased (14.9% and 23.5% respectively) while, the portion of savannah decreased: herbaceous savannah by 24.4%, degraded savannah by 10.32% and Shrubby Savannah by 3.6%. Sa-

vannah areas in Koda catchment is converted to agricultural land and urban area due to human activities. The decline of 8.4% in groundwater recharge might become so far obvious in the future if the current rate of deforestation continues in the Koda catchment. There is a need to closely monitor the changes in LULC for sustainable development. The results of this study could help to well understand the recharge pattern across Koda catchment under a changing LULC.

Keywords

LULC Change, Groundwater Recharge, Gardenia Model, GIS, Koda Catchment, Mali

1. Introduction

In many developing countries one of the principal driving forces of global environmental change is Land use and land cover (LULC) change (Botlhe et al., 2019). According to Wondie et al. (2011), the LULC change is impacting many sectors of the economy. Changes in the LULC component could be observed spatially and temporally. This is mainly due to the intensity of land use and extent of area. On the temporal scale, LULC changes from a few months to several years, characterized by short term and long term changes, respectively (Lambin & Ehrlich, 1997). The long-term change is of major concern and the most significant for global environment change. Furthermore, groundwater resources and regional hydrology are controlled by many factors including the LULC change (Stonestrom et al., 2009; Ashaolu et al., 2019). Many authors have investigated the long term LULC change to evaluate the sustainability of natural resources (Scanlon et al., 2005; Lin et al., 2018; Ashaolu et al., 2019). Most of the results of the previous studies show clearly that the causes of LULC change are many being of natural and anthropogenic effects (Tamba & Li, 2011; Pervez & Henebry, 2015; Yin et al., 2017; Diallo et al., 2019). Some of human effects are the causes of increases of population growth rate, rural-urban migration, agricultural expansion, deforestation and climate change (Toure et al., 2017). Urbanization is the most irreversible form of land use. In developing countries, especially in Africa, urban land expansion has been observed since the 1980s which is more related to urban population growth than the growth in the Gross Domestic Product (GDP) (Ashaolu et al., 2019). In West African countries, large of extents of natural land cover classes have been replaced by human influenced landscape mainly dominated by agriculture (CILSS, 2016). Most of the rural population are migrating to look for better survival opportunities (Pandey et al., 2013). Consequently to feed the growing population, the agricultural land area has been increased in order to meet the demand for food (Jamtsho & Gyamtsho, 2003). All these phenomena could lead to LULC changes. In Mali, due to the increase of population growth rate leading to an important pressure

on agricultural sectors in order to satisfy the food demand, the portions of savannah and forests land have decreased by 23% from 1975 to 2013 (CILSS, 2016).

The southern part of Mali including the study catchment is the most populated region over the country. Population is continuing to expand and it is strongly connected to the high demand of fresh water. The population of the Koda catchment registered an increase of 26% from 2009 to 2019 with 3.6% as population growth rate (RGPH, 2009). The principal land use in the catchment is agriculture. The quantification of LULC changes is crucial to better understand the variability and its ecological effects on the natural resources (Turner, 2005). The main objective of this study is to assess the effects of LULC change on groundwater resources over 1990-2016 period in Koda catchment. To achieve this objective, the remote sensing coupled with GIS is used to study the dynamics of the LULC over Koda catchment between 1990 and 2016. The supervised method has been used to classify the LULC classes existing in Koda catchment while the Gardenia model developed by Roche and Thiery (1984) has been used to estimate the recharge pattern. The study reveals that the potential effects of LULC can be properly quantified for a given catchment using a hydrological model.

In the current study, the effects of LULC change on groundwater were assessed for the period 1987-2016 and the results can be used as water resources management tool.

2. Study Area

The study area is located in the semi arid zone of West Africa. The study catchment, Koda, occupied the southern part of Mali at 120 km in the North of Bamako, the capital of Mali. Koda catchment is lies between in Latitude: 13°56'00"N and 12°57'80"N and the Longitude: 7°30'8"W and 8°28'5"W (Figure 1). The study area is located in the southern part of Mali at 120 km in the North of Bamako. With the area of about 4921 km² (Diancoumba et al., 2018) the Koda catchment has a Sudano-sahelian climate. The mean annual temperature is about 28.3°C with minimal temperature varying from 15°C to 26.6°C and the maximal temperature ranges from 31.4°C to 40.5°C. The overall annual average of rainfall for the last 30 years (1987-2016) is 500.4 mm in 1992 and 1164.3 mm in 1988 at Katibougou station, while the overall mean over 30 years (1987-2016) is 836 mm (Diancoumba et al., 2020).

The principal Land Use of the Koda catchment is Agriculture area. The main crops are millet, maize, cotton etc. The catchment is mainly constituted by sandstones. Some geological formations such as dolerites intrusions, conglomerate, glauconite and quartzite are associated with the sandstone of the Koda catchment. Two types of permeability are characterized the catchment, the porous permeability in the sandstones and the permeability due to the fissures in the dolerites (Diancoumba et al., 2019).

