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By

Oumou DIANCOUMBA

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ASSESSMENT OF THE EFFECTS OF CLIMATE AND LAND USE /LAND COVER CHANGE ON GROUNDWATER RESOURCES IN KODA CATCHMENT, MALI, WEST AFRICA.

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Supervisors:

Nelly Carine KELOME, (Full Prof), University of Abome Calavi, UAC, Benin

Hamadoun BOKAR, (Associate Prof), National Engineering School, ENI-ABT, Mali

Kwasi PREKO (Associate Prof), Kwame Nkrumah University of Science and Technology, KNUST, Ghana

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Reviewers:

Bamory KAMAGATE, Full Prof, University of Nangui Abrogoua, Côte d'Ivoire

Masamaeya D.T. GNAZOU, Associate Prof, University of Lomé, Togo

Abel AFOUDA, Associate Professor**,** University of Abomey Calavi, Benin

======

JURY

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Masamaeya D.T. GNAZOU	Associate Prof, University of Lomé, Togo	Reviewer
Abel AFOUDA	Associate Prof**,** University of Abomey Calavi, Benin	Reviewer
Nicaise YALO	Associate Prof**,** University of Abomey Calavi, Benin	Examinator
Hamadoun BOKAR	Associate Prof, National Engineering School, Mali	Co-supervisor
Nelly Carine KELOME	Full Prof, University of Abomey Calavi, Benin	Supervisor

Dedication

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Abstract

Both Climate and Land Use/Land Cover (LULC) changes are the key factors that can modify water resources availability. Water resources which are a vital necessity for any existing life form are controlled by Climate Change and LULC changes. As Groundwater resources are considered to be more resilient to global changes and many studies have been conducted in order to assess the effects of CC and LULC changes on these resources. Groundwater is the permanent source of water in the Koda catchment, which occupies a surface area of 4921 km^2. Surface water body abounds during the rainy season and dries a few months after this season. Groundwater resources are used to meet most water needs of the inhabitants of the Koda catchment, therefore a careful assessment of the effects of Climate and Land Use/Land Cover changes on groundwater resources is required to better manage these resources. To meet this objective scientific tools and models have been employed in this work to study the groundwater resources over Koda catchment. This study analyses, both at local and regional scales, the rainfall variability across Koda catchment over the period of 1987-2016. Rainfall data recorded from three meteorological stations (Bamako, Katibougou and Toubougou) were used. The standard precipitation index has been estimated in order to characterize the interannual variability of rainfall. In addition, the non-parametrical Pettitt's method (1979), U-statistic of Buishand (1982), Lee and Heghinian test (1977) and Hubert Segmentation (1989) have been evaluated through Khronostat software in order to detect the break point in the rainfall series. Furthermore, the study found that groundwater recharge is one of the most difficult fluxes to define, particularly in arid and semi-arid areas. To make a good estimation of the groundwater recharge which is the key parameter and essential for integrated water management and adaptation the Thornthwaite method, Water Table Fluctuation method and Gardenia model were used to estimate the recharge at different scales. In addition, in order to understand the behavior of the aquifer system, Watershed-scale groundwater flow models was developed. The groundwater flow model (Visual Modflow) was used to simulate the groundwater flow in the Koda catchment. The groundwater flow of the Koda catchment has been calibrated under steady state condition. To evaluate the dynamics of the LULC change over Koda catchment, the spatiotemporal variation of the different units of LULC present in the catchment has been examined. The Supervised Classification method, using Envi 4.5 Software coupled with ArcGIS, was applied to subset Landsat images from 1990 to 2016. Also, the projected Rainfall and Temperature derived from the outputs of three Regional Climate Models (RCMs) driven by three Global Climate Models GCMs under the Representative Concentration Pathways RCP 4.5 and RCP 8.5 Scenarios, were statistically downscaled and corrected using Multiscale Quantile Mapping bias correction method. Therefore, the projected trend of rainfall and temperature for the period 2021-2050 across Koda catchment has been determined. The hydrogeological modeling has been done using Gardenia model to assess the effects of Climate Change on groundwater. The statistical parameters between historical and observed data recorded at Katibougou station have been calculated and the RCA4 driven by two GCMs (IHEC-EC-EARTH and MPI-M-MPI-ESM-LR) have been shown the best correlation. Therefore, the projected temperature and rainfall patterns of these two GCM/RCM pairs, the PET values and Groundwater levels GWL in three piezometers have been used also as the inputs of the Gardenia model. The results show that, during the period of rainy season, July, August, September and October, the GWL decreases in the piezometers within the Koda Catchment for all the two RCM/ GCM pairs under RCP 4.5 compared to historical period. According to the GCM IHEC-EC-EARTH, the predicted decrease of GWL is up to 1.09 m for the RCP 4.5 and 1.26 m for the

RCP8.5 within the Koda Catchment while the GCM MPI-M-MPI-ESM-LR showed the decrease of GWL during the rainy season from 0.62 m for the RCP 4.5 to 1.93 m for the RCP 85. The decrease is more significant for the RCP 8.5 than the RCP 4.5 except with one located near to the outlet of the studied catchment where the GCM MPI-M-MPI-ESM-LR projects an increase of 0.67 m of the observed GWL under the RCP 8.5. All the RCM/ GCM pairs project a decrease of Groundwater recharge over time. It is obvious that this decrease is more significant in RCP8.5 for all the piezometers. The results also show that the maximum recharge in the future is below the present dry conditions, which might lead to the drastic event (drought). The results show that recharge decreases from 1987 to 2050 and severe droughts occur from 2029 to 2039.

Finally, the effects of LULC change on groundwater were assessed for the period 1987-2016. The decline of 8.4 % in groundwater recharge associated to the decrease of savannah and the increase of bare land and cultivated land might become so far obvious in the future if the current rate of deforestation continues in the Koda catchment. The general conclusion of this study is that the Climate and Land Use Land Cover changes are negatively threatened groundwater resources over the study area. The projected effects of climate change will be obvious in the period 2029-2039 (where the simulated droughts events are expected) on groundwater which is projected to be inadequately scarce. Therefore, it is necessary to develop a proper water management plan of these resources to offset these difficulties.

Keywords: Groundwater resources, Climate Change, LULC change, RCM-GCM pairs, Koda catchment, Mali.

Résumé :

Le bassin versant de Koda est situé en Afrique de l'Ouest, au Sud Est du bassin de Taoudéni. A l'instar des autres localités du Mali, l'économie des habitants du bassin de Koda est basée sur l'agriculture. Les eaux souterraines sont les seules sources d'eau disponible pour les besoins en eau des populations, de l'agriculture et aussi pour le bétail. Certains facteurs comme le changement climatique, l'Occupation et l'Utilisation des Sols (OUS) et la croissance démographique ont un important impact sur la disponibilité des ressources en eau du bassin. Le présent travail évalue les effets du changement climatique et l'occupation et l'utilisation des sols sur les eaux souterraines du bassin de Koda. Dans un premier temps, la variabilité climatique à l'échelle du bassin a été étudiée pour la période 1987-2016. Ensuite, la recharge de l'aquifère a été estimée avec différentes méthodes à différentes échelles. La recharge est un paramètre difficile de ce fait, différentes méthodes et modèles ont été combinées pour une meilleure estimation de ce paramètre dans le bassin de Koda. Il s'agit des méthodes de : fluctuations du niveau d'eau et de Thornthwaite et le modèle Gardénia. Le système aquifère du bassin a été également étudié afin de déterminer ses paramètres hydrodynamiques. Enfin, l'évaluation des effets du changement climatique sur les eaux souterraines a été faite tout en utilisant différents modèles régionaux dévirés de différents modèles globaux. Les effets de l'occupation et de l'utilisation des sols (OUS) sur les eaux souterraines de ce bassin ont été évalués. Le modèle Gardénia développé par BRGM a été utilisé pour l'analyse de l'impact du changement climatique sur les eaux souterraines du bassin. Le choix de ce modèle est basé sur la disponibilité des données d'observation. En outre, les données mensuelles de précipitation et d'évapotranspiration obtenues à partir des données de température minimale et maximale de la station climatique de Katibougou couvrant les périodes 1987-2016 (période de référence) et 2021-2050 (simulations pour le futur) ont été réduites à l'échelle locale et corrigées avant d'être utilisées comme données d'entrée du modèle Gardénia pour simuler les niveaux piézométriques dans trois (03) piézomètres et estimer la recharge au sein du bassin. Les données climatiques concernent les projections du Modèle Climatique Régional (MCR), RCA4 piloté par deux (02) Modèles de Circulation Générale (MCG), ICHEC-EC-EARTH et MPI-ESM-LR pour les scénarios du GIEC RCP4.5 et RCP 8.5. Les impacts du changement de l'OUS sur les ressources en eau souterraine ont été évalués tout en étudiant la dynamique de l'OUS de 1987-2016 via trois cartes OUS (1987, 1990 et 2016) établies pour le bassin de Koda. Les résultats se sont avérés satisfaisant, les valeurs des critères de validation tels que le coefficient de corrélation « R^2 » et le coefficient de NASH « NSE » montrent une bonne performance du modèle Gardénia à simuler les niveaux d'eaux et les valeurs de la recharge à l'échelle mensuelle et annuelle. La modélisation hydrogéologique montre que durant la saison pluvieuse (Juillet, Août, Septembre et Octobre) le niveau piézométrique de l'eau diminue au sein du bassin de Koda pour les RCMs utilisés. Le GCM IHEC-EC-EARTH, prévoit une diminution du niveau de l'eau qui peut aller jusqu'à 1,09 m pour le scenario RCP4.5 et jusqu'à 1,26 m pour le scenario RCP8.5. Par ailleurs le GCM MPI-M-MPI-ESM-LR montre une diminution du niveau de l'eau dans le bassin durant les mois pluvieux. Cette diminution est estimée à 0,62 m pour le scenario RCP 4.5 et à 1,93 m pour le scenario 8.5 par rapport au niveau de l'eau observé dans la période de référence.

Les résultats montrent que tous les RCM projettent une diminution du niveau d'eau des nappes dans le temps. Cette diminution est très marquée par le scenario RCP8.5 dans le bassin. Les résultats montrent aussi que la valeur maximale de la recharge dans le futur est faible par rapport aux conditions actuelles. Tous les deux scenarii présentent une diminution de la quantité d'eau qui s'infiltre dans la nappe (recharge). Le scenario RCP8.5 projette la diminution la plus

spectaculaire comparé au scenario RCP4.5. La modélisation montre des années de sécheresse dans le temps vers les années 2029- 2039. Les résultats concernant l'évaluation des impacts de l'OUS montrent une diminution de 8,4 % de la recharge pendant que l'unité savane diminue et les unités de sols nus et les sols occupés par l'agriculture augmentent en quantité.
Cette étude peut être un outil pour la gestion intégrée des ressources en eau souterraine dans le bassin de Koda. Les résultats obtenus permettront aux décideurs de prendre des mesures d'adaptation et de mitigation au changement global (changement climatique et occupation des sols). Ces actions vont permettre d'atténuer voire prévenir les dommages liés au manque d'eau dans le futur à l'échelle du bassin.
Mots-clés : Changement climatique, Occupation et Utilisation des Sols, Ressource en eau souterraine, Scenario climatique, Bassin de Koda, Mali.

Introduction

Les ressources en eau occupent une place importante dans le système de développement socio-économique d’un pays. La disponibilité et l’accessibilité de l’eau ne sont pas toujours garanties dans plusieurs régions du monde, en particulier en Afrique. Selon Odada (2006), la disponibilité et l’accessibilité de l’eau d’une région définissent sa croissance économique. La demande en eau augmente à cause de la croissance démographique galopante, de l’expansion des surfaces irriguées en agriculture et de l’activité humaine mettant ainsi cette ressource naturelle à risque. Les changements climatiques aussi constituent un autre danger pour les ressources en eau. Selon le Groupe Intergouvernemental (IPCC, 2007), les températures des océans et de l’atmosphère augmentent à une vitesse supérieure à celle des décennies précédentes. Ces changements du climat affectent le régime pluviométrique et par la suite perturbent le cycle hydrologique (Mahe & Paturel, 2009). Les problèmes liés aux changements climatiques occupent une importante place parmi les préoccupations majeures contemporaines. En Afrique de l’Ouest, les effets du changement climatique se manifestent par la réduction de la pluviométrie et de l’augmentation de l’évapotranspiration potentielle (Kasei, 2009). A ces changements du climat, s’ajoutent tels d’autres modifications majeures telles que l’Occupation et l’Utilisation des Sols (OUS) (Stonestrom et al., 2009). Ces effets du changement climatique et de l’OUS sont observés sur les eaux de surface que sur les eaux souterraines.

A l’instar de tout le territoire du Mali, les ressources en eau souterraine sont très importantes pour la population du bassin versant de Koda, car cette ressource est utilisée à des fins domestiques, dans l’irrigation, l’industrie et aussi pour le besoin des bétails (USAID, 2006). Les eaux de surface sont insuffisantes et limitées aux précipitations saisonnières qui s’assèchent quelques mois après la saison des pluies. Les eaux souterraines constituent donc les seules ressources permanentes d’eau dans la zone.

En effet, l’économie du Mali, comme la plupart des pays en voie de développement, repose sur l’agriculture alors que cette agriculture subit les aléas du climat, réduisant ainsi la production agricole (USAID, 2006). L’une des plus fortes perturbations qui agit et continue d’agir encore sur les hydro systèmes est due à l’activité humaine et concerne l’occupation et l’utilisation des sols (Aggarwal et al., 2012). Cependant, des investigations sur les ressources en eau souterraine pour essayer de comprendre le comportement du système de l'aquifère sont primordiales pour les habitants de ce bassin en particulier et ceux de l'ensemble du Mali en général.

Très peu d'études ont abordé des sujets d'évaluation des effets du changement climatique et occupation et utilisation des sols sur les ressources en eau souterraine au Mali. La plupart de ces précédentes études étaient basées sur l'effet de la variabilité et/ou changement climatique sur les eaux souterraines, nous avons entre autres Bokar et al. (2012); Toure et al.(2017) et Sidibe (2019). Aucune étude n'a été faite jusque-là pour évaluer les effets du changement global sur les ressources en eau souterraines du bassin de Koda. Il y a donc un intérêt particulier des scientifiques à évaluer les effets du changement climatique et de l'Occupation et l'Utilisation des Sols (OUS) sur les ressources en eau du bassin de Koda. Cette étude est basée sur l'évaluation de la disponibilité des ressources en eau souterraine dans un contexte du changement climatique et de l'occupation et l'utilisation des sols (OUS).

Zone d'étude

Le bassin de Koda est situé dans la partie sud du bassin de Taoudéni. Il couvre une superficie de 4921 Km^2, entre les longitudes 7° 30' 8" O et 8° 28' 5" O et les latitudes 13° 56 ' 00" N et 12° 57' 80" N. Il est localisé à 120 km au Nord de Bamako, la capitale du Mali. Le bassin de Koda est drainé par deux rivières Dilamba et Dilanin. La saison pluvieuse commence généralement en Mai et se termine dans la plupart du temps en Octobre. Le climat est de type soudano-sahélien avec les précipitions moyennes annuelles qui varient entre 500,4 mm à 1164 mm avec une moyenne annuelle de 836 mm enregistrée à la station de Katibougou pour la période 1987-2016. La température moyenne annuelle est de 28,3°C pour la période 1987-2016 avec les températures minimales de l'ordre de 15 °Cà 26,6 °C enregistrées au mois de Décembre à Janvier. Durant la période d'Avril à Mai, les températures maximales tournent au de 31,4 °C à 40,5 °C.

Le climat de ce bassin est régi par le mouvement du vent de convergence intertropicale. La moyenne de l'évaporation potentielle annuelle dépasse les 2000 mm au sein du bassin et la moyenne mensuelle est de 173 mm. Une très grande variabilité climatique est enregistrée au sein du bassin et les épisodes de sécheresse s'y manifestent.

Matériels and méthodes

Pour atteindre ces objectifs, des données, des méthodes et des outils appropriés ont été utilisées durant cette étude.

Au nombre des données utilisées, on note les données d'observation climatiques, les données climatiques des modèles climatiques, les données hydrologiques, données démographiques, données satellitaires, des cartes de l'occupation des sols, données géologiques et hydrogéologiques.

Ces données ont été collectées sur le terrain, dans la littérature, à la Direction Nationale et Régionale de l'Hydraulique, à la Direction Nationale de la Météorologie, les ONG et les services privés et étatiques qui s'intéressent à la thématique de l'eau.

La variabilité climatique a été étudiée au sein du bassin pour la période 1987-2016 tout en déterminant les années de ruptures au moyen du logiciel Khronosat de l'IRD. A cela, s'ajoute l'étude des années sèches et humides à partir des Indices de précipitation. La recharge de la nappe a été estimée en combinant la méthode de fluctuation du niveau d'eau des nappes, la méthode physique de Thornthwaite et le modèle Gardénia. L'objectif principal de l'utilisation de plusieurs méthodes dans l'estimation de la recharge est d'obtenir un résultat optimal par comparaison. Par ailleurs, Visual Modflow a été utilisé pour la modélisation des eaux souterraines sous régime permanent afin d'estimer les paramètres hydrodynamiques du bassin de Koda. La valeur optimale de la recharge obtenue est directement utilisée comme paramètre d'entrée dans le modèle MODFLOW. Le modèle Gardénia a été utilisé pour l'évaluation des impacts du changement climatique sur les eaux souterraines. Enfin, la dynamique de l'Occupation et Utilisation des Sols (OUS) a été étudiée à travers les cartes de l'OUS 1990, 1998 et 2016. De là, les effets de ce changement de l'OUS sur les eaux souterraines du Bassin de Koda ont été déterminés.

Résultats et discussion

Le bassin versant de Koda a enregistré des années de sécheresses et d'humidités pour la période 1987-2016, et les années sèches sont plus fréquentes que les années humides. Les résultats de l'étude de la variabilité climatique au sein du bassin révèlent une grande variation de la quantité de pluie reçue chaque année dans le bassin. Une légère modification de la quantité de pluie pourrait entraîner des changements importants au cycle hydrologique du bassin. Concernant l'estimation de la recharge de la nappe, la méthode de Thornthwaite donne une recharge de 1% à 8 % de la pluie annuelle. Cette valeur en dessous de la valeur obtenue en appliquant la méthode de fluctuation du niveau d'eau (7% - 29%) et celle obtenue à partir du modèle Gardénia (10%-

24%). Ces résultats montrent que les valeurs de la recharge de la nappe obtenues par ces deux dernières méthodes sont proches l'une de l'autre. La valeur annuelle de la recharge de la nappe au sein du bassin de Koda est comprise entre 7 % - 29 % de la pluie annuelle. La méthode de Thornthwaite a sous-estimé la recharge, cela pourrait être dû à la surestimation de l'évapotranspiration par cette méthode. Les résultats de la simulation de l'écoulement souterrain, montrent une bonne performance du model Visual Modflow, ces valeurs sont mentionnées dans le **tableau 1** ci-dessous :

Tableau 1: Valeurs des paramètres d'évaluation du modèle Visual Modflow.

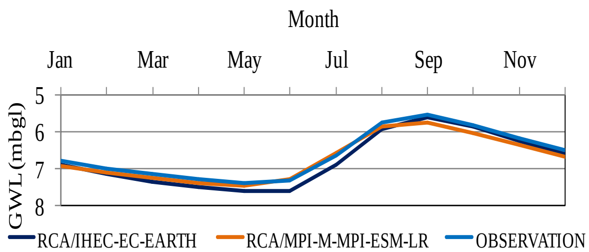
Coefficient de correlation (R^2)	**Root Mean Square (RMS)**	**Normalized RMS**
0,98	3,75 m	4,69 %

Cette modélisation nous a permis d'estimer de façon optimale les paramètres hydrodynamiques qui ont été utilisés par la suite dans le modèle Gardénia pour mieux définir le contexte hydrogéologique du bassin.

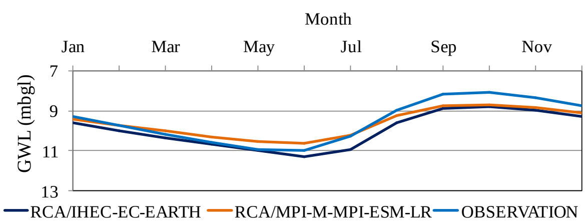
Les sorties des modèles climatiques (pluie et température) ont été obtenues à partir la base de données du projet de Cordex puis corrigées en appliquant la méthode Quantile-Quantile transformation. Une étude comparative a été faite entre les données non corrigées, les données corrigées et les données d'observation. Les données corrigées ont montré les mêmes tendances que les données d'observation. Les données de la pluie montrent des tendances positives et négatives (1,5 % à 10,1 %) pour le scenario RCP4.5 et (-0,10 % à 25,29 %) pour le scenario RCP8.5. Contrairement aux données de pluie, les données de températures montrent uniquement des tendances positives. L'augmentation de la température maximale s'élève de 2,3°C pour (température maxi. Tmax) pour le scenario RCP4.5 et 2,47°C pour le scenario RCP8.5. Par ailleurs la température minimale (température mini. Tmin) s'augmente de 2,2°C pour le scenario RCP4.5 et de 2,5 °C pour le scenario RCP8.5. Les données de températures ont été bien simulées par les modèles climatiques contrairement aux données de pluie.

Les résultats de la modélisation montrent que durant la saison pluvieuse (Juillet, Août, Septembre et Octobre) le niveau piézométrique de l'eau diminue au sein du bassin de Koda par rapport aux données d'observation.

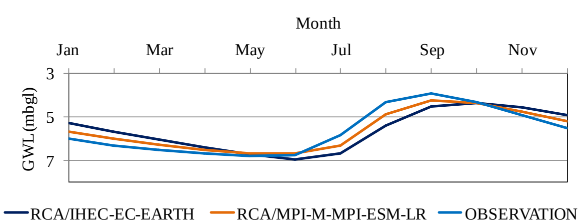
Le modèle global GCM IHEC-EC-EARTH, prévoit une diminution du niveau de l’eau qui peut aller jusqu’ à 1,09 m pour le scenario RCP4.5 et jusqu’à 1,26 m pour le scenario RCP8.5. Par ailleurs, le modèle global MPI-M-MPI-ESM-LR montre une diminution de 0,62 m pour le scenario RCP 4.5 et 1,93 m pour le scenario RCP8.5 du niveau piézométrique dans le bassin durant les mois pluvieux par rapport aux données d’observation.



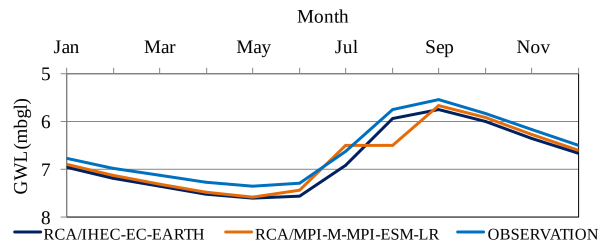
a. Piézomètre F1; RCP 4.5



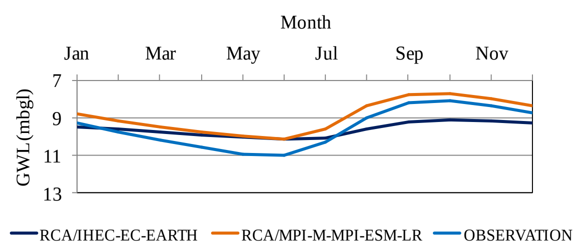
b. Piézomètre K1; RCP 4.5



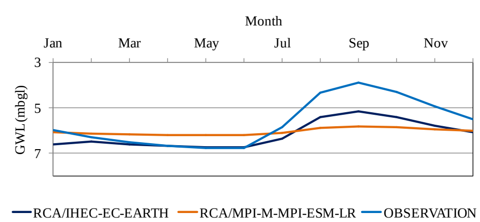
c. Piézomètre N1 ; RCP 4.5



d. PiézomètreF1; RCP 8.5



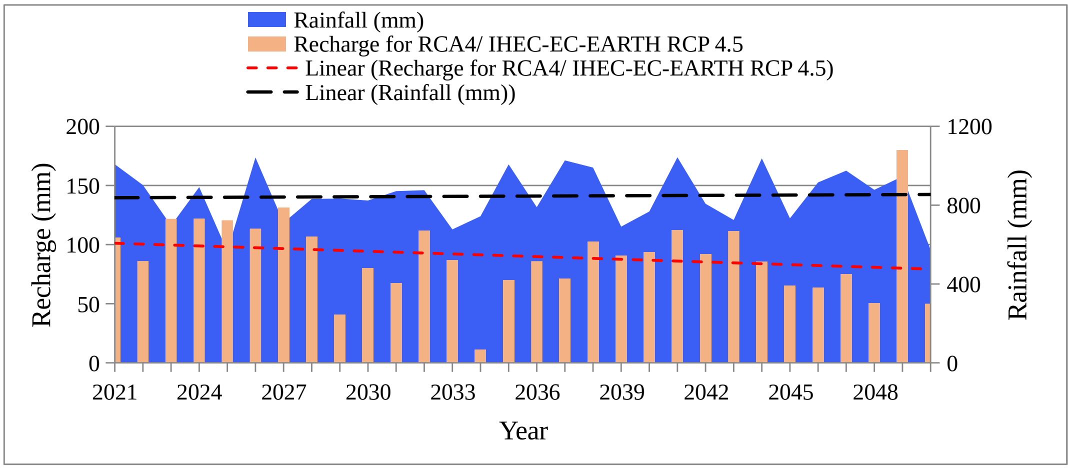
e. Piézomètre K1; RCP 8.5



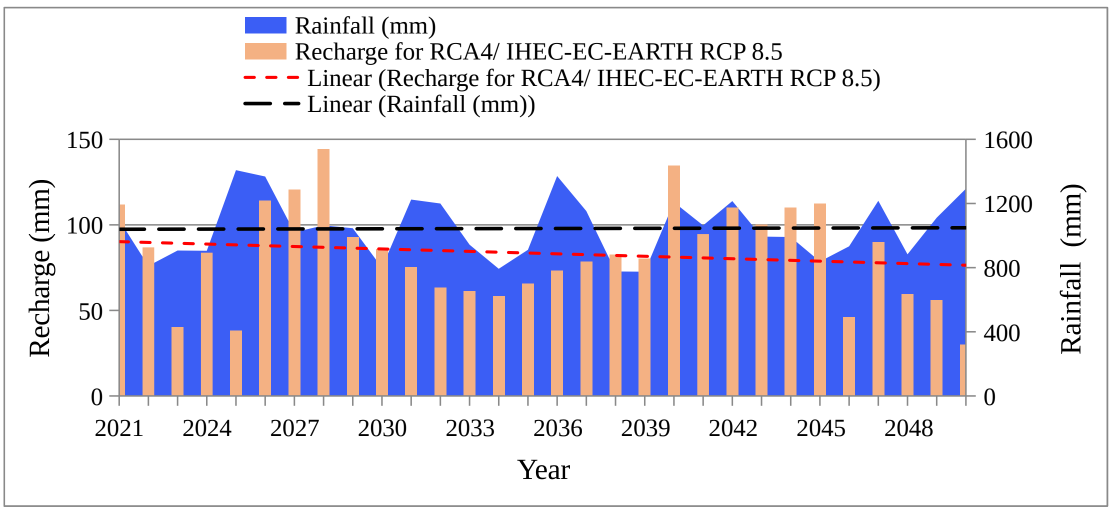
f. Piézomètre N1 ; RCP 8.5

Figure 1 : Comparaison des niveaux d’eau dans les piézomètres à différentes périodes d’observation (1987-216) et de simulation (2021-2050).

La modélisation montre une diminution de la recharge de la nappe durant la période étudiée (2021-2050), les plus sévères années de sécheresse se situent entre les années 2029- 2039. La **figure 2** montre les résultats des modèles climatiques RCA/IHEC-EC-EARTH et la **figure 3** ceux du modèle RCA/MPI-M-MPI-ESM-LR sous les scenarii 4.5 et 8.5.

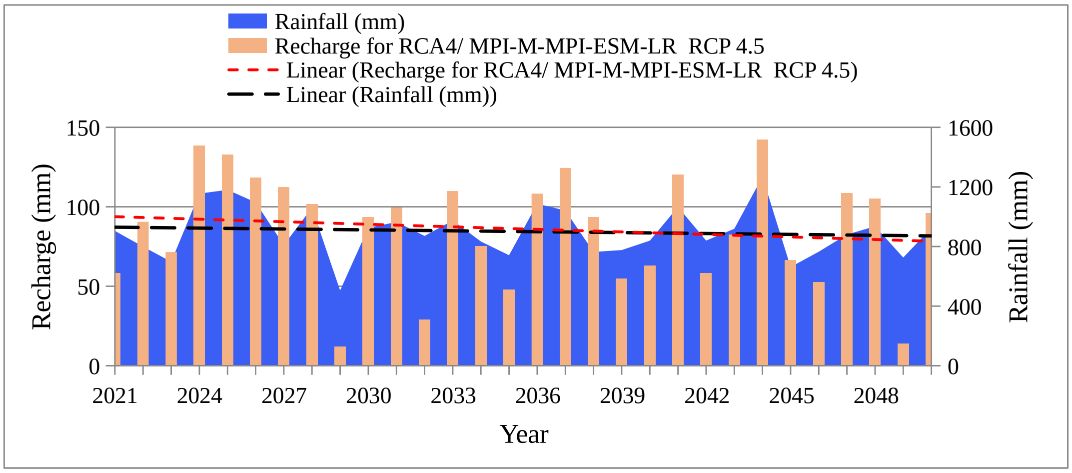


a. RCA4/ IHEC-EC-EARTH-RCP 4.5

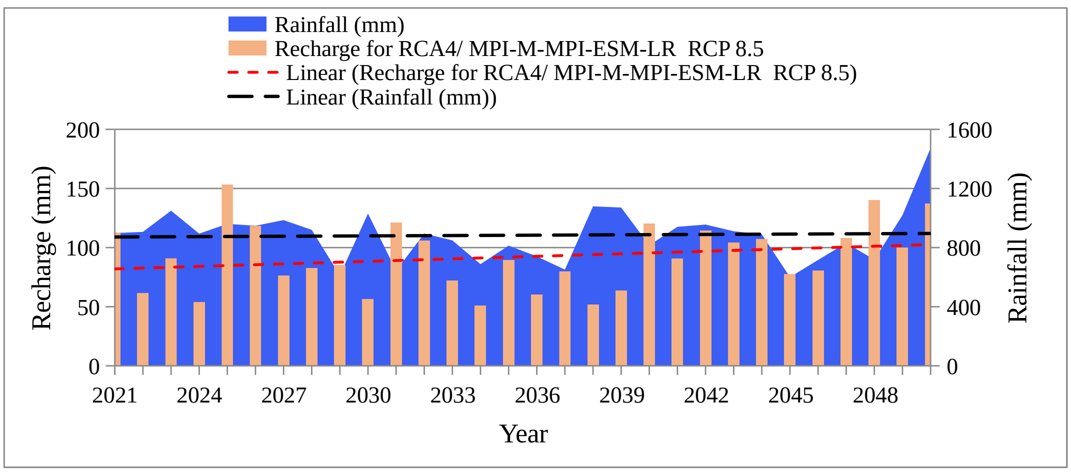


b. RCA4/ IHEC-EC-EARTH-RCP 8.5

Figure 2 : Variation de la recharge annuelle sur la période 2021à 2050 pour le RCA4/ IHEC-EC-EARTH, a. RCA4/ IHEC-EC-EARTH-RCP 4.5, b. RCA4/ IHEC-EC-EARTH-RCP 8.5.



a. RCA4/MPI-M-MPI-ESM-LR-RCP 4.5



b. RCA4/MPI-M-MPI-ESM-LR-RCP 8.5

Figure 3: Variation de la recharge annuelle sur la période 2021 à 2050 pour le RCA4/MPI-M-MPI-ESM-LR, a. RCA4/MPI-M-MPI-ESM-LR-RCP 4.5, b.RCA4/MPI-M-MPI-ESM-LR-RCP 8.5

Par rapport à la dynamique du changement de l'OUS, nous constatons un changement des unités de l'OUS pendant la période 1990-2016. La proportion des unités est entre autres, Champs 14.9 % de l'année 1990 à l'année 2016, une augmentation de 23.5 % des sols nus et une diminution de 38.3 % des unités de savane (**figure4**).

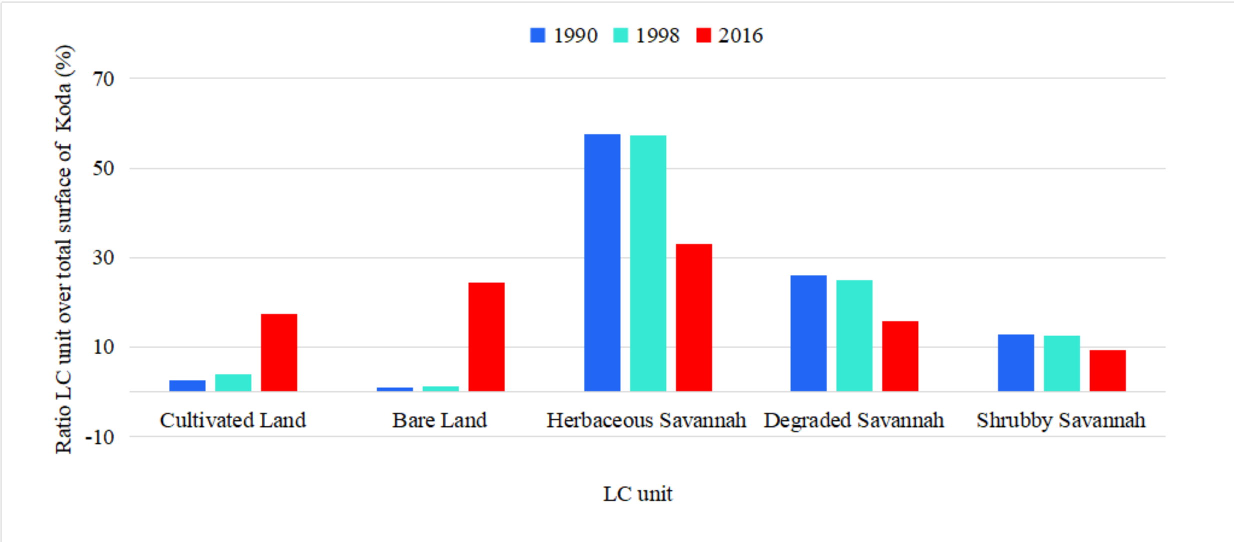


Figure 4: Unités de l'OUS de 1990, 1998 et 2016 au sein du bassin de Koda.

La variation de la recharge moyenne de 1990-2016 dans le bassin de Koda pour la période 1990-2016 est mentionnée dans le **tableau 2**. La réduction de la recharge de 24 % est observée de 1990 à 1998 pendant que l'augmentation de la recharge de 1998-2016 est de 21,4 %. Pour la période 1990-2016 (27 ans), nous observons une diminution générale de 8,32 % de la recharge au sein du bassin de Koda.

Tableau 2: Effets du changement de l'OUS sur les ressources en eau souterraine dans le bassin de Koda.

Année	Pluie (mm)	Changement de la recharge		
		Période	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

-signifie la diminution de la recharge

+ signifie l'augmentation de la recharge

Conclusion

En conclusion générale, cette étude a montré que le changement climatique et le changement de l'OUS ont un effet néfaste sur les eaux souterraines du bassin versant de Koda. La quantité d'eau qui recharge la nappe souterraine, le niveau de l'eau dans les nappes sont entrain de diminuer dans le temps. Cette diminution du stockage d'eau dans les nappes souterraines est observée durant toute la période 1986-2050 et la plus importante est prévue pour la période 2029-2039 pour tous les modèles climatiques utilisés durant cette étude.

Une diminution de la recharge est associée aux changements de l'OUS. Ces changements de l'OUS peuvent être expliqués par l'accroissement démographique et aussi l'utilisation du bois comme source d'énergie dans le bassin de Koda. Si rien n'est fait et que la déforestation continue d'être pratiquée à la vitesse actuelle au sein du bassin, la recharge de la nappe d'eau souterraine va de plus en plus diminuée. Utilisation des modèles Visual Modflow et Gardenia s'est avérée bien adaptée aux conditions géologiques et climatiques du bassin versant. Les résultats obtenus de cette étude peuvent être utilisés pour mieux gérer les ressources en eau du bassin et aussi peuvent être un guide pour les futures études qui vont être entreprises dans ce bassin ou un bassin similaire à ce bassin.

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List of abbreviations

CORDEX	Coordinated Regional Climate Downscaling Experiment
CCIS	Climate Change Impacts Studies
DEM	Digital Elevation Model
DNM	National Meteorology Direction (Direction Nationale de la Météorologie)
DNH	National Hydraulic Direction (Direction Nationale de l'Hydraulique)
DRH	RegionalHydraulic Direction (Direction Régionale de l'Hydraulique)
DNPIA	Direction Nationale des Productions et Industries Animales
ECHAM	European Centre Hamburg Model
FAO	Food and Agriculture Organization
GARDENIA	Modèle Global À Réservoirs pour la simulation de DÉbits et de NIveaux Aquifères
GCM	Global Climate Model
GIS	Geographic Information System
GDP	Gross Domestic Product
HydroSHEDS	Hydrology of data and map based on SHuttle Elevation Derivatives at multiple Scales
IPCC	Intergovernmental Panel on Climate Change
ITCZ	Inter Tropical Convergence Zone
ITF	InterTropical Front
LULC	Land Use Land Cover
Lpcpd	Liter per capital per day
Mamsl	Meters above mean sea level
Mbgl	Meters below ground level
MPI-ESM-LR	Max Planck Institute for Meteorology Earth-System Model Lower Resolution
NSE	Nash Sutcliffe Efficiency
OUS	Occupation et Utilisation des Sols
PCA	Principal Component Analysis
PMWIN	Processing MODFLOW for Windows
RCA	Rossby Centre Regional Atmospheric Model
RCM	Regional Climate Model
RMSE	Root Mean Square Error
RCP	Representative Concentration Pathways
RGPH	General Census of Human Population (Recensement General de la Population Humaine)
SEI	Stockholm Environment Institute
SMHI	Swedish Meteorological and Hydrological Institute
SPI	Standard Precipitation Index
SRTM	Shuttle Radar Topography Mission
UN	United Nations

UNDP	United Nations Development Programme
UNEP	United Nations Environmental Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNFCCC	United Nations Framework Convention on Climate Change
USAID	United States Agency for International Development
USGS	United States Geological Services
WMO	World Meteorological Organization
WTF	Water Table Fluctuation

Chapter 1: General introduction

This chapter describes the general introduction of the research. It presents research background, problem statement, objectives, hypothesis, research questions and novelty of the study. A clear literature review on the subject is investigated in this chapter. The chapter provides the definition and explanation of the concept of key terminology of research. Furthermore, the effects of climate change and land use/land cover (LULC) on groundwater recharge is widely discussed and the lack of an appropriate water management system over Koda catchment highlighted. Finaly, the application of the various Regional Climate Models (RCMs) and Global Climate Models (GCMs) to the catchment is highlighted.

1.1. Context and problem statement

1.1.1. Context of the study

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 Tabular Infracambrian Layer (112 000 km^2) and is a sub-catchment of the Taoudeni basin (DNHE-PNUD, 1990). 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.

Koda catchment occupied the south eastern part of Taoudeni basin .The Taoudeni basin is the largest one in West Africa having its more parts in Mali. The southern border side shared by Mali , Burkina faso and Niger is mainly constituted of sandstones. In the area the main cities (Bamako, Sikasso, Koutiala Kati, etc.) are located and their water supply demand is high and mostly assured with groundwater through fractured and fissured area. Koda catchment is located in Tabular Infracambrian Layer (112, 000 square kilometers) of Taoudeni basin (DNHE-PNUD, 1990; Dakoure, 2003). The catchment is situated in the upper Niger River basin. Niger River is the third largest river in Africa with an area draining of 2.117.700 km^2 (Mahé & Olivry, 1995; Henry,2011). The upper Niger River crosses Koulikoro region where the interested catchment is located. Koulikoro region is one of the main regions where agriculture is the main land use, with crop type such as wheat, grounnuts, vegetables and rice as principal crops.

Livestock comes as second source of income of its inhabitant after agriculture. So far, all these activities are watered by groundwater and seasonal rainfall which let us assume that groundwater is the main source of water in the catchment. Groundwater is very important in the study area because it is the only permanent water resources and the majority of people rely on groundwater to satisfy their water needs. Some of the effects of climate and LULC changes (global change) have been observed throughout the world by floods, droughts and also the variability of the amount of rainfall (Boko et al., 2007; World Bank, 2008; Ibrahim et al., 2014; Yin et al., 2017; Sekela & Manfred, 2019; Quenum et al., 2019). That variability is manifested by decreasing or increasing infiltration over time depending on the place. According to Djibo et al. (2015) the variability of the summer precipitation regime in semi arid zones has a large impacts on hydrological cycle, water resources and food security. The decrease in the rainfall patterns has been predicted by Taylor et al. (2002) over the whole Mali.

Previous studies (Traore, 1985; ARP Developpement, 2003; Henry, 2011, Toure et al., 2016; Diancoumba et al., 2020) done in the southern part of Taoudeni concluded that the infiltration is linearly related to precipitation in the tabular infracambrian aquifers where Koda catchment is located. Therefore, this decrease of annual rainfall leads to decrease in groundwater table in the Niger River basin (Mahe & Paturel, 2009; Henry, 2011). In addition, Bokar et al. (2012)studied the impact of climate variability for the period 1940-2008 in the Kolondieba catchment, in the southern part of Mali through Visual Modflow package and found that groundwater level declines from 2 to 15 cm per year. A study carried out by Toure et al. (2016) using Processing Modflow (PMWIN) software, in Klela basin situated in the sikasso region, southern Mali concludedthat groundwater storage slightly reduces by 39 Mm^3/year (approximatively 10.6 mm/year). A recent study using PMWIN conducted by Sidibe (2019) in the Niger basin, hightlihted that the surface water volume flow in hydrological station decreases considerably every year due undoubtedly to climate condition. According to that study, the low flow which has been observed from 1970 to date can also affect the groundwater and its recharge over the river Niger and Bani basins.

The overall conclusion of these studies is that groundwater recharge, groundwater level and storage are decreasing over time. The consideration of the effects of climate and land use/land cover on water resources is placed in a wider context, the chain reactioncrosses the interfaces between climate, hydrology, water-resource systems and society (WMO, 1988).

This current study is focused on the assessment of the effects of global change (climate and LULC changes) on groundwater resources in Koda catchment. The target of the Malian government is to improve the knowledge on natural resources and also to cope with climate change impacts on naturals resources. Water is one of the main factors that controls the development especially in rural areas where the economy is based on agriculture, livestock, etc.

1.1.2. Problem statement

In the study area, all their activities are watered by groundwater because the surface water is related to rainy season. Therefore, groundwater is used as the main water resource in the study area. The issue is how to manage this resourcesustainability. Nowadays, the demand of water is increasing due to the population growth, urbanization and human activities. There is a need to study present and future availability of groundwater in the Koda catchment. A clear picture of impact of climate change on groundwater resources in the Koda catchment is missing. No known study has been completed to evaluate the availability of the present and future groundwater in the study area in the context of climate and land use changes. The amount of rainfall that recharges the aquifer is unknown in the Koda catchment. Groundwater dynamics have not been studied to plan the water supply in the future. The hydrogeological response of the Koda catchment using a set of Regional Climate Model (RCM) driven by Global Climate Model (GCM) is not investigated. Many people (116,837 inhabitants) live in this area therefore, it will be better to understand how climate and LULC change will affect the availability of groundwater resources in this part of Mali.

The results of the present research will be a tool for groundwater management and also a guide for future studies in the Koda catchment.

1.2. Literrature review

According to Lefort (1996), water is one of the main factors that control development as it plays an important role in addressing issues related to poverty, heath and hunger. Water cover 70 % of the earth’s surface but, only 3 % of it is fresh water (surface and groundwater). Only a small percentage of the fresh water is accessible for human use. The major part (three-quarters) of fresh water is present in the earth surface in the form of ice caps and glaciers located in the polar regions. Only a small amount of water (0.01 %of the world’s total water) is considered available for human use on a regular basis. Fresh water especially groundwater constitutes the main water resources in the Tropics and many Sub-Saharan Africa (SSA) countries. People depend on it to satisfy their domestic needs and for irrigation purposes (Dakoure, 2003).

But its availability and distribution are limited. Population is continuing to expand and is strongly connected to the high demand of fresh water. According to Abramovitz (1996); humans withdraw water far faster than it can be recharged. The amount of withdrawn water continues to rise. Population growth is considered as the major of factor leading to the increase of water demand, to which some factors such as urbanization, economic development and improved living standards are responsible for the high water demand (Gleick, 1993).

Over the last decades, the increase in groundwater extraction has led to a considerable reduction of groundwater storage, and then amount of groundwater pumping rates have greatly exceeded their natural recharge (Abramovitz, 1996). Some efforts have been applied to meet projected increases in freshwater demand over the next few decades in Sub-Saharan countries (MacDonald, 2012).

Climate change is one of the main challenges impacting Sub-Saharan African countries from physical,social, economic, and environmental repercussions (Mamadou et al., 2019). These issues were underlined in the latest report of the Intergovernmental Panel on Climate Change (IPCC, 2014), and they are likely to become more significant in the future. According to Wuebbles & Ciuro (2013), the change on temperature and rainfall which constitute the key climate variables will impact the hydrological regimes and the change could become more significant in the future.

This change adds to the demographic pressure and land use change could have negative effects on people and all activities depending on the availability of water. Nowadays, the demand of water is increasing due to the population growth, urbanization and human activities such as farming, overgrazing, mining, construction and development.

Groundwater resources will not only be impacted by Climate and Land Use/Land Cover directly through the interaction with surface water bodies, but also, indirectly, through the recharge process(Jyrkama and Sykes, 2007).

Land Use/Land Cover (LULC) is another crucial factor that may affect water resources (Stonestrom et al., 2009). Previous studies have been shown the effects of LULC change on hydrological cycle (Li et al., 2009;Elfert & Bormann, 2010;Yin et al., 2017, Pervez & Henebry, 2015). Therefore, an understanding of the hydrological cycle with assessment of different drivers and factors affecting these processes is required (Aggarwal et al., 2012). Some studies carried out in West Africa in the past decades have shown the significant advances in the understanding of hydrological processes (Giertz, 2004; Elfert & Bormann, 2010). In fact, the assessment of the impacts of Land Use on hydrological cycle has been done over West Africa (Hiepe, 2008; Bossa et al., 2014; Yira, 2016; Aziz, 2017; Diallo et al., 2019). Only few studies have been conducted in Mali to study the dynamics of LULC. For example Daou et al. (2019) has recently studied the dynamics of LULC over Nyamina in Koulikoro region. A number of studies have been done in West Africa to evaluate the impacts of Climate Change (CC) on water resourcesand hydrological cycle (Kasei, 2009; Ibrahim et al., 2014; Yira, 2016; Toure et al., 2016; Aziz, 2017; Adeyeri, 2019).

Mali is a landlocked country in West Africa. With the high levels of vulnerability to climate change (Ayodotu et al., 2019). Climate change and LULC impact on water resources are very perceptible in sahelian and soudanian zone of Mali where high evaporation demand and short recharge period led to groundwater level variability in this area (Bokar et al., 2012). According to Bates et al.(2008), the global surface temperature increased from 1906 to 2005 by 0.74°C, with a more rapid warming trendover the past 50 years. This increase in temperature may affect groundwater availability and quality (Bates et al., 2008). The study area is located in the tabular infracambrian layer which is composed mainly of sandstones. The tabular infracambrian are considered in Mali as the important aquifers in term of quantity and quality of water. 41.1 % of groundwater uses in Mali are provided by the Tabular Infracambrian aquifers (DNHE-PNUD b, 1990). Accoriding to Toure et al. (2016) groundwater level is decreasing over time in the Klela catchment, southern part of Mali.

Demographic explosion, in addition to the Climate context and land use change has led to highly increased needs of water for human consumption. Assessment of the effects of climate change and land use land cover on groundwater is a issue for West Africa especially for Sub-Saharan Africa (SSA) countries like Mali. This study remains a priority for Mali, principally for the population of Koda Catchment. The issue is how to manage these resources in the context of sustainable development. To answer this type of question the selected tools and methods used in the current study have been used in the southern part of Mali and the best results have been found. For example, Mahé & Olivry (1995); Paturel et al. (1997) and Dao et al. (2010) used Khronostat to study the variability of rainfall over Kolondieba basin in southern part of Mali while finite difference method was used to simulate groundwater flow using Visual Modflow and Processing Modflow respectively by Bokar et al. (2012) and Sidibe (2019). Water Table Fluctuation method as well as Thornthwaite has been widely used in the soutern Mali to estimate the groundwater recharge (Traore,1985; DNHE-PNUD, 1990; ARP Developpement, 2003; Dakoure, 2010; Toure et al., 2016). Gardenia model has been used by Dakoure (2010) in the transboundary basin (Mali-Burkina) to estimate the component of water budget. Finaly, the recharge was forecasted using Gardenia model. A set of GCM/RCMs pairs have been considered as a great tool for Climate Change Impacts Studies (CCIS) over West Africa (Karambiri & Garc, 2011; Angelina et al., 2015 ; Yira, 2016; Sylla & Nikiema, 2016; Aziz, 2017; Boko et al., 2020). According to Kirchner (2003); the envisaged impacts of climate change and the increase of groundwater demand in the future required to forecast groundwater recharge.

1.3. Research questions

The main research questions addressed in this thesis were:

1- How does rainfall variability occur in the Koda catchment ?

2- What is the annual recharge in the Koda catchment?

3- What are the hydrogeological parameters of the Koda Catchment?

4- How will changes in Climate Change impact the availability of groundwater resources in the Koda catchment by 2050 using a set of RCM/ GCM pairs?

5- What are the effects of the Land Use/ Land Cover change on groundwater recharge?

1.4. Thesis objectives

1.4.1. Main objective

The main objective of this study is to assess the effects of climate and land use/land cover changes on groundwater resources in the Koda catchment of Mali.