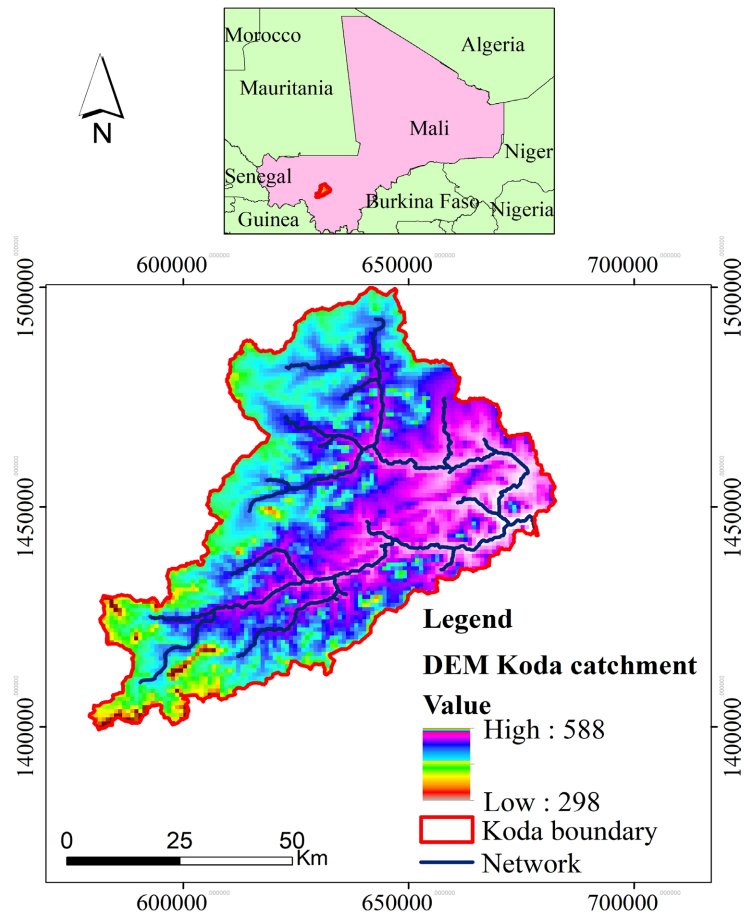


Figure 1. Study area location.

3. Methodology

3.1. LULC Dynamics

The Supervised Classification method, using Envi 4.5 Software coupled with ArcGIS 10.3, was applied to subset Landsat images from 1990 to 2016.

In order to produce the land cover map, the coordinates of some points were taken throughout the catchment scale on May. Based on the fact that there is no cloud form the images in this period of the year. These points have been selected as unit pixel of the study area to make the land cover classification. The supervised classification method was selected using the Envi 4.8 software, and the Landsat images downloaded from USGS website:

<https://www.usgs.gov/tools/earthexplorer> was used for that. Three years Landsat images (March 1990, March 1998 and February 2016) were used in assessing the evolution over time of LULC change. The time steps of the Landsat images are based on the quality of the available data. The output from Envi software was used into ArcGIS for the mapping purpose (**Figure 2**).

Figure 2 shows the flow chart of the methodology used in this study.

Maximum likelihood classification algorithm was applied to get the best algorithm for classification. The threshold option has been used to calculate the area

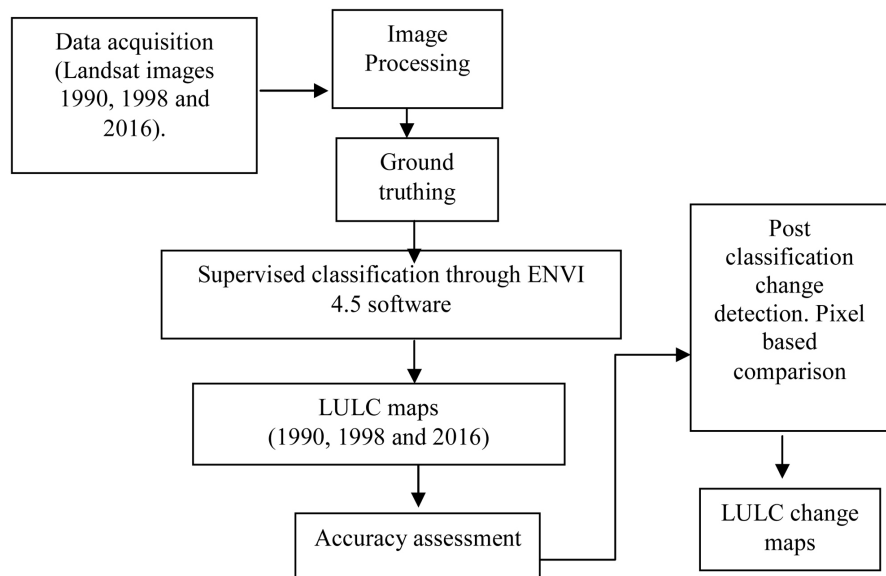


Figure 2. Flow chart of methodology of LULC change.

of each LC units over the Koda catchment.

The change of LULC over Koda catchment was carried out based on the 1990, 1998 and 2016 LULC maps developed for the catchment. Using the overall function in ArcGIS 10.3 and the Microsoft excel 2007, the percentage changes in LULC was calculated for the twenty-seven (27) years period.

The main objective of this work is to evaluate the dynamics of the land cover change in the past 27 years. The choice of those years has been based on the availability of the Landsat data set with good quality.

Accuracy Assessment

The coefficient of KAPPA (K) has been evaluated in the view to better assess the classification of LULC units done over Koda catchment. The Kappa coefficient (K) is computed based on the error matrix.

According to Amler et al. (2015) and Ren et al. (2018) the K value is used to assess the accuracy of remote sensing data using Equation (1).

$$K = \frac{N \sum_{i=1}^n \widehat{P}_{ii} - \sum_{i=1}^n (\widehat{P}_{i+} * \widehat{P}_{j+})}{N^2 - \sum_{i=1}^n (\widehat{P}_{i+} * \widehat{P}_{j+})} \quad (1)$$

where P_{ij} is error matrix, \widehat{P}_{i+} row total pixel, \widehat{P}_{j+} column total pixel, \widehat{P}_{ii} corrected mapped pixel of a particular class i and N total number of pixel.

The quantification disagreement and allocation disagreement method have been proposed by Pontius & Millones (2011) and showed the limitations of the use of the K values in comparing the maps viewed. Nevertheless, in several studies, K is still considered as a vital tool for accuracy assessment measurement (Biondini & Kandus, 2006; Ren et al., 2018). The value of K that shows the consistency of data classification has been statistically classified by Fitzgerald and Lees (1994) from

poor to excellent as follows:

Poor if $K < 40$;

Good if $40 \leq K < 75$;

Excellent if $K \geq 75$.