1.4.2. Specific objectives

The specific objectives are to:

i. assess the rainfaill variability over the 30 past decades of the Koda catchment;

ii. estimate the groundwater recharge with various techniques at different scales;

iii. simulate the groundwater flow over the Koda Catchment in steady state conditions;

iv. evaluate the future effect of Climate Change on groundwater level fluctuations in the Koda catchment using a multi-climate model data sets; and

v. improve the undestanding of LULC Change on soil infiltration rate in the Koda Catchment

1.5. Hypotheses

This study is governed by three hypotheses:

1. The variabilty of rainfall of the Koda catchment will consequently impact the groundwater flow regime.
2. The Climate and LULC change will negatively affect groundwater recharge in the Koda catchment.
3. Due to the effects of Climate Change, the groundwater level will decrease over time.

1.6. Novelty

This study is the first of its kind over Koda in the context of the impacts of Climate Change on the availability of groundwater resources. Futhermore, the sensitivity of LULC change on soil infiltration rate has been assessed over Koda catchment. Toadequately quantify the uncertainties associated to climate projections used in Climate Change Impacts Studies (CCIS), this research used a set of RCM driven by GCMs. The results from this study could be used to build a great management strategy over the Koda catchment to take adaptation measure within the Koda catchment in order to cope with climate change. Finaly, the results should be used as a guide for future studies.

1.7. Scope of the thesis

The thesis took into account the thematic areas related to Climate and LULC Change Impacts Studies on Groundwater. The variability of rainfall over the Koda catchment was studied for the period 1987-2016. The estimation of groundwater recharge at different scales using various methods has been done. The Simulation of Groundwater flow of Koda catchment has been made. A hydrogeological response of Koda Catchment using an ensemble of RCM/GCM pairs has been studied. The simulation of the potential future Land Use Land Cover (LULC) distributions was not address in this study. Only the dynamics of LULC cover 1990 to 2016 has been studied and its effects on groundwater recharge were assessed.

1.8. Expected results and benefits

The outputs of the study are outlined below:

1. The estimation of groundwater recharge in the Koda catchment.
2. The simulation of groundwater flow using Visual Modflow.
3. The assessment of the imapct of Climate Change in the Koda catchment and its projections up to 2050 and the sensitivity of LULC changes over soil infiltration rate will be done.
4. Scientific papers in peer reviewed journals will be published.

The **outcomes of the study:**

The expected outcomes of the research will be very usefull for the local population by increasing their knowledge regarding climate and LULC change and the adoption of the strategies to deal with the climate and LULC effects.

1. The results can help to determine the favorable areas or sites for the implantation of new boreholes.
2. The results will help also to take some adaptation measure to Climate and Land Use changes. For instance, famers will have a possibility to know the period of groundwater recharge where they have more water infiltration therefore, where to seek crops that need less or more water.
3. The study area presents enormous potential of groundwater. We will make some previsions concerning the availibity of groundwater in terms of time and space for policy makers and Integrated Water Resources Management (IWRM) workers. In another hand , the results can be a tool for groundwater management.

1.9. Outline of the thesis

a) **Chapter 1** addresses the general overview of study, it also reviews the context of the research, problem statement, novelty,outputs and outcomes of the research. The objectives and research questions are chiefly clarified in this first chapter.

b) **Chapter 2** provides a detailed description of the study area. Its localization, topography, geology, hydrogeology and hydrology are presented.

c) **Chapter 3** provides a comprehensive discussion on data, materials and methods used in the research.

d) **Chapter 4** presents and discusses the rainfall variability over the study area

e) **Chapter 5** deals with the estimation of groundwater recharge using empirical methods and models

f) **Chapter 6** simulates groundwater flow using Visual Modflow.

g) **Chapter 7** describes the Projected Changes in Precipitation and Temperature over Koda Catchment

h) **Chapter 8** illustrates the impacts of climate change using a set of RCM drivers underthe various GCMs.

i) **Chapter 9** addresses the impact of LULC change on soil infiltration rate over Koda catchment

j) **Chapter10** describes the general conclusion and the recommadations of the research

The conceptual frameworkfor the study is presented in **Figure 1**.

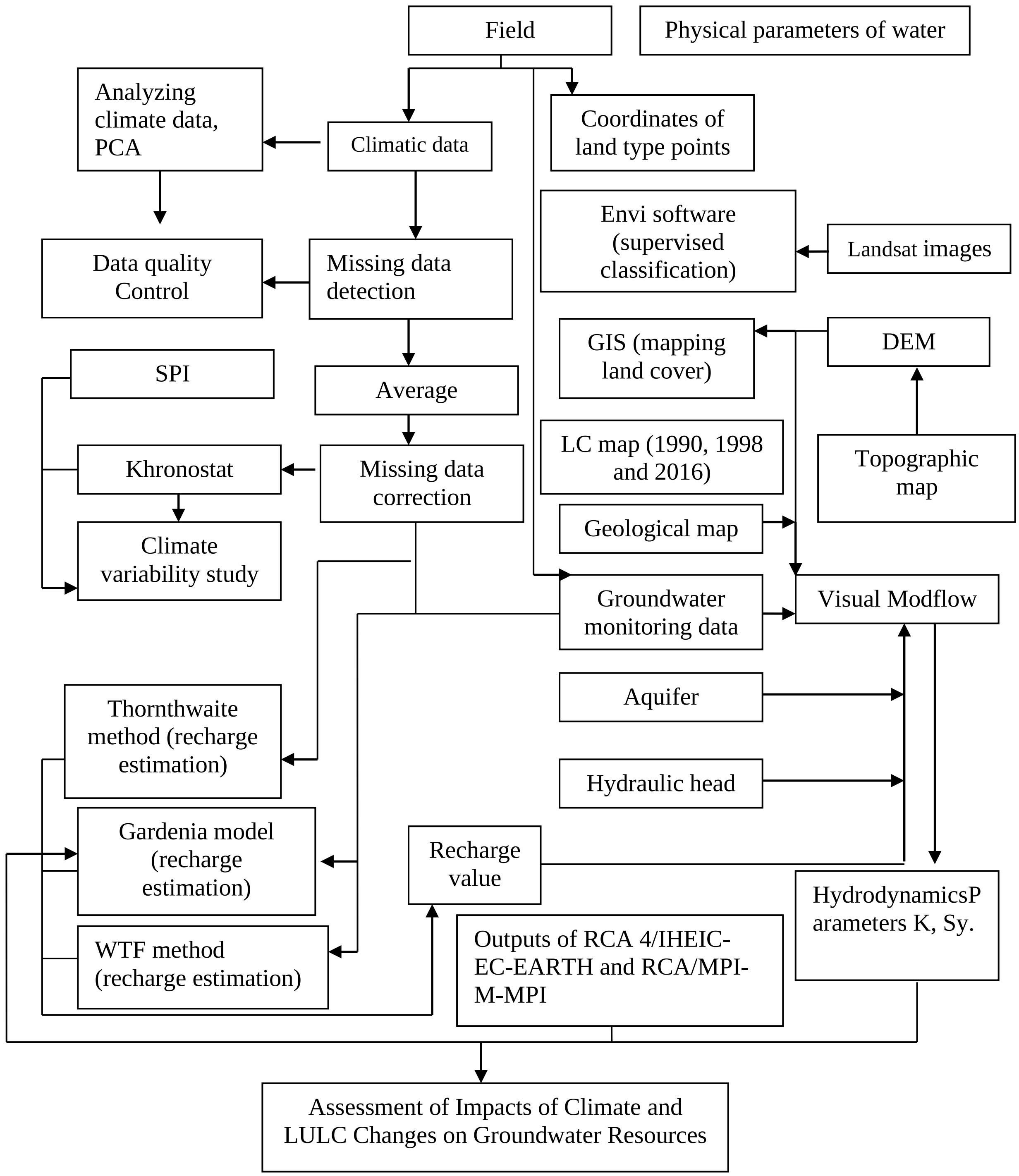


Figure 1: Flow chart of the methodology used in this study.

Chapter 2: Study area

The general description of the study catchment is discussed in this chapter. This includes its location, hydrology, topography, geology, hydrogeologyical, hydrochemistry, land cover use and soil information.

2.1. Location of the study area

The study area is located in the tabular infracambrian layer which is composed mainly of sandstones (**Figure 2**). The tabular infracambrianaquifers are considered in Mali as the important aquifers in term of quantity and quality of water 41.1 % of groundwater uses in Mali are provided by the Tabular Infracambrian aquifers (DNHE-PNUD b, 1990). Accoriding to Toure et al. (2016) groundwater level is decreasing over time in the Klela catchment, southern part of Mali.

Demographic explosion, in addition to the Climate context and land use change has led to highly increased needs of water for human consumption. The Koda catchment (the study catchment) 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 in the semi-arid zone of West Africa, precisely in the southern part of Mali 120 kilometers in the North of Bamako, the capital of Mali (Diancoumba et al., 2018). The catchment is located in Infracambrian rocks and is a sub-catchment of the Taoudeni basin, (DNHE-PNUD b, 1990). The main surface water body in the study area is the Koda stream, one of the tributaries of the Niger River. The study catchment has a total surface area of about 4921 km^2. It comprises the main localities of Beledougou (Massantola, Kambila,Yelekebougou, Nonkon…) (**Figure 2**) .

❖ **Physical characterization of the Koda catchment**

The parameter of Gravelius compactness coefficient K_G has been calculated in order to characterize the form of the catchment. K_G is the ratio of the perimeter of the watershed to the circumference of a circle whose area is equal to that of the given drainage basin. According to Roche(1963) and Hubert (2002) when the value of the K_G ranges from 1.5 and 1.8, the catchment basin is considered as elongated. The Koda catchment is therefore caracterized as elongated as K_G = 1.5. The values of area, perimeter, K_G, Length of rectangle and width of rectangle that describe Koda catchment are outlined in **Table 1**.

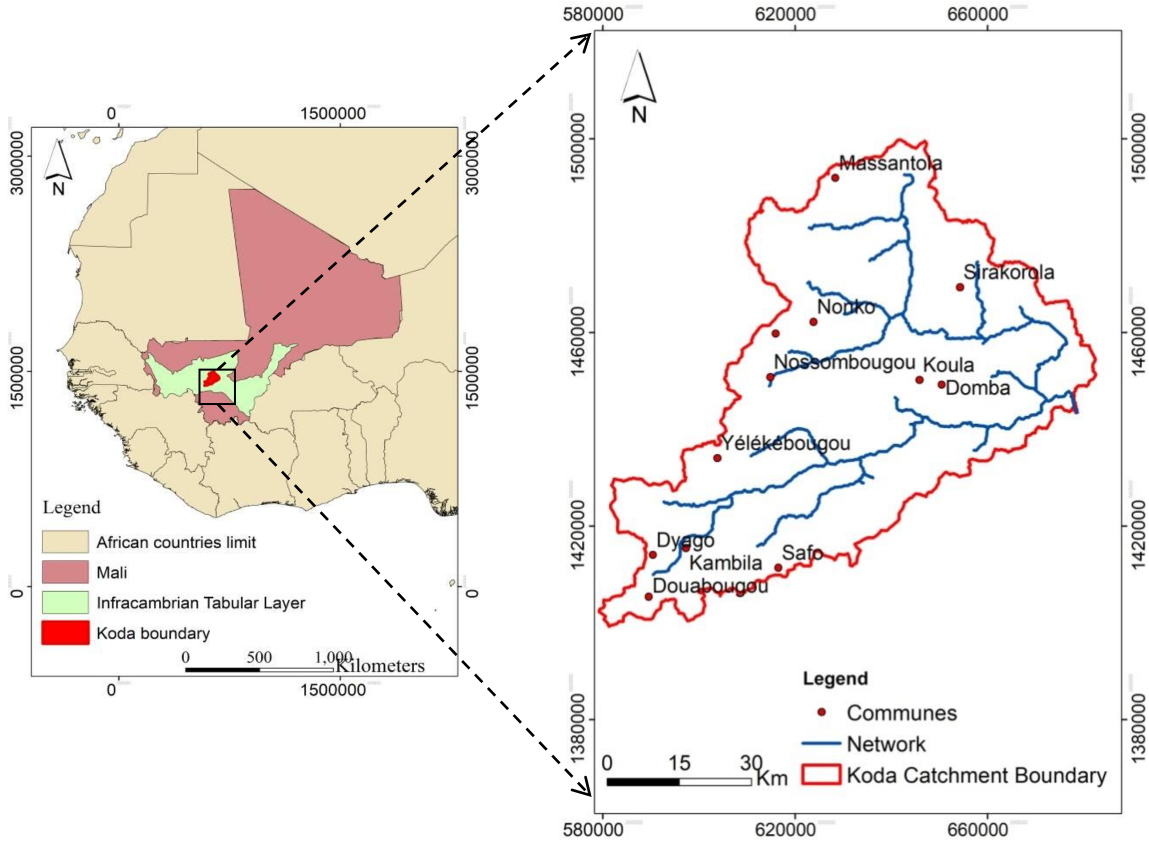


Figure 2: Location of the study area

Table 1: Physical characteristics of Koda catchment after (Hubert, 2002)

Parameters	**Notation**	**Unit**	**Value**
Area	A	km^2	4921
Perimeter	P	km	373
Compacity Index	$K_G = \frac{p}{2\sqrt{\pi - A}} = 0.28\frac{p}{\sqrt{A}}$	-	1.5
length of rectangle equivalent	$L = \frac{K_G\sqrt{A}}{1.12}\left[1 + \sqrt{1 - \left(\frac{1.12}{KG}\right)2}\right]$	km	154.7
Width of rectangle equivalent	$L = \frac{K_G\sqrt{A}}{1.12}\left[1 - \sqrt{1 - \left(\frac{1.12}{KG}\right)2}\right]$	km	31.8

2.2. Relief

The Koda catchment is predominated by a flat topography. The elevation values are ranged between 298 mamsl (meter above sea level) and 588 mamsl with the mean elevation value of 443 mamsl (**Figure 3**).

The flat topography of the Koda catchment is occasionally interrupted by high rising plateaus named “plateaux mandingues’’. The topographic information is from Digital Elevation Model (DEM).

- **Descripition and source of Digital Elevation Model**

The Digital Elevation Model (DEM) was used to provide the topographic information of the study area and also it was used to delineate the watershed boundaries of the Koda catchment. The Digital Elevation Model is provided by the HydroSHEDS (Hydrlogy of data and map based on SHuttle Elevation Drivatives at multiple Scales). HydroSHEDS is derived from elevation data of Shuttle Radar Topographic Mission (SRTM). The resolution used is approximatively 90m x 90m. To correct the error due to the existence of no data, a void-filling technique was applied to the SRTM Digital Elevation Model (DEM) for hydroSHEDS. The SRTM can be downloaded for free of charge from the following HydroSHED site: http://hydrosheds.cr.usgs.gov. The following Figure 3 represents the DEM map of the Koda cathment.

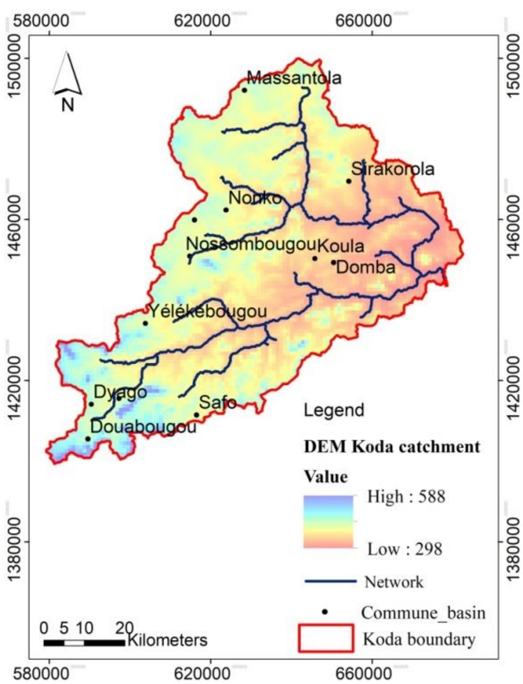


Figure 3: Digital Elevation Model of the Koda catchment (source: HydroSHEDS)

Some Hydromorphological parameters of the Koda catchment has been estimated from the DEM in order to determine the hydromorphology of the study area and the values and the formula are presented in **Table 2** :

Table 2: Hydromorphological parameters of the Koda catchment

Parameter	**Notation**	**Unit**	**Value**
Maximum Elevation	Hmax	m	588
Minimum Elevation	Hmin	m	298
Mean Elevation	Hmean	m	443
Height difference	D = Hmax-Hmin	m	290
Global slope index	Ig= D/Leq	m/km	1.87
Specific Height difference	Ds= Ig *√A	m	131.8

Koda catchment has a gentle elevation according to the classification of Bouzaiene in Baccar, 1988 with 100 m< Ds< 250m.

2.3. Vegetation

Two broad zones of vegetation are presented in the study. The Sudanian zone is distinguished by the region of tree covered savannah mainly by dry savannah with annual rainfall ranging from 500 to 1000 mm. Those zones are characterized by the presence of herbaceous plants and shrub with *Acacia albida*, *Borassus aethiopum*, *Bombax costatum*, *Guirea senegalensis*, *Balanites aegyptiaca* (UNESCO, 2006). Furthermore, the Sahelian zone is characterized by spiny vegetation (N ’Djim & Doumbia, 2009).

2.4. Climate

The movement in the Inter-Tropical Convergence Zone (ITCZ) dominates the West African climate. The ITCZ is defined like an inter-phase of the hot, dry and dusty northeast trade (Obuobie, 2008). The climate of the study area is entirely controlled by the movement of the ITCZ. Two types of seasons characterize the climate of Koda catchment, the rainy season from June to October and the dry season from November to May (USAID, 2006). During the dry season, there is the winter from December to February; it is dominated by the Harmattan, characterized by a dry wind, from the Sahara while the rainy season is dominated by the monsoon from the Gulf of Guinea, which is wet wind (USAID, 2006).

The main directions of wind in the study area is North East to South West (WATER Aid, 2007). In the Koda catchment, the rainfall is unimodal (Dakoure, 2010) with 60 to 80 rainy days between June to October with high evapotranspiration (WATER Aid, 2007).

2.4.1. Rainfall

In the study catchment, the rainfall seasons are well known but the onset is unpredictable (located between mid-May to end of June).

The climate type of the Koda catchment is the Sudano-sahelian , which is defined with an annual precipitation ranges from 700-1200 mm (DNHE-PNUD a, 1990). The data collected from the National Meteorological Direction (Direction Nationale de la Meteorologie, DNM) of Mali used to compute rainfall statistics from 1987 to 2016 shows similar range except some five years with an annual precipicitation less than 700 mm (for the years 1987,1992,1993,1996 and 2006).

The overall annual average of rainfall for the last 30 years (1987-2016) varies from 500.4 mm in the year 1992 to 1,164.3 mm in the year 1988 at Katibougou station. The overall mean over 30 years (1987-2016) is 836 mm (**Figure 5**).

At the Bamako station, the annual average of rainfall over the last 30 years is ranged from 644.3 mm (year 2007) to 1205 mm (year 2008). The overall annual mean from 1987-2016 is 862.62 mm (**Figure 5**).

A dataset includes the monthly rainfall data collected from Toubougou pluviometric station. The overall annual mean rainfall for the period 2001-2007 at Toubougou is 729.1 mm with 207 mm and 1123 mm respectively with minimum and maximum annual rainfall. The Figure 5 shows the mean annual rainfall over the three stations

2.4.1.1. Coefficient of variation (CV)

The variation coefficient of the rainfall series has been calculated in order to check the homogeneity of the datasets using the relationship CV= σ /m, where σ is the standard deviation and m is the mean value.

For the three stations, the Variation coefficient CV of the datasets are less than 50% meaning that the datasets are homogeneous. The values of CV, Standard Deviation, max, min and mean are summarized in **Table 3**.

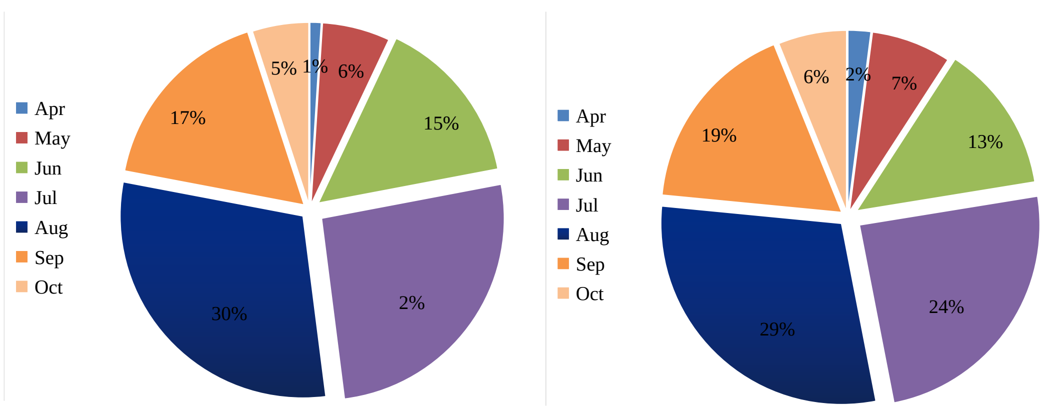
Table 3: Results of statistics analysis using XLSTAT software

Summary statistics: (using XLSTAT)									
Stations	Variable	Obs year	Obs. with missing data	Obs. without missing data	Min (mm)	Max (mm)	Mean (mm)	Std. deviation	C.V (%)
Katibougou	Annual rainfall (mm)	30	0	30	500.4	1164.3	836	154.1	18.4
Bamako		30	0	30	644.3	1205.1	862.6	155.3	17.9
Toubougou		17	0	17	207	1123	729.1	192.6	26.4

Obs means observations.

2.4.1.2. Determination of the rainy month in terms of percentage of the overall monthly rainfall 1987-2016

Two types of seasons characterize the climate of Koda catchment, the rainy season from June to October with 93% of the annual rainfall and the dry season from November to May with 7% of the annual rainfall. The highest values are recorded in July and August with 56% of the annual rainfall followed by September and June with 17% and 15% respectively of the annual rainfall (**Figure 4**).The pluviometric data of Toubougou are available at yearly step therefore, the portion of the annual rainfall for each month could not be determined.The Figure 4 shows the portion of the annual rainfall for each month for Katibougou and Bamako stations.



a. b.

Figure 4: Portion of the annual rainfall for each month of the Koda catchment for the period 1987-2016; a. Katibougou station and b. Bamako station.

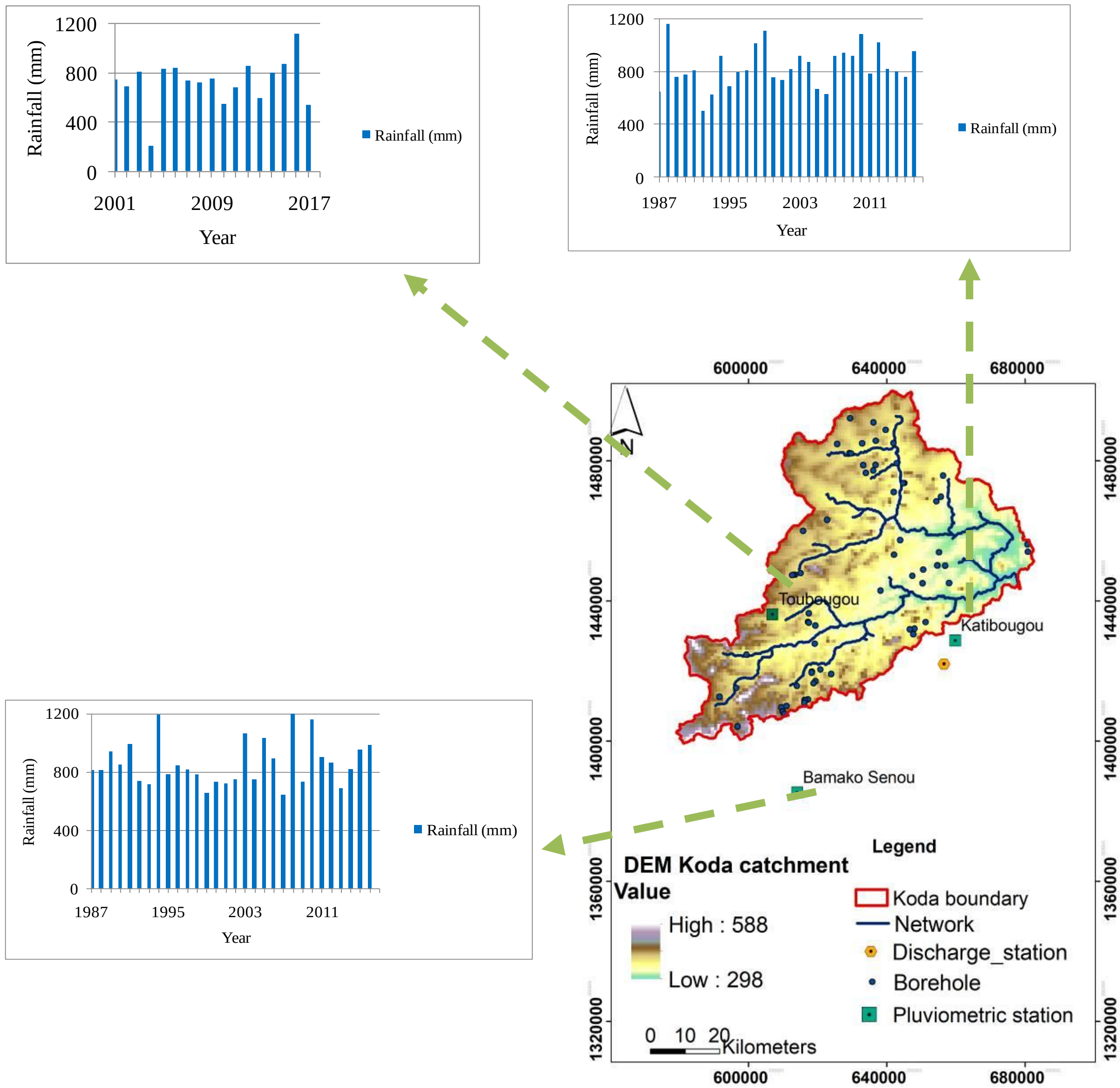


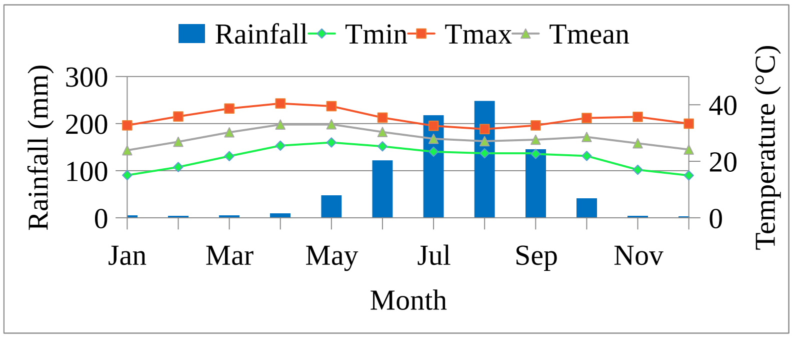
Figure 5: Mean Annual Precipitation over the three pluviometric stations and their location

2.4.2. Temperature

The values of temperature recorded at two stations such as Katibougou and Bamako are used to describe the study area. At Katibougou station, the highest values of the temperature are recorded in April and May while the lowest values are registered in December and January.

At Katibougou station, the maximum temperatures vary from 40.5°C (in April) to 31.4°C (in August), and the minimum temperature up to 26.7°C (May) can be as low as about to 15°C (December) with the mean annual temperature about 28.3°C.

At the Bamako station, the highest values of temperature of 39.5°C and 38.0°Care recorded in April and May respectively. The lowest values of 17.17°C and 17.41°C are recorded in December and January respectively. The overall mean annual temperature is about 28°C with minimum 25°C in January and the maximum up to 32.4°C in April. **Figure 6** shows the temperature pattern over Bamako and Katibougou stations.



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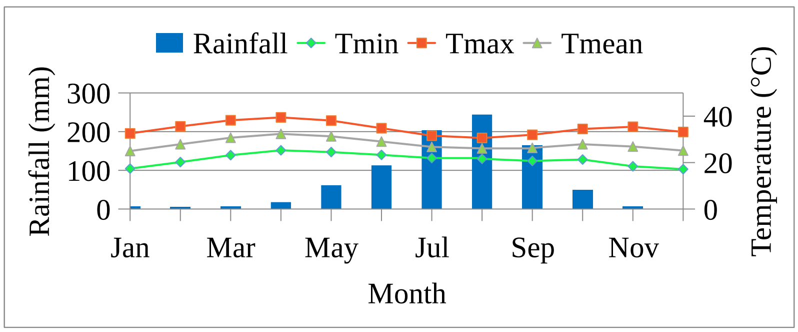


b.

Figure 6: Monthly Temperature (max, mean, and min) and Rainfall from 1987 to 2016, a**.** station of Katibougou and b**.** station of Bamako (data source from DNM of Mali).

2.4.3. Evapotranspiration

Evapotranspiration is the most important parameter in the water budget in arid and semi-arid regions like Mali. The mean annual value of PET over 30 years (1987-2016) exceeds 2,000 mm in the study catchment. The maximum and minimum values of the mean monthly PET obtained respectively in May and December are 217 mm and 131 mm in Katibougou station with a mean annual value estimated at 2032 mm (**Table 4**). At the Bamako station, the same trend has been observed, the annual value of PET was 2437.8 mm, 240 mm as maximum in May and 176 mm obtained in December (**Table 5**)

During the year, the overall mean monthly value of potential evapotranpiration, PET,always exceed the value of the rainfall except in July, August and September (rainy season), (**Figure 7**). This may be due to the high temperature, strong wind of harmattan during the dry season and the low humidity as explained by DNHE-PNUD, (1990 b).

The mean values of PET were obtained from three methods: the Penman-Monteith equation, Blaney-Cridlle and Thornthwaite according to the report of FAO 56. The PET calculation is explained in chapter 3.

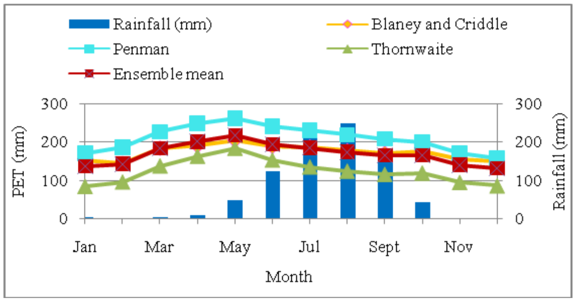
Table 4: Monthly Evapotranspiration estimated through diverse methods for Katibougou station (mm).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
PET Penman (mm)	169.7	185.4	226.3	248.1	261.3	239.7	229.8	218.6	207.7	198.5	171.0	157.1
PET Blaney and Criddle (mm)	152.8	144.2	184.0	190.3	204.6	188.1	187.5	177.5	170.8	176.7	154.1	150.5
PET Thornwaite (mm)	85.12	96.84	138.5	163.9	184.6	153.9	135.9	125.0	116.62	120.03	95.5	86.5
Mean Values (mm)	135.8	142.1	182.9	200.8	216.8	193.9	184.4	173.7	165.07	165.12	140.26	131.4

Table 5: Monthly Evapotranspiration estimated through diverse methods for Bamako station (mm).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
PET Penman (mm)	221.4	237.5	281.0	248.0	281.1	241.3	223.6	216.4	208.3	208.9	196.4	206.8
PET Blaney and Criddle (mm)	157.1	147.5	184.9	188.2	199.3	182.0	182.6	173.7	167.3	174.4	155.9	154.9
PET Thornwaite (mm)	90.0	87.5	141.7	168.5	168.5	134.0	126.0	116.0	104.4	115.0	94.1	90.1
Mean Values (mm)	189.2	192.5	233.0	240.2	240.2	211.7	203.1	195.1	187.8	191.7	176.1	180.9

Figure 7 shows the mean monthly Potential Evapotranspiration PET estimated using various methods and the mean annual rainfall over Katibougou and Bamako stations.



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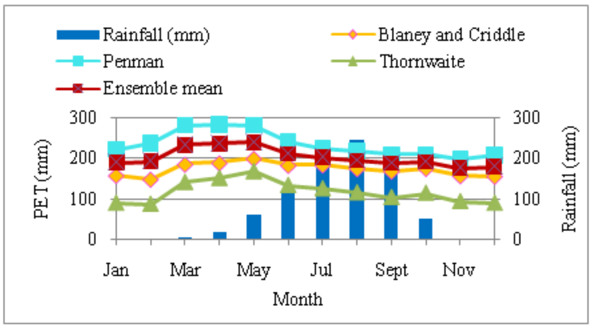
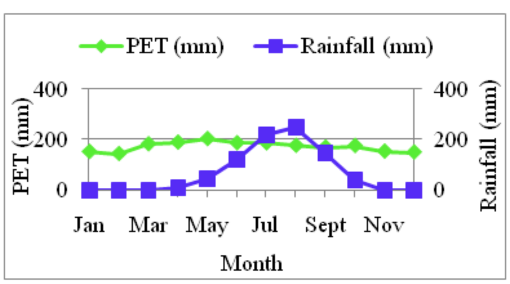


b.

Figure 7: The mean monthly Potential Evapotranspiration PET estimated using various methods and the mean annual rainfall over, a. Katibougou station and b. Bamako station in the Koda catchment, from 1987-2016 (data source from DNM of Mali).

The PET parameter is one of the principal elements of the water budget component in arid and semi arid zone which is controlling the recharge of the aquifer. According to PET value, the infiltration occurs only during the months which for the rainfall value isgreater than the PET value especially in July, August and September as shown in **Figure 8** :



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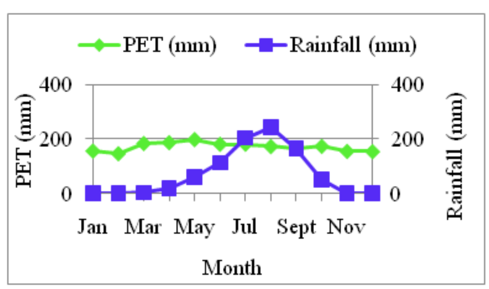


b.

Figure 8: Mean monthly rainfall and potential evapotranspiration at a. Katibougou and b. Bamako stations in the Koda catchment, from 1987-2016 (data source from DNM of Mali)

2.5. Hydrography

The Koda River is one of the tributaries of the Niger River. It constitutes the only surface water present over the Koda catchment. According to the data obtained from the National Hydraulic Service of Mali, over the period of 55 years (1960-2015), the overall mean annual discharge of the Niger river at Koilikoro was approximatively 1164.50m^3/s with the maximun in 1969 and the minimum value in the year 1989(**Figure 9**).

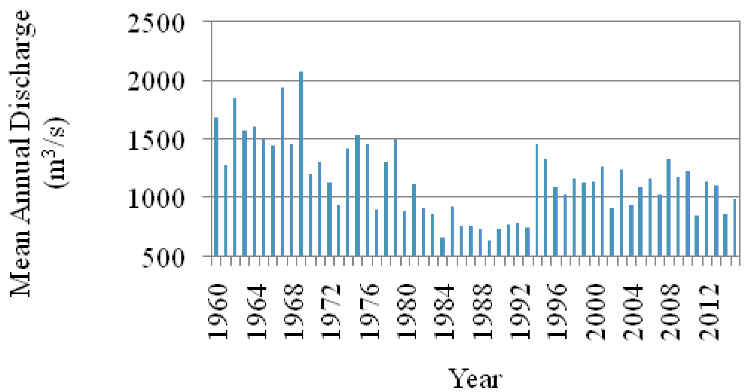


Figure 9: Mean annual discharge (m^3/s) from1960-2015 at the Koulikoro discharge station (data source from DNH of Mali)

The overall monthly mean hydrograph for the period 1960-2015 shows the peak in September (rainy season) and the low flow in April (dry season). The maximum monthly mean can be observed in October 1967 around 7844.32m^3/s and the minimum monthly mean in May 1973 was around 16.01 m^3/s (**Figure 10**).

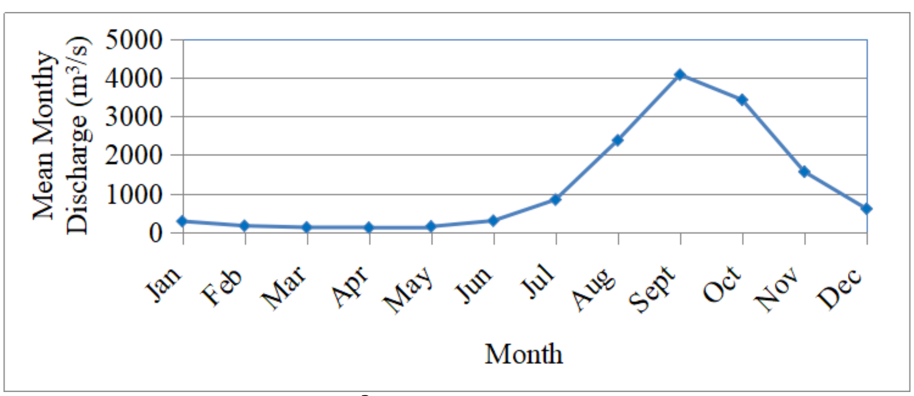
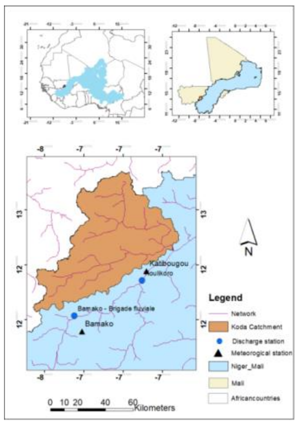
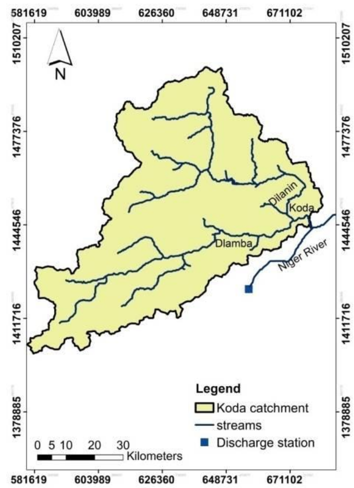


Figure 10: Mean monthly discharge (m^3/s) from1960-2015 at the Koulikoro discharge station (data source from DNH of Mali).

The study catchment is drained by many streams which dry up during the dry season. Their flow duration is varying from hours to days depending on the amount of the precipitation. All the water is drained by the Niger River by two tributaries of Koda catchment: the Dilamba and the Dilanin (**Figure 11**).



a. Location of Niger River over West Africa and Mali.



b. The main streams in the Koda catchment

Figure 11: Localization of Niger River over West Africa and its tributaries in Mali (data source from DNH of Mali).

2.6. Geology

The study area is a subbasin of the Taoudeni basin. It is located in its West Eastern part. The Taoudeni basin is the largest sedimentary basin in West Africa with a total surface of about 2,000,000 km^2. About 1,400,000 km^2 located in Mali and Burkina Faso, 500,000 km^2 in Mauritania and 360,000 km^2 in Algeria (OSS-GICRESAT, 2012). According to Traore (1985), the sedimentairy rocks occupy more than 2/3 of Mali. In 1990, UNDP investigated the geology and hydrology of the entire Mali and produced a document entitled “The hydrogeology synthesis of Mali” (DNHE-PNUD, 1990). This document is used as a field guide. According to that study, nine (9) major geological subdivisions define the lithostratigraphic systems of Mali. These nine subdivisions are:1-The Birimian basement (Precambrian C), 2- Infracambrian (Precambrian A)**,** 3- Cambrian, 4- Primary of Taoudeni, 5- Dolerite intrusion, 6- Continental intercalary, 7- Upper cretaceous/lower Eocene, 8- Continental terminal and 9- Overlying formations.

The Infracambrian unit comprises Sandstone plateau, Gourma basin and Hombori threshold-Douentza. The Koda catchment is located in the Infracambrian layer especially in the sandstone plateaus. The area is mainly constituted by tabular sandstone dated of infra- Cambrian (DNHE-PNUD, 1990 a).

Silstones and fine to coarse sandstones are the main geological formation and occupy the most area where the study is undertaken. Also some geological formations are sometimes associated to the sandstone rocks such as dolerite intrusions, conglomerate, glauconia and quartzite (**Figure 12**). The sandstone of the Koda catchment is the dominant aquifer types and it presents various types of lithology with different thicknesses. Some few area of the sandstone aquifer are overlaid by some dolerites, quartzite, glauconie and conglomerate. The dolerite intrusions are of Pemian or Trias age (British Geological Survey, 2002).

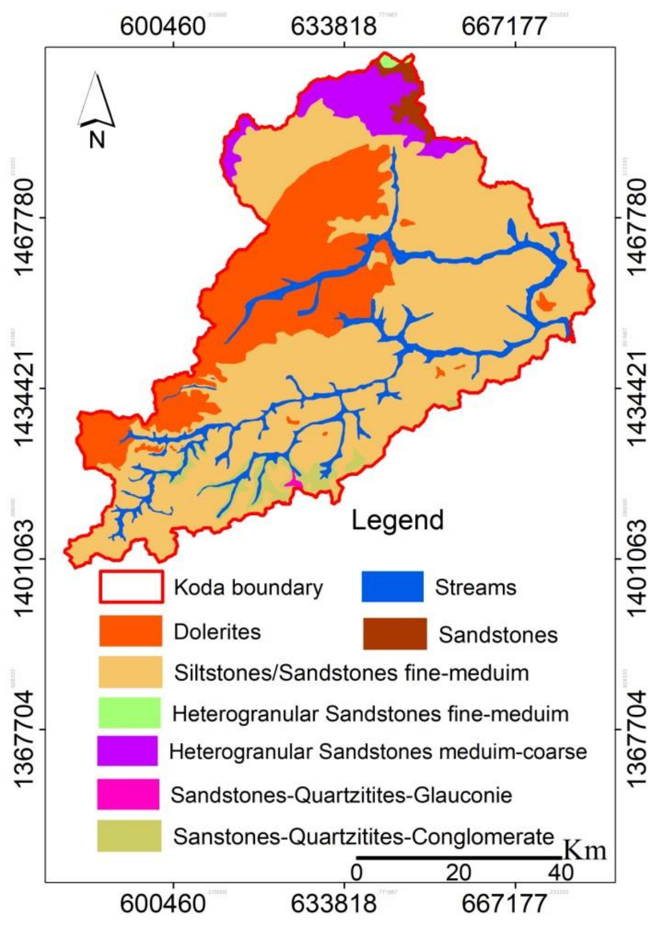


Figure 12: Geological map of the study area (map source from DNH of Mali).

2.7. Hydrogeology

According to previous studies, in Mali groundwater resources include two (2) main types of aquifer: homogeneous with intergranular permeability and discontinuous aquifer types with fissured permeability. The first type is located in the Intercalaire Continental and Terminal layers and the second type characterized the aquifers of the Infracambrian and Paleozoic layers (Traore, 1985). The Koda catchment belongs to the Tabular Infracambrian aquifer and represents discontinuous aquifers, mainly composed by sandstones associated with the intrusion of dolerite. The geology and the tectonic conditions are strongly controlled by the hydrogeology of the study area. The Koda catchment is part of the hydrogeological unit defined in DNHE-PNUD (1990a). Two types of aquifers characterize the aquifers of the study area:

- The shallow aquifer in the unconsolidated superficial-altered formations (laterites, clay, sand) is reached in the first 15 mbelow ground surface with thickness ranging from 4 to 34 m. Shallow groundwater aquifers are readily used by the traditional population of Koda through hand-dug wells.

The transmissivity of the superficial aquifer ranges from 1 to 176 m^2/ day (PNMRE, 2017; HYDRO MALI sarl, 2011b; Diancoumba et al., 2020). The deep aquifer in the epicontinental sandstones with oblique stratifications, schist, and dolerites formations is located around 20-60 m benath the ground surface in most of the several boreholes. The fractured or deep aquifersprovide a great amount of groundwater through deep boreholes. The hydrogeology of that fractured aquifer is very complex. The presence of dolerite is favorable for a secondary porosity while the sandstone is of primary porosity. The aquifer transmissivity varies from 1 to 541 m^2/ day (HYDRO MALI sarl, 2011b; PNMRE, 2017). There is an interconnection between the two aquifers depending on the pluviometry and the degree of fracture of the sandstone (Diancoumba et al., 2020). In the study area, the boreholes are widely used compared to the traditional wells because they provide the best quality and quantity of water. That can be explained by the low depth of traditional wells, which make them more exposed to high evapotranspiration rates, chemical and bacteriological contaminations.

In **Table 6** below some values of transmissivity, storage coefficient and yield are summarized based previous studies undertaken in the study area.

Table 6 : Values of hydrodynamic parameters of the Koda catchment after (DNHE-PNUD , 1990 a: HYDRO MALI sarl, 2011b).

Parameters	Maximum	Minimum	Mean
Transmissity ($m^2.s^{-1}$)	1.0 .10^{-2}	5.0 .10^{-7}	2.6 .10^{-4}
Storage coefficient (‰)	1.0	0.06	0.54
Yield ($m^3.h^{-1}.m^{-2}$)	12 .8	0.1	1.4

2.8. Soil and land use

2.8.1. Soil

The soil map of the Koda catchment has been extracted from the soil map established by FAO-UNESCO available at https://www.fao.org/earthexplorer.

According to FAO classification, three major soil types are presented in the study area (Figure 13), which are Lf12-1a, Lf41-2a and I-1a (FAO-UNESCO, 1977).

FAO is describing the soil types as follows, the first two letters indicate the dominant soil in the association (the first capital letter is for the group and the small letter for the subgroup). These first two letters are followed by a number which denotes the association. The numbers 1, 2 or 3 are for the textural class of the dominant soil; they represent coarse, medium and fine materials. These small numbers are followed by some letters like a, b or c, which describe the topographical information like the slope.

The main soil unit which is Lithosol occupies more than 87% of the soils of the study area. The two ferric luvisols cover 12.44 % of the totalsoils in the study area. The differences between the two types of Livisols are their associations and the textural classes with the dominant soil (**Figure 13**).

2.8.1.1 Luvisols

According to FAO-UNESCO (1977), this type of soil occurres mainly in the Mediterranean and semi-arid tropical zones. Luvisols are characteristic of long dry season.They occurr under unfavourable ecolimatic conditions of water supply and poor drainage often leading to failures in irrigation agriculture. These soils are best for livestock raising combined with cultivation of essential food crops like sorghum, millet and maize (Bouwman, 1990).

2.8.1.2. Lithosols

The poorest soil in terms of nutritents occupies 87.52 % of the catchment. Erosion and leaching constrain the production. Therefore, strategies are developed to increase soil fertility in the long term. The main crops cultivated are cotton, cereals and irragated rice (FAO-UNESCO, 1977; Scoones, 2010). **Table 7** describes the details of the soil types based on their texture, parent material and area occupied by the soil type over the studied cathment.

Table 7: Characteristics of the soil types present over Koda catchment

FAO Soil types	Dominant soils	Texture description	Parent material	Area (Km^2)	Area (%)
I-1c	Lithosols	Sandy , loamy and gravel	Cambrian : sandstone, tillite , minor limestone	4307	87.52
Lf12-1a	Ferric Luvisols	sandy clay loams, silt loams, silty clay loams	Cambrian sandstone and tillite : recent alluvial deposits	607	12. 33
Lf 41-2a	Ferric Luvisols	sandy clay loams, silt loams, silty clay loams	Cambrian sandstone and tillite	5.7	0.11

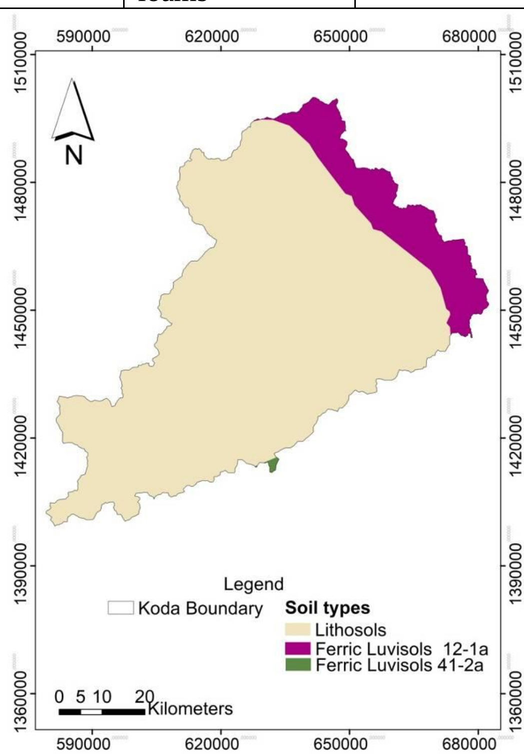


Figure 13: Soil types map of the Koda catchment (Map source FAO-UNESCO, 1977)

2.8.2. Land Use Land cover

In order to produce the land cover map, the coordinates of some points have been taken from the field. They have been selected as unit pixel of the study area to make the land cover classification. The supervision method was selected in the Envi 4.8 software using a Landsat image of 20th February 2016 (wet dry season) downloaded from USGS website: https://www.usgs.gov/earthexplorer

The output from Envi software was used in ArcGIS for the mapping purpose.

The Koda catchment is chiefly characterized by five (5) types of Land Cover units such as Herbaceous Savannah, Degraded Savannah, Cultivated Land, Shrubby Savannah and Bareland (**Figure 14**) with represnting respectively 33.08 %, 15.75 %, 17.40 %, 9.32 % and 24.49 % of the total area.

The principal Land Use of Koda catchment is for Agriculture. Agriculture is the main activity of the population of the study area. The main crops are cereal crops like millet, maize, cotton and rice. A detailed description of the LULC dynamics change from 1986- 2006 over the study is done in the chapter 3.

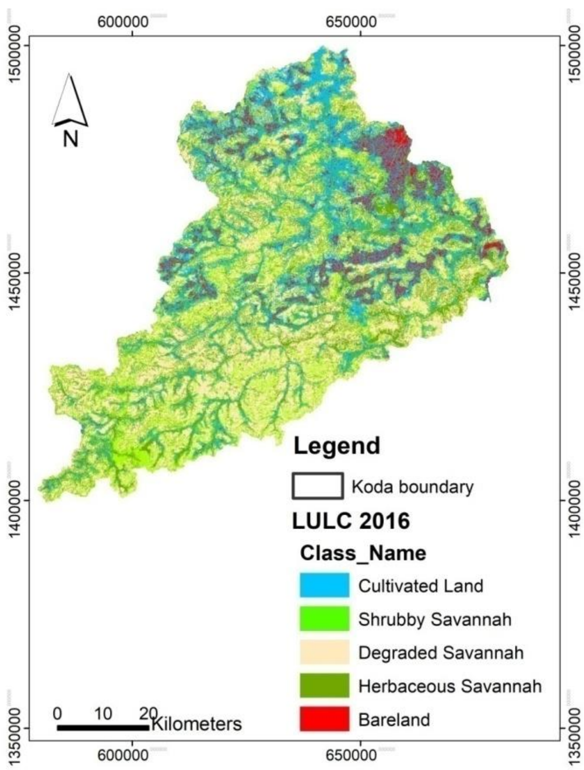


Figure 14: LULC map 2016 of the Koda catchment

2.9. Population

The Northern part of the whole Mali is dominated by the desert area; therefore the Southern part of the country is the most populated place. The population of Mali was estimated to be 14,528,662 inhabitants with 50.4 % Women in 2009(RGPH, 2009).

According to the same source (RGPH, 2009), Koulikoro region including the study area was populated by 2,422,108 inhabitants, while the Koda catchment was estimated with 116,837 inhabitants in the year 2009. The population is estimated to be 164,149 inhabants in 2019 (Figure **15**) considering a population growth rate of 3.6 % (RGPH, 2009).

In Mali the localities are classified in villages, semi urban or urban based on the number of population. When the area has less than 2000 inhabitants, this is classified as a village; for semi urban or urban area the number of the population is greather than 5000 inhabitants.

The population of Koda catchment is almost entirely rural, therefore the principal activities are crop and livestock farmings. The population dependson natural resources (chapter 3 and chapter 6 for more details) for their livelihoods.

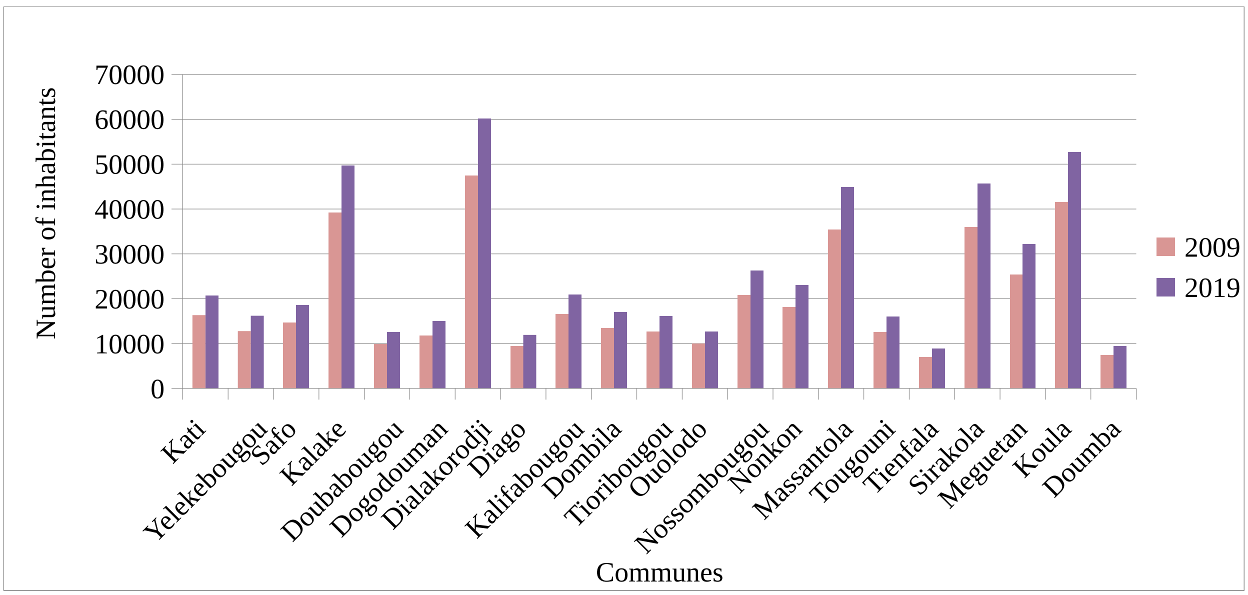


Figure 15: Population map of Koda catchment in 2009 and 2019 (data source from RGPH 2009)

2.10. Groundwater resource utilization

All the domestic water supply as well as water used for crop and livestock farming are mainly groundwater abstracted through deep boreholes and hand dug wells over the year (including the dry and rainy seasons). During the rainy season, from June to October, the pressure on groundwater is barely reduced due to the use of rainfall.

- Due to its importance, groundwater in the study *area* is facing some issues such as its overexploitation and the lack of an appropriate groundwater management system. Others problems related to groundwater issues are inadequate sanitation facilities, deforestation, population growth and global change.

2.11. Economic activities

Mali is considered as one of the word's least developed countries with US$300 per capita income as the annual gross domestic product (GDP) (N 'Djim & Doumbia, 2009). Since most of the population in the Koda cathment is rural, crop and livestock farming are the principal economic activities. Agriculture (63.74%) is the highest income earner of the population of the study area. Herding comes as second source of income with 20,36%(WATER Aid, 2007). Water resource availability is crucial in all of these activities, especially, groundwater because they are used for irrigation.

2.12. Agriculture

Agriculture is mainly rain-dependent and irrigation plays an important part in the whole country Mali. The principal agricultural produce in the study area are: cotton, millet, sorghum, maize, groundnuts and vegetables (USAID, 2006).

2.13. Physical description of water

During the fieldworks, a multi-parameter was used to measure the physico-chemical parameters of groundwater of 20 boreholes and 19 hand-dug wells spatially well distributed within the Koda catchment. The highest values of the conductivity both in the boreholes and the hand dug wells are found in Nossombougou in the western part of the basin while the lowest values are observed in the northern part at Saabougou and Kale (Figure 16).

The maximum values of the water level in the boreholes and wells were respectively 27.51 mbgl (meter below ground level) and 17.2 mbgl in the northern part (at Massantola). The minimum values are found in the southern part of the basin (8.55 m in the borehole in Kambila and 3.27 m in the well in Sonikieni).

The values of pH range from 5.84 to 7.74 in the boreholes while the values range from 5.68 to 7.51 in the hand dug wells. The salinity varies from 0 to 0.25 (g/l) in the boreholes and from 0 to 0.17 (g/l) in the hand dug wells. The TDS represents the Trace metal concentration and follows the same trend as salinity and conductivity parameters. The highest values are observed in the northern part of Koda catchment (Kale and Saabougou) and the lowest values are found in Nossombougou (Western part of the study catchment).

In **Table 8**, the maximum as well as the minimum and the mean values of physicochemical parameters (pH, Temperature, conductivity, salinity, TDS) and water level are summarized.

Table 8: Physicochemical parameters and water level recorded within Koda catchment

Parameters	**Boreholes**			**Wells**		
	Max	Min	Mean	Max	Min	Mean
Ph	7.74	5.84	7.02	7.51	5.68	6.28
Temperature (°C)	33.34	25.69	30.30	38.41	27.19	30.36
Conductivity (µS/cm)	609	2	282	395	4	106
Salinity (g/l)	0.25	0.00	0.12	0.17	0.00	0.05
TDS (g/l)	0.526	0.020	0.250	0.360	0.003	0.097
Water level (mbgl)	27.51	8.55	16.82	17.12	3.27	10.55

These values seem good and in line with those values found in similar hydrogeological regions cited in (DNHE-PNUD, 1990a and Dessouassi, 1997). According to Dessouassi (1997) the mean value of the conductivity and pH of the water of Infracambrian aquifers in Mali are 280 and 6.7 respectively.

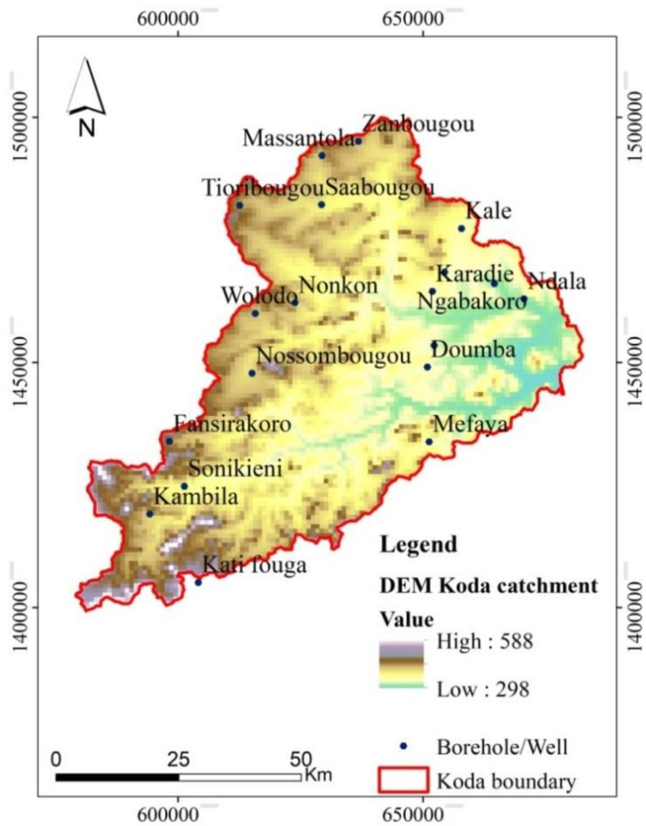


Figure 16 : Location of the communes where the monitoring wells and boreholes are located over Koda catchment.

2.14. Water demand of the Koda catchment

The water demand was estimated in the entire Koda catchment to be 1.64 Mm^3 in 2009 and 2.27 Mm^3 in 2019 where the increase is about 27.4%. From year to year, the demand increases and the rural zones depend more on groundwater than the urban cities. The demand of water is increases by 28 % from 2009-2019 in rural zones while the increase is estimated to be about of 25 % from 2009 to 2019 in urban cities. The rate of water demand within Koda cathment is shown on **Figure 17**. The water demand has been estimated by considering the water used by inhabitants for household, crop and livestock farming and industries. As shown in

Figure 18, the most part of groundwater is used for irrigation purpose (86%) followed by livestock (8 %) and human consumption (6%). All the estimation has been done based on the data obbtained from the DNPIA and the increase by 2019 has been estimated using their respective growth rates.

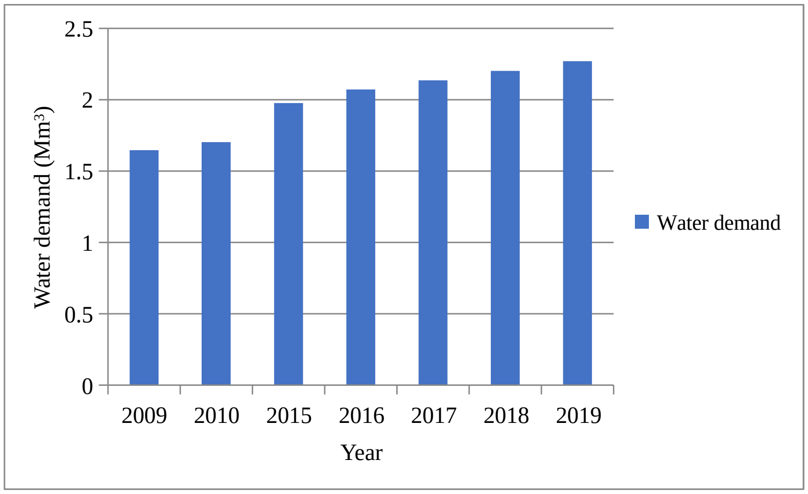


Figure 17: Water demand in Mm^3 in urban and rural zones over Koda catchment from 2009 to 2019.

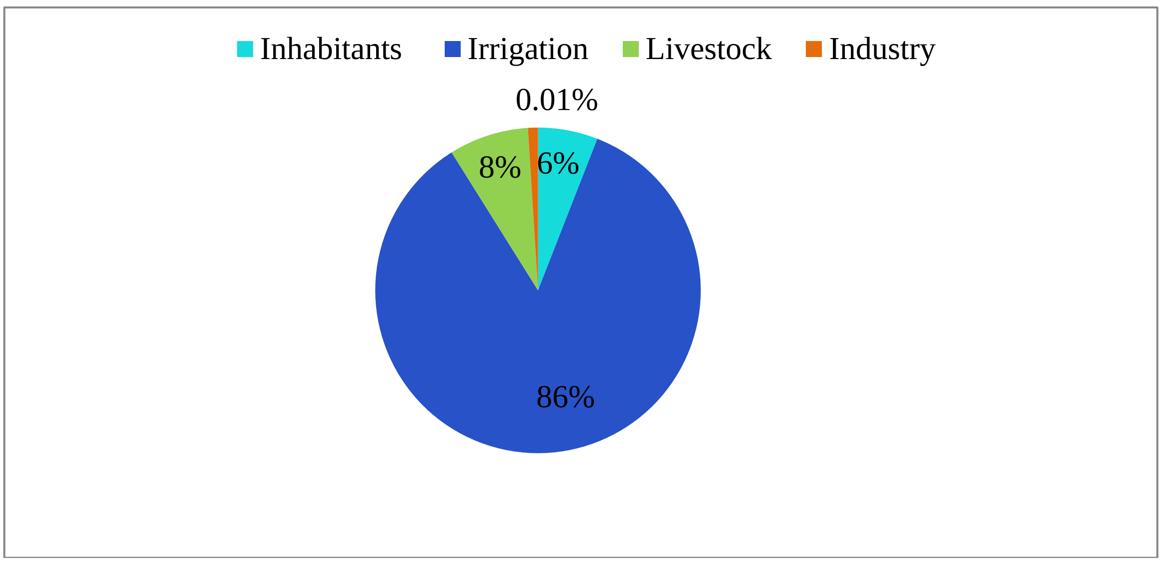


Figure 18: Portion of water needs in % by sector over Koda catchment for the period 2009 – 2019.

2.15. Conclusion of the chapter

A detailed description of the crucial aspects of the Koda catchment has been given in this chapter in order to improve the reader's general knowledge for a suitable study of the catchment.

Chapter 3: Data, materials and methods

This chapter describes in detail all the data, materials and methods used in this study for answering the research questions and achieving the objectives of this study.

3.1. Data

3.1.1. Climate data

The temperature, precipitation, wind speed and relative humidity data from two meteorological stations have been collected and described below:

3.1.1.1. Temperature, Precipitation, Wind speed, Insolation and Relative humidity data

Daily precipitation as well as daily insolation, air temperature (minimum and maximum), relative humidity (maximum and minimum) and wind speed data from 1987 -2016 registered at the Katibougou, Bamako and Didieni from (1994 to 2016) stations were 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 (WaterAID, AMPFFE) within the basin. The climate data for the period 1987-2016 recorded at Katibougou station have been used as historical data in Climate Change Impacts Study (CCIS). The projected rainfall and temperature data (max and min) have been obtained fromCoordinated Regional Climate Downscaling Experiment (CORDEX) for the period 2021-2050 for the RCP 4.5 and RCP 8.5. All these data were used to describe the climate of the study area. Rainfall data have been also used in chapter 4 to study the rainfall varibility over the study area . In chapter 5 and chapter 6, rainfall and temperature data have been used for recharge estimation and for groundwater flow modelling. Also, these data have been used in chapter 8 as observed historical period and the projected data for the period 2021-2050 from CORDEX data to assess the impact of climate change on groundwater resources.

3.1.1.2.Evapotranspiration data

Observation Evapotranspiration were not available.Therefore, it has been estimated through various methods. Accurate assessment of evapotranspiration is essential for managing the water resources of a given catchment. In this study, we used three (3) methods to compute the ET_0 values of the Koda catchment, one radiation-based method (Penman-Monteith equation) and two temperature-based methods (Thornthwaite and Blaney-Criddle). The radiation based method is recognized as accurate method for PET calculation. However, it required a detailed meteorological data which is not always available. The availability of the data was an issue because the available climatic data had many gaps in them.

a. Penman-Monteith equation

We used the Penman formula to calculate the ET_0 (equation 1).The daily Potential Evapotranspiration data at Katibougou stations were obtained by applying the Penman-Monteith method validated by the FAO ETo calculator (FAO, 1998).The radiation data is not available; it was derived from the (average) daily actual duration of bright sunshine (hours per day).

The wind data at Katibougou station was measured at 10 m, therefore we used a formula to convert it at 2 m which is requested by Penman method. Also, as the station of Katibougou is an agro station not a synoptic station, we used the isolation data to get the radiation through formula. For more details pleaserefer to the report of FAO (1998). The following equationdescribed the ET_0 calculation from FAO Penman-Monteith equation(1):

$$ET_0 = \frac{0.408(Rn - G) + \gamma \frac{900}{T+273} U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (1)$$

where ET_0 is reference evapotranspiration [mm day^{-1}], $R_n$is net radiation at the crop surface [MJ m^{-2} day^{-1}], G is soil heat flux density [MJ m^{-2} day^{-1}], T is mean daily air temperature at 2 m height [°C], $u_2$is wind speed at 2 m height [m s^{-1}], e_s is saturation vapour pressure [kPa], e_a is actual vapour pressure [kPa], e_s-e_a is saturation vapour pressure deficit [kPa], Δ is slope vapour pressure curve [kPa °C^{-1}] and γ is psychrometric constant [kPa °C^{-1}].

The data required for the calculation of the ET_0 using Penman is outlined below:

- **Location**

Altitude above sea level (m) and the latitude in degrees of the location should be specified. In the calculation procedures the extraterrestrial radiation (Ra) is determined and the daylight hours (N), the latitude is expressed in radian (decimal degree time's π/180).

- **Temperature**

The average air temperature in degree celsuis at daily time scale are required.

- **Humidity**

The average daily actual vapour pressure, $e_a$in kilopascals (kPa)is required. The e_a can be derived from maximum and minimum relative humidity (%).

- **Radiation**

The (average) daily net radiation expressed in megajoules per square metre per day (MJ m^{-2} day^{-1}) is required

- **Wind speed**

The (average) daily wind speed in metres per second (m s^{-1}) measured at 2 m above the ground level is required. The wind speed is measured at Katiougou station at 10 m above the ground level. The calculation procedure to adjust wind speed to the standard height of 2 m was done.

a- Blaney Criddle 1952 method

b- DailyET_0valueswere obtained via Blaney Criddle using mean daily temperature and evapotranspiration depletion factor K, which is function of latitude. The monthly ET_0 values have been from daily ET_0 (Blaney & Criddle, 1962).

c- Thornthwaite method

The Thornthwaite method required the mean monthly temperature (T, in degrees Celsius) as well as the monthly total precipitation (P, in millimeters) and the latitude (in decimal degrees) of the location of interest are required as inputs to the model. In the current case the temperature and rainfall data used are for the period 1987 to 2016 recorded at Katibougou station. More details on Thornthwaite method are available on http://onlinecalc.sdsu.edu/onlinethornthwaite.php.

Conclusion

We used the Penman formula to calculate the ET_0, but the availability of the data was an issue, due to many gaps in their datasets. The Blaney-Criddleand Thornthwaite formula require knowledge of components of which were available in the study area. Therefore, we calculated the potential evapotransipiration using three methods (Penman,Thornthwaite and Blaney-Criddle methods) in order to get an idea of the best method that can be used in this area of interest to calculate the ET_0 component. We observe that the Penman overestimated the PET patterns while the thornthwaite method underestimated it. The measured values obtained from Blaney and Criddle method were closed to the overall mean value of the three methods. **Figure 19** presents the plots of the estimated monthly PET against rainfall.

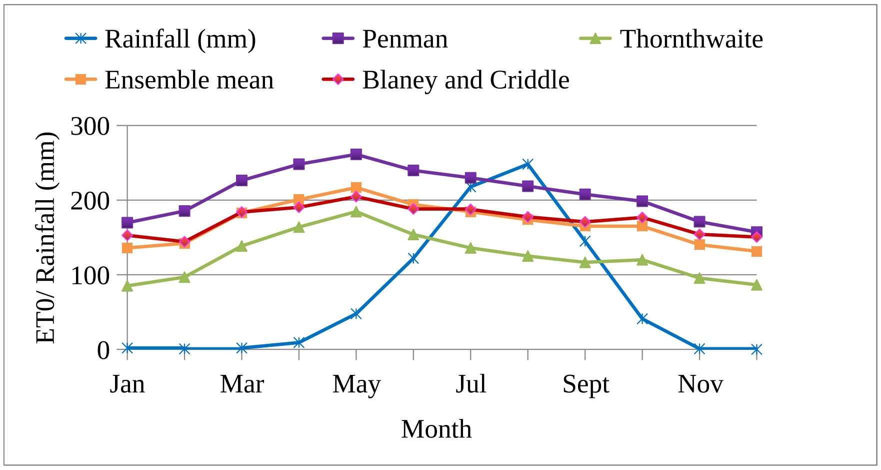


Figure 19: Monthly ET0 estimated from three different methods for the period 1987-2016 over Katibougou station

The ET0 values were used in chapter 2 to describe the climate of the study area; in chapter IV as Gardenia model input; in chapter 6 for groundwater flow modelling purpose using Visual Modflow. Finaly, the estimated ET0 in Gardenia model as historical observed data was used in chapter 8 for Climate Change Impacts assessment.

3.1.2. Discharge data

The daily discharge data from 1960 to 2015 of Niger River registered at Koulikoro Hydro-Station were collected from the National Hydraulic Service of Mali. At the outlet station of Koda, there is no station to measure the discharge of the Koda catchment. Therefore, Koulikoro station is the nearest hydrostation of the study catchment.

The task was to determine the value of the discharge at the Koda outlet, for that the water velocity at the outlet was monitored in the field (low and high water period) from 2016 to 2019 using a moulinet and we used Hydraccess software to estimate the discharge value at Koda catchment.

3.1.3. Hydrogeological data

Hydrogeological data used in this current study are essentially based on piezometric data, pumping test data and drilling data.

a) Piezometric data

Some Piezometers and wells have been monitored and the water level data has been used in chapter 5 to estimate groundwater recharge using WTF method. These data were also used as

GWL input data in Gardenia in chapter 5 and chapter 8. Their description is described in details below:

i. **Piezometer Kossaba**: the data is available from 1986 to 1991and recordedt weekl**y**
ii. **Piezometer Fansiracoura**: The groundwater level data is available for 12 years from 2008 to 2019. The data were recorded annually and weekly.
iii. **Piezometer Nossombougou**: The water level data is available for the years 2016 - 2019. The water level was recorded automatically every minute.

b) Pumping test data

Pumping data are collected from the National Service of Hydraulic, the NGO WaterAid, Association Malienne Pour l'Education du Public et la Protection de l'Environnement (AMEPPE) and from field. Historical transient pumping test data from boreholes were used to calculate the hydraulic conductivity data through following empirical equation 2:

$$T = K*e \qquad (2)$$

With T defined as transmissivity (m^2/s), e as thickness (m) and K hydraulic conductivity (m/s). The interpretation of the pumping test data has been done to determine the transmissivity and the coefficient of storage of the aquifer using Cooper-Jacob method (Cooper & Jacob, 1946). These data were used in chapter 5 for groundwater modeling purpose and in chapter 3 and 4 in Gardenia model to settle the hydrodynamic parameters in the model.

Groundwater level data from piezometers and wells have been collected from the National Hydraulic Service of Mali, Farmers and NGOs (**AMEPPE and WaterAid**).

c) Drilling log data

The drilled boreholes data from about 150 boreholes were collected and used in this study (**Figure 20**). These data have been used to determine the historical groundwater level used in Chapter 5 and in chapter 6 to settle the starting hydraulic head value under steady state simulation.

The stratigraphic log of these boreholes has been used to determine the number of aquifer layers and their thickness in chapter 6 for groundwater flow simulation in the catchment of interest.

Figure 20 shows the location of the boreholes used in this study.

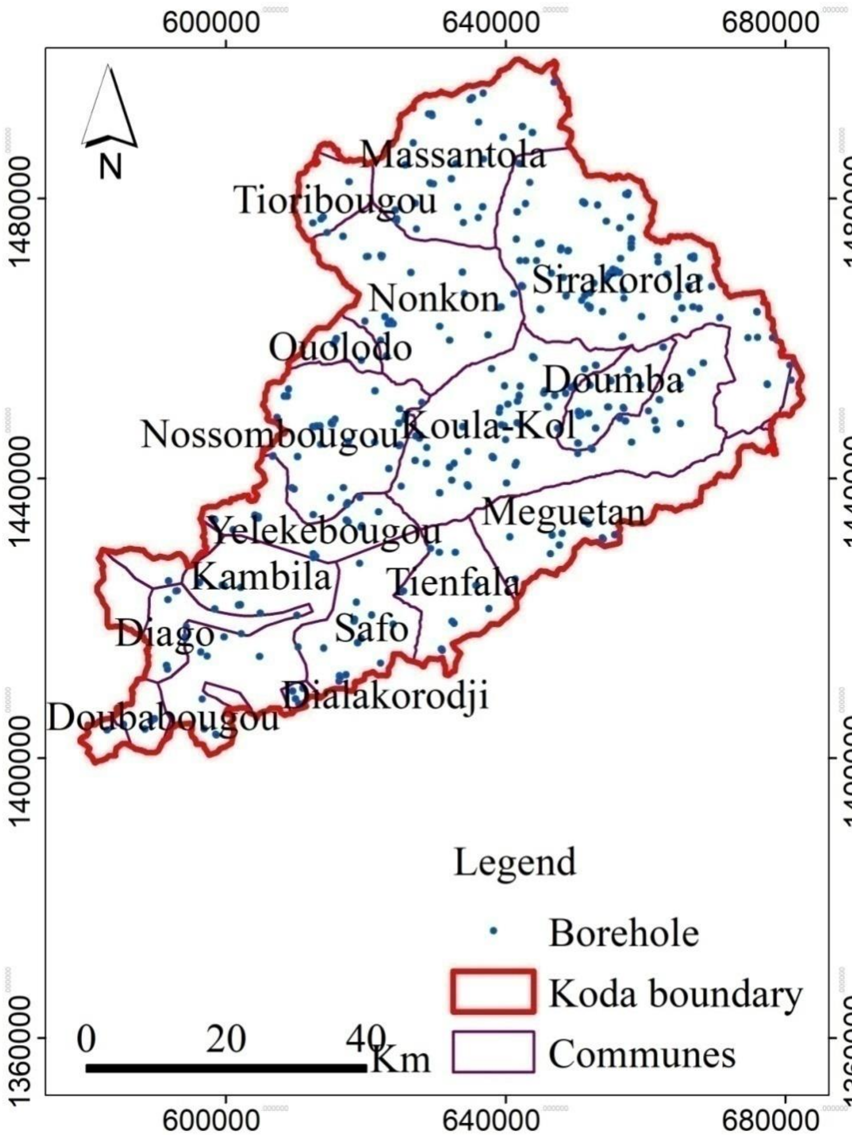


Figure 20: Location of the boreholes used in this study to get the historical groundwater level.

More than 20 boreholes and 19 wells spatially well distributed within the Koda catchment were monitored during the field visit and the data were used in chapter 6 for groundwater flow simulation in steady-state calibration.

3.1.4. Topographical data

The slope information of the study area was extracted from the Digital ElevationModel provided by hydroSHEDS. The decription of the DEM is detailled in chapter 2.

3.1.5. GIS dataset

The soil map of the Koda was derived from the Food Organization of the United Nations (FAO) 20 09. The maps are based on the original FAO-UNESCO done in 1974 at 1/5 000 000 scale used in Chapter 8 to study the dynamics of LULC change. LC maps of 1990, 1998 and 2016 have been made using Landsat, ENVI software and Arcgis. The characteristics of the landsat images are outlined in the **Table 9**.

Table 9 : Characteristics of the Landsat images used in this study.

Proprieties	**LC 1990 map**	**LC 1998 map**	**LC 2016 map**
Landsat type	Landsat 5 (TM)		Landsat 8
Date	Archive : 1984 - 2012		2013 to present
Spatial resolution	30 m		
Sensors	• Multispectral Scanner (MSS) • Thematic Mapper (TM)		OLI TIRS
Scene size	170 km x 185 km (106 mi x 115 mi)		

The geological and hydrogeological maps of the Koda catchment are derived from the lithological map of Mali obtained from National Hydraulic Service of Mali was used in chapter 2 for study area description and in chapter 5 for groundwater flow modelling purpose.

3.1.6. Hydrochemical data

Some hydrochemical information and the physical description of water were collected from previous studies and the field and these data have been used in chapter 2 for groundwater hydrochemical parameter within Koda catcthment.

3.1.7. Population data

The current population data was estimated using the last report of RGPH of Mali done in 2009. We used the following formula to estimate the population of the year 2019 using 3.6 % as population growth rate (equation 3) .

$$P = P_0 Exp\left(\frac{K}{100}\Delta t\right) \qquad (3)$$

Where P_0 is the initial population value at t_0 , K is the growth rate and P is the population value at time $t+\Delta t$.

The population data were used in chapter 2 to describe the demographic aspect of the Koda catchment. In addition, the population data were used to calculate the water needs over the study catchment in modelling purpose (chapter 5).

3.1.8. Water demand data

The water demand data has been estimated using the daily amount of water required by inhabitants, livestock, irrigation and industry.

3.1.9. Quality control of the Hydro-meteorological data

The quality of the model results depends on the quality of the input data; therefore the data analysis is important. The models have used the weather data as input, their quality determine the accuracy of model simulation. In Africa, particularly in West Africa, many of the hydro-meteorological stations have been abandoned or at best irregularly followed. This situation has strongly negatively affected the quality and quantity of the available dataset. In terms of quality, some analysis and observation have been done. The first task of the control is to detect erroneous data in order to correct where possible or to delete it as recommended in the third edition of the guide to climatological practices (WMO, 2011).

Some procedures were applied such as Statistical techniques, graphical display and visual examinations. Therefore, three checking quality techniques have been done: (1) thoroughness check, (2) consistency check and (3) plausibility test.

a. Thoroughness check

That test was applied in order to check the length of the dataset and determine the presence of the missing data. The completeness of the data of the three stations around the study catchement are decribed in **Table 10**.

We observe that Bamako station has the most complete dataset compared to Katibougou and Didieni stations. Within this station, all the climate parameters such as Precipitation, Temperature and Humidity (minimum and maximum) have missing data less than 1% over 30 past years (1987-2016). Wind and Insolation data present some gaps where the percentage of the missing data is less than 5%. Katibougou station has the most thoroughness of dataset after Bamako station. It presents less than 5% of missing data for 5 parameters (Tx , Tn, P, RH and

W) less than 45% of missing data for RH and less than 60% of missing data for insolation. As for Didieni station, it is the station with most incomplete dataset. The temperature data (max and min) show around 60% of missing data, the humidity data and wind display 1 % of missing data. The missing data of precipitation is represents 45% of the whole precipitation data of Didieni while the missing data of insolation is 60%.

Table 10: available daily meteorological data time series of the three stations: length and completeness.

	Tx	Tn	P	RH	Rh	W	In	Type	Time step
Bamako								Synoptic-station	Daily
Katibougou								Agro-station	Daily
Diedini								Synoptic-station	Daily

< 1% missing	< 5% missing	<45 % missing	< 60% missing

The completeness of the dataset of each of the meteorological parameters registered at the stations over the years are presented (**Table 11; Table 12** and **Table 13**).

Table 11: Available yearly meteorological data time series of Bamako station: length and completeness.

	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Tx																														
Tn																														
RH																														
Rh																														
P																														
W																														
In																														
PET																														

Complete	<1% missing	<5% missing	<10% missing	<20% missing	<30% missing	<40% missing	<50% missing	<70% missing	>90% missing	No data

Table 12: Available yearly meteorological data time series of Katibougou station: length and completeness

	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Tx																														
Tn																														
RH																														
Rh																														
P																														
W																														
In																														

Complete	<1% missing	<5% missing	<10% missing	<20% missing	<30% missing	<40% missing	<50% missing	<70% missing	>90% missing	No data

Table 13: Available yearly meteorological data time series of Didieni station: length and completeness

	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Tx																							
Tn																							
P																							
W																							
In																							
RH																							
Rh																							

Complete	<1% missing	<5% missing	<10% missing	<20% missing	<30% missing	<40% missing	<50% missing	<70% missing	>90% missing	No data

b. Consistency test

The consistent test done in this study was to compare minimum value to maximun value because it is logic that maximum value is always greater than the minimum value. This test was applied to the temperature and humudity datasets.No apparent inconsistency was found inside the dataset.

Figure 21 shows an example of the consistency test applied to the temperature dataset recorded at Katibougou station for the 1986-2016 period.

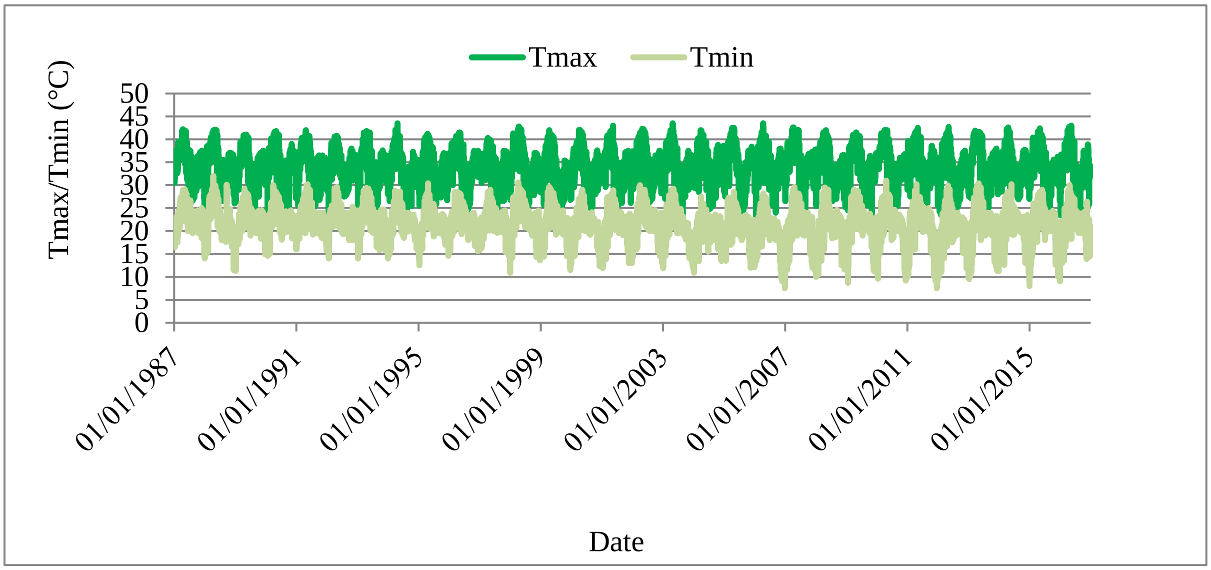


Figure 21: Example of quality control (Consistency Test) in daily temperature data at Katibougou station

c. Plausibility test

According to the knowledge on the study area based on the previous, the temperature and rainfall are including in a plausible interval of variation. Therefore, we solely applied the plausibility test to temperature and rainfall data. Also, since Koda catchment is located in the sudano-sahelian zone, we have an idea of the range of the mean annual rainfall. Two meteorological stations are not too far from each other and they are all located in the sudano sahelian zone. Therefore there should exist a high correlation between their datasets. The correlation value was 98 % between the rainfall dataset from Bamako and Katibougou stations (**Figure 22**).

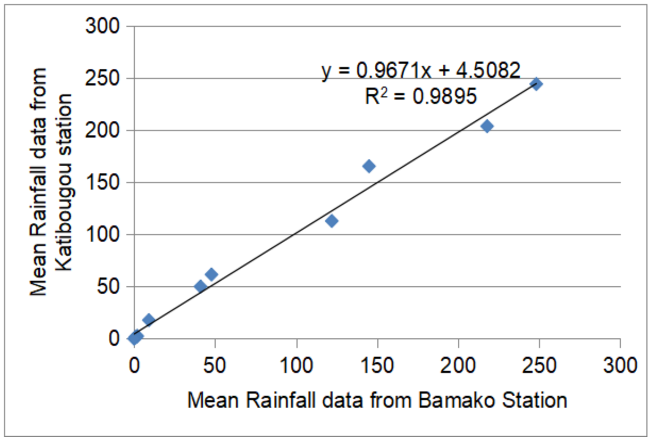


Figure 22: Correlation between mean rainfall data from Bamako and Katibougou stations

After completed all these tests and analyses, the missing data were filled by replacing the missing value by a preditor with the average value of that predictor. At the end of the tests, we decided to not use the datasets recorded at Didieni during this study because of the high percentage of missing data. Most of the works has been done using the climate data of Katibougou station since it is the nearest station to Koda catchment.

To explore more the climate data from the Katibougou and Bamako stations, multivariate statistical analysis has been applied.

d. Multivariate statistical analysis

The multivariate statistical analysis has been done through Principal Component Analaysis (PCA) to extract the important information of the climate data recorded from the two meteorological stations. According to some authors (Daigle et al.,2011; Onema et al.,2011) PCA is wisely used in hydrological studies and frequently applied in pre-processing of a set of variables. It captures the essence of the data in few Prinicipal Components (PC). These PC contain useful information; the sum of the variance expressed by these PC is 80.73 % and 76.16 % respectively for Katibougou and Bamako stations regarding the difference in datasets.

In Katibougou station PC1 can explain 42.93 % of variantion, PC2 explicates 24.58 % and PC3 explains 13.22% of variation; while in Bamako station PC1 interprets 37.58 %, PC2 explains 23.77% and the PC3 which defines 14.82% accounts for most of the total variance of the original dataset of Bamako station. The tables (**Table 14** and **Table 15**) outline the results.

Table 14: Eigenvalues and inertia of Katibougou station

	PC1	PC2	PC3	PC4	PC5	PC6	PC7
Eigenvalue	3.00	1.72	0.93	0.80	0.27	0.25	0.02
Total Variance (%)	42.93	24.58	13.22	11.46	3.92	3.57	0.31
Cumulative (%)	42.93	67.50	80.73	92.19	96.11	99.69	100.00

Table 15: Eigenvalues and inertia of Bamako station

	PC1	PC2	PC3	PC4	PC5	PC6	PC7
Eigenvalue	2.63	1.66	1.04	0.65	0.54	0.36	0.13
Total Variance (%)	37.58	23.77	14.82	9.30	7.65	5.10	1.79
Cumulative (%)	37.58	61.35	76.16	85.47	93.11	98.21	100.00

A particular problem of the meteorological data is the complexity associated with analyzing large dataset. Therefore, in this study, the loading plot was used to visually interpret the variance. The results show that Rainfall, Relative Humidity (maximum and minimum) are strongly influenced by PC1 with positive associations with it while the second component PC2 has large negative associations with Temperature (maximum and minimum). The third component has large negative associations with Wind and Insolation patterns.

The variables Rhmax and Rhmin are positively correlated while Rainfall and Insolation are negatively correlated. This seams logic and expectable because when it is raining the sun does not appear.

3.2. Materials

The materials used in this study are:

- **ArcGIS version**, used for mapping purpose, to interpolate some missing data through Kriging method for LULC Classification. It was used in chapter 2, chapter 3, Chapter 5, Chapter 6 and Chapter 9.
- **Bacth Downscalling program** used to downscale CORDEX data used in chapter 7
- **Camera** used during the field visit to take pictures.
- **Envi software version** used in chapter 9 for LULC units classification
- **Excel spreadsheet**, used for inputs data preparation for models, for plotting and for statistical parameters calculation.

- **Gardenia** model used in chapter 5 to estimate the water budget component over the study and in chapter 8 to assess the impact of Climate change on groundwater resources.
- **Geographical Position System (GPS)** used to get the coordinates of the data point.
- **Khronostat** wasused in chapter 4 to study the rainfall variability over Koda catchment for the period 1986-2016.
- **Matlab** was used in chapter 3 for the coding of Principal Component Analysis PCA and multivariace statistics analysis of the climate time series date over the study catchment
- **Multiparameters** was used to measure physico chemical parameters in wells and boreholes
- **Moulinet** was usedfor discharge measurement in the field
- **Visual MODFLOW** was used in chapter 6 to simulate groundwater flow under steady state
- **Probe** was used to measure the water level in boreholes and piezometers
- **Standard Precipitation index (spi_sl_6)**, was used in chapter 4 to compute the standard precipitation index over Koda Catchment
- **Thornthwaite model**, was used in chapter 4 to simulate the groundwater recharge

3.3. Methods

3.3.1. Rainfall variabilty over Koda catchment

3.3.1.1. Rainfall variability

This part of the study analyses, at both local and regional scales, the rainfall variability across Koda catchment for the period 1987-2016. Rainfall data recorded from three meteorological stations (Bamako, Katibougou and Toubougou) are used. Several methods such as rainfall index and Lamb index have been used in order to characterize the inter-annual variability of rainfall. Furthermore, the three moving average was used to determine the dynamics of the mean seasonal cycle of the precipitation. In addition, the non-parametrical Pettitt’s method (1979), U-statistic of Buishand (1982), Heghinian test (1977) and segmentation of Hubert (1989) have been evaluated through Khronostat software in order to detect the break points in the rainfall series.

The variability of the rainfall patterns affects many aspects of daily life. It can affect the economy of a given place where agriculture is the main activity of the inhabitants.

In order to determine the homogeneity of the datasets, the variation coefficient has been calculated for the datasets using this relationship.

$$CV = \sigma / m \qquad (4)$$

Where σ is the standard deviation and m is the mean value. For the three stations, the variation coefficient, CV, of the datasets are less than 50% meaning that the datasets are homogeneous. Daily and monthly climatic data recorded from two meteorological stations (Bamako and Katibougou) and yearly rainfall data of Toubougou are used.

3.3.1.2. Moving average

The analysis of the 3 years moving averages shows the succession of humid and dry year over the past 30 years. That method works to adjust the contrasts between the highest and the lowest values of the rainfall. One of the advantages of that analysis is to estimate the three years average value of the rainfall, therefore, the wet and dry periods are determined. The years with the values less than the average are considered as dry period while that over the mean value are considered as the wet period for Katibougou.

3.3.1.3. Standard Precipitation Index (SPI)

We used the Standard Precipitation Index to characterize the wet and dry years within the Koda catchment. In the current study, values of the time steps of 1,3,6,9 and 12 months were computed for the period 1987-2016. The SPI of 6 months for the period 1987 to 2016 was used because in the Koda catchment the rainy season is unimodal from June to October. It is also confirmed by Toure (2017) that the use of SPI for 6 months' time scales for a unimodal rainy season is standard. The values of SPI are shows in **Table 16.**

Table 16: SPI values after (McKee et al., 1993)

SPI Value	Description
≥ 2	Extremely wet
1.5 to 1.99	Very wet
1 to 1.49	Moderately wet
-0.99 to 0.99	Near normal
-1 to -1.49	Moderately dry
-1.5 to -1.99	Severely dry
≤-2	Extremely dry

3.3.1.4. Lamb Index

The Lamb rainfall index is used to estimate the deficit or excess of annual rainfall. It is calculated using equation 5.

$$IP = (P_i - P_m) / \sigma \qquad (5)$$

Where P_i stands for the value of the annual rainfall of the year i; P_m, the average over the study period and σ the standard deviation of the data. **Table 17** shows the rainfall patterns from the rainfall indices.

Table 17: Patterns of rainfall from the indices

Lamb Index	Description
IP > 0.5	Excess
IP < –0.5	Deficit
-0.5 < IP < 0.5	Normal

The lamb rainfall index has been calculated for three pluviometric stations over the study catchment.

3.3.1.5. Detection of break points

Four statistical tests are used in this study, which are the non-parametric Pettitt's method (1979), the U-statistic of Buishand (1982), Lee and Heghinian test (1977) and the segmentation of Hubert (1989). The Pettitt's and Heghinian tests are applied to detect single break point while the segmentation of Hubert (1989) is used to detect multiple break points if they exist. These tests have been applied to the rainfall datasets using Khronostat 1.01 software developed by IRD-Orstom (1998).

3.3.2. Groundwater recharge estimation

3.3.2.1. Thornthwaite method

The Thornthwaite method is considered as one of the most suitable methods for precise computation of monthly and annual water budgets (Scozzafava & Tallini, 2001). It has been used to estimate various components (Potential Evapotranspiration PET, Actual Evapotranspiration AET, Recharge and Runoff) of the water cycle many of which are unavailable for the region of interest. A Thornthwaite Monthly Balance Method has been applied by many researchers under different climatic zones to estimate the global water balance (Mather, 1969; Legates & Mather, 1992; Legates and McCabe, 2005) to develop climate classifications (Thornthwaite, 1948), to estimate soil moisture storage and runoff (Alley, 1984; Mintz & Serafini, 1992; Yates, 1996; Wolock & McCabe, 1999) and to evaluate the hydrologic effects of climate change (McCabe and Ayers,1989; Yates, 1996; Wolock & McCabe, 1999). It is recommended to apply the Thornthwaite method to estimate the water balance components in an area when it is difficult to use the direct method due to the lack of data availability (Varni & Usunoff, 1999; Zimmermann, 2006). The Thornthwaite method was used to estimate the groundwater recharge based on the availability of the data. In addition, this method has been demonstrated as the best method to evaluate the recharge patterns in the arid and semi-arid zones.

Principle of Thornthwaite Method

The Thornthwaite method allows comparison between the values of PET and that of Precipitation in order to deduce the value of infiltration (Thornthwaite, 1948). Based on this method, two cases are discussed (**Figure 23**):

i. When P > PET (2), **AET=PET**, when there is ample water in the soil such that the soil reaches total saturation. When the saturation is observed, the excess water constitutes the superficial or groundwater flow (3).
ii. When P <PET (1) and (4), the deficit water will be taken from the water soil reserve to meet the demand of the potential evapotranspiration PET (AET is always lower or equal to PET). In this case, the AET is equal to **P+RFU**. When the water soil reserve is equal to zero, the AET is equal to the Precipitation, P.

RFU or SWS stands forthe reserve of water in the vadose zones.

ETr or AET is Actual Evapotranspiration which is the amount of water that is really removed or evaporated.

ETP or PET refers to Potential Evapotranspiration and is the ability of the atmosphere to remove water or amount of water that is assumed to evaporate.

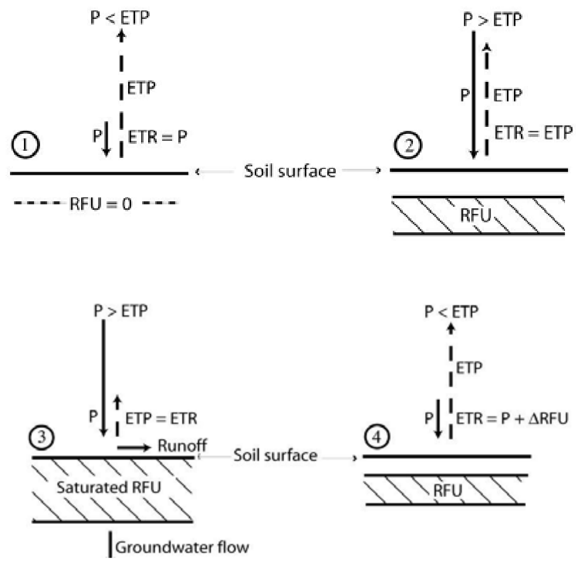


Figure 23: Different cases of the Thornthwaite water budget calculations at the Katibougou station. **1:** September to June, **2:** July, **3:** August and September, **4:** October (figure modified from Thornthwaite, 1948).

The Thornthwaite method required the average of monthly temperature, soil moisture and the monthly rainfall data as input data. In this current study, the monthly temperature and rainfall data used from the period 1987 to 2016 and were recorded at Katibougou station.

3.3.2.2. Water Table Fluctuation method

The Koda catchment is one of the catchment basins in Africa with sparse records of data due to the data gaps in most of its observations. Using the WTF method, the groundwater recharge was estimated in the catchment based on the data from three piezometers and four wells. It is important to notice that all the piezometers and wells are located in the same aquifer. The monthly rainfall and weekly piezometric data have been used to estimate the annual groundwater recharge. From these recharge results, the percentage of the annual rainfall that arrive to the water table was deduced.

The monitoring wells, which have been monitoring groundwater levels since 2012, were established by the Malian Association for Public Education and Environmental Protection (AMEPPE) and WaterAid Mali. Monitoring piezometers and wells with short time durations (less than one year) were considered. Seven monitoring sites with a total of three piezometers and four wells located in the same hydrogeological environments were studied. The wells serve for water supply for the inhabitants.

The groundwater levels in the piezometers Fansiracoura F1 and Kossaba K1 were recorded manually once a week using a probe, while groundwater in Nossombougou N1were recorded automatically every minute. The static groundwater levels in all the wells were measured twice a month using a probe. The complementary hydrogeological data (drilling logs, water levels, pumping tests, etc.) and rainfall data were collected from the National Direction of Hydraulic of Mali (DNH-Mali), NGOs (WaterAid, AMEPPE). The climate data was collected from National Meteorological agency of Bamako and the Regional meteorological Agency of Koulikoro (Katibougou) and some meteorological information were collected from the farmers and NGOs within the basin. The length of the available data varies from one to nine years.