3.2. Estimation of Groundwater Recharge

Gardenia model is used in this study to estimate the recharge for the period 1987-2016 through a global hydrological modelling rainfall-groundwater level. All files in Gardenia model are free format, they are easy to edit by the user. It required Potential Evapotranspiration (PET) data as input data, which were estimated using Blaney Criddle (1962) method. Refer to Blaney & Criddle (1962) for the detail of the PET calculation process. The Groundwater Level (GWL) data, used from three (3) piezometers, have been used as input data in Gardenia model for calibration purpose.

The length of the whole input data used were from 1990-2016; the rainfall and PET data present a complete dataset for the 27 years period while the missing data from the GWL data were completed by 9999 as required. To run the model, we also used the hydrodynamics parameters (hydraulics conductivity, etc.) of the aquifers, those values were found from the simulation of the groundwater flow over the catchment using Visual Modflow (Diancoumba et al., 2019).

3.3. Calibration and Validation Process

This section describes methods for evaluating the calibration and validation results. This includes a discussion of calibration acceptance criteria and descriptions on various qualitative and quantitative methods for comparing field measurements to the same parameter as calculated with the model. Two (2) quantitative statistics R^2 and NSE were used in evaluating the performance of the GARDENIA model with respect to GWL in the calibration and validation periods.

The correlation coefficient is calculated using Equation (2):

$$R^2 = \frac{(\sum(O - \bar{O})(S - \bar{S}))^2}{\sum(O - \bar{O})^2 \sum(S - \bar{S})^2} \quad (2)$$

The NSE was proposed by Nash and Sutcliffe (1970). The Nash coefficient quantifies the relative magnitude of the relative magnitude of the residual variance compared to the observed data variance (Equation (3)):

$$NSE = 1 - \frac{\sum_{i=1}^n (O - S)^2}{\sum_{i=1}^n (O - \bar{O})^2} \quad (3)$$

where O is the observed value, S the simulated value, \bar{O} is the mean of observed dataset and \bar{S} the mean simulated dataset.

4. Results and Discussion

4.1. Dynamics of LULC

The Koda catchment is mainly characterized by five (5) types of Land Cover units and these are Herbaceous Savannah, Degraded Savannah, Cultivated Land, Shrubby Savannah and Bareland (Figure 3). These five (5) types of LULC over

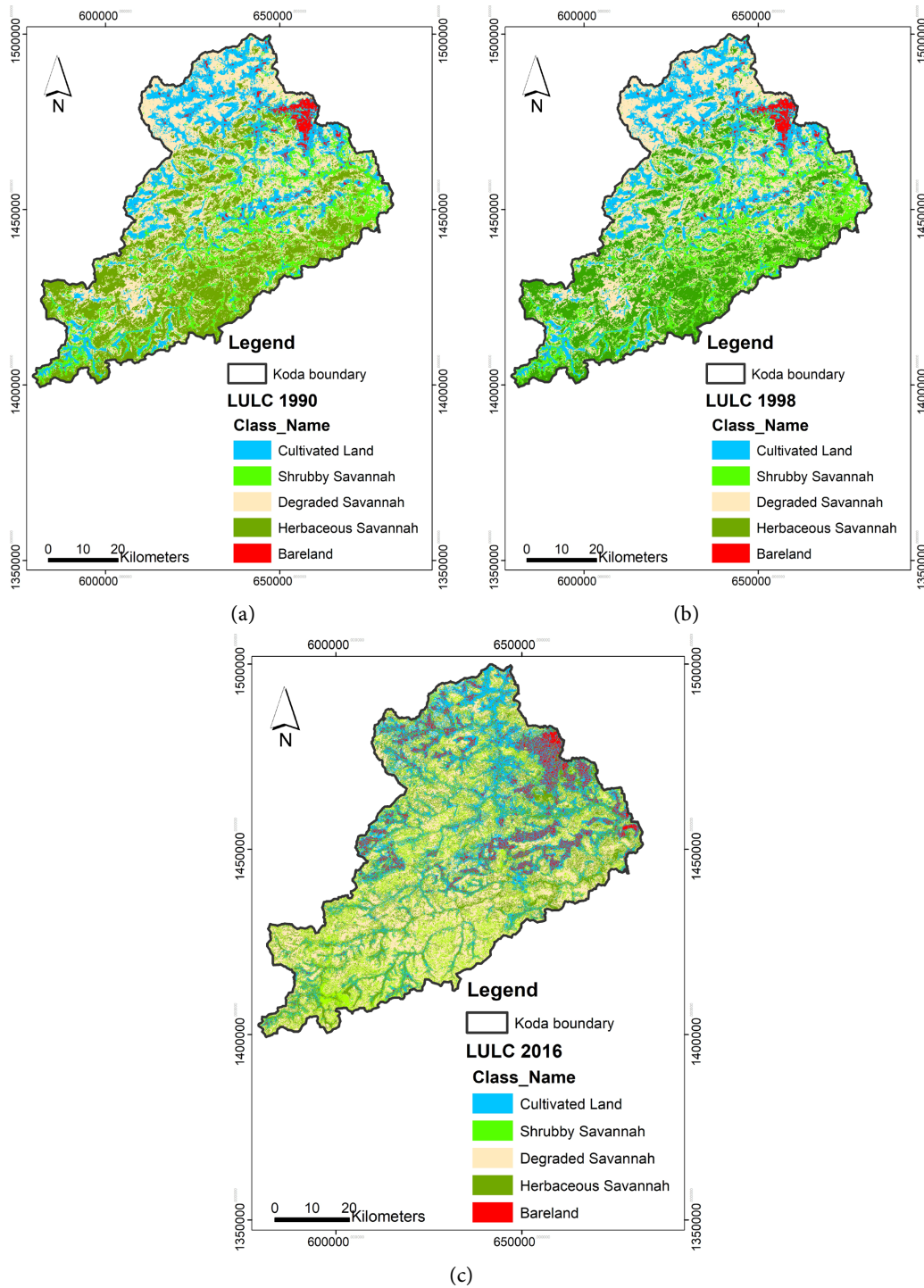


Figure 3. Different units of LULC in the Koda catchment, (a) year 1990, (b) year 1998 and (c) year 2016.

the study area could be represented by three major types of LULC based on the classification proposed by Penman et al., (2003) in the IPCC Guidelines in the Kyoto protocol in 2001. The three LULC are savannah, cropland and settlement. Savannah is represented by three types of savannahs: herbaceous savannah, Shrubby Savannah and degraded Savannah. The cropland includes the cultivated land which is seasonal rained crops land and farms. Settlement is called bare land in this study and it is defined as villages, towns and cities, roads and others buildings.

The comparison in terms of total area of LULC category has been done and the results are outlined in **Table 1**. The land used for agriculture purposes changes considerably from 125 km² in 1990, 200.39 km² in 1998 and to 856 km² in 2016 representing respectively an increase of 2.54%, 4.07% and 17.40%. In general, bare land varied from 50 km² to 1204 km² between 1990 and 2016 while there was an increase of 23.5% (representing 1154.57 km² of the basin). Herbaceous savannah decreased from 57.46% of the total area of the catchment (2827.68 km²) to 57.21% in 1998 and 33.08% in 2016 respectively. This is followed by degraded savannah with a total coverage area of 26.07% (1282.90 km²) in 1990, 24.84% in 1998 and 15.75% in 2016 while there was a decrease of 10.32%. In 1990, the shrubby savannah represents 12.90% (635 km) but, this was decreased to 12.49% (613 km) in 1998 and 9.32% (458.54 km) in 2016.

The graphic representation of the results is given by **Figure 4**. This figure clearly shows the increase in the areas of cultivated land and bare land and the decrease of degraded savannah and shrubby savannah areas.

Based on these results, there was an increase of 1% and 9.78% of Bare land and Cultivated land respectively. The increase of these two LULC units over Africa has been explained by many authors such as (Koglo et al., 2018). The same trend has been examined in Mali by (CILSS, 2016) where the increase of the cultivated land increased by a factor of 2.3 for the period 1975-2013 (38 years) equivalent to an average annual increase of 3.5 percent.

For many authors, this increase could be related to the increase in population

Table 1. Land use and land cover area and area change for the years 1990, 1998 and 2016.

Unit	Area km ²			Ratio of LC unit over Koda's total area (%)		
	1990	1998	2016	1990	1998	2016
Cultivated Land	125	200.39	856	2.55	4.07	17.40
Bareland	50	69.11	1204.76	1.02	1.4	24.49
Herbaceous Savannah	2827.68	2815.3	1627.54	57.46	57.21	33.08
Degraded Savannah	1282.9	1222.54	774.886	26.07	24.84	15.75
Shrubby Savannah	635	613.04	458.49	12.9	12.49	9.32
Total	4920.58	4920.38	4920.52	100	100	100

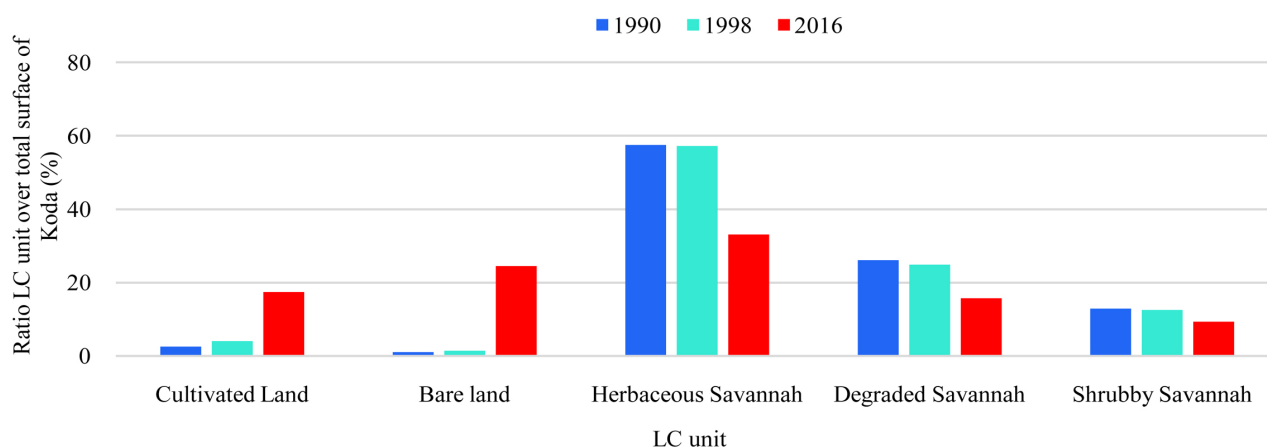


Figure 4. Ratio of LULC unit over total surface of Koda catchment in the years 1990, 1998 and 2016.

and their food demand (Koglo et al., 2018; CILSS, 2016; Daou et al., 2019). The decrease of different types of Savannah area is represented by a decrease of herbaceous savanna area of 24.4% degraded Savannah 10.32% and 3.6% for shrubby savannah.

According to Koubodana et al. (2019) and Aziz (2017), the decrease of savannah is further amplified by using wood as energy sources and the lack of forest management. In the Koda catchment, deforestation is still occurring.