According to Allison, 1988 and Foster, 1988, the recharge method can be physical or chemical methods. The WTF method is among the physical method which is considered as an attractive method due to its accuracy, the ease of its use and its low cost of the application in the semiarid areas. The WTF method is widely applied throughout the world by scientists since 1920s to estimate groundwater recharge (Meinzer, 1923). Many studies under different climatic conditions from 1920s until now have been carried out (Rasmussen and Andreasen, 1959; Traore, 1985; Ordens et al., 2011; Diouf et al., 2012; Toure et al., 2016; Kotchoni et al., 2018). The large application of this method is due to its simplicity and also the availability of groundwater level data. The method is also appropriate to the fractured media (Risser et al., 2005). 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. According to Healy & Cook (2002), the specific yield is linked to the change in water table height as shown in equation 6.

$$R_t = S_y \frac{\Delta h}{\Delta t} \qquad (6)$$

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

3.3.2.2.1. Determination of the water level

According to Healy & Cook (2002), 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. The recession curve is defined as the trend that the well hydrograph will follow when there is no rise in the level from rainfall (Delin et al., 2007; Healy and Cook, 2002).

In this current study, the graphical extrapolation was used to determine the water level rise in the monitoring wells and piezometers. It is a simple method requiring a visual examination, 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 (**Figure 24**):

For the year 2008 in Fansiracoura piezometer while Sy=0.011; Δh = 4.2 m. The annual recharge was estimated by R=0.011*4,200 = 46.2 mm.

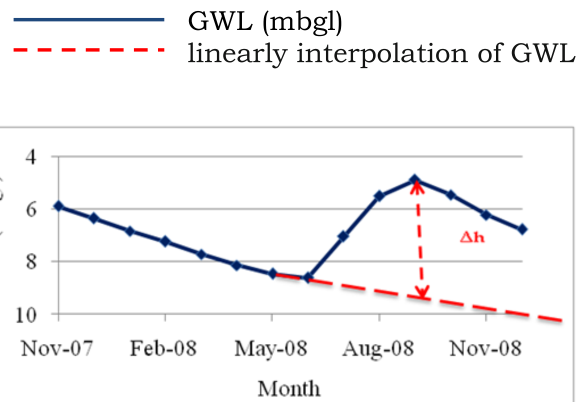


Figure 24: Recharge estimated using the graphical approach to the WTF method (Diancoumba et al., 2020).

3.2.2.2.2. Determination of the specific yield

Once the groundwater level rise is determined, there is a need to determine the specific yield. S_y of a rock or soil is considered as the portion of the volume of water that will drain by gravity from a saturated rock per total volume of the rock (Rasmussen and Andreasen 1959; Johnson, 1967). The specific yield S_y is linked to the porosity and specific retention by equation 7:

$$S_y = \varphi - S_r \qquad (7)$$

where φ is the porosity and S_r is specific retention (Healy and Cook, 2002)

Sy is plays a crucial role in the calculation of groundwater recharge (Sophocleous, 1985). To get an accurate value of the Sy, many methods have been developed to estimate it. Some of them are field methods such as aquifer tests, water budget methods, volume balance methods, geophysical methods, and laboratory methods. Lerner et al. (1990) 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 varies as a function of depth to water table (Childs, 1960 and Delin et al., 2007). According to many authors like Lerner et al. (1990) and Obuobie (2008), the use of the value of Sy from the literature is highly recommended when the laboratory data are not available. However, when the geological conditions and climatic conditions are the same, the same value of Sy can be applied.

In the current study, the value of specific yield is taking from the literature. Sinha & Sharma (1988) and Lerner et al. (1990) used the value of Sy of the sandstones which ranging from 0.01 to 0.08 in the recharge calculation in India. According to Healy and Cook (2002), the values of Sy of the sandstones are range from 0.005 to 0.19 .Toure (2017) determined the specific yield of Klela basin in Mali from pumping test data of ten boreholes using Ramsahoye & Lang (1961)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 (2017) found that the values of Sy ranged from 0.011 to 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.

3.2.2.2.3. Estimation of Recharge

Recharge was calculated on the annual scale based on the observed groundwater level fluctuations (Scanlon et al., 2002; Healy and Cook,2002; Sibanda et al., 2009; Obuobie et al., 2012; Jassas and Merkel, 2014;Toure, 2017; Kotchoni et al., 2018).

3.3.2.3. Estimating groundwater recharge through Gardenia model

Some mathematical models have been developed by scientists to help understanding surface and groundwater systems. Global Reservoir Model for Simulating Flows and Aquifer Levels (M odèle Global À Réservoirs pour la simulation de DÉbits et de NIveaux Aquifères) with acronym GARDENIA is a lumped hydrological model developped by the BRGM. GARDENIA model is focused on the water balance equation for aquifers. For a given catchment, Gardenia simulates the main water cycle mechanisms by applying simplified laws of physics to flows through three (3) sucessives reservoirs (production and transfer) (**Figure 25**).

Flow equations are applied in the catchment using transmissivity parameter, storage coefficient and infiltration coefficient. A detailed description, is provided by Roche and Thiery (1984) and Thiery (2013).Great simulation to determine the recharge of aquifers using the numerical models such as the Gardenia model has been widely done in different geological and climatic conditions (Thiery, 1987; Thiery, 1988).

3.3.2.3.1. Reservoirs of the model Gardenia

The reservoirs of the model are described below:

i. Superficial reservoir U

The superficial reservoir U represents the first centimeters of the soil where evaporation occurrs through vegetation. The production function is present only in this reservoir U. It contains the reliefs centimeters that will be satured before runoff starts. The reservoir U is supplied by rain and is emptied by evapotranspiration. This reservoir recharges the intermediate reservoir H when its level RU exceeds the retention value RUMAX. The excess ALIMH is calcuated by this equation 8:

$$ALIMH = RU - RUMAX \qquad (8)$$

ii. Intermediate reservoir H

The intermediate reservoir represents the unsaturated zone. It is supplied by surplus from the reservoir U and it is drained by two outlets. Percolation to the lower reservoir G1 according to a linear law of time constant (THG) and external flow in the form of a rapid component of the QH flow following a non linear law controlled by RUIPER parameter. The RUIPER parameter is in fact the height H for which the ALIMG percolation and the QH flow are equals (equation 9 and equation 10):

$$ALIMG = \frac{H.dt}{THG} \qquad (9)$$

$$QH = \frac{H.dt}{\left(THG.\frac{RUIPER}{H}\right)} \qquad (10)$$

where dt is the change over time

iii. **Reservoir G**: The reservoir G produces slow flow and represents the saturated zone (aquifer zone). This lower reservoir is supplied with the water by the intermediate reservoir H and it is drained by outlets:

The flow is drained toward the outlet in the form of slow flow QG following an exponential draining law where the loss is assumed to be constant over time TG, equation 11.

$$QG = \frac{G.dt}{TG} \qquad (11)$$

As in reservoir H , the calculation is done through the water supply ALIMG1.

The main components of the hydological cycle are the outputs of the Gardenia model, they are Recharge, Actual Evapotranspiration AET, Discharge data, Effective Rainfall and the Groundwater Level GWL.

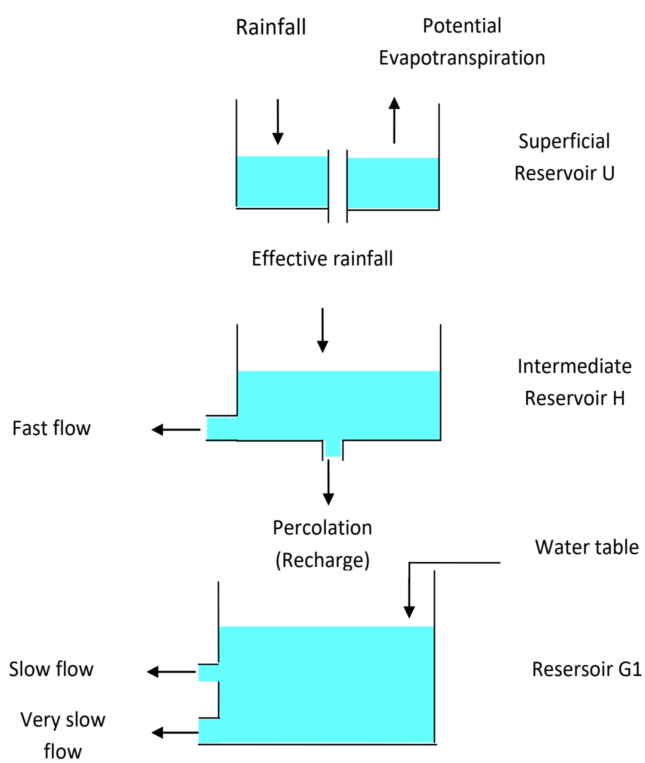


Figure 25: Principle of Gardenia model(Dominique Thiery, 2013)

3.3.2.3.2. Input data

The three (3) main input data required to run GARDENIA model are: rainfall data, potential evapotranspiration data, river flow data and/or groundwater level data.In the current study, we have used the data of the nearest meteorological station because there was no stations in the study area. The historical and the projected data from the scenarios have been used in the model.

The PET values estimated from Blaney and Criddle1962 method were used as PET input data.

Refer to (Blaney & Criddle, 1962) for the detail of the ETP calculation process.

The Groundwater Level (GWL) data used of three (3) piezometers have been used as –input data for the Gardenia model.

Piezometer Fansiracoura F1: The GWL data are available for 12 years (2008-2019). The data were recorded manually and weekly as frequency.

Piezometer Nossombougou N1: The water level data is available only for 4years (February 2016 to December 2019). The water level was recorded automatically every minute.

Piezometer Kossaba K1: the data is available from 1986 to 1991 recording at weekly time step.

The historical piezometric data have been collected from National Hydraulic Service of Mali and from the field. The value -9999 has been assigned as missing data.

For the historical period, the length of the whole input data used were from 1987 - 2016. Projected data of Rainfall and PET for the period 2021-2050 have been used to feed the model. The projected GWL data were complete by 9999 as required by the model .

To run the model, we also used the hydrodynamics parameters (K and Sy) of the aquifers, those values were from the simulation of groundwater flow chapter 6.

3.3.2.3.3. Calibration process

The calibration process is a crucial step in modelling. The initial sensitive parameters are changed until the best correlation between simulated and observed GWL is reached.

The model is calibrated using some parameters:

Some are the RUMAX defined as the maximm water available in the soil reservoir for evapotarnspiration. RUIPER represents the heights of water in the resersoir H in saturated zone.There is an equal distribtution between the rapid flow contributing to the flow of the source and the percolation. THG is another calibration parameter which corresponds to the half rise time of the reservoir H (1/2 perolation rise). TG is also used to calibrate Gardenia model.It is the time taken for groundwater component HQ in the absence of recharge to flow. Other sensitive parameters are runoff, storage coefficient and finaly the loss of water.

It is recommend to correct two coeficients such as rainfall data and PET allowing the model to be adjusted as best as possible because the measurements available at the stations may differ from the actual averages of the watershed. Gardenia model has an optimization function for each of the parameters allowing the best calibration from a mathematical point of view. Therefore, in this study,thecalibration has been performed manualy and semi automatically using optimization function.

3.3.2.3.4. Model performance criteria

Two types of comparisons (qualitative and quantitative) have been done to evaluate the performance of the models (**Table 18**).

The qualitative comparision is made through visual comparision between similated and observed GWL, while Correlation coefficient (R^2) and Nash-Sutcliffe coefficient (NASH) were used to evaluate the quantitative model calibration.

The coefficient of correlation R^2 provides information about the goodness of fit of the model output to the measured data, and can range from 1 (perfect fit) to 0 which implies no correlation between observed and simulated data (Krause et al., 2005).

The correlation coefficient is calculated using equation12:

$$R^2 = \frac{\left(\sum\left(O-\bar{O}\right)\left(S-\bar{S}\right)\right)^2}{\sum\left(O-\bar{O}\right)^2\sum\left(S-\bar{S}\right)^2} \qquad (12)$$

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 13):

$$NSE = 1 - \frac{\sum_{i=1}^{n}(O-S)^2}{\sum_{i=1}^{n}\left(O-\bar{O}\right)^2} \qquad (13)$$

Where O is the observed value, S the simulated value, $\overline{O}$ is the mean of observed dataset and S the mean simulated dataset.

Table 18: General Performance ratings for recommended statistics *(Moriasi et al., 2007)*

Performance rating	R^2	NASH
Very good		$0.75 < NSE \leq 1.00$
Good		$0.65 < NSE \leq 0.75$
Satisfactory	>0.6	$0.50 < NSE \leq 0.65$
Unsatisfactory	<0.6	$NSE \leq 0.50$

3.3.2.3.5. Validation of the model

After calibrating the model, it was validated. During the validation process the model was verified against an additional piezometer dataset without adjusting the model parameters.
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

3.3.3. Simulation of Groundwate flow of Koda catchment

A groundwater model is considered as a real simplified representation of the aquifer. The quantification of quality (pollution) and quantity (Groundwater flow dynamic) of groundwater has been done by scientists through groundwater flow model. Those models are based on continuity (mass conservation equations) and Darcy's law (Schweizer, 2015). Darcy's law combined the continuity equation (Governing equations) to give Laplace equation and Poison equations as partial differential equations. The specification of the Boundary conditions of the flow domain is required to solve those partial differential equations (Anderson & Woessner, 1992). Two types of mathematical and physical models considered groundwater flow models and they are solved using numerical and analytical solutions. Physical models can be used to solved by simple equations using analytic models whereas mathematic models are solved through analytical models and complex field problems are solved via numerical models (Essink, 2000). Analytic solution is exact and allows the calculation of values of unknown parameters at any time and any point of the domain. The definition of the conceptual model using analytic solution is oversimplified. Numerical solutions are used in complex groundwater system to simulate the system with much greater accuracy. Mathematical models use numerical approximation through matrix algebra and discretization of the domain to solve equations (Kouliet al., 2009).

Groundwater flow model is commonly run under steady state and transient simulations. In the steady state, the storage is considered as invariable while in the transient state, the storage is variable. In this study, the simulation is only done under steady state.

Groundwater flow models are constituted by several types: finite volume, finite element and finite difference methods. Representative Element Volume REV is determined to solve continuity equation by estimating flow in and flow out in 2D steady state (Anderson & Woessner, 1992; Council, 1999; Zhou & Li, 2011).

3.3.3.1. Step of the modeling

The development of Groundwater Flow Model goes through conceptualization, calibration, sensitivity analysis, uncertainty and prediction (Anderson & Woessner, 1992). Conceptualization of the model is the step where the translation of the real world to mathematical model is done. The identification of physical elements that control groundwater flow and the relevant processes, the specification of the dimension and grid of the model, determination of data deficiencies are settled to complete the conceptualization process of the model. After conceptualization, the model calibration will take place where the adjustment of independent variables is done to produce agreement between observed and simulated data (Anderson & Woessner, 1992). Once the model is calibrated, the sensitivity analysis will be done in order to determine effect of uncertainty on calibrated model. Verification (validation) of the model is necessary in order to do prediction where the past is the key to the future. The details regarding the modeling processes are outlined in **Figure 26**.

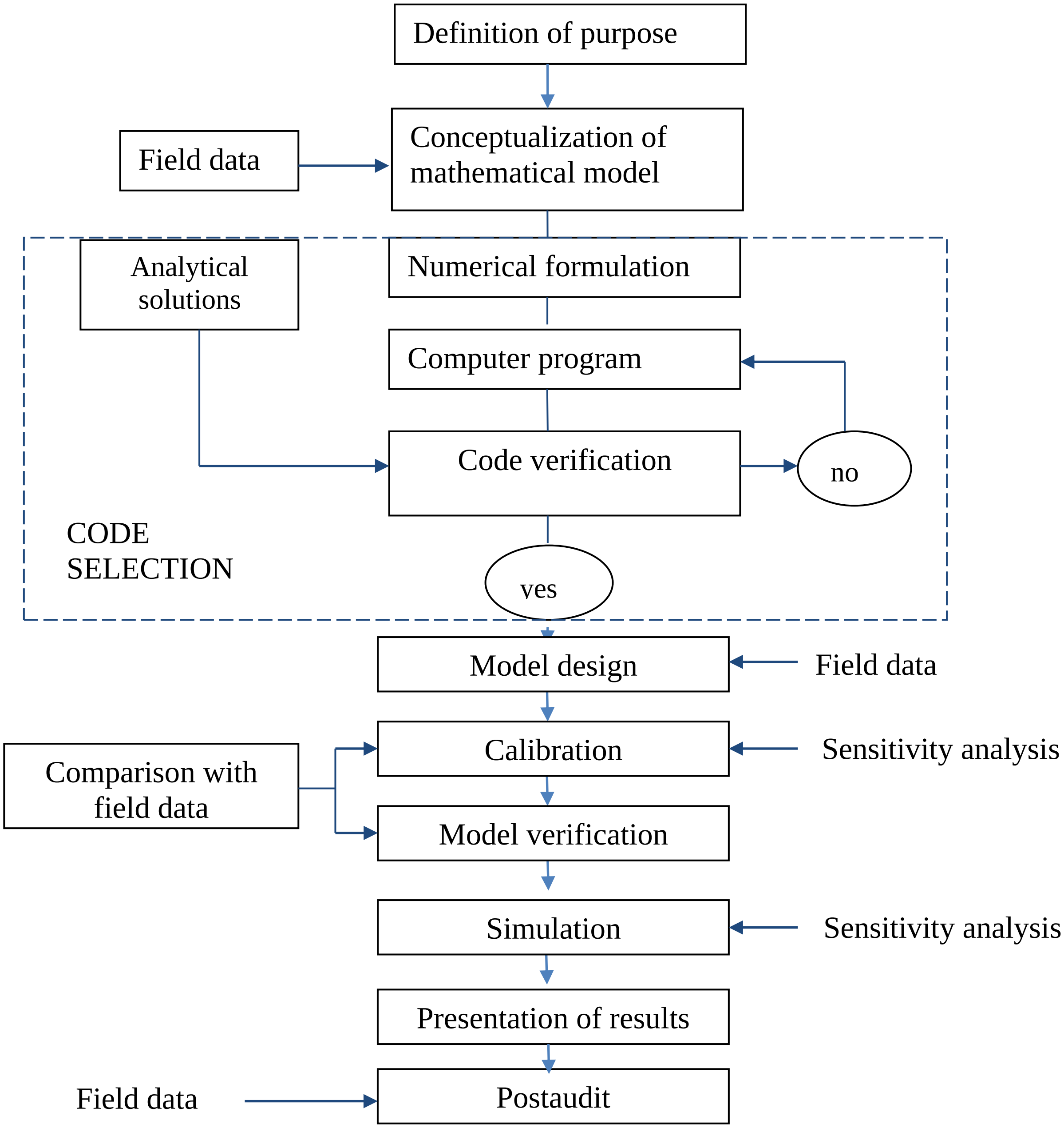


Figure 26: Flow chart of modelling process (modified from Anderson & Woessner, 1992).

The conceptualization of the model is the first step of the modeling, then the definition of the dimension and the building of a model grid were achieved, then model properties and boundary conditions were inserted as model inputs, finally the model was run.

The development of the model conceptualization passes through the description of the study area the characterization of the geology and the hydrogeology of the aquifer.

iv. Conceptualization

The definition of relevant processes (process identification) and how they are represented within the model (understanding of the natural system) is primordial as a first step of each modeling (Baalousha, 2003). Process identification is not easy for transport aspect while it is considered in principle as an easier step for groundwater flow (Barnett et al., 2012). However, some questions must be answered related to the nature of the aquifer (confined or unconfined), variability of the transmissivity with saturated thickness, surface groundwater interaction. To answer those questions, modeler should make simplifications and assumptions where many of them can be revised later. Deep information on hydrology, geology, pumping drilling data, topography are required to model a study catchment (Mandle, 2002).

In this study, the lithology of the Koda catchment is described using the stratigraphical logs of boreholes collected from National Direction of Hydraulic of Bamako.

3.3.3.2. Model used

Since the conceptual model was developed, it is mandatory to select the code of the model in order to translate it to computer code. It is recommended to select a code which is suitable to simulate the natural conditions of the study area.

Finite element and finite difference are widely used in groundwater modeling (Baalousha, 2003). MODFLOW (Harbaugh, 2005) uses the finite–difference method to describe the three-dimensional ground-water flow. It is programmed under the FORTRAN 77 language environment (American National Standards Institute 1978). Since 1984 it has been used to simulate groundwater flow (Harbaugh & McDonald, 1996) and has been continually upgraded with several new packages.

In this current study, the modeling package used is Visual MODFLOW package which is more user friendly and works for small to large groundwater basins (Anon, 2000).

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. The partial-differential equation of ground-water flow (Harbaugh & McDonald, 1996) used in MODFLOW is shown in equation 14.

$$\frac{\partial}{\partial x}(-K_{xx}\frac{\partial h}{\partial x})+\frac{\partial}{\partial y}(-K_{yy}\frac{\partial h}{\partial y})+\frac{\partial}{\partial z}(-K_{zz}\frac{\partial h}{\partial z})-w=S_s\frac{\partial h}{\partial t} \qquad (14)$$

Where K_{xx}, 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; w: is the volumetric flux per unit volume representing source and /or sink of water groundwater within the aquifer and is simulated using a block-centered finite-difference approach. The finite-difference equations can be solved using different solvers.

3.3.3.3. Input data and outputs of the model

The modeling process requires several various types of input data such as:
Study area geometry, aquifer geology and geometry (top and bottom elevations), aquifer proprieties, boundary conditions, initial hydraulic heads, initial values of recharge, evapotranspiration above water table, observational water level and pumping rates, etc. The outputs of the model are principally: Hydraulic head in steady state, adjusted hydraulic conductivities, adjusted recharge and predicted hydraulic heads.

Visual Modflow package was applied to simulate the steady state groundwater flow for Koda catchment. Furthermore, the hydrodynamic parameters (K and S_y) values of the aquifer were estimated.

3.3.3.4. Model construction

To construct a model, a number of steps are required, and the main steps are described below:

3.3.3.4.1. Model discretization

The definition and building of the dimension of the model grid is the most important part in model construction. The Visual Modflow model domain was discretized into a grid 50 columns, 50 rows based on the aquifer extension and hydrogeological data availability. The total grid cell number of 2500 with a grid dimension 300m *300 m is considered.

3.3.3.4.2. Number of layers

The main geologic unit of the Koda catchment is sandstone with some dolerite intrusion. Based on borehole drilling logs data, more than 85% of the rocks are represents by sandstones with different facies such as sand-clayey, sandstone schist, *etc.* To settle the number of layer with in the model domain, the simplification of the aquifer as a single numerical layer under unconfined condition has been made.

3.3.3.4.3. Thickness of aquifer

According to the of borehole logging data collected from Directions and NGOs, the thickness of aquifer is varying from 20 m to 150 m. The reports from HYDRO MALI sarl (2011c) and PNMRE (2017),the thickness of the aquifer of the study area is more than 250 m. These previous studies (HYDRO MALI sarl, 2011b; HYDRO MALI sarl, 2011c; PNMRE,2017) recommended to dig until 250- 300 m to characterize the aquifer of the zone of interest. The thickness of the aquifer was settled to 300 m.

3.3.3.4.4. Top of the aquifer and bottom of the aquifer

The Digital Elevation Model (DEM) with a resolution of 90 m*90 m provided by the Hydrosheds was converted to 300 m *300 m and used as the top elevation of the aquifer.
The bottom of the Layer is interpolated from the value of the top by extracting the thickness of the aquifer, which it is settled to 300 m.

3.3.3.4.6. Aquifer depth

From drilling boreholes data, the depth of aquifer observed was from 5 to 120 m. This was used to characterize the lithology of the aquifer. Figure 27shows the location of the boreholes and the aquifer depth within the study area.

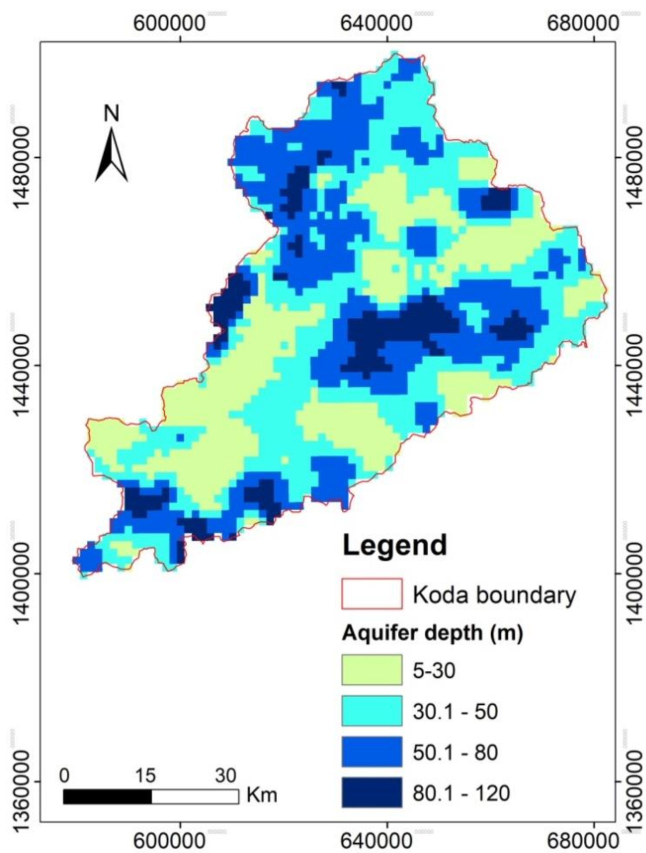


Figure 27: Drilling boreholes showing the depth of the aquifer (source PNMRE, 2017)

3.3.3.4.7. Types of aquifer within the study area

Two types of aquifers are characterized in the study area:

1- Shallow aquifer in the unconsolidated superficial-altered formations (laterites, clay, sand,) is reached in the first 15 m below ground surface with the thickness values ranging from 4 to 34 m. The transmissivity of the superficial aquifer ranges from 1 to 176 m^2/ day.

2- Deep aquifer in the epicontinental sandstones with oblique stratifications, schist and dolerite formations is located around 20-60 m beneath the ground surface in most of the several boreholes. That aquifer transmissivity is between 1 and 541 m^2/ day.

There is an interconnection between the two aquifers and that relationship between them is dependent on the pluviometry and the degree of fracturing in the study area.

3.3.3.4.8. Lithology and rock type determination

Some electrical profiling and electrical soundings have been done in the southern part of the study area by NGOs (HYDRO MALI sarl, 2011a; HYDRO MALI sarl, 2011b;HYDRO MALI sarl, 2011c and (PNMRE, 2017) in the context of dam construction to and lead to the lithology described as following from the top to the bottom as follow:

Laterite with the thickness 1 to 7m

Clay presents the resistivity value below 50 Ohm.m with the thickness 5 to20 m

Sandstones –Schist, the resistivity value is ranged from 50 to 200 Ohm-m with 30-40 m as thickness.

Dolerites, the resistivity value greater than 200 Ohm.m with the thickness around 20-40 m

3.3.3.4.9. Pumping test

The pumping tests were operated using standard method test C.I.E.H 4 hours of pumping and 1 hour of drawdown recovery analysis. The interpretation of the results has been done using Jacob and this method is used to determine the transmissivity and the storativity of the aquifer.

3.3.3.4.10. First arrival of drilling water

First arrival water is observed from 0 to 35 m for 50% of the boreholes, 50-120 m for 30 % of borehole.

3.3.3.4.11. Lineaments

The principal direction of lineaments existing in the study area is NE-SW some of them are intercepted by secondary lineaments in the perpendicular direction.

3.3.3.4.12. Boundary conditions

A river boundary condition was used to simulate the long tributary of Koda River. Outside the interested catchment, all the zones are considered inactive (Figure 28). Since we don't have information about horizontal flow therefore, the aquifer discharge to the river or vice versa was not taking into account. The Boundary conditions, isopiestic lines of the Koda catchment and locations of the wells used in steady-state simulation are shown in **Figure 28**.

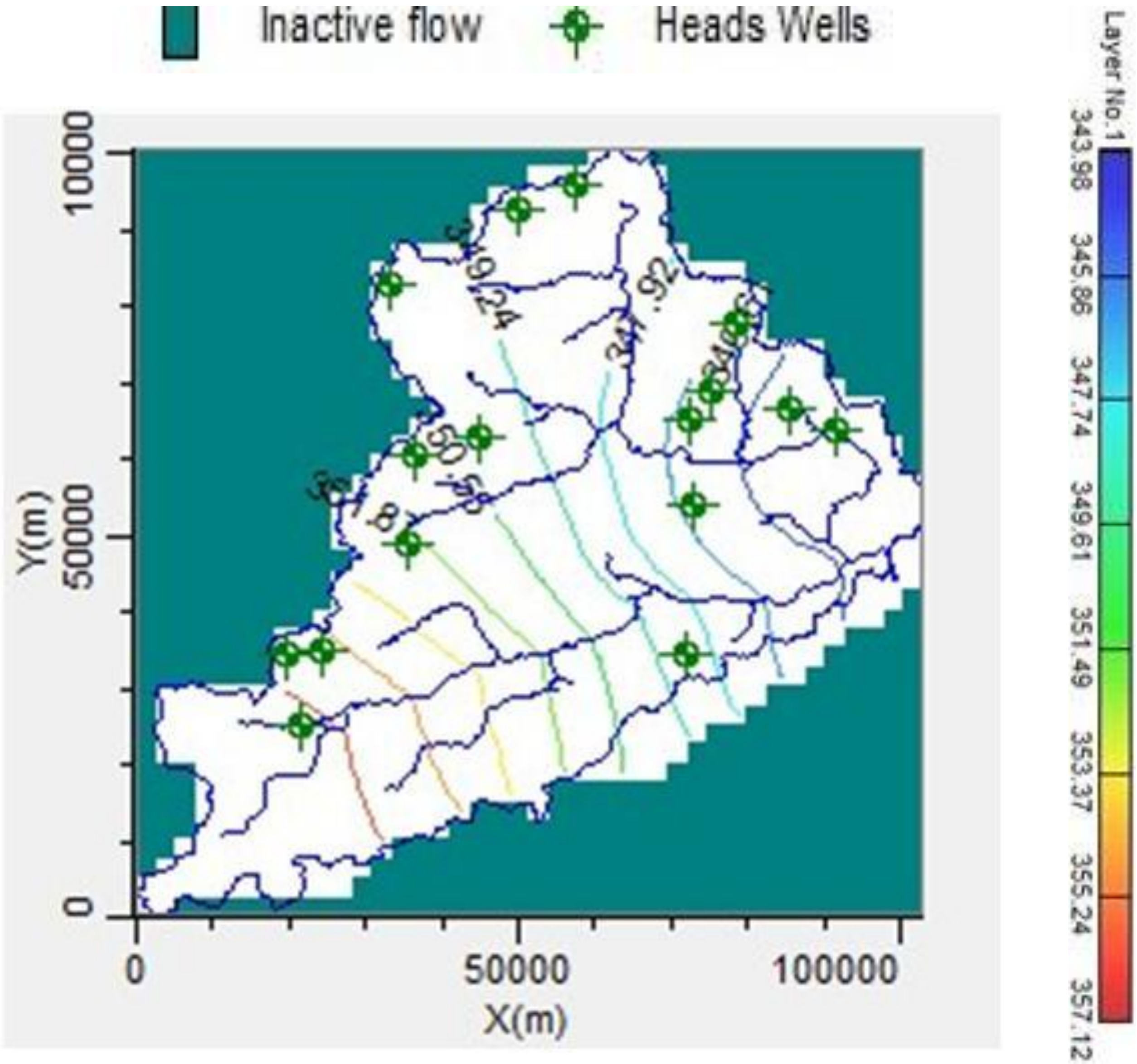


Figure 28: Boundary conditions, isopiestic lines of the Koda catchment and location of the wells used in steady-state simulation

3.3.3.4.10. Recharge value

The value of the annual recharge is up to 180 mm / year meaning 41*10 $^{-5}$m/day according to the previous methods used in this study to characterize the recharge value of the aquifer for the period 1987-2016. The distribution of the recharge patterns of the Koda catchment is shown in the following **Figure 29**.

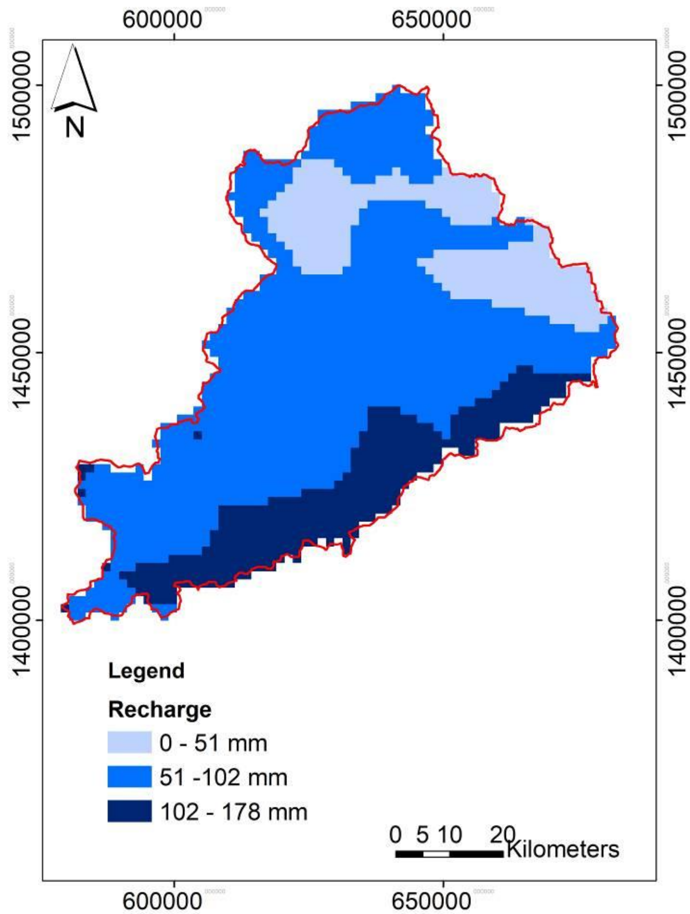


Figure 29: Recharge from previous methods used in this study

3.3.3.4.11. Evapotranspiration

According to the calculation of Potential Evapotranspiration using Blaney-Criddle method 1962, the mean annual evapotranspiration value is 2082 mm over the study catchment.

3.3.3.4.12. Hydraulic Conductivity K

All the model layers have been assumed to be hydraulically homogeneous and isotropic (K_{xx}=K_{yy}=K_{zz}). The visual modflow was run under steady state where the parameters are time independants. The conductivity is determined by the following formula equation 15;

$$Kxx\frac{\partial^2 h}{\partial x^2}+Kyy\frac{\partial^2 h}{\partial y^2}+Kzz\frac{\partial^2 h}{\partial z^2}+q'=0 \qquad (15)$$

Where K_{xx}, K_{yy} and K_{zz} are values of hydraulic conductivity along the x, y, and z coordinate axes, Ss: specific storage coefficient, q': the algebraic sum of the flow rates taken and brought, h: hydraulic conductivity (L/T) and t: time (t).

It means there is no change over the axes. The hydraulic conductivity values have been estimated from previous studies done over the study area. Five zones of hydraulic conductivity have been determined. The hydraulic conductivity is calculated by equation 16:

$$T=K*e \tag{16}$$

Where T is transmissivity, K is hydraulic conductivity and e is the thickness of the layer.

3.3.3.4.13. Discharge

The value of the discharge of the boreholes of the study area is varying form 0.5 m^3/h to 60 m^3/h. More than 80 % of the boreholes realized in the study area are positive (HYDRO MALI sarl, 2011a and PNMRE, 2017).The positivity of a borehole depends on what the driller is looking for? For example, when the borehole is destined to satisfy the water need of a population, the discharge value requested depends on the number of inhabitants of the zone in question. In the area of interest, some boreholes are considered positive when the discharge is greater or equal to 0.5m^3/h (HYDRO MALI sarl, 2011a). In the study area some boreholes were interpreted as positive when the discharge reach 5 m^3/h (PNMRE, 2017).

3.3.3.4.14. Depth of the borehole

The minimum depth of the borehole in the study area is 20 m and the maximum depth reached more than 146 m (**Figure 30**). According to the previous results of the geophysics method applied in the study to investigate the geology of the site, 20 m-50 m are adjudged sufficient to detect fractures of the study area. However, for the best knowledge on the geometry of the aquifer, it is recommended to dig until 250-300m. This information has been used to define the thickness of the aquifer and the geology and the lithology of the study area.

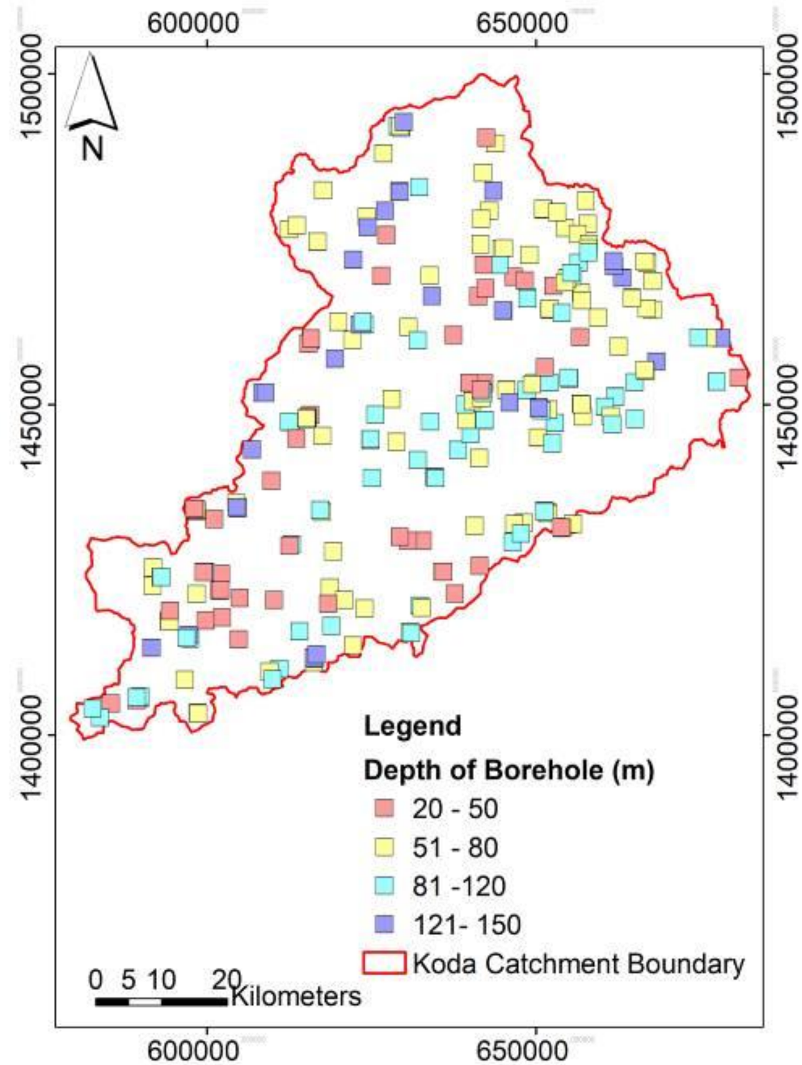


Figure 30: depths of boreholes over the study area (source PNMRE, 2017)

3.3.3.4.15. Static water level

The monitoring water level at the site indicates a flat-water table with static water level situated between 2.5 m and 20 m in more than 90 % of the boreholes. The maximum static water level measured in all boreholes, wells and piezometer is 27 m. Those high values are recorded in the northern part of the study area such as Sirakorola, Massantola, Tioribougou and Nonkon (**Figure 31**). Most of the values of the static water level fluctuated between 3 m and 15 m.

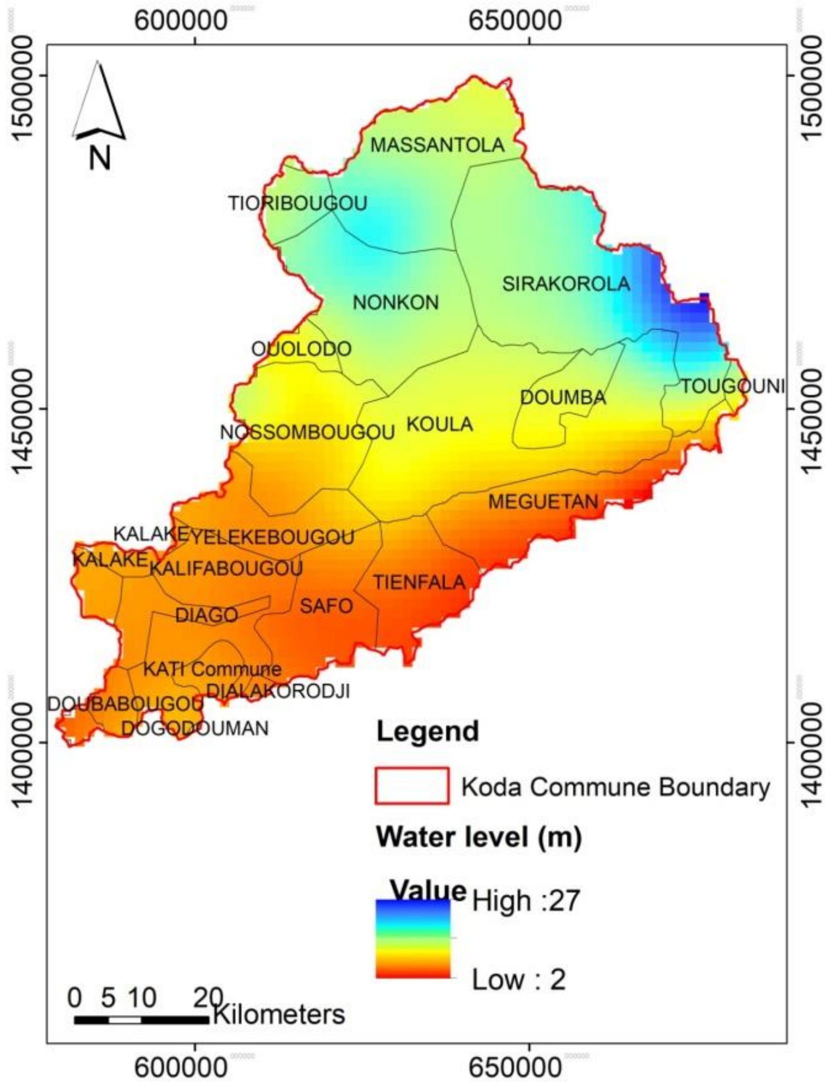


Figure 31: Variation of water level over Koda catchment (source: field and PNMRE, 2017)

3.3.3.5. Run of the model under steady state

Under steady state conditions, the parameters such as boundary conditions and heads are unchangeable over time. In the transient model state changes in the boundary conditions, heads and the inflow/outflow from storage are taken into account. In this study the model was run under steady state conditions.

3.3.3.5.1. Calibration

Every model must be calibrated before it can be used as predicted tool of future field behavior (Lakshmi & Narayanan, 2015). The target of calibration process in Modflow is to minimize the difference between observed and predicted head. This difference comes from an inaccurate model conceptualization , the errors from the numerical solution or when the field parameter values are unavailable (Konikow & Reilly, 1998). The aquifer proprieties (hydraulic conductivity, transmissivity, storativity, etc.) are commonly not well known or unknown. In this study, the unknown parameter is adjusted until a good fit between observed and simulated values of the known parameter reached (Hill & Tiedeman, 2007). The hydraulic conductivity taken from the transmissivity was used to calibrate the model under steady state conditions. The calibration has been done through manual and automated Parameter Estimation by Sequential Testing (PEST) methods as explained by (Anderson & Woessner, 1992; Hill & Tiedeman, 2007).

i. **Manual Trial-and-Error Calibration**

In trial-and-error calibration, the model input parameters are changed manually by the modeler in order to minimize the difference between simulated (model output) parameters and observed (field) parameter values. During the Manual trial-and-error calibration only one parameter is changed at a time or different combinations of parameters are tried. This is the most common method used in calibration process. In contrast, it is time consuming and required more effort from the modeler. Through the trial-and-error calibration method, the factors controlling the system are highlighted.

ii. **Automated calibration (PEST package)**

Computer codes such as PEST are used for the automated calibration. Automated parameter estimation process should be used only after completion of at least some initial manual calibrations. The special experience of the modeler is required.

3.3.4. Evaluation of effects of Climate Change on groundwater

To assess the effects of Climate Change on groundwater over Koda catchment, climate scenarios have been used in this study. There are four pathways: RCP8.5, RCP6, RCP4.5 and RCP2.6 (Moss, 2008). From divers Global Climate model (GCM), a number of Regional Climate Model (RCM) has been obtained from the Coordinated Regional climate Downscaling Experiment (CORDEX) program.

In this study, the effects of climate change have been investigated using an ensemble of three GCMs each driven by three RCMs. The two scenarii that have been chosen to assess the impact of climate change are RCP4.5 and RCP8.5. The RCP 4.5 is a stabilization scenario that supposes that all the world countries undertake emission mitigation policies(Thomson et al., 2011) and the

RCP 8.5 (the worst case). It is a reference scenario representing the highest RCP scenario regarding GHG emissions without any explicit climate policy. Both permit to know how climate change will affect the groundwater with some mitigation actions and without mitigation actions.

Precipitation and temperature data were obtained for the basin area from the CORDEX archives. These data were analyzed and compared to the historic data (baseline) to find out spatial and temporal changes in amount and trends in the future climate.

The station specific climate data was used as input of the Gardenia model. The CORDEX project gives regional climate and the Cordex downscaling tool named Batch downscaling program was used to get station specific data through statistical downscaling.

3.3.4.1. Climate data time series

From CORDEX-Africa project (www.cordex.org), simulated daily precipitation and temperature climate data were retrieved. These data are represented in two-time windows: (a) the historical period from 1987-2005 and (b) the projected period from 2021- 2050. The outputs of two Regional Climate Models RCMs (CCLM4 and RCA4) under Representative Concentration Pathways RCP 4.5 and RCP8.5 scenarios are used in this study. The RCMs are driven by three Global Climate Models GCMs (IHEC-EC-EARTH, MOHC –HadGEM2-ES and MPI-M-MPI-ESM-LR) (**Table 19**). The simulated data as compared to the observed data show some biases which need to be corrected. Therefore, the data were downscaled statistically via the Multiscale Quantile mapping bias correction method. The description of the RCMS set driven by GCMs used in this study is described in the **Table 20**.

Table 19: Characteristics of Representative Concentration Patways (RCP) used in this study (IPCC, 2013)

Name	Radiative Forcing	Concentration (ppm)	Emissions Pathways
RCP 8.5	> 8.5 W/m^2 in 2100	CO_2 at 1370 ppm.	Rising
RCP 4.5	~ 4.5 W/m^2 at the stabilization level after 2010	~ 660 eq CO_2 at the stabilization level after 2100	Stabilization without overshoot

Table 20: Regional climate models (RCMs) and the drivers global climate models (GCMs) used in this study

Institution	**RCMs**	**RCP**	**Resolution**	**Boundary forcing (GCMs)/ Institution**
CCLM: Climate Limited-area Modelling Community, model version 4, Germany	CCLM4	4.5	50 km	EC-EARTH/ ICHEC (Europian consortium)
		8.5		
		4.5	50 km	HadGEM2-ES/MOHC (Met Office Hadley Centre, UK)
		8.5		
		4.5	50 km	MPI-ESM-LR /MPI-M (Max Planck Institute for Meteorology, Germany)
		8.5		
Swedish Meteorological and Hydrological Institute- Rossby Centre Atmosphere model version 4, SMHI	RCA4	4.5	50 km	EC-EARTH/ ICHEC (Europian consortium)
		8.5		
		4.5	50 km	HadGEM2-ES/MOHC (Met Office Hadley Centre, UK)
		8.5		
		4.5	50 km	MPI-ESM-LR /MPI-M (Max Planck Institute for Meteorology, Germany)
		8.5		

3.3.4.2. Bias correction of Precipitation and Temperature time series

The bias is defined as the discrepancy between a model output characteristic and the observations. It is obvious that the distribution of projected scenario may differ from the historical period; that leads to which raises some questions: What is the bias and what is the signal in this study? To answer these questions, the Empirical Quantile Mapping is used to correct the daily precipitation and temperature outputs from RCMs over the studied catchment (Bardossy& Pegram, 2011**;** Teutschbein & Seibert, 2012). The correction is done in order to improve projections of the future rainfall and temperature (maximum and minimum) data under the Representative Concentration Pathways RCP 4.5 and RCP 8.5. The bias correction is a crucial step for any Climate Change Impacts Studies CCIS (Vannitsem, 2011). In order to match the statistical distribution of the observed data and the RCM output time series, the empirical statistical technique was applied at monthly time step as described by Amadou et al.(2015) and Sarr et al. (2015).

The historical data were divided into two parts, one part for calibration and the second part for validation. From observation and RCM simulation data, the daily time series of the month were extracted for both calibration and validation periods. Fobs and FRCM the developed two cumulative distribution functions were generated using observations and RCM outputs respectively on the calibration period. Bias Corrected RCM (XBC) simulations were generated on the validation period and future periods using the transformation explained by equation 17:

$$X\mathrm{BC} = Fobs^{-1}\,(FRCM(XRCM)) \qquad (17)$$

Where $XRCM$ is the variable extracted from raw simulated RCM data. The Dry day correction, maximum and minimum temperatures values were taking account in order to produce corrected future RCM simulations close to the observations.

3.3.4.3. Simulated Model performance evaluation

Assessing the performance of the simulated models is a necessary step for model predictions. The demonstration of the importance of the bias correction of RCM data for the use in Climate Change Impact Studies (CCIS) is also needed. For that, the performance of the individual RCMs in simulating the historical period (1987-2005) of rainfall and temperatures of the Koda catchment was evaluated. The comparison among the RCMs for the historical period (1987 to 2005) has been made and also the comparison between monthly rainfall and temperature of the model-simulated uncorrected, model-simulated bias-corrected and observed data for the Katibougou climate station has been done. The statistical parameters such as R^2, NASH and RMSE between Uncorrected –Observed- Corrected have been calculated

The model performance criteria

The coefficient of correlation R^2 and the Nash coefficient quantifies NASH have been used to evaluate the performance of the model. In addition, the Root Mean Square Error (RMSE) also has been calculated to evaluate the performance of the model. RMSE provided a good overall measure on how close modeled values are to observed values. If RMSE is close to 0, it means the difference between simulated and observed value is low. RMSE is calculated via as follows equation 18:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(O-S)_i{}^2} \qquad (18)$$

Where n is number of samples, O is observed data and S is simulated data

3.3.4.4. Modelling purpose

The GARDENIA and the Thornthwaite models were run for the past 30 years (1987-2016) as baseline and 2021-2050 as the projected period in this study. The figure 9999 settled for missing data was used to refer to the future value of the piezometric data in the Gardenia model.