No water body is observed in the study area as a land cover unit, that lack of water bodies can be explained by the following reasons: the Landsat image used is dated of February (dry period) corresponding to the period where there is no surface water because only few surface water characterize the Koda catchment are present during the rainy season. The existence time of all these surface water bodies is driven by the amount of the rainfall received within the study area.

Accuracy Assessment

In this study, all the values of Kappa coefficient (K) are greater than 75%, therefore, the results are considered excellent. The results of K values are outlined in **Table 2**.

Table 2. Coefficient of Kappa (K) values of each land use and land cover type.

Year	1990	1998	2016
K values (%)	82	83	91

4.2. Recharge Calculation

4.2.1. Model Performance Evaluation

The model was calibrated on the basis of monthly time step of GWL. Three piezometer data were used for this calibration purpose. Based on the availability of data, the calibration was carried out using ten years (2008-2017) for piezometer F1, three years (2016-2018) for Nossombougou N1 and five years (1987-1991) for Kossaba K1 observed monthly GWL. The calibration process was ended when satisfactory values of the coefficient of determination— R^2 (2) and the Nash-Sut-

cliffe efficiency—NSE (3), were achieved.

Thereafter, the model was validated for GWL by using the calibrated model to simulate GWL for periods other than those used for the calibration and without any further changes to the model GWL parameters. The GWL was validated

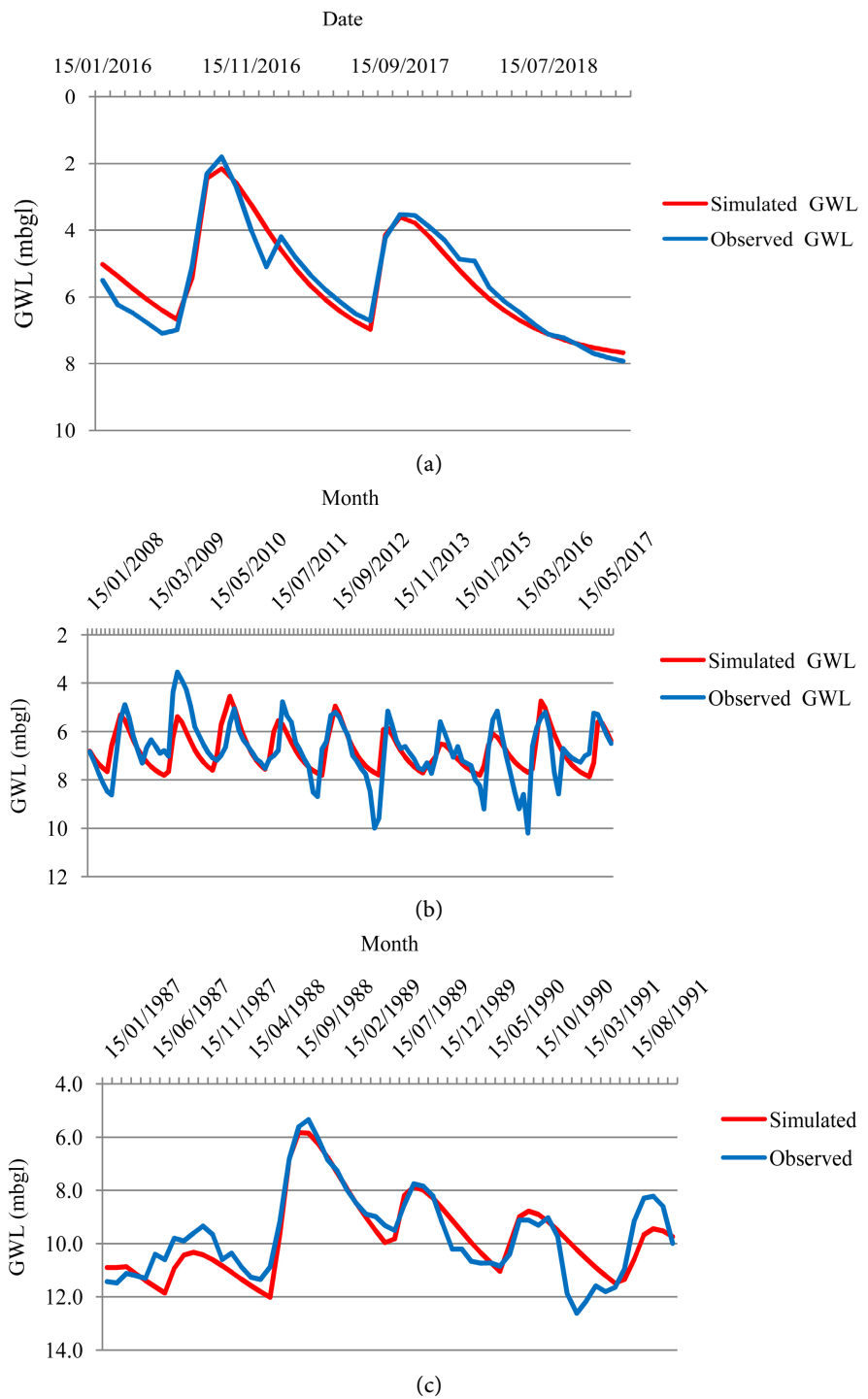


Figure 5. Calibration process in the Koda catchment for the period 2008-2016 in piezometers (a) Piezometer Nossombougou N1, (b) Piezometer Fansiracoro F1 and (c) Piezometer Kossaba K1.

with two years (2018-2019) for piezometer F1 and one year (2019) for Nossombougou N1 monthly observed GWL data. There was no recent available data for the piezometer Kossaba K1 which could be used in its validation. Therefore, only the first two piezometers were used for the validation.

Figure 5 described the calibration while **Figure 6** describes validation of the various piezometers in Koda Catchment with reference to the simulated and observed groundwater levels.

The model performance was satisfying and the values are outlined in **Table 3**.

Table 3. Results of gardenia calibration and validation for GWL for Koda Catchment.

Piezometers	Parameters	Calibration	Validation
Piezometer F1	R ²	0.70	0.73
	NASH	0.50	0.53
Piezometer N1	R ²	0.96	0.90
	NASH	0.92	0.80
Piezometer K1	R ²	0.89	-
	NASH	0.79	-

4.2.2. Effects of Land Use/Land Cover Change on Groundwater Recharge over Koda Catchment

From 1990 to 2016, the groundwater recharge has been considerably varying over Koda catchment. The mean annual recharge decreases from 1990 to 1998 while its increase is observed from 1998-2016. The mean annual groundwater recharge of the Koda catchment for the LULC in the years 1990, 1998 and 2016 are 117, 93 mm/y and 109 mm/y, respectively for the piezometer F1; 278, 21 mm/y and 257 mm/y respectively for piezometer K1 and finally 118, 87 mm/y and 108 mm/y for the piezometer N1. The variation of the recharge pattern for the years 1990, 1998 and 2016 in the three piezometers (F1, K1 and N1) over Koda catchment is shown in **Figure 7**.

The overall mean recharge variation from 1990-2016 over the entire catchment of Koda is outlined in **Table 4**. There was decrease of 24% in groundwater recharge between 1990 and 1998, while it was 21.4% increase between 1998 and 2016. Generally, for the 27-year period of investigation, the change in land use/land cover accounts for only 8.32% reduction in mean groundwater recharge occurrence from 1987 to 2016.

There exists a variation in recharge pattern in the study area during the period 1990-2016. The change of the groundwater recharge is influenced by the change in Land Use/Land cover which is manifested by the transition from one LULC class to another. According to [Ashaolu et al. \(2019\)](#) the degree of transition that took place is controlling the influence of groundwater recharge pattern over the Koda catchment. The characteristics of the dominant LULC units at a particular area of the catchment is also one of the principal parameters that controls the groundwater recharge.

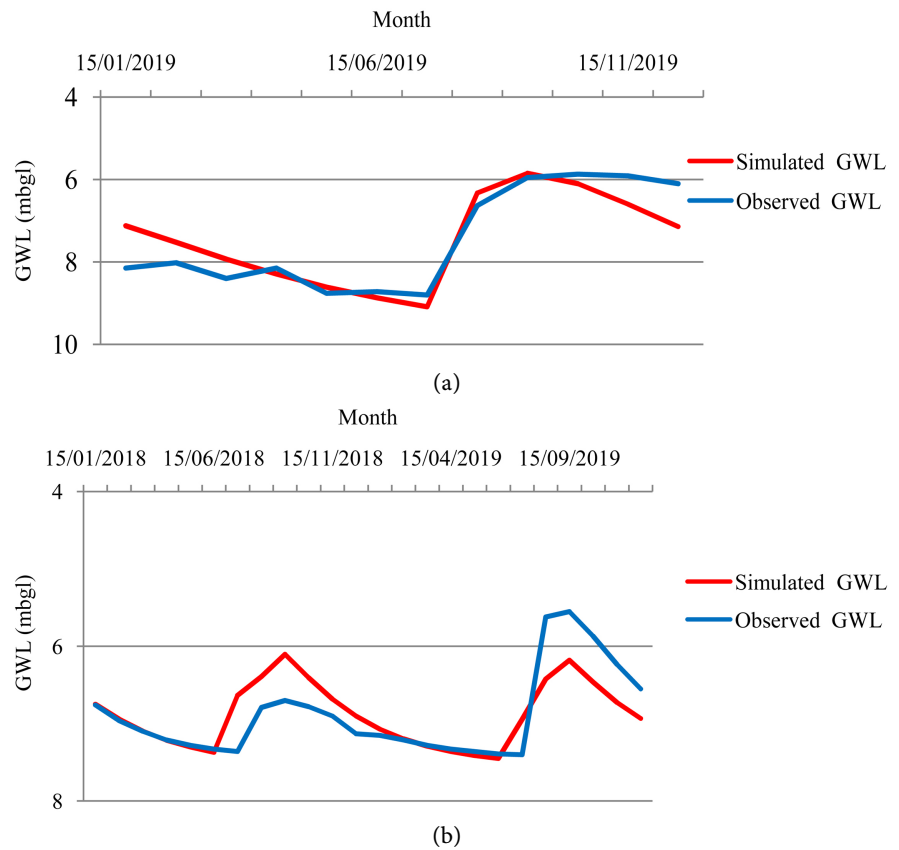


Figure 6. Validation process in the Koda catchment for the period 2018-2019, (a) Piezometer Nossombougou N1, (b) Piezometer Fansiracoro F1.

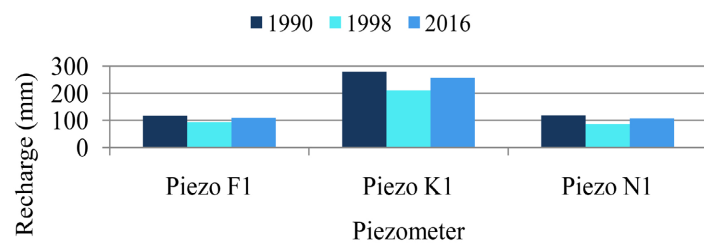


Figure 7. Mean annual recharge in the three piezometers for the year 1990, 1998 and 2016.

Table 4. Overall effect of LULC change on groundwater recharge in Koda catchment.

Year	Rainfall (mm)	Change in groundwater recharge		
		Period	Mm	%
1990	171	1990-1998	-41.05	-23.96
1998	130	1998-2016	+27.88	+21.41
2016	158	1990- 2016	-13.16	-8.32

The effect of LULC change on groundwater recharge in Koda catchment indicates that there are only little changes in recharge pattern that can be asso-

ciated to change in LULC. The overall mean annual recharge revealed a decrease of 8.4% from 1990-2016. This decrease is associated with the decrease of savannah and increase of bareland and cultivated from 1990-2016 over the Koda catchment.