3.3.5. Land Use Land Cover dynamics from 1986 to 2016 over Koda catchment

The flow chart of methodology used to classify the LULC types, and its dynamics is given below:

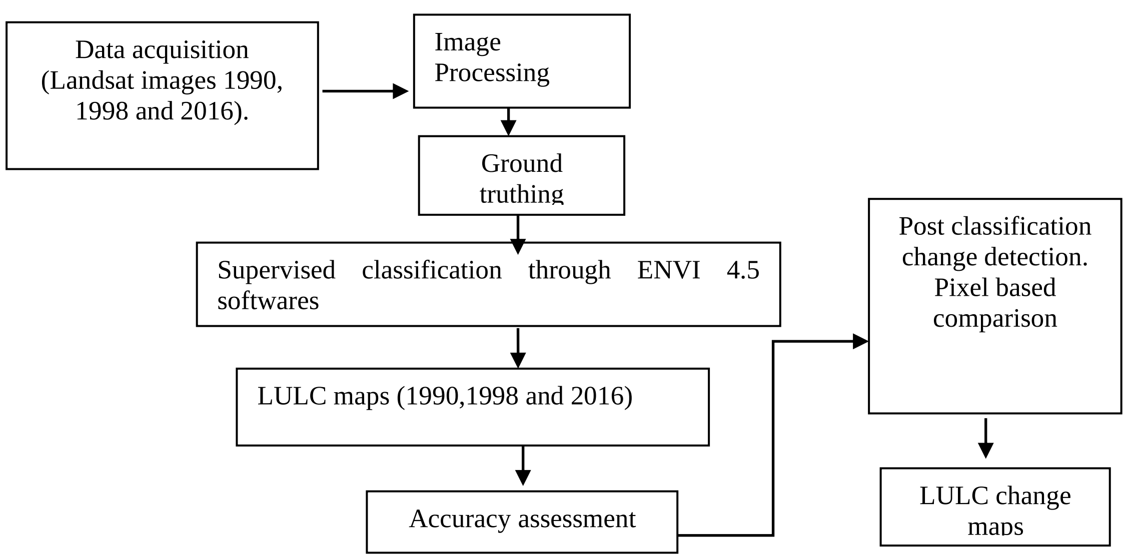


Figure 32: Flow chart of methodology of LULC change

The change of LULC over Koda catchment was carried out based on the 1990, 1998 and 2016 LULC maps developed for the catchment. Supervised classification method was used which required to collect data from the field survey and to use these data as the reference samples considered as the representative of each surficial Land cover unit to be classified.

The maximum likelihood classification algorithm was applied to get the best algorithm for classification. The threshold option has been used to calculate the area of each LC units over the Koda catchment. Using the overall function in ArcGis 10.3 and the Microsoft Excel 2007, the percentage change in LULC was calculated for the twenty-seven (27) years period.

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 19:

$$K = \frac{N \sum_{i=1}^{n} \widehat{P_{ii}} - \sum_{i=1}^{n} \left(\widehat{P_{i+}} * \hat{P}_{j+} \right)}{N^2 - \sum_{i=1}^{n} \left(\widehat{P_{i+}} * \widehat{P_{j+}} \right)} \qquad (19)$$

where P_{ij} is error matrix, $\widehat{P_{i+}}$row total pixel, $\widehat{P_{j+}}$colum 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:

i. Poor if K <40
ii. Good if 40 ≤ K <75
iii. Excellent if K ≥ 75

3.4. Conclusion

The chapter clearly described the data and software used in this research. All the methods used to achieve the objectives of this thesis have been described in detail in this chapter.

Chapter 4: Rainfall Variability across Koda Catchment for the period 1987-2016

The variability of the rainfall patterns affects many aspects of daily life. It can affect the economy of a given place where agriculture is the main activity of the inhabitants. Any change of the precipitation regime leads to the change in water cycle and then in water resources (Ibrahim et al., 2014; Ta et al., 2016). According to Wuebbles & Ciuro (2013) the change on temperature and rainfall constitute the key climate variables that will impact the hydrological regimes and the change could become more significant in the future. The good understanding of the change in rainfall patterns is crucial for socioeconomic management. The lack of water is generally caused by the unfavorable weather conditions specially the long droughts periods. The prolonged droughts added to the rapid population growth led to increasing water demand from the inhabitants. Therefore, the study related to any change in the precipitation regime is required to understand the climate and to investigate its different impacts. Several studies have been done related to the analyze of rainfall regime over the world at large and small scales (Bodian et al., 2011; Majid, 2016; Kabo-Bah et al., 2016). Some studies were investigated in West Africa on the climate variability in the past decades. Most of these studies showed the drought for the period 1960-1970 (Mahé & Olivry, 1995; Mahé et al., 2000; Lebel & Vischel, 2005).

The drought period is characterized by decreasing precipitation from 20% to 30 % of coupled with a decrease of river discharge (Servat et al., 1995; Paturel et al., 1997; L'Hôte et al., 2002; Lebel & Vischel, 2005; Dao et al., 2010).

Some few studies have been done in Mali to characterize the rainfall regime patterns. For example Dao et al. (2010) analyzed the climate variability over Kolondieba catchment in the southern part of Mali and highlighted the magnitude of drought for 1960-2008 period and described two break points 1969 and 1992. There is no study done over Koda catchment related to the rainfall variability. Therefore, there is a need to characterize the rainfall variability across this catchment for the past decades.

The main objective of this study is to characterize the spatiotemporal variability of rainfall at local scale, especially the southern part of Mali for the past 30 years (1986-2016).

The three pluviometric stations (see in chapter 2) are surrounded by the study catchment. The daily climatic data recorded at Bamako and Katibougou stations has been collected from the National Meteorological Agency of Bamako and Regional Meteorological Agency of

Katibougou and from the traditional pluviometer used by the famers in the field. The annual rainfall data of Toubougou station has been collected from the field with farmers. The datasets of Bamako and Katibougou stations are respectively 30 years (1987-2016) and 30 years (1987 - 2016) and 17 years for Toubougou (2001-2016).

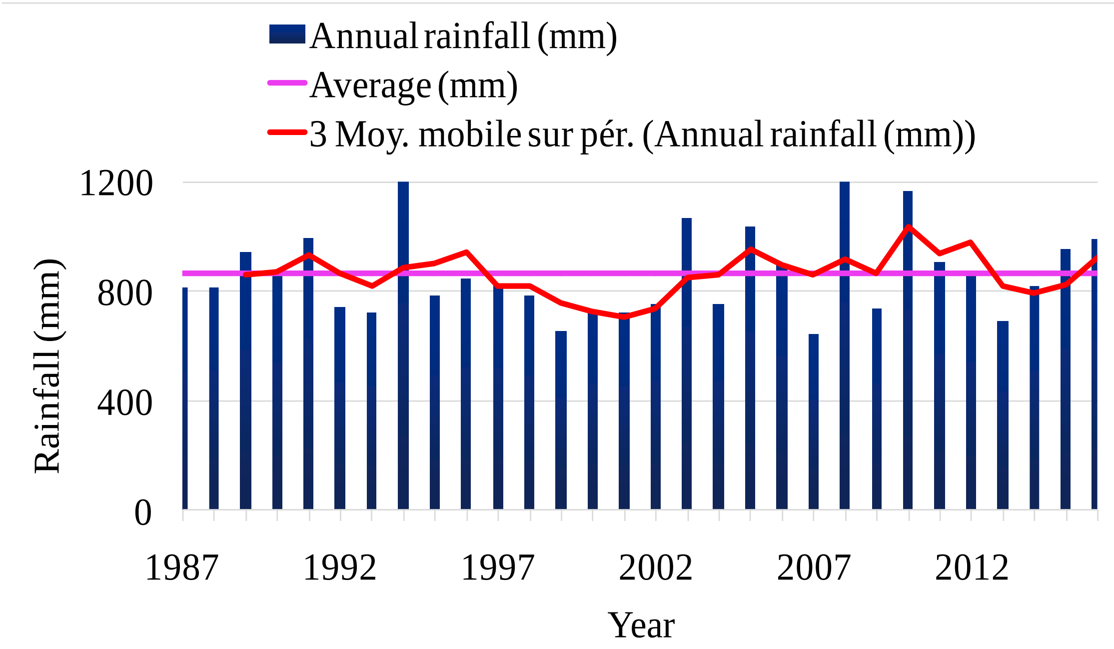
At Bamako station, the mean annual rainfall over the last 30 years is ranged from 644.3 mm (year 2007) to 1,205 mm (year 2008). The annual mean rainfall for 1987-2016 is 862.62 mm. The overall annual average rainfall for the last 30 years (1987-2016) varies from 500.4 mm in the year 1992 to 1,164.3 mm in the year 1988 at Katibougou station while the mean value over 30 years (1987-2016) is 836 mm. The overall annual mean rainfall for the period 2001-2007 at Toubougou is 729.1 mm with the minimum and maximum annual rainfall as 207 mm and 1123 mm respectively.

4.1. Results and Discusion

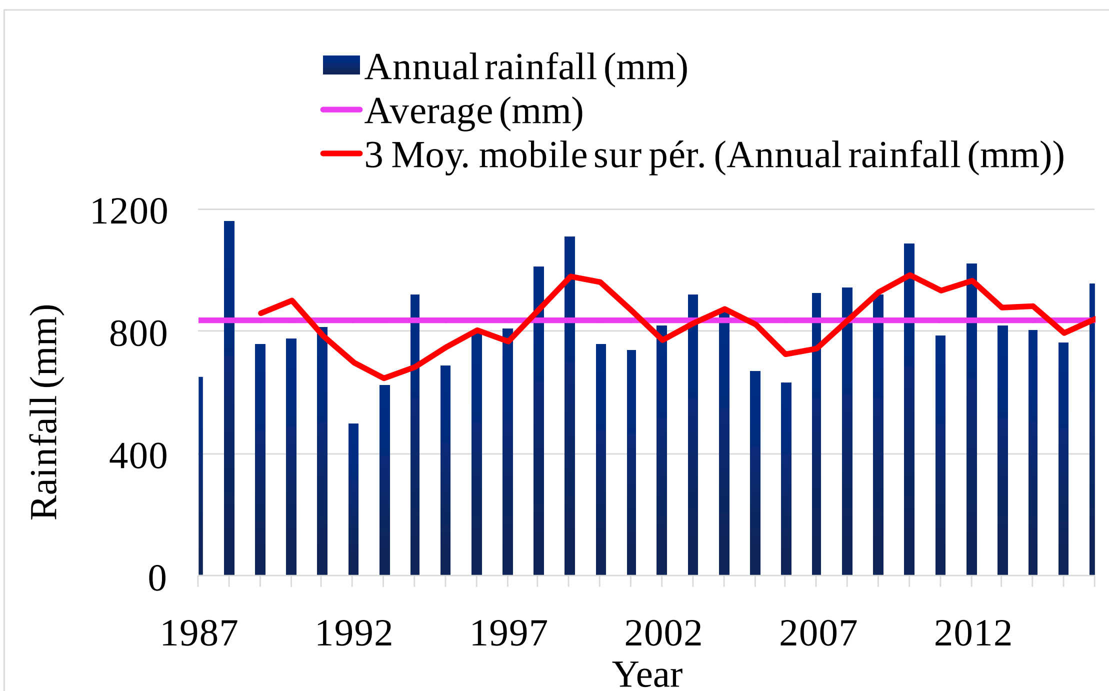
4.1.1. The 3 years moving average analysis

The 3 years moving has been applied to Bamako and Katibougou stations. For the Bamako station, the period 1990-1992, 1996-2002 and 2012-2016 are defined as dry period while 1989-1990, 1993-1995, 2003-2011 are defined as wet periods.

Concerning Katibougou station, the driest period is observed in 1992, the long dry period is from 1989-1997 and 2005-2008; 2000-2001 is the short dry period while the wet period is represented by 1998-2001, 2003-2004, 2009-2015 and 2016. The dry and wet periods have been successive over Koda catchment and the years considered as dry are greater than the years defined as wet (**Figure 33**).



a.



b.

Figure 33: Three (3) years moving average over Koda catchment, a. Bamako station and b. Katibougou station.

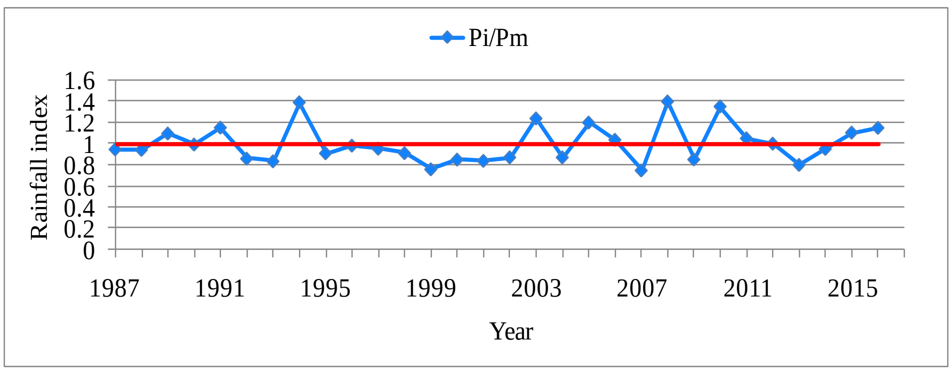
4.1.2. Casas Rainfall Index IP

The IP index of Casas et al.(2010) has been also calculated in order to classify rainfall events using the equation 20.

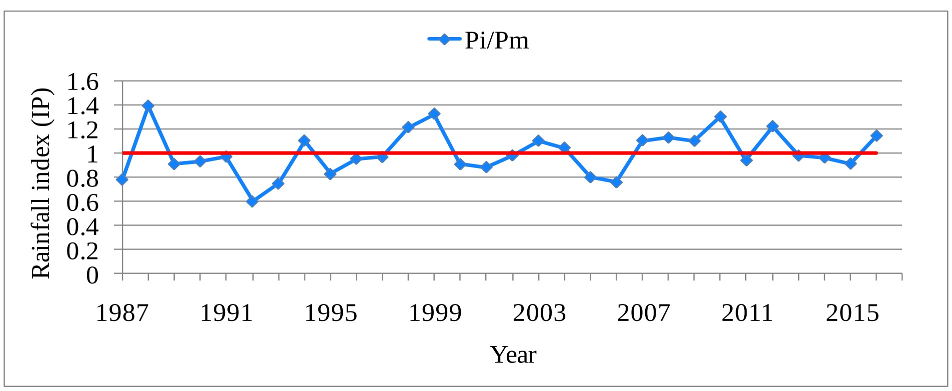
$$IP = P_i / P_m \quad (20)$$

Where P_i the rainfall of the year i, P_m is the mean precipitation of the Koda catchment.

When the IP is over 1, the year is considered wet while when it is below 1 the year is called dry year. The overall drought period is manifested from 1987 to 2002 while the humid period occurred from 2003 to 2014.The results are shown in **Figure 34**.



a.



b.

Figure 34: Rainfall Index IP over Koda catchment, a: Bamako station and b. Katibougou station

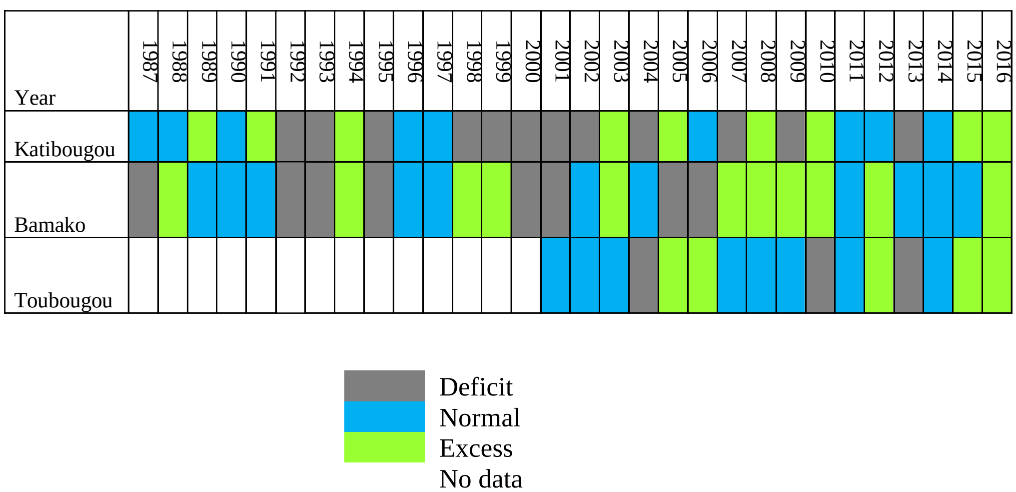
4.1.3. Lamb Rainfall index

The rainfall dataset has been also analyzed using Lamb Rainfall in order to characterize the year as normal, deficit or excess. For the data recorded at Katibougou station 1986-2016, the year's corresponding to normal and wet are represented by 9years each (26.6 %) while 12years stand for dry years (36.6 %).

In Bamako station, the 30 years (1986- 2016) dataset has been used to calculate the Lamb Index Rainfall to define the year as normal, deficit or excess. Years corresponding to normal are 40 % wet years represent 40 % while the dry years are about 30% of the dataset

The 17 annual rainfall datasets recorded in Toubougou station are summarized in the **Table 21.** The analysis using Lamb rainfall index showed that 47% corresponds to normal year while 29.4 % are representing wet years and 23.5 % are dry.

Table 21: Lamb Rainfall Index over the three stations



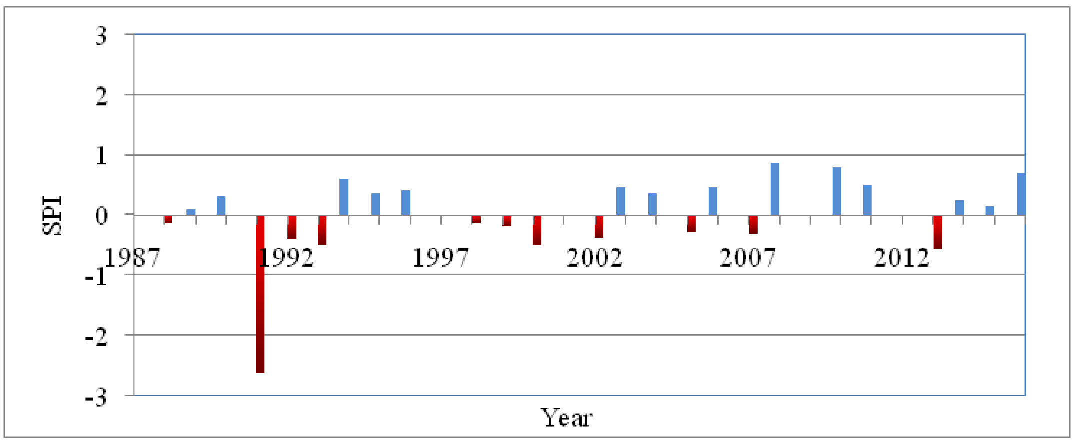
4.1.4. Standard Precipitation Index (SPI)

The figure below displays the results of SPI-6 of Bamako station. All the values are between 0 and 0.99 (considered as near normal) except the year 1991 with more than -2.5 as SPI value which is interpreted as extremely dry (**Figure 35**).

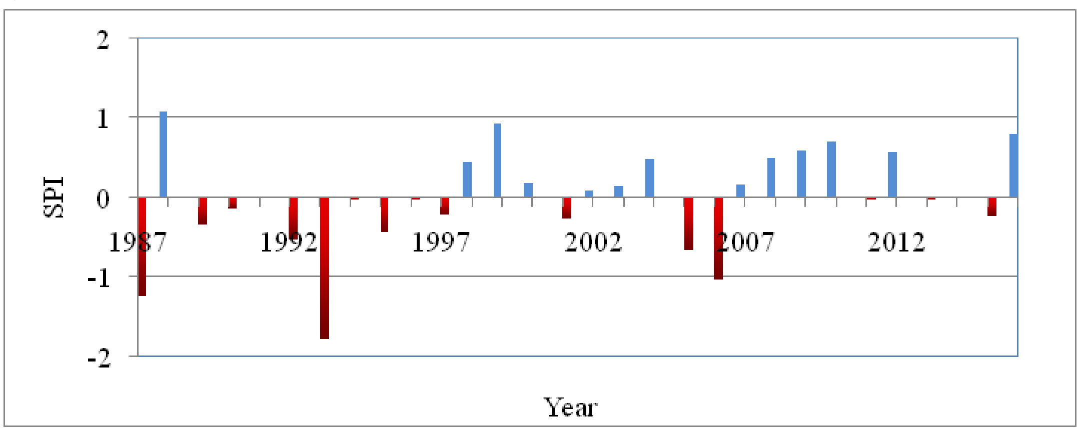
The years considered as near normal represent 87 % over the 30 years rainfall datasets while the year defined as extremely dry is about 3.33 %.

Most of the Standard Precipitation Index, for 6 months from 1987 to 2016 is interpreted as Near normal, the values of SPI ranged from -0.99 to 0.99 except some dry years such as the years 1987 and 2006 which were moderately dry with SPI values of -1.5 and -1 respectively, and the year 1993 considered as Severely dry. Only one year (1988) was considered as moderately wet with the value of SPI is between -1.5 to -2 (**Figure 35**).

The years considered as near normal represent 87 % of the rainfall datasets (30 years) while the years defined as moderately dry are about 6.4 %. The remaining years interpreted as severely dry and moderately wet are represent 3.3 % each.



a.



b.

Figure 35: Standardized Precipitation Index for the rainy season (June to November) for the period 1987-2016 (data source from DNM of Mali), a. Bamako station and b. Katibougou station

4.1.5. Detection of break points using Khronostat

The results obtained from the statistical tests applied to three pluviometric datasets (Table 22) are described as follow. The period 1986–2017 cannot be considered as a stationary series, since, in the test of Pettitt method (1979) and the U-statistic of Buishand tests (1982), the zero hypothesis of absence of break is rejected at the 99% confidence level.

The Lee and Heghinian test (1977) allow one to detect a break point in the record in the three stations in 2006, 2015 and 2016 with a *posteriori* probability density function mode of the break point position: 0.0669 in 2006, 0.0769 in 2015, and 0.1175 in 2016.

Finally, the procedure of segmentation of Hubert (1989) gives a significance level of the test of Scheffé at 1%, which is considered as adequate.

The climate change in this catchment is characterized by some major breaks in rainfall occurring in 1988, 1991, 2006, 2015 and 2016, as presented in the **Table 22**

These failures have resulted in a deficit in two (2) years represented by 1991 (13 %) and 2016 (39%) and an excess in three years 1988 (16 %), 2006 (36%) and 2015 (21%). The study shows the number of years which experienced severe droughts over the period 1986 –2016 (**Table 23**).

Table 22: Detection of break points over the three pluviometric stations

Stations	Period	Break point
Bamako	1987-2016	1991 ***,** 2015******
Katibougou	1986-2016	1988 ***,** 2006******
Toubougou	2001-2017	2016******

* Pettit test, ** Lee and Heghinian test (1977)

Table 23: Break points with percentage of deficit or excess

Station	Break point	Before break point Average rainfall (mm)	After break point Average rainfall (mm)	Deficit % Or excess
Katibougou	1988	657.9	759.9	+16 %
Bamako	1991	854.7	740.1	-13.4 %
Katibougou	2006	668.4	924.7	+38%
Bamako	2015	819.3	990.6	+21 %
Toubougou	2016	877.8	538.5	-36%

The year 1988 is characterized as wet year with an excess of 16 %. The year 1988 has been defined as a break point through Lee and Heghinian test (1977) by Dao et al. (2010) in the southern part of Mali. The second break point is the year 1991 with 13.4 %. The drought of 1991-

1992 has been described by many authors across Africa. It has been detected by many studies over Bani basin in Mali (Mahé et al., 2000; Goula et al., 2006; Dao et al., 2010; Dao, 2013) with 13 % of decrease in rainfall. The break point of 2006 has been detected by Lee and Heghinian test (1977) as a wet year with 38% in Katibougou. It has been defined across Koda catchment as a year extremely wet through the Standard Rainfall Index SPI analysis. According to the World Meteorological Organization "**O**rganisation **M**étéorologique **M**ondiale" (OMM, 1996) the period 2006-2010 has been considered as wet period. The years 2006-2007 are defined extremely wet based on the flooding event that occurred in this period over the world. The years 2015 and 2016 have been detected as respectively break points with excess of 21 % and a deficit of 39 %. The break points of the 2015 and 2016 should be confirmed by future studies.

4.2. Conclusion

The results show a modification of rainfall over the years across the Koda catchment. The decrease in annual rainfall is one of the important factors to characterize the variability of the hydrologic regime. In semi-arid and arid zones, the hydrological regime of catchments is sensible to climate. A small change of the amount of the annual rainfall could have important effects on the hydrological cycle. The results could be a guide for future studies and also be a great tool for water resources management.

Chapter 5: Groundwater Recharge Estimationn

Groundwater recharge is one of the most difficult fluxes to define, particularly in arid and semi-arid areas.Groundwater recharge is one of the principal components of the water budget. It is really difficult to quantify that parameter due to the complexity of recharge processes and limited observations.

The amount of rainfall that is converted into groundwater recharge is not understood. This knowledge gap can be primarily explained by the limited avialibility of the observations of the change in groundwater storage in this region (Taylor et al., 2013). Mali, described as an arid and semi-arid countryis facingthis issue of groundwater recharge. It is useful to notice that the important aquifers in Mali in terms of quantity and quality are located in the sandstones plateaus of the infracambrian age (DNHE-PNUD, 1990b).

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 and accordingly pumping rates have greatly exceeded their natural recharge. Many researchers (Osterkamp et al., 1995; Carrillo-Rivera, 2000; Sharda et al., 2006; Muller et al., 2016; Ali Rahmani et al., 2017; Lilia et al., 2018) in these regions are working to understand recharge processes and to determine effective ways by which recharge can be enhanced naturally. According to PNMRE (2017), the quality of water in the tabular infracambrian layer is good for irrigation and this could increase the groundwater availability stress. Like many of the arid and semi-arid regions, groundwater is the main water resource in the Koda catchment. All the domestic water supplies as well as water used for agriculture, drinking and livestock entirely depend 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 is used for all the water needs in the Koda catchment. The groundwater resource dynamics are poorly understood in the study catchment and this may be due scarce of historical data. According to (Lutz et al., 2015) 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 are no appropriate groundwater management systems to face the problems related to the use of groundwater.

A few studies have been conducted in the Infracambrian sandstones of Mali to evaluate the groundwater recharge. Most of these studies were carried out in the Bani catchment (DNHE-PNUD, 1990a; Traore, 1985; ARP Developpement,2003; Bokar et al., 2012; Toure et al., 2016; Sidibe, 2019; Diancoumba et al., 2018). For example, the ARP Developpement (2003) 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 (2003) used various methods different from the WTF method to characterize the recharge in the southern part of the Taoudeni basin where the study area is located and observed recharge values of 75 - 120 mm (from Thornthwaite method) and 127 mm (14% of annual rainfall) from a lumped Earth model have been recorded. These differ from the values (147 mm.y-1 or 13% of total rainfall as the annual total recharge) obtained by Bokar et al. (2012) using the Thornthwaite method in the Kolondieba catchment (Sudanese Climate Zone in Mali). In addition, Toure et al. (2016) used the lumped Earth model method and obtained a value of 156.8 mm as the 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. Although those researches were carried out in the southern part of Mali, no groundwater recharge studies were carried out in the Koda catchment. Thus, a clear picture of the variation of annual groundwater resources in the Koda catchment was missing.

There is hence, the need to study the spatiotemporal variation of groundwater in the Koda catchment using an appropriated method. As infiltration plays an important role for most water budget models, it is essential to know the amount of the precipitation that infiltrates into the aquifer as recharge and how the recharge rate influences the precipitation regime.

The choice of the method of recharge estimation

Groundwater recharge varies from site to site, region to region and country to country. For a given site the recharge varies year to year according to the amount of annual rainfall. All the projects of groundwater exploitation depend on the available resources.

Due to the many efforts made to exploit the groundwater resources in the semi and arid zones careful management of those resources is very essential. The evaluation of renewable resource (recharge) is the key step of groundwater resources management. According to Jyrkama and Sykes (2007) the assessement of climate change impacts on groundwater recharge in time and space is very complex.To make a good estimation of the groundwater recharge (at different scale)which is the key parameter essential for integrated water management and adaptation. Thornthwaite method, Water Table Fluctuation method and Gardenia model were used.

5.1. Estimation of recharge Monthly Water –Balance Model Driven by A Graphical User Interface (Thornthwaite method for groundwater recharge estimation)

The determination of the water contributing to recharge of the aquifer is one of the major problems in hydrogeological investigations in arid and semi-arid regions.

Results

All the components of the water budget have been estimated through this method. The estimation of the parameters has been done for 30 past years (1987-2016) and it is divided into 3 decades, 1987-1996, 1997-2006 and 2007 to 2016. The results are outlined below:

5.1.1. Precipitation

The precipitation is linked to the other components of the water budget through this following equation 21:

$$P=AET + (I + R + \Delta RU) = AET + Reff \qquad (21)$$

With P: Precipitation, I: infiltration, R: Runoff, AET: Actual Evapotranspiration, ΔRU: variation of soil storage and Reff: Effective Rainfall.

5.1.2. Potential Evapotranspiration (PET) calculation

The empirical equations are frequently used in arid and semi-arid zones to calculate the PET. Some of examples of those equations are the Turc, Blaney-Criddle, Penman-Monteith and Thornthwaite.

One of the reasons for developing many equations to estimate the PET is due to the difficulties to get reliable results for a special area. It is therefore recommended to try some methods in order to reduce the uncertainty using this parameter value as input for other hydrological models. For that reason, three methods have been chosen in this study based on the data available and the access of tools allowing the use of these methods.

First of all, we used the Penman-Monteith method to estimate the PET value. As reported by Castany (1982), this formula requires the knowledge of many climatic parameters that are not often available in the Sahelian zone. Although the climate data availability is a problem in the study area, the method has been tested to calculate the PET quite well in comparison with other methods. The Blaney-Criddle and Thornthwaite methods were applied for the same purpose. The first one requires only monthly temperature data as input data while the second requires not only temperature but also runoff and soil moisture. The results from the three methods (Penman-Monteith, Thornthwaite and Blaney Criddle methods) allowed us to better evaluate the PET of the study area. From these results, it is observed that the Penman-Monteith method overestimated the PET patterns while the Thornthwaite method underestimated it. The monthly average values obtained from the Blaney and Criddle method was close to the overall mean value of the three methods (**Figure 36**).

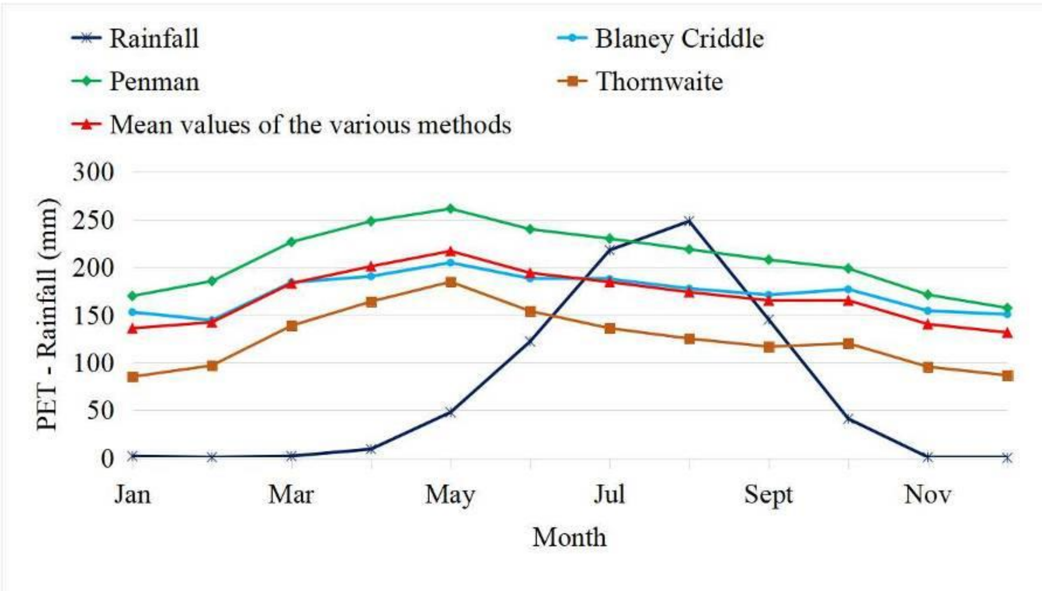


Figure 36: Monthly PET estimated through various methods against rainfall recorded at Katibougou station

The mean monthly distribution of the PET is bimodal; there is a peak in the end of dry season (May) and another peak in the end of rainy season (October). Thus, the higher values of PET correspond to the months with maximum temperature (dry season) and the low values are observed in the wet season. **Figure 37** displays the mean monthly PET and Rainfall over Koda catchment for the period 1987-2016.

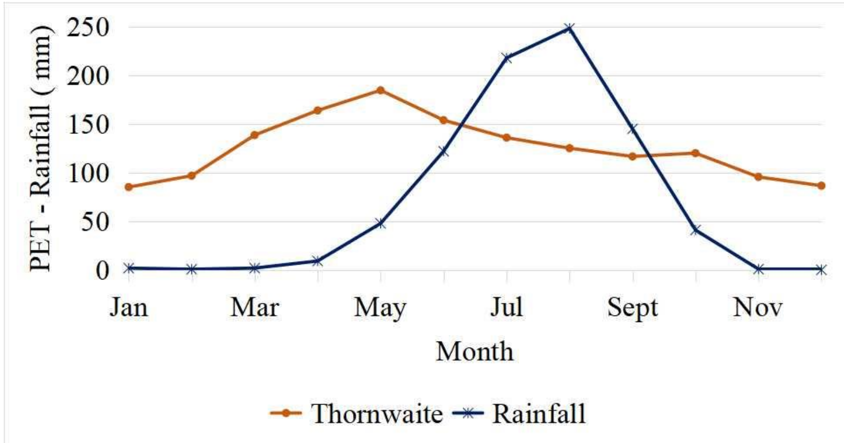


Figure 37: Mean monthly PET estimated from Thornthwaite method against monthly rainfall recorded at Katibougou station

5.1.3. Actual Evapotranspiration (AET)

Actual Evapotranspiration (AET) is the real quantity of water that is evaporated from a system. AET is always lower or equal to Potential Evapotranspiration ETP. For the first 10 years 1987-1996 and the last decade 2007-2016, from September to June, rainfall was lower than the Potential Evapotranspiration (PET). For the period 1997-20016 the evapotranspiration was greater than the precipitation from October to June. Therefore, the Actual Evapotranspiration (AET) and the precipitation are so far well balanced. Thus, the water stock in the soil is equal to 0.

In July and August for the periods (1987 -1996 and 2007- 2016) and July, August and September for the period 1997-2006, precipitation was greater than the PET, that led to AET being equal to PET. The excess rain goes to soil and constitutes its reserve (July). After saturation (August and September), recharge occurred.

The values of AET obtained from 1987-2016 period vary from 66% to 100 % of the annual rainfall.

5.1.4. Effective Rainfall (Reff)

The effective rainfall calculated by the following relationship Reff = Runoff- AET. The calculation has been done at two scales (monthly and annual scales).

The following relationships describe the different ways of effective Rainfall (Reff) calculation formula. It depends on the comparison between the precipitation (P) and Potential

Evapotranspiration (PET) and also the value of Rmax. The conditions are described in equations 22- 24 where RU is soil storage.

$$R_{\mathrm{eff}} = P - \mathrm{AET} | P \geq \mathrm{PET}, \mathrm{RU} = R_{\mathrm{max}} \qquad (22)$$

$$R_{\mathrm{eff}} = P - \mathrm{AET} - R\mathrm{RU}P\mathrm{PET}, \mathrm{RU}R_{\mathrm{max}_{max}} \qquad (23)$$

$$R_{\mathrm{eff}} = 0 | P < \mathrm{PET} \qquad (24)$$

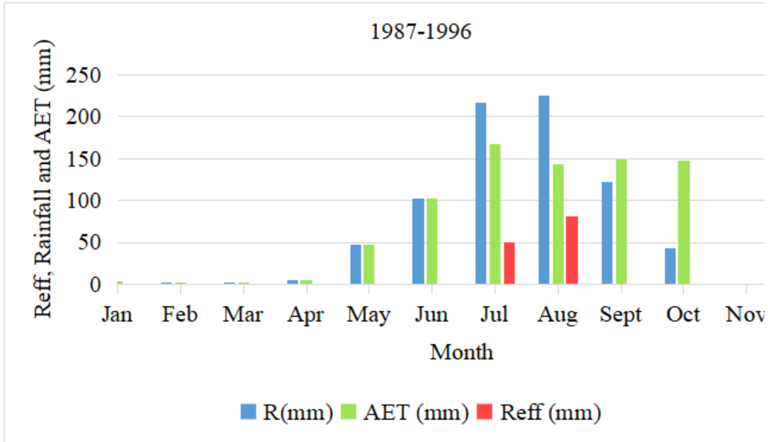
Effective rainfall exists only when the actual evapotranspiration AET is lower than the potential evapotranspiration. At annual scale, most of the years over the 30 years period do not register effective rainfall. The other years, particularly the years 1988, 1998, 1999, 2003, 2007, 2009, 2012, 2013 and 2016 have registered favorable rainfall therefore the deducing effective rainfall could improve the recharge of the aquifer. At monthly scale, the effective rainfall occurs only in July and August.

The effective rainfall ranges from 0 to 34 % of the overall annual rainfall **Table 24** displays the results obtained in the study area.

Table 24: Rainfall, Potential and Actual Evapotranspiration and Effective Rainfall from 1987-2016.

Year	P (mm)	PET (mm)	AET (mm)	R_{eff} (mm)
1987	652.5	2497.0	652.5	0.0
1988	1164.3	2372.3	914.5	249.8
1989	759.9	2507.8	759.9	0.0
1990	779.0	2565.0	779.0	0.0
1991	812.1	2400.4	812.1	0.0
1992	500.4	2492.4	500.4	0.0
1993	624.8	2549.5	624.8	0.0
1994	923.3	2489.9	923.3	0.0
1995	690.6	2485.9	690.6	0.0
1996	796.9	2443.7	796.9	0.0
1997	808.8	2490.3	808.8	0.0
1998	1015.8	2531.8	914.4	101.3
1999	1109.3	2467.1	1003.3	105.9
2000	758.3	2508.3	758.3	0.0
2001	738.6	2638.7	738.6	0.0
2002	820.2	2720.8	820.2	0.0
2003	921.7	2677.6	849.2	72.4
2004	873.6	2687.1	873.6	0.0
2005	668.4	2678.5	668.4	0.0
2006	633.0	2601.1	633.0	0.0
2007	924.7	2479.9	608.8	315.9
2008	943.3	2527.5	943.3	0.0
2009	920.7	2539.1	909.0	11.6
2010	1088.8	2606.1	1088.8	0.0
2011	785.6	2594.1	785.6	0.0
2012	1022.5	2534.9	1000.6	21.8
2013	818.5	2579.0	762.8	55.6
2014	805.5	2438.1	805.5	0.0
2015	763.3	2577.5	763.3	0.0
2016	956.8	2642.5	865.5	91.2

The figures (**Figure 38** and **Figure 39**) describe the monthly R_{eff}, AET and Rainfall for the 30 past periods (1987-2016) over the Koda catchment. The representation is done on decade basis for 1987-1996, 1997-2006 and 2007-2026.



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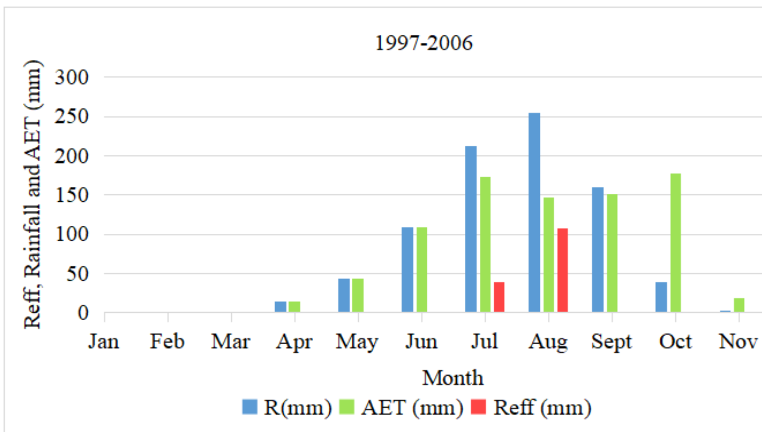

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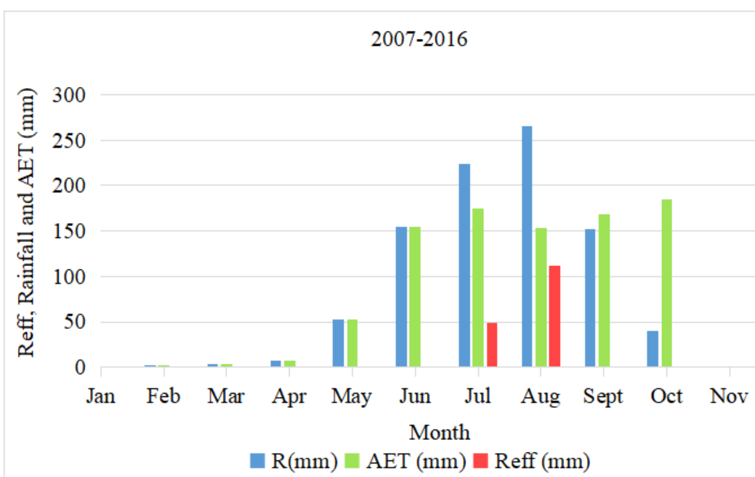


c.

Figure 38: Monthly Effective Rainfall (Reff) and Acutal Evapotranspiration (AET) over Koda catchment for; a: decade 1987-1996, b: decade 1997-2006 and c. decade 2007-2016.

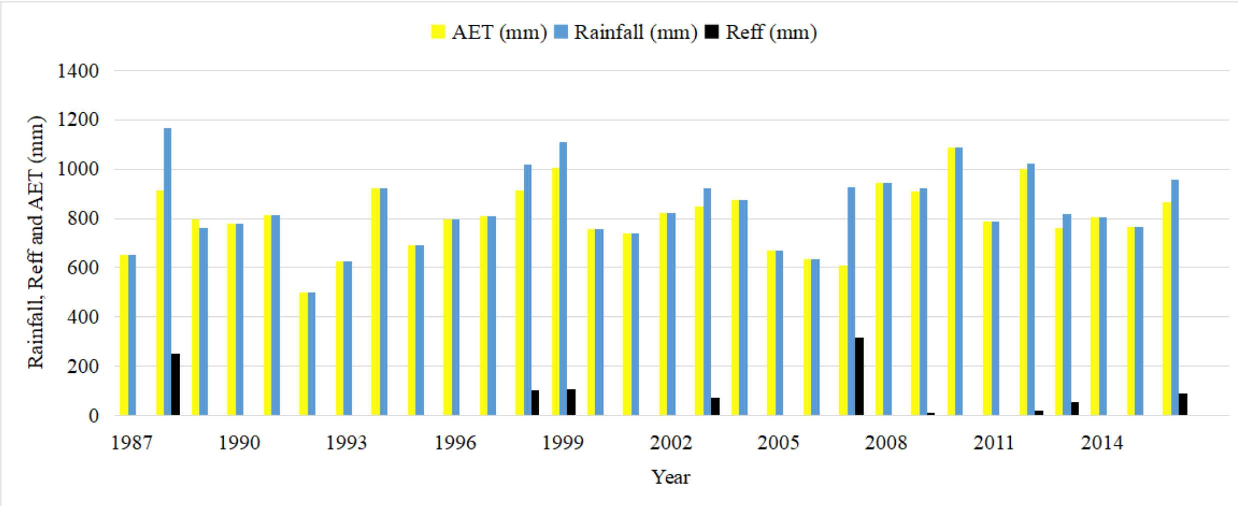


Figure 39: Monthly Effective Rainfall (Reff) and Actual Evapotranspiration (AET) over Koda catchment for the 30 years past period 1987-2016

5.1.5. Soil Water Storage (SWS)

SWS represents Soil Water Storage. It constitutes the amount of water that exists in the first few meters of the soil (unsaturated zones) used by plants through transpiration (Salvayre, 1990; De Marsily, 1994). A percentage of that water is evaporated.

In the current study, the first value of the SWS which equals zero was attributed to the end of low water (May) and the maximum is considered as 100 mm. These values have been chosen based on the previous studies undertook in the same climatic zone in Mali (Dakoure, 2003; Bokar et al., 2012)

5.1.6. Estimation of Recharge

The estimation of infiltration over Koda catchment has been done for three past decades (1987-1996, 1997- 2006 and 2007-2016) and the results are outlined in the tables (**Table 25; Table 26**and **Table 27** based on the formula described above, the AET has been estimated. The recharge values were determined for 30 years and ranged from 1 % to 8 % of the annual

Table 25 shows the Thornthwaite computing method to determine the recharge pattern over the decade 1987-1996.

Table 25: Thornthwaite computing method to determine the recharge pattern over the decade 1987-1996

	Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Decade 1987-1996	**R(mm)**	4	1.08	1.22	5.54	47.8	102.1	217.6	225.3	122.1	43.57	0.07	0	770.3
	PET (mm)	74.3	132.7	205.7	338.9	349.7	256.1	167.3	143.6	149.8	162.2	113	78.2	2171.7
	AET (mm)	4	1.08	1.22	5.54	47.81	102.12	167.38	143.63	149.8	147.73	0.07	0	770.3
	SWS (mm)	0	0	0	0	0	0	50.2	100	100	0	0	0	
	I + Runoff (mm)								31.85	4.16				36.01

R: 10 years average rainfall for the period 1987-1996, PET: 10 years average evapotranspiration (1987 to 1996) AET: Actual Evapotranspiration and I + Runoff: Combining Runoff and Infiltration. According to previous studies (Dakoure, 2003) the Runoff is estimated at 4 % of the rainfall in the southern part of the Toudeni Basin where Koda catchment is located. Using this value, the Runoff = 770*4/100 = 30 mm while Infiltration = 36 mm -30 mm = 6 mm. The annual total recharge for the decade 1987-1996 is estimated at 1% of annual rainfall. The same procedure has been done for the decades 1997-2006 and 2007-2016 and the results are outlined in the tables 26 –27 below:

The **Table 26** shows the Thornthwaite computing method to determine the recharge pattern over the decade 1997-2006.

Table 26: Thornthwaite computing method to determine the recharge pattern over the decade 1997-2006.

	Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Decade 1997-2006	**P (mm)**	0.05	0.58	0.33	14.45	43.31	108.91	211.72	254.08	160.58	39.64	1.08	0.02	835
	PET (mm)	86.2	134.7	231.2	350.9	362.2	224.7	173.1	146.57	151.14	177.4	122.1	83.2	2244
	AET (mm)	0.05	0.58	0.33	14.45	43.31	108.91	173.1	146.57	151.14	177.45	18.85	0.02	835
	SWS (mm)	0.0	0.0	0.0	0.0	0.0	0.0	38.6	100	100	17.7	0.0	0.0	0.0
	I + Runoff (mm)								46.13	55.57				102

The runoff pattern is estimated at 33 mm while the annual recharge is about 8 % of annual rainfall representing 69 mm.

The **Table 27** shows the Thornthwaite computing method to determine the recharge pattern over the decade 2007-2016

Table 27: Thornthwaite computing method to determine the recharge pattern over the decade 2007-2016.

Decade 2007-2016	Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
	P(mm)	1.48	0.41	4.02	7.41	52.17	154.94	224.16	265.11	152.22	39.74	1.29	0.02	903
	PET (mm)	69.99	130	249.06	353.3	369.16	271.69	175.29	152.8	168.6	190.5	122.4	77.75	233
	AET (mm)	1.48	0.41	4.02	7.41	52.17	154.94	175.29	152.8	168.6	184.54	1.29	0.02	903
	SWS (mm)	0	0	0	0	0	0	48.8	100	100	0	0	0	
	I + Runoff (mm)								61.18	44.8				106

For the decade 1997-2016, the annual recharge was 7% of annual rainfall corresponding to 64 mm while the Runoff is about 36 mm per year.

Range of values for water balance components of the Koda catchment for the period 1987- 2016 were estimated in the following ranges: AET 66% to 100 %, Recharge 1 % to 8 % and Effective Rainfall 0 to 34 % of the annual rainfall.

These results are close to those obtained in the similar geological basin, for example Krautstrunk (2012) used Water Table Fluctuation method in Northern Region of Ghana in the Cambrian-Precambrian fractured sandstone aquifer to estimate the recharge and found a range of 1-13% of mean annual rainfall. In the same region, Lutz et al. (2015) estimated the recharge ranging from 1 to 20% of mean annual rainfall. Henry (2011) estimated the net recharge using GRACE and found the value ranging from 2.8 % of annual rainfall to 5.4 % in some parts of the southern part of Mali for the period 2002–2008.

5.1.7. Coefficient of Wetnesss

The coefficient of wetness has been calculated over the studied catchment using the following relationship CW= Ri/PAW where Ri is the runoff and PAW is Soil Water Reserve of the corresponding month. The month is considered wet where the wetness coefficient is greater than 0 otherwise the month is defined as dry. The results show that only the months July, August and September are wet for the 30 years past period (**Figure 40**). The monthly estimation of the recharge value for a period of30 years using Thornthwaite method shows that the main source of excess water that contributes to recharge the aquifer is the rainfall primarily the July, August and September rain.