5. Conclusion

The effect of LULC change on groundwater recharge in Koda catchment is that there are only little changes in recharge pattern that can be associated with to change in LULC. The overall mean annual recharge revealed a decrease of 8.4% from 1990-2016. This decrease is associated with decrease of savannah and increase of bare land and cultivated land from 1990-2016 over the Koda catchment. The decrease of the recharge over the catchment might become so more significant in the future if the current rate of deforestation continues in the Koda catchment

Therefore, a proper LULC management strategy is needed within the study catchment. The results of this study can be used for predicting the future LULC changes. To reduce the vulnerability of Koda catchment from the effects of Land Use Land Cover Change, we recommend to policy makers to promote and develop the use of sources of energy (Solar energy, wind energy) in order to reduce the use of renewable fuel wood.

Acknowledgements

We thank the National Direction of Hydraulic of Mali (DNH-Bamako). We also thank the National Meteorological Agency of Bamako (MALI-METEO) and the Regional Meteorological Agency of Koulikoro (Katibougou) and farmers within the basin for providing climate data.

Author Contribution

O. D. was responsible for this current research paper. O.D., A.T., I.D., S.K., T.H. and Z.B. designed the study and developed the methodology. O.D., A.T., I.D. and S.K collected data. O.D. performed the analysis while I.D., A.T., S.K., H.B., N.G and M.K supervised the data analysis. O.D. initially wrote the manuscript. I.D., S.K., A.T., H.B. and M.K. contributed to paper write up while T.H. and M.K. improved the quality of the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

References

- Amler, E., Schmidt, M., & Menz, G. (2015). Definitions and Mapping of East African Wetlands: A Review. *Remote Sensing*, 7, 5256-5282. <https://doi.org/10.3390/rs70505256>
- Ashaolu, E. D., Olorunfemi, J. F., & Ifabiyi, I. P. (2019). Geoecology. *Journal of Geology, Geography and Geoecology*, 28, 381-394. <https://doi.org/10.15421/111936>

- Aziz, F. (2017). *Assessing the Impact of Climate and Land Use/Land Cover Change on Streamflow and Sediment Yield in the Black Volta River Basin Using the Swat Model*. Universite d'Abomey-Calavi (UAC) I.
- Biondini, M., & Kandus, P. (2006). Transition Matrix Analysis of Land-Cover Change in the Accretion Area of the Lower Delta of the Paraná River (Argentina) Reveals Two Succession Pathways. *Wetlands*, 26, 981-991.
[https://doi.org/10.1672/0277-5212\(2006\)26\[981:TMAOLC\]2.0.CO;2](https://doi.org/10.1672/0277-5212(2006)26[981:TMAOLC]2.0.CO;2)
- Blaney, H., & Criddle, W. (1962). *Determining Consumptive Use and Irrigation Water Requirements Technical Bulletin No. 1275*.
- Botlhe, M., Kenabatho, P. K., Parida, B. P., & Maphanyane, J. G. (2019). Evaluating Land Use and Land Cover Change in the Gaborone Dam Catchment, Botswana, from 1984-2015 Using GIS and Remote Sensing. *Sustainability*, 11, Article No. 5174.
<https://doi.org/10.3390/su11195174>
- CILSS (2016). *Landscapes of West Africa—A Window on a Changing World*. U.S. Geological Survey EROS.
- Daou, I., Coulibaly, A., Sidibe, A., Sangare, H., Keita, I., Bolozogola, Y. et al. (2019). Suivi de la dynamique environnementale de 1985 a 2018 en zone soudano-sahélienne par Télédétection: Cas de la commune rurale de Nyamina. *Revue Ivoirienne des Sciences et Technologie*, 34, 13-24.
- Diallo, S., Armand, Z. B. T. R. A., Noufé, D., Dao, A., Kamagaté, B., Effebi, R. K. et al. (2019). Dynamique de l'occupation du sol du bassin ivoirien de la lagune Aghien. *International Journal of Innovation and Applied Studies*, 26, 203-217.
- Diancoumba, O., Bokar, H., Toure, A., Kelome, N., & Preko, K. (2020). Characterization of Groundwater Recharge Using the Water Table Fluctuation Method in the Koda Catchment, Mali. *Cloud Publications, International Journal of Advanced Earth Science and Engineering*, 8, 665-681.
- Diancoumba, O., Toure, A., Bokar, H., & Kelome, N. (2019). *Modelling of Groundwater Dynamics Using Visual Modflow in the Koda Catchment, Mali*. Poster Presented at AGU Fall Meeting 2019 in San Francisco, CA, USA.
- Diancoumba, O., Gaaloul, N., Bokar, H., Toure, A., Hermassi, T., Bargaoui, Z., & Kelome, N. C. (2018). Hydrogeological Modelling Using Gardenia Model in the Koda Catchment, Mali. *Journal International Sciences et Technique de l'Eau et de l'Environnement*, 3, 95-100.
- Fitzgerald, R. W., & Lees, B. G. (1994). Assessing the Classification Accuracy of Multi-source Remote Sensing Data. *Remote Sensing of Environment*, 47, 362-368.
[https://doi.org/10.1016/0034-4257\(94\)90103-1](https://doi.org/10.1016/0034-4257(94)90103-1)
- Jamtsho, K., & Gyamtsho, T. (2003). *Effective Watershed and Water Management at Local Level: Challenges and Opportunities; National Resources Training Institute: Lobsa, Bhutan, 2003*. National Resources Training Institute.
- Koglo, Y. S., Agyare, W., Diwediga, B., Sogbedji, J., Adden, A., & Gaiser, T. (2018). Remote Sensing-Based and Participatory Analysis of Forests, Agricultural Land Dynamics, and Potential Land Conservation Measures in Klotu District (Togo, West Africa). *Soil Systems*, 2, Article No. 49. <https://doi.org/10.3390/soilsystems2030049>
- Koubodana, D. H., Diekkrüger, B., Näschen, K., Adoukpe, J., & Atchonouglo, K. (2019). Impact of the Accuracy of Land Cover Data sets on the Accuracy of Land Cover Change Scenarios in the Mono River Basin, Togo, West Africa. *Cloud Publications International Journal of Advanced Remote Sensing and GIS*, 8, 3073-3095.
- Lambin, E. ., & Ehrlich, D. (1997). Land Cover Changes in Sub-Saharan Africa (1982-1991): Application of a Change Index Based on Remotely Sensed Surface Temperature

- and Vegetation Indices at a Continental Scale. *Remote Sensing of Environment*, *61*, 181-200. [https://doi.org/10.1016/S0034-4257\(97\)00001-1](https://doi.org/10.1016/S0034-4257(97)00001-1)
- Lin, X., Xu, M., Cao, C., Singh, R. P., & Chen, W. (2018). Land-Use/Land-Cover Changes and Their Influence on the Ecosystem in Chengdu City, China during the Period of 1992-2018. *Sustainability*, *10*, Article No. 3580. <https://doi.org/10.3390/su10103580>
- Nash, J.E., Sutcliffe, J. V. (1970). River Flow Forecasting through Conceptual Models Part I—A Discussion of Principles. *Journal of Hydrology*, *10*, 282-290. [https://doi.org/10.1016/0022-1694\(70\)90255-6](https://doi.org/10.1016/0022-1694(70)90255-6)
- Pandey, S. ., Cockfield, G., & Maraseni, T. N. (2013). Major Drivers of Deforestation and Forest Degradation in Developing Countries and REDD+. *I International Journal of Forest Usufructs Management*, *14*, 99-107.
- Penman, J., Gytarsky, M., Hiraishi, T., Krug, T., Kruger, D., Pipatti, R., & Wagner, F. (2003). *Good Practice Guidance for Land Use, Land Use Change and Forestry. Institute for Global Environmental Strategies (IGES) for the IPCC.* <https://www.ipcc-nggip.iges.or.jp>
- Pervez, S., & Henebry, G. M. (2015). Regional Studies Assessing the Impacts of Climate and Land Use and Land Cover Change on the Freshwater Availability in the Brahmaputra River Basin. *Journal of Hydrology: Regional Studies*, *3*, 285-311. <https://doi.org/10.1016/j.ejrh.2014.09.003>
- Pontius, R., & Millones, M. (2011). Death to Kappa: Birth of Quantity Disagreement and Allocation Disagreement for Accuracy Assessment. *International Journal of Remote Sensing*, *32*, 4407-4429. <https://doi.org/10.1080/01431161.2011.552923>
- Ren, H., Cai, G., Zhao, G., & Li, Z. (2018). Accuracy Assessment of the GlobeLand30 Dataset in Jiangxi Province. *Remote Sensing & Spatial Information Sciences*, *42*, 1481-1487. <https://doi.org/10.5194/isprs-archives-XLII-3-1481-2018>
- RGPH (2009). *4 ème Recensement général de la population et de l'habitat du Mali (RGPH-2009) Analyse des résultats définitifs*, thème mortalité. Ministère de l'Economie des Finances et du Budget. Institut National de la statistique, Bureau central du recensement, INSTAT, Décembre 2012.
- Roche, P. and Thiery, D. (1984). *Simulation globale de bassins hydrologiques. Introduction à la modélisation et description du modèle GARDENIA*. Rapport BRGMno 84 SGN 337 EAU.
- Scanlon, B. R. S., Reedy, R. C., Stonestrom, D., Prudic, D. E., & Dennehy, K. F. (2005). Impact of Land Use and Land Cover Change on Groundwater Recharge and Quality in the Southwestern US. *Global Change Biology*, *11*, 1577-1593. <https://doi.org/10.1111/j.1365-2486.2005.01026.x>
- Stonestrom, D. A., Scanlon, B. R., & Zhang, L. (2009). Introduction to Special Section on Impacts of Land Use Change on Water Resources. *Water Resources Research*, *45*, Article ID: W00A00. <https://doi.org/10.1029/2009WR007937>
- Tamba, S. K., & Li, J. (2011). Analysis of Land Use and Land Cover Changes, and Their Ecological Analysis of Land Use and Land Cover Changes, and Their Ecological Implications in Wuhan, China. *Journal of Geography and Geology*, *3*, 104-118. <https://doi.org/10.5539/jgg.v3n1p104>
- Toure, A., Diekkrüger, B., Mariko, A., & Cissé, A. S. (2017). Assessment of Groundwater Resources in the Context of Climate Change and Population Growth: Case of the Klela Basin in Southern Mali. *Climate*, *5*, Article No. 45. <https://doi.org/10.3390/cli5030045>
- Turner, M. G. (2005). Landscape Ecology in North America: Past, Present, and Future. *Ecology*, *86*, 1967-1974. <https://doi.org/10.1890/04-0890>

- Wondie, M., Schneider, W., Melesse, A. M., & Teketay, D. (2011). Spatial and Temporal Land Cover Changes in the Simen Mountains National Park, a World Heritage Site in Northwestern Ethiopia. *Remote Sensing*, *3*, 752-766. <https://doi.org/10.3390/rs3040752>
- Yin, J., He, F., Xiong, Y. J., & Qiu, G. Y. (2017). Effects of Land Use / Land Cover and Climate Changes on Surface Runoff in a Semi-Humid and Semi-Arid Transition Zone in Northwest China. *Hydrology Earth System Sciences*, *21*, 183-196. <https://doi.org/10.5194/hess-21-183-2017>