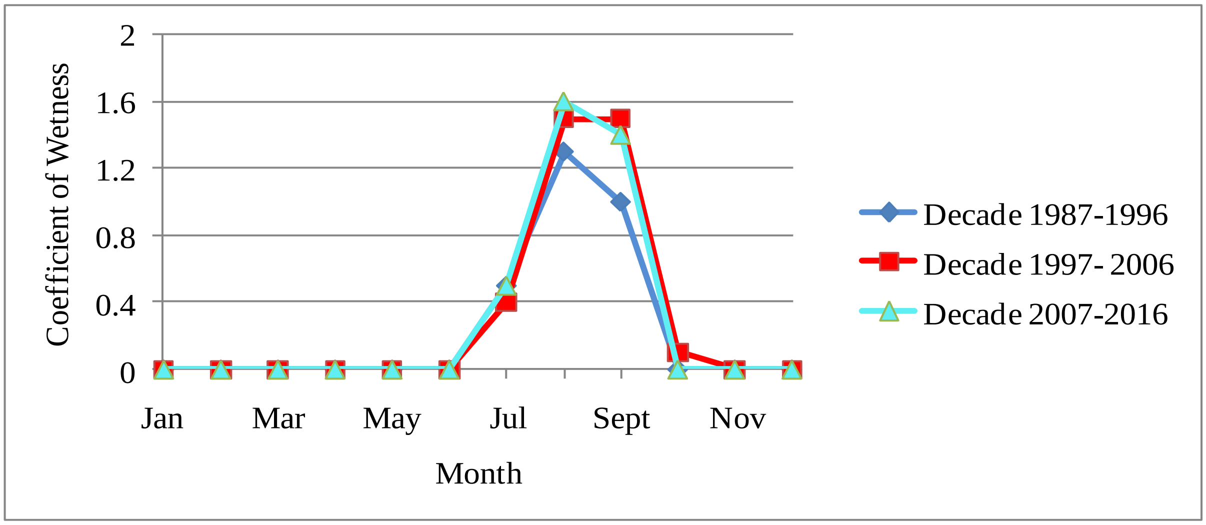


Figure 40: The coefficient of Wetness for the period 1987-2016 over Koda catchment.

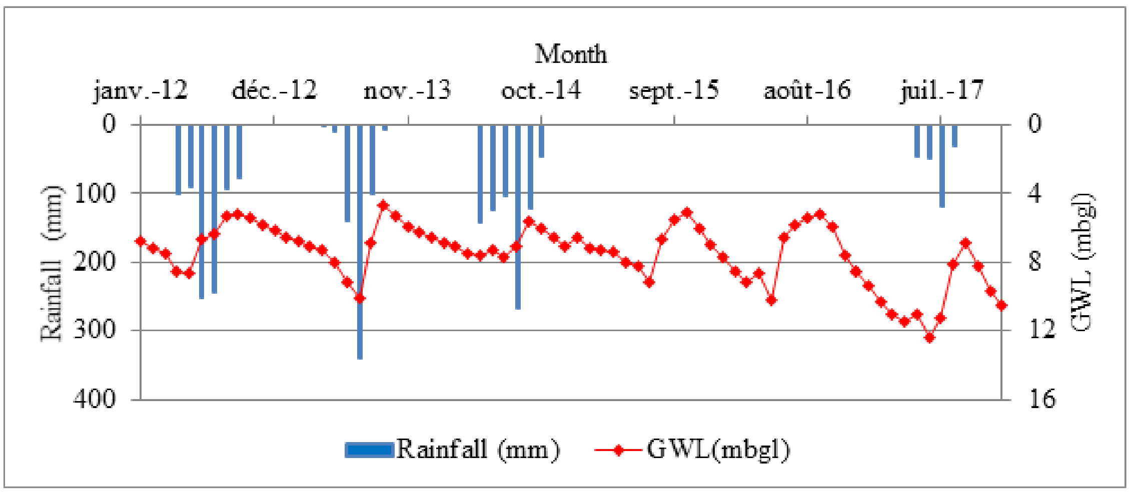
5.2. Water Table Fluctuation method

The need to study the spatio-temporal variation of groundwater in the Koda catchment using an appropriate method is needful. As infiltration plays an important role for most water budget models, it is essential to know what amount of the precipitation goes into the aquifer as recharge. In order to answer these questions, the Water Table Fluctuation (WTF) method was applied to four wells and three piezometers to characterize the recharge rate of the Koda catchment, Mali. The WTF method is widely used in groundwater recharge studies, mainly in the areas where 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 the application [Beekman and Xu, ((2003) cited in Maréchal et al. (2006)]. The method requires water level data and the specific yield to estimate the groundwater recharge. Details of the method were discussed in chapter 3.

The overall objective of the study is to evaluate the seasonal and annual variations in water level rise, characterize the groundwater recharge and to determine the percentage of rainfall that infiltrates Koda catchment. Most of this paragraph is published as Diancoumba et al. (2020).
The results obtained from Water Table Fluctuation Method are discussing below:

5.2.1. Rainfall-Infiltration Relationship

From the visual inspection of hydrographs, the water level starts rising during the rainy season implying that precipitation is the main source of groundwater recharge in the study catchment. In the three piezometers, we noticed that the groundwater level rose in July, two months after the rainy season onset (May) and decreased in October corresponding to the end of the rainy season. For more details, see Figure 41which shows the rainfall and groundwater level fluctuations of the three monitoring piezometers and the four monitoring wells.



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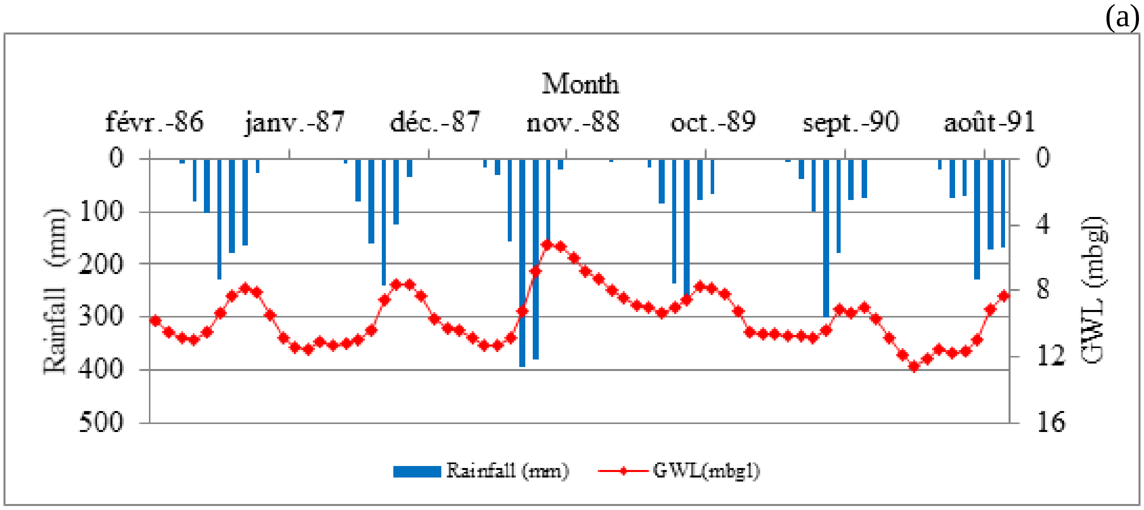

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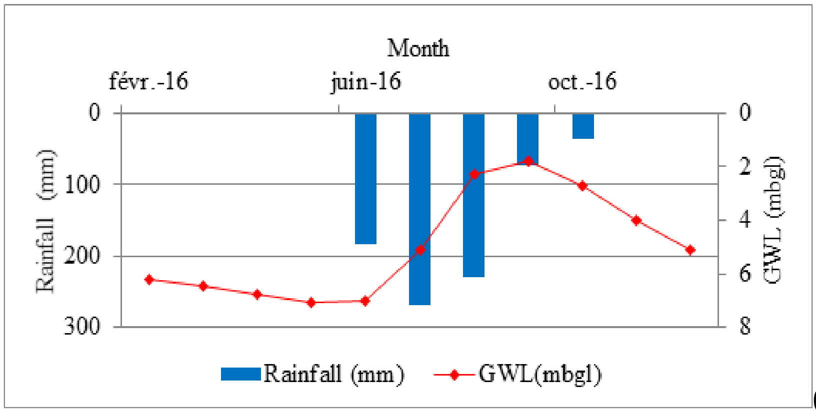

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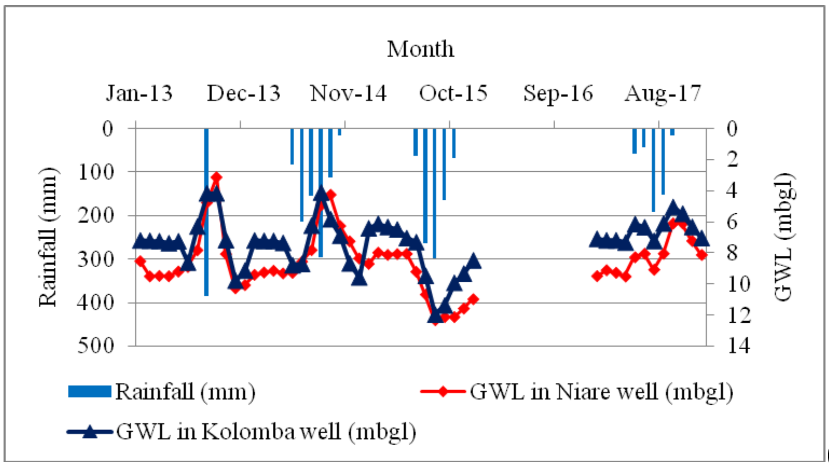

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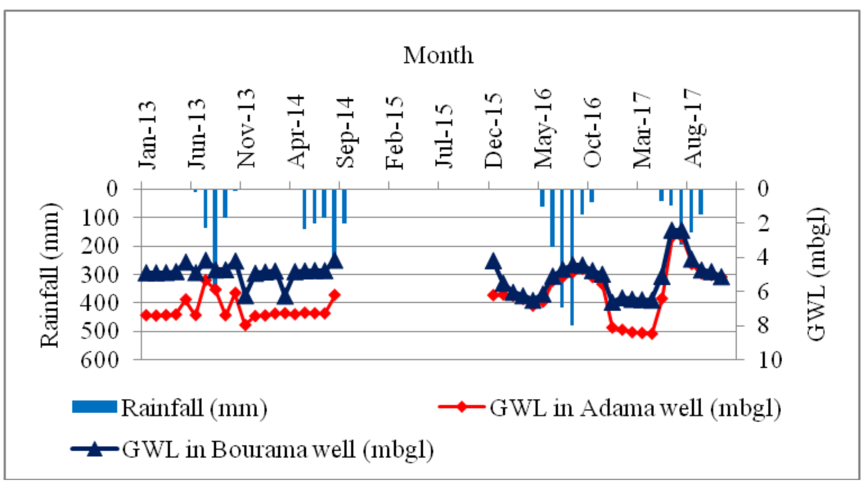


(e)

Figure 41: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) after (Diancoumba et al., 2018).

In the four wells, the rise in the groundwater level was observed at the beginning of the rainy season, which could indicate that they were located on the unsaturated (vadose) zone (with depths varying from 9 to 17m). As already indicated by many researchers cited in Kotchoni et al. (2018) we observed that, the fluctuation of water table was influenced by many phenomena apart from rainfall. The increase of gas pressure in the vadose zone, the earth tides, the pumping and the lateral flow are some of the causes of the rising level of water. The results show that recharge occurs annually in response to seasonal rainfall. The values of recharge vary from shallow to deep aquifers through wells and piezometers, respectively. The values of recharge are also varying from place to place and from year to year. These differences could be primarily due to the local climatic conditions (precipitation and temperature regimes). Other additional causes could 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 stastic level), the thickness of the aquifer, the soil and geology types, local land cover and land use activities.

5.2.2. 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 Fansiracoura F1 varied from 61 mm to 133 mm representing 8 % to 29 % respectively 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 ranged from 7% to 19 % for the period 1986 to 1991. The highest value of recharge recorded in Nossombougou N1 in the year 2016 was 223 mm (25 % of annual P) and minimum recharge was estimated to be 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 varied from 26 mm to 152 mm representing respectively 3 % to 28 % of the annual rainfall, while for Bourama well, the mean annual recharge ranged from 40 mm to 109 mm (5 % to 20% of annual rainfall). The highest value of water infiltrated in Niare and Kolomba well was recorded in the year 2013 representing 159 mm and 186 mm respectively, about 22% and 26 % of the annual rainfall. The lowest value was estimated in the year 2017 for Niare well with 80 mm (14% of annual rainfall) while for Kolomba well, the lowest amount of recharged water was 53 mm (6% of annual rainfall) in the year 2015.

These values were similar to the results obtained from previous studies undertaken in similar zones using 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 was infiltrated varied from 140-220 mm/year (10-20 % of annual rainfall) (DNHE-PNUD, 1990c). The project ARP Developement (2003) evaluated the recharge value as 15% of the annual rainfall in the southern part of Mali using the WTF. Dakoure, 2003used various methods to characterize the recharge in the southern part of Taoudeni basin where the study area is located and found recharge values of 75 - 120 mm from Thornthwaite method and 127 mm (14% of annual rainfall) from a lumped model. CIEH-USAID (1987) cited in Dakoure (2003) estimated the mean annual recharge for sandstone aquifers vary from 0 to 200 mm. Varni et al. (1999) applied the WTF method to characterize groundwater recharge in Argentina and found that minimum recharge was about 23 mm (4% of annual rainfall) and the greatest value of recharge equal to 539 mm , i.e. 33% of annual rainfall. Jassas and Merkel (2014) used the WTF to estimate the mean annual groundwater recharge of about 111.6 mm (17 % of annual Precipitation) in North Iraq under semi-arid climatic zone. Naylor et al. (2016) used 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. (2013) used 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. (2016) obtained 156.8 mm as overall mean annual recharge for the 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 by applying WTF method to characterize the groundwater recharge in the Koda catchment ranged within that interval. The results of this study are reliable because the values of the recharge are similar to the recharge values found in previous studies in the infracambrian sandstone aquifers in the arid and semi-arid regions. The values of annual rainfall, recharge and the mean annual recharge for the three piezometers and four wells are outlined in **Table28** and **Table 29** .

Table28: 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 29: Annual rainfall and calculated recharge in the four wells (Diancoumba et al., 2020).

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

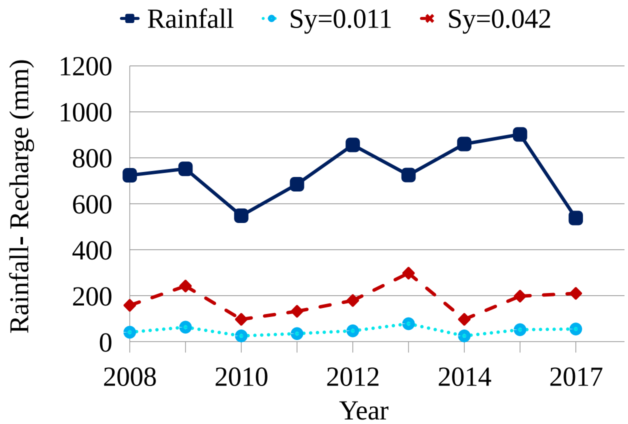
The main differences between piezometers and wells may be due to the fact that monitoring wells are located in the vadose zone where the phenomenon of evapotranspiration is occurred.

5.2.3. Magnitude of recharge

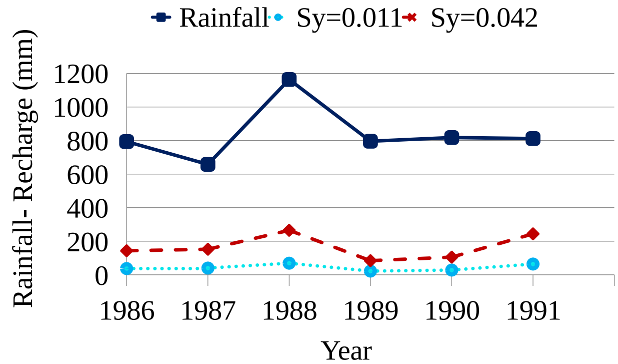
The magnitude of recharge was based on its minimum and maximum values obtained over the study area. These values of recharge obtained from the Koda catchment using WTF method ranged from 61 mm to 173 mm, i.e., 7% and 29 % of annual rainfall for the three monitoring piezometers while for the four wells,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

5.2.4. Uncertainty

The uncertainty in using the WTF method is related to the Sy values. The reliable value for a specific aquifer is difficult to find, therefore, used two values of the Specific 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 show that the uncertainty is 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 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 representing 97 mm (12% of precipitation) and 25 mm (3% of the annual rainfall) respectively which was also the minimum of the period. The mean recharge values for piezometer Fansiracoura F1 was varying from 61 mm to 133 mm representing 8 % to 29 % respectively of annual rainfall. The mean maximum value obtained in the year 2013 was 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 Precipitation) for Sy =0.011 which is also the minimum of the period. The mean values of groundwater recharge ranges from 7% to 19 % for the period 1986 to 1991. The Figure 42 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 (i.e., Figure 42 (g) in the year 2015); we observed an augmentation of the annual rainfall and the decreasing of the annual recharge that might be due to the intensity of the rainfall. Heavy rainfall tends to increase surface runoff. Additional causes are that the wells are located in the unsaturated zones and the degree of facture of the rocks. In conclusion the relationship between the recharged water and the amount of rainfall is not linear. Previous studies (e.g., ARP Developpement (2003)) proved it to be logarithmic using the WTF method in the southern part of Mali.



(a)



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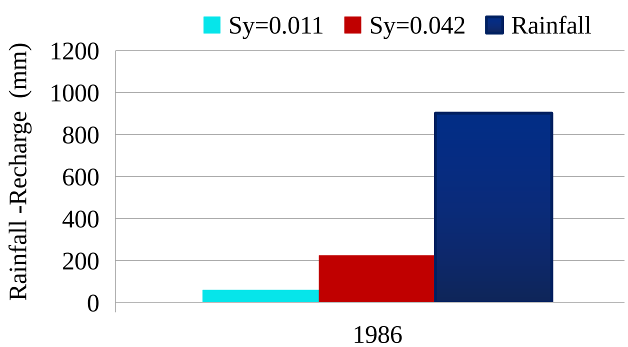

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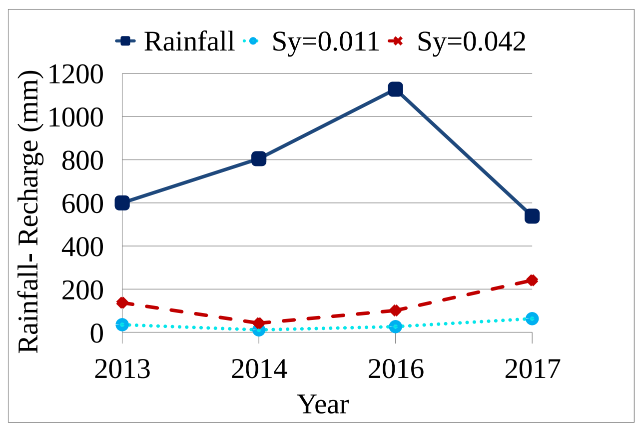

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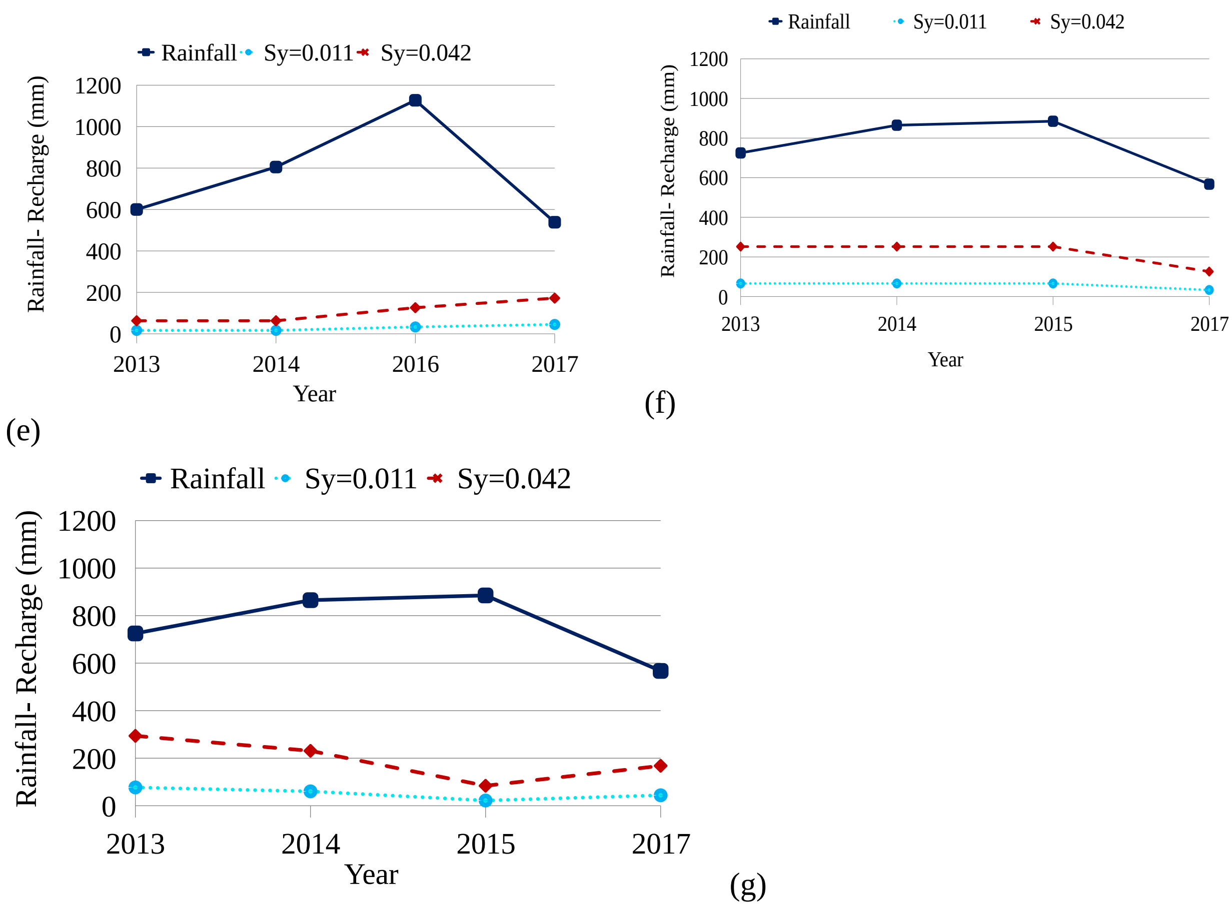


Figure 42: Annual variations in precipitation and groundwater recharge (with Sy=0.011 and Sy= 0.042) (a): Piezometer Fansiracoura F1 (2008-2017); (b). Piezometer Kossaba K1 (1986-1991), (c). Piezometer Nossombougou N1(2006);(d).Well Adama (2013-2017); (e).Well Bourama (2013-2017), (f).Well Niare (2013-2017), (g).Well Kolomba (2013-2017).

5.3. Estimation of groundwater recharge using Gardenia model

The main objective of the use of the gardenia model is to estimate the recharge for the period 1987-2016 trough a global hydrological modelling rainfall-groundwater level. All files in Gardenia are free format, they are easy to edit by the user. To support a good management system of water, hydrologic modeling of water resources is an important tool.

5.3.1. 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.

The model was calibrated on the basis of monthly time step for GWL. Three piezometer data were used for this calibration purpose. For piezometer F1, the calibration was carried out using ten years (2008-2017), 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 Nash-Sutcliffe efficiency (NSE) and the coefficient of determination – R^2, 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 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. The following figures (

Figure 43; Figure 44 and **Figure 45**) described the calibration while **Figure 46** and **Figure 47** describe validation of the various piezometers in Koda Catchment with reference to the simulated and observed groundwater levels.

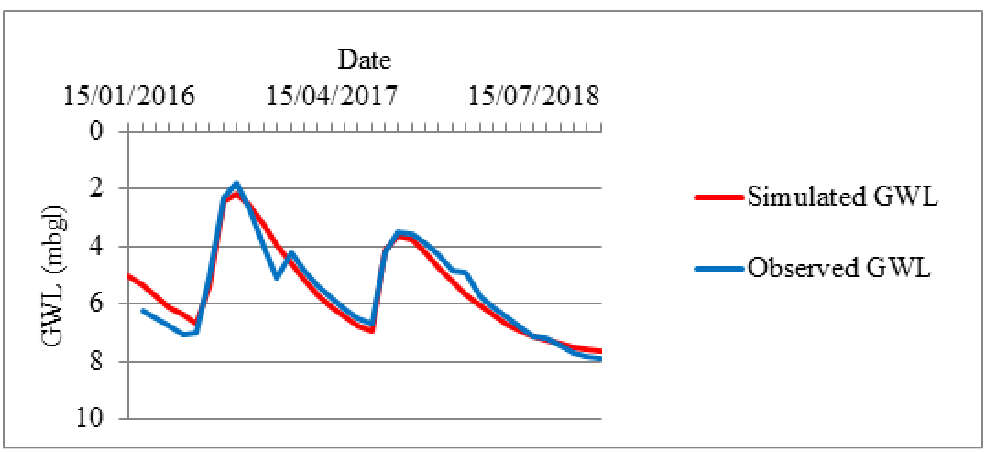


Figure 43: Calibration of Piezometer Nossombougou N1 in the Koda catchment for the period 2016-2018.

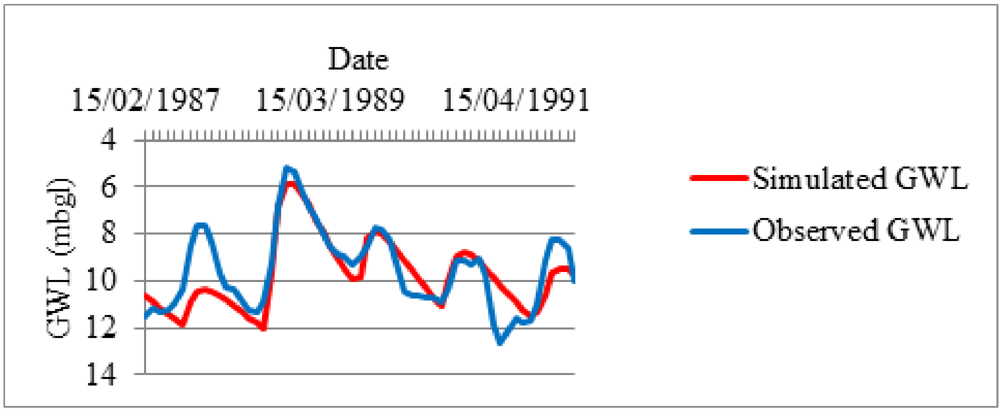


Figure 44: Calibration of Piezometer Kossaba K1 in the Koda catchment for the period 1987-1991.

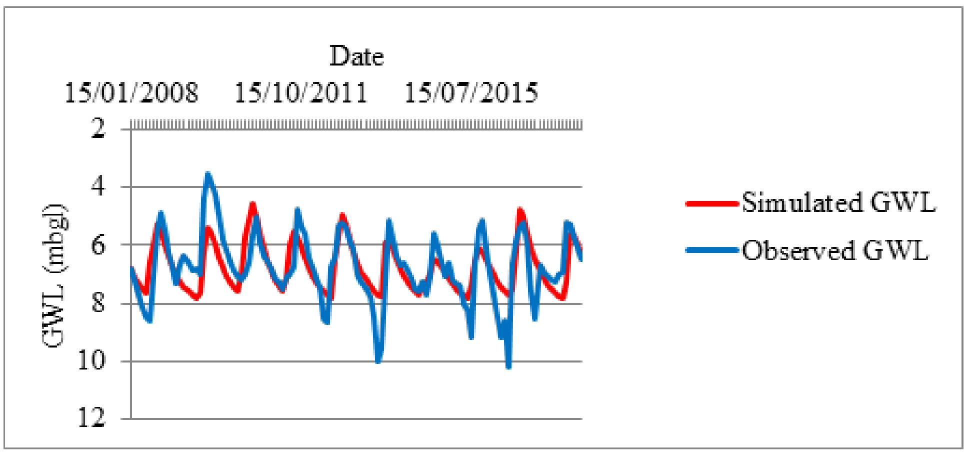


Figure 45: Calibration process Piezometer Fansiracoura F1 in the Koda catchment for the period 2008-2016

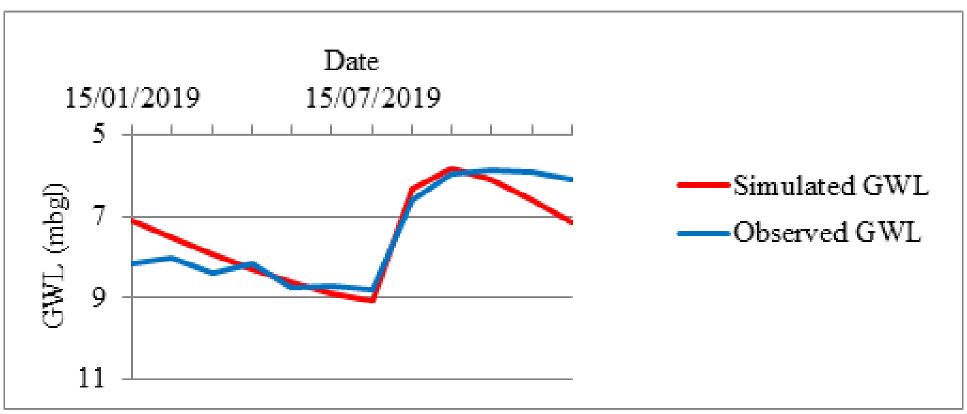


Figure 46: Validation process for the piezometer Nossombougou N1 in the Koda catchment for the year 2019.

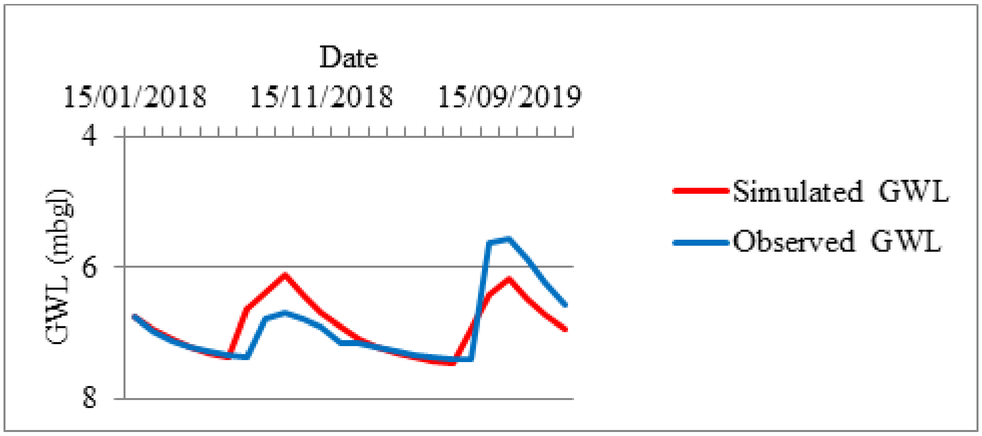


Figure 47: Validation process for the piezometer Fansiracoura F1 in the Koda catchment for the period 2018-2019.

5.3.2. Model performance evaluation

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 model performance was satisfying, and the values are outlined in **Table 30**.

Table 30: 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	-

5.3.3. Determination of water budget components of the Koda catchment

The components of water budget of the Koda catchment for the last 30 years (1987-2016) are outlined in the table 1 and the minimal, maximum and the mean annual ratio recharge over annual rainfall are shown in the **Table 31**

.

Table 31: Water balance components of the Koda catchment (1987-2016).

Piezometers	Mean annual rainfall (mm)	Effective Rainfall (mm)	AET (mm)	Runoff (mm)	Recharge (mm)	Diff stock (mm)
Fansiracoura F1	1056	380	676	260	119	0.26
Kossaba K1	1056	422	633	175	246	2.50
Nossombougou N1	1056	310	746	205	103	0.52

The mean recharge values were ranged from 10 % to 24% of the annual rainfall. Different researchers have estimated recharge of aquifers in the same region. According to Dakoure (2003), the mean annual recharge using Gardenia model of the year 1985 ranged from 125 mm to 267 mm in a sudano-sahelian basin of Burkina Faso. The project (DNHE-PNUD b, 1990) states that in the infracambrian tabular aquifers of Mali where the Koda is localed, recharge was found between 140mm and 220 mm (10 % and 20 %) using GARDENIA model for the period 1983-1985. An investigation of recharge using interpreted GRACE–derived net, estimates recharge as ranging between 8.7 % and 26.8% of rainfall for Bamako 2002-2008 located in the sudano sahelian zone like Koda (Henry, 2011). A study using a lumped model (Earth model) estimates the recharge of the Klela cathment (located in the Primary Sandstones)to be percentages of about 13.3 % - 14 % of rainfall for the period 2012-2013(Toure et al., 2016). Other researchers (Bokar et al., 2012) estimated the groundwater recharge in the infracambrian sandstones aquifers in Mali to be12 % of mean precipitation as recharge value.

Jassas and Merkel (2014) used various method to estimate recharge in the semiarid zone (North Iraq) and found it to be 17% to 24 % of annual rainfall. These values are consistent with those found in this work. The annual ratio of recharge over rainfall is outlined in **Table 32** below :

Table 32: Annual recharge/rainfall ratio (%).

Mean annual ratio recharge/rainfall (%)			
Piezometers	**Min**	**Max**	**Mean**
Fansiracoura F1	8	12	10
Kossaba K1	19	29	24
Nossombougou N1	9	31	20

5.3.4. Interaction Rainfall, GWL and Recharge at Monthly scale for the period 1987-2016

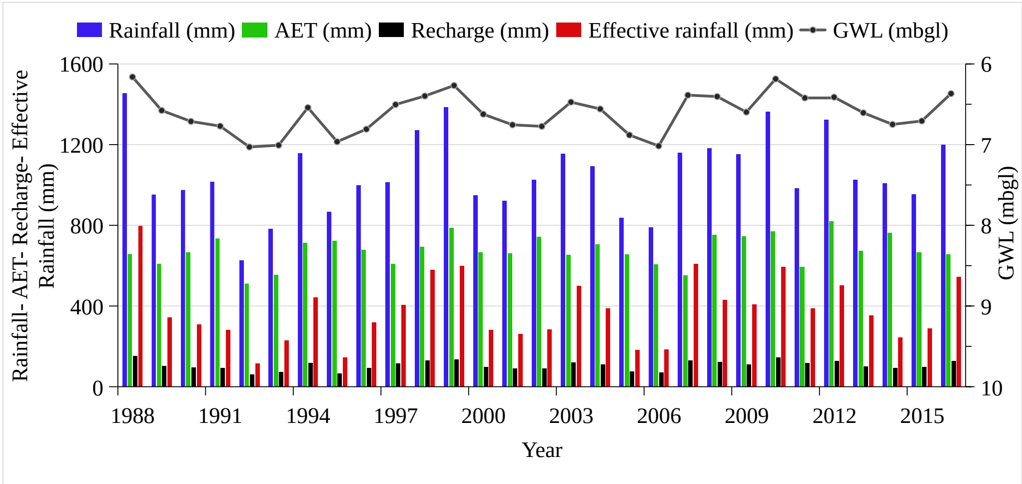
The Groundwater Level GWL and the mean monthly recharge were correlated to the rainfall; however, sometimes recharge lags behind rainfall by approximately one month. For example, the peak of recharge occurs in September while the peak of rainfall occurs in August (one month later).

The highest amounts of recharge was in July, August and September. The lowest amounts of recharge occurred from February to May. It means that it takes a significant amount of rainfall in June to infiltrate the soil and to drive the water present in the storage to the bottom layer.

5.3.4. Interaction of Rainfall-GWL-AET- Effective rainfall and Recharge at yearly scale for the period 1987-2016

The plots (**Figure 48**) showed that the GWL followed the same trend as the rainfall. Therefore, the rainfall was the main source of the groundwater recharge. The amount of the recharged water varied yearly and mainly depended on the amount of the annual rainfall. Different investigators had confirmed that hypothesis (Henry, 2011).

The highest value of the precipitation (500.4 mm)was recorded in the year 1988 while the lowest in the year 1992 over the Koda catchment. During the year 1988, with total annual rainfall of 1164.3 mm , the highest values of groundwater recharge were varied from 152 mm to 220 mm for three piezometers while the lowest values of the groundwater recharge for the year 1992, ranged from 45 mm to 141 mm. Those values were different from the percentage of precipitation (6 to 29 % of annual rainfall) and we confirm that precipitation is not the only parameter to influences the groundwater recharge. Infiltration depends on the saturation state of the soil and the stock of water before the rainfall season. The total rainfall is considered as the sum of the Effective Rainfall and the Actual Evapotranspiration (Rainfall=Eff Rainfall+ AET). The amount of the AET was estimated to be 60% to 67% of the annual rainfall. The high values of the AET were due to the high values of the temperature over the study area. The overall annual effective rainfall varied from 310 mm to 422 mm corresponding to 23 % and 40 % of the annual rainfall.represents the annual Rainfall-GWL-Recharge- Effective rainfall and AET on yearly scale for the period 1987-2016 in the three piezometers within Koda catchment.



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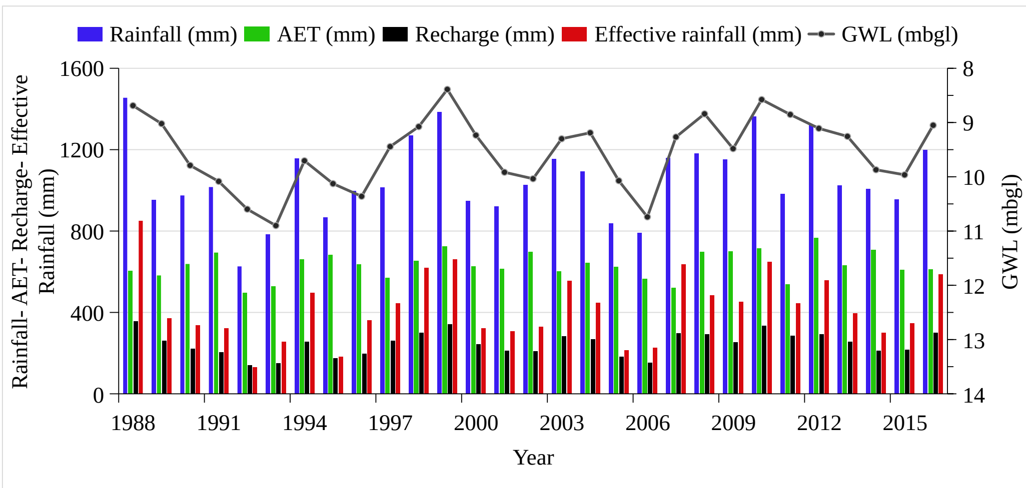

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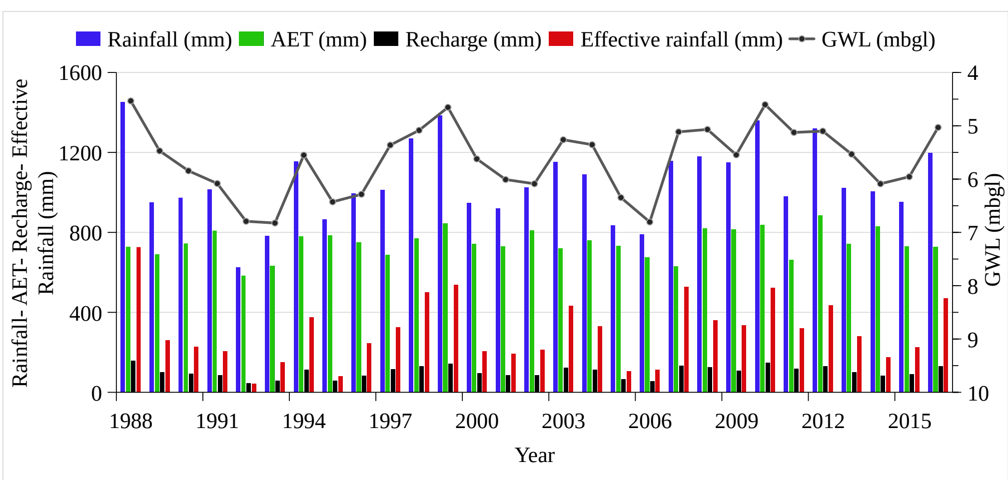


c.

Figure 48: Interaction Rainfall-GWL-Recharge- Effective rainfall and AET on a yearly scale for the period 1987-2016. a. Piezometer Fansiracoura F1, b. Kossaba K1 and c. piezometer Nossombougou N1(Diancoumba et al., 2018).

5.4. Preliminary conclusion

a) 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 to properly manage the groundwater resources in the Koda catchment where the surface water resources are scarce.

b) The combination of three methods used to estimate the accurate range of the groundwater recharge over Koda catchment permits the following conclusions which are listed below:

i. This study has shown that the Thornthwaite method is still effective in semi-arid zones. The results of the calculation of the evapotranspiration parameter are similar to previous values obtained from various methods applied to the study catchment. The application of the Thornthwaite method for a period of 30 years (1987-2016) shows that all the years' experience annual rainfall deficit. It is only during the months of July and August that effective rainfall contributes positively to groundwater recharge. The Thornthwaite method overestimates the use of soil water storage by evapotranspiration in the vadoze zone. Unfortunately, deriving a recharge value from this method requires estimates of all the components of the hydrological cycle, many of which are unavailable for the study region.

ii. The WTF method is considered as a reliable method due to its accuracy, easy to use and low cost of application in the semi-arid areas. The results obtained from this method as mean annual recharge are very similar to those found in previous studies undertaken in similar aquifers systems and under same climatic conditions. The values of recharge obtained from WTF method applied to Koda catchment ranged from 7% to 29 % of annual rainfall for the three monitoring piezometers while the mean recharge varied from 3% to 26 % of the annual precipitation. The relationship between recharge and rainfall is not linear. Ground water 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 the use of water level fluctuations, which is subjective.

c) Finally, the use of hydrologcal model showed that the simulation of piezometric levels, discharge and recharge in the period 1987-2016 from available piezometric measurements permitted the evaluation of the variability of recharge.

Recharge in the study area varied from 117 mm to 246 mm corresponding to 10% to 24

% of annual rainfall. The outputs of the model showed that, in the absence of surface flow measurements, it is not possible to estimate the storage coefficient of aquifers. The hydrogeological modelling of the Koda catchment using Gardenia model was a satisfactory tool for the calculation of the water budget components and the estimation of groundwater recharge. The results of the hydrogeological modellling of the Koda catchment in the steady state seem good and ranged with those values found in similar hydrogeologic regions. The values of Thornthwaite method (1 % - 8 %) are bit below those obatained from WTF and Gardenia model. The results of the Water Table Fluctution methods (7% -29 %) and those from the Gardenia model (10 % -24 %) were very close and they could be used as an accurate range of the groundwater recharge characterizing the studied catcthment.

Chapter 6: Simulation of groundwater flow over Koda catchment

The valuable and most widely distributed natural water resource on the earth is groundwater (Pathak et *al*.,2018). It is used for water supply and irrigation in semi-arid regions. To develop and well manage water supply system in the context of climate change in the Sahel where rainfall is projected to be reduced, groundwater modeling plays an important role. Nowadays, many groundwater models have been made available which make the groundwater modeling as a standard and powerful tool for hydrogeologists to effectively perform various tasks including the assessment and prediction of groundwater, the detection of groundwater pollution, etc. (Pathak et al., 2018 and Namitha et al., 2019). Groundwater flow have been used diversely under different geological and climatic conditions around the world (Yang et al., 2011; Ginaya et al., 2013; Pande, 2016; Namitha et al., 2019).

Historical and current field hydrogeological, geological, topographical, climatic data are required and were used as model inputs. Another most important input parameter of the model is groundwater recharge, which was found to be 17% of annual precipitation based on the lumped Gardenia model applied in the study area (Diancoumba et al., 2018). The Visual Modflow model domain was discretized into grids (50 columns, 50 rows) with a total grid cell number of 2500. The grid dimension is 300m*300 m. Digital Elevation Model (DEM) from Hydroshed was used to interpolate hydraulic head through the study catchment scale, which was entered to the model as starting hydraulic head. The boundary conditions were set as a no-flow boundary. The groundwater flow of the Koda catchment was simulated under steady state and the results are outlined below:

6.1. Calibration purpose

The hydraulic conductivity (K) was used to calibrate the Precambrian sandstones aquifer in the study area under the steady state conditions. The simulations under the steady state conditions are used to model equilibrium conditions, the changes in groundwater storage are insignificant (Middlemis, 2001). The model was running under steady state with 21767 days (from 27/5/1960 to 31/12/2019) as time of reference. After development and calibration of the model through 12 boreholes data (Figure 49) using trial and error estimation of hydraulic head, the results of model evaluation are shown in the **Table 33**.

Table 33: Model evaluation results, R^2 correlation coefficient; RMSE, Root mean square error; Normalized RMS and Standard Error of the Estimate

Coefficient of correlation R^2	Root Mean Square	Normalized RMS	Standard Error of the Estimate
0.98	3.75 m	4.69 %	1.08 m

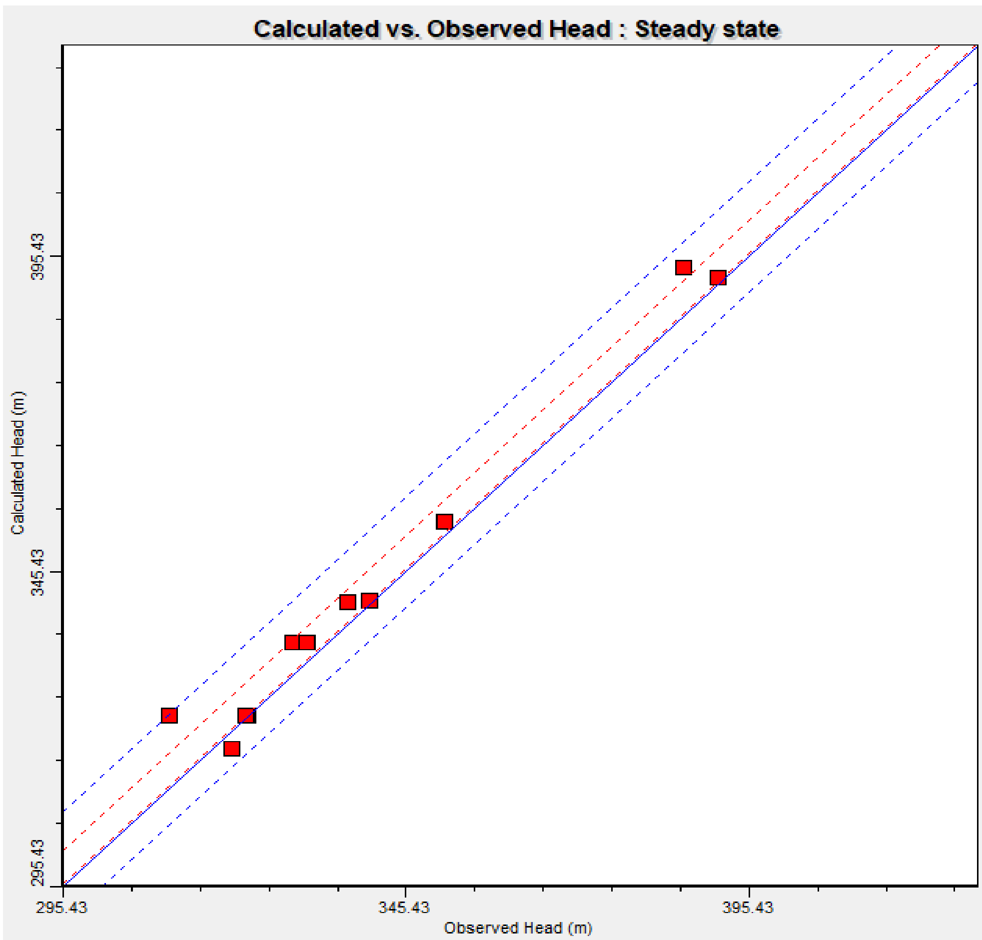


Figure 49: Calculated vs Observation head under steady state conditions in the Koda Catchment, (Diancoumba et al., 2019).

6.2. Hydraulic head

As the data are not well distributed through the study area the steady state has been used to obtain the hydraulic head values which will be used in transient simulation as starting heads seven zones of hydraulic head characterize the study area and these values vary from 310.5 m to 400.4m. The highest values are observed in the northern part of the Koda catchment while the lowest values are located in the other parts of the catchment. The hydraulic heads decrease from the North to the South. Therefore, groundwater flow direction is SW-NE (**Figure 50**).

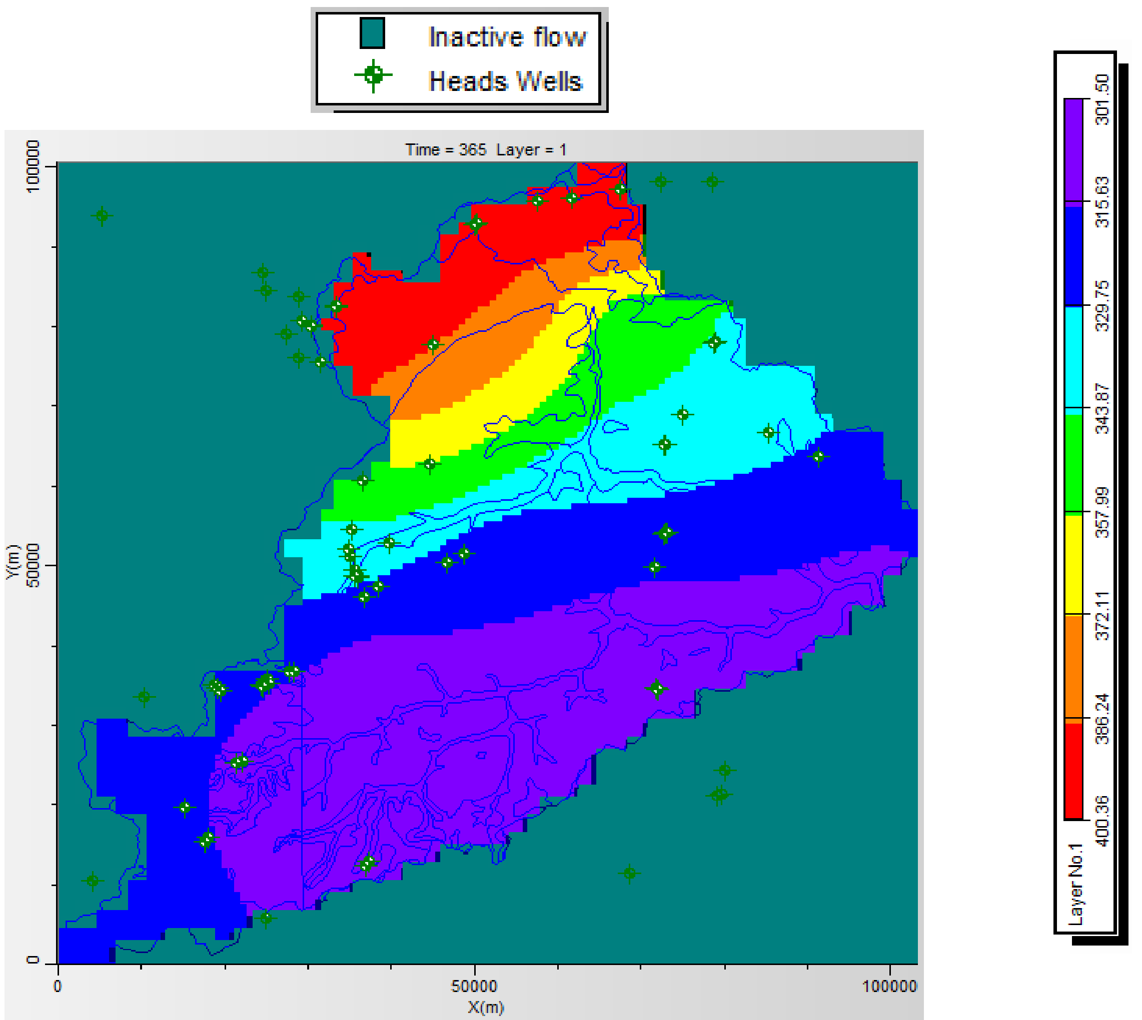


Figure 50: Hydraulic head zones of the Koda catchment in meters (Diancoumba et al., 2019)

6.3. Hydraulic conductivity (K)

The values of K ranged from 4.9 10 $^{-5}$ m/s to 11 10 $^{-2}$ m/s within five zones where the conductivity is homogenous and isotropic (**Table 34).**

The value of K of the sandstones is greater than the other parts of the catchment. Two types of permeabilities characterized the catchment, the rapid variation of the permeability in the sandstones and the slow to moderate permeability due to the fissures in the dolerites (HK2) in the western part of the catchment (**Figure 51**).

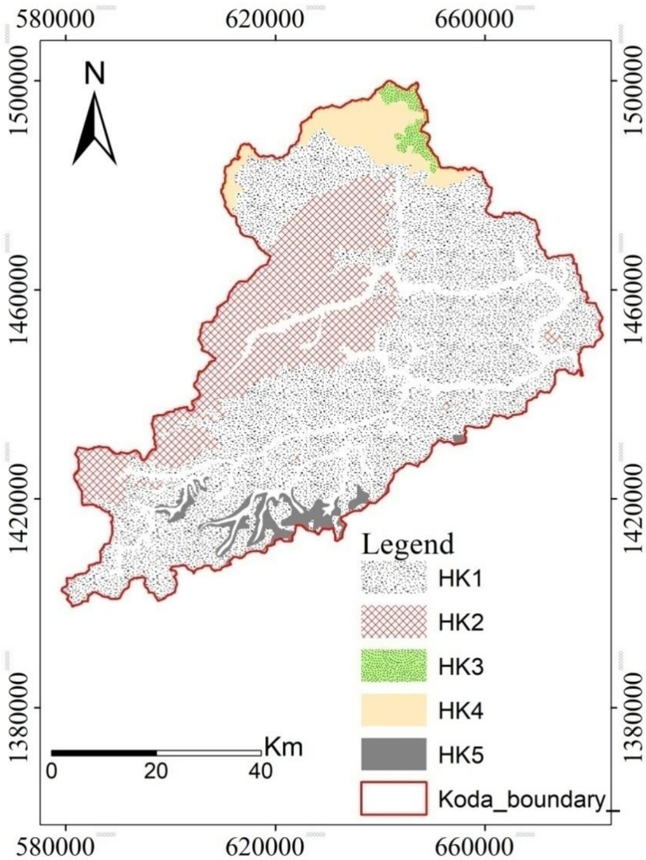


Figure 51: Hydraulic conductivity zones of the Koda catchment

Table 34: Values of hydraulic conductivity of the Koda catchment

Zone 1 HK1	Zone 2 HK2	Zone 3 HK3	Zone 4 HK4	Zone 5 HK5
17 10^{-4} m/s	1.2 10^{-4}m/s	1.1 10^{-3}m/s	11 10^{-2}m/s	4.9 10^{-5}m/s

6.4.Conclusion

Visual Modflow has been calibrated under steady state condition. The model was calibrated with 0.98 as coefficient of correlation (R^2) between observed and simulated head.

The values of hydrodynamic parameters of the aquifer (Hydraulic conductivity, storage coefficient, heterogeneity and transmissivity) will be used to run the Gardenia model in transient flow for Climate Impacts study.

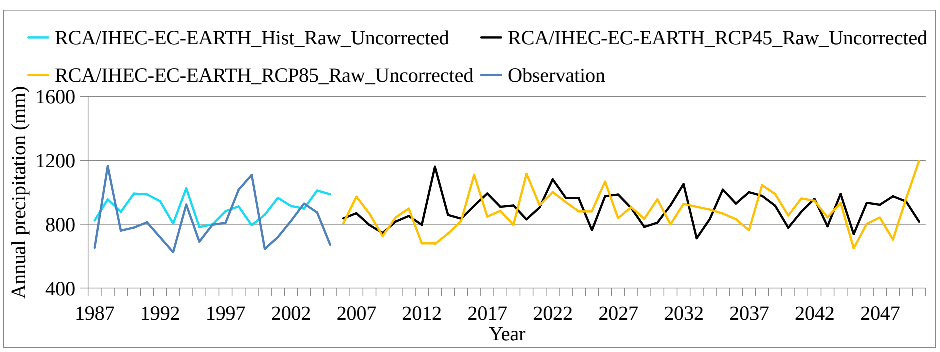
The piezometers within the basin are not well spatially distributed thus it is recommended to implement more piezometers with automatic data loggers which are easy to use, the measurements are accurate, and they are low of a price. The Koda catchment is an ungauging basin which was a real handicap in the choice of some robust hydrological model which required discharge data as imput therefore the authorities should think to make Koda catchment as gauged basin. An accurate data about the quantity of water which is draw from the aquifer system is unkown, some actions must be done about that issue. The future studies should concentrate on studying the dynamics (simulation of groundwater flow under transient state) of the studying catchment by using Visual modflow.

Chapter 7: Projected changes in precipitation and temperature over Koda catchment

The analysis of the projected changes in rainfall and temperature patterns over the Koda catchment for the period 2021-2050 has been completed in this chapter. The bias correction of the future datasets used in this study and the performance analysis of the modeled climate time series are presented and discussed.

7.1. Bias correction

For instance, the overall annual average rainfall obtained from one RCM (RCA /IHEC-EC-EARTH, Scenario 45 and scenario 85), with and without bias correction, is presented in the **Figure 52**. The historical period is ranged from 1987 to 2005 and the projected period is from 2006 to 2050. From the visual interpretation, the data before bias correction is not following the same trend as the data after the bias correction. To investigate more about the advantage of bias correction, the simulated model performance has been studied.



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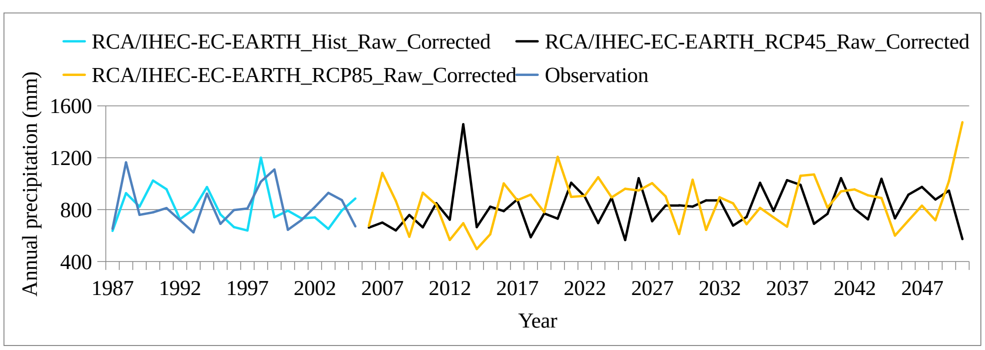


b.

Figure 52: Annual Precipitation for the historical period 1987-2005 and the projected period from 2006-2050 for RCA/IHEC-EC-EARTH against Observed values recorded at Katibougou station a. before Bias Correction and b. Bias Corrected.

7.2. Simulated Model performance evaluation

Assessing the performance of the simulated models is a necessary step for model projections. The demonstration of the importance of the bias correction of RCM data for the use in Climate Change Impact Studies (CCIS) is also needed. For that, the performance of the individual RCMs in simulating the historical period (1987-2005) of rainfall and temperatures of the Koda catchment was evaluated. The comparison among the RCMs for the historical period from 1987 to 2005 has been made and also the comparison between monthly rainfall and temperature of the model-simulated uncorrected, model-simulated bias-corrected and observed data for the Katibougou climate station has been done. The statistical parameters such as R^2, NASH and RMSE between Uncorrected –Observed- Corrected have been calculated and the results are outlined in **Table 35** and **Table 36** describe the sensitivity parameters of the two RCMs RCA4 and CCLM4 respectively. Both RCMs were simulated by the three driving GCMs (IHEC-EC-EARTH, MOHC –HadGEM2-ES and MPI-M-MPI-ESM-LR).

The coefficient of correlation R^2, the NSE and the Root Mean Square Error were calculated to evaluate the performance of the model and the details of these statistical parameters are described in Chapter 3.

The best correlation coefficient R^2 in the rainfall data was obtained while the satisfactory performance values of NSE and RMSE coefficients were obtained from the output of the corrected temperature series of the RCM _RCA4.

For example, the modeled rainfall from the RCA4 by the driving IHEC-EC-EARTH gives R^2 values ranging from 0.76 to 0.8 while the NASH coefficient varied from 0.52 to 0.55 with the minimum RMSE of 0.92 and the maximum of 1.08. The modeled maximum temperature fitted the observed values with the values of R^2 ranging from 0.68 to 0.8, 0.23 to 0.55 for NASH coefficient and 0.06 and 0.23 for the RMSE. The output of the minimum temperature presented the R^2 parameter between 0.85 and 0.88. Nash values were between 0.54 and 0.76 with 0.09 and 0.17 as the range of the RMSE (**Table 35**). The RCA4 by the driving GCM-HadGEM-MOHC shows the unsatisfactory performance of NSE and RMSE with regards to the correlation coefficients. Furthermore, the output of the RCM CCLM4 by HadGEM-MOHC has shown the poor correlation between the modeled and observed climate time series data.

The statistical parameters between the historical data and the observed data recorded at Katibougou station were calculated in order to select the best set of RCMs with best correlation parameters. Therefore, RCA4 and CCLM4 by the two driving GCMs (IHEC-EC-EARTH and MPI-M-MPI-ESM-LR) have been seen to show very good performance between the modeled and the observed climate time series data (**Figure 53**).

Table 35: Performance evaluation of uncorrected and bias corrected RCA4 model simulations of historical (1987-2005) temperature and rainfall of Koda Catchment.

GCMs	Parameter	RCP	Correction	R^2	NSE	RMSE
			Uncorrected	0.76	0.55	0.9 3
		4.5	Corrected	0.80	0.56	0.92
			Uncorrected	0.76	0.55	0.93
EC-EARTH	Rainfall	8.5	Corrected	0.79	0.52	0.96
			Uncorrected	0.70	0.39	1.08
		4.5	Corrected	0.75	0.30	1.16
			Uncorrected	0.70	0.39	1.08
MOHC	Rainfall	8.5	Corrected	0.74	0.29	1.17
			Uncorrected	0.80	0.59	0.89
		4.5	Corrected	0.78	0.50	0.98
			Uncorrected	0.80	0.59	0.89
M-MPI	Rainfall	8.5	Corrected	0.81	0.56	0.92
			Uncorrected	0.68	0.23	0.08
		4.5	Corrected	0.80	0.55	0.06
			Uncorrected	0.68	0.23	0.23
EC-EARTH	Tmax	8.5	Corrected	0.81	0.56	0.06
			Uncorrected	0.55	0.17	0.08
		4.5	Corrected	0.76	0.47	0.07
			Uncorrected	0.55	0.47	0.07
MOHC	Tmax	8.5	Corrected	0.76	0.48	0.06
			Uncorrected	0.71	0.45	0.07
		4.5	Corrected	0.78	0.53	0.06
			Uncorrected	0.71	0.45	0.07
M-MPI	Tmax	8.5	Corrected	0.78	0.53	0.06
			Uncorrected	0.82	0.24	0.17
		4.5	Corrected	0.88	0.76	0.09
			Uncorrected	0.82	0.24	0.17
EC-EARTH	Tmin	8.5	Corrected	0.88	0.77	0.09

GCMs	Parameters	RCP	Correction	R^2	NSE	RMSE
MOHC	Tmin	4.5	Uncorrected	0.85	0.54	0.13
			Corrected	0.87	0.74	0.10
		8.5	Uncorrected	0.85	0.54	0.13
			Corrected	0.87	0.74	0.10
M-MPI	Tmin	4.5	Uncorrected	0.73	0.30	0.16
			Corrected	0.72	0.45	0.14
		8.5	Uncorrected	0.83	0.48	0.14
			Corrected	0.89	0.78	0.09

Table 36: Performance evaluation of uncorrected and bias-corrected CCLM4 model simulations of historical (1987-2005) temperature and rainfall of Koda Catchment.

GCMs	Parameter	RCP	Correction	R^2	NSE	RMSE
EC-EARTH	Rainfall	4.5	Uncorrected	0.40	0.23	82.54
			Corrected	0.38	0.00	93.59
		8.5	Uncorrected	0.38	0.00	93.59
			Corrected	0.32	-0.39	110.63
MOHC	Rainfall	4.5	Uncorrected	0.15	-2.84	183.71
			Corrected	0.20	-2.75	181.55
		8.5	Uncorrected	0.14	-2.88	184.68
			Corrected	0.19	-2.79	182.56
MPI	Rainfall	4.5	Uncorrected	0.33	-0.17	101.30
			Corrected	0.31	-0.06	96.54
		8.5	Uncorrected	0.32	-0.22	103.46
			Corrected	0.30	-0.18	101.72
EC-EARTH	Tmax	4.5	Uncorrected	0.46	-1.38	4.74
			Corrected	0.40	0.16	2.82
		8.5	Uncorrected	0.47	-1.53	4.89
			Corrected	0.36	0.16	2.82
MOHC	Tmax	4.5	Uncorrected	0.60	-0.30	3.51
			Corrected	0.60	0.51	2.14
		8.5	Uncorrected	0.17	-6.38	8.35
			Corrected	0.08	-5.51	7.84
MPI	Tmax	4.5	Uncorrected	0.37	-1.20	4.56
			Corrected	0.36	0.14	2.85
		8.5	Uncorrected	0.37	-1.17	4.53
			Corrected	0.38	0.18	2.78

GCMs	Parameters	Correction	R^2	NSE	RMSE	
			Uncorrected	0.42	0.33	3.32
		4.5	Corrected	0.51	0.42	3.08
			Uncorrected	0.46	0.29	3.42
EC-EARTH	Tmin	8.5	Corrected	0.47	0.37	3.20
			Uncorrected	0.23	-2.05	7.07
		4.5	Corrected	0.26	-1.84	6.82
			Uncorrected	0.23	-2.05	7.07
MOHC	Tmin	8.5	Corrected	0.76	0.75	2.04
			Uncorrected	0.43	0.22	3.58
		4.5	Corrected	0.51	0.41	3.11
			Uncorrected	0.43	0.22	3.57
M-MPI	Tmin	8.5	Corrected	0.53	0.44	3.03

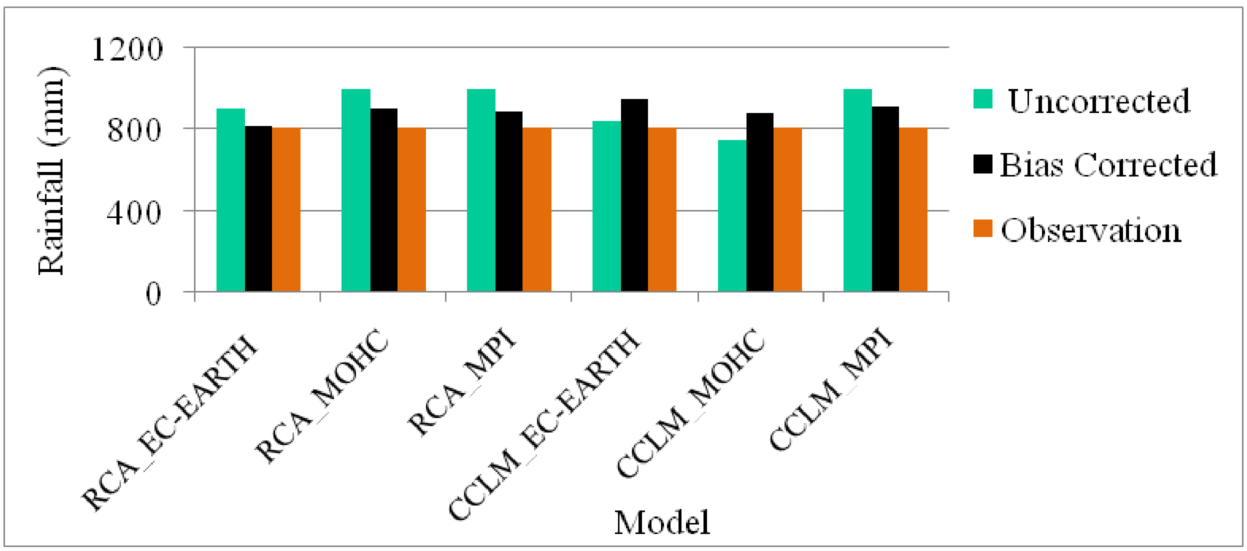
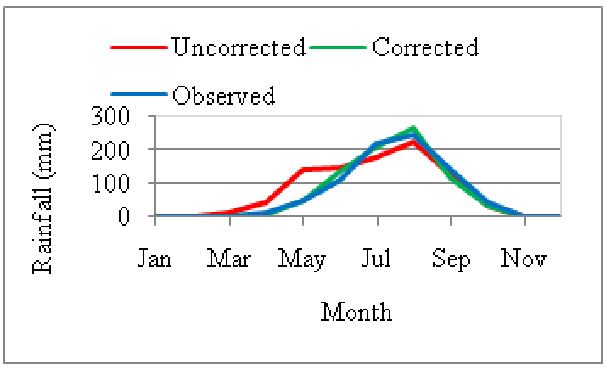


Figure 53: Model performance on mean annual rainfall from1987-2005, from the RCA4 and CCLM4 by the driving EC-EARTH, MOHC and MPI- M-MPI of model-simulated uncorrected and bias-corrected vs historical data of the Koda catchment

7.3. Assessment of model-simulated uncorrected and bias-corrected vs historical data of the Koda catchment for the period 1987-2005

In order to show the importance of bias correction as applied to the RCM data for the direct use in Climate Change Impacts Studies CCIS, plots of monthly rainfall and temperatures of the model-simulated uncorrected, model-simulated bias-corrected and observed data were constructed for the Katibougou climate station (**Figure 54**). The aim is to know which RCM dataset by driving GCM fits more closely to the reality (observations). The analysis included the comparison of observed and modeled precipitation and the temperature datasets with and without bias correction at monthly scale. The results show clearly that precipitation and temperature bias corrected data matches better with the observed data than the uncorrected bias from the model outputs.

The uncorrected output from the model RCA4 by the driving IHEC-EC-EARTH underestimated the rainfall, while the CCLM4 by the driving and MPI-M-MPI-ESM-LR overestimated of peak rainfall of the uncorrected RCM projection data.



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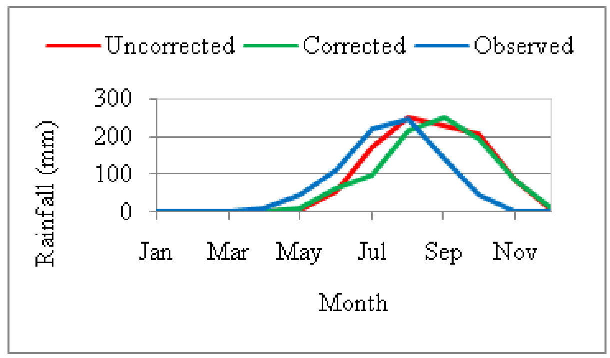

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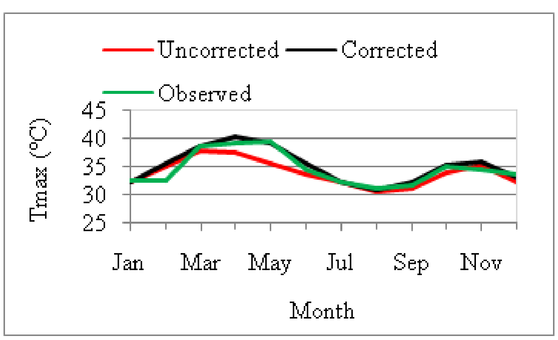
Figure 54: Mean monthly sum of precipitation for the period 1987-2005 for a. RCA4/IHEC-EC-EARTH and b.CCLM4/MPI-M-MPI-ESM-LR. The uncorrected temperature output from RCA4/MPI-M-MPI-ESM-LR and CCLM4/IHEC-EC-EARTH showed an underestimation of maximum and minimum temperature (**Figure 55** and **Figure 56).**



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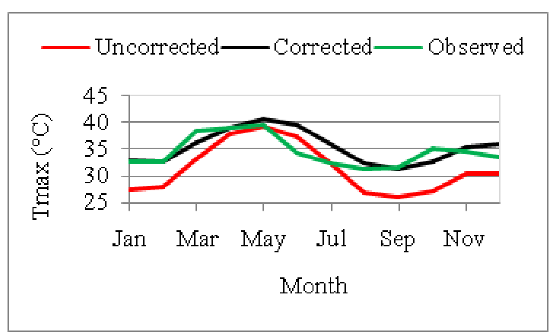

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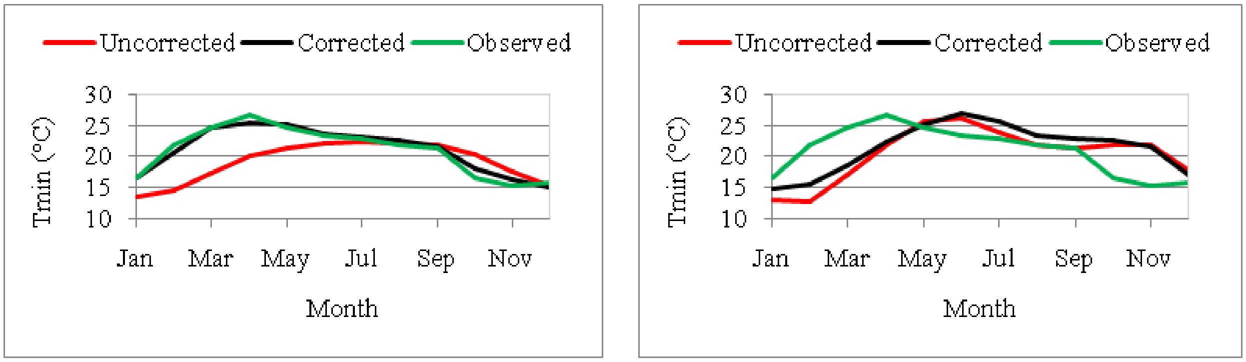
Figure 55: Mean monthly sum of Tmax for the period 1987-2005; a. RCA4/MPI-M-MPI-ESM-LR and b.CCLM4/IHEC-EC-EARTH



a.

b.

Figure 56: Mean monthly sum of Tmin for the period 1987-2005 for driver models; a. RCA4/MPI-M-MPI-ESM-LR and b.CCLM4/IHEC-EC-EARTH

The results of the computed mean and standard deviation for the selected station of Katibougou proved further that the corrected data was much closer to the observed data than the uncorrected data was (**Table 37**). The direct use of the output of the RCM data without bias correction may lead to wrong climate change projections.

Table 37: Analysis of uncorrected and bias-corrected RCM model simulations of historical (1987-2005) temperature and rainfall of the Koda catchment.

Variable	RCM	Mean (1987-2005)			Stantard Deviation		
		Uncorrected	Corrected	Observed	Uncorrected	Corrected	Observed
Rainfall (mm)	RCA/EC-EARTH	906.0	814.5	812.5	81.3	92.3	89.1
	CCLM4/M-MPI	998.6	912.8	812.5	100.9	89.1	93.6
Tmax (°C)	RCA/EC-EARTH	34.0	35.1	34.6	2.3	2.9	3.0
	CCLM4/M-MPI	31.3	35.3	34.6	4.6	2.9	3.1
Tmin (°C)	RCA/EC-EARTH	19.0	21.0	20.9	3.3	4.0	3.7
	CCLM4/M-MPI	20.4	21.3	20.9	4.4	4.0	4.0

7.4. Projected Changes in Climate Time series (Precipitation and Temperature) over Koda Catchment

7.4.1. Observed historical period 1987-2016

Results of the historical simulation of rainfall over the Koda catchment by the two RCMs (RCA4 and CCLM4) by two driving GCMs (ICHEC-EC-EARTH and MPI-M-MPI-ESM-LR) and their ensemble mean are presented in **Figure 57**. The intra-annual rainfall plots show that the RCA4/ ICHEC-EC-EARTH and RCA4/MPI-M-MPI-ESM-LR captured well the rainfall pattern of the studied catchment, with the peak of the rainfall in August. In contrast to the other 2 models, CCLM4/ICHEC-EC-EARTH and CCLM44/MPI-M-MPI-ESM-LR have the maximum value in September. The simulated rainfall from RCA fitted much better to the observed than that by the CCLM 4 models (**Figure 57)**. Historical temperature simulations by the RCMs are exhibited in Figure 58. The output of RCM RCA4 by the driving ICHEC-EC-EARTH and MPI-M-MPI-ESM-LR estimated the historical Tmax and Tmin of the catchment show the same peaks and trends. The RCM CCLM4/ICHEC-EC-EARTH and CCLM4/MPI-M-MPI-ESM-LR overestimated the average maximum temperature for the months from April-August while the minimum temperature has been overestimated from May-December (**Figure 58**).

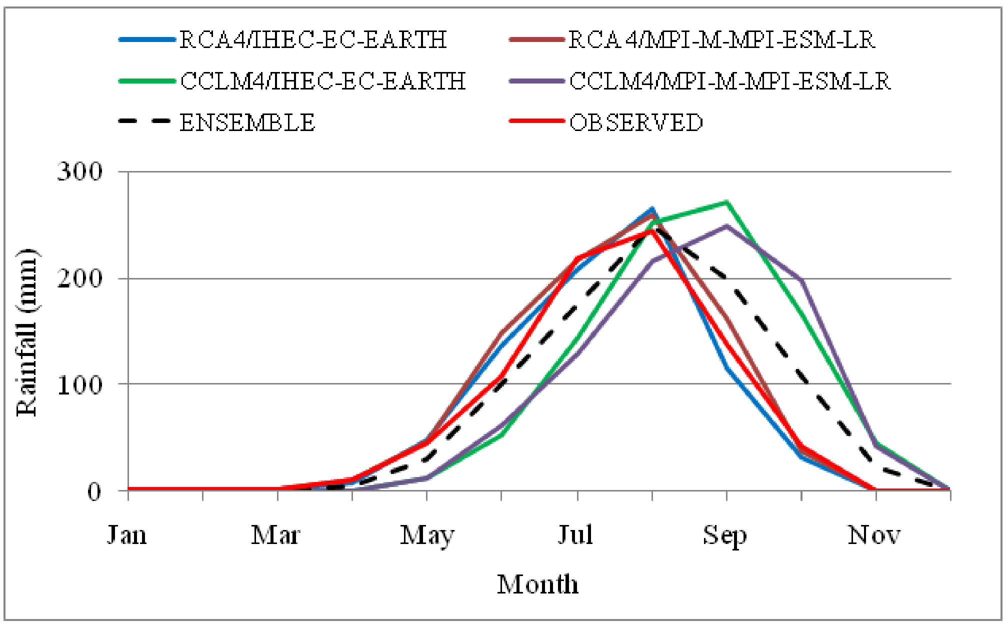


Figure 57: Observed and simulated monthly rainfall over the Koda catchment from 1987 to 2016

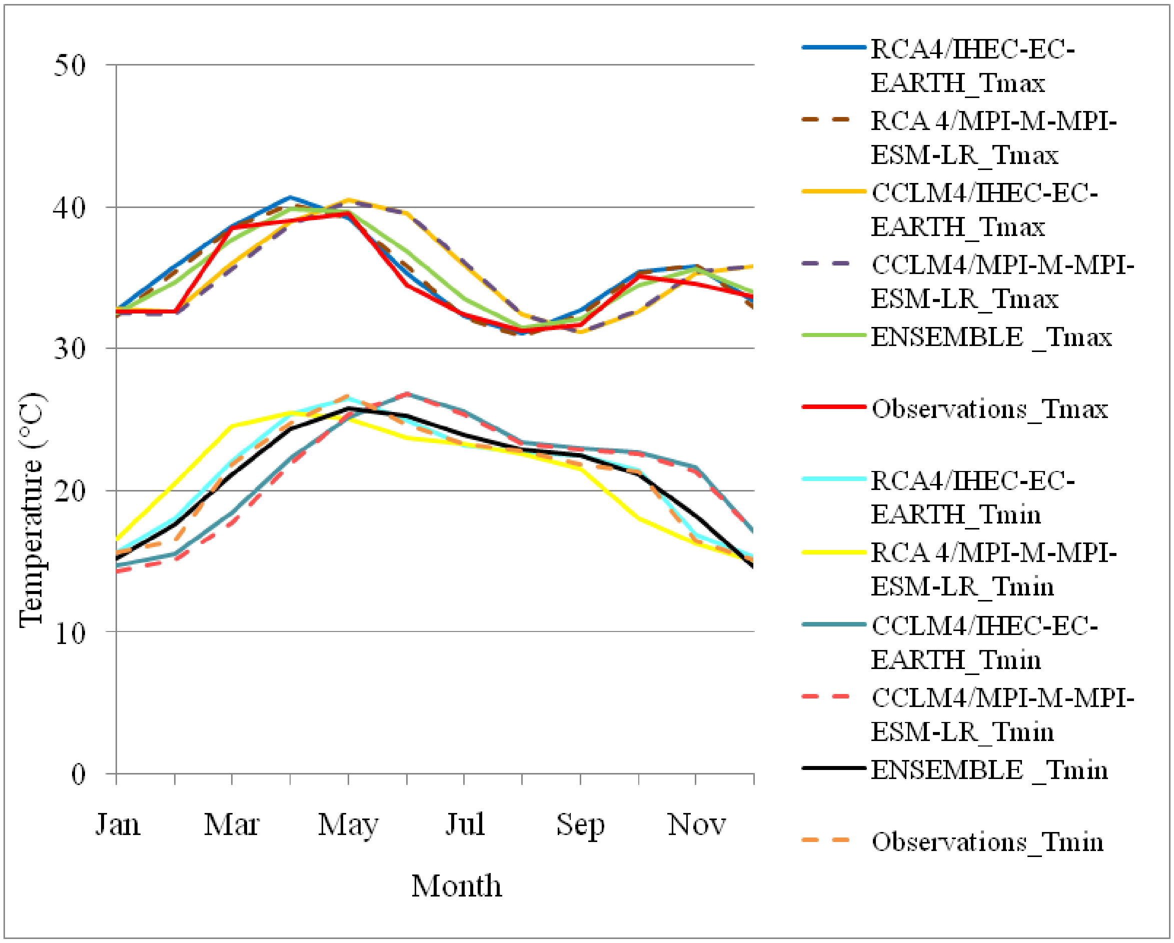


Figure 58: Observed and simulated monthly maximum and minimum temperature (tmax and tmin respectively) over the Koda catchment from observed historical period 1987–2016

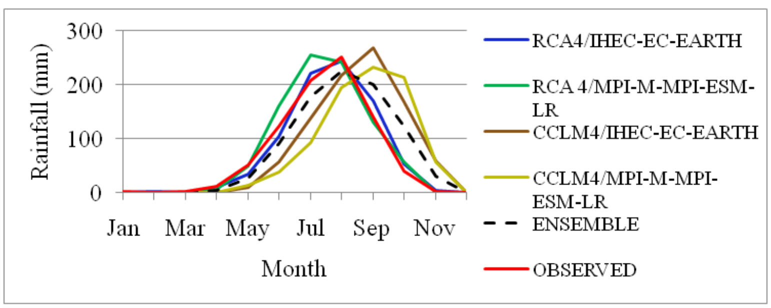
7.4.2. Projected changes in rainfall over the Koda catchment for the period 2021-2050.

The average of annual rainfall over the interested catchment has been analyzed and the results are outlined in the **Table 38** and **Figure 59**. The level of uncertainties associated with increase and decrease in rainfall amounts through the models. The RCA predicted increase of rainfall of 1.5% and 8.1% for RCP 4.5 and 6 % and 25.3% for RCP 8.5 while the RCM-CCLM predicted a rising of rainfall amount up to 1.7 % and 10.1 % for RCP 4.5 and -0.10% and 14.62 % for the RCP 8.5. For the scenario 4.5, the overall mean of all models projected an increase of 5.4 % from the baseline (1987-2016) and the change is more significant for the scenario 8.5 (11.47%) shown in **Table 38**.

Table 38: Projected changes in rainfall for the period 2021-2050 in the Koda Catchment under RCPs 4.5 and 8.5.

RCMs	Baseline 1987-2016 observed rainfall mean value (mm)	Projected period 2021-2050			
		Scenario 45		Scenario 85	
		Average (mm)	% Change	Average (mm)	% Change
RCA_EC-EARTH		845.9	1.5	1043.9	25.29
RCA_MPI		900.5	8.1	883.6	6.05
CCLM_EC-EARTH		917.5	10.1	832.3	-0.10
CCLM_MPI		847.2	1.7	954.9	14.62
ENSEMBLE	833.1	877.0	5.4	928.7	11.47

Figure 59 describes the mean monthly rainfall from different RCM/GCM pairs for the period 2021-2050 and observed mean rainfall recorded at Katibougou station for the period 1987-2016.



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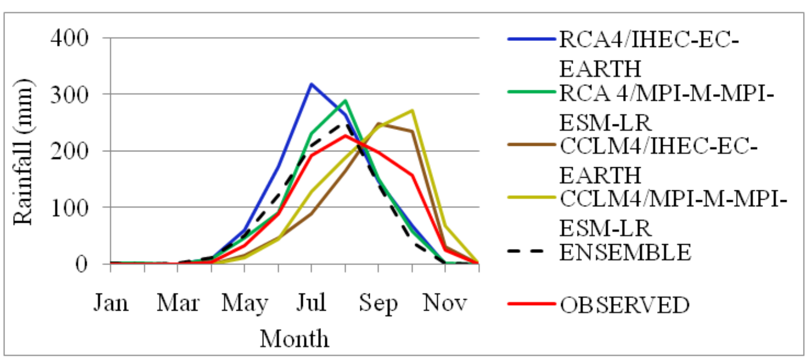


b.

Figure 59: Observed (1987-2016) and projected (2021-2050) monthly rainfall under a. RCP 4.5 Scenario and b.RCP 8.5 Scenario

7.4.3. Projected changes in Temperature (Tmax and Tmin) over the Koda catchment for the period 2021-2050

The results of the analysis of the projected data chiefly show an increase in temperatures (maximum and minimum) for the Koda catchment (**Table 39** and **Table 40**).

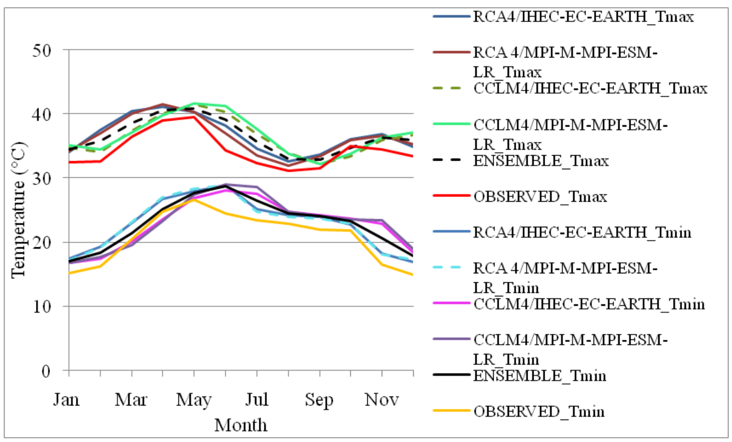
This increase leads to a warm climate in the 2021-2050 periods under both RCP scenarios, relative to the baseline (Figure 60). The scenario 4.5 projects an increase of Tmax from 2.01°C to 2.24 °C representing 5.9% (RCA by the driving MPI) to 6.5 % (RCA/EC-EARTH and CCLM/MPI). The Scenario 8.5 points out an increase of Tmax from 2.10°C (6.1%) to 2.47°C (7.2 %) according to RCA/MPI and RCA/EARTH, respectively. The projected increase in maximum temperature by all the ensemble models as well as from the mean of the ensemble is statistically significant and varies from 6.2 % for the Scenario 4.5 to 6.7 % for the scenario 8.5.
Similarly, for Tmin, the scenario 4.5 highlighted an increase of 2 °C representing 9.7% (CCLM4 /EC-EARTH) and 2.3 °C corresponding to 10.8 % (CCLM/MPI). The scenario 8.5 shows that the projected data rises from 2.3 °C to 2.6 °C (CCLM4/MPI and CCLM/EC-EARTH respectively). The ensemble of the whole RCM/GCM pairs project an increase of 10.2 % for the scenario 4.5 and 11.8 % for the scenario 8.5 from the baseline.
As expected, the increase in temperature is more significant in the RCP8.5 scenario than in the RCP4.5 scenario

Table 39: Projected changes in maximum temperature (°C) for the period 2021-2050 in the Black the Koda Catchment under RCPs 4.5 and 8.5.

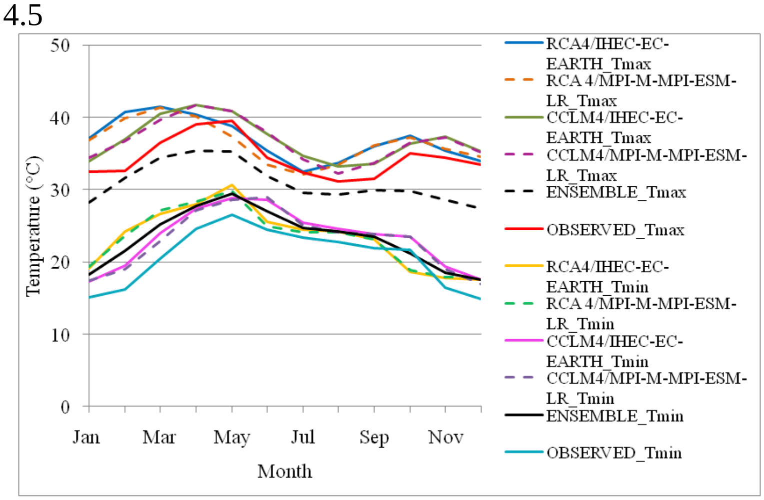
RCMs	Baseline 1987-2016 observed mean value (°C)	Projected period 2021-2050			
		Scenario 45		Scenario 85	
		Average (°C)	% change	Average (°C)	% change
RCA_EC-EARTH		36.6	6.5	36.9	7.2
RCA_MPI		36.4	5.9	36.5	6.1
CCLM_EC-EARTH		36.4	5.8	36.8	7.0
CCLM_MPI		36.7	6.5	36.7	6.6
ENSEMBLE	34.4	36.5	6.2	36.7	6.7

Table 40: Projected changes in minimum temperature (°C) for the period 2021-2050 in the Koda Catchment under RCPs 4.5 and 8.5.

RCMs	Baseline 1987-2016 observed mean value (°C)	Projected period 2021-2050			
		Scenario 45		Scenario 85	
		Average (°C)	% change	Average (°C)	% change
RCA_EC-EARTH	20.8	22.9	10.1	23.3	12.1
RCA_MPI		22.9	10.0	23.3	12.0
CCLM_EC-EARTH		22.8	9.7	23.3	12.3
CCLM_MPI		23.0	10.8	23.1	11.0
ENSEMBLE		22.9	10.2	23.3	11.8



a. Scenario RCP 4.5



b. Scenario RCP 8.5

Figure 60: Observed (1987-2016) and projected (2021-2050) intra-annual Tmax and Tmin under a.RCP 4.5 and b. RCP 8.5.

7.5. Conclusion

The empirical bias correction Quantile-Mapping transformation method applied for bias correction of the rainfall and temperature data was useful in reducing the biases in the RCMs. The corrected output data fitted much closer to the observed data than the uncorrected ones. The RCMs under RCPs 4.5 and 8.5 displayed some biases in reproducing the historical rainfall pattern of the Koda catchment and showed increase and decrease of the rainfall pattern from the baseline. The change is varying from 1.5 % to 10.1 % for the scenario 4.5 and -0.10 % to 25.29 % for the scenario 8.5. The historical temperature of the studied catchment was however well simulated. Unlike rainfall, the projected temperature by the model showed statistically significant increases. Warming of the Koda Catchment is settled up to 2.3°C for Tmax under RCP 4.5 and 2.47°C for the RCP 8.5. The scenario 4.5 projects an increase of Tmin 2.2°C under RCP4.5 and 2.5 °C under RCP8.5.

Chapter 8: Assessment of the effects of Climate Change on Groundwater Resources in the Koda catchment

This chapter discusses the projected changes in groundwater level GWL and the recharge pattern for the period 2021-2050 in the context of climate change. The input data (historical and climate projection data) for the Gardenia model are described in this chapter.

The GARDENIA model was used the observation monthly precipitation data for the past 30 years (1987-2016) for the Katibougou station. The PET data obtained from Blaney and Criddle (1962) method has been used in this study. The piezometric data from three piezometers have been used to calibrate the Gardenia model.

The outputs of RCA4 of the CORDEX experiment at 50 km resolutions by the two driving GCMs (IHEC-EC-EARTH and MPI-M-MPI-ESM-LR) were downscaled statistically and corrected using Quantile Mapping method. The simulation has been done under two RCPs (Representative Concentration Patways) RCP4.5 and RCP8.5. The corrected rainfall and temperatures (Tmax and Tmin) data for the period 2021-2050 have been used in this study. Tmax and Tmin data have been used to obtain the projected PET values applying the Blaney and Criddle (1962) formula (See Chapter 3). A value of 9999 which was settled as missing data was used to refer to the future value of the piezometric data. Futhermore the Thornthwaite method has been used to estimate the future recharge for the period 2021-2050. The Comparison of the groundwater recharge of the two models (Gardenia and Thornthwaite) has been done in order to determine which RCM/ GCM set is more indicate for Climate Impacts Studies in the study area.

8.1. Results

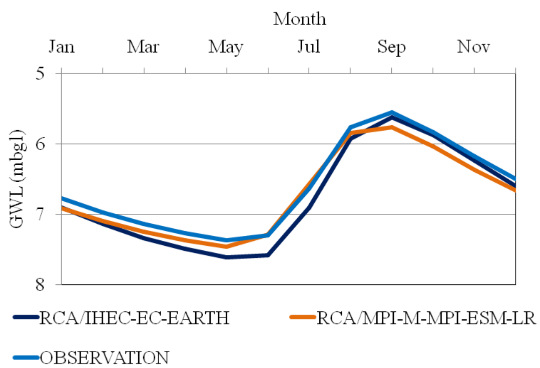
8.1.1. Changes in GWL for the period 2021-2050 under RCP4.5 and RCP8.5 scenarios compared to the baseline period (1987-2016) in the Piezometers using Gardenia model

The analysis of the Water Table Fluctuation in three piezometers has been done through the RCM/GCM pairs (IHEC-EC-EARTH and MPI-M-MPI-ESM-LR) under RCP 4.5 and RCP8.5 and the results are discussed below:

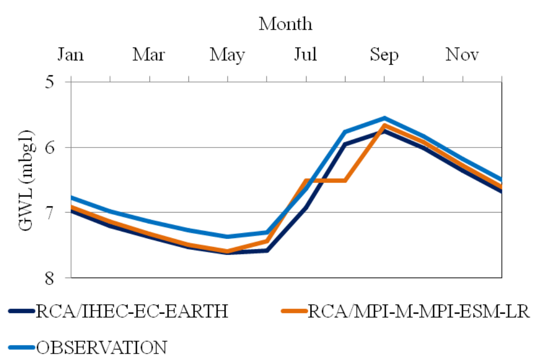
i. **Piezometer Fansiracoura F1**:

For the RCA/ IHEC-EC-EARTH under the scenario RCP4.5, the decrease of GWL is observed over the whole year (January to December). During the recharge period of the aquifer

(September, October and November), the mean monthly GWL recorded from the scenario RCP4.5 was a bit below the observed GWL (decreased from 0.04 to 0.07 m). From December to August, the decrease of GWL was up to 0.28 m compared to the GWL for the months of June and July while under the scenario 8.5, the decrease of GWL as compared to the historical observation period is perceived to be 0.20 m during the renewal period of the water. The reduction is up to 0.30 m during the months June and July. MPI-M-MPI-ESM-LR predicts (under the Scenario RCP4.5) the monthly GWL below the monthly observed GWL and the value is ranged from 0.09 m (May) to 0.21 m (September, October and November). An increase in 0.06 m of the GWL has been observed during the months (June and July). The higher scenario RCP8.5 shows an increase in 0.12 m in July while the decrease was observed over the whole year with significant decrease of up to 0.75 m was recorded in August. **Figure 61** shows the GWL changes of RCA4/ IHEC-EC-EARTH and RCA4/MPI-MMPI-ESM-LR in the piezometer F1 under the scenario 4.5 and 8.5.



a. Scenario RCP 4.5



b. Scenario RCP 8.5

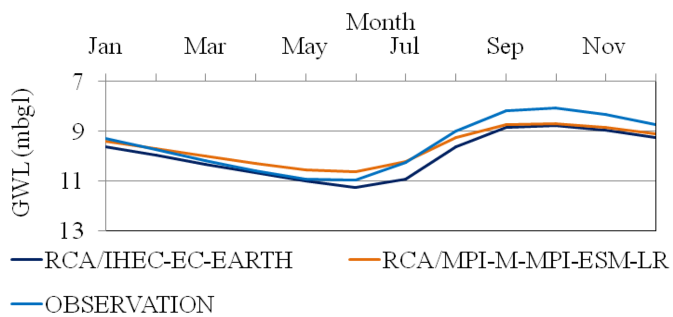
Figure 61: Changes in GWL for the period 2021- compared to the baseline period (1987-2016) in Piezometer F1; a. Scenario RCP 4.5 and b. Scenario RCP 8.5.

ii. Piezometer Kossaba K1

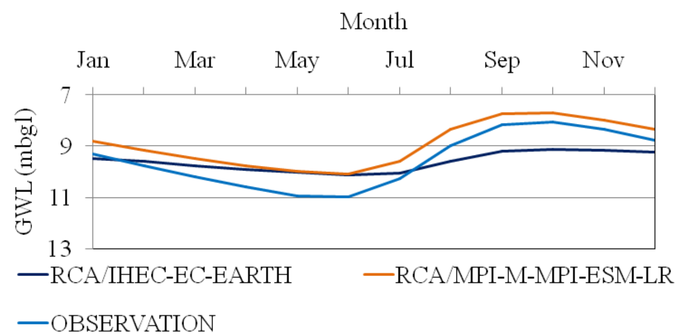
For the RCA/ IHEC-EC-EARTH under the RCP 4.5, the decrease of GWL was recorded over a period of year. The maximum values were recorded from July to November and the values varied from 0.63 m to 0.71 m. The RCP 8.5 shows an increase of up to 1m from February to July and a decrease in GWL from August to January where the maximum value is estimated at 1.05m (**Figure 62**).

The MPI-M-MPI-ESM-LR, under RCP 4.5 shows a decrease of up to 0.7 m of projected water table compared to the observed from August to January. From February to July an increase in GWL of around 0.5 m was observed. Compared to the RCP 8.5, the increase of GWL was observed over the year (January to December). The increase is up to 1 m in May and June (**Figure 62**).

Figure 62 shows the GWL changes of RCA/ IHEC-EC-EARTH and RCA/MPI-MMPI-ESM-LR in the piezometer K1 under the scenario 4.5 and 8.5.



a. Scenario RCP 4.5

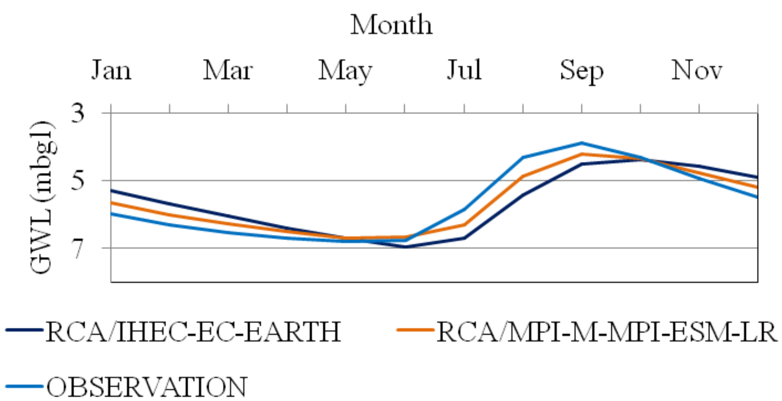


b. Scenario RCP 8,5

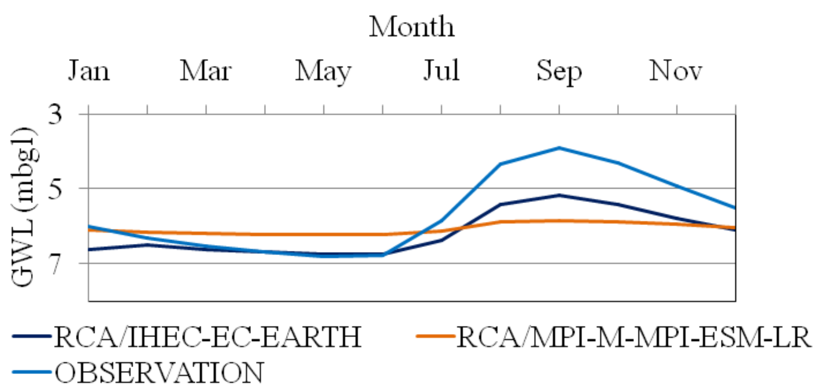
Figure 62: Changes in GWL for the period 2021-2050 compared to the baseline period (1987-2016) in Piezometer K1, a. scenario RCP 4.5 and b. scenario RCP 8.5

iii. Piezometer Nossombougou N1

Under the stationary scenario 4.5, the RCA4/ IHEC-EC-EARTH and RCA4/M-MPI-ESM-LR show a decrease of GWL from June to October and from July to October respectively. In July and August, the RCA4/ IHEC-EC-EARTH shows a decrease of 1.1 m while the RCA/M-MPI-ESM-LR predicts a decrease of 0.6 m. As opposed to the RCP 4.5, the RCA4/ IHEC-EC-EARTH under the RCP 8.5 predicts from July to March a decrease of GWL varying from 0.20 m to 1.26 m where the high level GWL is observed in August, September and October. However, the RCA4/M-MPI-ESM-LR records a decrease of GWL from July to January and the value goes up to 2m in September. The GWL changes of RCA4/ IHEC-EC-EARTH and RCA4/MPI-MMPI-ESM-LR in the piezometer N1 under the scenario 4.5 and 8.5 is highlighted in the **Figure 63**.



a. Scenario RCP4.5



b. Scenario RCP 8.5

Figure 63: Changes in GWL for the period 2021-2050 under RCP4.5 scenario compared to the baseline period (1987-2016) in Piezometer N1; a. RCP 4.5 and b. RCP 8.5.

8.1.2. Changes in Recharge for the period 2021-2050 under RCP4.5 and RCP 8.5 scenarios compared to the baseline period (1987-2016) in the Piezometers.

The projected variation of groundwater recharge over 2021-2050 period in the three piezometers F1, K1 and N1 under RCPs 4.5 and 8.5 of the RCA4 by IHEC-EC-EARTH and MPI-M-MPI-ESM-LR is outlined in the tables (**Table 41, Table 42**and **Table 43**) below:

i. Piezometer Fansiracoura F1

The value of the recharge predicted by the two RCM/GCM pairs in the piezometer F1 ranges from 11.8 mm/y to 46.1 mm/y under the scenario 4.5 while the recharge under 8.5 scenario is estimated from 6.4 mm/y to 44 mm/y. The RCA4/ IHEC-EC-EARTH and RCA4/MPI-M-MPI-ESM-LR under the scenario 8.5 shows the overall decrease of the recharge value compared to the scenario RCP4.5 and the historical observed period 1987-2016.The maximum, minimum and the mean values of groundwater recharge in piezometer F1 for the historical and projected period of the different RCM/GCM pairs are outlined in **Table 41**.

Table 41: Groundwater recharge recorded in Piezometer F1 of observation and projected periods of the RCM/GCMs pairs (RCA4/ IHEC-EC-EARTH and RCA4/MPI-M-MPI-ESM-LR) under 4.5 and 8.5 scenarios.

OBSERVATION period 1987_2016				
	Recharge (mm)		**Recharge/rainfall (%)**	
Maximum	125.7		12.0	
Mean	104.8		10.0	
Minimum	83.8		8.0	
RCA4/ IHEC-EC-EARTH period 2021_2050				
Scenario 4.5			**Scenario 8.5**	
Recharge (mm)		**Recharge %**	**Recharge (mm)**	**Recharge %**
Maximum	46.1	4.6	44.0	3.3
Mean	33.1	3.6	25.2	2.1
Minimum	20.1	2.6	6.4	0.9
RCA4/ MPI-M-MPI-ESM-LR period 2021_2050				
Scenario 4.5			**Scenario 8.5**	
Recharge (mm)		**Recharge %**	**Recharge (mm)**	**Recharge %**
Maximum	33.9	3.0	31.0	2.0
Mean	22.9	2.3	22.6	1.8
Minimum	11.8	1.7	14.2	1.6

ii. PiezometerKossaba K1

Regarding the piezometer K1, the scenario RCP8.5 does not show the similar trend as in the Piezometer F1 described below. The recharge ranges from 11.51 mm/y to 209.4 mm/y under the scenario. However, the recharge is estimated from 15.9 mm/y to 271 mm/y for the high scenario 8.5. The overall mean annual recharge decreases as compared to the historical observed period. The maximum, minimum and the mean values of groundwater recharge in piezometer K1 for the historical and projected periods of the different RCM/GCM pairs are outlined in **Table 42**.

Table 42: groundwater recharge recorded in Piezometer K1 of observation and projected periods of the RCM/GCMs pairs (RCA4/ IHEC-EC-EARTH and RCA4/MPI-M-MPI-ESM-LR) under 4.5 and 8.5 scenarios.

OBSERVATION period 1987_2016				
	Recharge (mm)		**Recharge/rainfall (%)**	
Maximum	303.88		29	
Mean	251.49		24	
Minimum	199.10		19	
RCA4/ IHEC-EC-EARTH period 2021_2050				
Scenario 4.5			**Scenario 8.5**	
Recharge (mm)		**Recharge %**	**Recharge (mm)**	**Recharge %**
Maximum	209.44	18.09	271.2	16.33
Mean	128.49	11.72	143.57	9.18
Minimum	47.542	5.35	15.94	2.03
RCA4/ MPI-M-MPI-ESM-LR period 2021_2050				
Scenario 4.5			**Scenario 8.5**	
Recharge (mm)		**Recharge %**	**Recharge (mm)**	**Recharge %**
Maximum	196.43	15.34	228.30	13.73
Mean	103.97	8.59	152.19	10.69
Minimum	11.51	1.83	76.09	7.64

iii. Piezometer Nossombougou

All the scenarios are projecting the recharge from 11mm/y to 250 mm/y. The scenario 8.5 shows the greatest range of recharge compare to the scenario 4.5. However, the observed historical period was the period which showed more recharged water in that part of the studied catchment.

The maximum, minimum and the mean values of groundwater recharge in piezometer N1 for the historical and projected period of the different RCM/GCM pairs are outlined in **Table 43**:

Table 43: groundwater recharge recorded in Piezometer N1 of observation and projected periods of the RCM/GCMs pairs (RCA4/ IHEC-EC-EARTH and RCA4/MPI-M-MPI-ESM-LR) under 4.5 and 8.5 scenarios.

OBSERVATION period 1987_2016				
	Recharge (mm)		**Recharge/rainfall (%)**	
Maximum	251.69		31.23	
Mean	147.06		20.08	
Minimum	42.42		8.94	
RCA4/ IHEC-EC-EARTH period 2021_2050				
Scenario 4.5			**Scenario 8.5**	
Recharge (mm)		**Recharge %**	**Recharge (mm)**	**Recharge %**
Maximum	185.15	16.03	251.99	14.85
Mean	102.77	9.21	131.56	8.16
Minimum	20.39	2.39	11.14	1.47
RCA4/ MPI-M-MPI-ESM-LR period 2021_2050				
Scenario 4.5			**Scenario 8.5**	
Recharge (mm)		**Recharge %**	**Recharge (mm)**	**Recharge %**
Maximum	196.43	15.34	200.77	12.72
Mean	103.97	8.59	127.69	8.87
Minimum	11.51	1.83	54.61	5.03

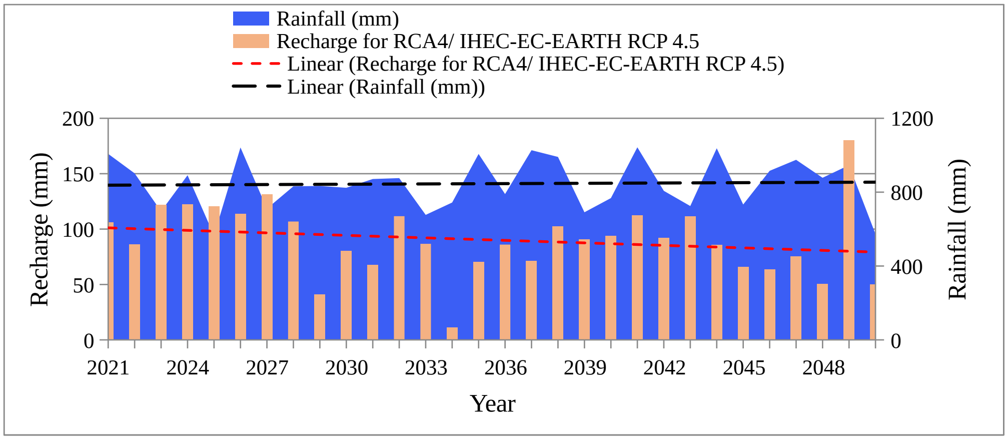
The results show that, during the period of rainy season, the groundwater level decreases in the piezometers within Koda catchment for all the two RCMs compared to the observed data. According to the RCA4/ IHEC-EC-EARTH, the predicted decrease of GWL is up to 1.1 m for the RCP 4.5 and 1.3 m for the RCP 8.5 within the Koda catchment while the RCA4/ MPI-M-MPI-ESM-LR showed the decrease of GWL during the rainy season from 0.7 m for the RCP 4.5 to 2 m for the RCP 85. The decrease is more significant for the RCP 8.5 than the RCP 4.5 except in the piezometer Kossaba located near to the outlet of the studied catchment where the RCA4/MPI-M-MPI-ESM-LR projects an increase up to1 m in May –June of the observed GWL under the RCP 8.5.

8.2. Changes in annual Recharge for the period 2021-2050 under RCP4.5 and RCP 8.5 scenarios for the RCA4/IHEC-EC-EARTH and RCA4/MPI-M-MPI-ESM-LR climate simulations.

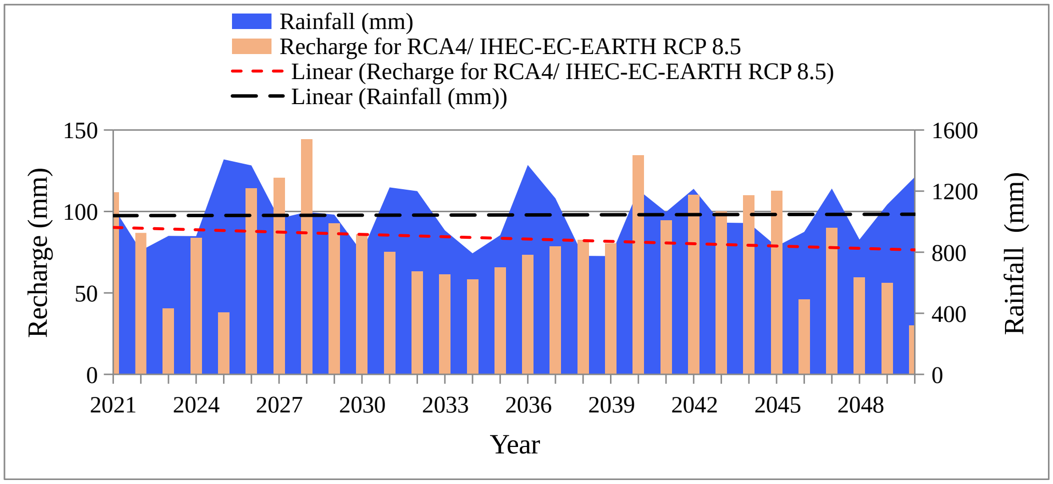
8.2.1. Recharge for RCA4/IHEC-EC-EARTH

The recharge for RCA4/IHEC-EC-EARTH in the RCP 4.5 is decreasing for the year from 2029 to 2034 and from 2044 to 2047. The dry period is observed in the years 2023, 2025 and 2029 to 2039, and 2046-2050 under the RCP 8.5scenario (**Figure 64**).

The recharge is decreasing over time for both scenarios, but it is so highlighted in RCP 8.5 than RCP 4.5. The projected mean annual recharge of the RCA4/IHEC-EC-EARTH corresponds to 90 mm (11% of the Mean Annual Rainfall, MAR) for the RCP 4.5. The RCP 8.5 scenario projects the mean annual recharge at 84 mm (8% of MAR).



a. RCA4/ IHEC-EC-EARTH-RCP 4.5

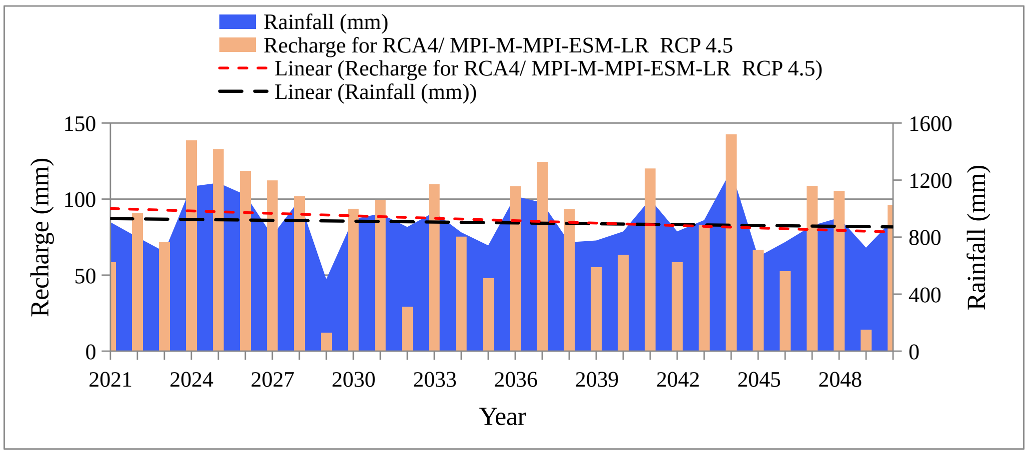


a. RCA4/ IHEC-EC-EARTH-RCP 8.5

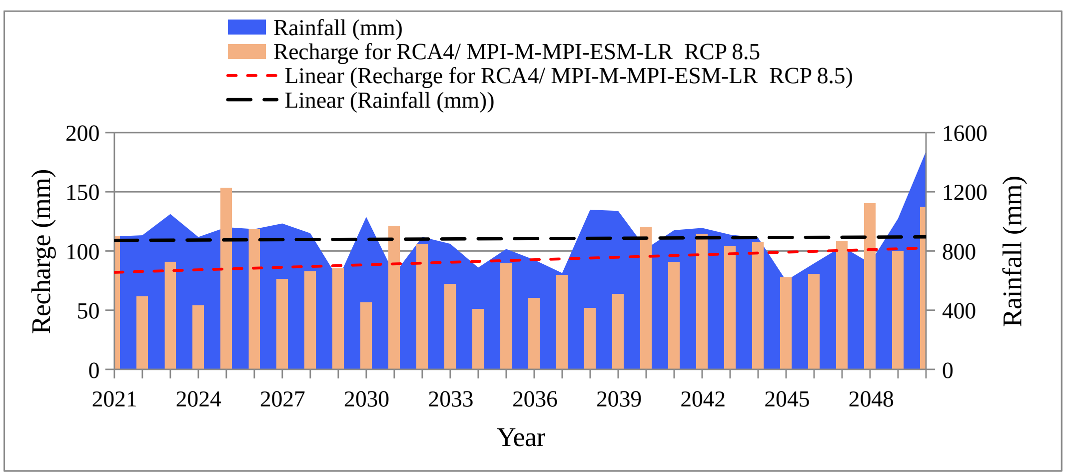
Figure 64: Changes in annual Recharge for the period 2021-2050 for the RCA4/IHEC-EC-EARTH

8.2.2. Recharge for RCA4/MPI-M-MPI-ESM-LR

The RCA4/MPI-M-MPI-ESM-LR under the scenario RCP 4.5 projects the decrease of the annual recharge for the period 2029 to2050. Some wet periods have been observed in the year 2024, 2041 and the year 2044. In the RCP 8.5 shows globally the increase of the projected recharge over the period 2021-2050. The decrease is observed in the year 2024, 2009, 2034 to 2039 (**Figure 65**). The RCP 4.5 scenario settle the projected recharge at 86.06 mm (9.5 % of MAR) while the RCP 8.5 scenario project the mean annual recharge is about 92 mm corresponding to 10.4 % of MAR. The recharge is decreasing in the RCP 4.5 while it is increasing in the RCP 8.5.



a. RCA4/MPI-M-MPI-ESM-LR-RCP 4.5



b. RCA4/MPI-M-MPI-ESM-LR-RCP 8.5

Figure 65: Changes in annual Recharge for the period 2021-2050 under a. RCP4.5 and b. RCP 8.5 scenarios for the RCA4/MPI-M-MPI-ESM-LR

The recharge decreases from 2021-2050 where the severe drought period is projected in the 2030s especially from 2029-2039. This same trend has been observed from the Thornthwaite method used to estimate the projected annual recharge for the period 2021-2050. The estimation of the recharge is based on the mean recharge value obtained from Gardenia model. The Soil Moisture Storage (SMS) capacity has been calibrated to be 250 mm by comparing the groundwater recharge of the two models (Gardenia and Thornthwaite).

8.3. Partial conclusion

The hydrogeological response of a catchment to climate change is strongly depended on the input data. Gardenia model was run using the outputs of RCA4 downscaled from two driving GCMs (IHEC-EC-EARTH and MPI-M-MPI-ESM-LR) under RCP 4.5 and RCP 8.5. The results show that, during the period of rainy season, the groundwater level decreases in the piezometers within Koda catchment for all the two RCMs compared to the observed data. According to the RCA4/ IHEC-EC-EARTH, the predicted decrease of GWL is up to 1.1 m for the RCP 4.5 and 1.3 m for the RCP 8.5 within the Koda catchment while the RCA4/ MPI-M-MPI-ESM-LR showed the decrease of GWL during the rainy season from 0.7 m for the RCP 4.5 to 2 m for the RCP 85. All the two RCMs project a decrease of groundwater recharge over time. It is obvious that this decrease is more significant in RCP8.5 some parts of the Koda catchment. The results also show that the predicted mean annual recharge (90 mm) in the future is below the recharge of the present dry conditions which is 180 mm. This might lead to scarce groundwater resource in future.

In both models (Gardenia and Thornthwaite), the RCP 4.5 projects a dry period in IHEC-EC-EARTH model and in MPI-M-MPI-ESM-LR model. The opposite is observed in the projection of 8.5, i.e., the recharge decreases in Earth model while it is increasing in MPI-M-MPI-ESM-LR model for the RCA4- IHEC-EC-EARTH the recharge is decreasing over time for both scenarios (RCP 4.5 and RCP 8.5), but it is so highlighted in the scenario 8.5 than the scenario 4.5. The RCA4 –IHEC-EC-EARTH has shown the best simulation over the Koda catchment for the Gardenia model as well as for the Thornthwaite model.

Chapter 9: Effects of Land Use and Land Cover change on groundwater recharge over Koda catchment.

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. 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 (Ashaolu et al., 2019). 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). 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 a 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 been 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 for better understanding 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 periods 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.

9.1 . Results and discussion

9.1.1. Dynamics of LULC

The Koda catchment is chiefly characterized by five (5) types of Land Cover units and these are Herbaceous Savannah, Degraded Savannah, Cultivated Land, Shrubby Savannah and Bareland (**Figure 66**). These 5 types of LULC over 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 the year 2001. The three LULC are savannah, cropland and settlement. Savannah is represented by three types of savannah: 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 other buildings.

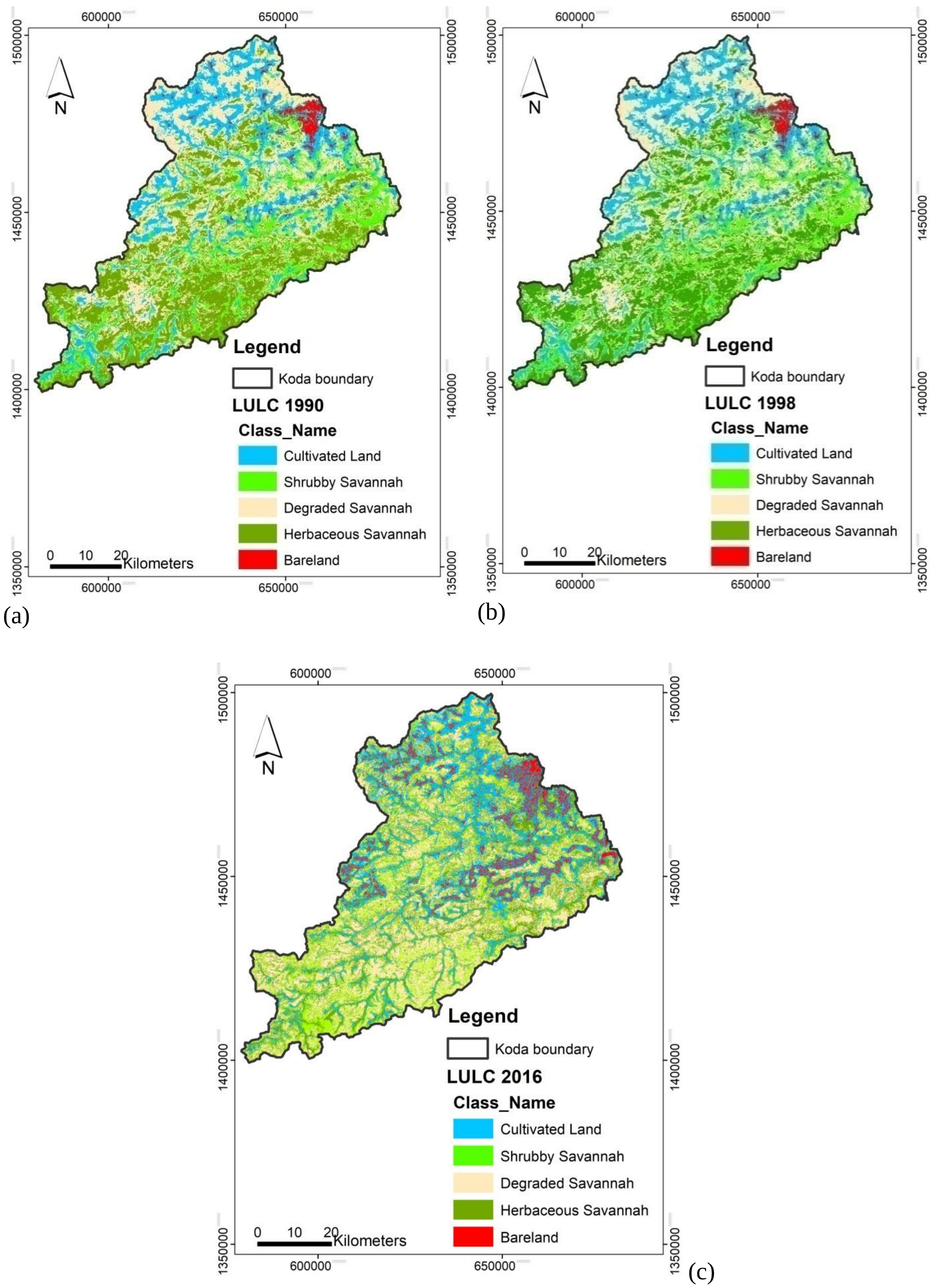


Figure 66: Different units of LULC in the Koda catchment, (a) year 1990, (b) year 1998 and (c) year 2016.

The comparison in terms of total area of LULC category has been done and the results are outlined in **Table 44**. The land used for agriculture purposes changes considerably from 125 Km^2 in 1990, 200.39 km^2 in 1998 and to 856 km^2 in 2016 representing respectively an increase of 2.54%, 4.07 % and 17.40 %. In general, bare land varied from 50 km^2 to 1204 km^2 between 1990 and 2016 while there was an increase of 23.5 % (representing 1154.57 km^2 of the basin). Herbaceous savannah decreased from 57.46 % of the total area of the catchment (2827.68 km^2) 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 Km^2) 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.

Table 44: Land use and land cover area and area change for the years 1990, 1998 and 2016.

	Area km^2			Ratio of LC unit over Koda's total area (%)		
Unit	**1990**	**1998**	**2016**	**1990**	**1998**	**2016**
Cultivated Land	125	200.39	856	2.55	4.07	17.40
Bare land	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

The graphic representation of the results is given by the **Figure 67**. 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.

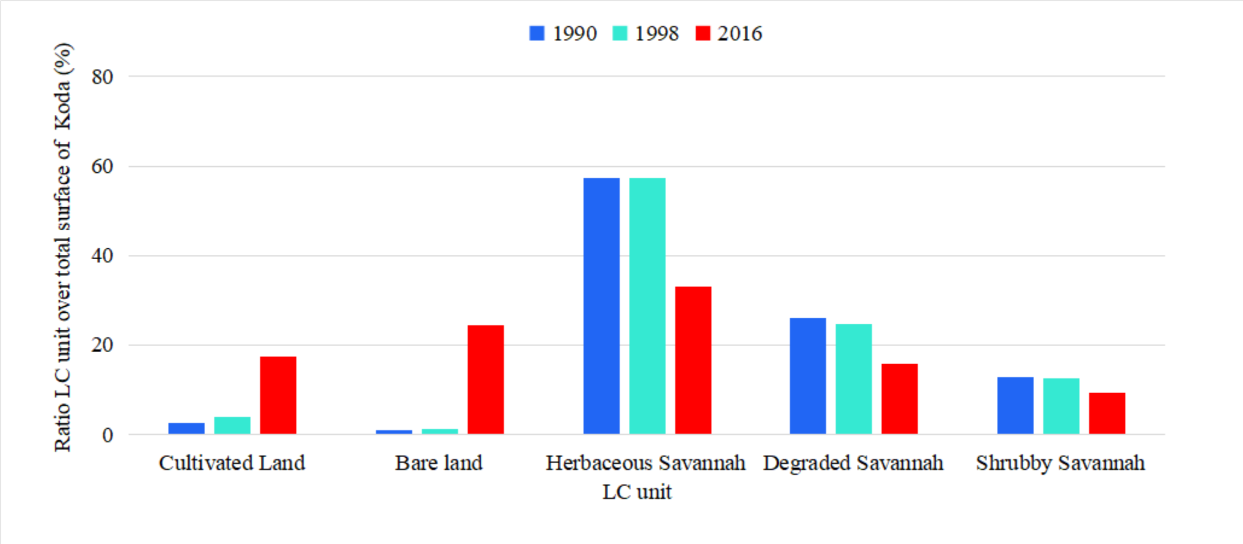


Figure 67: Ratio of LULC unit over total surface of Koda catchment in the years 1990, 1998 and 2016

Based on these results, there was an increase of 23.5 % and 14.9 % 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 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 savannah 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 are 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.

9.1.2. 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 45**.

Table 45: Kappa coefficient (K) values of each land use and land cover type

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

9.1.3. 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; 278,21mm/y and 257 mm/y respectively for piezometer K1 and finally 118, 87mm/y and 108 mm/y for the piezometer N1. The variation of the recharge pattern for the years 1990, 1998 and 2016in the three piezometers (F1, K1 and N1) over Koda catchment are shown in the **Figure 68**.

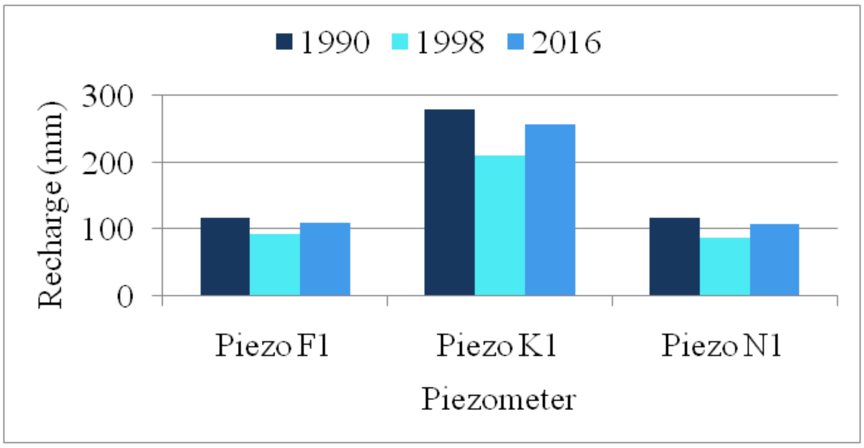


Figure 68: Mean Annual Recharge in the three piezometers for the years 1990, 1998 and 2016

The overall mean recharge variation from 1990-2016 over the entire catchment of Koda is outlined in **Table 46**. 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.

Table 46: 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

-signifies decrease in groundwater recharge

+ signifies increase in groundwater recharge

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 are also one of the principal parameters that control the groundwater recharge.

The effect of LULC change on groundwater recharge in Koda catchment indicates that there are only little changes in recharge pattern that can be associated 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 from 1990-2016 over the Koda catchment.

9.2. Conclusion

The classification of LULC has been done with satisfactory with the excellent range of the Kappa coefficient (K). Five major types of LULC (bare land, cultivated land, herbaceous savannah, degraded savannah and shrubby savannah) have been identified over Koda catchment. 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 24.4 %, degraded savannah, 3.6 % and Shrubby Savannah 10.32 %. Savannah areas in Koda catchment are converted to agricultural land and urban area due to human activities. The types of LULC over Koda catchment could be described as Savannah (herbaceous, shrubby and degraded savannah), Settlement (bare land) and Cropland (cultivated land). The decline of 8.4 % in groundwater recharge associated to the decrease of savannah and the increase of bare land and cultivated land might become so far obvious 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 can be used for predicting the future LULC changes.

Chaper10: General Conclusion

10.1. Core Findings

This study assessed the effects of global (Climate and Land Use/Land Cover) change on groundwater resources over Koda catchment. The study reveals that the potential effects of projected Climate and LULC can be properly quantified for the Koda catchment using a hydrological model with the outputs of a set of Regional Climate Model RCM driving by Global Climate Models (GCM). The use of various climate scenarios provided a great idea on the sensitivity of groundwater to the changes in climate patterns. The general conclusion of this study is that Climate and Land Use Land Cover changes are negatively threatened by groundwater resources over the study area. The groundwater recharge decreases with time from 1987-2050 in the Koda catchment. The projected effects of climate change will be obvious by the period 2029-2039 on groundwater; this means that the socioeconomic activities such as agriculture which depend on water resources and will be negatively affected. Therefore, it is necessary to develop a proper water management plan of these resources.

The study of LULC dynamics reveals some alterations in the LULC classes from 1990 to 2016. Furthermore, the decline of 8.4 % in groundwater recharge associated to LULC change might become so far obvious in the future if the population continue to use wood as energy source with the current rate of deforestation over the Koda catchment. There is the need to develop a proper LULC management strategy within the study catchment. The results can be used by environmentalists and decision makers for predicting the future LULC changes. The obtained information on the projected potential consequences of these warming scenarios might help policy makers to well manage the groundwater resources over Koda catchment by reorienting their planning strategies in the context of global (Climate and LULC) change.

10.2. Solutions to Thesis Specific Objectives

The thesis has found solutions to all of its specific objectives and these are discussed as follows:

OBJECTIVE 1: Assessment of rainfall variability over the 30 past decades of the Koda catchment.

This study analyses, at local and regional scales, the rainfall variability across Koda catchment for the period 1987-2016. Rainfall data recorded from three meteorological stations (Bamako, Katibougou and Toubougou) were used. Several methods such as rainfall index and Lamb index have been used in order to characterize the inter-annual variability of rainfall.

Furthermore, the three moving averages were used to determine the dynamics of the mean seasonal cycle of the precipitation. In addition, the non-parametrical Lee and Heghinian test (1977), Pettitt's method (1979), the U-statistic of Buishand (1982) and the segmentation of Hubert (1989) have been evaluated through Khronostat software in order to detect the break point in the rainfall series. Some break points have been detected for example 1988, 1991, 2006, 2015 and 2016. These breaks have resulted in various deficits over two different years given by 1991 (13 %), and 2016 (39%) and an excess over three years which are 1988 (16 %), 2006 (36%), and 2015 (21%). The study shows that the following years 1991 and 2016 have suffered from a severe drought within the period of 1987–2016. The years 1988, 2006and 2015 were extremely wet.

OBJECTIVE 2: Estimation of groundwater recharge with various techniques

The 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. To have a reliable groundwater recharge value it is recommended to combine groundwater recharge estimation methods. Therefore, empirical methods (Water Table Fluctuation method and Thornthwaite method) and Gardenia model have been combined to characterize the annual recharge of the Koda catchment. These methods are considered as attractive due to their simplicity, accuracy, the ease of use and low cost of application in the semiarid areas:

i. **Estimation of groundwater recharge using Thornthwaite method**

Thornthwaite method was used in this study in order to estimate the groundwater recharge as well as the other components of the water cycle over the study catchment.

The study estimated the values for water balance components of the Koda catchment for the period 1987- 2016: AET 66% to 100 %, Recharge 1 % to 8 % and Effective Rainfall 0 to 34 % of the annual rainfall.

ii. **Estimation of Groundwater recharge through Water Table Fluctuation method**

The annual groundwater recharge was estimated from the annual precipitation of the Koda catchment using Water Table Fluctuation (WTF) method. 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 between 61 mm and 173 mm, i.e., between 7% and 29 % of annual rainfall while for the four wells the mean recharge varied from 26 mm to 186 mm corresponding to 3% and 26 % of the annual precipitation.

The results obtained as mean annual recharge are very similar to those found in the previous studies undertaken in similar aquifers systems and under same climatic conditions. The values of recharge obtained from WTF method applied to Koda catchment ranged between 7% and 29 % of annual rainfall for the three monitoring piezometers while the mean recharge varied from 3% to 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 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.

iii. **Estimation of groundwater recharge using Gardenia model**

Gardenia model was used in the Koda catchment, southeastern part of Taoudeni basin using hydrological and hydrogeological data (1987-2016).

The hydrogeological modelling of the Koda catchment using Gardenia model was a great tool of the calculation of the water budget components and the estimation of groundwater recharge. The simulation of piezometric levels, discharge and recharge in the period 1987-2016 from available piezometric permitted the evaluation of the variability of recharge.

Recharge in the study area varied from 117 mm to 246 mm corresponding respectively to10% and 23 % of annual rainfall. The amount of the AET was estimated from 60% to 67% of the annual rainfall. The overall annual effective rainfall varied from 310 mm to 422 mm corresponding to 23 % and 40 % of the annual rainfall. The outputs of the model showed that, in the absence of surface flow measurements, it is not possible to estimate the storage coefficient of aquifers. The hydrogeological modelling of the Koda catchment using Gardenia model was a satisfactory tool for the calculation of the water budget components and the estimation of groundwater recharge. The results of the hydrogeological modellling of the Koda catchment seem good and in line with those values found in similar hydrogeologic regions.

OBJECTIVE 3: Simulation of groundwater flow over the Koda Catchment.

The groundwater flow model Visual Modflow was used to simulate the dynamics of groundwater flow in the Koda catchment. Hydrogeological, geological, topographical, climatological data collected from historical and current field data were used as model inputs.

Another most important input parameter of the model is groundwater recharge, which was estimated applying the lumped Gardenia model in the study area and obtained 20% of annual precipitation as the recharge value. The Visual Modflow model domain was discretized into grids (50 columns, 50 rows) with a total grid cell number of 2500 with a grid dimension 300m *300 m. Digital Elevation Model (DEM) from Hydroshed was used to interpolate hydraulic head through the study catchment scale, which was entered to the model as starting hydraulic head.

The infra-Precambrian sandstones aquifer in the study area was simulated under steady state condition. After development and calibration of the model using trial and error's estimation of hydraulic head, the correlation coefficient (R^2) was 0.98 with 4.84 m and 6.05 % as Root Mean Square and Normalized RMS respectively while the Standard Error of the Estimate was 1.19m. The results showed the good fit between measured and calculated water levels. In conclusion, the Visual Modflow model can be used to simulate the underground water level in the research area.

OBJECTIVE 4: Evaluation of future effect of Climate Change on groundwater level fluctuations in the Koda catchment using a multi-climate model data sets.

This study evaluates the impact of Climate Change on groundwater resources in semi-arid Catchment in Mali, West Africa. The Hydrogeological modeling was set up using Gardenia model with the Rainfall and Temperature values for the Baseline using values for the past 30 year period (1987-2016) and projected for the future 30 years (2021-2050). The projected Rainfall and Temperature derived from the outputs of three Regional Climate Model (RCMs) by three driving GCMs under the Representative Concentration Patways RCP 4.5 and RCP 8.5 Scenarios, were statistically downscaled and corrected using Multiscale Quantile Mapping bias correction method. The sensitivity parameters between historical data and the observed data recorded at Katibougou station have been calculated in order to select the best set of RCMs with best correlation parameters. Therefore, RCA4 driving by two GCMs (IHEC-EC-EARTH and MPI-M-MPI-ESM-LR) was selected in this study. The Rainfall, PET values and groundwater levels in three piezometers were used as the inputs of the Gardenia model. The results show that, during the periods of rainy season, July, August, September and October the Groundwater level decrease in the piezometers within Koda catchment for all the two RCMs. According to the GCM IHEC-EC-EARTH, the predicted decrease of GWL is up to 1.09 m for the RCP 4.5 and 1.26 m for the RCP 8.5 within the Koda catchment while the GCM MPI-M-MPI-ESM-LR showed the decrease of GWL during the rainy season from 0.62 m for the RCP

4.5 to 1.93 m for the RCP 85. The decrease is more significant for the RCP 8.5 than the RCP 4.5 except in the piezometer Kossaba located near the outlet of the studied catchment where the GCM MPI-M-MPI-ESM-LR projects an increase of 0.67 m of the observed GWL under the RCP 8.5.

All the two RCMs project a decrease of Groundwater recharge over time. It is obvious that this decrease is more significant in RCP8.5 for all the piezometers. The results also show that the mean recharge (90 mm) in the future 2021-2050 is below (180 mm) that of the present (1987-2016) dry conditions, which might lead to severe droughts events.

OBJECTIVE 5: Improvement of the undestanding of LULC Change on soil infiltration rate in the Koda Catchment.

A Land use land cover LULC dynamics study is crucial for any global environmental change evaluation. LULC change is considered as an important factor that affects water cycle components for a given place. To evaluate the dynamics of the LULC change over Koda catchment, the spatiotemporal variation of the different units of LULC present in the catchment has been examined. The Supervised Classification method, using Envi 4.5 Software coupled with Arcgis, was applied to subset Landsat images from 1990 to 2016.

Five major LULC categories, cultivated land, bare land, herbaceous savannah, shrubby savannah and degraded savannah, were identified in the catchment. 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 %.

Savannah areas in Koda catchment is converted to agricultural land and urban area due to human activities. There is a need to closely monitor the changes in LULC for sustainable development. The decline of 8.4 % in groundwater recharge associated to the decrease of savannah and the increase of bare land and cultivated land might become so far obvious in the future if the current rate of deforestation continues in the Koda catchment. The results can be used for predicting the future LULC changes. It can be used by environmentalists and policy makers to well manage the groundwater resources over Koda catchment.

10.3 Answers to research questions

Climate and Land Use/Land Cover changes are two major challenges for water resources in West Africa. The assessment of the effects of global change (Climate and Land Use/Land Cover Change) on water resources has been carried out in this study in Koda catchment. The scientific approach of this study combined field investigations, physical methods, hydrological modeling and application of different scenarios of Climate and LULC.

The methodology followed by the study was varied and precise and the obtained results allow answering all the research questions formulated in chapter 1. The answers to the research questions are discussed below.

a) How does rainfall variability occurr in the Koda catchment ?

   The variability of rainfall has been manifested in the Koda catchment through a deficit varying from 13 % to 39 % and an excess ranging from 16 % and 21% over the period 1987-2016.In the Koda catchment, the rainfall is unimodal, the rainy season from June to October with 93% of the annual rainfall and the dry season fromNovember to May with 7% of the annual rainfall. The highest values are recorded in July and August with 56% of the annual rainfall followed by September and June with 17% and 15% respectively of the annual rainfall.

b) What is the annual recharge in the Koda catchment?

   The values of annual recharge estimated from Thornwhaite method (1 % - 8 % of annual rainfall) are a bit below those obtained from WTF and Gardenia model. The results of the Water Table Fluctution methods (7% -29 %) and those from the Gardenia model (10 % -24 %) were very close and they could be used as an accurate range of the groundwater recharge characterizing the studied catcthment. The overall mean annual recharge was settled to 17 % of the Mean Annual Rainfall (MAR).

c) What are the hydrogeological parameters of the Koda Catchment?

   Hydraulic conductivity and effective permeability describe the main hydrogeological parameters in the Catchment. The values of hydraulic conductivity (K) ranged from 4.9 10^{-5} m/s to 11 10^{-2} m/s within five zones where the K value is homogenous and isotropic over every single zone. The value of K of the sandstones is greater than the other parts of the catchment. Two types of permeabilities characterized the catchment, the rapid variation permeability in the sandstones and the slow to moderate permeability due to the fissures in the dolerites in the western part of the catchment. The value of the specific yield (Sy) is settled to 0.11.

d) How will changesin Climate Changeimpact the availability of groundwater resources in the Koda catchment by 2050 using a set of RCM/ GCM pairs?

   The changes in climate patterns will negatively impact the availability of groundwater resources over Koda catchment. All the GCM/RCM pairs used in this study project a decrease of groundwater level and groundwater recharge over time. It is obvious that this decrease is more significant in RCP8.5. The recharge is decreases over time from 1987-2050 especially in the period 2029-2039. The results also show that the mean annual recharge in the future (90 mm) is below the present dry conditions (180 mm), which might lead to the severe drought events. The RCA4 –EC-EARTH has shown to be the best simulation over the Koda catchment for the Gardenia model as well as for the Thornthwaite model.

e) What are the effects of the Land Use/ Land Cover change on groundwater recharge?
   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 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

10.4 Contribution of research findings to the field in general

The various findings from this research have contributed creditably to knowledge in the field. Although some previous studies were done in West Africa, some few in Mali, no known study has been done in Koda catchment addressing the assessment of Climate and LULC effects. This study differs from the previous existing works. The study was carried out on a local scale where there is a lack of the historical data. Among others, this research has considered the following:

a) The variability of rainfall over the 30 past years period in the Koda catchment.
b) the investigation into groundwater recharge at different scales over Koda catchment using various methods and models.
c) the simulation of groundwater flow over Koda catchment.
d) the projected temperature and precipitation trends over the Koda catchment by 2050.
e) the GCM/RCM pairs in Climate change assessment; and finally
f) the dynamics of LULC change from 1990 to 2016 and its effects on groundwater.

10.5 General Implications of Research Findings

a) The results of the thesis could be used as a great tool of Integrated Water Resources Management (IWRM) at the Koda catchment scale.

b) The projected effects of climate change will be obvious by the 2030s (2029-2039) on groundwater; this means that the socioeconomic activities which depend on water resources such as agriculture will be negatively affected.

10.6 Summary of what has been learned and how they can be applied

a) The general conclusion of this study is that the Climate and Land Use Land Cover changes are negatively threatened groundwater resources over the study area.
b) The projected effects of climate change will be obvious in the period 2029-2039 (where the simulated droughts events are expected) on groundwater which is projected to be inadequately scarce. Therefore, it is necessary to develop a proper water management plan of these resources to offset these difficulties.

10.7 Variations, extensions or other applications of the central idea

The central idea is that climate and LULC changes affect groundwater recharge in the Koda Catchment. This idea was finding to be true over the all GCM/RCM pairs used except the-MPI-M-MPI-ESM-LR under the scenario RCP 8.5 where this idea deviated. The GCM/RCM pairs used in this study project the decrease of groundwater level and groundwater recharge over time. Only the RCA4/MPI-M-MPI-ESM-LR -project under the scenario 8.5 an increase of groundwater recharge over time. This may be due to the quality of the climate simulations data of the MPI-M-MPI-ESM-LR. The central idea of this thesis can be extended to the entire Mali in order to help to develop sustainable adaptation strategies and reduce water resources vulnerability to climate and LULC changes.

10.8 Outlook

a) Since groundwater is the main source of water supply to the inhabitants of the Koda catchment it is recommended to protect these resources by reducing its vulnerability with respect to the effects of Climate and Land Use/ Land Cover Changes. This study will serve as a useful resource in the water management purpose of the region, and it can be also a guide for future studies.
b) To reach a more definitive conclusion, future work must seek to explore and improve climate simulation by using more models to increase the level of confidence in the projections in order to reduce uncertainties and discrepancies in model outputs. The

future work should be concentrated on the simulation of the potential future Land Use Land Cover (LULC) distributions over the Koda catchment.

c) This study has been done in the region with scare observational data, it is recommended that policy makers take action about building a great dataset of hydrological and hydrogeological data which will be continuously updated.

d) The piezometers within the basin are not well spatially distributed, thus, it is recommended to install more piezometers with automatic data loggers which are easy to use.

e) The Koda catchment is an ungauged basin, and this was a real handicap in the choice of some robust hydrological model which required discharge data as input. Hence, it is recommended for the authorities to put plans into place to make Koda catchment a gauged basin.

f) To reduce the vulnerability of Koda catchment from the effects of Climate and Land Use Change, we recommend to policy makers:

- To take an informative decision about allocation and protection of groundwater under a changing climate and land use land cover changes.
- To plan future irrigation based on the annual recharge value.
- To advise farmers to use crops which are resistant to water stress.
- Some water saving technologies could also be developed to reduce the consequences of water shortage.
- To promote and develop the use of sources of energy (Solar energy, wind energy) in order to reduce the use of renewable fuel wood.
- To extend this study to the entire Mali country.

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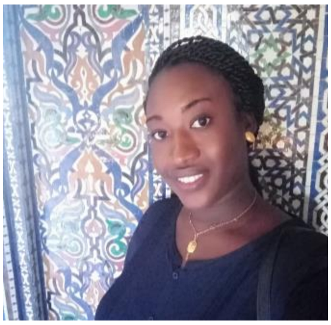

Candidate biography

Oumou DIANCOUMBA (Mrs) was born at Bamako, Mali. After bagged her baccalaureate degree in Bamako, she was selected as a recipient of Morocco government scholarship for international students where she earned her bachelor's degree in Hydrogeology (2006) at the Faculty of Science and Technology ofCaddy Ayyad University, Marrakech, Morocco. She completed her master's degree in Natural Resources (2008) at Ibn Tofail University of Kenitra, Morocco. Mrs. DIANCOUMBA joined in 2009 the team of Sonatrach International for Petroleum Exploration and Exploitation, SIPEX- MALI Branch before travelling to Japan in 2011 where she was involved in many activities and researchsponsored by EPIC and the University of EHIME, Matsuyama, Japan. In 2016, Mrs DIANCOUMBA proceded her Doctoral study in Abomey Calavi University in Benin which was sponsored by the German Federal Ministry of Education (BMBF) through the West African Science Centre on Climate Change and Adapted Land Use (WASCAL) initiative. During her doctoral she wins travel grants from many international organizations such as UNESCO, AUF and AUSTIN grants which permit her to present her work in Tunisia, France and USA respectively. Her research involves Climate Change Impacts Studies, groundwater resources, hydrological modeling and Geology. She speaks French, English, Japanese and Bambara.

***Abstract*:**

Climate and Land Use/ Land Cover (LULC) changes are the key factors that can modify water resources availability. Water resources especially groundwater is a vital and permanent source of water in the Koda catchment (4921 km^2). This study aimed to assess the effects of global (Climate and Land Use/Land Cover) change on groundwater resources in the southern part of Mali, case of Koda catchment. Investigations and Analyses carried out in this study include (a) the study of the variability of rainfall over the 30 past years period (b) the estimation of groundwater recharge at different scales over the catchment using various methods and model (c) the simulation of groundwater flow (d) the exploration of projected temperature and precipitation change trend by 2050, (e) the use of GCM/RCM pairs in Climate change assessment study and finally (f) the determination of the dynamics of LULC change from 1990 to 2016 and its effects on groundwater. The study reveals that the potential effects of projected Climate and LULC can be properly quantified for a given catchment using a hydrological model with the outputs of a set of Regional Climate Model RCM driving by Global Climate Models (GCM). The results show that the groundwater recharge is decreasing over time from 1987-2050 in the Koda catchment. The severe projected drought events occur in the period 2029 -2039. The study of LULC dynamics reveals some alterations in the LULC classes from 1990 to 2016. Furthermore, the decline of 8.4 % in groundwater recharge associated to LULC change might become so far obvious in the future if the population continue to use wood as energy source with the current rate of deforestation over the Koda catchment. The general conclusion of this study is the Climate and Land Use Land Cover changes are negatively threatened groundwater resources over the study area Therefore it is necessary to develop a properly water management plan of these resources. The obtained information on the projected potential consequences of these warming scenarios might help policy makers to well manage the groundwater resources over Koda catchment by reorienting their planning strategies in the context of global (Climate and LULC) change.

***Key words*:** Groundwater resources, Climate Change, LULC change, RCM-GCM pairs, Koda catchment, Mali.

Aside page

PhD	**Candidate Name** Oumou DIANCOUMBA	**Thesis Title** Assessment of the Effects of Climate and Land Use /Land Cover Change on Groundwater Resources in Koda Catchment, Mali, West Africa	**GRP/CCWR/INE/WASCAL – UAC** **November, 2020**